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STUDY OF REDUCTION OF GLARE, REFLECTION, HEAT AND NOISE TRANSFER IN AIR TRAFFIC CONTROL TOWER CAB GLASS

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FINAL REPORT

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16. Abstract

The results of a study to formulate methods to reduce the glare, reflections and heat and noise transmission of the glass area of ATCT cabs are described. As a result of field surveys of various ATCT cabs, consultation with glass manufacturers, and technical report searches, several recommendations (to reduce the foregoing disturbances) were submitted.

Practical factors considered include the shape of the cab, tilt angle of cab glass, type of glass, heating and air conditioning requirements, window fogging, and environmental noise. A cost versus benefit model has been made for evaluating the effect of glare and reflections on controller tasks in a simulated ATCT cab environment.

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1. INTRODUCTION

1.1 Background

Air traffic controllers in tower cabs are subject to many adverse physical and psychological factors which can degrade their operating performance. One such factor is impaired vision caused by reflections and glare in the cab window glass through which the operator must view air traffic operations. Problems associated with glare and reflections inside tower cabs originate from a variety of sources but mostly result from direct and reflected glare, reflections of objects in the cab windows, internal cab lighting and airport and aircraft lights. These influences can all affect visibility and cause distractions to the controllers. Other factors affecting controller discomfort include the heat and noise transferred into the cab from the outside environment.

Heat transmission problems in air traffic control tower (ATCT) cabs include the solar heat transferred into the enclosure, the heat loss from inside the cab especially at night and the moisture/fogging on the window glass. For the noise problem, transmission of external noise from air traffic activity into the cab depends, among other things, on the noise attenuation provided by the window glass. The location of the ATCT is also of major importance and increasing its height and distance from the aircraft taxiways and pavements provides a partial solution to the noise problem. Unfortunately, many ATCT cabs are located immediately adjacent to ramps which are obstrusive noise areas.

Recognizing these adverse influences, solutions for providing a comfortable working environment for controllers requires,

- a high level of visibility through the window glass
- a comfortable thermal environment for operating personnel
- reduction of external noise levels to assure minimum interference with communications.

Additional requirements relate to the large number of ATCT configurations and locations which vary with local airport conditions. Effective countermeasures to reduce the glare, reflections, noise and heat in one ATCT design at a specific location might not be suitable for all ATCT's. The present work for the Federal Aviation Administration was undertaken to provide solutions for the foregoing problem areas and to meet the following objectives:

- To identify and analyze possible methods of reducing glare, reflections, heat transmission and noise transmission of glass for use in various ATCT cabs.
- To develop a cost versus benefit model of evaluating methods for reducing these disturbances.
- To recommend, within the state-of-the-art, an optimal solution for reducing the disturbances.
- To prescribe recommended test procedures to be followed by testing the recommendations.

1.2 Scope of Work

The major program requirement was to study possible methods of reducing the glare, reflections, heat and noise transmission of glass for use in ATCT cabs of various geometrical configurations. The ATCT cab configurations investigated were the 4-sided, 5-sided, 6-sided and 8-sided shapes with emphasis on the 5-sided cab. To determine the extent of the existing glare, reflections, heat and noise transmission problems in representative ATCT's it was agreed by the FAA that four on-site surveys will be conducted with one supplemental site to be included in the work scope.

- O'Hare International Airport, Chicago, Illinois--4-sided cab
- Palm Beach International Airport, West Palm Beach, Florida--5-sided cab
- New Tamiami Airport, Miami, Florida--6-sided cab
- Dulles International Airport, Chantilley, Virginia--8-sided cab
- O'Hare International Airport, Chicago, Illinois--5-sided cab (supplemental)

The supplementary site survey was included for obtaining additional information on the light transmission, heat and noise transfer problems for the new 5-sided ATCT cab at O'Hare International Airport.

Measurements taken at these foregoing ATCT sites provided a basis for judging the merits and disadvantages of each design as far as the light, noise and heat transmission were concerned. It was recognized, however, that effective countermeasures to improve the visibility for air traffic controllers required contacting glass manufacturers on the availability and cost of certain types of window glass that would be practical to install in ATCT cabs.

The subjective nature of the effects of glare, reflections, heat and noise on operating personnel made a mathematical cost versus benefit model for each recommended countermeasure difficult to determine except from a psychological standpoint. With respect to visibility, how much a controller's reliability is degraded in viewing an aircraft through intense glare needs to be determined. Consequently, each source of glare considered an annoyance factor should be ranked on the basis of psychological test procedures under controlled conditions. While such procedures are recognized as being outside the scope of work, attempts should be made to rank the benefits obtained from reducing glare according to a rating scale against the costs necessary to reduce the glare problem. With respect to heat and noise transmission, the factors which govern controller discomfort are more easily defined in terms of hearing discomfort (dB level) and heat load reduction as a function of savings in unit air conditioning costs. For this reason countermeasures to reduce glare and reflection in ATCT cabs should be ascribed subjective ranking factors in determining the cost effectiveness of the proposed countermeasure.

1.3 Outline of Report

The work described in this report has been divided into four sections. First, a discussion of the technical aspects of the problem of glare, reflections and visibility for controllers in ATCT cabs. Second, the noise attenuating properties of various types of glass and the heating and air conditioning requirements for a given cab based on environmental factors. Third, a description of the ATCT field surveys carried out during the course of the program and an analysis of the results obtained from the surveys. Fourth, a discussion of the countermeasures that may be employed to reduce the glare, reflection, heat and noise transfer in a given ATCT cab. Fifth, the cost of benefits obtainable for those countermeasures considered feasible and the recommended design of cab window glass for a given size and configuration. Recommendations are submitted in accordance with FAA Order 1700.8 and included in a separate letter of transmittal.

2. TECHNICAL DISCUSSION

2.1 Glare and Reflections

2.1.1 Visual Considerations

Light has been defined as "radiant energy evaluated in proportion to its ability to stimulate our sense of sight" (Ref. 1). If light entering the eye is of sufficient magnitude it acts as a stimulus which results in the sensation of brightness. The stimulus which gives rise to the sensation of brightness is the luminance* of the object being viewed. That is, sensations differing in brightness are caused by stimuli differing in luminance.

The ability of a controller, for example, in an ATCT cab to see an object is basically a function of the luminance contrast between the object and its background. In general, the ability to detect an object is a function of the luminance level as well as the contrast and angular size of the object subtended at the observer (Ref. 1).

The luminance contrast, C is defined as

$$C = \frac{[(B \pm \Delta B) - B]}{B} = \frac{\Delta B}{B}$$

where B is the background luminance and $(B \pm \Delta B)$ is the luminance of the object.

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* Luminance is a photometric unit, where 1 ft-lambert is the luminance of a totally diffuse scattering material which reflects all incident light when illuminated by 1 lumen/ft^2. One lumen is the luminous power emitted by a standard candle into a unit solid angle, i.e., 1 candle emits 4π lumens.

The threshold of luminance contrast, ϵ is found to vary with object size. It has been found (Ref. 1) that for a 50 percent probability of detection ϵ varies from 0.01 at 2 deg. field of view to unity at 10 min field of view for luminance levels corresponding to the light adopted eye (photo-optic level). For large probabilities of detection, larger values of ϵ are required and approach twice the 50 percent values for 95 to 100 percent detection (Ref. 2). Because a wide variation exists it is difficult to select a threshold value for ϵ until it is experimentally determined for a specific task. For calculating the visual range from transmissometer data in common use in airports, a value of 0.02 has been chosen (Ref. 1).

The effect of other sources in the observers field of view also influences the luminance threshold. The simplest case is that of a veiling source, i.e., one that occupies a substantial area including the object. Such a condition is met in daylight when an observer in an ATCT cab views an object through a veiling reflection of the sky appearing upon the glass of the cab.

$$C_{effective} = \frac{(B \pm \Delta B + V) - (B + V)}{B + V} = \frac{\Delta B}{(B + V)}$$

where V is the veiling luminance.

The effect of veiling luminance may be restated in terms of an altered threshold of luminance contrast:

$$\epsilon' = \epsilon(1 + \frac{V}{B})$$

where: ϵ is the luminance contrast with no veiling luminance
ϵ' is the altered luminance contrast.

The value V is sometimes called "veiling glare" and may prove annoying as well as reducing the visibility if of sufficient luminance.

Another condition leading to contrast reduction is that of a small source or sources located within the visual field. Such a condition may exist at night in ATCT cabs where bright ground lights fall within the field of view of interest or may be caused by reflections from the interior cab lighting in the windows of the cab.

These small "dazzle" sources are found to produce the effect of veiling luminance whose magnitude is:

$$V_{effective} = K_1 \frac{E}{\phi^2}$$

where E is the illuminance of the "dazzle" source on the eye,

ϕ is the angle between the line of sight and the "dazzle" source

K_1 is a constant.

The value of K_1 has been determined by Holladay (Ref. 3).

2.1.2 Glare

The foregoing factors affecting visual performance are manifestations of glare. Glare is usually defined as any unwanted light that enters the eye that in anyway interferes with the performance of the visual task. Several types of glare are recognized.

- Veiling glare may be described as light superimposed in a uniform manner upon the visual field. As described above it may lead to discomfort, contrast reduction or decreased luminance contrast threshold.

- Dazzling glare results from one or more very intense sources within the visual field. This may be mathematically corrected to veiling glare.

- Blinding glare is produced by light entering the eye of such intensity as to reduce the sensitivity of the retina. Glare, may also be characterized in magnitude as disability and discomfort glare. It is also possible for glare to only increase the fatigue associated with the visual task without becoming noticeably uncomfortable.

2.1.3 Reflections

Veiling luminance or glare is produced in ATCT cabs by specular reflection in the glass window panes. The most serious reflections being those of a white sky. As discussed previously, these reflections are of two types--corner reflections and direct reflections of the rear sky background. The other possibility is that of the cab ceiling reflection. However since general practice is already to use dark ceilings this factor is negligible. The luminance of a reflected source is that of the original source multiplied by the reflectance factor of the particular glass. The reflection of a transparent glass pane is the Fresnel reflection from the two surfaces. Fresnel reflection is a function of the incidence angle and the polarization of the incident light. For unpolarized light at normal incidence in air the reflection factor is

$$R = \left(\frac{n - 1}{n + 1}\right)^2$$

where n is the index of refraction of the glass (Ref. 4).

For a single glass surface this amounts to a reflection of about 4 percent. For the two surfaces of a glass window the reflection is about 8 percent. Hence the luminance of the sky as reflected in the glass is 8 percent of the sky luminance with normal incidence. If the pane is double-glazed and the glass panes are clear, the reflections will amount to about 15 percent of the sky luminance. If one of the glass panes of the double-glazed window is tinted, the reflection will be reduced somewhat.

Table 1 shows the measured normal reflectance of a number of different glasses which may be used for ATCT cab windows.

Table 1

REFLECTION OF VARIOUS GLASS SAMPLES
AT NEAR NORMAL INCIDENCE

Type of Glass	*Normal Reflectance R	Visual Appearance
Single plate 1" thick	5.0%	Slight green tint
Double insulating glass 1/4" clear plate, 1/2" air space	12.4%	Clear
Double insulating glass 1/4" clear plate, 1/2" air space outer glass gray	10.4%	Slightly gray from outside. No noticeable effect inside.
Double insulating glass 1/4" clear plate 1/2" air space inner glass gray	6.4%	as above
Double insulating glass 1/4" clear plate, 1/2" air space outer glass heat absorbing	10.4%	Slight green tint
Double insulating glass 1/4" clear plate, 1/2" air space inner glass heat absorbing	6.4%	Slight green tint
Triple insulating glass 1/4" clear plate two 1/4" air spaces	16.0%	Very slight green tint

* The normal reflectance is defined as;

$$R = \frac{\text{luminance of reflected light}}{\text{luminance of the source}}$$

The values of R measured differ from Fresnel reflection because of absorption in the glass.

If, however, the light is reflected at angles other than zero degrees the reflection factor R will increase and in addition will be partially or completely linearly polarized. Figure 1 shows the polarization and reflectance for various angles of incidence. The corner reflections appearing in ATCT cabs are made up of light at angles varying from near zero to very large angles of 60 deg or more. Under such conditions the reflectance is higher than for normal incidence and the reflected light is partially or completely linearly polarized.

2.2. Heat Transmission

In ATCT cab structures the glass areas are very extensive and are therefore of major importance in determining the heating and cooling load.

Heat transfer through the glass areas is affected by environmental factors such as 1) radiation from the sun, atmosphere, and ground, 2) air temperature difference between outside and inside of cab, 3) air velocity over inside and outside surface. Heat transfer is also affected by the physical dimensions and shape of the ATCT cab.

Solar radiation received at the earth's surface varies with the season, time of day, geographical location, and degree of atmospheric attenuation (clouds, dust, moisture, etc.). The maximum intensity of solar radiation at normal coincidence is taken as 294 Btu/hr ft^2. For surfaces not normal to the sun, the maximum solar intensity must be multiplied by the cosine of the angle of incidence. The angle of incidence for various seasons and latitudes can be computed from published data (Ref. 5). Values of direct solar radiation and diffuse solar radiation can be obtained from Ref. 6.

Heat transfer due to differences between indoor and outdoor temperatures depends on the air temperatures, air velocity over the surfaces, and thermal conductance of the materials. The air velocity and thermal conductance are usually combined to produce an overall coefficient of heat transfer.

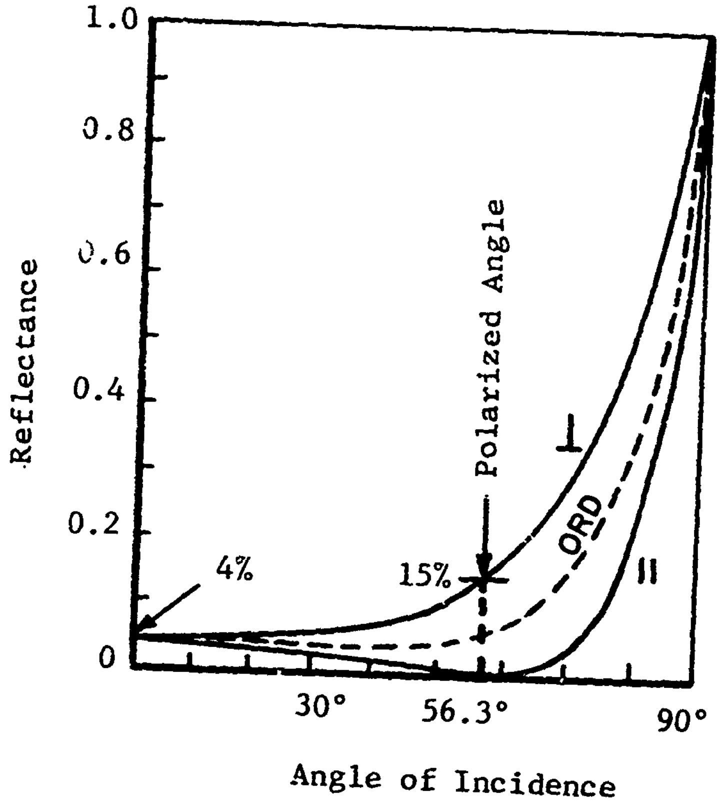


Fig. 1 REFLECTANCE OF GLASS (n=1.51) FOR UNPOLARIZED LIGHT (Ref. 4)

The thermal interchange between a glass window and its surroundings is shown by the heat balance in Fig. 2. The direct solar radiation can be divided into three parts; that which is transmitted through the glass, that which is reflected, and the remainder which is absorbed by the glass. The heat balance may be expressed as:

Total heat transfer through the glass	=	Transmitted solar radiation	+	Heat gain due to absorbed solar radiation	+	Heat transfer due to difference in indoor and outdoor air temperatures

This can be written as

$$\frac{q}{A} = F_D I_D + F_d I_d + U(t_o - t_i)$$

where

q/A = instantaneous rate of total heat transfer, Btu per (hour) (square foot).

F_D, F_d = ratio of the solar heat gain to the incident solar radiation for direct and diffuse solar radiation, respectively, dimensionless.

I_D, I_d = incident direct and diffuse solar energy, respectively, Btu per (hour) (square foot).

U = overall coefficient of heat transmission Btu per (hour) (square foot) per (Fahrenheit degree).

t_o, t_i = outdoor and indoor air temperature, respectively, Fahrenheit.

The factors F_D and F_d vary with the incident angle of the sun's radiation and differ with each type of glass window.

Although the solar heat gain may be computed from basic information, it is common practice, when possible, to utilize prepared tables in which this information has been computed. The heat gain due to solar radiation for various types and combinations of glass are related to that for single unshaded double strength (1/8 in.) sheet glass. This data is tabulated for each daylight hour for the 21st of each month from June through December for 24, 32, 40, and 48 deg north latitude and for directional orientation (Ref. 7).

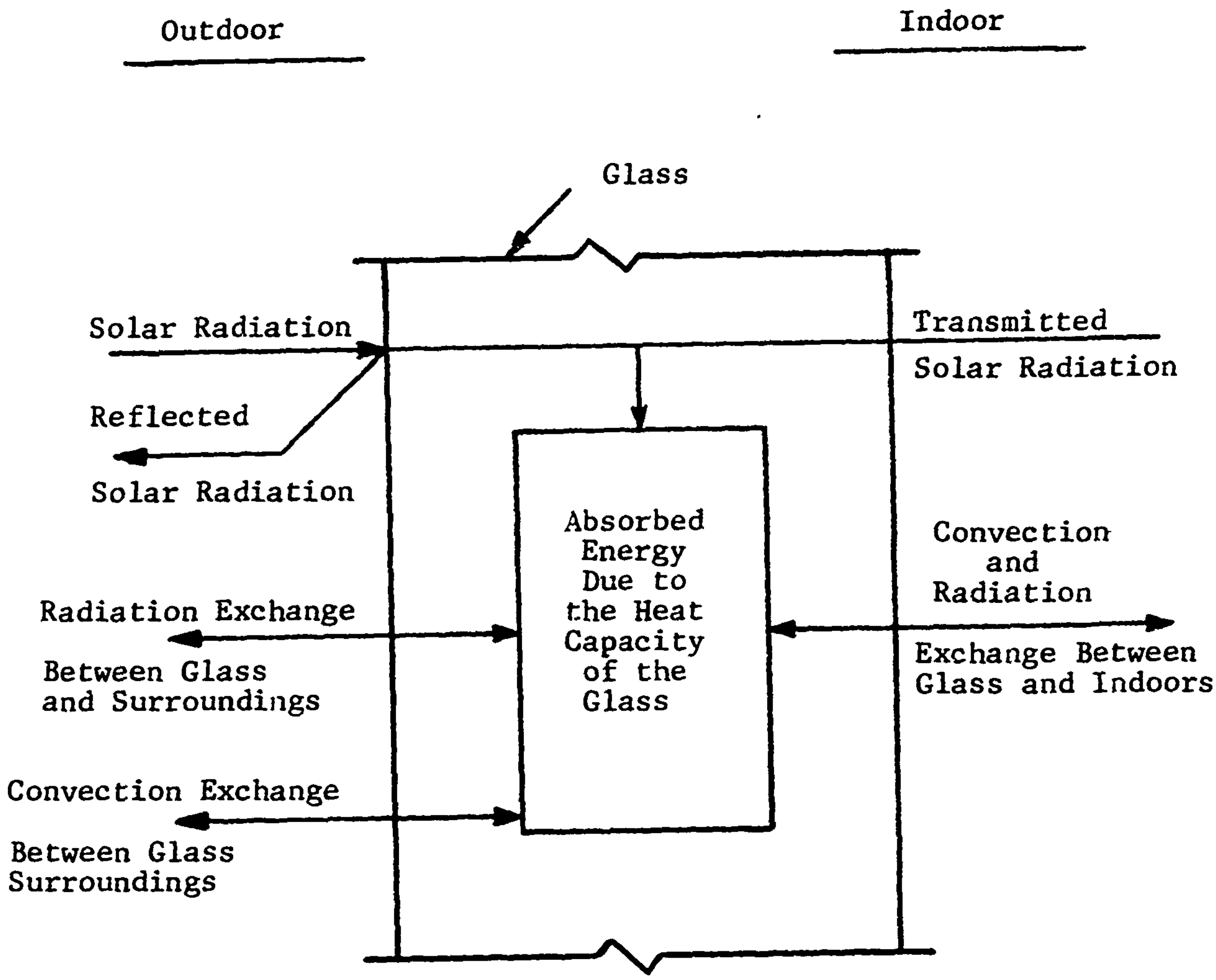


Fig. 2 INSTANTANEOUS HEAT BALANCE FOR GLASS PLATE

To determine the solar gain for other than single sheet glass, it is necessary to use a shading coefficient. The shading coefficient is the ratio of heat gain due to transmitted and absorbed solar energy to that of unshaded double strength sheet glass. The shading coefficients for glass in common use are shown in Table 2. Shading coefficient varies with the type of glass, thickness, coating, etc. Shading coefficients for glass windows with various types of shading devices are also available.

