CORNING GLASS WORKS
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IMPROVED SCREEN FOR REAR-PROJECTION VIEWERS

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ABSTRACT

This report contains a review of rear-view screen specifications based on our past and continuing theoretical and experimental research in this field. The objective is to present what we consider to be desirable and attainable specifications for a relatively well-defined projector-observer system. Both subjective and objective criteria are considered and lenticular as well as scattering screens are treated. It is assumed that the screen will be used for scanning of large quantities of film, while careful studying of details will be performed by the use of a direct magnifying device which will bypass the screen. In this context preservation of contrast at all levels of local screen brightness is judged to be of prime importance, followed by resolution and the comfort of the observer. These considerations lead to the following specifications. Resolution: At 14 inches, screen should not appear to limit resolution, MTF ≥ 0.7 at 10 mm^{-1}. Specular Reflection: Reflected images should not be distracting, reflectance less than 0.5% at all viewing angles. Diffuse Reflection: Should not unduly restrict ambient light level, reflectance $< 5\%$ for scattering screens. Less for lenticular screens. Brightness Variation: No "hot spots" and operator should not be forced to change head position to compensate, variation no more than $\pm$ 25% over the screen, gradient no more than 2% per inch. Efficiency: Diffuse transmittance into 45° semi-angle cone 20-30% for scattering and 60-80% for lenticular screens. Color effects, including non-white screen transmittance spectrum, color variation with bend angle, diffraction spectra, and scintillation, should not be strong enough to be a distraction.

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I. INTRODUCTION

As a first step in the production of usable rear-view screens in actual projectors we have undertaken a thorough review of screen specifications.

In order to give proper weight to the various screen parameters, we have taken a more careful look at the complete viewing system, including the operator. While we have attempted to put these specifications into quantitative form wherever possible, it is recognized that for some characteristics a qualitative judgment is sufficient. Furthermore, since the suitability of a screen must finally be judged by the user on a subjective basis, both objective and subjective criteria have been taken into account. The important parameters are listed below along with qualitative, or subjective, specifications, where applicable. These are followed by what we consider to be reasonable and attainable quantitative, or objective, specifications. In some cases the values for lenticular screens differ from those for scattering screens. Following the listing, we discuss how each specification was arrived at. Central to this whole discussion is a recognition of the wisdom of separating the photo-interpretation task into two operations, scanning the image on a rear-view screen and examining details with a periscope arrangement bypassing the screen.

II. Screen Specifications

Parameter	Specification: Qualitative	Specification: Quantitative
1. Resolution	Screen should not appear to limit resolution.	MTF ≥ 0.7 at 10 mm^{-1}
2. Front reflection		
Specular	Reflected images should not be distracting.	< 0.5% at all viewing angles.
Diffuse	Should not unduly restrict ambient light level.	R_D < 5% for scattering screens. Less for lenticular screens.

Parameter	Specification: Qualitative	Specification: Quantitative
3. Brightness Variation	Should not force operator to change head position.	No more than ± 25% over the screen.
	No "hot spot"	No more than 2% per inch gradient.
4. Efficiency *	————————	20%-30% for scattering. 60%-80% for lenticular.
5. Color Effects		
Screen transmittance spectrum.	Should not be strong enough to be a distraction.	
Color variation with bend angle.		
Diffraction Spectra		
Scintillation		

III. Bypassing the Screen for Close Examination

A common mode of operation in photo-interpretation is scanning rapidly at low magnification, followed by examination of details at high magnification.[1] Any rear-view screen interposed between projector and observer must degrade resolution to some extent. Hence it is both natural and advisable to use the screen for scanning but to bypass the screen when the utmost resolution is required for scrutinizing details. Amplification of these ideas will be found in the following sections dealing with resolution and front reflection specifications.

Figure 1 shows how a screen, with its image degradations, can be avoided. The axial image can be passed into a periscope arranged to magnify and bring the image round the screen to the front, presenting a virtual image at a large eyepiece. Bearings mounted in the plane of the screen allow the periscope to be rotated out of the way when not in use.

This scheme offers several additional advantages over magnification of the screen image. If the periscope is used only on the projector axis, resolution is optimum.

*(Percentage diffuse transmission into 45° semi-angle cone).

The eye iris acts as the stop in the projection lens system and results in better quality imaging due to the smaller effective aperture. The rear-projection screen requires the whole aperture of the projection lens to focus a point in the transparency to a point on the screen. The periscope virtual image viewing scheme offers the possibility that the eyepiece and system can be combined to compensate for the chromatic aberration in the eye. The periscope <u>increases</u> the brightness relative to the screen display, so much so that we need a neutral density attenuator. This increase in brightness could be of extreme value in examining dark areas. The periscope magnifier should be designed to eliminate ambient light as should a hand magnifier, if used. A controllable peripheral light surrounding the periscope virtual image may be advantageous to ensure that the viewer's eye adapts optimally to image viewing.

