10 AN APPLICATION OF THE METHOD OF LENS DESIGN

10.1 STEP ONE - SELECTING THE LENS TYPE

10.1.1 The Taylor triplet. In order to illustrate the procedure described in Section 9, we shall now work through the design of a particular type of lens. The lens selected for illustration is the famous triplet, often referred to as the Taylor triplet. It is named after H. Dennis Taylor who first described how he was able to correct astigmatism and field curvature by using three air spaced lenses. His system consisted of a negative lens between two positive lenses.

10.1.2 Reasons for selection. The triplet lens system is a fundamental type, for there are enough degrees of freedom to specify the first order properties and to control all the first and third order aberrations. First order properties includes the focal length and the optical invariant. First order aberrations are axial and lateral color, and Petzval curvature. Third order aberrations are spherical aberration, coma, astigmatism, and distortion. This lens illustrates most of the problems encountered in the design of any optical system; many of the other types of lenses are merely derivatives of the basic triplet. The triplet has been used extensively in optics; there are probably more such objectives used in photographic instruments than any other type of lens. In describing this design procedure it is hoped that the logical design of an objective can be illustrated; at the same time it will be shown how exceedingly involved the design of a lens can become if it is necessary to arrive at an optimum solution.

10.1.3 Arrangement and notation. The lens arrangement for the triplet objective is shown in Figure 10.1 with the notation to be used in the following discussion. The lens is to work with an object at infinity and have a focal length of 10. It will be color corrected for F and C light. The individual lenses are shown as thick lenses but in the first stages of the design these lenses are assumed to be thin. By selecting this type of lens (the Taylor triplet), step 1 in the design procedure has been completed. The application of the method of design will therefore continue with step 2.

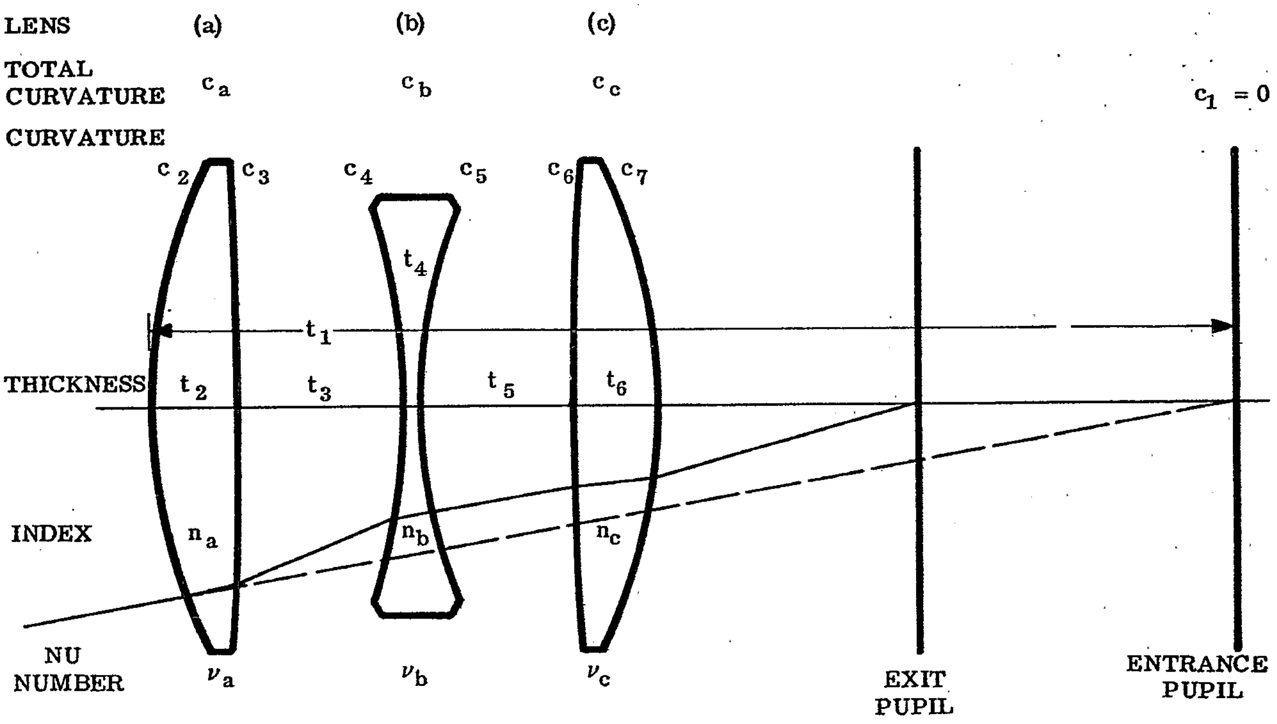

Figure 10.1 - A triplet objective used to illustrate design procedure.