Heat transfer due to indoor and outdoor air temperature differences depend on the overall coefficient of heat transfer (U) and the air temperature difference. The overall coefficient is composed of three parts; 1) the outside film coefficient, h_o, which is principally a function of the wind velocity, 2) the inside coefficient, h_i, which is a function of the air velocity circulated over the inside of the glass surface, and 3) the thermal conductance of the glass, air spaces, etc. The overall coefficient may be computed or can be determined in the laboratory. Typical values are given in Table 3 for outside winds of 15 miles per hour in winter and 7-1/2 miles per hour in summer and natural convection on the inside. The overall coefficient must be adjusted for actual wind conditions and increased for air movement across the inside surface caused by forced air from ducts.

The inside surface temperature and relative humidity of the inside air combine to produce condensation or fogging and frosting under certain environmental conditions. This, of course, restricts visibility and cannot be tolerated. Typical values for single and double glass windows are given in Figure 3.

Table 2

SHADING COEFFICIENTS

Single Glass				Insulating Glass				
Type of Glass	Nominal Glass Thickness in.	Solar Trans.	Shading Coefficient	Type of Glass	Nominal Glass Thickness in.	Solar Transmission		Shading Coefficient
						Outer Pane	Inner Pane	
Regular Sheet	1/8	0.86	1.00	Regular Plate Out Regular Plate In	1/4	0.80	0.80	0.83
Regular Plate	1/4 1/2	0.80 0.71	0.95 0.88	Heat-Abs Plate Out Regular Plate In	1/4	0.46	0.80	0.56
Heat-Abs. Plate	1/4	0.46	0.67	Grey Plate Out Regular Plate In	1/4	0.46	0.80	0.56
Grey Plate	1/4	0.47	0.70					

Table 3

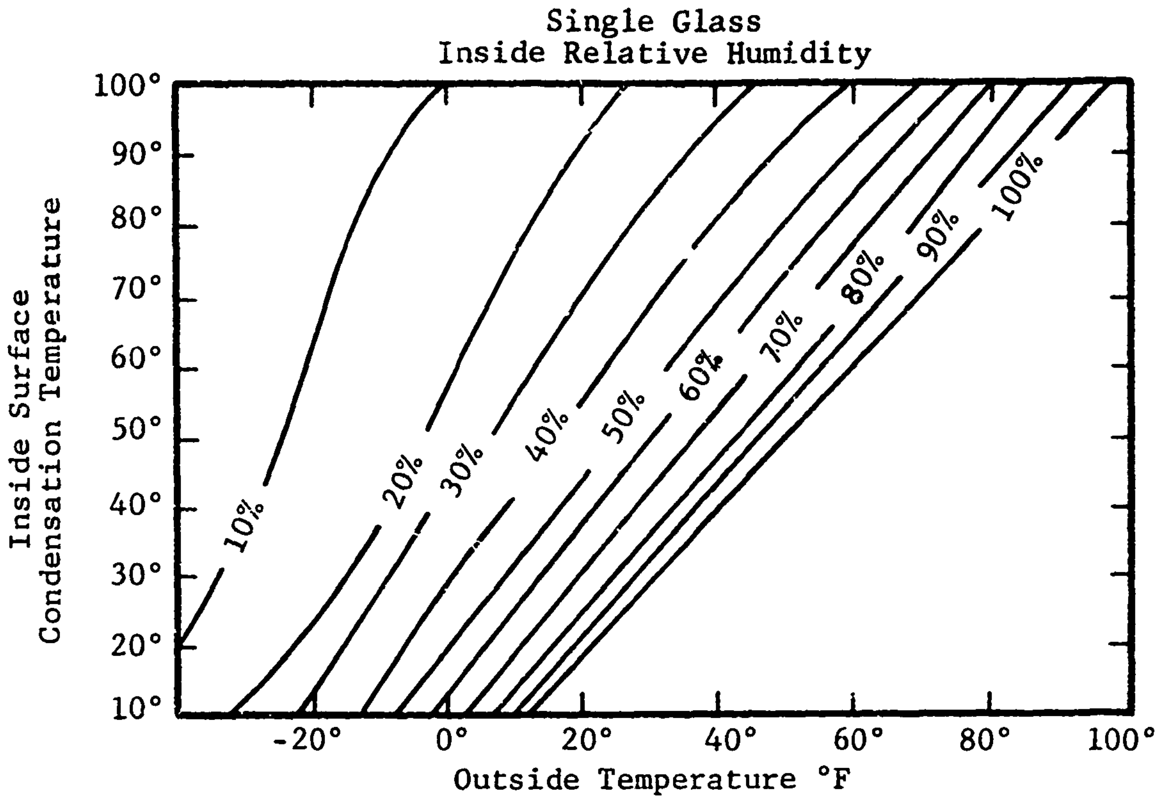
OVERALL COEFFICIENTS OF HEAT TRANSMISSION (U)*

Description	Exterior Winter	Exterior Summer
Single Glass	1.13	1.06
Double Insulating Glass		
1/4" Air Space	0.65	0.61
1/2" Air	0.58	0.56

* Btu per(hr) (sq ft) (°F)

2.3 Noise Transmission

The problem of reducing the noise penetration through an ATCT from aircraft in the vicinity of the tower involves using effective sound insulating materials in the building construction. The level and spectrum of the noise impinging upon the tower will depend on the type of aircraft and its location with respect to the tower. If the ATCT is located sufficiently remote from the flight paths and taxiways some loss of noise directivity will occur due to atmospheric sound attenuation. Consequently it is a desirable countermeasure to position the control tower some distance away from the aircraft pavements, taxiways and ramps. However, the building materials from which the tower and cab is constructed basically affects the noise transmitted into the tower. Because the major portion of the ATCT cab consists of window glass, the sound insulation the glass provides is of prime importance. In the cab therefore the observation glass and windows must be selected and installed to reduce the external noise to a level sufficient to permit the controllers to communicate with minimum interference from aircraft noise.



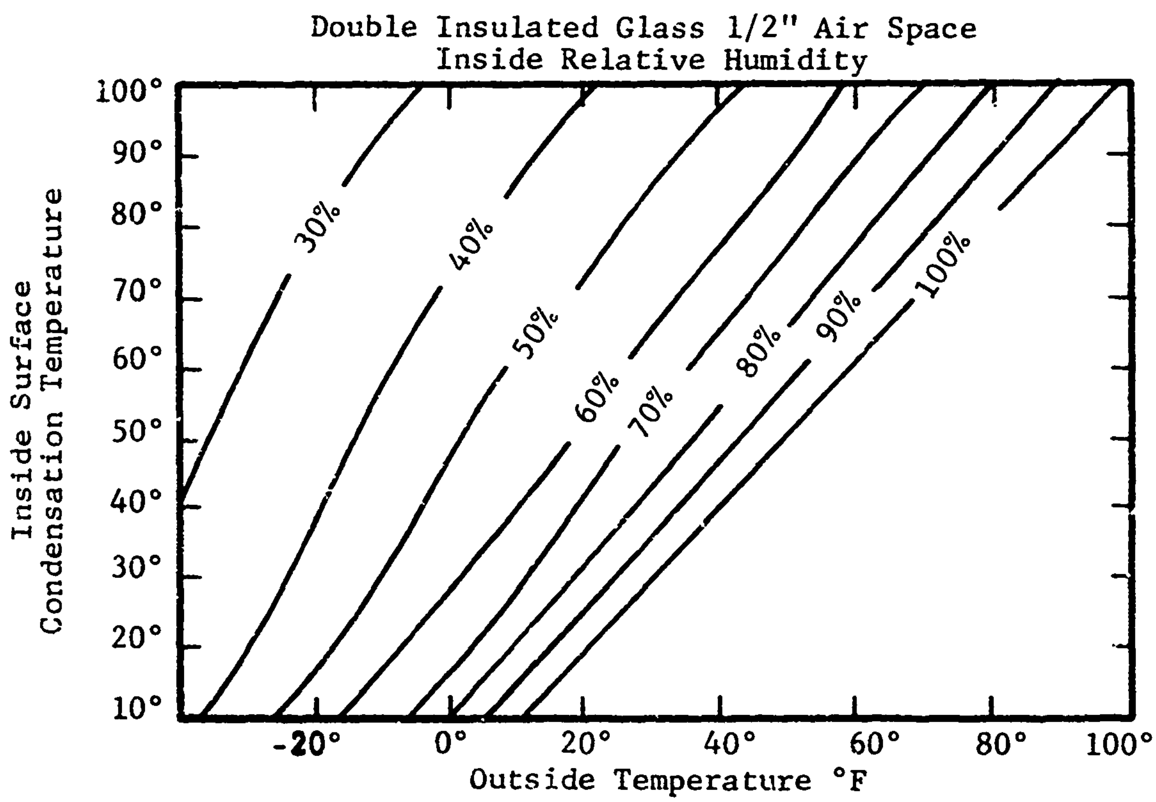


Fig. 3 INSIDE SURFACE CONDENSATION TEMPERATURES AND INSIDE RELATIVE HUMIDITY (RH)

2.3.1 Noise Reduction Requirements

For a sound absorbing partition, the noise reduction (NR) is the difference in sound pressure level (dB) between the adjoining source and receiving areas separated by the partition. For example, if the outside noise level is 95 dB (A scale) and the acceptable inside level is 65 dBA, the barrier, or window in this case, must provide at least 30 dBA isolation. For practical purposes, however, the sound transmission class* (STC) of the glass window should be specified (See Ref. 8).

Table 4

STC RATINGS FOR VARIOUS GLASSES

Glass Type	STC Rating Range**
1/4 in. plate	26-33
1/2 in. plate	31-35
3/4 in. plate	37
Double pane 1/4 in. plate with 1/2 in. airspace	31-34
Double pane, 1/2 in. plate outside, 1/4 in plate inside width 6 in. airspace	42+
1/2 in. laminated 2 ply plastic interlayer with 1/4 in. plates	37-43
3/4 in. laminated 2 ply with 3/8 in. plates	42-45

* The method rates partitions by comparing their sound transmission loss test curve with a "standard contour" comparable with the A-weighting curve of a sound level meter.

**Smaller glass specimens provide higher STC values due to increased stiffness provided by edge clamping. The sound insulation properties of laminated glass are temperature dependent with the highest STC ratings corresponding to ambient temperatures of 90°F, and the lower ratings to temperatures of 50°F.

In the above example a glass partition with an STC rating of 30 or better would provide adequate sound insulation. It is the STC values for various types of glass for ATCT cab windows that should be considered.

Tests carried out at the IITRI Riverbank Acoustical Laboratories have established a range of STC* values for glass used in building construction. There are several points to be emphasized when glass is employed for noise reduction purposes.

1. The noise reduction increases with increased glass thickness.
2. The noise reduction will decrease only slightly with increased glass surface area.
3. The window glazing must meet safety code requirements defined in architectural handbooks.**

2.3.2 Sound Insulating Glass

Information in Table 4 indicates that several types of glass might be suitable for ATCT cab windows.

- Double-walled Insulating Glass

Double pane windows of two 1/4 in. plate glass separated by a 1/2 in. dehydrated airspace and mounted in an airtight seal provide a sound transmission loss of 34 dB. This configuration commonly used for ATCT cab windows may provide adequate sound insulation in most airport tower locations. The glass-airspace combination attenuates higher frequencies more than solid plate glass. However, more effective acoustic isolation may be obtained by increasing the distance between the glass plates instead of increasing the thickness of each plate.

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* This rating is a means of comparing the sound insulation performance under identical conditions using ASTM Test Method E90 66T.

** PPG Architectural Data Handbook, pp 48-51.

For instance, 1/4 in. plates separated by 6 in. of airspace increases the sound transmission loss by at least 8 dB more than 1 in. double pane glass with a 1/2 in. airspace. Unfortunately, increasing the distance between panes beyond 1/2 in. creates visibility problems. In particular, multiple images in the glass from objects outside the ATCT cab would be widely separated due to internal light reflections between the glass plates. This effect would be an undesirable feature for air traffic controllers. One serious objection to double windows is the difficulty of controlling the airspace between the two plates of glass. Should a partial leak occur under the influence of a large temperature gradient and humid air occupy the space, the dew point may be reached and moisture condenses on the inside glass surface. Such a situation would render the window useless for visual purpose.

- Single Plate Glass

From Table 4 it is seen that 3/4 in. plate glass provides an STC rating of 37. This value is in excess of the sound insulation for double walled glass of 1 in. total thickness with a 1/2 in. airspace. However, the double walled glass is capable of attenuating higher frequencies much better than the plate -- a factor which is not apparent when comparing STC ratings. Plate glass less than 3/4 in. thickness would not be suitable for ATCT cab windows. Unfortunately, plate glass does not have as good heat insulating properties as the double walled configuration and has a higher mass per unit area.

- Laminated Glass

Laminated glass is a single glazing unit consisting of thin layers of transparent plastic, e.g., polyvinyl butyral, sandwiched between two glass plates. The sound insulating performance of laminated glass is superior to that of ordinary glass of equivalent thickness. For example, two layers of 0.045 in. plastic fused between two 3/8 in. glass plates provides a STC rating varying from 37 to 43 compared with a single 3/4 in. plate of 37. Generally the cost of laminated glass is higher than ordinary glass. A disadvantage of laminated glass is temperature dependence. For example, while its higher STC ratings are suitable for warmer climate conditions, laminated glass has no advantage over ordinary plate glass of equivalent thickness in northern colder climates (See Table 4).

One further point regarding the use of glass for sound insulation is the problem of glazing. Great care must be taken since the slightest crack in sealing the window glass can produce substantial acoustic leaks. All sections of the glass at the frames and joints must be sealed with a good grade of glazing compound. This factor is particularly important in double-window glazing since an airtight seal around the inside edges of the glass is necessary to prevent leaks to the atmosphere.

3 ATCT CAB SITE SURVEYS

The purpose of the on-site surveys was to determine the extent of the glare, reflections and heat and noise transfer problems in existing ATCT cabs of varying configurations. By agreement with the FAA the following sites were selected for field surveys:

- O'Hare International Airport, Chicago, Illinois--4-sided cab
- O'Hare International Airport, Chicago, Illinois--new 5-sided C-2A cab (Supplemental)
- West Palm Beach International Airport, Florida--5-sided cab
- New Tamiami Airport, Miami, Florida--6-sided cab
- Dulles International Airport, Chantilley, Virginia--8-sided cab

The information obtained from the field surveys was useful to the program in two respects. First, it provided IITRI with the opportunity to observe the extent of the existing glare, reflections and heat and noise problems for differing cab configurations. Second, data obtained from the surveys provided a physical basis to assess the merits of one cab window glass and cab configuration against other designs.

Studies were made of the visual aspects of each ATCT cab during daylight and nighttime conditions and measurements were made of the sound attenuation provided by the various cab enclosures. Any heat transmission problems were also noted during visits to the cabs. During daytime, reflections in the windows were the most objectional disturbance feature in all cabs. Qualitative observations of two types of reflections were made on all cabs. These reflections were:

- reflections appearing between the cab corners
- corner reflections

In general, it was found that as the number of cab sides increased, the area of the corner reflections decreased. Furthermore, for observers on the cab centerline bisecting the corner angle, the corner reflections become invisible in the 8-sided cab.*

To evaluate the magnitude of the veiling glare introduced by the reflections, measurements were made to determine the luminance ratio between the reflected luminance and the background luminance against which aircraft may be viewed. The worst conditions are those under which brightly lighted white clouds or sky are reflected. The worst condition usually exists in the morning or evening when the sky is very bright. In order to obtain a permanent record of the luminance ratios for future reference and study, photographs were made of window reflections and glare and by using photographic photometry, the luminance ratios were subsequently determined. The technique of photographic photometry consists of calibrating the film for density versus radiance and using a microdensitometer to measure the density of the film in the problem areas. This technique of photographic photometry is discussed in Appendix A. In addition to the photographic measurements, direct luminance measurements were made of selected areas with a Minolta Auto Spot exposure meter of 1 deg effective area.

Determination of the sound attenuation provided by each ATCT cab was made by measuring the noise levels both inside and outside the cab enclosure using a portable sound level meter. Exceptions were the 4 and 5-sided cabs at O'Hare Field where magnetic tape recordings of the noise levels during periods of peak air traffic activity were made using microphones positioned inside and outside the cab enclosures. The tapes were subsequently analyzed to determine the noise levels (A-weighted

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* It may be noted that reflections reappear when an observer moves to positions on each side of the centerline.

decibel scale). The difference between the inside and outside levels was employed as a measure of the sound attenuation for the ATCT cab. With respect to heat transmission problems only qualitative information was obtained with the exception of the 5-sided C-2A cab at O'Hare Field. In this case, the problem of window glass fogging during the winter was sufficiently important to investigate environmental conditions that must be maintained inside the cab to prevent moisture condensation on the windows. Observations made in the various ATCT cabs are discussed in the following subsections.

3.1 4-Sided ATCT Cab (O'Hare Field)

The 4-sided cab of the ATCT is located close to a passenger loading ramp at O'Hare Airport. The cab elevation above ground level is 62 ft. The glass windows were double-glazed insulating Thermopane with 1/4 in. plate and 1/2 in. air space. Heat absorbing glass was employed for the outer pane. Corner and central mullions supported the windows and roof substructure. The outward slope (tilt) of the cab windows is 15 deg to the vertical. Observations were made with the weather overcast with a very bright sky.

3.1.1 Reflections and Glare

Under daylight conditions both corner window reflections and those between corners were observed. Corner reflections were particularly annoying since they extended to the top of each window pane. Direct brightness measurements were made looking through the south corner. A direct reading of the sky background, through the reflection of a corner mullion was 1000 ft-lamberts. The luminance of sky plus reflection was 1500 ft-lamberts. Hence the luminance of reflection was 500 ft-lamberts. Figure 4, is a photograph of a corner reflection and gives the brightness ratio between the sky reflection and the pavement in the loading ramp area. The numbers shown in Fig. 4 refer to the luminance ratios at selected points along

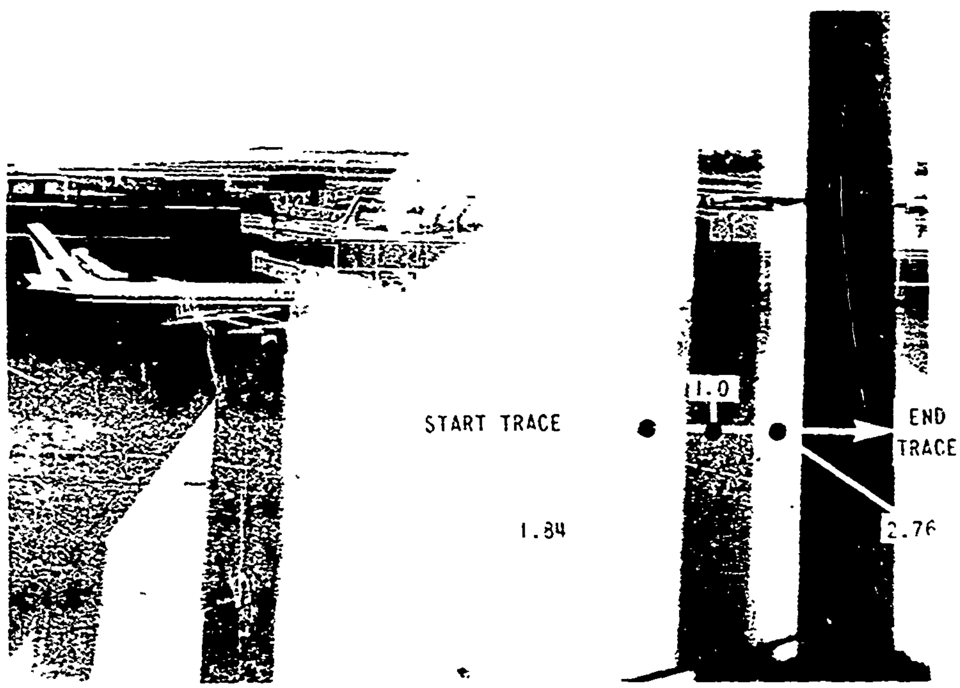

Fig. 4 WINDOW REFLECTIONS IN 4-SIDED CAB (O'Hare Field)

Note: Numbers indicated on photograph are the relative brightness.

the microdensitometer trace, indicated by the white line. In general, window reflections in this cab proved more annoying than in any other ATCT cab subsequently visited.

