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CHEMISTRY DIVISION
High Polymer Section

Report on

SURVEY OF TWO-COAT REFLECTION-REDUCING FILMS

by

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ABSTRACT

A comprehensive study (theoretical and experimental) of two-coat reflection reducing films was made with particular emphasis on the effects of variations of the thicknesses and of the refractive indices of the films on the reflection reducing efficiencies of the coatings. The experimental results were compared with theoretical values calculated through the use of equations developed by Dr. B. Salzberg, relating to the reflection of electromagnetic waves from coated surfaces.

Several combinations of films were found to give spectral reflection curves having reflection minima below 0.2% per surface and overall reflections approximately the same as that of the type recommended previously. At this time, no particular advantage would be gained by changing to any of these other combinations of films. No significant increase in effectiveness of these films is possible until a film having an index of refraction appreciably lower than 1.47 is adapted for use with a higher index film.

INTRODUCTION

1. Authorization. Bureau of Ordnance letter to the Naval Research Laboratory, NP14 (IRe4e) dated 11 February 1944.

2. Statement of Problem. It was considered desirable at this time to determine the theoretical and practical limitations to the reduction of reflection of light from glass surfaces coated with the present two-coat reflection-reducing films and also to determine which combinations of coatings would be the best for application to optical surfaces.

3. Known Facts Bearing on the Problem. The work covered in this report is an extension of that included in previous reports (1,2) by this Laboratory on the subject of two-coat reflection-reducing films. In these earlier reports it was shown that by application to glass of a high index film of a titanium compound followed by a low index film of a silicon compound, nearly complete extinction of reflection could be obtained for certain regions of the spectrum as well as a greatly reduced overall reflection of white light. The present work is concerned with a study of the effects of variations in the thicknesses and of the refractive indices of the films on the reflection-reducing efficiencies of the two-coat films. The theoretical curves were calculated and compared with experimental curves obtained in this Laboratory. Through such a comparison it was thought possible to determine the practical limitations to the reduction of reflection by the two-coat films.

4. Theoretical Considerations. Dr. B. Salzberg, consultant, Radio Division, Naval Research Laboratory, has developed equations which may be used to calculate the reflection of electromagnetic waves from surfaces coated with materials of various properties. The derivation of these equations will be reported at a later date. These equations can be adapted to the reflection of light from coated optical surfaces.

5. For a single film of index N_2 and thickness d_2 on a transparent material of index N_1 the following relation can be obtained:

(1)
$$R = \left(\frac{N_2(1-N_1) + i(N_1 - N_2^2)\tan W_2}{N_2(1+N_1) + i(N_1 + N_2^2)\tan W_2}\right)^2$$

where $W_2 = 2\pi N_2 d_2/\lambda$

6. The above expression may be shown to be identical with that developed by Bauer (3) and Schröder (4):

(2)
$$R = \frac{N_2^2(N_1 - 1)^2 - (N_1^2 - N_2^2)(N_2^2 - 1)\sin^2 \frac{2\pi N_2 d_2}{\lambda}}{N_2^2(N_1 + 1)^2 - (N_1^2 - N_2^2)(N_2^2 - 1)\sin^2 \frac{2\pi N_2 d_2}{\lambda}}$$

7. From the above relations, it is readily seen that the reflection is a minimum when $N_2 d_2 = \frac{(2m+1)\lambda}{4}$ and when N_2 is less than N_1

where m = 0, 1, 2, ------; that is, where $\tan W_2 = \infty$.

thus, $R_{min} = \left(\frac{N_1 - N_2^2}{N_1 + N_2^2}\right)^2$

The reflection becomes zero when the further condition is applied than $N_2 = \sqrt{N_1}$.

8. The reflection, similarly, is a maximum when $N_2 d_2 = \frac{2 m \lambda}{4}$, where m = 0, 1, 2 ---; that is, where tan W_2 = 0.

Thus $$R_{max} = \left(\frac{1-N_1}{1+N_1}\right)^2 .$$

9. The above equations are exact, taking into account multiple reflection within the films. The approximate form, neglecting multiple reflection, is accurate only when the reflection is small.

(3) $$R = A_1^2 + A_2^2 + 2A_1A_2 \cos \frac{2 \pi 2 n_2 d_2}{\lambda}$$

where $A_1 = \frac{N_2 - 1}{N_2 + 1}$ and $A_2 = \frac{N_1 - N_2}{N_1 + N_2}$

10. From the reflection of a quarter wave film deposited on a substance of known index, the index of the film may be calculated using a relation derived from equation (1):

(4) $$N_2 = \left\{ N_1 \cdot \frac{1 + R^{\frac{1}{2}}}{1 - R^{\frac{1}{2}}} \right\}^{\frac{1}{2}}$$

or from the approximate relation derived from equation (3):

(5) $$N_2 = \frac{R^{\frac{1}{2}}(N_1 + 1) + (R(N_1 - 1)^2 + 16N_1)^{\frac{1}{2}}}{4 - 2R^{\frac{1}{2}}}$$

11. The general equation for the reflection of light from a transparent surface coated with two superimposed films is given by the following relation:

(6) $$R = \left| \frac{[N_2N_3(1-N_1)+(N_1N_3^2-N_2^2)\tan W_2 \tan W_3] + i[N_3(N_1-N_2^2)\tan W_2 + N_2(N_1-N_3^2)\tan W_3]}{[N_2N_3(1+N_1)-(N_1N_3^2+N_2^2)\tan W_2 \tan W_3] + i[N_3(N_1+N_2^2)\tan W_2 + N_2(N_1+N_3^2)\tan W_3]} \right|^2$$

where N_1 is the index of refraction of the material coated, N_2 is the index of the first coat and d_2 is its thickness, N_3 is the index of the second coat and d_3 is is its thickness,

$$W_2 = \frac{2 \pi N_2 d_2}{\lambda}$$

and $$W_3 = \frac{2 \pi N_3 d_3}{\lambda}$$

12. For two superimposed quarter wave films deposited on a transparent surface, it is readily seen from equation (6), that the reflection is given by the expression:

$$R = \left(\frac{N_1N_3^2 - N_2^2}{N_1N_3^2 + N_2^2}\right)^2$$

and the reflection is zero when

$$N_2 = (N_1N_3^2)^{\frac{1}{2}}$$

METHODS

A. Apparatus.

13. The method of application of the films to glass disks (2") was by spinning using the apparatus described in the previous reports (1,2). The spinning mechanism consisted of a centrifuge whose head had been replaced with a chuck suitable for holding disks up to 3" diameter and for rotating them in a horizontal plane. The speed was controlled by means of a variable voltage transformer ("Variac") and was measured by means of a "Strobotac".

14. The efficiencies of the films in decreasing the reflection were determined by allowing light that had passed through a Corning daylight blue filter (#5900) and through a converging lens to fall on the coated disks at an angle of about 7° from the normal and measuring the intensity of the light reflected (and focused) onto a "Photox" photoelectric cell. The intensity of the reflected light was determined by the deflection of a sensitive galvanometer to which the "Photox" cell was attached. A piece of uncoated glass (1.525 index) was used as a standard and its reflection taken as 8.28% of the incident light for two surfaces.

15. Spectral reflection curves were determined at the Naval Gun Factory through use of a General Electric Recording Spectrophotometer.

16. Materials.

(a) Glass disks, 2" diameter x 1/8" thick, about 1.528 index, from Semon-Bache & Co. New York.

(b) Titanium tetrachloride, technical. Eimer and Amend.

(c) Ethyl silicate (tetraethyl orthosilicate), commercial. Carbide and Carbon Chemicals Corporation, New York.

(d) Solution #155. Titanium tetrachloride in ethyl alcohol (see appendix).

(e) Solution #157c. Titanium tetrachloride and ethyl silicate in suitable solvents (see appendix).

(f) Solution #180. Modification of #157c (see appendix).

(g) Solution #50-B. Ethyl silicate in suitable solvents (see appendix).

17. Preparation of Films. The two-coat reflection-reducing films were applied to 2" glass disks by the procedure outlined in the previous reports (1,2). A clean glass disk was mounted in the chuck of the centrifuge, spun at a predetermined rate, and a portion of the high index solution (#155, #157c, #180) added from a dropper. After baking one-half hour at 105°C and cooling to room temperature, the low index solution (freshly prepared #50-B) was applied in a similar manner and baked 18 - 48 hours at 105°C. - no appreciable difference in color due to difference in time of baking being noted. The rates of spinning during the applications were closely controlled since they determined the thicknesses of the films produced. The films were applied in an atmosphere of low relative humidity (10-15%) and at a temperature of about 80-85°F.

18. Eighth-wave films of #157c were prepared by applying a diluted solution of #157c (20 ml #157c + 5 ml 95% ethyl alcohol) to the disks at 3600 R.P.M. Quarter-wave films were prepared by applying the above solution to the disks twice with a half-hour bake between applications. The estimate of the film thickness was obtained from the spectral reflection curve shown on Plate 1. The maximum reflection is obtained with a film a quarter-wave length in optical thickness when the index of the film is greater than that of the glass. The concentration and rate of application of solution #157c were so adjusted that two applications of solution gave a maximum reflection in the neighborhood of 5000 A°. From the fact that two coats of #157c gave films a quarter-wave in optical thickness, it was assumed that one coat applied at the same speed would give films an eighth-wave in thickness.

19. Eighth wave films of #180 were prepared similarly to the above by applying solution #180 to the disks at 3600 R.P.M.; quarter wave films were prepared by applying the solution twice; and three-eighth wave films by applying the solution three times at 3600 R.P.M. The coatings were hardened between applications of the solution by baking a short while at 105°C or by allowing to stand a short while at room temperature, no differences in the two procedures being noted.

20. Eighth wave films of #155 were prepared by applying a diluted solution of #155 (20 ml #155 + 10 ml 95% alcohol) to the disks at 3600 R.P.M. Repeating this process after a short bake at 105°C gave quarter wave films.

21. To find the most effective thickness of #50-B to be used with each of the above high index films, a series of disks of each type and thickness was recoated with solution #50-B at various rates and baked at 105°C. The member of each series having the lowest reflectivity toward daylight blue light was assumed to be representative of the most effective combination of the two coatings. The spectral reflectances of these disks were determined at the Naval Gun Factory.

RESULTS

22. The reflection values obtained experimentally were for the reflection of two coated surfaces. This was converted to give reflection for one surface by the relation:

$$R_{\text{one surface}} = \frac{R_{\text{two surfaces}}}{2-R_{\text{two surfaces}}}$$

23. Plate 1 contains spectral reflection curves of quarter-wave films of #155, #157c and #180 deposited on glass of 1.528 index. From the maxima of these curves, the indices of refraction of the films were calculated through use of equations (4) and (5). The values of the refractive indices calculated in this manner should be exact only for the wave lengths at which the maxima occur. However, the fact that the indices may be assumed to be constant for all practical purposes is indicated on Plate 2 where the spectral curve of a quarter-wave film of #155 is compared with the theoretical curve of a film having an index of 2.00 and having a maximum reflection at the same point as the experimental curve.

24. Plate 3 contains a curve of the reflection of light of wave length λ_o by two-coat reflection reducing films composed of films of 1.80 index material of various thicknesses recoated with quarter-wave ($\lambda_o/4$) films of 1.47 index material on glass of 1.53 index. This theoretical curve indicates that it is possible to keep the reflection of light of a given wavelength (λ_o) below 0.2% per surface even though the high index film varies from 0.21 λ_o to 0.29 λ_o in optical thickness. Thus in preparing coatings of this type, extremely close control of the thickness of the high index film is not necessary.

25. Plate 4 is similar to Plate 3 except that here the low index film varies in thickness while the high index film remains a quarter-wave thick. The theoretical curve indicates that it is possible to keep the reflection of light of a given wavelength (λ_o) below 0.2% per surface only while the optical thickness of the low index film remains in the range 0.23 - 0.27 λ_o. Thus it is readily seen that much closer control of the low index film than of the high index film is required.

26. Plate 5 contains experimental curves which verify the above conclusions qualitatively. Thus it may be seen that if the high index film is applied at 2000-4000 R.P.M. and then recoated with the low index film at 1800 R.P.M., there are no appreciable differences in reflection of daylight due to the differences in thicknesses of inner film. However, for a given rate of application of the high index film, for example, 3000 R.P.M., small changes in the rate of application of the low index film cause rather large differences in the reflectivity; thus, the reflectivity is 0.6% per surface when the low index coat is applied at 1800 R.P.M., 0.85% per surface when applied at 2100 R.P.M. and 1.5% per surface when applied at 2700 R.P.M.

27. Plate 6 shows the effect of the variation of the refractive index of the glass on the reflection of light of wave length λ_o when the glass is coated with a two-coat film composed of a quarter-wave film of 1.47 index superimposed on a quarter-wave film of 1.80 index. With this combination of films the reflectivity remains below 0.1% per surface for any glass having an index between 1.42 and 1.60 and gives zero reflection for glass having an index of refraction of 1.51. However, by suitable choice of the refractive indices of the films, almost any glass could be so coated that it would have zero reflection for some particular wavelength of light and a very low reflectivity toward white light. For comparison, the minimum reflectivity attained by a coating composed of a single film of 1.40 index material - roughly corresponding to the magnesium fluoride film - on glasses of various indices is included.

28. Plates 7 and 8 show the effects on the reflection of light of a given wavelength (λ_o) with changes in the refractive indices of two superimposed quarter-wave films ($nd = \lambda_o/4$) on glass. It may thus be seen (Plate 7) that the reflection remains below 0.2% per surface when the coating is composed of a quarter-wave film of 1.47 index on a quarter-wave film having a refractive index in the range 1.73 - 1.89 on glass of 1.525 index. This curve is substantiated by several experimental points. Plate 8 indicates that the reflection remains less than 0.2% per surface for glass of 1.525 index coated with a quarter-wave film of 1.80 index and having a top quarter-wave film whose index is in the range 1.39-1.52.

29. Plates 9, 10 and 11 contain spectral curves of two-coat films composed of various thicknesses of #157c and #50-B. On the same plates are shown the theoretical curves for the same films as calculated from equation (6). In the calculation of the curve on plate 9, for example, the assumption was made that the coating was composed of an eighth-wave film of 1.80 index and a 3/10 wave film of 1.47 index on glass of 1.53 index. These are taken to be optical thicknesses at 5300 A°, the point of minimum reflectivity of the experimental film. The divergence of the two curves and the displacement of the minimum of the calculated curve indicate that the assumptions regarding the film thicknesses were not quite correct.

