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IMPROVED SCREEN FOR REAR-PROJECTION VIEWERS

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1. Introduction

Eight experimental scattering-type screens and one commercial scattering-type screen have been evaluated in terms of observed resolution and judged quality by the Aerospace Group of the Boeing Company. Their final report is included in this report as Appendix CG3.

In the quality tests, each of the 12" x 15" screens was compared side by side with every other screen in a projector using standard imagery. Observations were made by several experienced photointerpreters and a quality scale factor Z was determined for each screen depending on how many times it was chosen as the better screen. For the resolution tests, a standard USAF tribar resolution chart was projected onto the screens and the photointerpreters recorded the highest resolvable spatial frequencies. The correlation of these quality and resolution judgments with measured screen properties such as axial gain, brightness variations, MTF, substrate transmittance, etc., was then investigated. In general, the differences among screens were found to be small both in judged quality and in judged resolution. This was true in spite of the fact that significant differences existed in measured screen properties. These results can be understood when the following factors are taken into account:

1. Projector MTF
2. Projector brightness
3. Ambient light level

In many of the tests these factors had the effect of diminishing observed differences among screens.

2. Projector MTF

The highest resolution reported in CG3 is about 4 li/mm (p. B9) for the unaided eye viewing, from a distance of about 7 inches, a high contrast target projected onto the rear-projection screen under acceptable ambient light conditions.

On the other hand, typical square-wave MTF values obtained by the contact method (P-19-41) for these screens were 0.97 at 5 lines/mm, 0.91 at 10 lines/mm, and 0.75 at 15 lines/mm. If these contact MTF values are even approximately valid for projected resolution targets, then the MTF of the projector must have been the controlling factor in the resolution determinations of CG3.

It is possible to estimate the projector MTF from the limit-of-resolution determinations described in 2.7.3 of CG3, in conjunction with the square-wave response of the eye. With screen removed, the target images in the screen plane were observed by use of a 7X magnifier. The independently-measured contrast C_T and maximum resolvable resolution number RN for each target contrast are reproduced here from p. 15 of CG3. Included also are the corresponding

TABLE I

Limit-of-resolution data on targets of CG3

Contrast (C_T)	Modulation (M_T)	Resolution Number (RN)	Spatial Frequency (F) (mm^{-1})
4.45	0.69	43.5	13
0.86	0.30	42.0	11.2
0.38	0.16	40.0	9
0.073	0.035	22.0	1.12

modulation of the target

$$M_T = \frac{C_T}{2 + C_T} ,$$

and maximum resolvable spatial frequency for that target

$$F = \frac{2^{RN/6}}{11.4} ,$$

calculated from C_T and RN. Square-wave modulation thresholds for the human eye are adapted from the data of DePalma and Lowry[1/] and are plotted in Fig. 1. for a viewing distance of 7 inches. The 7X magnifier used at 7 inches effective viewing distance provides a magnification of approximately 6. The effect of the magnifier is to reduce the spatial frequency on the retina by a factor of 6. Thus, for a target having modulation M_T and a maximum resolvable spatial frequency F, the appropriate point of the eye response curve is at $\frac{F}{6}$ in Fig. 1. The corresponding modulation threshold is read from the curve. The product of the target modulation M_T and the projector modulation $M_P(F)$ must be equal to this modulation threshold M_{TH} at frequency F/6. Hence the projector square-wave MTF is

$$M_P(F) = \frac{M_{TH}\ (F/6)}{M_T} \quad . \qquad (1)$$

When these calculations are carried out for the four resolution targets listed in Table I, the results are as shown in Table II and in Fig. 1. The intersection of the

TABLE II

Target Modulation M_T	Observed Resolution with 6X Magnification F (mm^{-1})	F/6 (mm^{-1})	Modulation Threshold of Eye M_{TH} $(\frac{F}{6})$	Projector Modulation $M_P(F)$
0.69	13	2.17	.010	0.014
0.30	11.2	1.87	.0075	0.025
0.16	9	1.50	.0045	0.028
0.036	1.12	0.187	.0022	0.063

eye modulation threshold curve and the projector modulation curve falls at 4.6 lines/mm. This implies that even with a perfect rear-projection screen the maximum resolution would be 4.6 lines/mm. This low projector MTF largely explains the 4 lines/mm limit to the observed resolution and also explains the difficulty encountered in distinguishing significant differences in resolution and quality among the screens.

The above calculation is not highly accurate, because of differences in experimental conditions for the eye response measurements of DePalma and Lowry and the projector resolution determinations. The eye modulation threshold depends upon the observer, the nature of the test object, the threshold criterion chosen, the angular field covered by the target, the luminance, and the condition of visual adaptation.[1/] The eye response data of Fig. 1. were adapted from an experiment in which the target was square-wave over a broad angular field, the luminance was 20 F.L., and the criterion for threshold was ability to detect modulation.[1/] Thus in the CG3 projector resolution measurements the observer was different, the threshold criterion was more stringent, and the angular field was smaller. For these reasons, the projector MTF calculation must be considered as an estimate.