Glare from counter tops was also very severe. The counter tops were finished in smooth light colored Formica and reflections approached specular conditions. These reflections were of such intensity as to be extremely annoying to observers and interfered with viewing external objects. The cab shades were gray 10 mil acetate and badly scratched and wrinkled. When the shades were drawn the glare was reduced slightly. However, because the shades could only be drawn vertically a large window area at each corner of the cab was unshielded from direct sunlight.

At nighttime, observations indicated that the cab location and its low elevation caused ground light sources to be annoying. Multiple reflections surrounding or closely adjacent to ground lights were observed. These reflections were produced by the four reflecting surfaces of the double-glazed windows, and varied according to the window. It was felt that this phenomenon depended on the parallelism of the glass surfaces at the point of interest. Reflections from internal lights were also observed but these were not especially severe with the overhead light intensity at the normal operating level.

3.1.2 Noise Transmission

Because of its proximity to the loading ramps and low elevation the 4-sided cab was exposed to nearby aircraft noise. Tape recordings of the noise inside and outside the ATCT were made at several periods corresponding to peak aircraft activity. Subsequent analysis of the tapes determined the noise levels (dBA scale). The results from the analysis are shown in Table 5.

Table 5

NOISE TRANSMISSION DATA
4-SIDED O'HARE CAB

Outside Noise dBA	Inside Noise dBA	Noise Reduction dBA	Outside Noise dBA	Inside Noise dBA	Noise Reduction dBA
84	60	24	92	65	27
88	65	23	98	68	30
91	64	27	100	66	34
94	64	30	95	65	30
90	62	28	89	65	24
87	62	25	87	65	22
94	65	29	87	66	21
88	62	26	90	67	23
87	62	25	93	67	26
86	62	24	96	66	30
79	61	18	104	66	38
83	61	22	101	65	36
85	61	24	91	65	26
87	61	26	86	64	22
82	61	21	87	64	23
84	63	21	89	65	25
80	60	20	87	64	23
83	61	22	87	65	22
92	62	30	89	65	24
89	62	27	91	65	26
81	61	20	97	67	30
83	60	23	96	66	30
85	61	24	94	66	28
92	62	30	88	65	23
86	61	25	93	65	28
89	63	26			

Referring to Table 5 , it is seen that the noise inside the cab varies between 60 to 68 dBA depending on the aircraft activity. The outside noise is seen to vary between 80 to 104 dBA, with the higher values due to aircraft taxiing at the loading ramps near the base of the tower. It is apparent from these results that the maximum sound attenuation provided by the 4-sided cab is about 36 dBA.

It is difficult to assign a permissible noise level inside the cab because such standards are presently being evaluated by IITRI under separate contract for the FAA (Ref. 9). However, the sound isolation provided by the cab enclosure and Thermopane windows is remarkably good in view of the ATCT's proximity to aircraft loading ramps and taxiways.

It must be emphasized that the 4-sided cab was vacated of equipment and personnel when the survey was performed at O'Hare Airport. Comparison with the fully-operational 5-sided C-2A cab at O'Hare which indicated internal noise levels between 62 and 75 dBA points out the difference resulting from personnel and equipment noise.

3.2 5-Sided ATCT Cab (O'Hare Field) - Supplemental Site

The O'Hare 5-sided C-2A tower cab became operational in May 1971. The tower is located approximately 300 ft from the terminal and the elevation of the cab is 196 ft. The new tower cab provides not only a better perspective of the ground environment than the old 4-sided cab at O'Hare, but because of increased elevation and distance from noisy terminal areas, reduced the controllers exposure to nearby aircraft noise.

The glass used in the 5-sided cab is 7/8 in. clear plate supplied by Libbey-Owens-Ford. This glass has a slight greenish tint due to its large thickness. However, the green tint is not visible from inside the cab, and the apparent color is only seen when viewed from the outside against the sky as background.

Central mullions support the windows, roof and substructure with no corner mullions. The glass corners of the 5-sided cab are cemented with special sealing compound to apparently provide the controllers with fewer obstacles, i.e., corner mullions in the field of view. The walls of the cab and windows are tilted outward at 15 deg to the vertical.

3.2.1 Reflections and Glare

Both types of reflections in the glass were observed, i.e., corner reflections and reflections between the corners. In late afternoon, the reflections were very bright and a source of annoyance to controllers. The luminance ratios of several areas where window reflections were seen were measured photographically. Figure 5 shows a typical series of values of luminance along several scanning lines in the photograph.

Under daylight conditions, the counter tops of the consoles produced no objectional reflections or glare. For direct and/or reflected sunlight control the cab windows are each equipped with roller shades consisting of dyed mylar plastic 3 mil thickness and housed in a ceiling pocket. For this type of shade, the visual transmission* at normal incidence is 9 percent. Internal floors, ceiling and consoles were all finished in a low reflectance dark material and no annoying glare was seen.

At nighttime the ground lighting was unobstrusive due to the high elevation of the cab. Reflections from lights within the cab were of low intensity. The overhead lighting fixtures in the cab were recessed in the ceiling and baffled so that the bright light source was not visible and illuminated only the desired area. The counter tops and ceiling were of low reflectance dark material and reflected no noticeable light into the windows.

In fact the most annoying light source was the well-lighted stairwell leading into the cab. The stairwell walls have a light-colored matte finish which appeared very bright, scattering light into the cab. A dark paint on these walls would provide an effective countermeasure to reduce light scattering from the stairwell.

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* This value is rated in terms of a CIE 1931 standard observer.

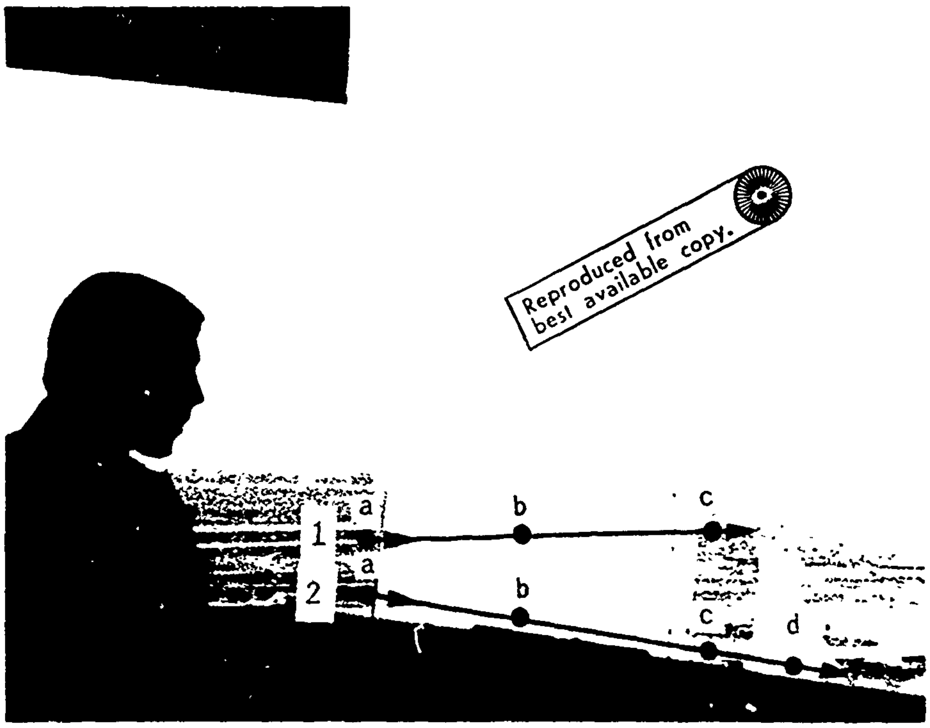


Fig. 5 WINDOW REFLECTIONS IN 5-SIDED C-2A CAB (O'Hare Field)

Note: Luminance of points indicated along two scans
1 - a = 75 ft lamberts, b = 138 ft lamberts
c = 75.5 ft lambers.
2 - a = 52 ft lamberts, b = 155 ft lamberts,
c = 52.5 ft lamberts, d = 155 ft lamberts

3.2.2 Noise Transmission

Recordings of the noise levels inside and outside the cab were taken over a 24 hour period. The outside microphone was suspended from the cab roof to record the environmental aircraft noise. The results in Table 6 are representative of the outside noise during a 1 hr recording period corresponding to peak air traffic activity (5:30 to 6:30 p.m. CST 29 July 1971). The inside cab noise levels varied between 62 to 68 dBA in the absence of speech communication from controllers and loudspeakers. It must be emphasized that this background noise was mainly attributable to air conditioning noise.

During speech communcation the noise levels varied between 68 to 75 dBA (maximum) with approximately 130 communication voice peaks over 70 dBA in the recording period shown in Table 6. The sound attenuation of the cab glass is difficult to estimate from these data since the noise levels outside varied appreciably during the survey. However, an indication of the sound attenuation is to take the difference between the maximum and/or minimum noise levels at a given time. It is seen from Table 6 that the cab glass provides at least 30 dBA maximum sound attenuation which is adequate isolation for controller operations.

The important result emerging from this noise survey was that external aircraft noise was hardly discernable inside the cab. This conclusion indicates that the sound attenuation provided by the cab enclosure was sufficient to isolate the air traffic noise.

3.2.3 Heat Transmission

Because the 5-sided C-2A cab has only recently become operational, a number of factors needed to be determined with respect to heating, ventilating and air conditioning controls inside the cab. The cab temperature is controlled by circulating air through a heat exchanger coil in which chilled water is circulated in summer and hot water in winter. A thermostat in the cab can be adjusted by personnel to the temperature level desired. This allows considerable flexibility and appears quite adequate for comfort.

Table 6

NOISE TRANSMISSION DATA 5-SIDED C-2A O'HARE CAB

Outside Noise dBA	Inside Noise dBA	Outside Noise dBA	Inside Noise dBA
79	66	84	66
83	65	81	65
82	66	87	67
89	66	88	64
87	67	86	64
85	67	81	64
83	67	90	68
86	65	88	69
91	65	88	68
89	65	91	65
83	66	92	66
89	64	83	68
90	67	91	68
89	65	91	66
89	66	93	66
89	67	94	64
86	68	94	67
87	65	93	68
85	66	93	68
84	65	94	65
83	68	88	65
83	68	90	65
83	67	90	64
87	67	88	64
89	66	91	66
88	67	90	65
88	66	89	65
90	68	88	65
91	67	84	66
89	62	88	67
90	64	89	66
80	68	81	65
89	63	84	65

Note: Inside Noise represents background levels in absence of speech communication. Noise levels shown represent average values over 1 min intervals.

Although there were initial problems with the cooling control system, these appear to have been satisfactorily resolved so that comfortable conditions can now be maintained.

The relative humidity in the cab is controlled by a humidistat which operates a steam humidifier. The humidistat is set for 40 percent relative humidity. The humidity controls for the cab are separate from the remainder of the tower.

Operation of the cab during the 1971-1972 winter season will occur for the first time during the next several months. However it appears that moisture condensation may occur on the inside surface of the glass window during the winter season due to the use of single plate glass. Under severe winter weather conditions, the inside glass surface temperature may reach the dew point temperature unless the cab relative humidity is maintained at a very low level. This would necessitate turning the humidistat to a very low setting (or off entirely) and may produce some discomfort due to the very dry air and problems of static electricity generation.

In order to calculate the inside glass surface temperature, the air velocity over the inside glass surface must be known. Since this information was not obtainable, it was decided to make these measurements in the tower cab. An Almor velometer was used to measure the air velocity at a point midway between the top and bottom of the windows. Measurements were taken at several different windows. The air velocity was found to range from 250 to 300 ft per min.

Using the inside air velocity of 300 ft per min (5 ft per sec) and an outside air velocity of 15 miles per hour, calculations were made to determine the inside surface temperature of the glass windows for several outside air temperatures. Then the inside relative humidity, at an inside air temperature of 75°F, which will produce condensation on the windows was taken from psychrometric charts and tabulated in Table 8 of Section 4.4. It can readily be seen from these results that a very low relative humidity must be maintained in the cab to prevent condensation on the windows during winter. These results indicate that the use of single plate glass in ATCT cabs is a disadvantage because of its poor heat insulating properties.

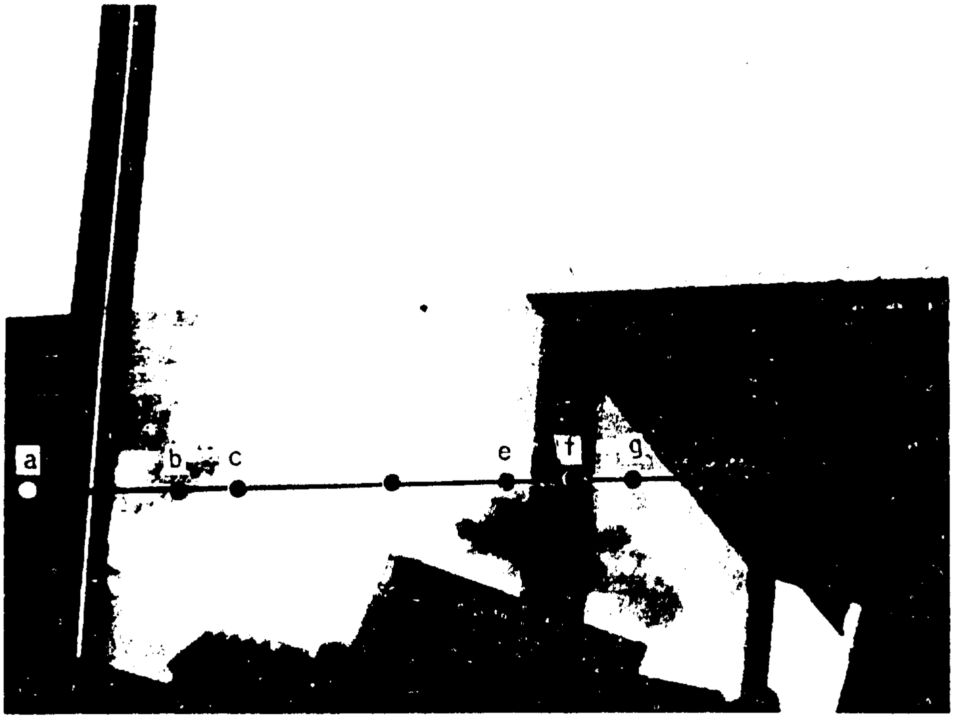
3.3. 5-Sided ATCT Cab (West Palm Beach, Florida)

The tower is a concrete shaft with a 5-sided C-1C cab containing corner and central mullions supporting 10 panes of double-glazed Thermo-O-Proof insulating glass (Shatter Proof Glass Company). The glass windows have a 1/2 in. dehydrated air space separating the inner and outer window 1/4 in. plates. The outer pane is heat absorbing glass. The glass windows appear clear from the inside but have a slight blue-green tint when viewed from the outside against the sky background. The cab windows are tilted at 15 deg to the vertical.

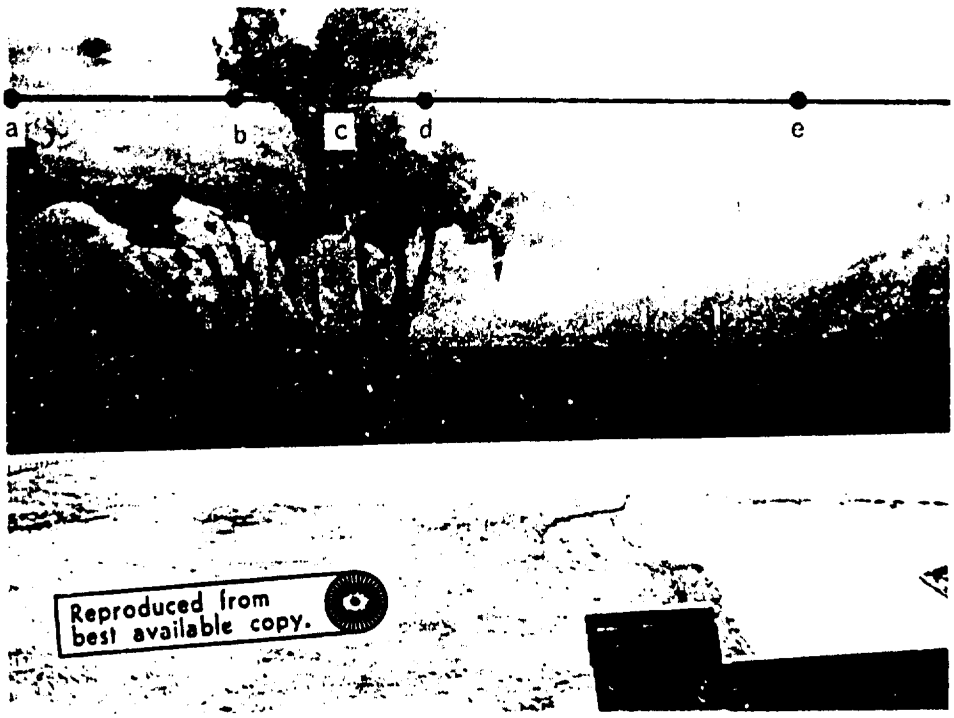
3.3.1 Reflections and Glare

Under daylight conditions the corner reflections and between corners reflections inside the cab were substantially the same as the O'Hare 5-sided cab. A typical photograph of reflections is shown in Fig. 6. The counter tops were of a low reflectance dull-finish and the reflected glare from these sources was negligible. For controlling external glare plastic window shades could be drawn from the cab ceiling. The shades were neutral gray mylar plastic of 5 mil thickness as used in the New Tamiami and O'Hare C-2A cabs. Dark glasses to supplement the use of drawn shades were worn by the controllers.

At nighttime ground lighting on the east side of the cab proved to be of annoyance from nearby buildings and multiple reflections surrounding these ground lights were observable. It is felt that shaded street lights could be employed to reduce these glare sources. Internal cab lighting was found to be adequate for controllers with the ceiling lights recessed and baffled as in the O'Hare 5-sided cab.



a) Window Corner
Scan along taxiway, luminance of points indicated
a = 5.2 ft lamberts; b = 22.6 ft lamberts; c = 370.0 ft lamberts
d = 82.5 ft lamberts; e = 36.6 ft lamberts; f = 7.0 ft lamberts
g = 36.6 ft lamberts.



b) Reflections in window shade
Scan along shade, luminance of points indicated
a = 24.2 ft lamberts; b = 43.3 ft lamberts; c = 33.4 ft lamberts
d = 75.0 ft lamberts; e = 426.0 ft lamberts.

Fig. 6 REFLECTIONS IN 5-SIDED CAB (West Palm Beach)

3.3.2 Noise Transmission

Noise measurements were taken both inside and outside the ATCT cab. A portable sound level meter was used and recordings were made of the noise levels, dBA scale, for conditions of aircraft landings, take off, etc., and during periods of minimal aircraft activity. It was noted that during aircraft activity the outside noise levels varied between 76 to 80 dBA, and the inside levels were between 62 to 68 dBA. During quiet periods, with background noise mostly from cab air conditioning equipment, the levels were about 58 dBA. External aircraft noise in the cab was remarkably low with much of the cab noise being associated with speech communication.