10.2 STEP TWO - THE FIRST ORDER THIN LENS SOLUTION

10.2.1 Power and spacing.

10.2.1.1 The first problem is to decide on the power and spacing of the elements. This is a lens system composed of three thin elements; therefore we immediately set up a thin lens table of the type shown in Table 6.14, and start to fill in the known quantities as shown in Table 10.1. At this stage nothing is known about the design, except that the object is to be at infinity ($u_o = 0$) and the focal length should be 10. Since y_1 may have any value, we choose 1 for convenience. From Equation 6-(13) if $f' = 10$ and $y_1 = 1$ then $u_{k-1} = -0.1$. The computing table appears now as shown in Table 10.2.

SURFACE NO.	Entrance Pupil 1	Lens (a) 2, 3	Lens (b) 4, 5	Lens (c) 6, 7	Focal Plane k
$-\phi$	0				0
t					
y					0
u 0					
$\bar{y}$	0				
$\bar{u}$					

Table 10.1- Computing table 1 - quantities known at start of procedure.

SURFACE NO.	Entrance Pupil 1	Lens (a) 2, 3	Lens (b) 4, 5	Lens (c) 6, 7	Focal Plane k
$-\phi$	0				0
t					
y	1	1			0
u 0	0			-0.1	
$\bar{y}$	0				
$\bar{u}$					

Table 10.2- Computing table 2 - first order assumptions added.

10.2.1.2 In order to specify the lateral color for F and C light, the conditions given in Equation 6-(41) must be fulfilled. Thus,

$$Tch_{F-C} = \frac{1}{n_{k-1}\, u_{k-1}} \left[\frac{y_a\, \bar{y}_a\, \phi_a}{\nu_a} + \frac{y_b\, \bar{y}_b\, \phi_b}{\nu_b} + \frac{y_c\, \bar{y}_c\, \phi_c}{\nu_c} \right].$$

If Tch_{F-C} is to be zero, then

$$\frac{y_a\, \bar{y}_a\, \phi_a}{\nu_a} + \frac{y_b\, \bar{y}_b\, \phi_b}{\nu_b} + \frac{y_c\, \bar{y}_c\, \phi_c}{\nu_c} = 0 .$$

If we assume the condition that the chief ray shall pass through the center of lens (b) (not as shown in Figure 10.1), then $\bar{y}_b = 0$, and

$$\frac{y_a \bar{y}_a \phi_a}{\nu_a} = -\frac{y_c \bar{y}_c \phi_c}{\nu_c} .$$

Equation 6-(24) shows that in a thin lens $y\phi = (u_{-1} - u)$, which is the angular deviation that the axial ray experiences as it passes through the lens. If R is defined as

$$R = \frac{y_a \phi_a}{y_c \phi_c} ,$$

the condition for zero lateral color is then

$$\frac{\bar{y}_a}{\bar{y}_c} = -\frac{1}{R} \frac{\nu_a}{\nu_c} .$$

Since the chief ray passes through the center of the thin negative (b) lens, it is undeviated. Therefore $\bar{y}_b \phi_b = 0$, and $(\bar{u}_{-1} - \bar{u})_b = \bar{u}_4 - \bar{u}_5 = 0$. Then

$$\frac{t_3}{t_5} = -\frac{\bar{y}_a}{\bar{y}_c} = \frac{1}{R} \frac{\nu_a}{\nu_c} .$$