IV. Resolution

If the screen is used only for scanning, we can assume the screen to be 14 inches from the eye and never viewed under auxiliary magnification. Under these conditions the sine wave detection threshold data for the eye imply a need for a screen MTF of unity at a spatial frequency of about 10 MM^{-1} in order that the screen not degrade resolution at all. [2] This should be taken as a guideline rather than an absolute limit, especially in view of the fact that the curve beyond 7 mm^{-1} was extrapolated. However, even if this sine wave detection threshold data is taken to be exact, we can show that the scanning task can be performed in such a way that a screen with an MTF falling below unity at 10 mm^{-1} is still not a limiting factor in resolution. In an objective sense, there is a clear trade-off between projector magnification and required screen resolution. That is, it is always possible to magnify details to a size such that their spatial frequencies fall within the unity-MTF region of the screen, in which case the screen does not limit the resolution. But the subjective criterion for resolution is that the observer should see a sharp display and not feel that the screen is limiting his performance. This means that screen grain should not be visible at 14 inches and that increasing magnification to compensate for low screen MTF must not be taken too far. We suggest that a moderate fall-off of screen MTF, say to 0.7 at 10 mm^{-1}, can be compensated in this way without noticeably reducing the sharpness of the display. The operator automatically adjusts the projector magnification to allow him to resolve details of interest.

V. Front Reflection

Front reflection, both specular and diffuse, has the simple effect of reducing the contrast, or effective MTF, uniformly for all spatial frequencies. If front-reflection contributes a uniform brightness equal to 5% of the average screen brightness, the MTF is multiplied by the factor $\frac{1}{1.05}$ or is reduced by about 5%. From the curves of sine wave contrast threshold versus spatial frequency, it can be seen that the resolution attained by the eye, expressed as maximum detectable spatial frequency, is reduced by only about 2% by this 5% reduction of contrast.[2] Thus, for a film of reasonable contrast and relatively uniform brightness, 5% front reflection presents no serious problem.

On the other hand, if there are dim areas on the slide, even though the intrinsic contrast is high a small amount of front-reflection can reduce the observed contrast by a large factor and thus reduce the resolution markedly. For example, suppose the bright areas have a brightness level of 600 units, the average brightness is 120 units and the dim areas have 1 unit. Assume a film contrast of unity and screen MTF of unity. Then front reflection which amounts to 5% of average screen brightness increases the brightness level in the dim area by 600%. The observed contrast is then reduced by the factor $\frac{1}{1 + 6} \approx .14$ and the resolution drops by almost 50%. Furthermore, in dim areas where slide contrast is already very low, the effect of the front reflected light will be to reduce the contrast below detectability for objects of all sizes.

It can be seen, then, that front reflection profoundly affects the ability of the screen to maintain contrast over a large range of local brightness levels, or film density levels. In the case of scattering screens, the front reflection can be reduced by controlling ambient light, by reducing the diffuse reflectance R_D of the diffusing layer, by inserting an absorbing material between the diffusing layer and the observer, and by the use of an antireflection coating on the surface facing the observer. The specular reflectance can be reduced to somewhat less than 0.5% by means of a triple-layer coating. However, the diffuse reflectance of the diffusing layer cannot be less than about 5% if the angular brightness variation specification is to be met. If a 50% absorbing medium is placed between diffusing layer and observer the diffusely reflected light is attenuated by at least a factor of 4 while the screen efficiency is reduced by a factor of 2. This may well be a reasonable price to pay for the reduction of effective diffuse reflectance to a value more nearly comparable with the limit set by specular reflectance. In addition, the 50% absorption is even more effective in attenuating projector light and ambient light which becomes trapped within the screen substrate by total internal reflection. In lenticular screens it should be possible to keep the front reflectance down to this low level without an attendant loss of efficiency. With either type of screen, once this low level of front reflectance is achieved, it is still necessary to carefully control the amount of ambient light reaching the screen in order that front reflection not be the limiting factor in contrast in dim areas.

VI. Brightness Variation

Since in scattering screens the diffuse reflectance increases as the brightness variation is decreased, it is advisable to tolerate as much brightness variation as possible. If there is enough variation within the bend angles utilized to force the operator to compensate by adjusting his head position it will be an annoyance and the scanning operation will be less efficient. A gradual brightness variation of ± 25% of the mean brightness over the screen should be small enough to prevent this.