3.3.3 Heat Transmission

Air for heating and ventilation inside the cab is supplied from louvers beneath each window pane. Interviews with the Tower Chief indicated that the major heat transmission problems were twofold. First, the problem of leaking window seals which produced moisture/fogging on the inside glass panes rendering the window useless for visual purposes. This problem has led to several windows being replaced. Second, the heat load transmitted into the cab, when the sun is low in the sky. The use of drawn shades reduces the magnitude of the heat glare but still causes controller discomfort.

3.4 6-Sided ATCT Cab (New Tamiami Airport, Florida)

The New Tamiami ATCT cab is a 6-sided Type L (USAF modified) configuration with corner and central mullions supporting 12 equal panes of double-glazed Polarpane insulated glass (Combustion Engineering Company) with a 1/2 in. dehydrated air space separating the inner and outer window 1/4 in. plate glass. The outer pane is heat absorbing Solex glass. The windows are tilted outward at 15 deg to the vertical. When viewed from the outside against a clear sky the cab glass exhibits a blue tint.

3.4.1 Reflections and Glare

Reflections in the windows between the corners were quite strong and especially noticeable on the east side of the cab with a bright western sky. Values of luminance ratios shown in Fig. 7 are typical of those existing within the cab. Corner reflections were not visible because of the 6-sided cab construction. Other sources of daylight glare included the counter tops, which consisted of walnut colored Formica with a glossy surface finish. Specular reflections from the smooth surfaces of the counter tops from a bright sky were observed. The curvature of the counter tops always contained a bright reflection which was unaffected by changing the observers viewing position. The reflections from the curved top would have been less annoying had the transition from a flat surface to a curved one been through a sharp angle. However, angular changes appear undesirable since it is more difficult to eliminate the reflections from both flat and curved surfaces by changing the viewing position. A practical countermeasure would be to use a darker matte finish for the counter tops.

Window shades of 5 mil gray mylar plastic were also used to reduce the sky luminance to a tolerable level and shield the controllers from direct sunlight. The window shades have a visible light transmission of about 10 percent, which is typical of plastic films. It was noted, however, that the shades were badly "wrinkled" making it difficuit to view aircraft through the shades. Reflections of the sun appeared in a wrinkled shade whose reflected brightness was beyond our ability to measure photographically or with a brightness meter. Controllers recognizing this problem tend to scan the sky area under a partially drawn shade and use dark glasses. From these observations it appears that shades do reduce the heat discomfort annoyance factor from direct sunlight to a controller but do not affect the heat input into the cab enclosure because the solar heat is re-radiated within the cab.

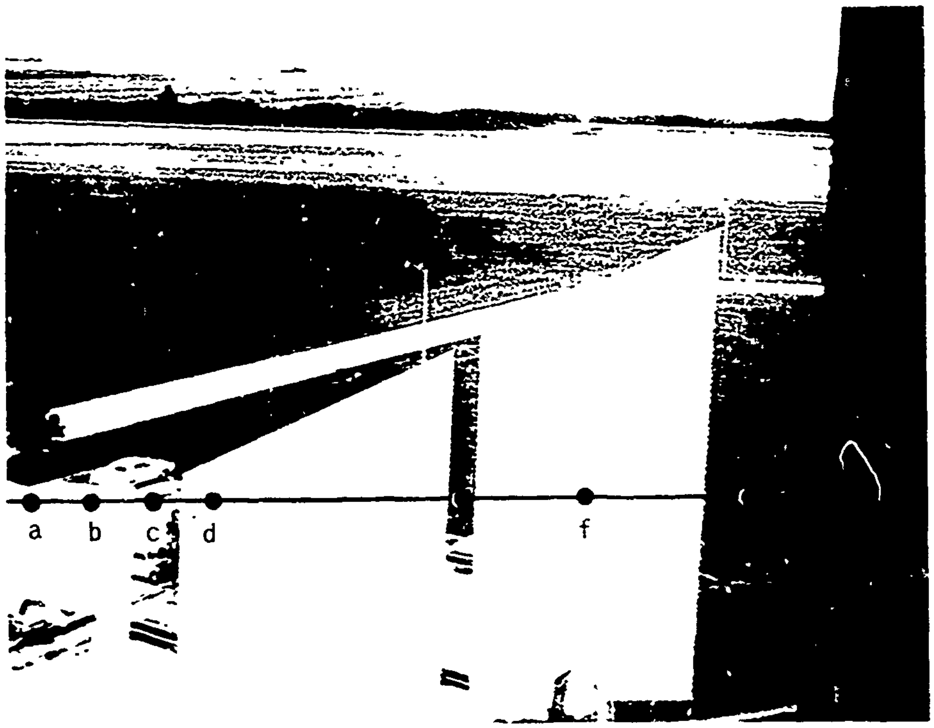


Fig. 7 WINDOW REFLECTIONS IN 6-SIDED CAB (New Tamiami)

Note: Luminance of points indicated
a = 180 ft lamberts; b = 750 ft lamberts;
c = 305 ft lamberts; d = 556 ft lamberts;
e = 113 ft lamberts; f = 407 ft lamberts;
g = 99 ft lamberts.

At nighttime annoying street lights were visible from the cab, especially along the roadway entering the airfield. These external glare sources could be reduced by providing the road lights with shades. Multiple reflections from the double-glazed windows were visible surrounding other pavement lights. However, these lights were of very low luminance and noticeable only upon close examination. The cab lighting also resulted in objectionable reflections in the windows at night. Ceiling lights used for counter top illumination, while of low luminance, were also visible in the window glass and could lead to false aircraft sightings.

3.4.2 Noise Transmission

Noise recordings were taken inside the cab and also on the catwalk outside the cab during a period of several hours duration. The aircraft noise outside the cab was mostly associated with light aircraft taking off and landing. Levels varying from 63 to 73 dBA were attributed in nearby aircraft noise. Inside the cab the noise was remarkably low 52 to 56 dBA since the controllers employed headsets which minimized speech communication. The use of loudspeakers increased the noise levels to about 66 dBA. Background noise (in the cab) was mainly associated with air conditioning equipment.

3.4.3 Heat Transmission

The ATCT cab at New Tamiami is only operational during daytime hours. The air conditioning requirements during operating hours is such as to require a five ton capacity unit for which cooled air is ducted into the cab through louvers beneath the cab windows. Nighttime problems have arisen due to moisture condensing on the outside window. The reason for the window fogging is:the dew point corresponding to condensation is reached because of the cooler window temperature with respect to higher outdoor temperatures and relative humidities. Presently, the cab heating system is operated at night to minimize the condensation problem. The use of infrared heating lamps directed onto the outer windows might be a better solution.

3.5 8-Sided ATCT Cab (Dulles International Airport)

This cab is an irregular octagon with four sides approximately one-half the width of the other sides. The cab windows supplied by PPG are double-glazed Twindo and consist of 12 panes of 1/4 in. plate and 1/2 in. dehydrated air space with the outer glass heat absorbing. The windows are tilted outward at 15 deg to the vertical. A slight blue tint is observable in the glass from outside the cab but appears clear within the cab.

3.5.1 Reflections and Glare

The window reflections in daylight are substantially similar to those observed in the 6-sided cab. Corner reflections in this cab are minimal* but reflections between the corners are visible. Figure 8 shows a typical reflection. The counter tops and other surfaces within the cab are finished in a dark nonglossy material which produced no serious reflections under daylight conditions. The cab radarscope, however, which is flush-mounted in the horizontal plane, reflected sky light from the oscilloscope face. This reflection was an annoyance to controllers. A semicircular sheet metal baffle was employed to shield the radarscope face and minimize the reflection.

The important feature of this cab was the lack of window shades for controllers. The glare associated with direct and reflected sunlight through the unshaded windows resulted in all the controllers wearing sunglasses. The sunglasses of the USAF type were supplied by the FAA for controller use in the Dulles cab. Because the ATCT is located about 1/2 mile from the airport loading area, only the nighttime lights from this area were sufficiently bright to promote any annoyance. However the illumination inside the cab was maintained at higher levels than in any other cab visited. The ceiling lights were visible in the windows only from certain positions in the cab. In general, the nighttime visibility was excellent and the cab lighting was not a visual handicap.

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*Modified 8-sided cab gives rise to double set of corner reflections.

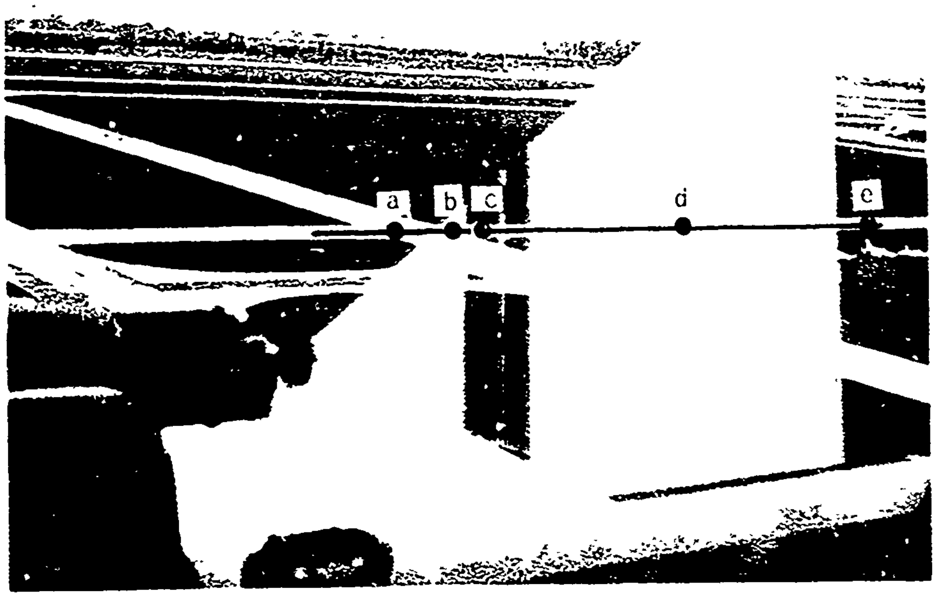

Fig. 8 WINDOW REFLECTIONS IN MODIFIED 8-SIDED CAB (Dulles International)

Note: Luminance of points indicated
a = 12.6 ft lamberts; b = 20 ft lamberts;
c = 10.8 ft lamberts; d = 23.2 ft lamberts;
e = 13.1 ft lamberts.

3.5.2 Noise Transmission

Noise levels inside the cab were generally low since the controllers used headsets with no loudspeakers. Typical noise readings varied from 62 to 65 dBA. Measurements of the noise levels at the base of the ATCT were also taken during periods of aircraft activity. The outside noise levels were found to vary between 60 to 74 dBA. Inside the cab the aircraft noise was hardly discernible.

3.5.3 Heat Transmission

The cab air-conditioning exhaust ducts were situated close to the windows. Because of the lack of window shades the major problem was the heat transferred through the windows by the late afternoon sun. This factor was a source of complaint by the controllers who cannot understand why shades are not used in the Dulles cab. Increasing the air conditioning capacity of the cab enclosure might be a partial solution but this would be less practical than using window shades.

4. DISCUSSION OF COUNTERMEASURES

Countermeasures to reduce glare and reflections in tower cabs must meet certain standards. Specific FAA requirements include the following:

- Visibility

  The glass system used as a countermeasure should provide clear and distinct viewing of aircraft without distortion at distances not exceeding 6 miles under weather conditions with visibility of 15 miles or greater (see Appendix C).

- Glass Size and Loading

  The glass system recommended should conform to the glass window areas available in ATCT cabs with a maximum glass area of 60 sq ft and withstand wind speeds up to 100 miles/hour and wind gusts not exceeding 150 miles/hour.

- Glass and Electrical/Mechanical Systems

  Various types of glass and electrical/mechanical systems should be analyzed to determine the best system to reduce glare, reflection and heat transmission in ATCT cabs.

  Other considerations involve the noise reduction a glass system provides and the cost of the countermeasure weighed against benefits gained.

4.1 Techniques for Improving Visibility

4.1.1 Reflection Control--Number of Cab Sides

Reflections appearing in the corner window panes of ATCT cabs due to light entering adjacent panes are especially annoying to air traffic controllers. These corner reflections extend to the upper segment of a window and slope diagonally downward from the corner. Because of their relatively high elevation these corner reflections can interfere with viewing aircraft in flight. It has been observed that the area occupied by the corner reflections is greatest for the 4-sided cab with the area diminishing with increasing number of cab sides[+]. In particular, the corner reflections disappear for an observer in the center of a 8-sided cab. For the 5-sided cabs, however, the corner reflections are visible. The importance of these reflections as a possible source of interference to air traffic operations can be vividly illustrated in the following example. During a nighttime visit to the O'Hare 5-sided C-2A cab the first quarter moon could be seen in the north window. The realism of this event was so startling that the writer asked the cab orientation. However, upon moving several feet east or west the illusion disappeared.

The problem of cab geometry that underlies the theory of light reflections has been investigated in several FAA reports; "Investigations of Characteristics of the Pentagonal Tower Cab" (Ref. 10) and "Evaluation of Hexagonal ATC Tower Cab for Intermediate Activity Level VFR Airports" (Ref. 11).

In order to study the effect of number of cab sides on the corner reflections it was decided to construct four model cabs at IITRI. The models were constructed from plate glass sheets and cardboard to represent a half section, i.e., half the number of windows of the full-sized cabs. However, each model was fitted with a complete ceiling. Scaled models were constructed to simulate the geometry of the 4-sided (O'Hare cab), 5-sided (O'Hare and West Palm Beach cabs), 6-sided (New Tamiami) and 8-sided (Dulles International cab). Photographs were taken with a camera located at the center of each cab[*] of the visible corner reflections and those reflections between corners (See Section 4.1.2). Corner reflections were clearly visible in both the 4-sided and 5-sided cabs, but disappeared in the 6-sided and 8-sided cabs. However, corner reflections were seen to reappear in the 6-sided cab when the observer moved

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* Height corresponded to an observer 66 in. above floor level.
+ Provided cab has equal sides.

to a position on either side of the corner bisector. In the 8-sided cab, corner reflections were minimal irrespective of the observer's position in the model cab. It must be emphasized that these model cab studies were only approximate representations of the light entering an actual cab. In particular all reflections were accentuated by covering the corner panels, where light entered the models, by using diffusing white paper. The adjacent corner pane was covered with black paper. The reflection of the white diffuse panel was clearly visible on the black side. These model studies confirmed experimentally the theoretical conclusions given in FAA reports (Refs. 10 and 11).

In summary, corner reflections become the most objectionable when a bright sky or sun is reflected in ATCT cab corners. Therefore, critical conditions exist when the sun is low (early morning or late afternoon), which in turn produces a very bright sky. The octagonally shaped cab* minimizes these corner reflections and is recommended as an effective countermeasure.

4.1.2 Reflection Control--Glass Tilt

Light reflections appearing between the corners in ATCT cabs have been considered by the FAA in several reports (Refs. 10 and 11). It has been shown in these FAA reports that the height (and area) of the reflections is controlled by the glass tilt, ceiling height, and depth of the cab. These reflections are produced by light entering from behind an observer from cab windows other than adjacent corner windows and are bounded on the upper window area by the ceiling reflection. This source of reflection becomes especially bright in the early morning and evening when the bright sky is reflected in opposite windows. It is also possible for the direct sun to be reflected in this way. The reflection of the sun has been investigated using model ATCT cabs in a report entitled "Report of Investigation of Reflections in Air Traffic Control Towers--Department of Civil Aviation, Australia" (Ref. 12).

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* This is correct provided octagon has equal sides.

All ATC tower cabs visited during the course of this study have a outward glass window tilt of 15 deg. This angle appears to have been selected by the FAA as a compromise between construction costs and window reflection area. For a controller standing a few feet away from the counters observing aircraft in flight or taxiing on distant runways most reflections at 15 deg glass tilt appear quite low in the windows. However, on approaching the cab counters to view aircraft closer to the tower these reflections rise and interfere with the visual task if they coincide with the observer's line of sight. It was noted that in all ATCT cabs visited these reflections were of equal area and location in the cab windows irrespective of the number of sides. Consequently, all reflections between tower cab corners are a function only of the glass tilt. A window glass tilt of 20 deg has been recommended by the FAA (Ref. 10). Such a countermeasure would be of considerable benefit in minimizing the visual annoyance due to reflections between corners in the cab.

4.1.3 Reflection Control--Ceiling Treatment

The cab window reflections discussed above are in general bounded (by reflections of the cab ceiling) in the upper segment of a window. In order that the ceiling reflection is not objectional, the ceiling radiance must be sufficiently low to be unnoticed in the window glass. This can be achieved by using a dark colored ceiling paint. In all the ATCT cabs visited during the program ceiling reflections were controlled using dark ceiling colors. However, light colored areas in the ceiling such as illumination fixtures can be a problem. By installing properly baffled illumination sources this problem can be eliminated. Consideration of this aspect becomes important at night where light scattered from the floor and overhead lights produces reflections from large flush ceiling fixtures, e.g., the New Tamiami cab.

Small illumination sources for working areas such as counter tops must also be sufficiently baffled to prevent their reflection in the cab window glass. Baffles should be arranged and light sources recessed so that a bright source cannot radiate in the window direction. This illumination problem was effectively controlled in the O'Hare 5-sided C-2A cab where lighting fixtures with black colored baffles were recessed into the cab ceiling. In this way the light direction and illuminated areas were properly controlled.

4.1.4 Reflection Control--Special Glass

4.1.4.1 Antireflection Coatings

Reflections appearing in ATCT cab window glass may be reduced by coating the surfaces with an antireflection material. Coatings are applied by vacuum evaporation techniques. Antireflection coatings have for years been used in optical instruments. They are an indispensible part of present day multicomponent photographic lenses.

The equation for the transmittance T of a plane parallel plate, as shown in Fig. 9 , for monochromatic light undergoing multiple reflections is derived in optics texts as (Refs. 13 and 14)

$$T = \frac{T_{max}}{1 + F \sin^2 \beta/2}$$

where

$$T_{max} = \frac{T_1 T_2}{(1-R)^2} = \text{maximum transmittance}$$

$$F = \frac{4R}{(1-R)^2}$$

$$R = (R_1 R_2)^{1/2}$$

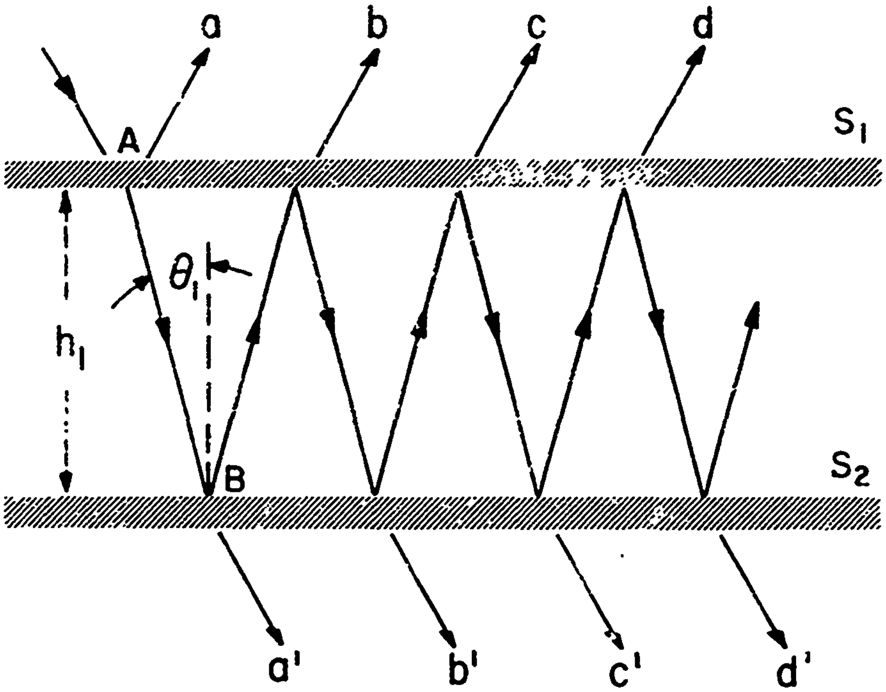

Fig. 9 PATHS OF MULTIPLE REFLECTIONS BETWEEN TWO PARALLEL SURFACES

R_1, R_2 = reflectivities of surfaces 1 and 2

β = $\frac{4\pi}{\lambda} n_1 h \cos \theta_1 - (\epsilon_1 + \epsilon_2)$

ϵ_1, ϵ_2 = phase changes upon reflection at surfaces 1 and 2.