They are close enough, however, to give a reasonable check of the theory. On Plate 10, the theoretical and experimental curves lie much closer together, indicating that the assumed values for the film thicknesses are more nearly correct. Divergence at the extremes of the curves may be due to the fact that the refractive indices are not constant over the spectral range covered.

30. Plates 12-16 contain experimental and calculated curves for various combinations of films of #180 and #50-B. Plate 17 shows a comparison of the spectral reflections of coatings composed of eighth-wave films of #180 recoated, in one case, with the thinnest film of #50-B that would give a reflection minimum in the desired range ($nd \sim 3\lambda_0/10$), and in the second case, with the next thicker coating that would give the desired reflection minimum ($nd \sim 4\lambda_0/5$). From this it may be concluded that the only satisfactory film for reducing the reflection of white light is of the first order in thickness; that is, it is in the neighborhood of $\lambda_0/4$ in optical thickness rather than $3\lambda_0/4$.

31. Plate 18 contains curves of the reflectivity of coatings composed of eighth- and quarter-wave films of #180 recoated with various thicknesses of #50-B. The theoretical curves corresponding to the experimental curves above are on Plate 19.

32. Plates 20 and 21 contain spectral curves of some combinations of #155 and #50-B. Here satisfactory results are obtained when the film of #155 is about an eighth-wave thick and is recoated with about a 5/16-wave film of #50-B. Two superimposed quarter-wave films of #155 and #50-B are not at all effective in reducing reflection.

33. Discussion of Results. The agreement between the theoretical and experimental curves is remarkably close considering the assumptions made and the possible experimental errors in the preparation and measuring of the films. An approximation was made that might have some effect on the shapes of the calculated curves; namely, that the refractive indices of the films and of the glass were constant over the range 4000 - 7000 A°. This perhaps accounts for the divergence of the theoretical and experimental spectral curves at the two extremes. Similarly, the errors in determination of the refractive indices of the films will cause some errors in the calculated spectral curves. However, since it has been shown that the indices of refraction are not too critical (Plates 6, 7 and 8), the actual error involved should not be large. The values taken for the thicknesses of the films are approximate only - particularly in the case of the low index film - but the close correspondence between the calculated and experimental curves indicates that the thicknesses used are of the right order of magnitude.

34. The most effective of the combinations of films investigated for the reduction of reflection from glass of 1.525-1.53 index were the following:

(1) quarter wave film of #157c plus quarter wave film of #50-B;
(2) 5/32 wave film of #157c plus 3/10 wave film of #50-B;
(3) eighth wave film of #180 plus 3/10 wave film of #50-B;
(4) quarter wave film of #180 plus quarter wave film of #50-B;
(5) three-eighth wave film of #180 plus 19/100 film of #50-B;
(6) eighth wave film of #155 plus 5/16 wave film of #50-B.

35. There are several combinations of the low and high index films that result in the practical elimination of reflection of light of some one particular wave length from the coated surface. Actually, complete elimination of reflection at any one wave length may be accomplished by only one combination of #50-B and #157c (two quarter wave films) and by two combinations of #50-B with #180, #155 or any film having an index of refraction greater than 1.82 (a film of high index less than a quarter wave in thickness recoated with a low index film greater than a quarter wave in thickness, or the reverse, the actual thicknesses depending on the indices of refraction of the films).

36. For all practical purposes, however, a film of #157c approximately 5/32 wave in thickness recoated with #50-B approximately 3/10 wave in thickness, gives nearly complete extinction of reflection for certain wave lengths (Plate 11) and a greatly decreased overall reflection toward daylight blue light. This is the type of coating recommended in the previous report (2) for use on optical surfaces. No significant decrease in reflection is to be accomplished by a change to another combination of films. However, it is suggested that solution #157c be applied at 2500 R.P.M. rather than at 3600 R.P.M., and then recoated with #50-B at 1800-2000 R.P.M., depending on the position of the point of minimum reflection desired.

CONCLUSIONS AND RECOMMENDATIONS

37. The close agreement between the calculated and experimental curves indicates that the assumptions regarding the films - film thicknesses, indices of refraction, etc. - are essentially correct.

38. The most reliable values for the refractive indices of the various films are the following: #50-B (baked 48 hours at 105°C) 1.47 at 5100 A°; #155 (baked 41 hours at 105°C) 2.00 at 4700 A°; #157c (baked 18 hours at 105°C) 1.81 at 4600 A°; and #180 (baked 20 hours at 105°C) 1.875 at 4650 A°.

39. Both theoretical and experimental results indicate that the thickness of the low index film is much more critical than that of the high index film. In other words, the rate of spinning during the application of the low index solution (#50-B) must be controlled fairly closely (± 50 R.P.M.), while the rate during the application of the high index solution (for example, #157c) need not be controlled so closely.

40. The recommended procedure is to apply solution #157c at 2500 R.P.M., to harden by allowing to stand 10-15 minutes or by baking, and then to apply #50-B (freshly prepared) at 1800-2000 R.P.M., the exact rate being determined by the position of minimum reflection desired; and finally to harden the coating by baking at 105°C for 18-48 hours.

41. Several other combinations of high and low index films investigated produced reflection-reducing films of the same order of effectiveness as those prepared by the usual procedure. However, none of these films showed any particular advantage over the usual type in regard to reduction of reflection or to simplicity of application.

42. It may be concluded from a study of the results obtained that no appreciably better reflection-reducing films may be prepared using the two-coat process unless a top coating having an index much less than 1.47 is employed (Plate 22). This may perhaps be done through use of a top coat of magnesium fluoride or of some of the newer silicone resins.

SUMMARY

1. A comprehensive study, both theoretical and experimental, was made of the two-coat reflection-reducing films and the close agreement of the experimental results with the theoretical is shown.

2. Not enough increase in effectiveness of reflection-reducing coatings through the use of different combinations of available high and low index films was found to make it worthwhile changing the combination of films previously recommended (2).

3. A simplified procedure for the application of the usual films of #157c and #50-B whereby the intermediate baking period was omitted was found to be entirely satisfactory.

4. It has been concluded that, until a material having an index of refraction substantially lower than 1.47 is adapted for use, no appreciable further reduction of reflection will be obtained.

5. The study of films of this type is being continued with an attempt being made to further simplify the procedure for their production.

APPENDIX

Solution #155. Prepared by the slow, careful addition of 15 ml of titanium tetrachloride to 320 ml of 95% ethyl alcohol* and diluting the resulting solution with an equal volume of 95% ethyl alcohol.

Solution #50. Prepared by mixing the following components:

Ethyl alcohol (95%)	41.3 ml
Ethyl silicate	4.0 ml
Ethyl acetate	37.5 ml
Hydrochloric acid (d 1.17)	3.2 ml

Solution #157c. Prepared by mixing 64 ml of solution #155 with 40 ml of solution #50.

Solution #180. Prepared by mixing 60 ml of solution #155 with 20 ml of solution #50 and 20 ml of 95% ethyl alcohol.

Solution #50-B. Prepared by mixing the following components and allowing to stand 15 minutes:

Ethyl alcohol (95%)	22.0 ml
Ethyl acetate	20.0 ml
Ethyl silicate	4.4 ml
Butanol	2.5 ml
Hydrochloric Acid (d 1.17)	1.7 ml

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* By error, this was previously reported to be 10 parts by weight of titanium tetrachloride to 90 parts of ethyl alcohol, rather than 10 to 100.

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4. H. Schröder, Ann. d. Phys. 39, 55 (1941).

TABLE I

OBSERVED REFRACTIVE INDICES OF THE FILMS

Film	Reflection of Quarter wave Film	Position of Maximum*	Index of Film		
			Calc. from Eq. (4)	Calc. from Eq. (5)	Used in Other Calc.
50-B	0.0293	5100 A°	1.469	1.470	1.47
157c	0.1325	4600 A°	1.810	1.794	1.80
180	0.1555	4650 A°	1.875	1.851	1.87
155	0.2000	4700 A°	2.000	1.958	2.00
	$N_{glass} = 1.528$		-	-	1.53

* Position of minimum in case of #50-B.

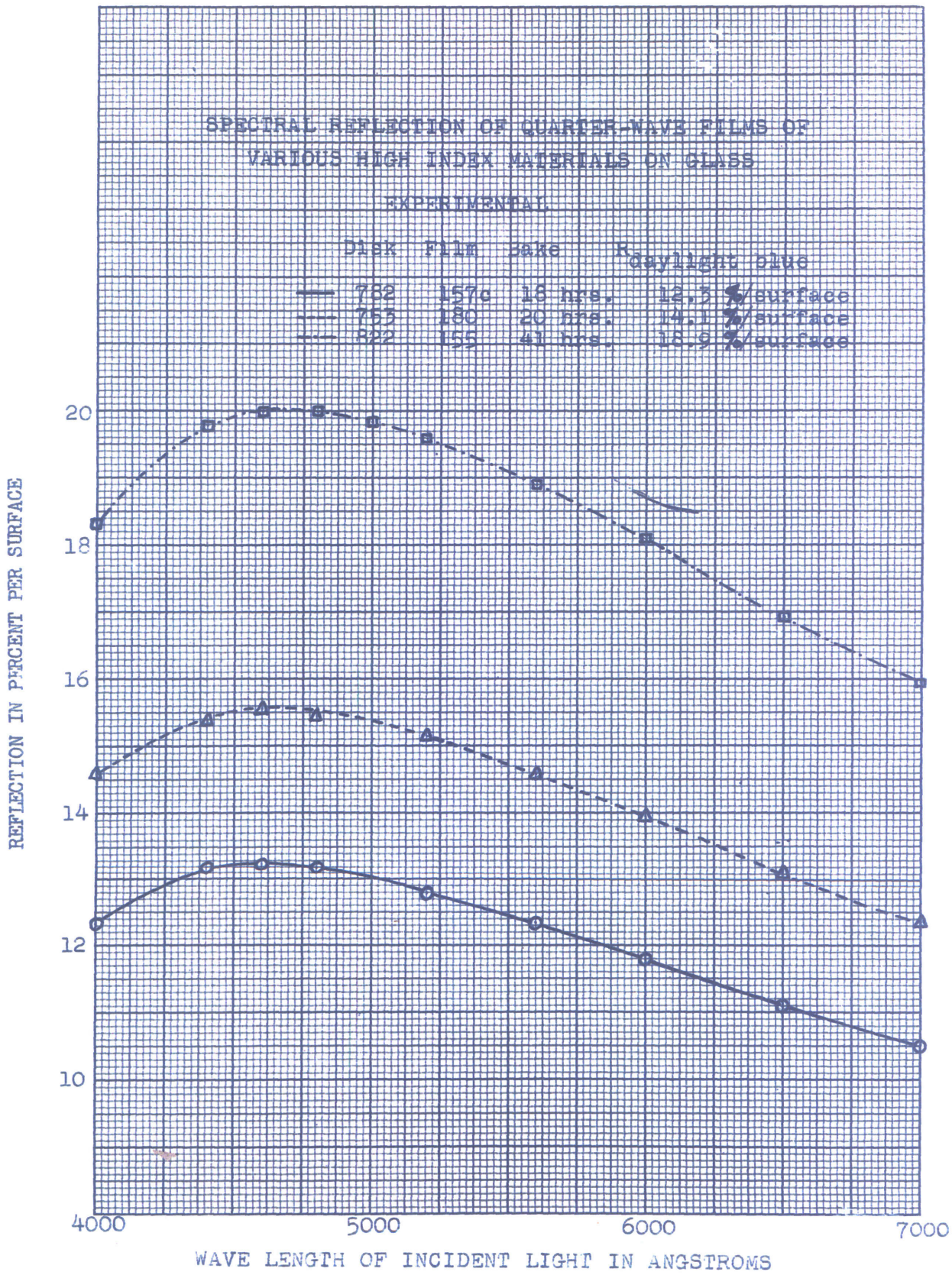

SPECTRAL REFLECTION OF QUARTER-WAVE FILMS OF
VARIOUS HIGH INDEX MATERIALS ON GLASS
EXPERIMENTAL
Disk Film Bake R daylight blue
762 157c 18 hrs. 12.3 %/surface
753 180 20 hrs. 14.1 %/surface
822 155 41 hrs. 18.9 %/surface
20
18
16
14
12
10
REFLECTION IN PERCENT PER SURFACE
4000
5000
6000
7000
WAVE LENGTH OF INCIDENT LIGHT IN ANGSTROMS