While the above analysis shows that the projector MTF was much lower than expected, it is also not clear from the CG3 measurements that even the best screens did not degrade the resolution. Direct viewing of the projected image with a 7X magnifier gave a limit of resolution of 13 li/mm without a screen. With a screen in place the limit of resolution with the 7X magnifier was about 7 li/mm for the average screen, perhaps 8 li/mm for the best screens (CG3, p. B 16). Thus it remains to be proved that contact square-wave MTF values provide a realistic measure of resolution in the projection situation.

3. Ambient Light

The ambient light level was 3 F.C. (CG3, p.7) and caused little modulation degradation in the resolution measurements. This was because the average film density was low for the resolution targets and the minimum input illumination to the screens was 10 F.C. (CG3, p. 13). But in quality tests, average film density was about 1.0 and the ambient-to-projector illumination ratio was often greater than unity. The approximate calculations below show a degradation of modulation by this effect of as much as a factor of 5. Trapped projector light was generally negligible compared with ambient.

Reflected ambient light and trapped projector light both have the effect of degrading the observed modulation transfer by a constant factor for all spatial frequencies. The ratio of the modulation, or contrast, γ displayed by the screen to the modulation γ_0 projected onto the screen can be calculated in an approximate fashion by reference to Fig. 2. The displayed modulation is

$$\gamma = \frac{\left(B_D^{max} + B_T + B_R\right) - \left(B_D^{min} + B_T + B_R\right)}{\left(B_D^{max} + B_T + B_R\right) + \left(B_D^{min} + B_T + B_R\right)} , \qquad (2)$$

where B_D^{max} and B_D^{min} are the maximum and minimum brightnesses directly transmitted through a local area of the screen, B_T is the brightness of the trapped projector light contributed by all parts of the screen, and B_R is the reflected ambient brightness. Since the modulation projected onto the screen is

$$\gamma_0 = \frac{B_D^{max} - B_D^{min}}{B_D^{max} + B_D^{min}} , \qquad (3)$$

the transfer of modulation by the screen can be written

$$\frac{\gamma}{\gamma_0} = \frac{1}{1 + \dfrac{2B_T + 2B_R}{B_D^{max} + B_D^{min}}} . \qquad (4)$$

The trapped light in Eq. (4) can be expressed in terms of the measured trapped light ratio

$$\alpha_T = B_T/\overline{B}_D = \frac{B_T}{\frac{N}{2}\left(B_D^{max} + B_D^{min}\right)} , \qquad (5)$$

where

$$N = \frac{\bar{B}_D}{\frac{1}{2}\left(B_D^{max} + B_D^{min}\right)} \tag{6}$$

is the ratio of the average brightness over the whole screen to the local average brightness.

The reflected ambient light B_R in Eq. (4) is expressible in terms of the measurable quantity $R_D T_S$. Since the ambient reflected light suffers one diffuse reflection and two traversals through the substrate, the reflected brightness is proportional to $R_D T_S{}^2 E_{amb}$. The local transmitted brightness makes a single pass through the substrate and is thus proportional to $T_S \left(E_D^{max} + E_D^{min}\right)$. The quantities E_D^{max} and E_D^{min} are the incident illumination maxima and minima in the local area corresponding to transmitted brightness B_D^{max} and B_D^{min}. The ambient illumination is E_{amb}. The reflected brightness as a fraction of the incident local average brightness is thus approximately

$$\frac{B_R}{\frac{1}{2}\left(B_D^{max} + B_D^{min}\right)} = \frac{R_D T_S{}^2 E_{amb}}{\frac{1}{2} T_S \left(E_D^{max} + E_D^{min}\right)} = \frac{R_D T_S \; E_{amb}}{\bar{E}_D / N} \tag{7}$$

where

$$N = \frac{\bar{E}_D}{\frac{1}{2}\left(E_D^{max} + E_D^{min}\right)} = \frac{\bar{B}_D}{\frac{1}{2}\left(B_D^{max} + B_D^{min}\right)} \tag{8}$$

Equation (7) holds if the reflected and transmitted light have approximately the same angular distribution.

Equations (4) - (8) can now be combined to yield

$$\frac{Y}{Y_0} = \frac{1}{1 + N\left(\alpha_T + R_D T_S \frac{E_{amb}}{\bar{E}_D}\right)} \tag{9}$$

Quality test II, in which the open gate screen brightness was limited to 10 F.L. for all screens, was most strongly affected by ambient light. A sample calculation of γ/γ_0 will be made for the LS-60 screen. According to CG3, p. 5, the projector provided a maximum of about 30 F.C. open gate to the screen under standard conditions. In order to reduce the brightness of screen LS-60 to 10 F.L. it was necessary to reduce this open gate illumination to

$$30 \text{ F.C.} \times \frac{10 \text{ F.L.}}{79 \text{ F.L.}} = 3.75 \text{ F.C.} \quad ,$$

since under 30 F.C. illumination this screen produced a brightness of 79 F.L. (LBRT-I = 1.82 from CG3, p. A2). Because the average imagery density was about 1.0, the average illumination projected onto this screen was $\overline{E}_D$ = 3.75 F.C./10. Then $E_{amb}/\overline{E}_D$ = 3 F.C./0.375 F.C. = 8. The assessment of image quality was made with emphasis on dense, shadowed areas of the imagery where the transmission was as low as 2% (CG3, p. 10). Then for an average film transmittance of 10%, the value of N was 5. The product $R_D T_S$ was calculated from the values in Table II of P-19-40 for all screens except LS-60, for which a separate measurement was made. The value for LS-60 was $R_D T_S$ = 4.4%. The value α_T = 0.11% can be found in Table A-1 of CG3. The quantity γ/γ_0 can now be calculated for this screen under the conditions of the test. The results of such calculations for all the screens appear in Table III.