10.2.1.3 Up to this point, no decision has had to be made with respect to the type of glass. At this point it is necessary to decide on ν_a / ν_c. Any ratio may be used, but up until the present no one has been able to prove any advantage to a ratio other than 1. If the same glass is used for both lens (a) and lens (c), then $\nu_a / \nu_c = 1$. This choice has the practical advantage that the lens maker does not have to worry about two different glasses for the positive lenses. (Any designer who uses two elements that look alike but are of slightly different index and/or dispersion can fully expect to find the elements switched in the prototype.) With no positive evidence indicating that ν_a / ν_c needs to be other than 1, the design will proceed with glass (a) and glass (c) the same. Then it follows that

$$t_3 = \frac{1}{R} t_5 .$$

10.2.1.4 Next, it is necessary to choose a value of R. Such a value may be selected for any number of reasons. For each value of R there are many solutions (designs). In the following study an attempt will be made to show how the choice of R affects the design, but in order to proceed with the numerical example it is necessary to assume a value of R. Later (Paragraph 10.3.2.3) it will be shown that R should be near 1. This means that the (a) lens will bend the axial ray through the same angle as does the (c) lens. It follows then, that if a value can be assigned to u_3, the angle the axial ray makes with the axis after emerging from the (a) lens, then the angle u_5 is determined. (This means if u_3 is assigned, then all the angles the axial ray makes with the axis are known). For example, if u_3 is made -0.20, then it follows immediately that $u_5 = 0.10$ because $u_{k-1} = u_7 = -0.1$.

10.2.1.5 The computing table may now be filled out as shown in Table 10.3. It is still not possible to compute ϕ_a, ϕ_b, ϕ_c, and complete the table. At this point it is necessary to make another guess. Let the guess be that the space t_3 will be 1; then t_5 must also be 1. Now the system is completed and ϕ_a, ϕ_b, and ϕ_c are determined using Equations 6-(23) and 6-(24). The values are shown in Table 10.4, which is filled out completely. To trace the chief ray any angle may be assumed for it while it passes through the (b) lens. In the example, $\bar{u}_b = 0.5$ was used.

10.2.2 <u>Glass types.</u>

10.2.2.1 So far the only decision on glass is that (a) = (b). Now we must specify the type of glass to use for (a) and (c), and for (b). The glass types are chosen now in order to specify both axial color and Petzval curvature. When the glasses are chosen, TAch is calculated by Equation 6-(40). This calculation is illustrated in Table 6.13. The Petzval sum, ΣP, may be calculated for each lens from Equation 8-(28) and summed for the (a), (b), and (c) lenses.

10.2.2.2 The choice of glass is a critical part of the design of a triplet. It is hoped that this will be demonstrated in the following study, but in order to show this, the glasses will be picked from experience. The following glasses will be used:

	n_D	ν
Lens (a)	1.620	60.3
Lens (b)	1.617	36.6
Lens (c)	1.620	60.3

SURFACE	Entrance Pupil 1	Lens (a) 2, 3	Lens (b) 4, 5	Lens (c) 6, 7	Focal Plane k
$-\phi$	0				0
t		1	1		
y	1	1			0
u 0	0	-0.2	0.1	-0.1	
$\bar{y}$	0		0		
$\bar{u}$					

Table 10.3- Computing table 3-quantities for zero lateral color, $\nu_a/\nu_c = 1$, and R = 1 , added.

SURFACE	Entrance Pupil 1	Lens (a) 2, 3	(Lens (b) 4, 5	Lens (c) 6, 7	Focal Plane k
$-\phi$	0	-0.2	0.375	-0.222	0
t	-1.25	1	1	9	
y	1	1	0.8	0.9	0
u 0	0	-0.2	0.1	-0.1	
$\bar{y}$	0	-0.5	0	0.5	4.0
$\bar{u}$	0.4	0.5	0.5	0.389	

$f' = 10$

Table 10.4- Computing table 4-assignment of quantities completed.

10.2.2.3 With this glass type data it is now possible to compute TAch and ΣP. The calculations for the sample are included in Table 10.5.