PLATE 1

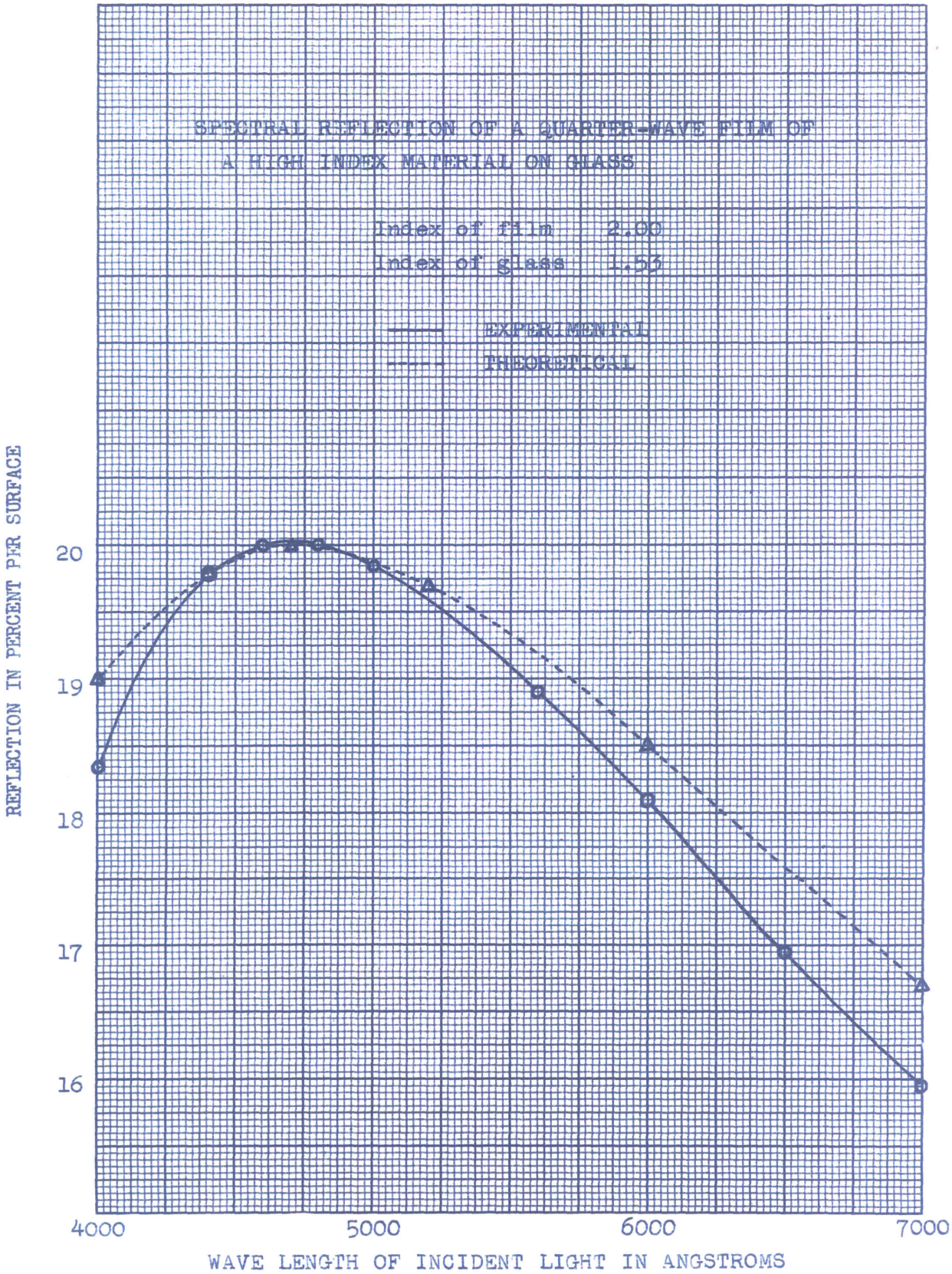

SPECTRAL REFLECTION OF A QUARTER-WAVE FILM OF
A HIGH INDEX MATERIAL ON GLASS
Index of film 2.00
Index of glass 1.53
EXPERIMENTAL
THEORETICAL
REFLECTION IN PERCENT PER SURFACE
20
19
18
17
16
4000
5000
6000
7000
WAVE LENGTH OF INCIDENT LIGHT IN ANGSTROMS

PLATE 2

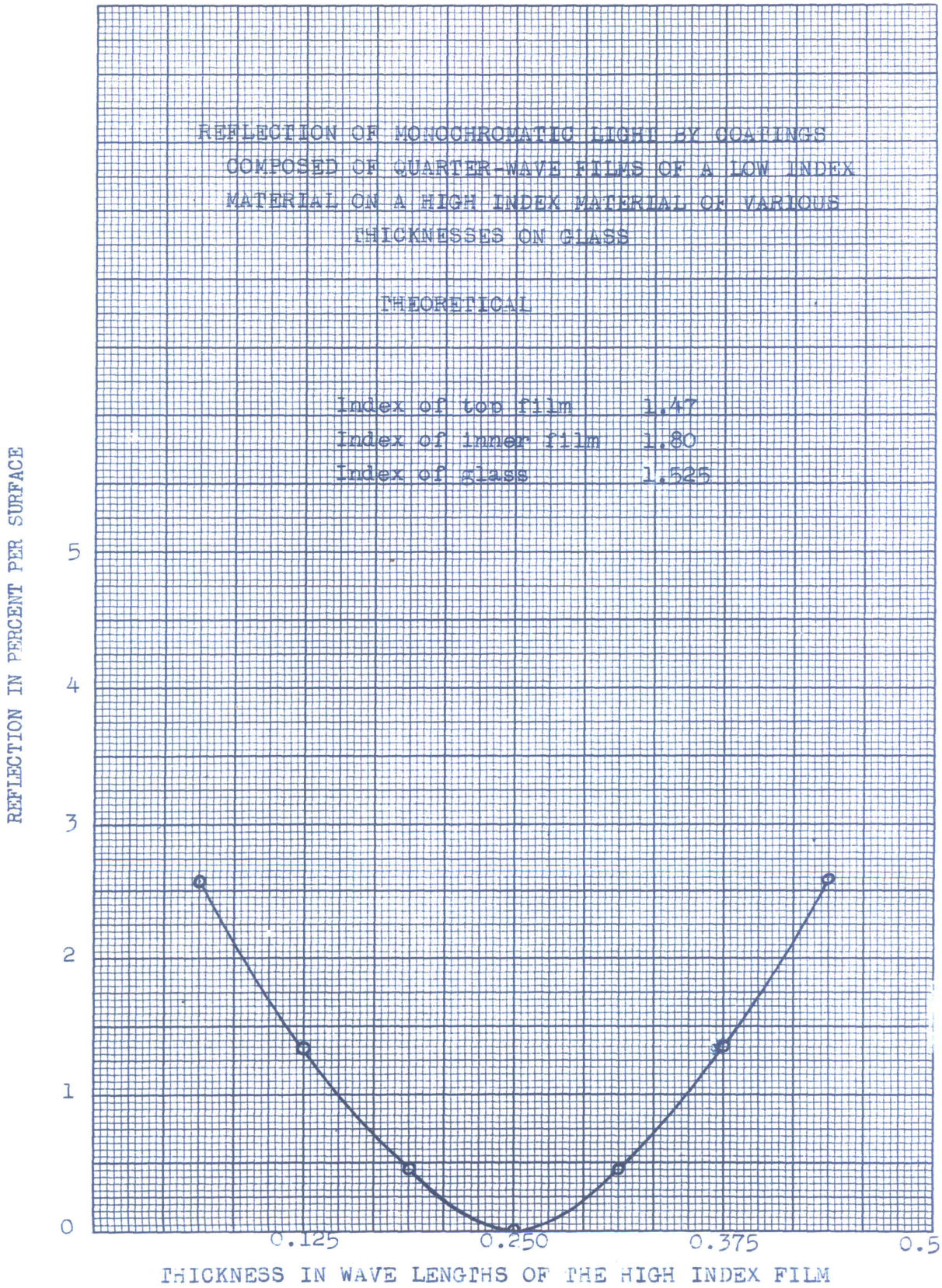

REFLECTION OF MONOCHROMATIC LIGHT BY COATINGS
COMPOSED OF QUARTER-WAVE FILMS OF A LOW INDEX
MATERIAL ON A HIGH INDEX MATERIAL OF VARIOUS
THICKNESSES ON GLASS
THEORETICAL
Index of top film 1.47
Index of inner film 1.80
Index of glass 1.525
REFLECTION IN PERCENT PER SURFACE
0
1
2
3
4
5
0.125
0.250
0.375
0.5
THICKNESS IN WAVE LENGTHS OF THE HIGH INDEX FILM

PLATE 3

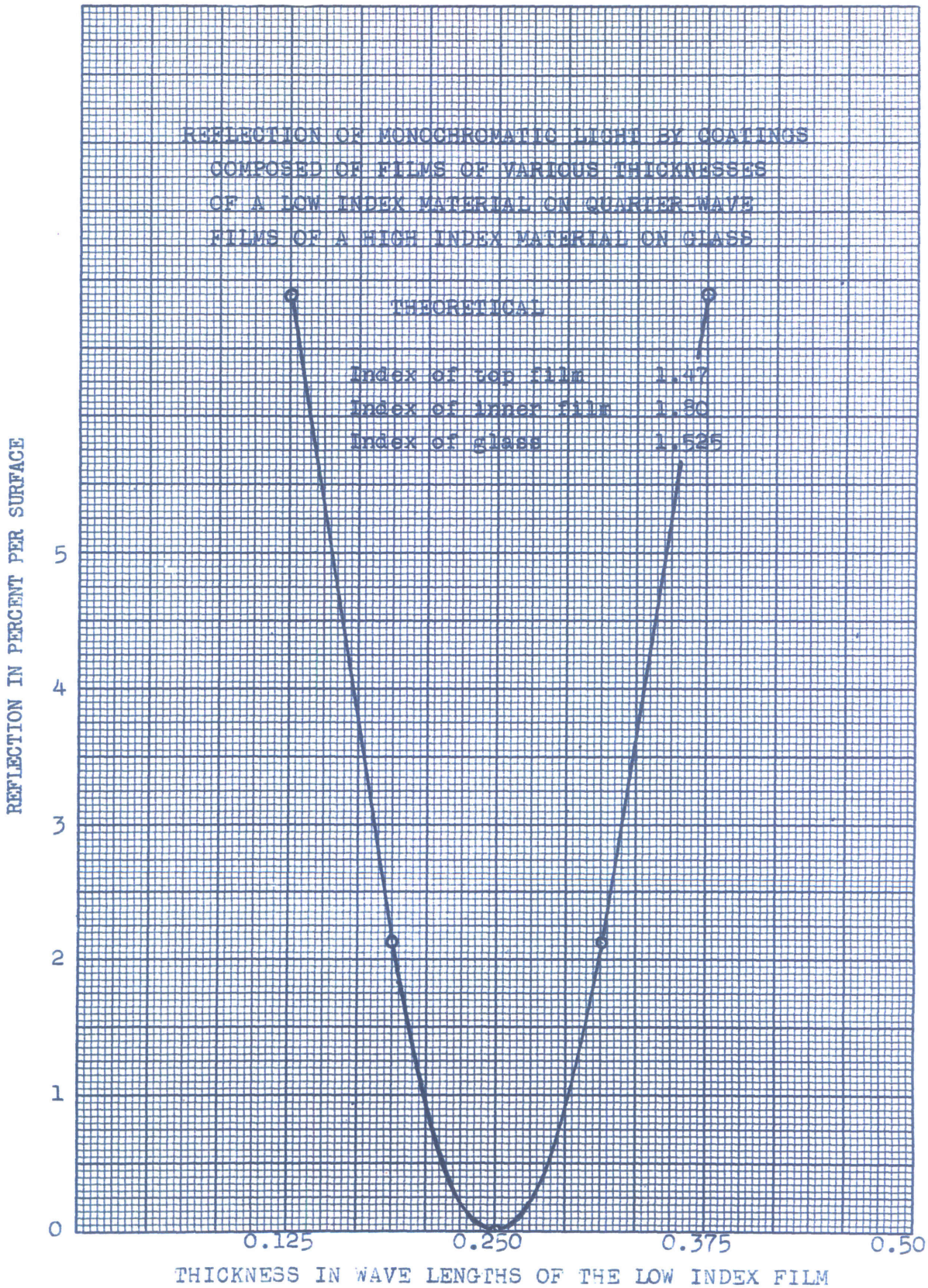
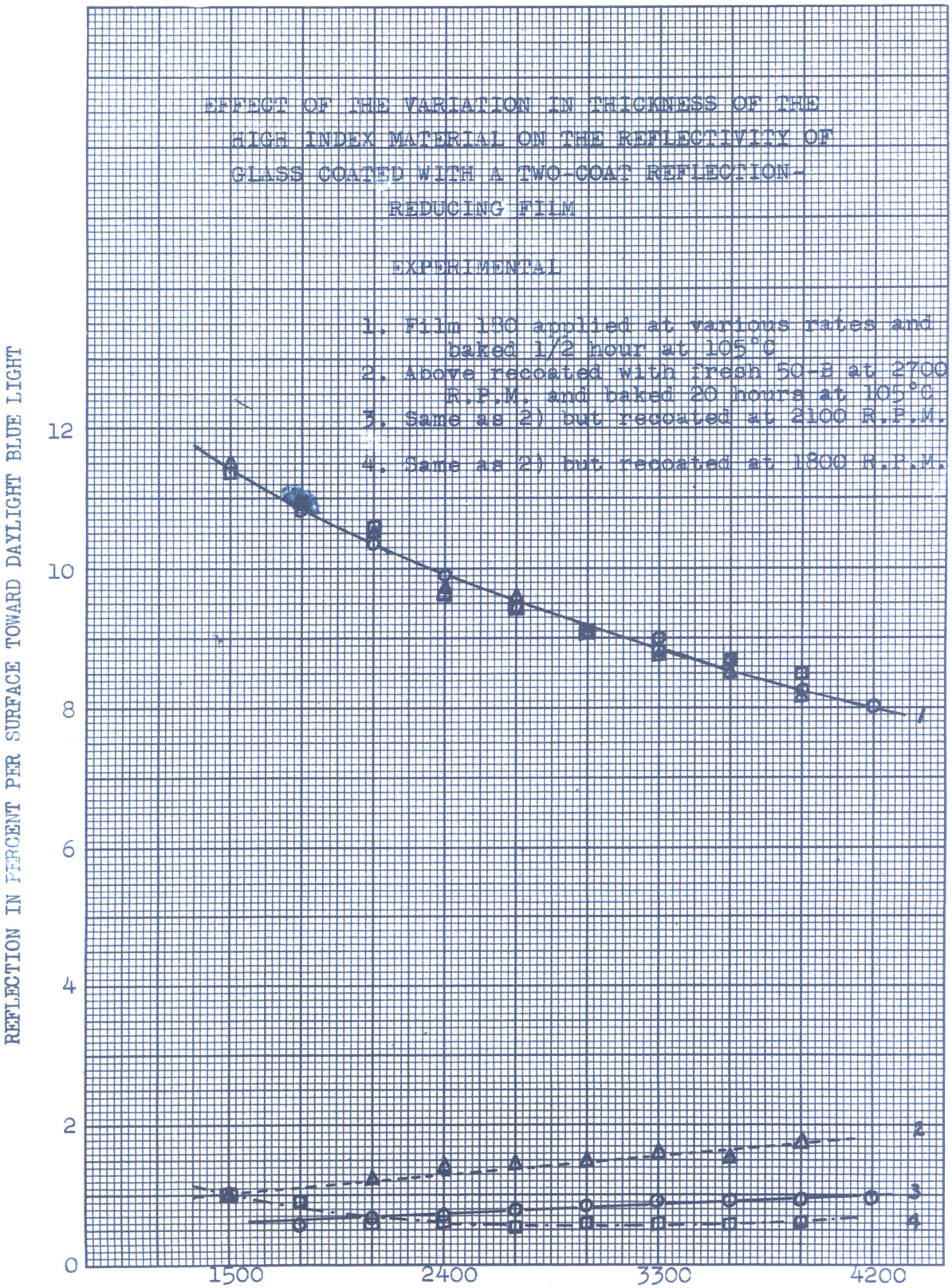