Table III

Parameters describing the effect of reflected ambient light and trapped projector light on the observed MTF.

(Quality Test II)

Screen	α_T (%)	$R_D T_S$ (%)	$E_{amb}/\bar{E}_D$	$\frac{\gamma}{\gamma_0}$	Z
AQ-20	0.062	2.1	1.0	0.90	1.01
AQ-17	0.081	3.1	2.8	0.70	0.67
AQ-11	0.133	4.9	3.6	0.53	0
AR-27	0.086	4.4	4.7	0.49	0.24
AQ-18	0.630	6.6	4.4	0.41	-0.08
LS-60	0.110	4.4	8.0	0.36	0.40
AL-5	0.135	9.2	4.0	0.35	-0.67
AR-28	0.240	6.6	10.7	0.22	-0.58
AL-4	0.740	14.0	5.4	0.21	-1.01

The quality factor Z is plotted against γ/γ_0 in Fig. 3, where it can be seen that the correlation is very good. The effectiveness of substrate darkening in suppressing reflected ambient light is well demonstrated. This is in excellent agreement with the correlation of -0.89 reported in CG3, Table C-10, between Z and $R_D T_S^2$. Figure 4 shows this correlation. The displacement of the LS-60 point from the others prompted a remeasurement of $R_D T_S^2$, this time by a direct method. The value of 2% obtained for LS-60 should replace the earlier value of 6.3%. This change causes LS-60 to fall in line with the others.

When γ/γ_0 is calculated for the Quality I and Quality II tests, the results are not so clear cut as in test II because the ambient light was not as large relative to the illumination provided by the projector. These results are plotted in Figs. 5 and 6. In Quality test I, projector luminance was held constant. Figure 5 shows the quality factor increasing as γ/γ_0 increases, at low values of γ/γ_0 in test I. But at high values of γ/γ_0, the reduced screen luminance caused a rapid drop in judged quality. LS-60 performed best here because of its high efficiency and adequate ambient light rejection.

In the Quality III tests, screen luminance was maintained constant, except for screen AQ-20. Figure 6 shows a general dependence on γ/γ_0 except for screen AQ-17 and AQ-20. The reduced luminance of AQ-20 explains its low judged quality, but no good explanation for the performance of AQ-17 is apparent.

As mentioned earlier, ambient light was of much less influence in the resolution determinations. The lowest value of γ/γ_0 calculated by use of Eq. (9) for the constant-luminance case was 0.93. Nevertheless, for the low-contrast targets a significant correlation was noted between RN and $R_D T_S^2$ (CG3, pp C13 and C15).

4. Projector Brightness

The illumination produced on the screen by the projector affected the tests through the ratio $E_{amb}/\bar{E}_D$ as described above. Also, in some cases the screen luminance fell low enough to cause decreased visual acuity, as in Fig. 5. If projector power had been unlimited, it would have been of great interest to see whether the highest resolution could be obtained by highly illuminating the very dark substrate screens.

5. Screen Parameters

The list of screen parameters in Table A-1 of CG3 was purposely made redundant on the chance that some unexpected correlations might be discovered. The following list is probably sufficient for interpreting the results:

$T_{30}T_S$

$R_D T_S^2$ or $R_D T_S$

$\bar{T}_S$

V_{30}

α_T

MTF

DRTHI

The correlations found between these parameters and resolution and judged quality are found in CG3, pp. C10 - C-15.

The last three parameters had negligible effect on the outcome, although dry thickness DRTHI correlated extraordinarily well with quality in the Quality II test and with resolution in the resolution tests. This must be considered as fortuitous, arising largely because the inefficient screens AL-4 and AL-5 had very thin layers, and the screen which was given the greatest substrate darkening, AQ-20, had the thickest layer. The low projector MTF precluded any significant dependence on MTF values of the screens at 6 li/mm, which were not very different anyway. The trapped light ratio α_T would be important only if the ambient light were quite low, which was not the case.

The parameter $T_{30}T_S$ is basically a measure of screen efficiency and could equally well be replaced by LBRT, $B(0)T_S$, or $T_{45}T_S$, for which the correlations were very similar. Not unexpectedly, at constant projector illumination $T_{30}T_S$ correlates highly with quality and with resolution for the high-contrast target. The correlation vanishes, however, for low-contrast targets.

A significant correlation exists for $R_D T_S^2$ in Quality test II for the reasons explained earlier. In all the other tests the correlation is weak, although in the constant-screen luminance resolution test with LS-60 excluded, the correlation may reflect a real ambient and trapped light effect.

Large correlations were found for the brightness variation V_{30} in the resolution tests and in Quality Test II. The latter is understandable in view of the strong dependence of V_{30} on B(0). The surprisingly high correlation in the resolution tests is at least partly fortuitous, since the low efficiency screens AL-4 and AL-5, which nearly always gave inferior performance, had very high brightness variation.