If we now turn to Fig. 10, we can derive the conditions for zero reflectance of a single layer deposited upon a substrate. For a nonabsorbing coating R = 1 - T and

$$T_{max} = \frac{(1-R_1)\ (1-R_2)}{(1-R)^2}$$

Thus, when $R_1 = R_2$, $T_{max} = 1.0$ and the condition for zero reflectance holds. In Section 2.1.3 the relationship between reflectance and index of refraction was written as

$$R = \left(\frac{n_1-n_2}{n_1+n_2}\right)^2$$

The reflectances R_1 and R_2 can therefore be written

$$R_1 = \frac{(n_1-n_o)^2}{(n_1+n_o)^2}$$

and

$$R_2 = \frac{(n_1-n_s)^2}{(n_1+n_s)^2}$$

Using the relationship $R_1 = R_2$, we can solve for n_1 in terms of n_o and n_s leading to the requirement

$$n_1 = (n_o n_s)^{1/2}$$

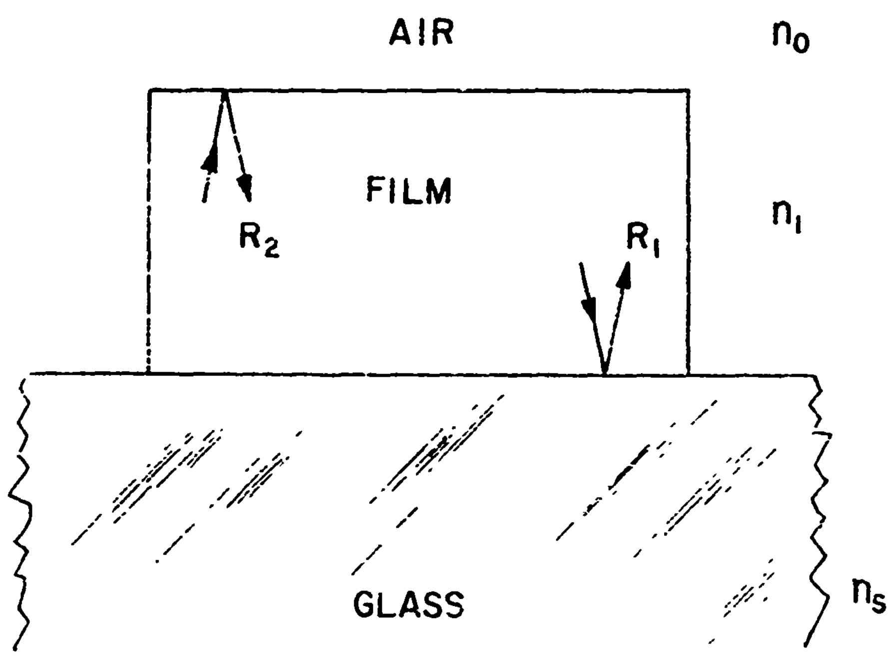

Fig. 10 GEOMETRY OF SINGLE-LAYER ANTIREFLECTION COATING

namely, that the index of refraction of the film should be the geometrical mean of the indices of the substrate and the incident medium. The thickness of the film is determined from the fact that

$$T = \frac{T_{max}}{1 - F \sin^2 \beta/2}$$

is a maximum when $F \sin^2 \beta/2 = 0$, or when $\beta/2 = m\pi$. Since $\epsilon_1 = 0$ and $\epsilon_2 = 180°$ (a phase change only occurs at reflection within the less dense medium), then we have

$$\beta = \frac{4\pi}{\lambda} n_1 h \cos \theta_1 - \pi = 2m\pi$$

or

$$n_1 h \cos \theta_1 = (2m + 1) \lambda_o/4.$$

Thus at normal incidence the optical thickness, n_1h, should be an odd number of quarter wavelengths.

In order to achieve a coating which perfectly antireflects glass (n = 1.51) to air at one wavelength, λ_o, the index of the film is

$$n_1 = (1.51)^{1/2} = 1.23.$$

Unfortunately, no durable coating materials are known to exist with this low refractive index. Available materials include magnesium fluoride (n = 1.38) and cryolite (n = 1.35). The reflectance for these coatings reaches a minimum at λ_o but does not go to zero. Figure 11 shows the computed reflectance a single MgF_2 layers for λ_o = 5500 Å and m = 0,1,2.

The single-layer coating has the disadvantage that in practice it does not attain zero reflectance. Double-layer and triple-layer coatings have the advantage that at one or more wavelengths they can provide a zero reflectance at an air-glass interface.

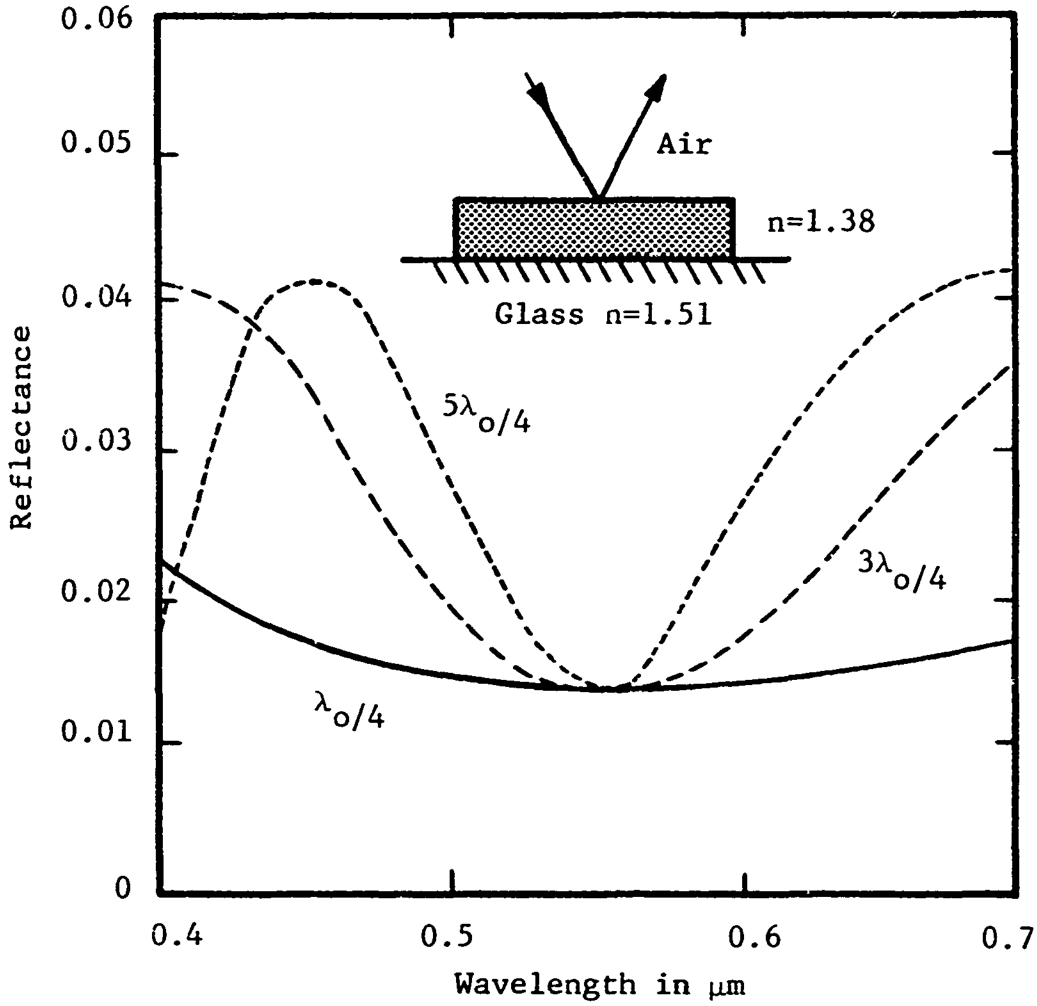

Fig. 11 COMPUTED SPECTRAL REFLECTANCE OF SINGLE-LAYER ANTIREFLECTION COATINGS

Double-layer coatings have two thicknesses and two refractive indices. Figure 12 compares the performance of a "double quarter" silicon monoxide-magnesium fluoride film and a single quarter wave film over the 4000-7000 Å region.

Triple-layer coatings provide a flat low reflectance curve for a wide spectral range. Figure 13 shows a "quarter-half-quarter" arrangement (Ref. 14) with films of MgF_2, SiO, and CeF_3. This coating has excellent antireflection properties in the near infrared.

Antireflection coatings are usually maximized for normal incidence and therefore become less effective as the incidence angle deviates from zero. This would not be too serious an objection for application to ATC tower cab glass since the most annoying window reflections are those whose source is behind the observer in the tower cab. It should be noted that the above calculations give the reflectance at one glass surface, and to be an effective countermeasure all surfaces must be coated. Equipment is presently available for evaporation coating of rectangular glass with diagonals up to 10 ft. It is within the state-of-the-art to apply the single layer coating, upon special order, to the above size. For example, the Liberty Mirror Division of LOF have made large size single layer coatings for use in television studios. Current price quotations are estimated at between $5 to $10 per sq ft. The single layer coating will reduce the reflection of each coated surface to approximately 2 percent from 4 percent for an uncoated surface.

Double-layer coatings are now available in 24 in. x 36 in. sizes from several suppliers. (Coatings of this type are designated SLR by Liberty Mirror -- also supplied by OCLI*.) It is estimated that in perhaps two years the capability for producing the large size in double layer will be available. (Coating of the double layer requires optical monitoring during evaporation over much of the area to ensure an even coating thickness.) These coatings will reduce the transmission to 1/2 percent for a chosen region in the visible spectrum. The coating is not neutral. It may be seen from Fig. 12 that the coatings give rise to a distinctly colored reflection.

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* Optical Coating Laboratory, Inc., Santa Rosa, California

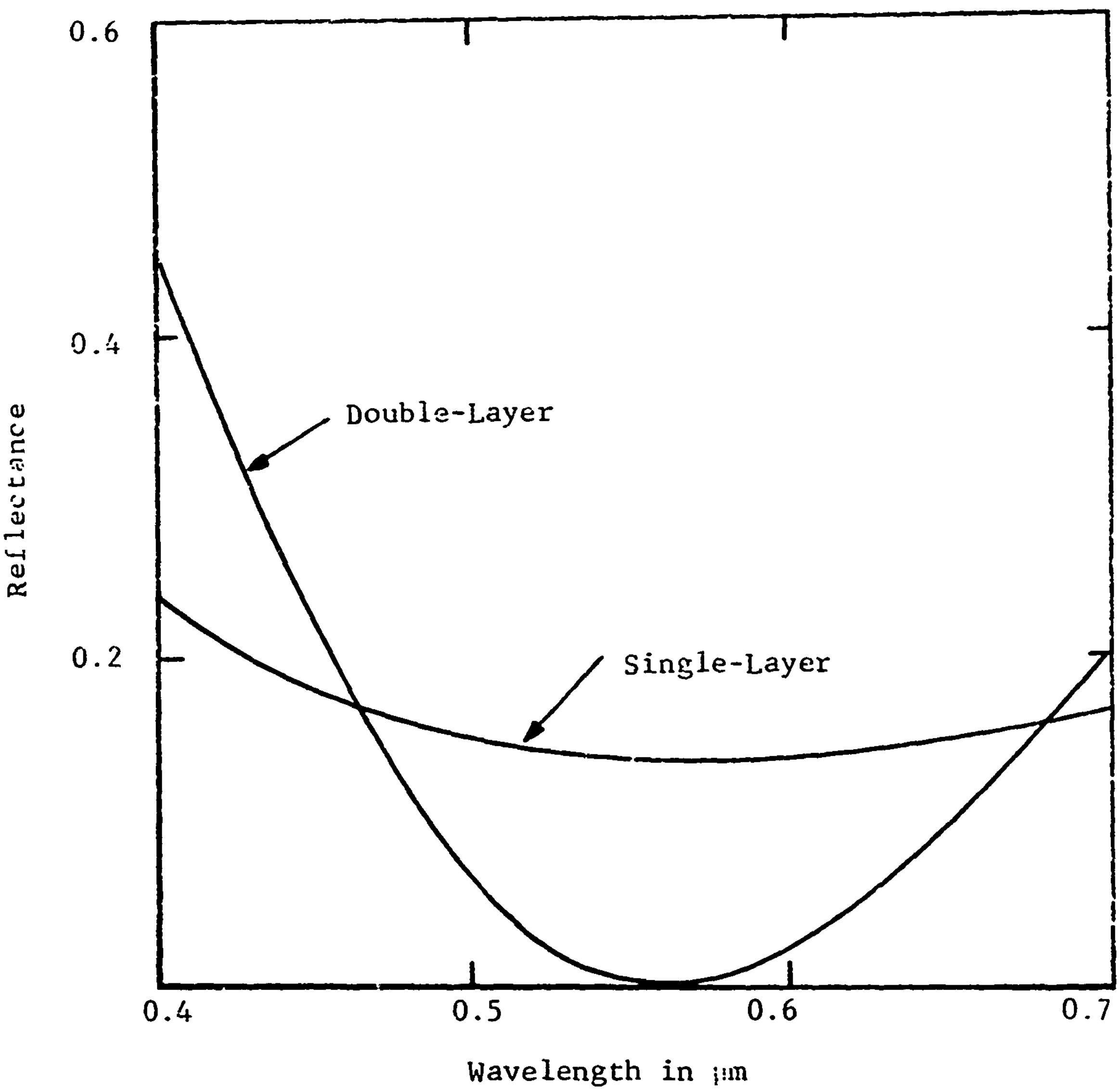

Fig. 12 COMPUTED SPECTRAL REFLECTANCE FOR SINGLE-LAYER (n_1=1.38) AND DOUBLE-LAYER (n_1=1.38, n_2=1.70) COATINGS

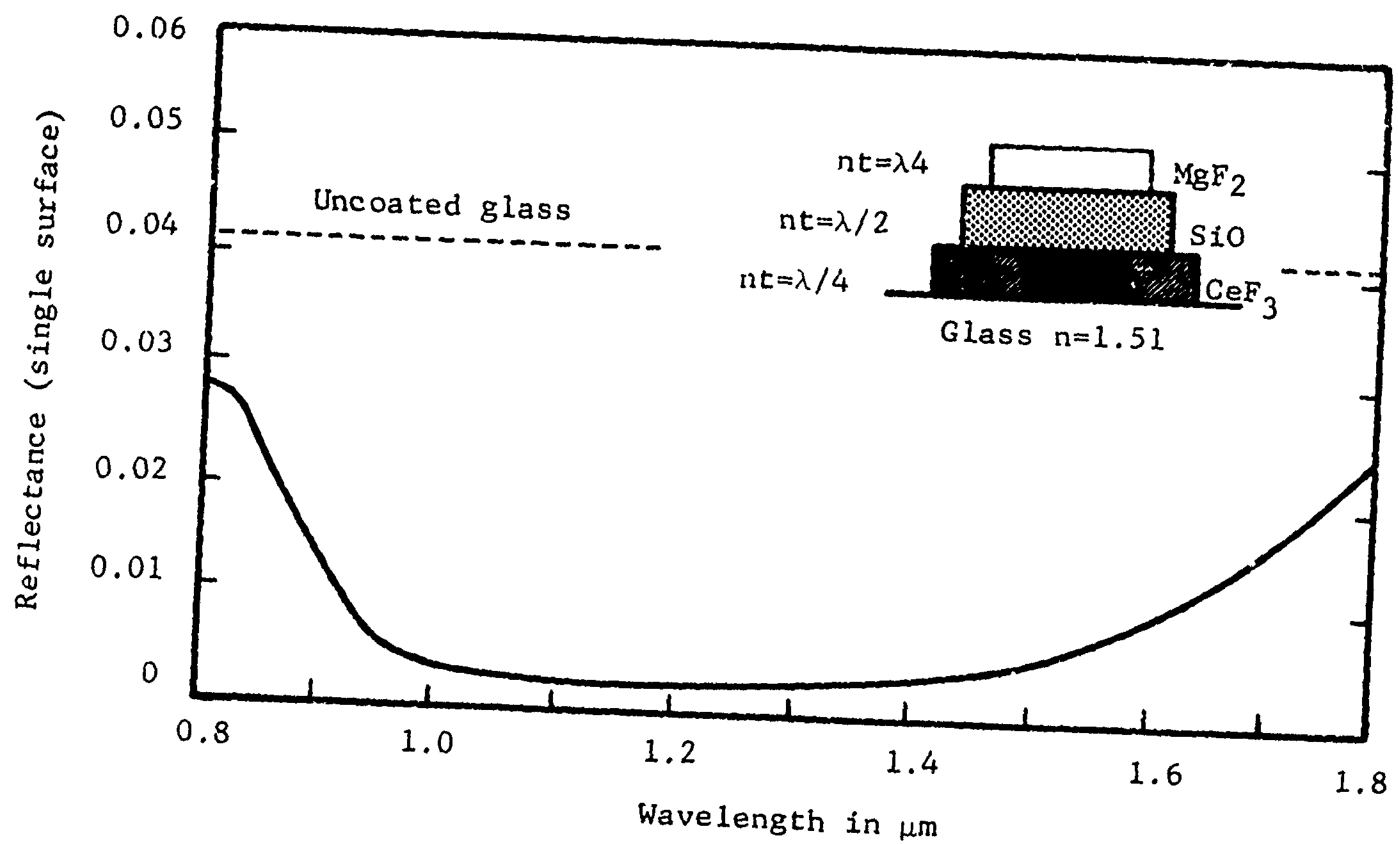

Fig. 13 MEASURED REFLECTANCE OF TRIPLE-LAYER COATING

Triple layer coatings can reduce the reflectance of the coated surface to less than 1/2 percent from 1.0 micron to 1.5 micron wavelength including the visible. This is now available up to 18 in. diagonal. No estimate can be given for the application of this to large areas. (This coating was developed for coating lenses and small critical optical parts and is designated ATLR by LOF and HEA by OCLI.

4.1.4.2 Antireflection Coatings for ATCT Cab Glass

The application of a single layer coating will reduce the reflection of each surface by 50 percent. Consequently, the use of a single layered coating on a clear double-glazed insulated window would produce a total reflection equivalent to a single plate glass such as the O'Hare 5-sided ATCT cab. The luminance of the reflections have been found to vary over such a wide range that is too difficult to determine whether this countermeasure would be a worthwhile improvement. The double-layer coating, while the total reflectance is reduced to a greater extent than the single layer, produces a colored reflection that may prove objectionable to air traffic controllers. The triple-layer coating meets all the criteria to permit the reflections to be reduced to a negligible amount. However, the present state-of-the-art prohibits its usage from a surface area versus cost benefit standpoint (see Section 6).

4.1.5 Reflection Control--Tinted Glass (Insulated Units)

The reflectance of a double-glazed window is approximately double that of a single plate because there are four surfaces instead of two for reflections to arise. If one of the double windows is tinted glass the reflectance will be reduced. This occurs when heat absorbing glass is used as the outer pane since heat absorbing glass is tinted blue or blue-green, and as a result attenuates reflected light from the outer surface.

For glare and reflection control, grey and bronze glass is used by architects for building applications. However, if bronze or grey glass is used as the outer pane for two 1/4 in. plates separated by 1/2 in. air space, the light transmission is reduced to only about 40 percent. Thus the use of grey or bronze glass for ATCT cabs would make the windows useless from a visibility standpoint. For regular insulated clear glass units, having the same dimensions as above, the light transmission is 79 percent. For heat absorbing glass (green tint) in the outer pane, the light transmission is about 68 percent. Consequently, heat absorbing glass in the outer pane of a double-glazed unit could be used as a practical countermeasure for reflection control since it meets the visibility requirements.