REFLECTION OF MONOCHROMATIC LIGHT BY COATINGS
COMPOSED OF FILMS OF VARIOUS THICKNESSES
OF A LOW INDEX MATERIAL ON QUARTER-WAVE
FILMS OF A HIGH INDEX MATERIAL ON GLASS
THEORETICAL
Index of top film 1.47
Index of inner film 1.80
Index of glass 1.525
REFLECTION IN PERCENT PER SURFACE
0
1
2
3
4
5
0.125
0.250
0.375
0.50
THICKNESS IN WAVE LENGTHS OF THE LOW INDEX FILM

PLATE 4



RATE OF SPINNING (R.P.M.) DURING APPLICATION OF THE HIGH INDEX FILM

PLATE 5

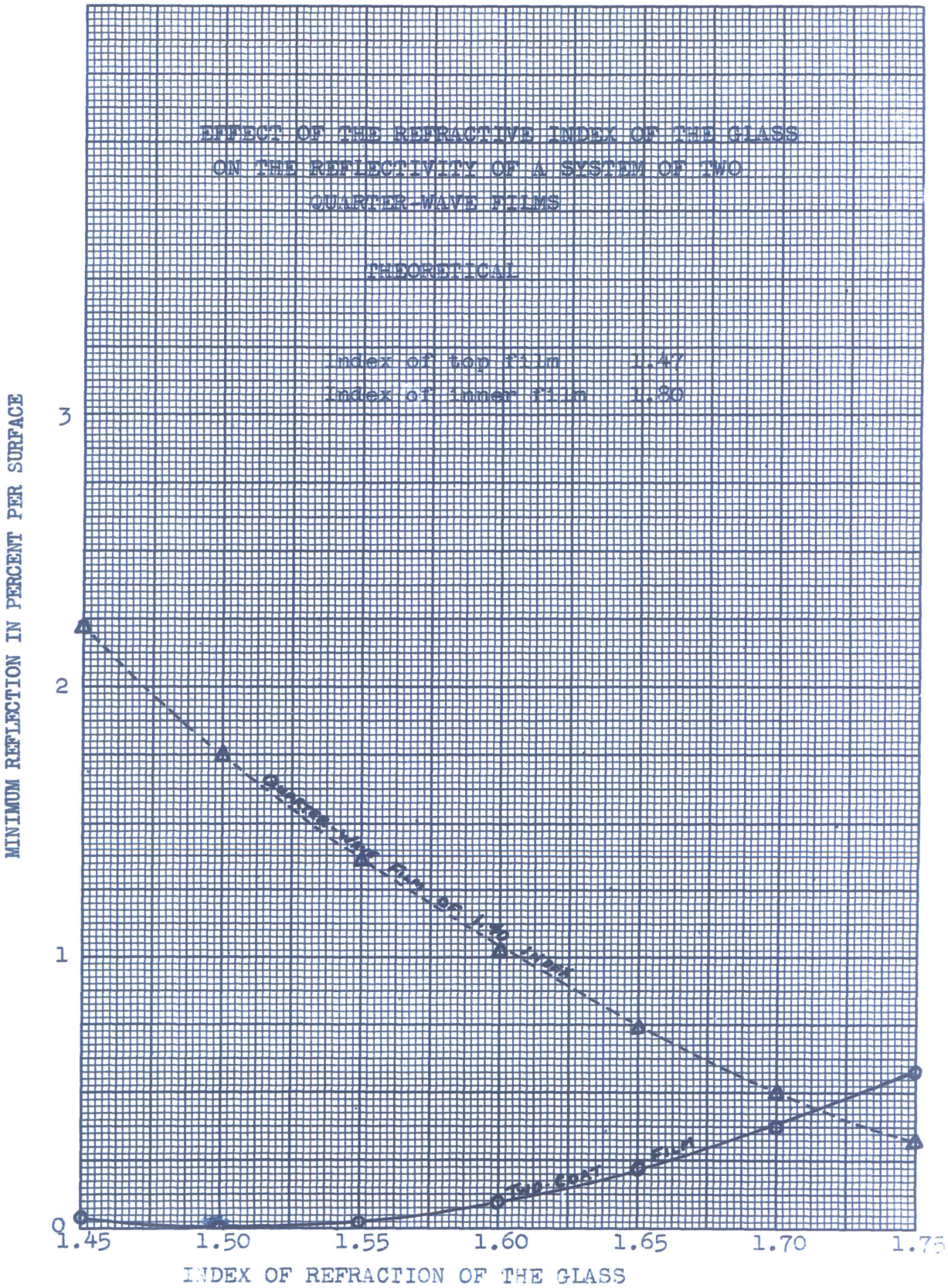

EFFECT OF THE REFRACTIVE INDEX OF THE GLASS
ON THE REFLECTIVITY OF A SYSTEM OF TWO
QUARTER-WAVE FILMS
THEORETICAL
Index of top film 1.47
Index of inner film 1.80
Quarter-wave film of 1.47 index
Top coat film
MINIMUM REFLECTION IN PERCENT PER SURFACE
0
1
2
3
1.45
1.50
1.55
1.60
1.65
1.70
1.75
INDEX OF REFRACTION OF THE GLASS

PLATE 6

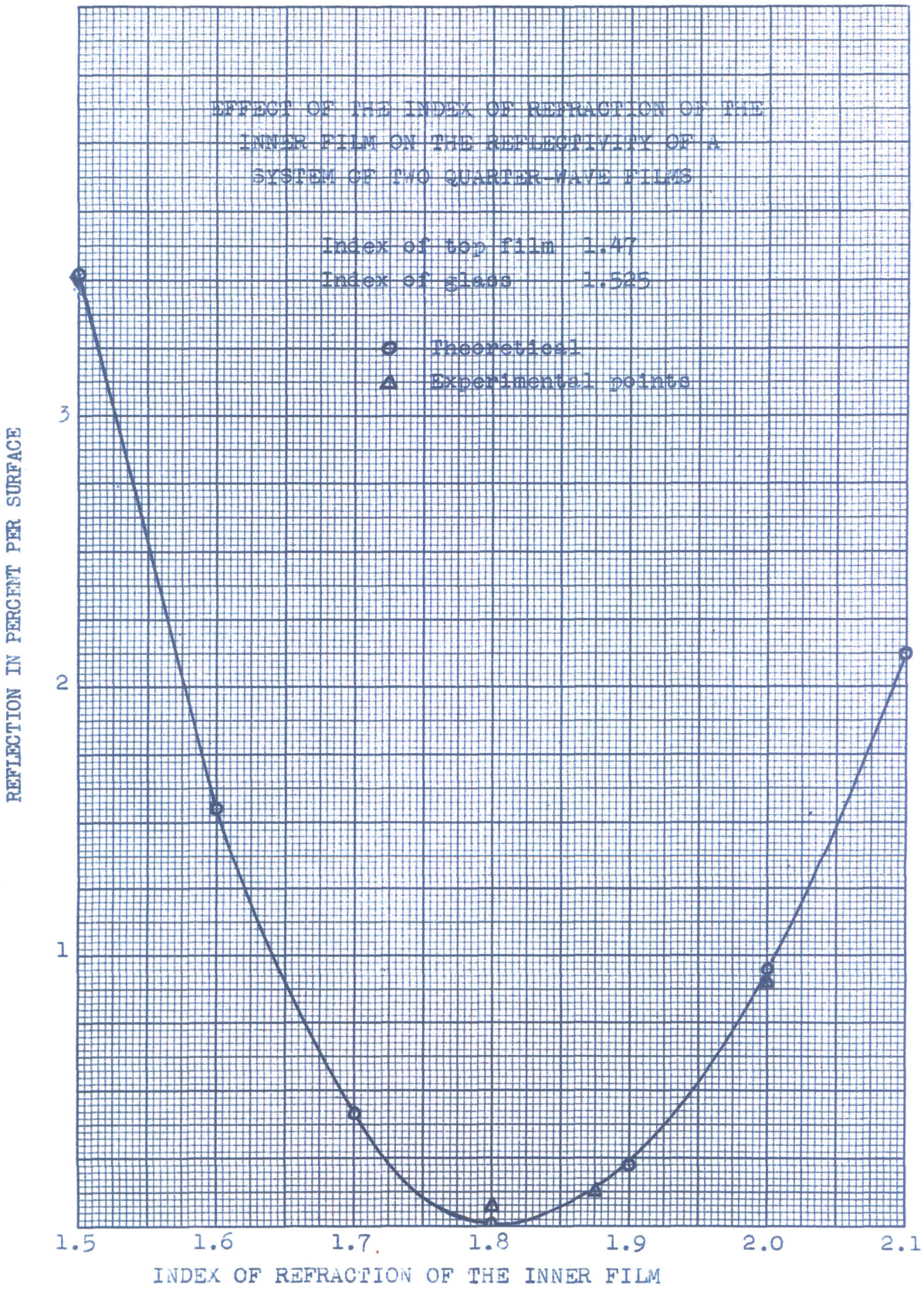

EFFECT OF THE INDEX OF REFRACTION OF THE
INNER FILM ON THE REFLECTIVITY OF A
SYSTEM OF TWO QUARTER-WAVE FILMS
Index of top film 1.47
Index of glass 1.525
Theoretical
Experimental points
REFLECTION IN PERCENT PER SURFACE
3
2
1
1.5
1.6
1.7
1.8
1.9
2.0
2.1
INDEX OF REFRACTION OF THE INNER FILM

PLATE 7

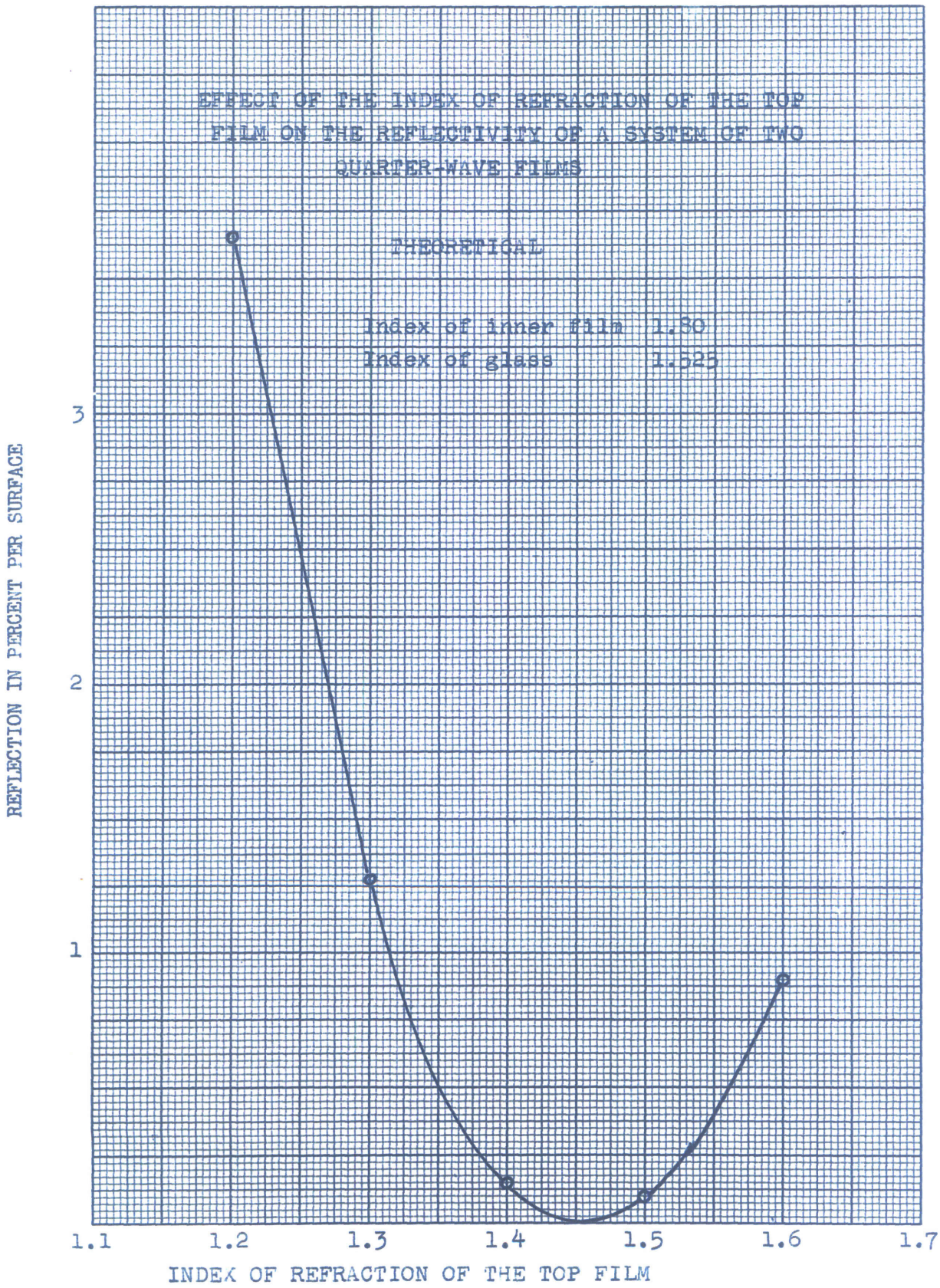

EFFECT OF THE INDEX OF REFRACTION OF THE TOP FILM ON THE REFLECTIVITY OF A SYSTEM OF TWO QUARTER-WAVE FILMS
THEORETICAL
Index of inner film 1.80
Index of glass 1.525
REFLECTION IN PERCENT PER SURFACE
3
2
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
INDEX OF REFRACTION OF THE TOP FILM