Due to the tailoring possible with many lenticular screen schemes the achievement of less than ± 25% variation should not be unduly restrictive of screen design. Because of tailoring possibilities a maximum step change of brightness must be specified. The meteorological visibility test corresponds to a 2% step being just detectable. There may be some evidence [3] that a 2% per inch brightness gradient is just detectable.

Thus the 2% figure is suggested as the step brightness variation tolerance and 2% per inch as the brightness gradient tolerance. The brightness variation should take into account the contribution to the bend angle provided by the projector optics.

The brightness variation should apply over the portion of the screen contained within a 45° semi-angle cone with its apex at the observer's pupil and centered on the normal from the observer's eye to the plane containing the screen. The observer's eye will be in front of the screen and not closer than 14 inches.

VII. Efficiency

Since the axial gain in diffusing screens is substantially determined by the opposing factors of diffuse reflectance and brightness variation, the efficiency of the diffusing layer must fall within the approximate range T_{45} = 40 - 60%. [4] If the recommended absorbing medium is used, having a transmittance of the order of 50%, the net efficiency will be 20 - 30%. That is, 20 - 30% of the incident power will be diffusely transmitted by the screen within a 45° semi-angle cone.

For lenticular screens, there is no clear-cut limit to the efficiency. In principle T_{45} can be very near 100%. Practically, we may be doing well to fabricate any masked lenticular screen of sufficient resolution. Most candidate schemes will have some wasted areas on the projector side so undue emphasis should not be placed on extreme efficiency to avoid rejection of most candidate schemes. Even the crossed cylinder approach does not give T_{45} = 100% since the transmitted light is not uniformly distributed into a 45° half-angle cone. Perhaps 80% is a reasonable target with 60% being tolerable since the efficiency of existing diffusing screens is probably less than 60%.

VIII. Color Effects

In our experience with scattering screens we have noticed a number of color effects, including non-uniform spectral transmittance, color variation with bend angle, and sparkle or scintillation. In lenticular screens we expect, in addition, to observe diffraction spectra under some conditions.

1. Screen Transmittance Spectrum

Both the diffusing layer and the substrate contribute to this, but the diffusing material can be chosen to exhibit a very flat spectrum, while some care is required to obtain an absorbing substrate with a sufficiently flat spectrum. At present we do not attempt to set quantitative limits. One way of estimating the eyes' sensitivity to color variations is to make use of Mac Adam's data on just noticeable differences in chromaticity discrimination for different positions on the chromaticity diagram.[5] These data imply that the addition of approximately 1% of monochromatic blue or red light to a white background is just detectable, while about 0.3% of monochromatic blue-green is detectable. This would not appear to be sufficient loss of color fidelity to affect the scanning operation. It remains to determine quantitative limits within which the presence of screen coloration does not hinder scanning.

It is desirable that the combination of projector source spectrum and screen transmittance spectrum produce white light. It may be desirable to tailor the substrate spectrum to compensate for source non-whiteness.

Lenticular screens could exhibit a tinge of color if long paths through high-index glasses are entailed.

2. Color Variation with Bend Angle

This has been observed in small-particle screens in which blue light is preferentially scattered. Again it is possible to apply the ≤ 1% chromaticity difference criterion, but this is probably too stringent for a gradual color variation. We prefer to judge screens qualitatively in this respect until further data are available.

3. Diffraction Spectra

In the case of lenticular screens, which are usually rectangular periodic arrays, color dispersion by a diffraction-grating effect becomes greater as the element size is reduced. This is observed as a rectangular array of color spectra superimposed on the display. With the screen in viewing position and illuminated by nearly parallel light from the projector we expect not to observe diffraction spectra when more than a single diffraction grating order, originating at a point of the screen, enters the eye and forms an image of that point of the screen. That is, diffraction spectra will be observed if $d < \frac{\lambda L}{D}$, where d is the spacing of lenticules, λ is a visible wavelength, L is the eye-screen distance of 14 inches, and D is the eye pupil diameter. For a pupil diameter of 3 mm and $\lambda = 500\ m\mu$, this means a lenticule spacing of $\leq 60\ \mu$ will produce detectable spectra. The departure from parallelism of the projector light tends to degrade the effect. Because of the patterned nature of diffraction spectra, they will tend to be distracting to the observer if at all detectable, that is, the $\leq 1\%$ chromaticity variation criterion applies here.

Experimentally, whereas no such effects are observable in white light for a lenticular screen with 250 μ lenticules, a fiber optic plate with 20 μ fibers exhibits strong diffraction-grating spectra. It may be possible to reduce this effect by randomizing the lenticule size and spacing or otherwise destroying the periodicity of the screen. The existence, however, of this phenomenon, as well as the difficulty in making small, highly tailored lenticules, suggests keeping the lenticules above the 20 μ size.