6. Variation of Resolution with Viewing Angle

This phenomenon should be investigated further. Since it occurs for all screens, it could be a property of the projector. Also, if the screens were being used to best advantage, i.e., in a high-MTF system, the effect might be smaller or even more pronounced.

7. Effect of Target Contrast

One unexpected result is that the darker screens showed lower resolution than the lighter screens for high contrast targets, but the reverse was true for low contrast targets. Figure 3-10 of CG3 illustrates this point for constant projector output and corresponding results hold for constant screen luminance. The greater separation of screens on the resolution scale for low contrast targets can be explained by reference to the slope of the eye response curve. At very low contrasts a given fractional change in modulation produces a greater fractional change in detectable spatial frequency than at higher contrasts. However this does not explain the observed interchange of rankings of light and dark screens, as occurs most convincingly for screens LS-60 and AQ-20. If this effect persists in a more ideal projector arrangement, incorporation of heavier substrate darkening may be justified.

8. Conclusions

Significant dependences on some screen parameters, notably efficiency $T_{30}T_S$ and diffuse reflectance times substrate transmittance R_DT_S, were established by the tests. The more efficient screens performed best for a fixed projector output.

The projector MTF limited observed resolution to about 4.6 li/mm, whereas the screens should have been capable of displaying considerably higher resolution.

Quality tests were dominated by the projector MTF and by the ambient-to-projector illumination ratio. Calculations based on the known ambient light level revealed a strong R_DT_S dependence, which was one of the principal aims of the investigation. The importance of T_S was underscored by an unexplained superiority of dark screens for the low contrast resolution targets.

No physical justification is apparent for the large negative correlation between brightness variation V_{30} and resolution. While it is partly fortuitous, it may be significant.

Similarly, the reason for the observed increase of resolution with viewing angle is obscure. This effect may or may not be evident under ideal projection conditions.

Ambient light was generally high enough that the trapped light ratio α_T had little effect. Likewise, measured contact MTF values for the screens were not sufficiently different at 5 li/mm to have an observable influence on the results.