PLATE 8

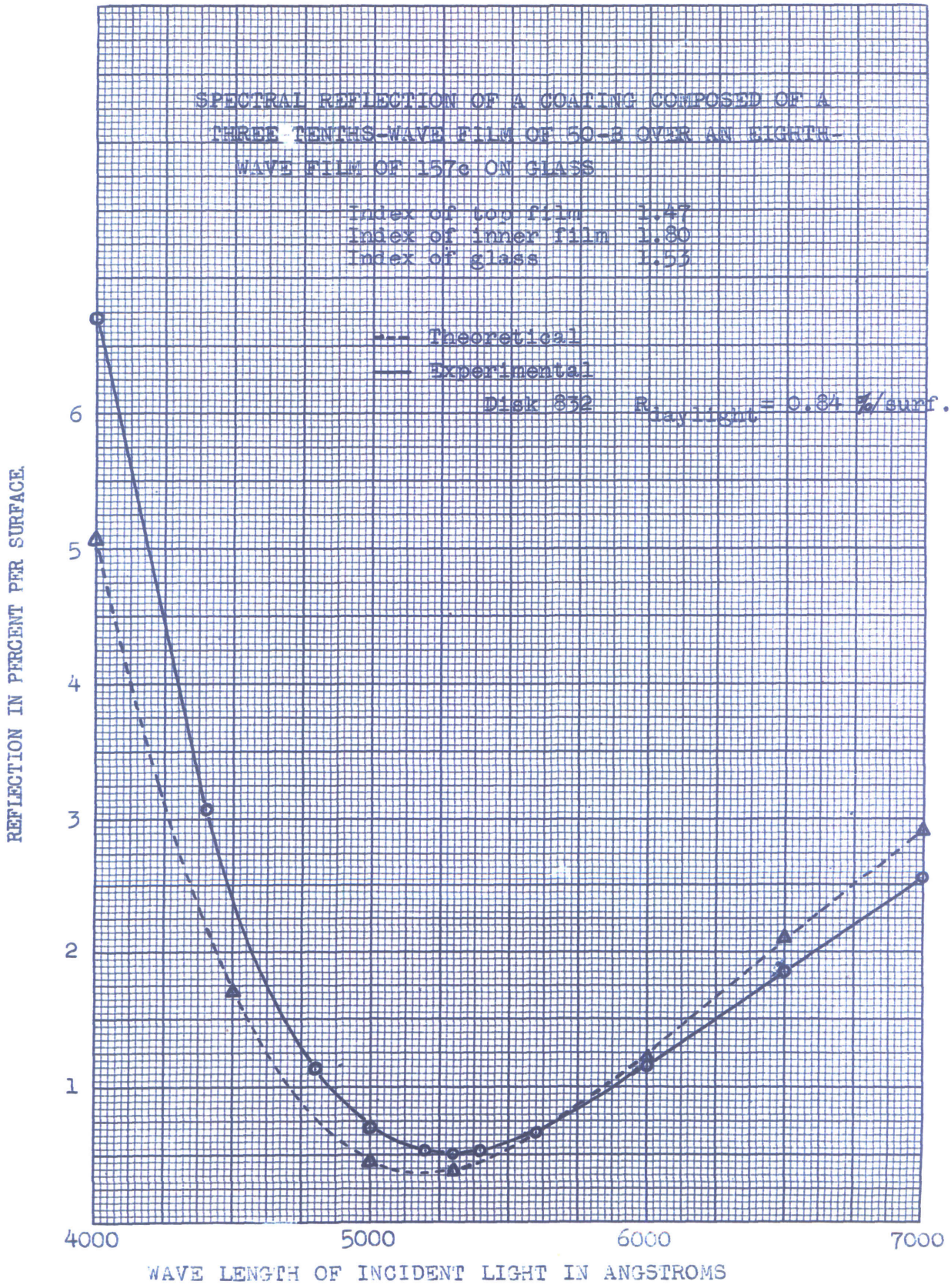

SPECTRAL REFLECTION OF A COATING COMPOSED OF A THREE TENTHS-WAVE FILM OF 50-3 OVER AN EIGHTH-WAVE FILM OF 157e ON GLASS
Index of top film 1.47
Index of inner film 1.80
Index of glass 1.53
--- Theoretical
—— Experimental
Disk 832 $R_{daylight}$ = 0.84 %/surf.
REFLECTION IN PERCENT PER SURFACE
1
2
3
4
5
6
4000
5000
6000
7000
WAVE LENGTH OF INCIDENT LIGHT IN ANGSTROMS

PLATE 9

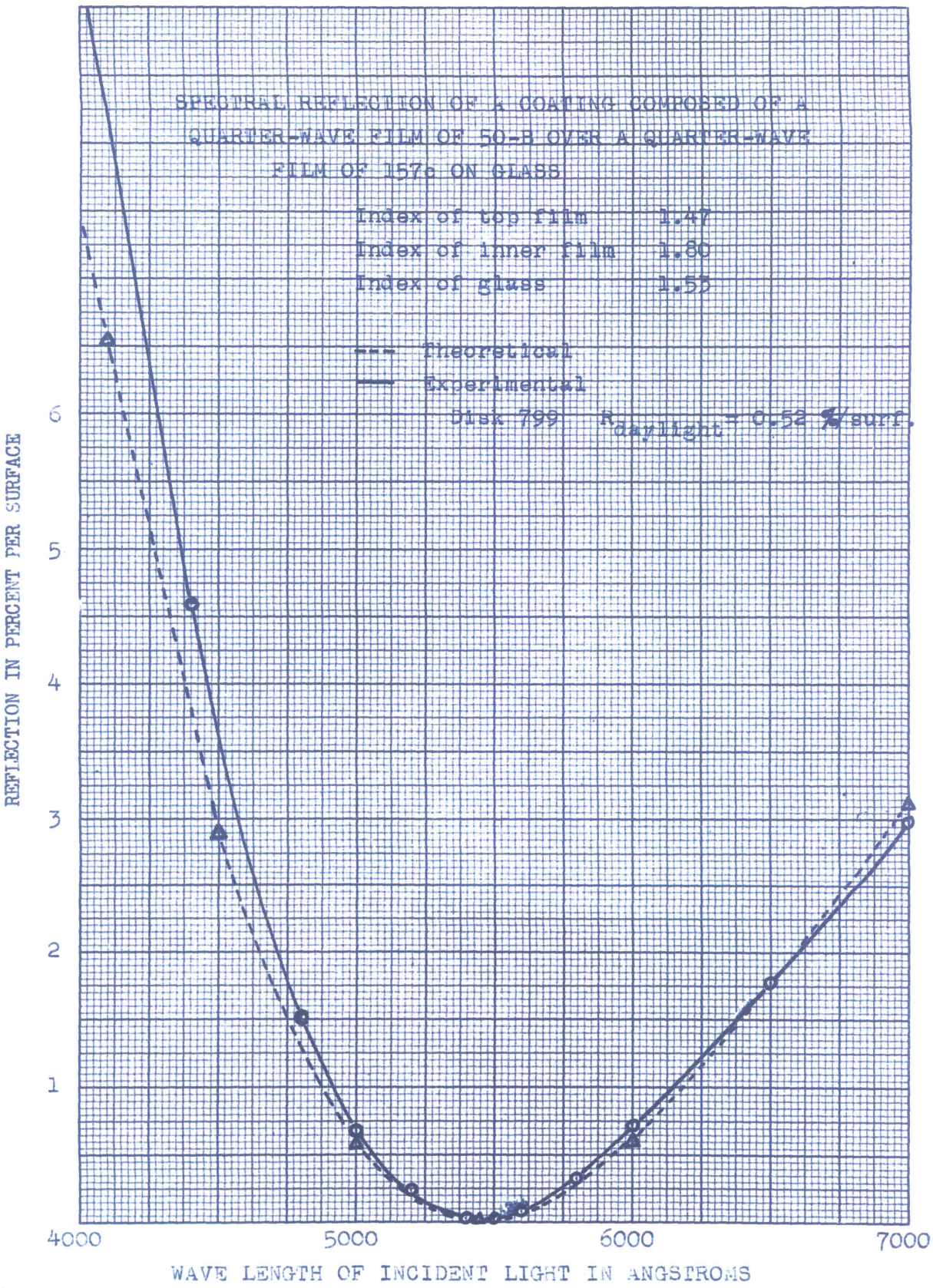

SPECTRAL REFLECTION OF A COATING COMPOSED OF A QUARTER-WAVE FILM OF 50-B OVER A QUARTER-WAVE FILM OF 157c ON GLASS
Index of top film 1.47
Index of inner film 1.80
Index of glass 1.55
--- Theoretical
—— Experimental
Disk 799 $R_{daylight}$ = 0.52 %/surf.
REFLECTION IN PERCENT PER SURFACE
6
5
4
3
2
1
4000
5000
6000
7000
WAVE LENGTH OF INCIDENT LIGHT IN ANGSTROMS

PLATE 10

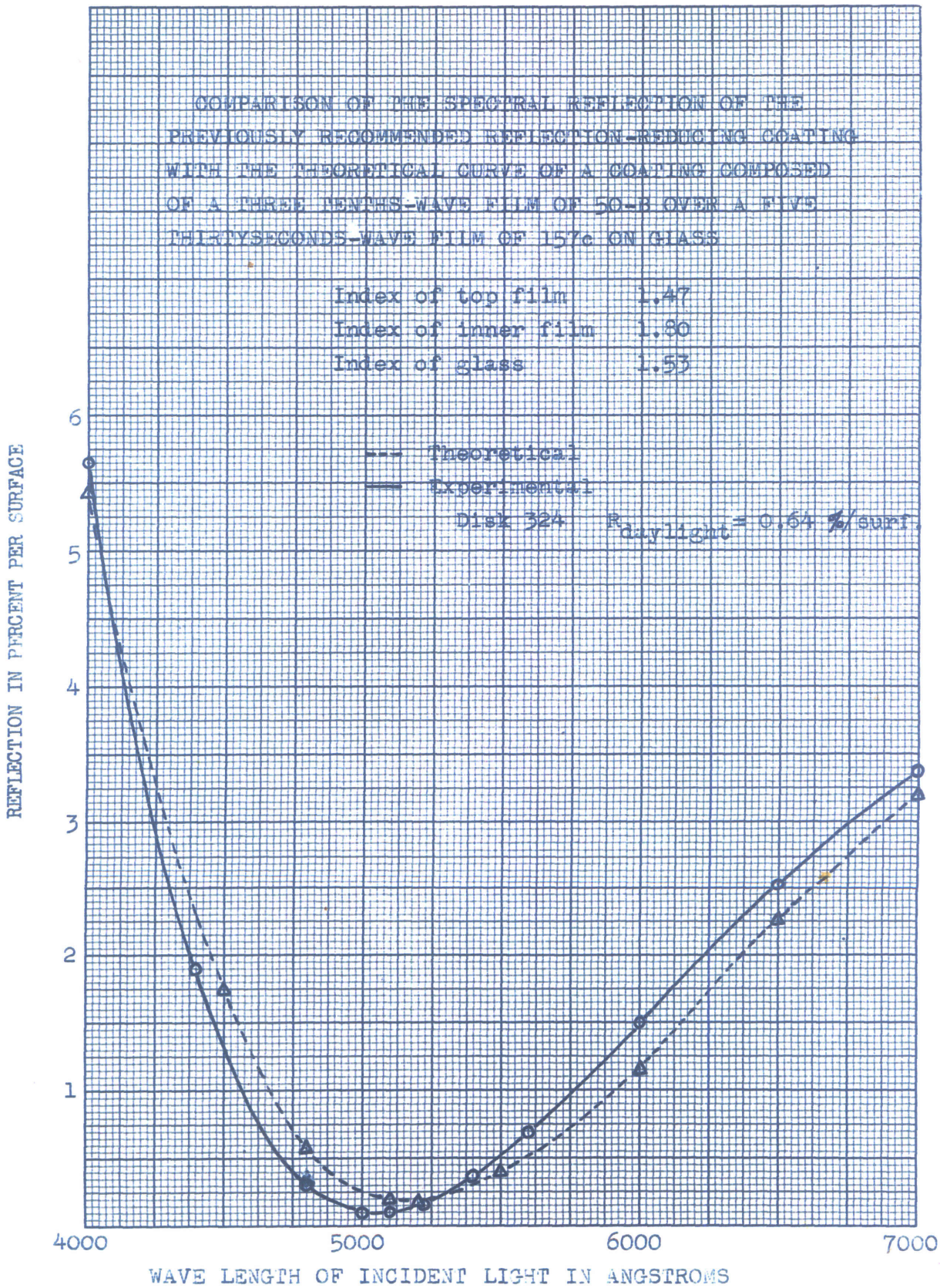

COMPARISON OF THE SPECTRAL REFLECTION OF THE PREVIOUSLY RECOMMENDED REFLECTION-REDUCING COATING WITH THE THEORETICAL CURVE OF A COATING COMPOSED OF A THREE TENTHS-WAVE FILM OF 50-B OVER A FIVE THIRTYSECONDS-WAVE FILM OF 157c ON GLASS
Index of top film 1.47
Index of inner film 1.80
Index of glass 1.53
--- Theoretical
=== Experimental
Disk 324 $R_{daylight}$ = 0.64 %/surf.
REFLECTION IN PERCENT PER SURFACE
6
5
4
3
2
1
4000
5000
6000
7000
WAVE LENGTH OF INCIDENT LIGHT IN ANGSTROMS