4.1.6 Reflection Control--Linear Polarizers

The polarization of light by reflection from a glass surface is illustrated in Fig. 1, Section 2.1.3. If unpolarized light is incident on a glass surface, the reflected light is partially or completely linearly polarized depending on the angle of incidence. Polarizing sunglasses take advantage of this fact since most outdoor objects are of dielectric material. Light reflected obliquely from a horizontal dielectric surface is linearly polarized in the horizontal direction. Polarizing sunglasses having their transmission axes vertical absorb almost all the horizontal variations and only the reflected light having a vertical component is transmitted. Polarizing sunglasses will therefore effectively remove the "shiny" reflections from roads, pavements, water surfaces, trees or grassy areas. In fact they will remove reflections from dielectric surfaces wherever the plane of incidence (and reflection) is vertical and oblique. Also polarizing sunglasses will similarly reduce the reflections from a glass surface wherever the plane of incidence is vertical and the incidence angle is oblique.

For application in the case of a tower cab, the light causing reflections must be transmitted from above and be reflected at an oblique angle. This would apply to all horizontal reflecting surfaces within the cab. Polaroid sunglasses would be effective against reflections from counter tops, glass covers used on counters, or in fact any polished object in the horizontal plane. The between corner reflections seen when an observer looks through the window perpendicular to the glass surface are due to light coming from behind the observer--in fact the observer may see his own reflection--and hence we have reflection at normal incidence. The effect of wearing sunglasses on these reflections will therefore be minimal. The effectiveness would depend more on the tilt of the windows. If the observer looks through the cab window obliquely (left or right of vertical), the reflected light will be polarized in the vertical plane and the sunglasses will transmit this light. Hence normal sunglasses are not suitable to remove these reflections A similar condition applies to corner reflections in a tower cab.

It is evident, therefore, that sunglasses orientated in the vertical plane are unsatisfactory for removing the window glass reflections. Polarizing glasses whose axes could be rotated in accordance with viewing directions might prove useful However, the continuous need to readjust their orientation seems to preclude their usage. It is felt, however, that a field study of polarizer orientation in tower cabs would prove useful to the FAA.

Polarizing sunglasses used at nighttime to remove reflections from overhead lights would be satisfactory if it were not for the low transmission, 32 percent, of the polarizing material. Such an attenuation of light is not acceptable for viewing aircraft at nighttime.

4.1.7 Reflection Control--Circular Polarizers

It has been indicated in the previous section that unpolarized light reflected perpendicularly from a glass surface is unpolarized and cannot be absorbed by a linear polarizer. It may however be controlled through the use of a circular polarizer in special situations.

Circular polarizers have been used quite effectively to remove unwanted reflections from room objects or lights interfering with the viewing of cathode ray tubes, e.g., radarscopes or television displays. A circular polarizer is mounted over the face of the radarscope. Unpolarized light incident upon the polarizer is converted to circularly polarized light. This circularly polarized light then falls upon the radarscope face at nearly normal incidence and is reflected back in the direction of the polarizer. The "handedness" of the circular polarization is reversed by reflection and therefore is absorbed by the circular polarizer.* Hence no reflection of objects or light sources may be seen in the radarscope face.

The transmission of the circular polarizer (plastic sheet) is approximately that of a single linear "polaroid" sheet, and so light from the radarscope is not too seriously attenuated. Also because reflections are destroyed the contrast is greatly enhanced. It must be emphasized that surface reflection from a circular polarizing sheet is essentially that of a glass surface and can itself lead to undesirable reflections. These reflections are commonly removed by inclining the sheet at an angle to the radarscope face. This preceding statement illustrates the impractibility of using this system for removing reflections from ATCT cab windows. The reason for this is essentially twofold. First, reflections from the cab windows at normal incidence could be removed but reflections at the surface of the polarizing sheet would be substituted instead. In fact, a greater tilt angle

* A circular polarizer consist of a polarizing sheet and a $\lambda/4$ retardation plate in series with their axes orientated at 45 deg. It is available as a single plastic sheet.

would be required on the polarizer than on the window glass. Second, the light transmission of the circular polarizer is theoretically only 50 percent, and in practice near to 30 percent, which would be unacceptable for use at nighttime.

4.2 Glare Control

4.2.1 Window Shades

With the exception of the Dulles ATCT cab all the cabs visited use neutral tinted window shades of 3 to 5 mil mylar plastic for attenuating the glare from a bright sky during the early morning and late afternoon. The high luminance of the sky leads to discomfort and disability glare when a controller must observe aircraft in the direction of a very bright sky. Dark plastic shades whose visual transmission is about 10 percent are generally used in tower cabs. These window shades are suspended in two ways; either in contact with the window or drawn vertically from a cab ceiling. Problems associated with the method of mounting the shades are:

- Although the shades are under tension they tend to wrinkle giving rise to a myriad of small bright reflections.
- Shades hung vertically have especially serious reflections since the near sky light source meets the shade at normal incidence with the result that reflections arise in the shade similar to untilted window glass.
- Shades hung along the plane of the window are an improvement, but are subjected to motion in the air stream emanating from vents the window. This effect causes reflections from the wrinkled shades to continuously move in the field of view.
- Both types of shade mounting produce undesirable gaps in the corner areas of a cab enclosure since the windows are trapazeoidal and the shades rectangular.

Each shade must be equipped with a window top roller since a controller tends to view beneath a partially drawn shade without changing his position inside the cab. It has also been found desirable to shade the upper portion of a window to attenuate the bright sky even when the sun is high since the sky becomes brighter above than near the horizon.

4.2.2 Sunglasses

Sunglasses may be worn by controllers to reduce the glare instead of using the dark window shades described above. Glasses have the advantage that they do not lead to objectionable reflections and may be quickly removed if desired. Polarizing sunglasses should not be used since they may or may not remove* the window reflections. Futhermore while they darken the polarized blue sky they do not reduce the brightness of a white cloud background to the same degree, since light scattered from overcast and white clouds is not polarized. Consequently, neutral glasses of specified transmission are required. There are several objections to the use of sunglasses.

If a controller normally wears glasses then he must either have the sunglasses ground to his perscription or wear an additional pair over his regular glasses. The latter is undesirable because of weight while the former is undesirable because he must substitute his regular glasses for comfortably observing fixtures within the cab.

If the observer does not regularly wear glasses it is a simple matter to remove the dark glasses whenever necessary.

4.2.3 Variable Transmission Glass

Several types of variable transmission glass have been devised. They are photochromic glass, electrically variable and variable transmission glass windows using a liquid and variable spacing.

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* See Section 4.1.6

4.2.3.1 Photochromic Glass

Photochromic glass consists of a glass that contains silver halide crystals which may be reduced to silver by illumination with light. The action is reversible and the transmission returns when the illumination is removed. Glass of this nature is currently manufactured by Corning Glass for use in sunglasses which darken on exposure. Corning Glass has given consideration to the use of the glass for windows but are not at the present pursuing the idea.

A major disadvantage to photochromic glass is its slow response, typically of the order of several minutes, to changes in lighting conditions. Thus for a controller rapidly changing his field of view when looking through photochromatic glass windows, variations in illumination (lumens/sq ft) would be difficult to detect which could lead to catastrophic results. Furthermore, while photochromic glass darkens with increased illumination it is not under the control of cab personnel. For example, if an observer wished to view air traffic through a "clear zone" this would be impossible with photochromic glass windows. In addition the density is a function of the illumination incident on the glass, and the maximum illuminance* does not necessarily occur during periods of objectionable glare. In conclusion, photochromic glass does not appear to offer a practical solution for reducing glare in ATCT cab windows.

4.2.3.2 Electrically Variable Transmission Glass

The control of radiation by electrical means offers the ability to regulate the window transmission to fit the viewing conditions.

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* The maximum illuminance occurs with a bright sun in a clear sky when the solar rays have minimum incidence angle.

One method of electric control of radiation is the electric polarization of dipole suspensions. A layer of liquid containing minute needle-like particles is sealed between two glass layers. The inner surface of each layer is coated with a transparent, electrically conductive material. When a voltage difference is applied to the conducting coatings an electric field is produced perpendicular to the layers. The dipoles align themselves with the field and the transmission of the window is high (of the order of 70 percent). With the field reduced, the dipoles become more random as a result of thermal motions, and the transmission is reduced. Nearly total opacity is achieved by removal of the electric field (Ref. 15).

Electrically variable glass surfaces have been produced in sizes up to 4 sq ft by Marks Polarized Corporation. These units may be manufactured with varying maximum densities. The ratio of maximum to minimum density is between 8 and 10. For example, a window having a closed (no electric field) optical density of 1.0 and an open (voltage applied) optical density of 0.125. In other words, the open light transmission would be 75 percent and the closed transmission 10 percent. Typically, the time required to activate such a window panel is 1 millisec (voltage on) and 30 millisecs (voltage off). While such window panels are still in the development stage there is theoretically no limit to the window sizes that could be produced. A quotation from Marks Polarized Corporation (Ref. 16) indicates that the cost of such a window panel "will eventually be in the range of $100 to $10 per square foot, in substantial production". A major disadvantage to this system is the problem of maintaining a variable voltage potential areas the window panel and the cost in electrical power consumption.

4.2.3.3 Liquid-Filled Glass Surfaces with Variable Spacing

A glass window using a dark .quid between two movable glass surfaces may be used to change the light transmission. When the glass surfaces are very close together all the liquid is expelled maximum light transmission is achieved. When the surfaces are separated a finite distance the dark liquid fills the available space between the glass surfaces and the transmission is reduced. No commercial manufacturer of this system is presently known. However a prototype system patented by the Spanish inventor, Luis Rodriquez Aparicio, (Ref. 17) uses two wedge shaped panes of glass, one of which is moved in a direction parallel to the wedge angle so as to vary the space between the two glass surfaces. The liquid filling the space is ethylene glycol containing a black dye.

4.3 Reduction in Heat Transmission

The reduction of heat transmission through glass can be accomplished in several ways. The use of heat absorbing glass can greatly reduce solar heat gain. Insulating glass can also be used to reduce heat transmission caused by the difference between outside and inside air temperature. However, reduction in heat transmission usually produces a reduction in light transmission which results in poor visiblity and increased reflections. To demonstrate the reduction in cooling load due to changing the glass window construction, calculations were made of the total heat load to the new O'Hare 5-sided C-2A cab for various types of glass construction that would be practical for cab windows.

The new O'Hare tower cab windows consist of 10 identical windows measuring 8.5 ft by 6.9 ft for a total area of 589.5 sq ft. The orientation of the windows is shown in Fig. 14. The glass has a nominal thickness of 3/4 in. However, according to Libbey-Owens-Ford Company, who supplied the glass, the actual thickness is 7/8 in.

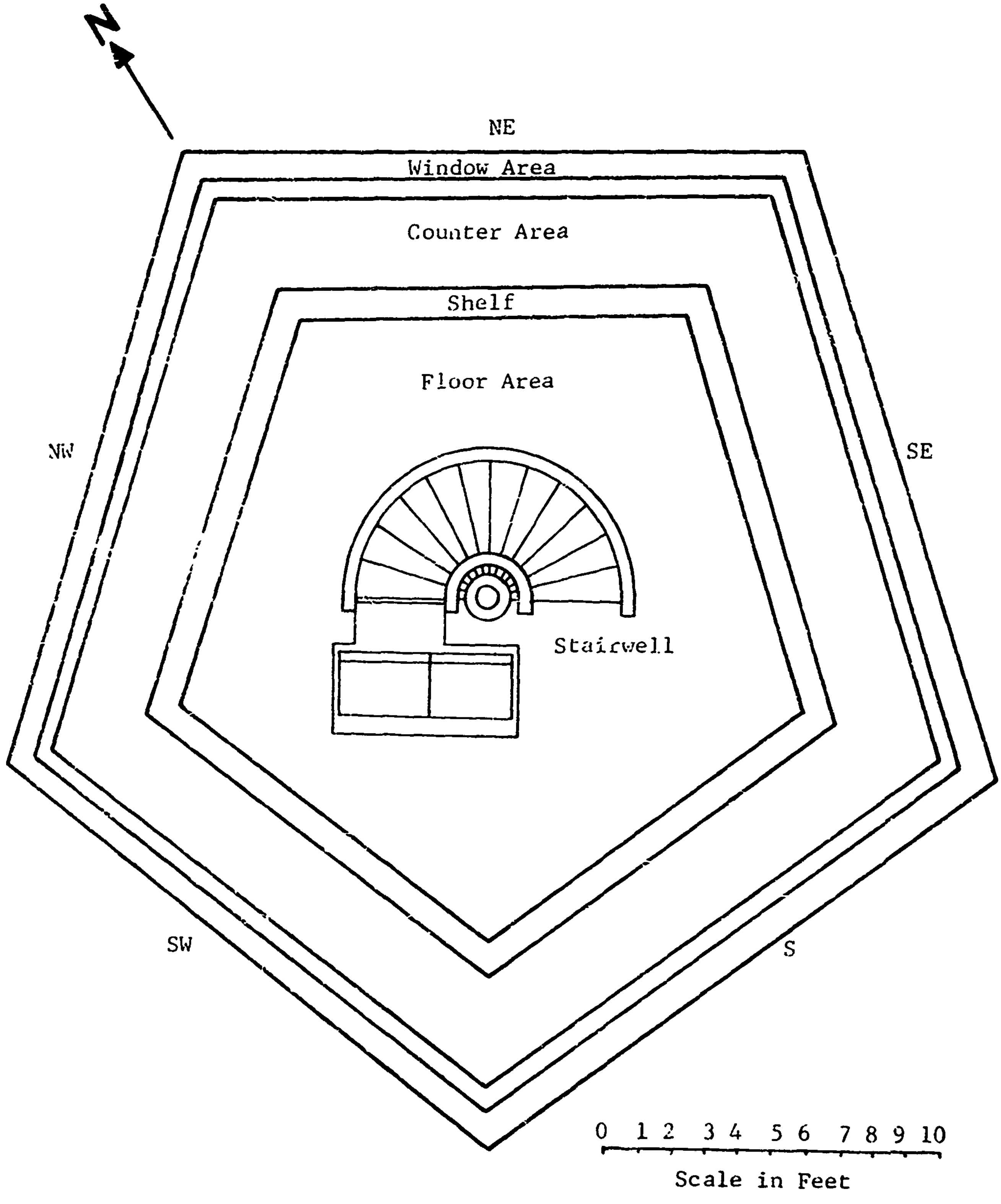

Fig. 14 PLAN OF NEW O'HARE FIELD C-2A 5-SIDED CAB

Solar heat gain through the cab windows was calculated according to procedure developed by ASHRAE (Ref. 6). In this method the solar heat gain through each window is calculated for each hour, day and month since the heat gain is a function of the altitude and azimuth of the sun. Since the maximum heat gain cannot be predicted by inspection, it is necessary to make calculations for one day in each of several months. In addition, since the peak heat gain is usually in the afternoon, it is necessary to calculate the heat gain at several hourly periods.

The total heat gain both solar and that due to the difference between indoor and outdoor temperatures, was calculated for several hourly periods on August 21, September 21, and October 21 for 40° N. latitude (approximately that of O'Hare Field). Details of the calculation procedure are given in Appendix B. Heat gain was calculated for single plate glass thicknesses of 1/8, 1/4, 1/2, and 7/8 in. --- and for double or insulated glass units consisting of two 1/4-in.-thick glass plates separated by 1/2 in. air space. One insulated unit has both plates of clear glass, while the other unit has an outside plate of heat absorbing glass and an inside plate of clear glass. The results of the calculations are given in Table 7. The results are given in units of Btu/hr and tons of refrigeration.

It can be seen that the cooling requirement for the 7/8 in thick windows is about the same as for clear glass double or insulating windows. However, by using a heat absorbing-clear insulating window unit, a reduction in cooling capacity of almost one-third can be obtained.

Table 7

TOTAL HEAT GAIN THROUGH WINDOWS AT NEW O'HARE FIELD TOWER CAB

Window Type	Total Heat Gain, Btu/hr (tons of refrigeration)							
	Aug. 21			Sept. 21		Oct. 21		
	4:00 p.m.	2:00 p.m.	3:00 p.m.	4:00 p.m.	5:00 p.m.	2:00 p.m.	3:00 p.m.	4:00 p.m.
Single Plate Thickness								
1/8 in.	48964 (4.1)	42680 (3.6)	42916 (3.6)	41831 (3.5)	33071 (2.8)	40015 (3.3)	39956 (3.3)	32988 (2.7)
1/4 in.	46240 (3.9)	40086 (3.3)	40263 (3.4)	39261 (3.3)	31113 (2.6)	37015 (3.1)	37162 (3.1)	30677 (2.6)
1/2 in.	43494 (3.6)	37621 (3.1)	37775 (3.1)	36843 (3.1)	29215 (2.4)	34816 (2.9)	34757 (2.9)	28697 (2.4)
7/8 in.*	39414 (3.3)	33295 (2.8)	34085 (2.8)	33248 (2.8)	26410 (2.2)	31208 (2.6)	31161 (2.6)	25726 (2.1)
Insulating Window (2-1/4 in. Plates, 1/2 in. Air)								
Outside / Inside								
Clear / Clear	33932 (2.8)	31561 (2.6)	31716 (2.6)	27986 (2.3)	23839 (2.0)	32010 (2.7)	31963 (2.7)	26386 (2.2)
Solex, Solargrey, Solarbronze / Clear	25584 (2.1)	22649 (1.9)	22755 (1.9)	22166 (1.8)	17438 (1.5)	21599 (1.8)	21576 (1.8)	17815 (1.5)

* Actual thickness of glass used in construction for O'Hare Field C-2A Tower Cab.

4 4 Reduction in Moisture Condensation--Window Fogging

Condensation of moisture on windows occurs when the glass surface temperature is equal to or less than the dew point of the surrounding air. During the winter season the glass surface temperature must be maintained above the dew point of the air. This can be accomplished by adjusting the relative humidity of the air inside the cab. However, for very low outside air temperatures, the inside relative humidity may have to be reduced to a value which produces a very "dry" atmosphere that can be uncomfortable and dangerous (static electricity generation) to personnel. Therefore, it is more desirable to be able to maintain a relative himidity that is comfortable by selecting glass window units tht do not allow the inside glass surface temperature to reach very low values. Additional control of the inside glass surface temperature can be obtained by the velocity and temperature at which air is circulated over the glass surface.

The inside glass surface temperature was calculated for the following environmental conditions and types of glass windows; outside conditions of 15 mile per hour wind velocity and outside air temperatures of -10, 0, and 20°F and inside conditions of 75°F air temperature and still air, 2, and 5 feet per second air velocity over the glass surface. Calculations were made for single plate glass thickness of 1/4, 1/2, and 7/8 in. and for double (insulating) plate windows of two 1/4-in plates separated by a 1/4 in. air space, two 1/4-in. glass plates separated by a 1/2 in. air space and one 1/4-in. and one 1/2-in. plate separated by a 1/2 in. air space. The results of the calculations are given in Table 8 and Figs. 15 through 17 which show the inside glass surface temperature and the inside air relative humidity which will result in condensation on the window. To prevent condensation, the inside air relative humidity must be less than that indicated in Table 8.