REFERENCES

1. J. J. DePalma and E. M. Lowry, J. Opt. Soc. Am. 52, 328 (1962).

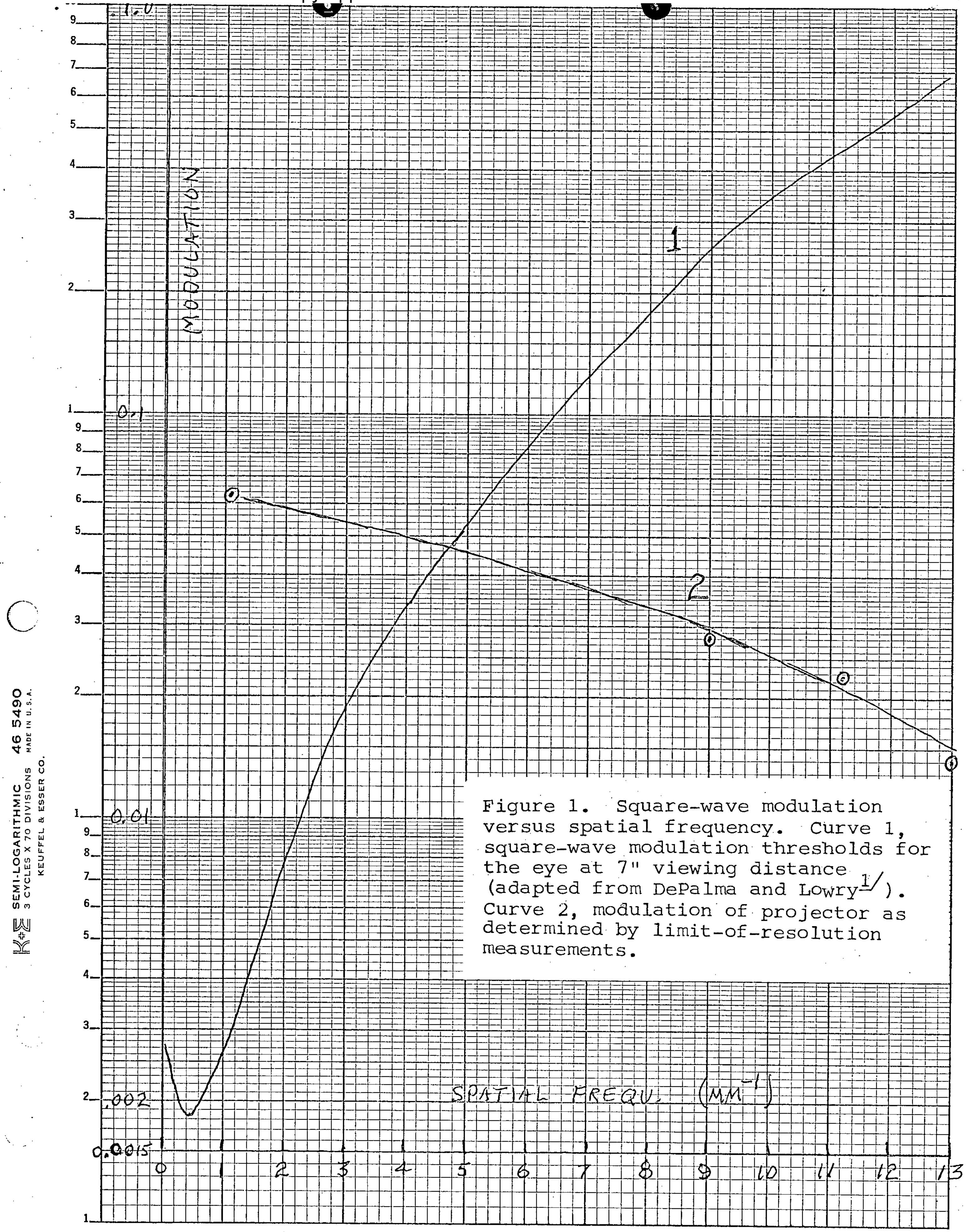

Figure 1. Square-wave modulation versus spatial frequency. Curve 1, square-wave modulation thresholds for the eye at 7" viewing distance (adapted from DePalma and Lowry[1]). Curve 2, modulation of projector as determined by limit-of-resolution measurements.

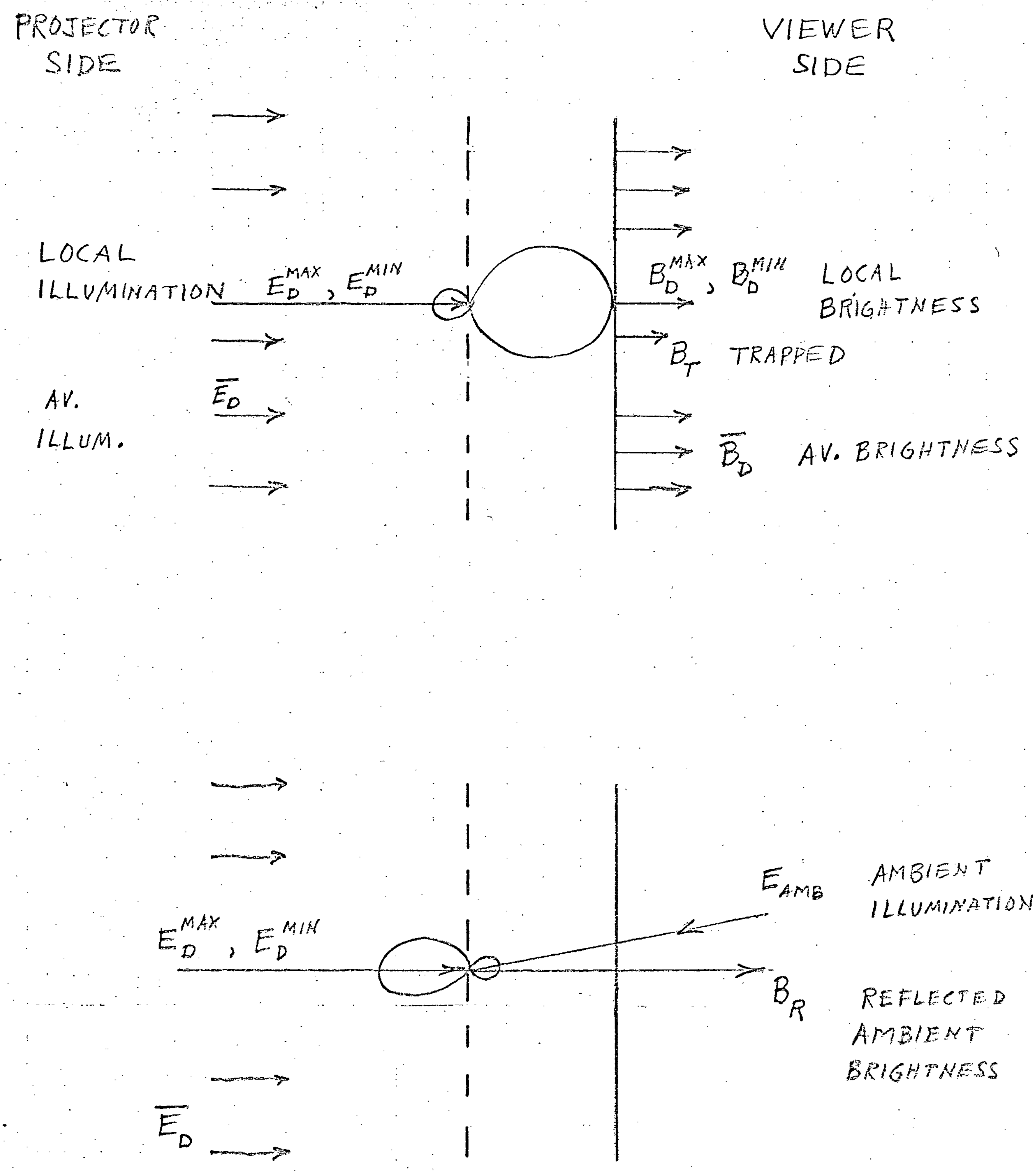

Figure 2. Geometry and nomenclature for describing trapped projector light and reflected ambient light.