10.2.2.4 The values of TAch and ΣP are plotted in Figure 10.2. The dot with a surrounding square, ⊡ , indicates where the solution should be for TAch = 0 and ΣP = -0.03. At this point it will be necessary to merely accept the fact that ΣP is set at -0.03. (A negative value of ΣP indicates a negative value for the Petzval curvature. In the case of the triplet example here considered, the field is concave toward the lens and is referred to as an inward curving field.) The next step is to assume a new value of t_3 . For example, suppose we pick a value of 1.25, and repeat the process to arrive at a new value for TAch and ΣP. This point is also plotted in Figure 10.2. Next, set u_3 = 0.18 and repeat the process with t_3 = 1.0 and 1.25. The procedure for finding the values of u_3 and t_3 which will provide a solution follows obviously. With a small amount of practice one can box in a design in this manner in very short order. This is an iterative procedure which can also be programmed for automatic correction on a computer. The graphs obtained in this manner are extremely useful for visualizing how to readjust the angles in the lens after the thickness has been added (step 4).

SURFACE	Lens (a)	Lens (b)	Lens (c)	Focal Plane
$-\phi$	-0.2	0.375	-0.222	0
t				
y	1	0.8	0.9	0
u	0	-0.2	0.1	-0.1
$\bar{y}$				
$\bar{u}$				
ν	60.3	36.6	60.3	
$-\phi y^2/\nu$	-0.00332	0.00656	-0.00299	$\Sigma a =$ 0.00026
$-\frac{\phi}{n}$	-0.12346	0.23191	-0.13717	$\Sigma P =$ -0.02872

TAch = 0.0026

Table 10.5 -Computing table 5 - calculation of TAch and ΣP.

10.2.2.5 This boxing in procedure is recommended for the preliminary set-up using thin lenses in designing a triplet. The procedure works equally well for more complicated lenses, and it provides the designer a graphical picture of how the variables affect the system. For those who prefer to manipulate algebraic equations a procedure similar to the above can be worked out to provide equations to be solved. Existing literature is adequately filled with methods of this type. A few of the well known papers are:

(1) Berek, M., Grundlagen der Praktischen Optik, Berlin, 123-130, (1930).

(2) Stephens, R. E. J. Opt. Soc. Am. 38, 1032 – 1039, (1948).

(3) Lessing, N., J. Opt. Soc. Am. 48, 558-562 (1958).

(4) Cruikshank, F. D. Rev. D'Optik 35, 292-299, (1956).

(5) Cruikshank, F. D. Australian J. Physics 11, 41-54, (1958).

A series of solutions for triplets with different types of glass has been worked out. The significant data for these systems are included in Table 10.6, sheets 1, 2 and 3. The glasses used in this study are shown plotted in Figure 10.3 on an n_D versus ν plot, which is used extensively by lens designers. The numbers alongside each point indicate the system number. The table includes calculations for $R = 1, 0.5$ and 2. One solution was calculated, for each set of glasses, using a target value of $\Sigma P = -0.03$. Notice that there are examples where $(\nu_a - \nu_b)$ is constant but $(n_a - n_b)$ changes.

10.2.3 Summary of thin lens first order study contained in Table 10.6.

(1) As $\nu_a - \nu_b$ is increased, the system length, T, always increases.

(2) $R = 1$ systems are always shorter than systems with $R = 2.0$ or $R = 0.5$.

(3) Changing ΣP from -0.03 to -0.02 shortens the system.

(4) Changing the index of the crown and flint elements, while maintaining the ν difference, has little effect on the overall length T.

(5) As one would expect, the higher the index of the positive elements, the lower the power of all the elements.

(6) Solutions for $R = 2$ and $R = 0.5$ are essentially inverted solutions. t_3 and t_5 are almost exactly interchanged. Also, ϕ_a is changed by the ratio of $1/R$.