Table 8

INSIDE GLASS SURFACE TEMPERATURE AND RELATIVE HUMIDITY TO CAUSE CONDENSATION

	Single Plate								
	Inside Glass Surface Temperature. °F (Relative Humidity, %)								
Glass Thickness, in.	1/4			1/2			7/8*		
Air Velocity, ft/sec	0	2	5	0	2	5	0	2	5
Outdoor Air Temperature, °F									
-10	9.6 (7)	13.0 (9)	17.4 (11)	12.4 (8)	16.0 (10)	20.7 (13)	16.0 (10)	19.9 (12)	24.9 (15)
0	17.3 (11)	20.3 (13)	24.1 (15)	19.7 (12)	22.9 (14)	27.1 (17)	22.9 (14)	26.4 (17)	30.7 (20)
20	32.7 (22)	34.9 (24)	37.7 (26)	34.5 (23)	36.8 (25)	39.9 (29)	36.8 (25)	39.4 (28)	42.5 (32)
	Insulating Units								
	2-1/4 in. Plates, 1/4 in. Air			2-1/4 in. Plates, 1/2 in. Air			1/4, 1/2 in. Plates, 1/2 in. Air		
-10	37.2 (25)	41.5 (30)	46.9 (37)	41.2 (29)	45.3 (34)	49.8 (40)	41.5 (30)	46.1 (35)	50.5 (42)
0	41.6 (30)	45.4 (34)	50.2 (41)	45.1 (34)	48.8 (40)	52.8 (45)	45.8 (35)	49.5 (40)	53.4 (47)
20	50.5 (42)	56.3 (43)	55.8 (50)	53.0 (46)	55.8 (50)	58.7 (57)	53.6 (47)	56.3 (51)	59.2 (58)

* Actual thickness of glass used in construction for O'Hare Field C-2A Tower Cab.

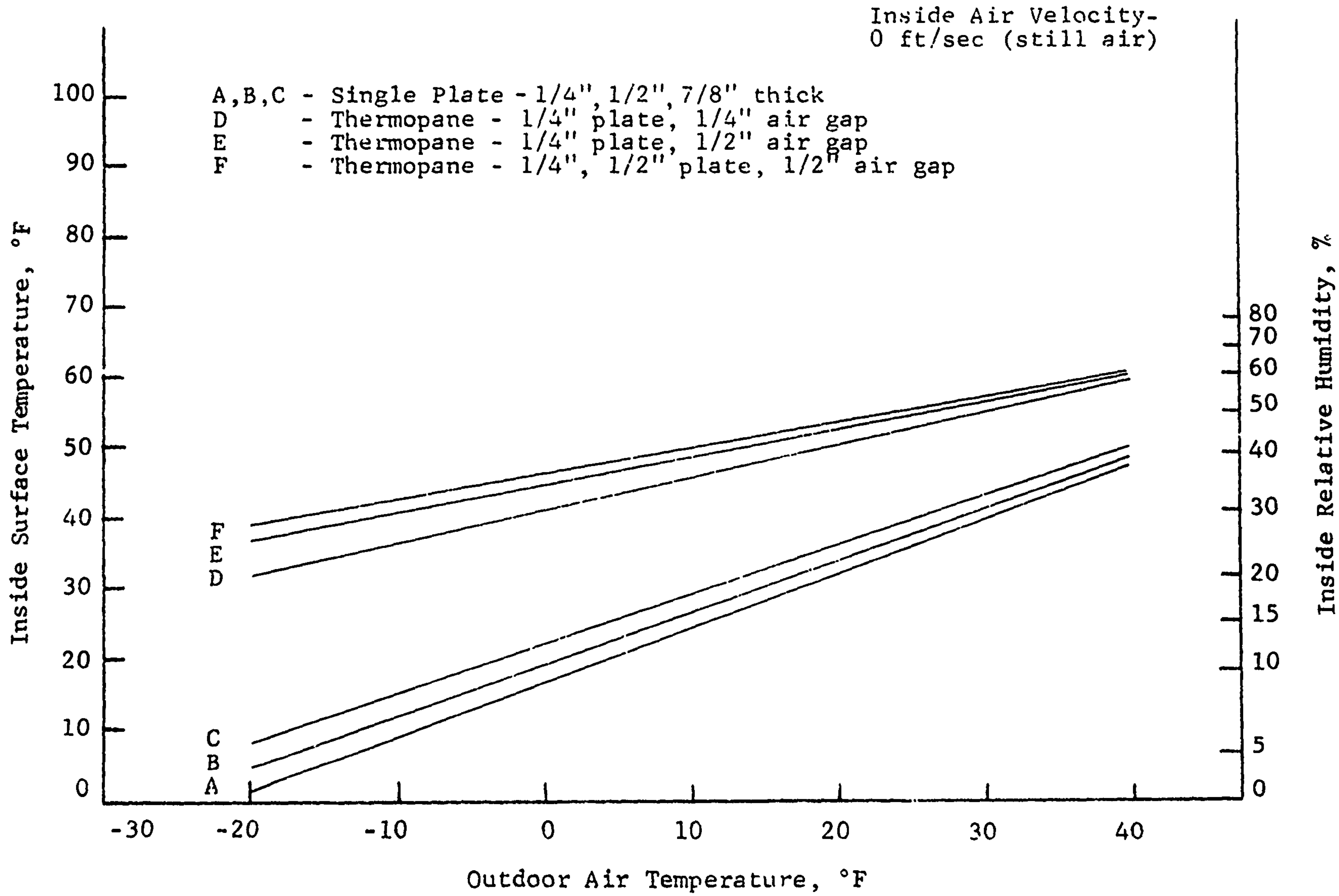

Fig. 15 INSIDE SURFACE TEMPERATURE AND RELATIVE HUMIDITY FOR CONDENSATION

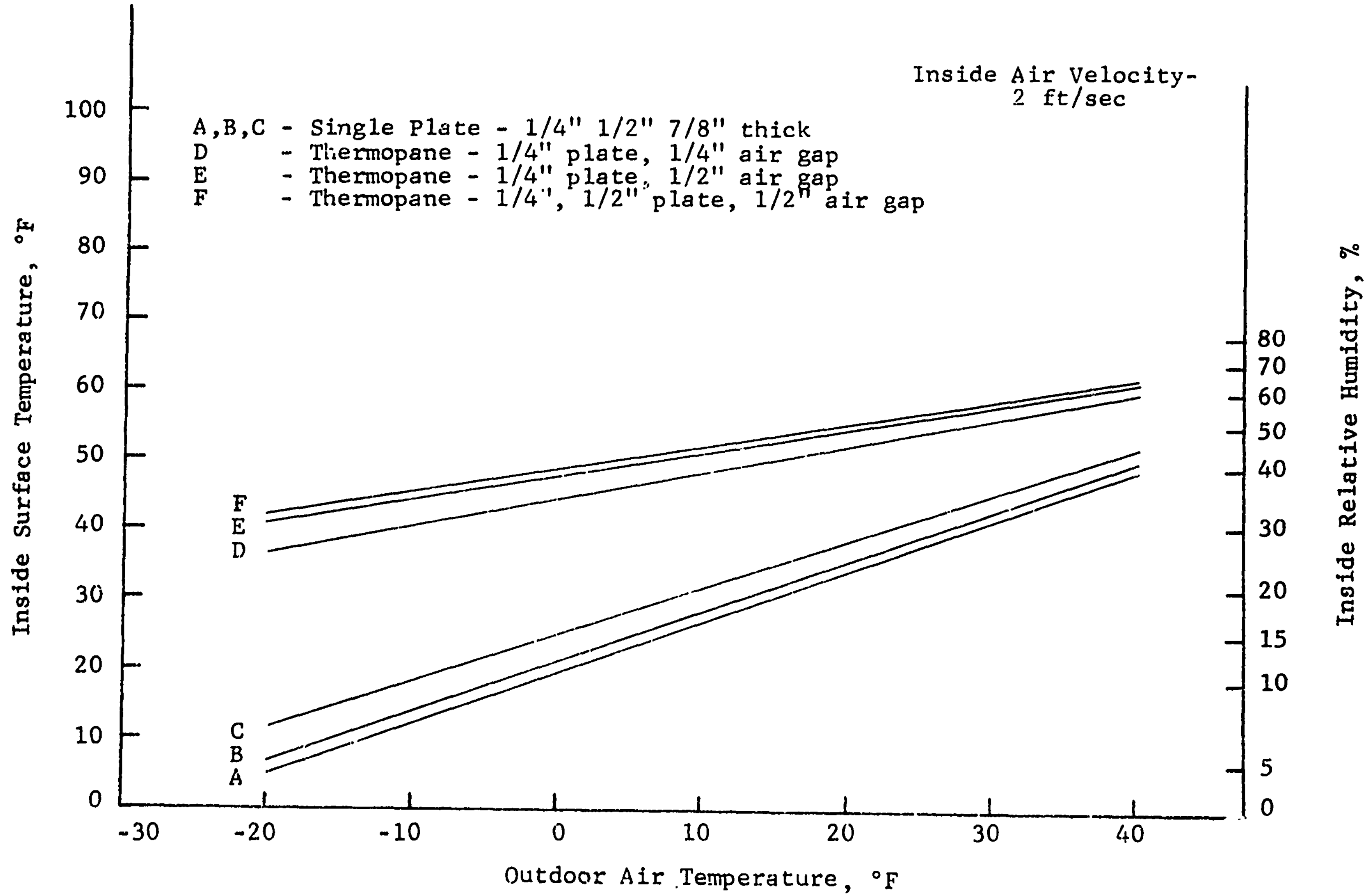

Fig. 16 INSIDE SURFACE TEMPERATURE AND RELATIVE HUMIDITY FOR CONDENSATION

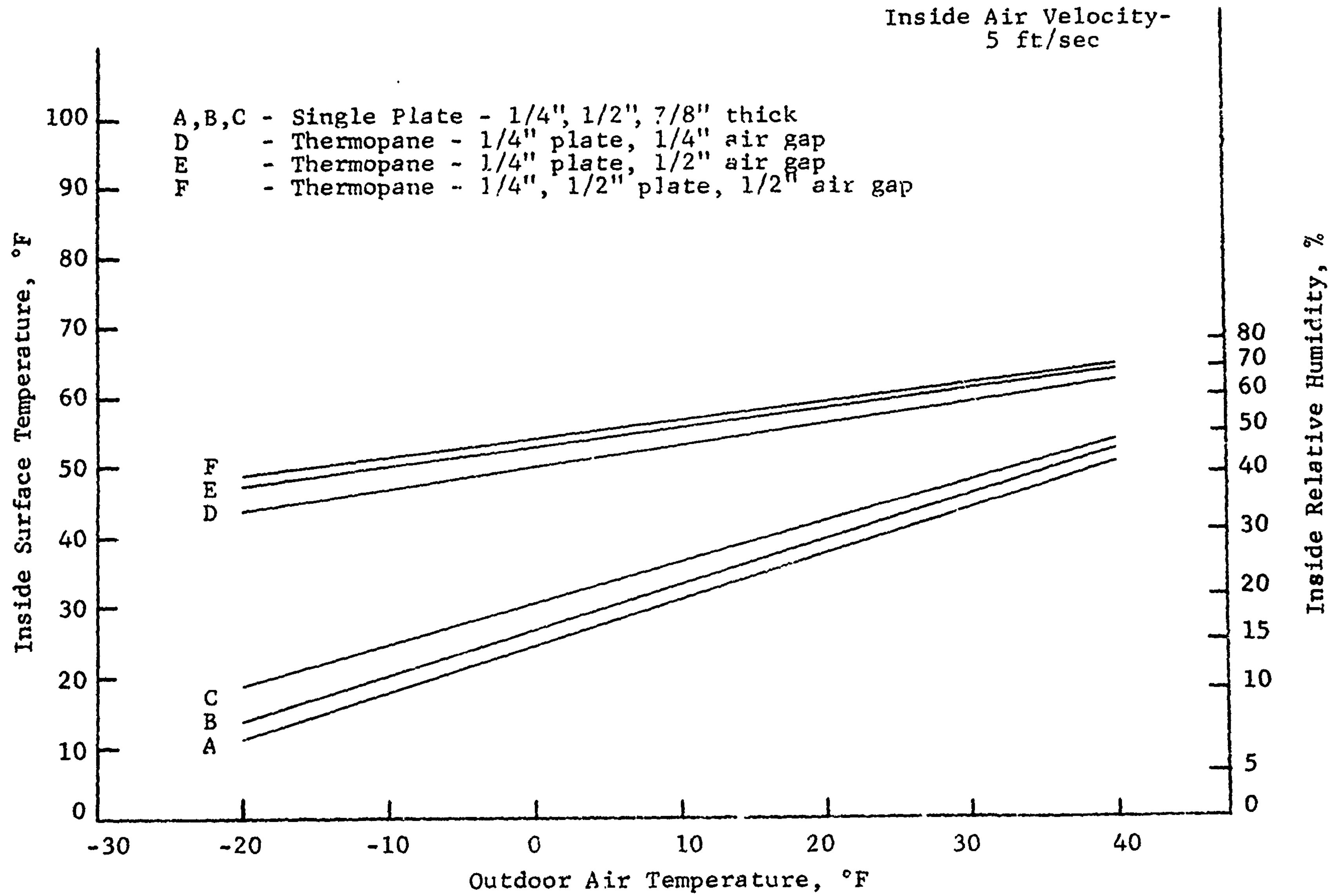

Fig. 17 INSIDE SURFACE TEMPERATURE AND RELATIVE HUMIDITY FOR CONDENSATION

4.5 Noise Reduction

As indicated in Section 3, the noise transferred into an ATCT cab, based on site surveys, is not sufficiently serious to warrant any new countermeasure. With the exception of the new 5-sided cab at O'Hare Field all the cabs visited during the course of the program have double-glazed (insulated glass) windows of 1/2 in. air space separating 1/4 in. plate glass. The new O'Hare cab windows are single plate glass of 7/8 in thickness.

Measurements of the noise for these cab enclosures have shown that the internal noise is mainly generated by speech communication, air conditioning equipment, etc., and not associated with external aircraft noise. It is suggested, however, that in cases where the external noise is intense, for example, towers situated near loading ramps, the use of laminated glass for the outside pane of a double-glazed window could be justified. Laminated glass for the outer window pane would increase the STC rating to 42 compared with a standard double-glazed unit of about STC 33. A major drawback to laminated glass is its sensitivity to temperature changes. As pointed out in Section 2.3.1 laminated glass has no advantage over ordinary plate in colder climates since its STC rating decreases with decreasing temperature. In warmer southern climates, however, laminated glass could be a useful substitute to plate glass. A cost comparison for these types of glass is given in Section 6. It may be concluded that noise transmission through tower cab glass is the least important consideration when weighed against the glare, reflection and heat transfer problems associated with glass used in constructing ATCT cabs.

5. STRUCTURAL MODIFICATIONS TO ATCT CABS

The purpose of this section is to discuss the feasibility of modifying a tower cab in order to increase the outward tilt of the glass windows. This increased tilt would reduce reflections on the glass windows by decreasing the vertical height of the between corner reflections. (See Section 4.1.2)

The ATCT cab of the C-2A type shown in specification FAA-E-2283 (Ref. 18) is a very complete prefabricated structure which is capable of being easily assembled on site and mounted on a steel or concrete tower. Mechanical and electrical subsystems are included in the prefabricated package. The 5-sided C-2A cab appears to be a well-engineered system whose design assures ease of erection and subsequent functional performance. One drawback, which is often encountered with prefabricated single-purpose systems, is that the design is a closed one, i.e., it is limited to several very specific configurations and therefore does not lend itself easily to modifications. The outward tilt of the glass windows and peripheral walls cannot be increased without a complete redesign of the basic load carrying components and thus most of the peripheral structural and architectural hardware The original designer did not foresee the possible need for variations and therefore did not provide for them.

From the structural point of view there is no question but that the C-2A cab can be easily and efficiently redesigned for an increased tilt angle of 10 deg. Such a modification would increase the outward tilt of the windows from 15 to 25 deg for the C-2A cab. The scope of the present work does not allow for the extent of a study in order to arrive at specific optimum changes in the present concept which would be most compatible with the present configuration and functional performance.

Assuming that the lower portion of the C-2A cab is kept to the same geometry, then geometric (size) and/or section (strength) changes would be required in the following components:

- column panel units
- roof and ceiling panels
- number of raceway brackets
- raceway
- closure panels
- upper and lower wall corner panels
- glass panels
- window shades
- associated connecting hardware, etc.

Components of the C-2A cab which would remain unchanged include:

- penthouse
- window washer
- consoles
- mechanical and electrical support systems

Most of the changes would occur due to the increased size of the upper portion of the cab resulting from the increased slope of the peripheral walls. Such changes would most probably be geometric rather than structural.

In conclusion, it is structurally feasible to increase the outward tilt angle of the cab windows from 15 to 25 deg in order to reduce the between corner reflections in the windows.

6. COST EFFECTIVENESS MODEL

One of the program objectives is to formulate a mathematical model to determine the cost versus benefit of a specific countermeasure to reduce the glare, reflection heat and noise transmitted through ATCT cab glass. The countermeasures discussed in Section 4 for reducing heat transfer has been related to reduced air conditioning requirements for cooling a C-2A type cab. The noise levels in the cabs surveyed were not sufficiently high to warrant any significant changes to the sound insulation provided by the glass windows. The use of laminated glass for sound insulation looks promising (in warmer climatic regions and) in locations where the ATCT is close to noisy loading ramps at airports. However, the increased cost of laminated glass may outweigh the advantage of improved sound insulation (see Table 9).

As far as reductions in glare and light reflections inside the cab are concerned it is difficult to assign a benefit except in terms of increased visibility. The question to be posed is to what extent does glare in the line of sight of an observer interfere with the visual search and identification tasks. To answer such a question, air traffic controllers should be subjected to simulated glare tests (Ref. 19). In this way a controlled visual environment in combination with visual detection and identification tasks could be selected to provide a representation of those task elements necessary to air traffic operations. These tests should be graduated to provide a set of conditions varying well within the range of capable to marginal. Performance measurements should include the percentage of correct responses and time delay from stimulus presentation to identification of aircraft. Controlled variables should consist of the type (direct or reflected) intensity and area covered by glare as well as stimuli configuration, background illumination and assigned work load. To permit generalization of the experimental results the stimuli and glare conditions must be equated with field conditions. It therefore becomes necessary to carry out pyschophysical test procedures to determine a controllers response to glare. Such procedures are beyond the present work scope but are necessary to accurately weigh the cost of a glare reducing countermeasure against the "benefits" afforded air traffic control operations. With respect to the heat and noise transfer problems, Table 9 shows the benefits obtainable in terms of cost versus heat load, condensation and noise reductions for the 5-sided C-2A cab for various types of glass.

Table 9

COST EFFECTIVENESS MODEL FOR C-2A TYPE 5-SIDED CAB

Type	Cost △ $ per sq ft	Noise Reduction STC Rating	Summer Heat Load Minimum Requirement + (Tons of Air Conditioning)	Maximum Indoor Relative Humidity x (No Condensation) (Percent)
7/8 in. Plate *	2.75	37	2.8	15
Insulated Glass 1/2 in. airspace 1/4 in. plates				
a) Standard Heat Absorbing	3.50	31-34 (attenuates higher frequencies)	1.9	40
b) Laminated Heat Absorbing	4.75	42+	1.9	40

△ Estimated cost by Globe-Amerada Glass Company

* Corresponds to glass used in O'Hare Field C-2A 5-sided cab

\+ Based on September 21st 2 p.m. conditions

x Outdoor temperature -10°F, 15 mph wind speed

APPENDIX A

OPTICAL MEASURING TECHNIQUES

1. PHOTOGRAPHIC PHOTOMETRY

Photographic photometry offers a convenient means of measuring glare. A photograph is taken of the observer's field of view and the relative luminance of the background and all glare sources is determined by measuring the density of the negative. The angular position of each sound is also measured from the negative. A gray scale composed of a known series of luminances is also photographed to serve as a calibration for the film response. The density of the negative must be measured by a precision microdensitometer so that the ratio of the luminance of the glare source and the background can be determined.

A transparent step wedge gray scale is photographed with the same color illumination as used on the background, or preferably against the background. The range of the step wedge is such that when the proper exposure is given in the camera some steps are underexposed and others overexposed. The transmission of each step of the original wedge must be known or measured. The density of the corresponding steps on the negative will be measured by a precision microdensitometer. Density is defined as

$$D = \log_{10} \frac{I_o}{I} = \log_{10} \frac{1}{T}$$

where

I_o = light incident on the negative

I = light transmitted by the negative

T = fraction of light transmitted by the negative.

If the density of the negative step wedge is plotted against the log of the exposure, the so called (H & D)* curve results. The exposure is defined as the product of time and illuminance of the film and is commonly given in meter-candle-seconds.

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* Named after Hurter and Driffield who used this technique of examining photographic response.