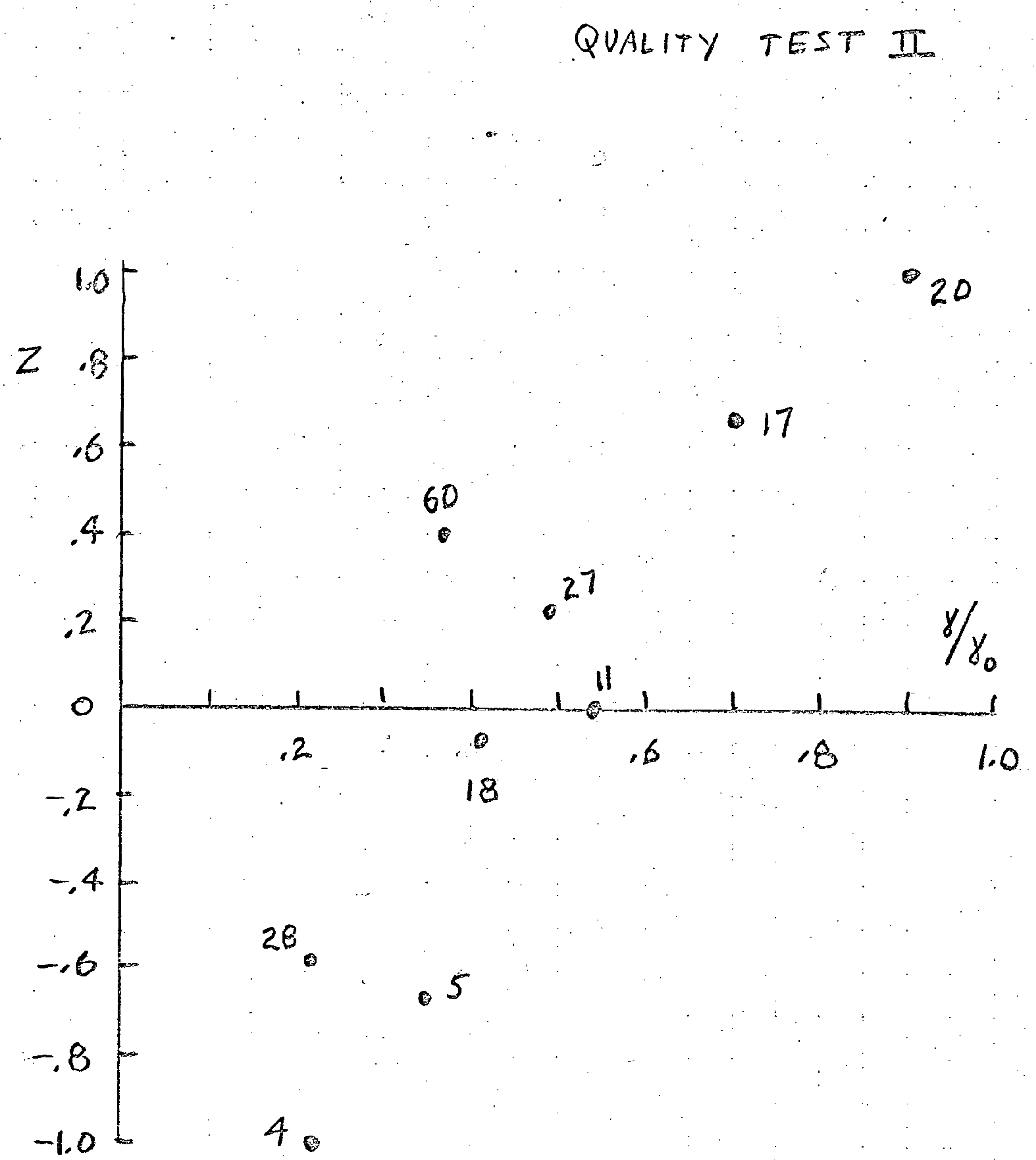

Figure 3. Quality scale factor Z versus modulation transfer factor γ/γ_0 produced by reflected ambient and trapped projector light. Numbers beside points are abbreviated screen numbers. Data for Quality Test II.