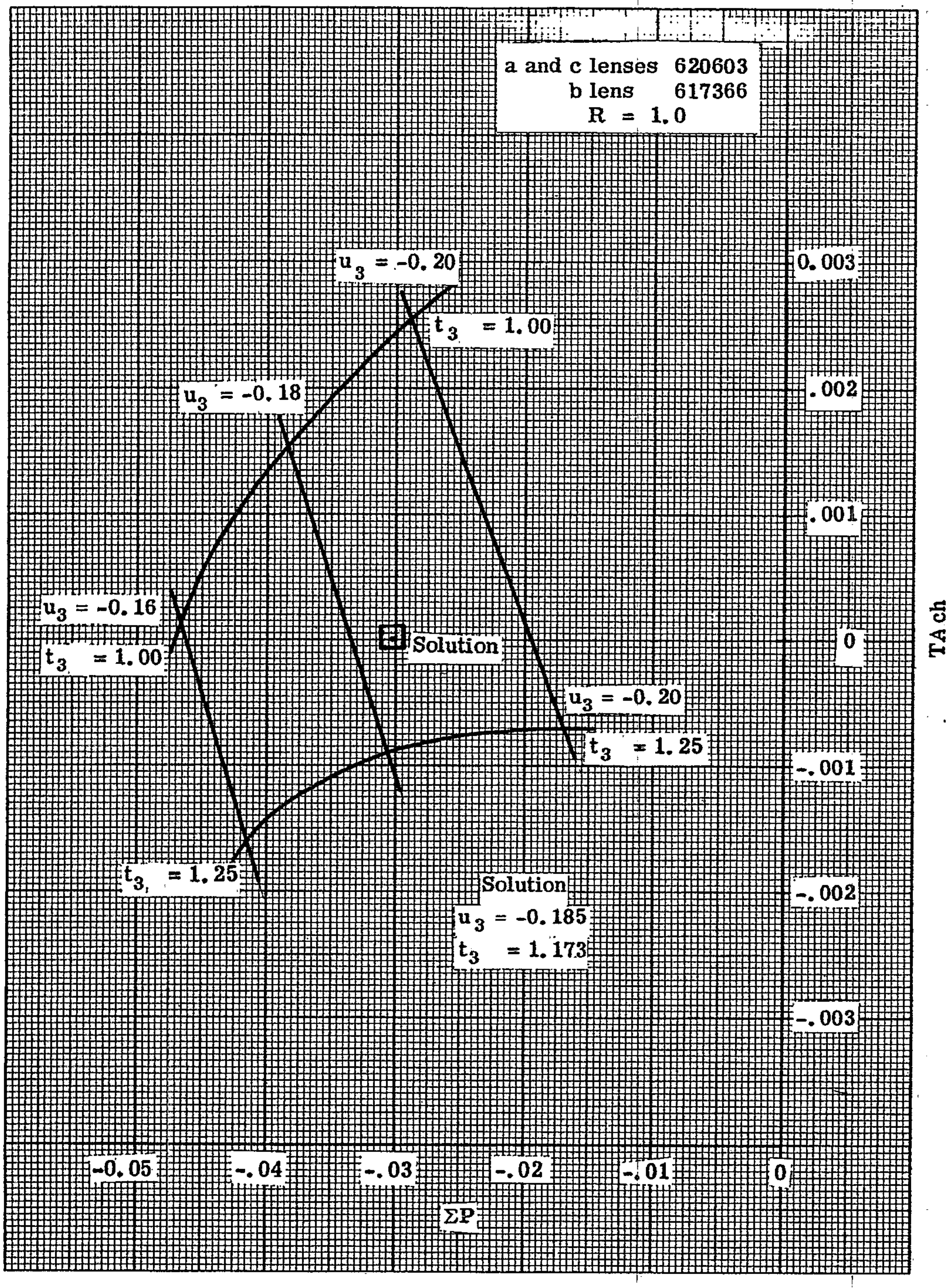

Figure 10.2 - Diagram used to find a thin lens first order solution.