PLATE 11

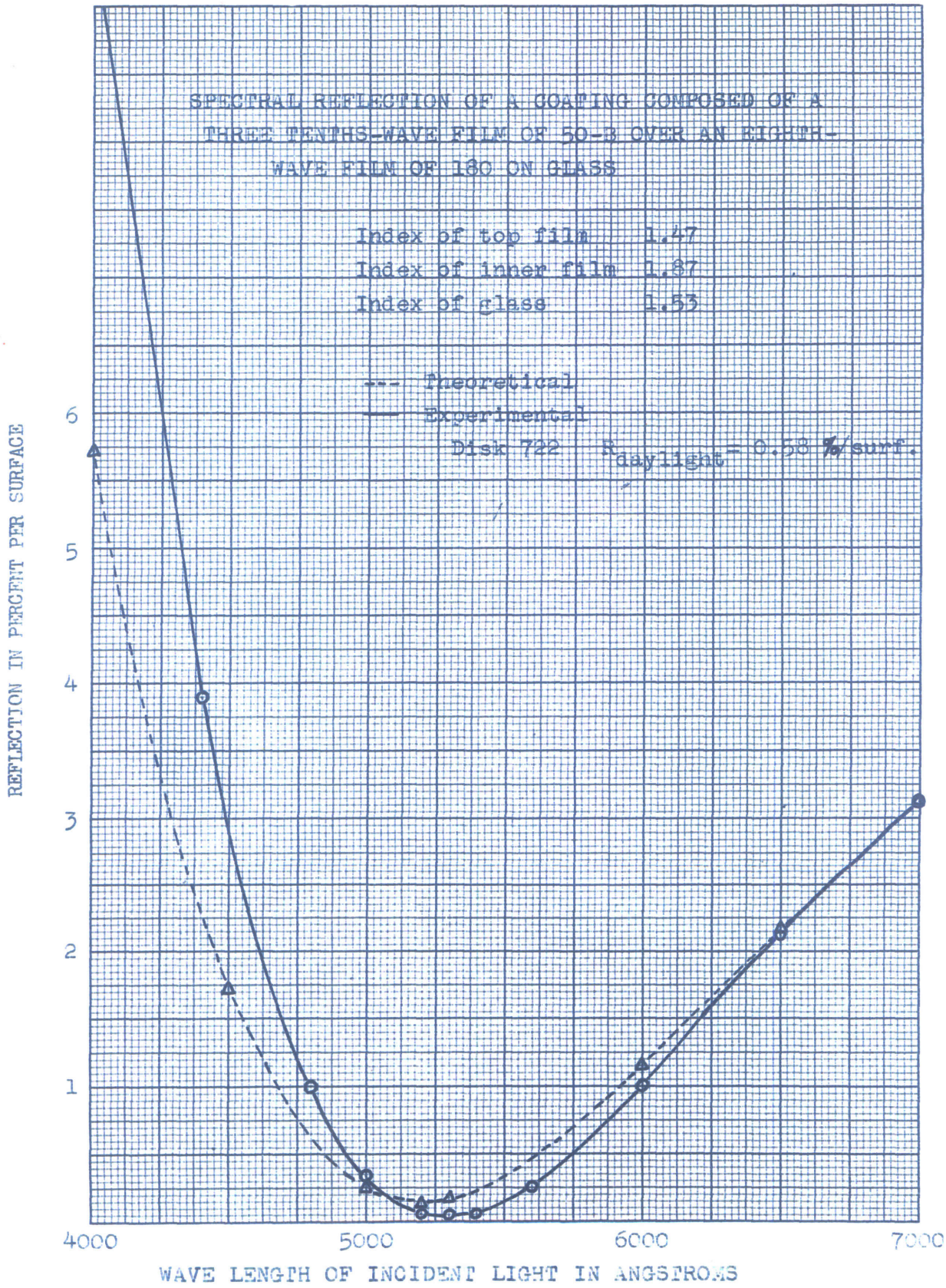

SPECTRAL REFLECTION OF A COATING COMPOSED OF A THREE TENTHS-WAVE FILM OF 50-B OVER AN EIGHTH-WAVE FILM OF 180 ON GLASS
Index of top film 1.47
Index of inner film 1.37
Index of glass 1.53
--- Theoretical
—— Experimental
Disk 722 $R_{daylight}$ = 0.58 %/surf.
REFLECTION IN PERCENT PER SURFACE
1
2
3
4
5
6
4000
5000
6000
7000
WAVE LENGTH OF INCIDENT LIGHT IN ANGSTROMS

PLATE 12

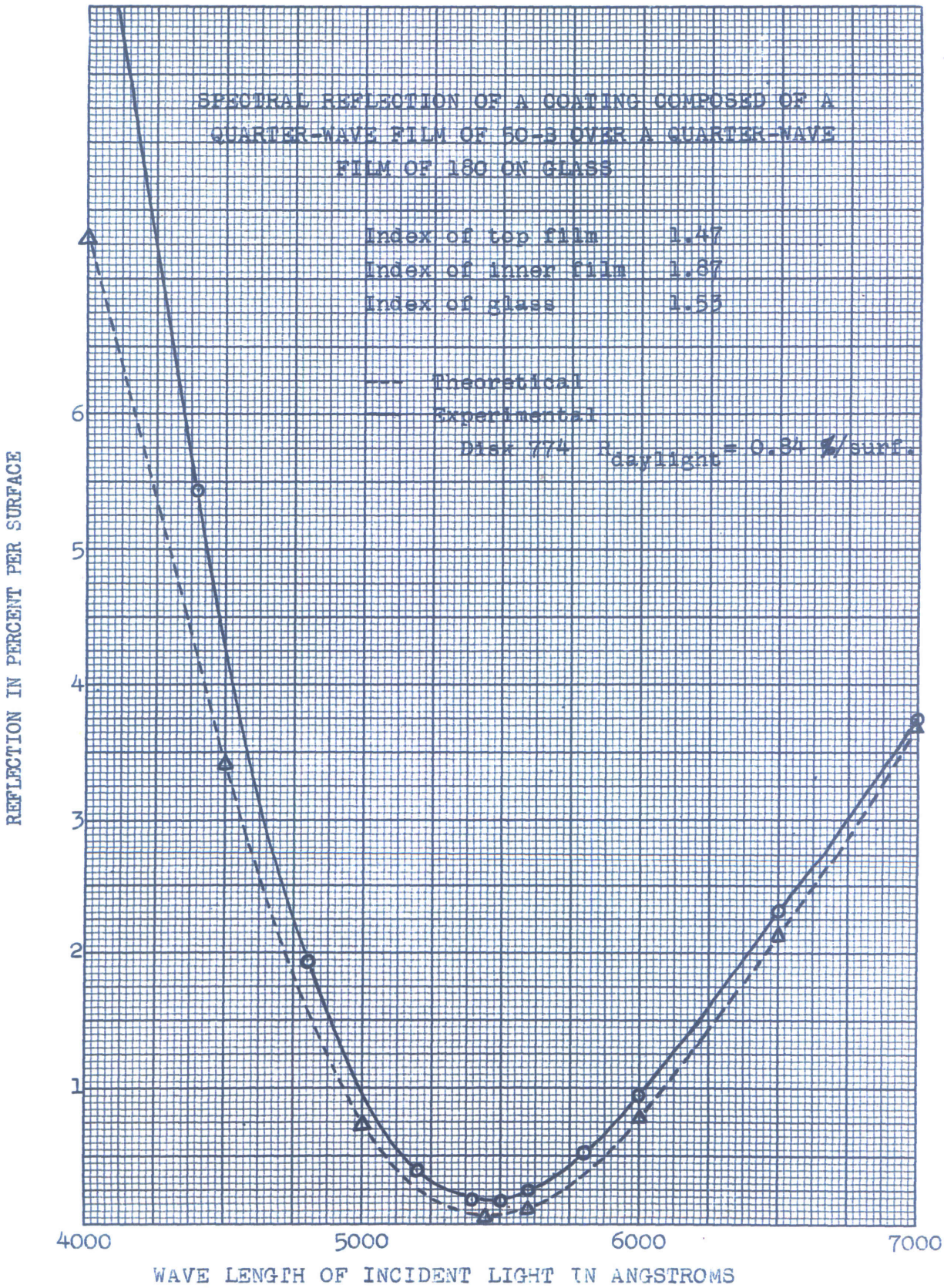

SPECTRAL REFLECTION OF A COATING COMPOSED OF A QUARTER-WAVE FILM OF 50-3 OVER A QUARTER-WAVE FILM OF 180 ON GLASS
Index of top film 1.47
Index of inner film 1.87
Index of glass 1.53
--- Theoretical
—— Experimental
Disk 774 R daylight = 0.84 %/surf.
REFLECTION IN PERCENT PER SURFACE
1
2
3
4
5
6
4000
5000
6000
7000
WAVE LENGTH OF INCIDENT LIGHT IN ANGSTROMS

PLATE 13

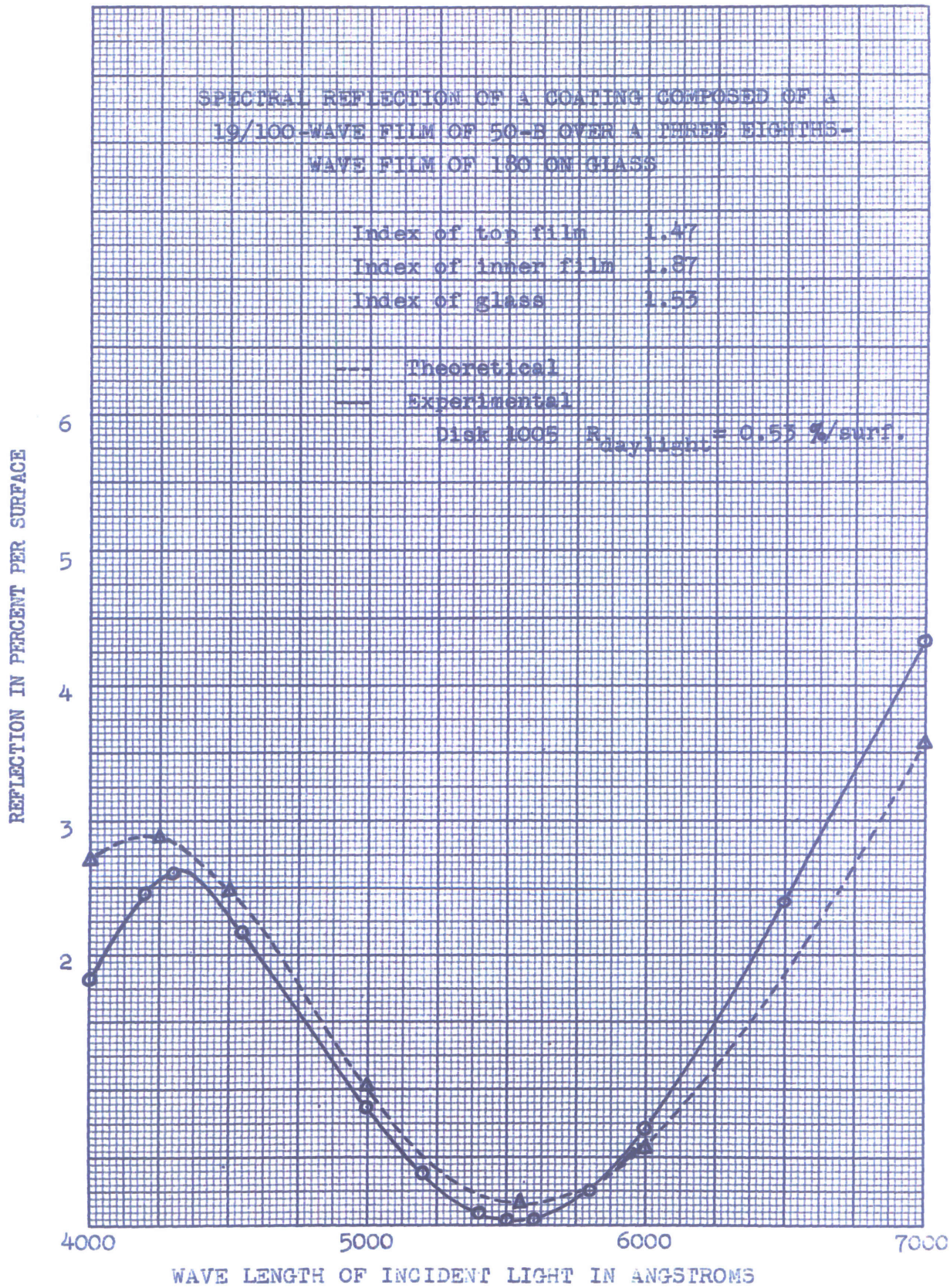

SPECTRAL REFLECTION OF A COATING COMPOSED OF A
19/100-WAVE FILM OF 50-B OVER A THREE EIGHTHS-
WAVE FILM OF 180 ON GLASS
Index of top film 1.47
Index of inner film 1.87
Index of glass 1.53
--- Theoretical
— Experimental
Disk 1005 $R_{daylight}$ = 0.55 %/surf.
REFLECTION IN PERCENT PER SURFACE
6
5
4
3
2
4000
5000
6000
7000
WAVE LENGTH OF INCIDENT LIGHT IN ANGSTROMS