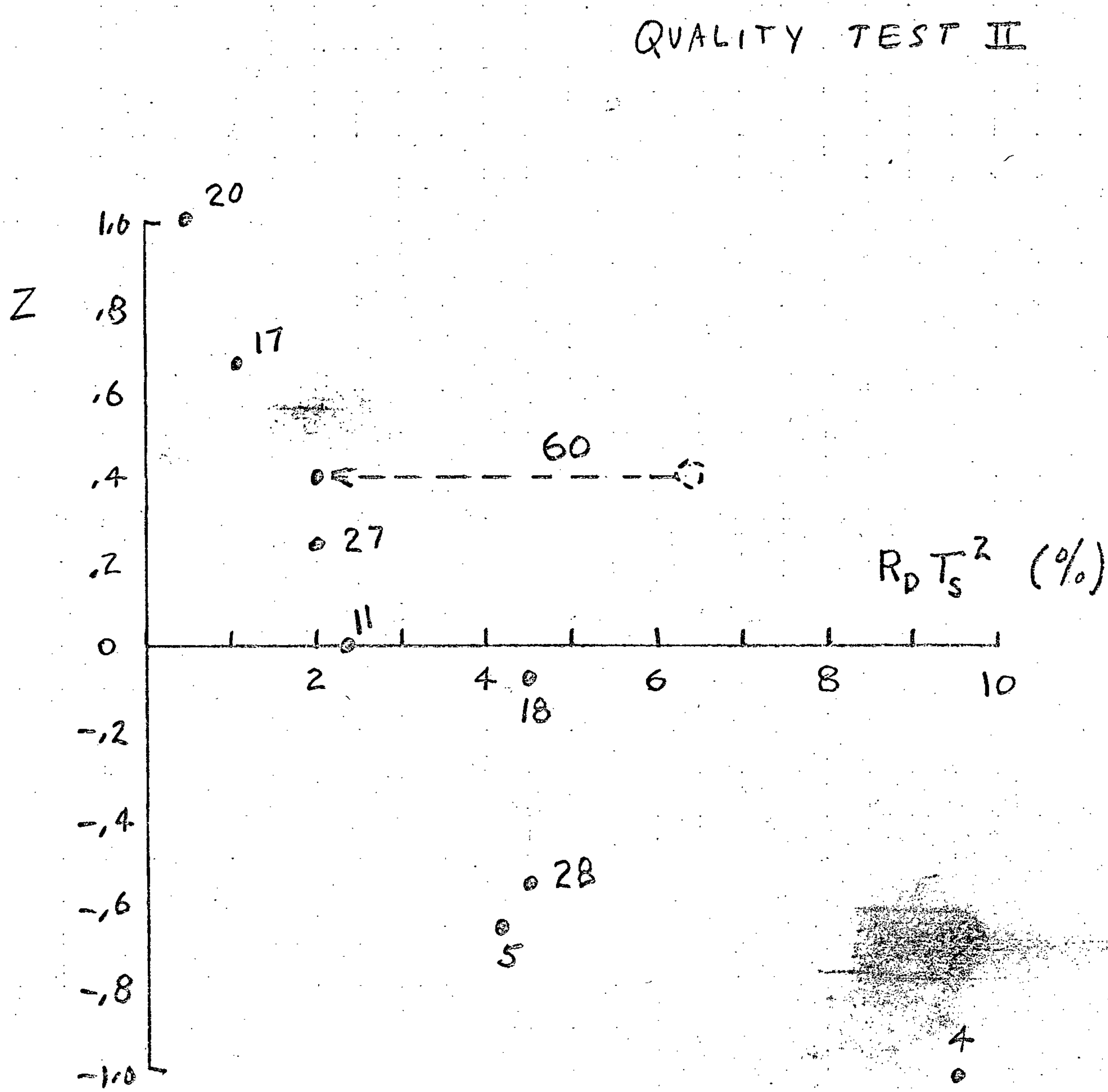

Figure 4. Quality scale factor Z versus $R_DT_S^2$ for Quality Test II. Screen LS-60 has corrected value of $R_DT_S^2$.