System No.	$R = \frac{t_5}{t_3}$	Glass (a and c) (lenses)	Glass (b lens)	$n_a - n_b$	$\nu_a - \nu_b$	ϕ_a	t_3	t_5	T = $t_3 + t_5$
1A	1	511635	596397	-.0846	23.8	0.220	1.062	1.062	2.124
1B	2	"	"	"	"	0.296	0.795	1.590	2.385
1C	0.5	"	"	"	"	0.146	1.583	0.792	2.375
2A	1	511635	617366	-.1060	26.9	0.195	1.442	1.442	2.884
2B	2	"	"	"	"	0.264	1.075	2.150	3.225
2C	0.5	"	"	"	"	0.130	2.138	1.069	3.207
3A	1	511635	649338	-.1380	29.7	0.180	1.850	1.850	3.700
3B	2	"	"	"	"	0.244	1.370	2.740	4.110
3C	0.5	"	"	"	"	0.1185	2.736	1.368	4.104
4A	1	511635	657366	-.1460	26.9	0.205	1.419	1.419	2.838
4B	2	"	"	"	"	0.275	1.066	2.132	3.198
4C	0.5	"	"	"	"	0.135	2.128	1.064	3.192
5A	1	541599	596397	-.0546	20.2	0.236	0.817	0.817	1.634
5B	2	"	"	"	"	0.317	0.615	1.230	1.845
5C	0.5	"	"	"	"	0.158	1.229	0.615	1.844
6A	1	541599	617366	-.0760	23.3	0.207	1.161	1.161	2.322
6B	2	"	"	"	"	0.278	0.874	1.748	2.622
6C	0.5	"	"	"	"	0.138	1.750	0.875	2.625
*6AA	1	541599	617366	-.0760	23.3	0.222	1.157	1.157	2.314
*6BB	2	"	"	"	"	0.298	0.867	1.734	2.601
*6CC	0.5	"	"	"	"	0.148	1.732	0.866	2.598
7A	1	541599	649338	-.1080	26.1	0.189	1.545	1.545	3.090
7B	2	"	"	"	"	0.255	1.155	2.310	3.465
7C	0.5	"	"	"	"	0.1245	2.300	1.150	3.450
8A	1	541599	657366	-.1160	23.3	0.218	1.154	1.154	2.308
8B	2	"	"	"	"	0.293	0.868	1.736	2.604
8C	0.5	"	"	"	"	0.147	1.736	0.868	2.604
9A	1	541599	689309	-.1486	29.0	0.172	2.005	2.005	4.010
9B	2	"	"	"	"	0.236	1.500	3.000	4.500
9C	0.5	"	"	"	"	0.113	3.000	1.500	4.500
10A	1	588612	596397	-.0076	21.5	0.211	0.880	0.880	1.760
10B	2	"	"	"	"	0.284	0.660	1.320	1.980
10C	0.5	"	"	"	"	0.141	1.330	0.665	1.995

Table 10.6- Thin lens triplet (first order solution), Sheet 1 of 5

System No.	$R = \frac{t_3}{t_5}$	Glass (a and c) (lenses)	Glass (b lens)	$n_a - n_b$	$\nu_a - \nu_b$	ϕ_a	t_3	t_5	$T = t_3 + t_5$
11A	1	588612	617366	-.0290	24.6	0.188	1.259	1.259	2.518
11B	2	"	"	"	"	0.253	0.947	1.894	2.841
11C	0.5	"	"	"	"	0.127	1.894	0.947	2.841
12A	1	588612	649338	-.0610	27.4	0.173	1.658	1.658	3.316
12B	2	"	"	"	"	0.235	1.246	2.492	3.738
12C	0.5	"	"	"	"	0.118	2.492	1.246	3.738
13A	1	588612	657366	-.0690	24.6	0.195	1.264	1.264	2.528
13B	2	"	"	"	"	0.264	0.950	1.900	2.850
13C	0.5	"	"	"	"	0.132	1.900	0.950	2.850
14A	1	611588	617366	-.0060	22.2	0.195	1.080	1.080	2.160
14B	2	"	"	"	"	0.261	0.790	1.580	2.370
14C	0.5	"	"	"	"	0.129	1.570	0.785	2.355
15A	1	620603	596397	.0244	20.6	0.207	0.810	0.810	1.620
15B	2	"	"	"	"	0.280	0.614	1.228	1.842
15C	0.5	"	"	"	"	0.140	1.228	0.614	1.842
16A	1	620603	617366	.0030	23.7	0.185	1.173	1.173	2.346
16B	2	"	"	"	"	0.248	0.882	1.764	2.646
16C	0.5	"	"	"	"	0.124	1.764	0.882	2.646
17A	1	620603	621362	-.0010	24.1	0.184	1.240	1.240	2.480
17B	2	"	"	"	"	0.246	0.930	1.860	2.790
17C	0.5	"	"	"	"	0.121	1.830	0.915	2.745
18A	1	620603	649338	-.0290	26.5	0.170	1.600	1.600	3.200
18B	2	"	"	"	"	0.231	1.180	2.360	3.540
18C	0.5	"	"	"	"	0.113	2.353	1.177	3.530
19A	1	620603	657366	-.0370	23.7	0.193	1.188	1.188	2.376
19B	2	"	"	"	"	0.259	0.895	1.790	2.685
19C	0.5	"	"	"	"	0.130	1.790	0.895	2.685
20A	1	620603	668323	-.0480	28.0	0.163	1.830	1.830	3.660
20B	2	"	"	"	"	0.222	1.372	2.744	4.116
20C	0.5	"	"	"	"	0.111	2.744	1.372	4.116