PLATE 14

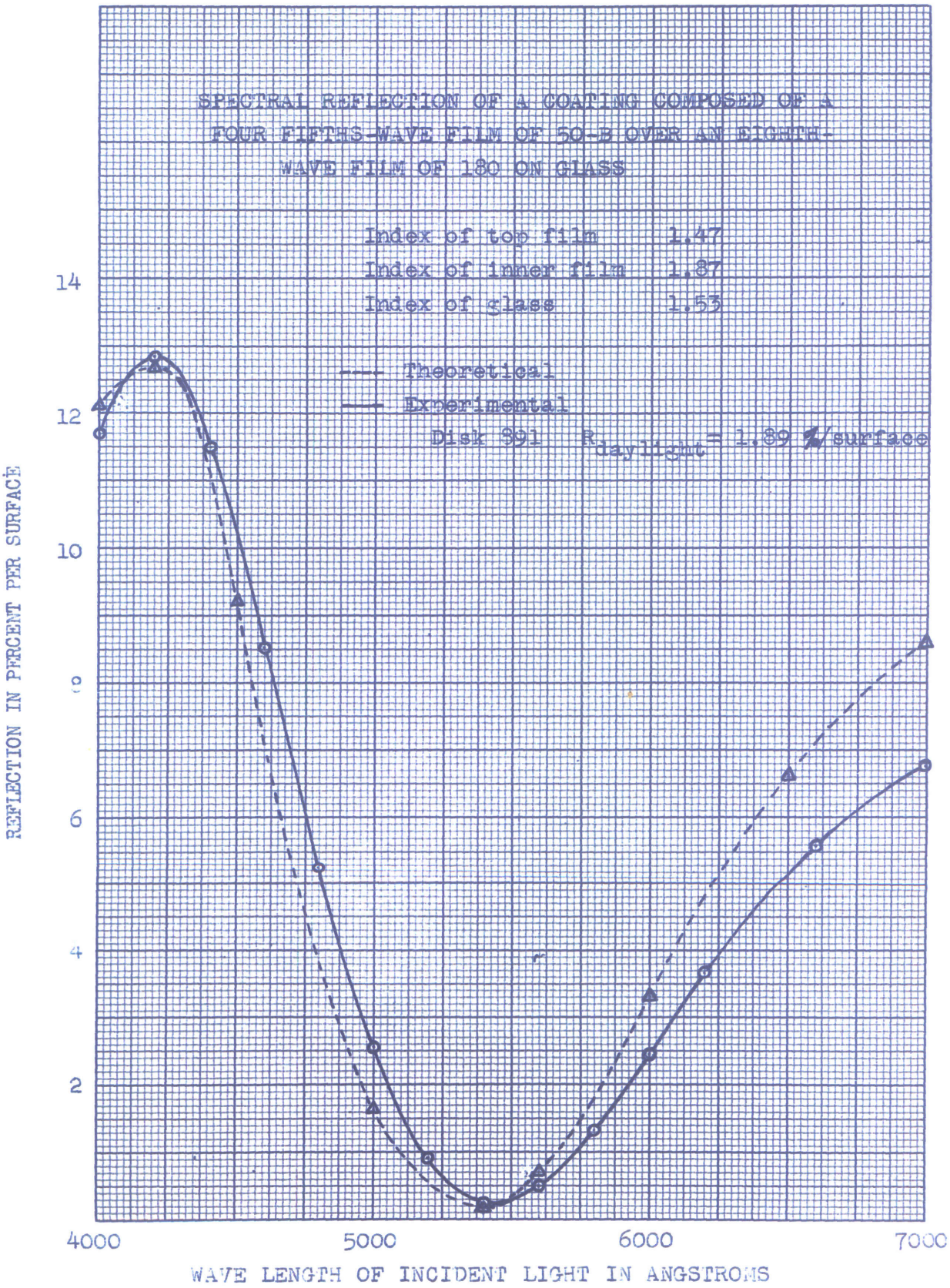

SPECTRAL REFLECTION OF A COATING COMPOSED OF A
FOUR FIFTHS-WAVE FILM OF 50-B OVER AN EIGHTH-
WAVE FILM OF 180 ON GLASS
Index of top film 1.47
Index of inner film 1.87
Index of glass 1.53
Theoretical
Experimental
Disk 391 $R_{daylight}$ = 1.89 %/surface
14
12
10
8
6
4
2
4000
5000
6000
7000
REFLECTION IN PERCENT PER SURFACE
WAVE LENGTH OF INCIDENT LIGHT IN ANGSTROMS

PLATE 15

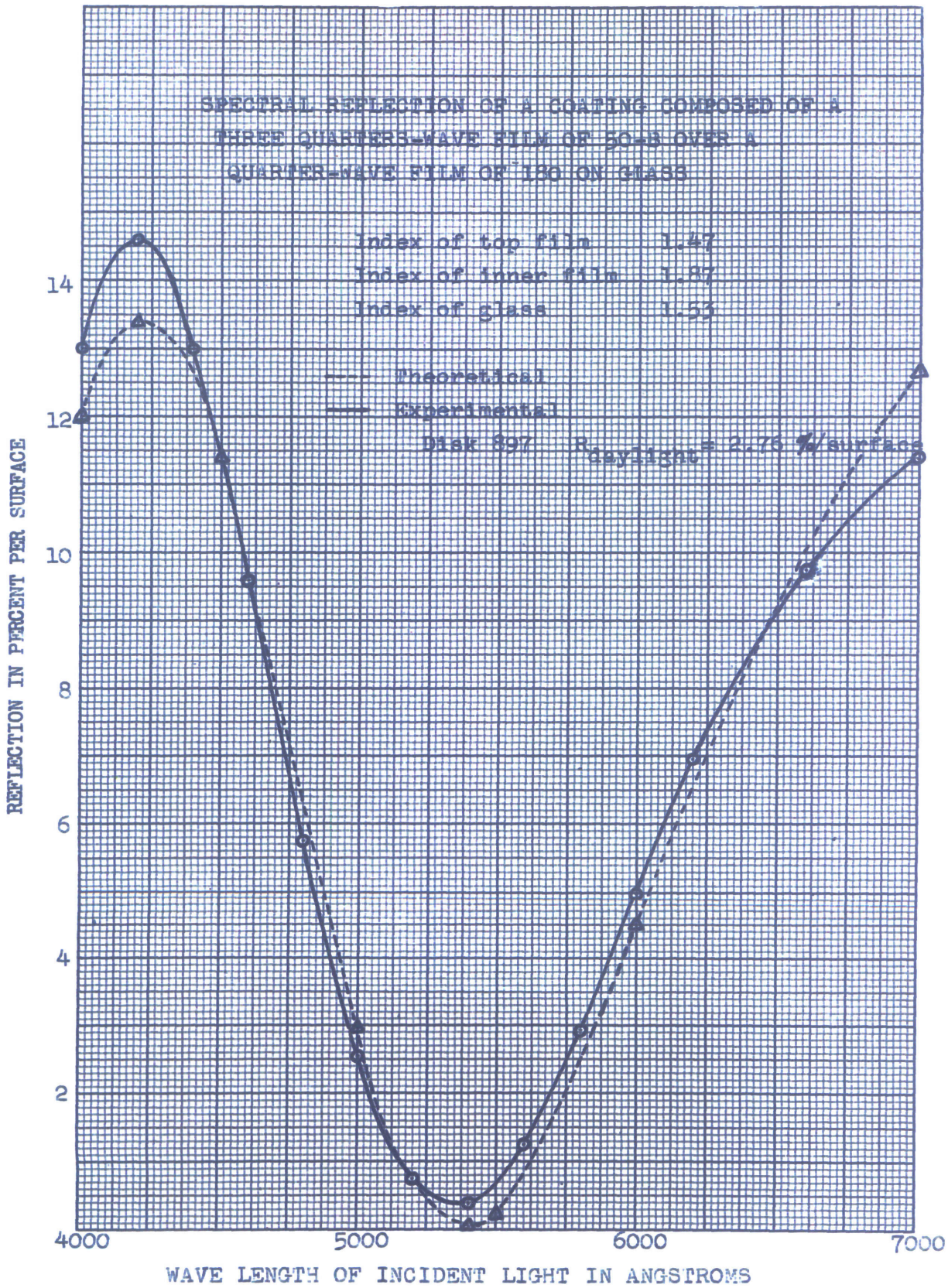

SPECTRAL REFLECTION OF A COATING COMPOSED OF A
THREE QUARTERS-WAVE FILM OF SO-2 OVER A
QUARTER-WAVE FILM OF IRO ON GLASS
Index of top film 1.47
Index of inner film 1.87
Index of glass 1.53
Theoretical
Experimental
Disk 897 R daylight = 2.75 %/surface
REFLECTION IN PERCENT PER SURFACE
14
12
10
8
6
4
2
4000
5000
6000
7000
WAVE LENGTH OF INCIDENT LIGHT IN ANGSTROMS

PLATE 16

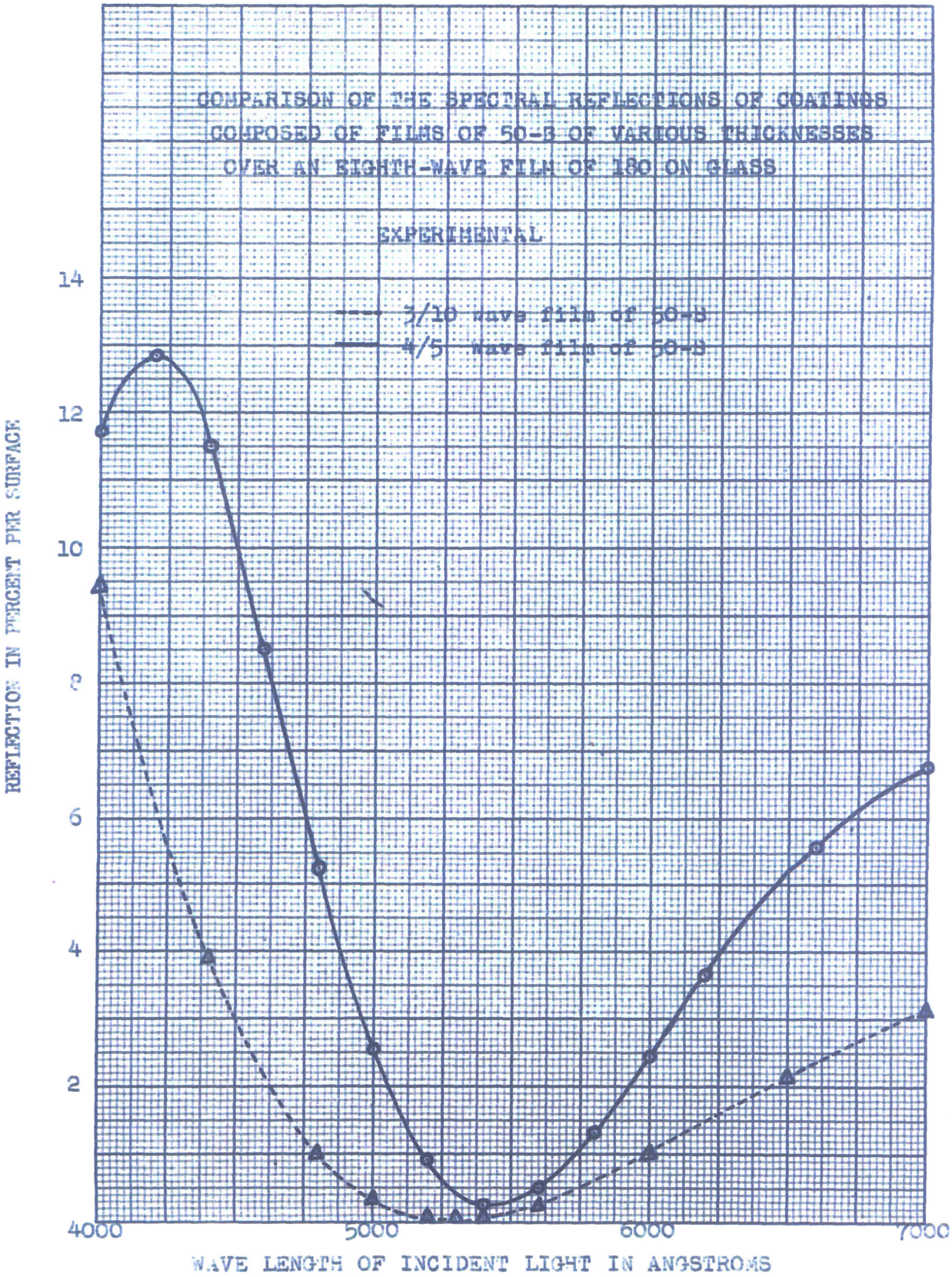

COMPARISON OF THE SPECTRAL REFLECTIONS OF COATINGS
COMPOSED OF FILMS OF 50-B OF VARIOUS THICKNESSES
OVER AN EIGHTH-WAVE FILM OF 180 ON GLASS
EXPERIMENTAL
3/10 wave film of 50-B
4/5 wave film of 50-B
REFLECTION IN PERCENT PER SURFACE
14
12
10
8
6
4
2
4000
5000
6000
7000
WAVE LENGTH OF INCIDENT LIGHT IN ANGSTROMS

PLATE 17

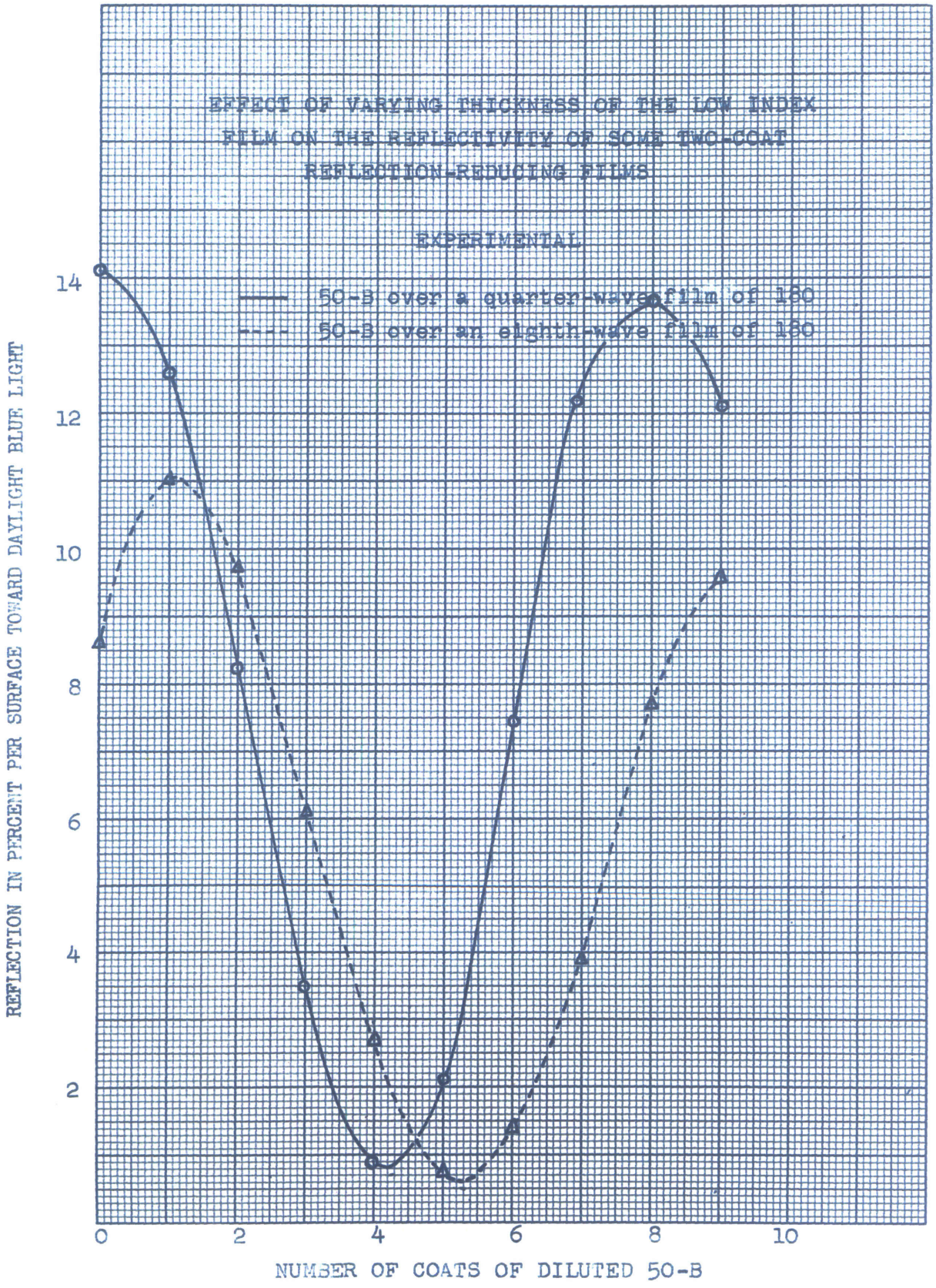

EFFECT OF VARYING THICKNESS OF THE LOW INDEX
FILM ON THE REFLECTIVITY OF SOME TWO-COAT
REFLECTION-REDUCING FILMS
EXPERIMENTAL
50-B over a quarter-wave film of 180
50-B over an eighth-wave film of 180
REFLECTION IN PERCENT PER SURFACE TOWARD DAYLIGHT BLUE LIGHT
14
12
10
8
6
4
2
0
2
4
6
8
10
NUMBER OF COATS OF DILUTED 50-B