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QUALITY TEST I

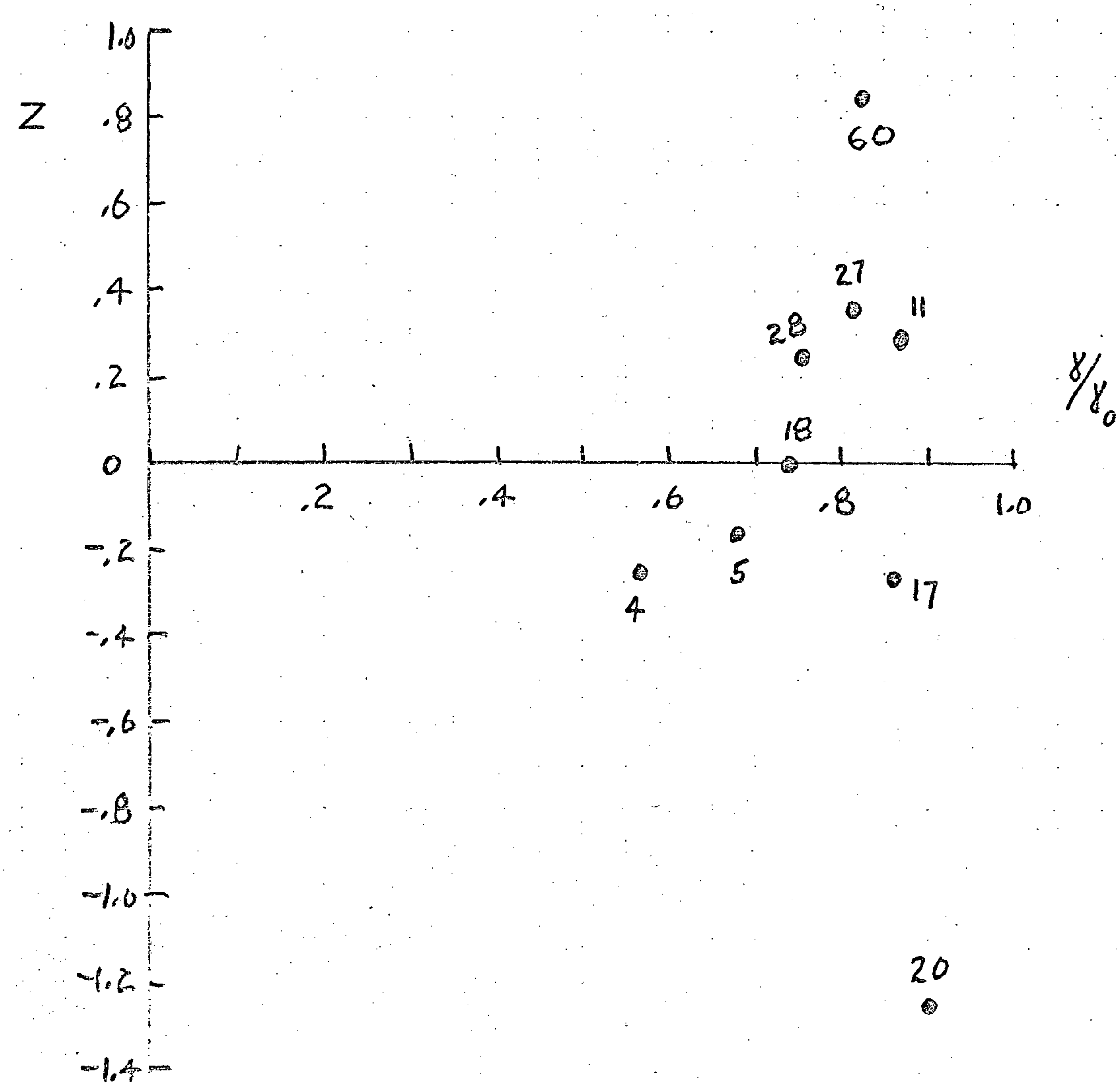

Figure 5. Quality scale factor versus γ/γ_0 for Quality Test I.

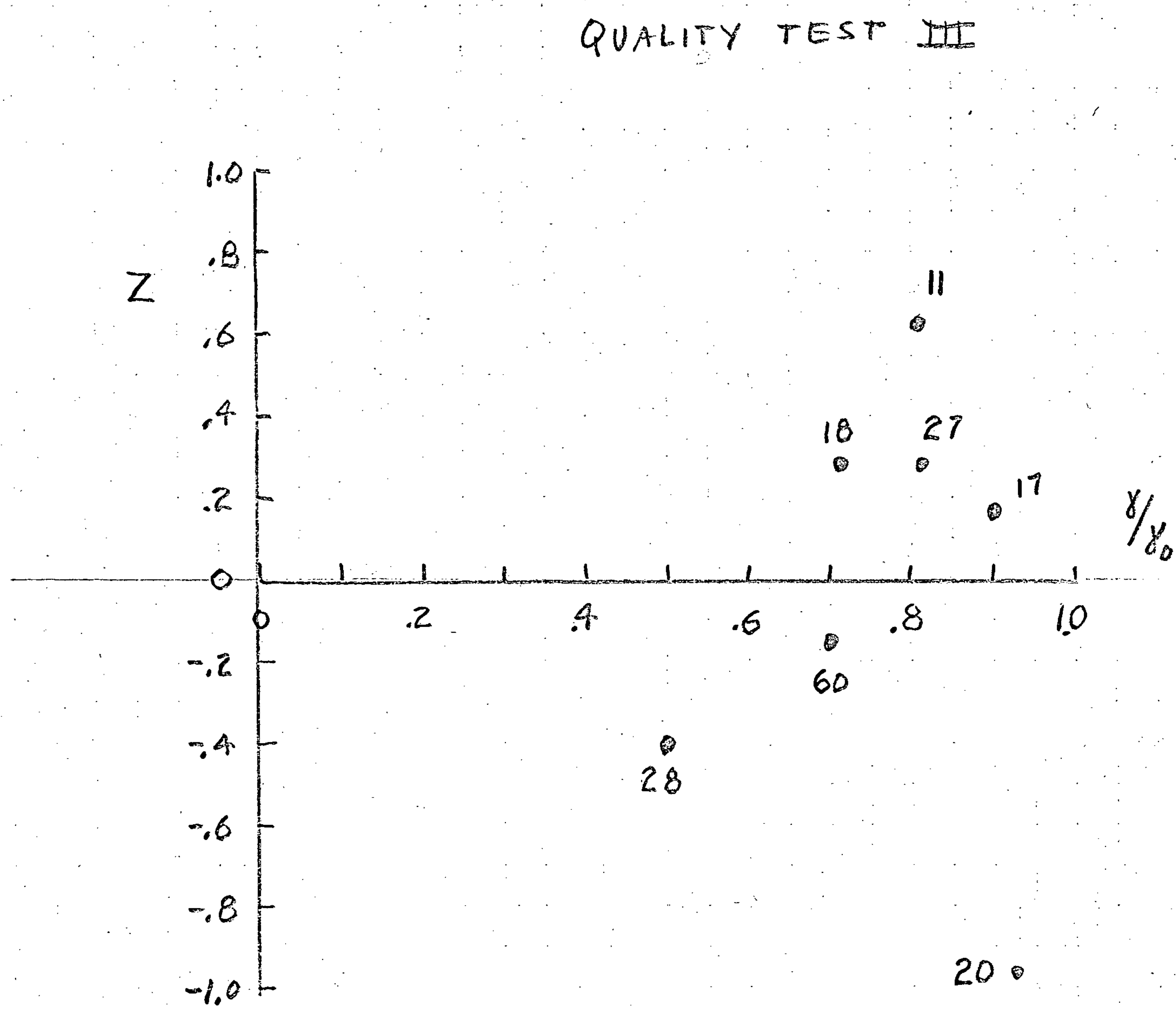

Figure 6. Quality scale factor versus γ/γ_0 for Quality Test III.