For our purposes it is not necessary to know the absolute value or exposure but rather to know the transmission ratic between the various steps of the gray scale. From the previous equation it is readily seen that the density of the original gray scale is equal to the negative log of the transmission. Hence the negative log of exposure is proportional to the density of the original gray scale. Consequantly, one may for convenience plot the data for the H & D curve as shown in Fig. A-1, where the density steps of the negative are plotted against the corresponding density steps of the gray scale. If the densities of the image of the glare source and the background are measured and compared to the H & D curve the exposure ratio may be directly determined.

It is characteristic of photographic film that a portion of the H & D curve is essentially a straight line. If the densities of the images whose exposure ratio we wish to measure lie on the straight line portion of the curve, then the density difference divided by the slope of the straight line gives the log of the ratio directly. A properly exposed negative takes advantage of this straight line portion to correctly render the luminances of the scene. The slope of the curve (commonly called "gamma") is controlled by the development and is constant over the entire length of the film. Hence a calibration step wedge need be photographed only ince on the film. In practice we will photograph this half at the beginning and end of each film to check on uniformity of development.

Figure A-2 illustrates the steps in determining the luminance ratio of a glare source to its background. Figure A-2(a) represents a negative obtained by photographing the operations field of view, A-2(b) represents the negative obtained by photographing the gray wedge, and A-2(c) represents an H & D plot of A-2(a).

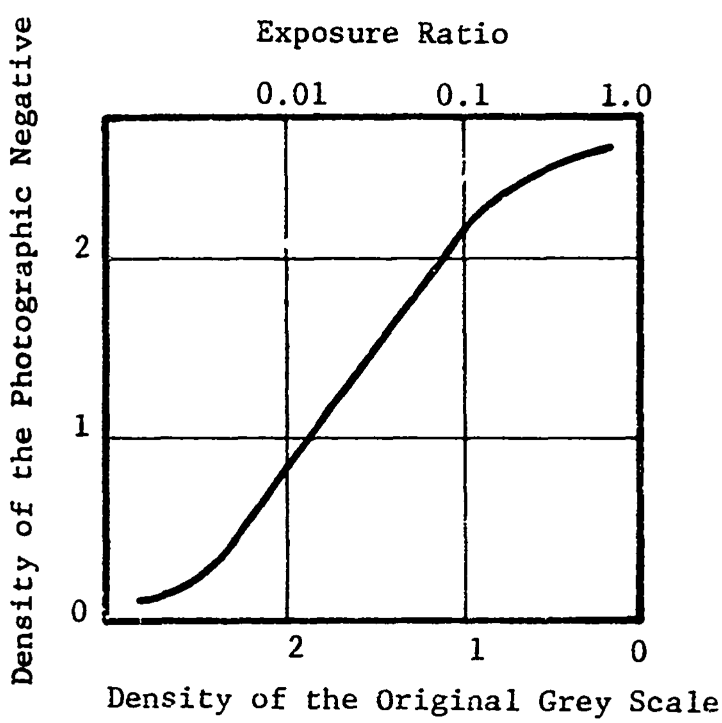
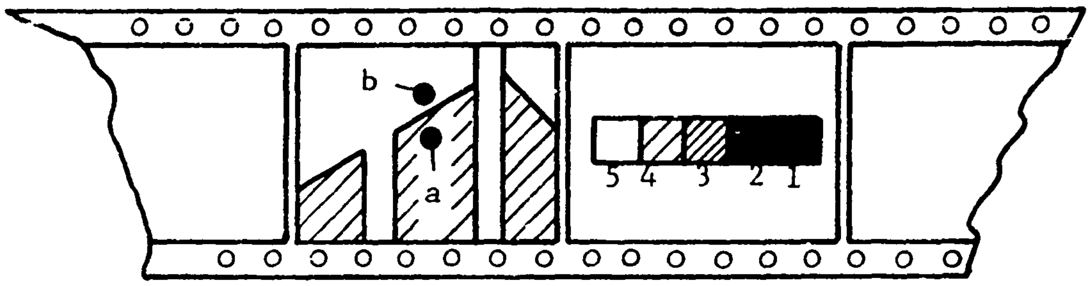
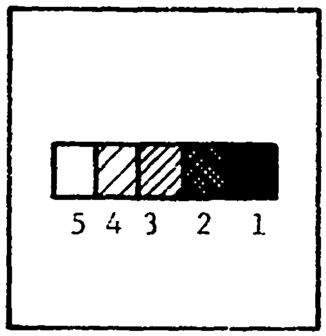


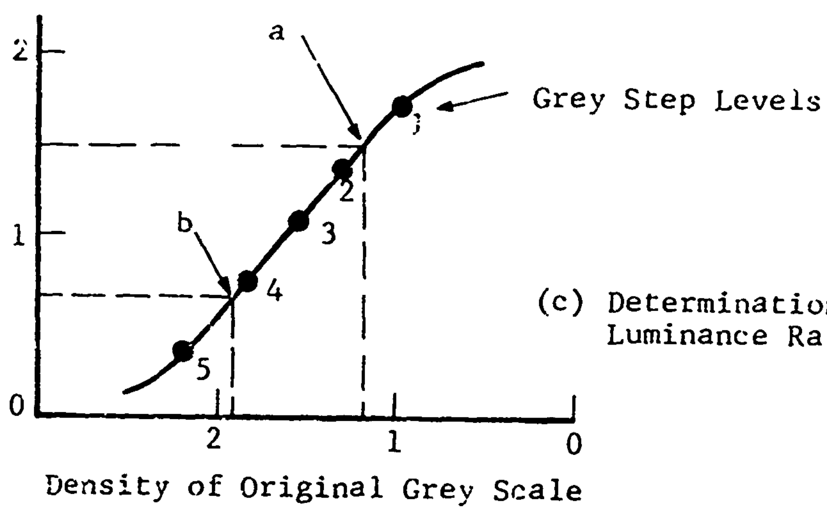
Fig. A-1 HUNTER AND DRIFFIELD CURVE



(a) Negative of Scene (b) Negative of Grey Stepwedge



(b) Negative of Grey Stepwedge



(c) Determination of Luminance Ratio

Fig. A-2 PROCEDURE FOR MEASURING THE LUMINANCE RATIO PHOTOGRAPHICALLY

The density of the steps in the gray step negative are plotted against the density of the original step wedge. In order to measure the luminance ratio for 2 points, a and b, the density of each of the 2 points is measured and the corresponding density of values read from the H & D curve (shown at a and b). The corresponding step wedge density difference is read for the abcissa of the curve. The density difference is equal to the $\log_{10}$ of the luminance ratio.

Example:

The density of point a is 1.5 (see ordinate)

The density of point b is 0.7

These two points correspond to the original wedge density value of 1.2 and 1.9 (see dotted lines on Fig. A-2(c)

Hence

$$\log_{10} \frac{\text{luminance of a}}{\text{luminance of b}} = (1.9 - 1.2) = 0.7$$

or

$\frac{a}{b}$ = antilog 0.7 = 5.0 = luminance ratio of the reflected area to the background.

2. OTHER METHODS OF MEASURING LUMINANCE

A small spot photographic exposure meter provides an excellent instrument for measurement of small areas. The Minolta small spot exposure meter (1 deg angle) calibrated in foot lamberts, was used for obtaining the absolute level. This permitted calculation of the luminance in foot lamberts from the photographic record as well as luminance ratios.

APPENDIX B

HEAT TRANSMISSION AND CONDENSATION CALCULATIONS
FOR O'HARE FIELD 5-SIDED CAB WINDOWS

1. HEAT TRANSMISSION

The total heat gain through the cab windows was calculated using the ASHRAE procedure (Ref. 6). The total heat gain is expressed by the following equation:

$$q_A = SC[I_D\tau_D + I_d\tau_d + N_i(I_D\alpha_D + I_d\alpha_d)] + U(t_o - t_i) \quad (1)$$

where

q_A = instantaneous rate of heat transfer through window, Btu/hr ft^2

I_D = direct solar radiation, Btu/hr ft^2

I_d = diffuse radiation, Btu/hr ft^2

$_D, \alpha_d$ = fraction of incident solar radiation transmittted, subscripts D and d refer to direct and diffuse, respectively

α_D, α_d = fraction of incident solar radiation absorbed

N_i = fraction of absorbed radiation transferred inside cab

U = overall coefficient of heat transfer, Btu/hr $ft^2 \, ^\circ F$

t_o, t_i = outdoor and inside air temperature, respectively

SC = shading coefficient

The shading coefficient in Equation 1 is defined as the ratio of solar heat gain through any type of glass window unit to the solar heat gain through double strength sheet glass exposed to the same conditions. Although shading coefficients can be calculated for single plate glass they are usually measured experimentally for more complex window units and given in company product literature. Thus, following the ASHRAE procedure, the total heat gain was calculated for 1/8 in. sheet glass and then calculated for other glass windows by multiplying the value calculated for 1/8 in. sheet by the shading coefficient given in the literature (PPG Architectural Glass Products Bulletin No. 8). A sample calculation showing the procedure is given below.

1.1 Sample Calculation

The total heat gain through the glass of the new O'Hare Field C-2A Type Tower Cab is calculated for conditions at 2:00 p.m. on September 21.

1.1.1 Direct Solar Radiation, I_D

$$I_D = I_{DN} \cos \theta \tag{2}$$

where

I_{DN} = direct normal solar radiation, Btu/hr ft^2

θ = incident angle between solar rays and a line normal to the surface, degrees

and

$$\cos \theta = \cos \alpha \cos \beta \tag{3}$$

where

α = angle between solar altitude and the normal to glass surface, degrees

β = solar azimuth, measured from South, degrees

For a latitude of 40 degree North (approximately that of O'Hare Field) the solar altitude - 41.6° and the solar azimuth = 41.9° (Ref. 6). Since the windows are slanted 15° from vertical the angle α is 41.6° + 15° or 56.6°. Also from Ref. 6, the direct solar radiation, I_D, is 279 Btu/hr ft^2. Then for the window with South exposure:

$$I_D = 279 \cos 56.6° \cos 41.9°$$

$$= 279\ (0.55)\ (0.745) = 114.3 \text{ Btu/hr ft}^2 \tag{4}$$

Similarly for the Southwest window exposure

$$I_D = 128.5 \text{ Btu/hr ft}^2 \tag{5}$$

The other three window exposures do not receive direct solar radiation.

The total direct solar radiation

$$I_D(\text{total}) = 114.3 + 128.5 = 242.8 \text{ Btu/hr ft}^2 \tag{6}$$

1.1.2 Diffuse Radiation, I_d

The diffuse or sky radiation is obtained by interpolation (Ref. 6) for a clear atmosphere and solar altitude of 41.6° and are given below. (See Fig. 13, Section 4.3)

Window Exposure	Diffuse Radiation, Btu/hr ft^2
S	21
SW	34
NW	24
NE	18
SE	18
Total	125

1.1.3 Transmittance, τ_D and τ_d and Absorptance, α_D and α_d

The solar transmittance and absorptance of 1/8 in. glass sheet is given as a function of the incident angle θ in Ref. 6 Values for the various incident angles are given below.

Window Exposure	Transmittance τ_D	Absorptance α_D
S	0.78	0.06
SW	0.79	0.06

For diffuse radiation, the solar optical properties are taken as equal to the properties for direct radiation when the incident angle is 60° (τ_d = 0.8, α_d = 0.07).

1.1.4 Fraction of Absorbed Radiation Transferred Inside Cab, N_i

The fraction of solar radiation absorbed by a single glass plate and transferred inside the cab is the ratio of the inside heat transfer coefficient, h_i, to the sum of the inside and outside heat transfer coefficient, $h_i + h_o$. In determining the cooling load the design conditions are normally taken as outdoor wind velocity of 7.5 miles per hour and inside as still air.

Since the inside window air velocity at the O'Hare Tower Cab was measured at about 5 ft per sec, the heat transfer coeffi- cient for this velocity instead of still air will be used for the calculation. The heat transfer coefficient for outdoors is 4.0 Btu/hr ft^2°F and indoors is 2.3 Btu/hr ft^2°F [illegible] values, the fraction of absorbed radiation transferred to the inside of the cab, N_i, is

$$N_i = \frac{h_i}{h_i + h_o}$$

$$N_i = \frac{2.3}{2.3 + 4.0} = 0.365$$

1.1.5 Overall Heat Transfer Coefficient, U

The overall heat transfer coefficient is ca[illegible] the following equation:

$$\frac{1}{U} = \frac{1}{h_i} + \frac{X}{K} + \frac{1}{h_o}$$

where

U = overall heat transfer coefficient.

X = glass thickness, inches

K = glass thermal conductivity, Btu-i[illegible]

For the 1/8 in. glass sheet

$$\frac{1}{U} = \frac{1}{2.3} + \frac{0.125}{6.5} + \frac{1}{4.0}$$

$$\frac{1}{U} = 0.70$$

$$U = 1.43 \text{ Btu/hr ft}^2\text{°F}$$

For the insulated window units, the values [illegible] from the PPG literature. These U values [illegible] an inside air velocity of 5 ft/sec from t[illegible] beneath the windows of the C-2A cab.

1.1.6 Outdoor and Indoor Temperature

Air indoor temperature of 75°F was used in all calculations. The outdoor temperature was taken as 95°F on August 21, 85° for September 21, and 75°F on October 21.

1.1.7 Total Heat Gain, q_A

Calculation of the total heat gain for 2:00 p.m., September 21 for 7/8 in. plate glass is:

$$q_A(\text{south window}) = 0.78 \left\{(114.3)\ (0.78) + (21)\ (0.8) + (0.365) \left[(114.3)\ (0.06) + (21)\ (0.07)\right]\right\} + 1.43(85-75) = 96.3 \text{ Btu/hr ft}^2 \qquad (10)$$

Similarly

q_A = (southwest window)	=	114.7
q_A = (northwest window)	=	26.6
q_A = (northeast window)	=	22.4
q_A = (southeast window)	=	22.4
Total q_A		282.4 Btu/hr ft^2

Total Heat Gain, Q, = q_A Area

$$Q = 282.4 \times 117.9 = 33{,}295 \text{ Btu/hr} \qquad (11)$$

$$\text{Cooling Load} = \frac{Q}{12{,}000} = 2.8 \text{ tons} \qquad (12)$$

2. WINDOW CONDENSATION

The inside glass surface temperature was calculated for winter conditions assuming all heat transfer through the windows results from the difference between outdoor and indoor temperatures (no solar heat). The heat transfer is

$$q_A = U(t_i - t_o) \tag{13}$$

and is shown in Equation 8,

$$\frac{1}{U} = \frac{1}{h_i} + \frac{X}{K} + \frac{1}{h_o} \tag{14}$$

The inside glass surface temperature, t_x, is obtained from

$$\frac{R_1}{R_T} = \frac{t_i - t_x}{t_i - t_o} \tag{15}$$

and

$$R_1 = \frac{x}{K} + \frac{1}{h_o} \tag{16}$$

$$R_T = \frac{1}{U} = \frac{1}{h_i} + \frac{x}{K} + \frac{1}{h_o} \tag{17}$$

Solving for t_x

$$t_x = t_i - \frac{R_1}{R_T}(t_i - t_o) \tag{18}$$

A sample calculation is given below.

Sample Calculation

The inside surface temperature is calculated for the following conditions:

t_o	=	-10°F
t_i	=	75°F
h_o (15 mph)	=	6.0 Btu/hr ft^2°F
h_i (5 ft/sec)	=	2.3 Btu/hr ft^2°F
x	=	7/8 in.
K	=	6.5 Btu in./hr ft^2°F

$$R_1 = \frac{1}{2.3} = 0.435 \frac{\text{hr ft}^2\text{°F}}{\text{Btu}} \tag{19}$$

$$R_T = \frac{1}{2.3} + \frac{7/8}{6.5} + \frac{1}{6.0} = 0.435 + 0.135 + 0.167 = 0.737 \frac{\text{hr ft}^2\text{°F}}{\text{Btu}} \tag{20}$$

$$t_x = 75 - \frac{0.435}{0.737} [75 - (-10)] = 24.9\text{°F} \tag{21}$$

For a discussion of the results of these calculations see Sections 4.3 and 4.4.

APPENDIX C

VISIBILITY CRITERIA FOR ATCT CAB GLASS

1. THRESHOLD OF BRIGHTNESS CONTRAST

The contrast of adjacent objects enables the eye to distinguish one object from another. Contrast is defined as,

$$C = \frac{(B \pm \Delta B) - B}{B} = \frac{\Delta B}{B} \tag{22}$$

where B = luminance of one object and $(B \pm \Delta B)$ = luminance of the other.

The threshold of brightness contrast is that value of C for which the objects are just distinguishable. The threshold of brightness depends upon a number of factors: 1) the visual angle subtended by the object, 2) the level of illumination, 3) the size of an object as seen against the other object as a background. A complete discussion of this is given in Ref. 1.

2. VISUAL RANGE

In the case of various meteorological observations, it is desirable to have a more convenient and standardized form for this threshold. The case of an object seen against the horizon sky forms a convenient subject. As the observer goes further away from the object, he observes that the visual contrast C decreases (Ref. 1). This reduction in contrast for horizontal paths is due to scattering by the atmosphere and is expressed as

$$C_R = C_o e^{-\sigma_o R} \tag{23}$$

where

C_R = contrast at range R

C_o = original contrast

σ_o = scattering coefficient

At some value of range R the contrast is reduced to the threshold value (ϵ) and this value of R is the visual range V. That is:

$$\epsilon = C_o e^{-\delta V} \tag{24}$$

$$V = \text{visual range} = \left(\frac{1}{\delta}\right) \log e \; \frac{C_o}{\epsilon} \tag{25}$$

3. METEOROLOGICAL RANGE

Since the value of ϵ depends upon a number of different factors, it is desirable to choose standardized conditions for the evaluation of V. This is commonly done by defining the distance at which the average eye can just detect a large black object against the horizon sky (see Ref. 1). The target is nonreflecting and nonemissive. In order to obtain a definition independent of individual eyes, a new term called the "meteorological range" is defined as that range for which the contrast between the black target and the background becomes 2 percent.

The meteorological range R_1 is commonly determined by measuring the attenuation coefficient σ by the use of a transmissometer. For the meteorological range (R_1) Equation (24) becomes

$$0.02 = e^{-\sigma R_1} \tag{26}$$

Simplifying Equation (26) gives

$$R_1 = \frac{3.912}{\sigma} \tag{27}$$

The attenuation factor σ may be determined by the use of a transmissometer from

$$T = e^{-\sigma x} \tag{28}$$

where x = optical path length of the transmissometer, and

T = measured transmission over the path.

By substituting the value of σ from Equation (28) into (27) we get the meteorological range.

4. DISCUSSION

It is to be noted that σ and R_1 describe a particular scattering condition for the atmosphere. From Equation (22) it may be seen that by reducing the luminance of the background and the target by proportionate amounts does not change the contrast.

Hence the reduction of overall intensity by the use of sun glasses (or dark glass in a control tower cab) does not change the visual range for an object (or the meteorological range) unless the level of illumination is so drastically changed that the visual conditions for operation of the eye is effected. The introduction of a scattering medium such as a dirty windshield or glass, will change the contrast and hence the range depending upon the amount of light[*] scattered in the direction of the observer.

It appears therefore that the FAA specification (see p 43) for providing distinct vision of aircraft at 6 miles when the visibility is 15 miles does not refer to the transmission of the glass but rather to the distortion or scattering of the glass since attenuation by pure absorption should not change the range. (Visibility is commonly determined as discussed above with a transmissometer.) There appears to be no way of relating the actual transmission through glass to change in the visual range. In other words the two criteria are independent.

The requirement (Ref. 10) for 70 to 75 percent[**] light transmission must originally have been a value which would permit reasonable luminance levels for all levels of illumination night and day and must be determined by studies involving the visibility of flying aircraft under all conditions of illumination.

It is to be noted that in the case of the atmosphere the attenuation (a reduction in transmission) is due primarily to scattering and not to absorption so the relationship between transmission as measured by the transmissometer and scattering is allowable.

* The light which is scattered may originate at the target and background or at any other place so long as it scatters to the observer.

** TSO M13 obsolete

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