4. Scintillation

In scattering screens scintillation or sparkle can arise from two sources. If the screen diffusing elements are too large, they are observed as randomly oriented prisms and from a given viewing direction appear varicolored. Making the screen elements sufficiently small effects an angular averaging of intensity distributions from individual elements and prevents this type of scintillation.

Scintillation may also be related to the coherence properties of the projection system.[6] This effect can be reduced by reducing the magnification or the f-number of the projector, or by using more densely packed screen particles. Thus, again, smaller screen elements are indicated. This effect presumably is important for lenticular screens also and should be further investigated. No scheme for correlating subjective and objective descriptions of this phenomenon have yet been devised.

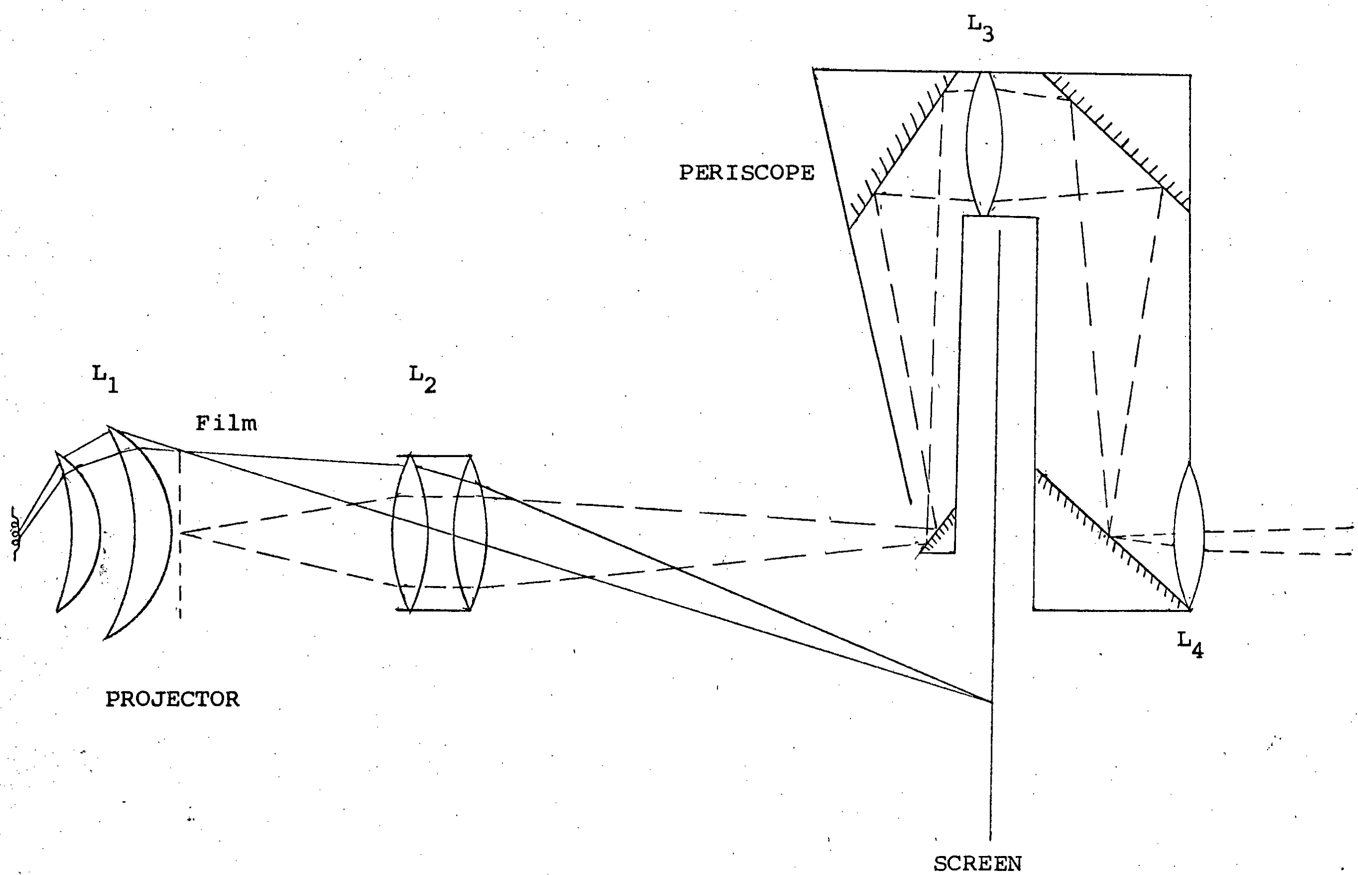

Figure 1. Optical plan of periscope. L_3 is a relay lens. L_4 is the eyepiece. Periscope can be moved into and out of the optical path when desired.

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