PLATE 18

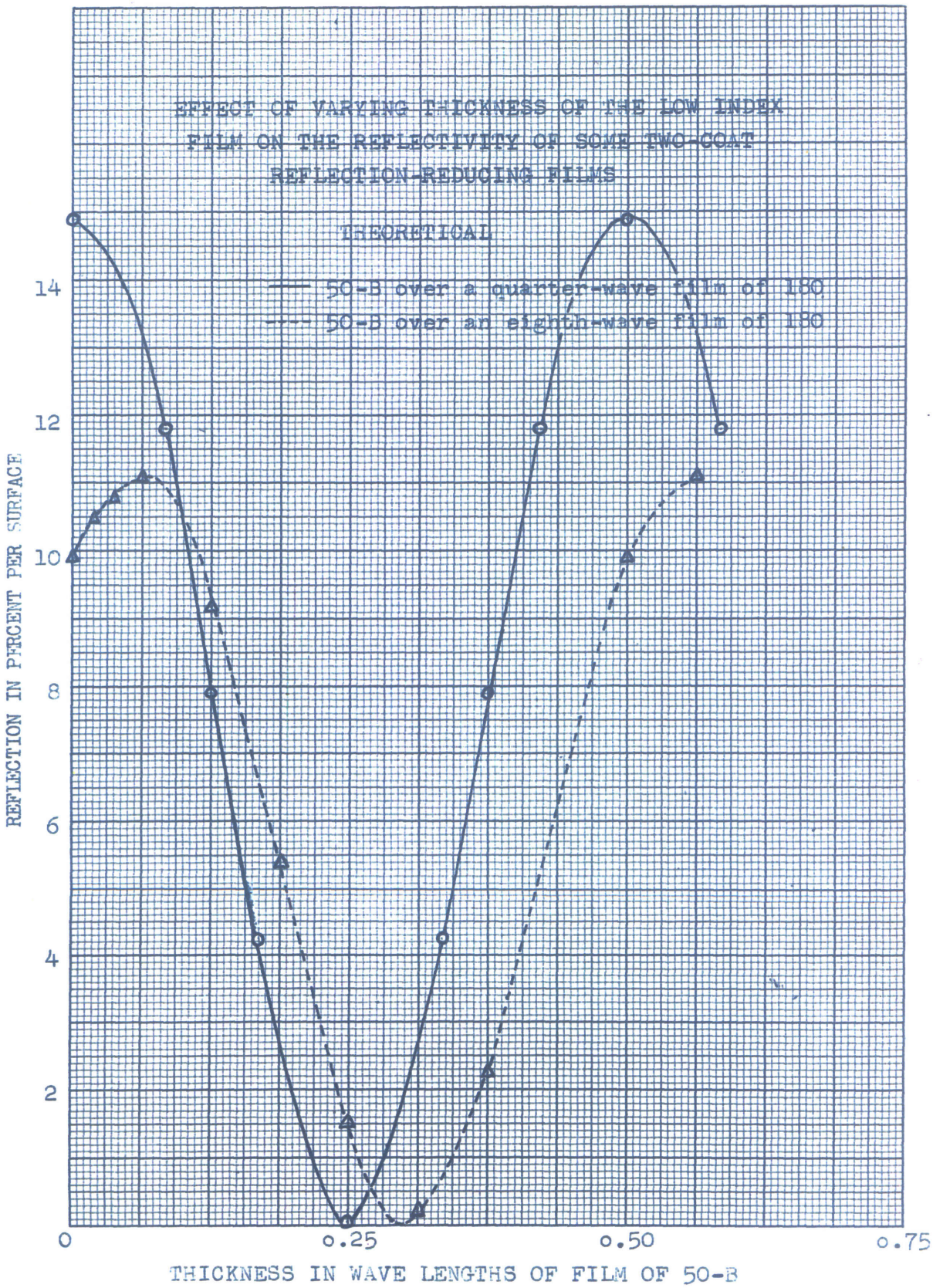

EFFECT OF VARYING THICKNESS OF THE LOW INDEX
FILM ON THE REFLECTIVITY OF SOME TWO-COAT
REFLECTION-REDUCING FILMS
THEORETICAL
50-B over a quarter-wave film of 180
50-B over an eighth-wave film of 180
REFLECTION IN PERCENT PER SURFACE
14
12
10
8
6
4
2
0
0.25
0.50
0.75
THICKNESS IN WAVE LENGTHS OF FILM OF 50-B

PLATE 19

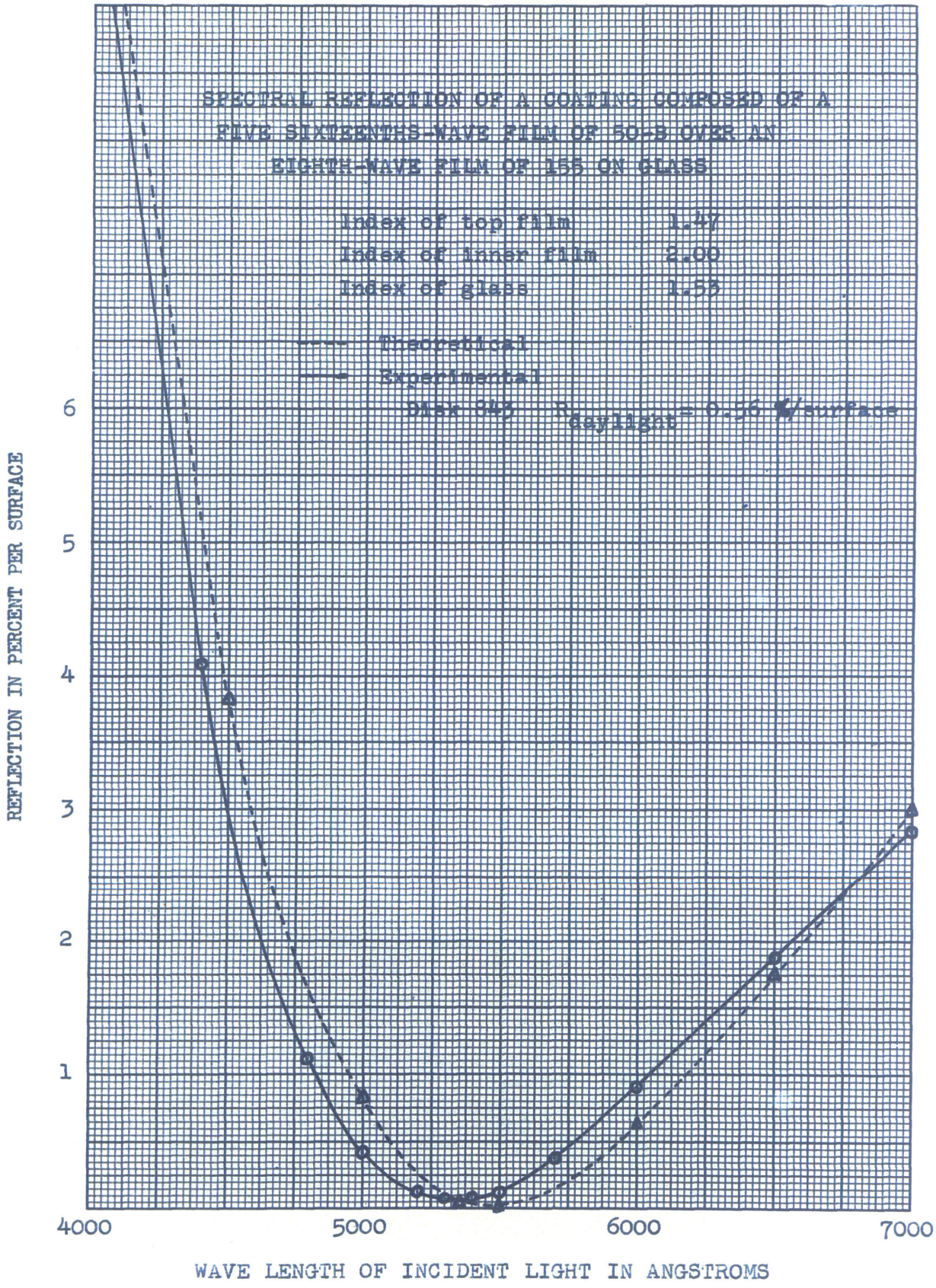

SPECTRAL REFLECTION OF A COATING COMPOSED OF A
FIVE SIXTEENTHS-WAVE FILM OF 50-B OVER AN
EIGHTH-WAVE FILM OF 155 ON GLASS
Index of top film 1.47
Index of inner film 2.00
Index of glass 1.53
Theoretical
Experimental
Max 343 R daylight = 0.56 % surface
REFLECTION IN PERCENT PER SURFACE
6
5
4
3
2
1
4000
5000
6000
7000
WAVE LENGTH OF INCIDENT LIGHT IN ANGSTROMS

PLATE 20

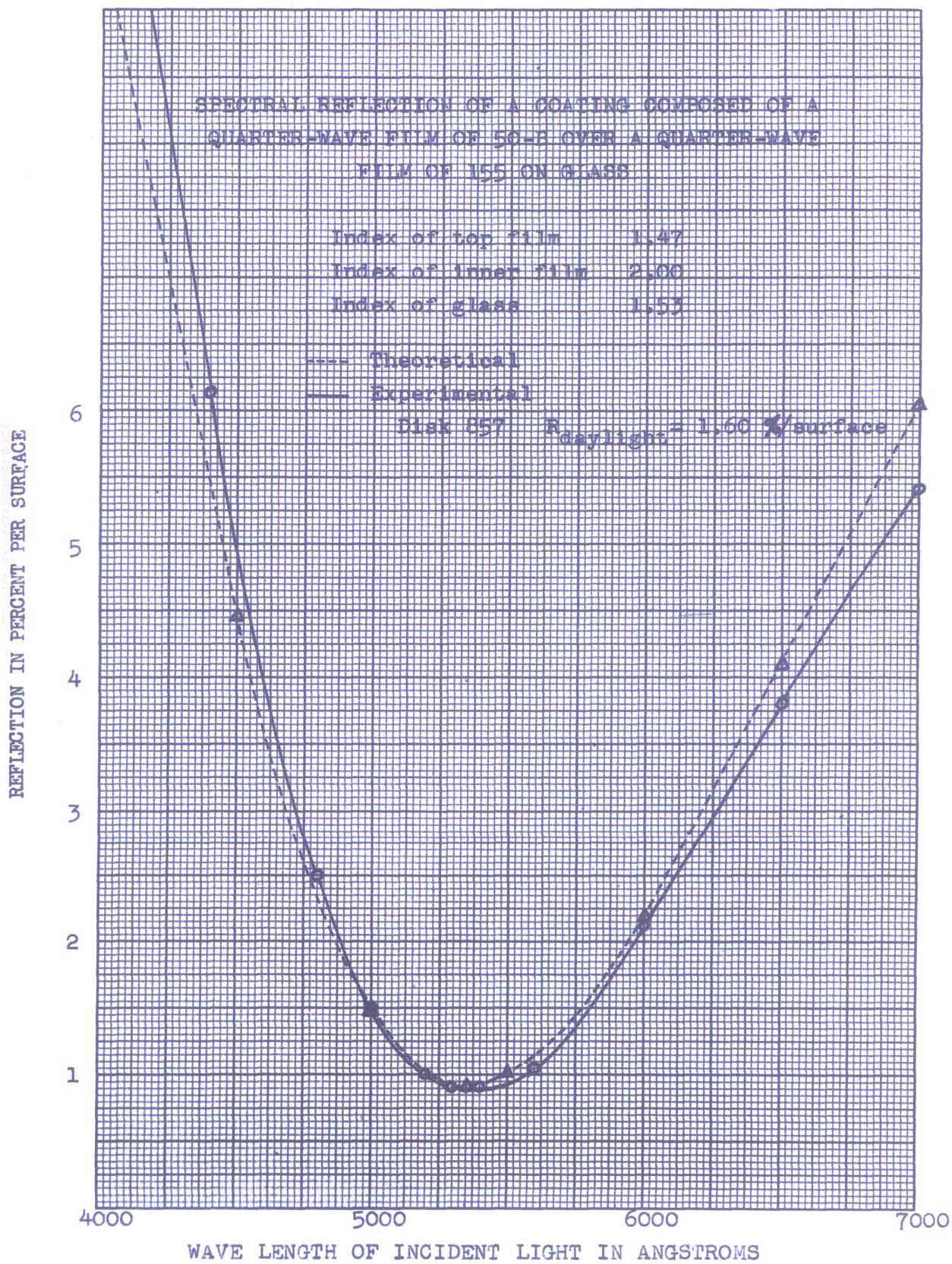

SPECTRAL REFLECTION OF A COATING COMPOSED OF A QUARTER-WAVE FILM OF 50-B OVER A QUARTER-WAVE FILM OF 155 ON GLASS
Index of top film 1.47
Index of inner film 2.00
Index of glass 1.53
---- Theoretical
—— Experimental
Disk 857 $R_{daylight}$ = 1.60 %/surface
REFLECTION IN PERCENT PER SURFACE
1
2
3
4
5
6
4000
5000
6000
7000
WAVE LENGTH OF INCIDENT LIGHT IN ANGSTROMS

PLATE 21