Table 10.6-Thin lens triplet (first order solution). Sheet 2 of 5

System No.	$R = \frac{t_3}{t_5}$	Glass (a and c) (lenses)	Glass (b lens)	$n_a - n_b$	$\nu_a - \nu_b$	ϕ_a	t_3	t_5	$T = t_3 + t_5$
21A	1	657572	617366	.0400	20.6	0.193	0.911	0.911	1.822
21B	2	"	"	"	"	0.258	0.686	1.372	2.058
21C	0.5	"	"	"	"	0.129	1.372	0.686	2.058
22A	1	657572	649338	.0080	23.4	0.176	1.289	1.289	2.578
22B	2	"	"	"	"	0.238	0.978	1.956	2.934
22C	0.5	"	"	"	"	0.119	1.956	0.978	2.934
23A	1	657572	668323	-.0110	24.9	0.168	1.540	1.540	3.080
23B	2	"	"	"	"	0.228	1.158	2.316	3.474
23C	0.5	"	"	"	"	0.114	2.316	1.158	3.474
24A	1	657572	689309	-.0320	26.3	0.162	1.773	1.773	3.546
24B	2	"	"	"	"	0.221	1.337	2.674	4.011
24C	0.5	"	"	"	"	0.108	2.625	1.313	3.938
25A	1	691548	649338	.0420	21.0	0.180	1.063	1.063	2.126
25B	2	"	"	"	"	0.242	0.805	1.610	2.415
25C	0.5	"	"	"	"	0.121	1.610	0.805	2.415
26A	1	691548	689309	.0020	23.9	0.166	1.530	1.530	3.060
26B	2	"	"	"	"	0.224	1.161	2.322	3.483
26C	0.5	"	"	"	"	0.112	2.322	1.161	3.483
27A	1	691548	720293	-.0290	25.5	0.159	1.836	1.836	3.672
27B	2	"	"	"	"	0.216	1.376	2.752	4.128
27C	0.5	"	"	"	"	0.108	2.752	1.376	4.128
28A	1	720475	689309	.0310	16.6	0.199	0.842	0.842	1.684
28B	2	"	"	"	"	0.266	0.632	1.264	1.896
28C	0.5	"	"	"	"	0.133	1.264	0.632	1.896
29A	1	720475	720293	0000	18.2	0.188	1.082	1.082	2.164
29B	2	"	"	"	"	0.248	0.820	1.640	2.460
29C	0.5	"	"	"	"	0.125	1.620	0.810	2.430
29D	1.5	"	"	"	"	0.228	0.890	1.335	2.225

Table 10.6 - Thin lens triplet (first order solution). Sheet 3 of 5

System No.	Vertex of Parabola $_3Y_k$	FD for c_2 at Vertex	Slope of FD Curve	c_2 at Vertex $_3Y_k$	c_4 at Vertex $_3Y_k$	c_6 at Vertex $_3Y_k$	c_a	c_b	c_c
1A	.029	-.008	-.19	.4320	-.2954	.1272	.4305	-.7449	.4817
1B	-.023	.004	-.30	.5150	-.2759	-.0504	.5792	-.7553	.3444
1C	-.030	-.021	-.18	.3750	-.3120	.1960	.2857	-.7381	.6205
5A	.094	-.005	-.11	.4500	-.3126	.1154	.4362	-.7738	.4750
5B	.029	.005	-.16	.5100	-.3015	.0082	.5860	-.7831	.3341
5C	.025	-.014	-.11	.4000	-.3435	.1947	.2921	-.7793	.6223
6A	.014	-.010	-.20	.4000	-.2518	.1209	.3826	-.6699	.4329
6B	-.030	.007	-.27	.4600	-.2466	.0299	.5139	-.6787	.3114
6C	-.032	-.022	-.19	.3400	-.2843	.1698	.2551	-.6709	.5591
*6AA	.033	-.010	-.25	.4200	-.2928	.1322	.4104	-.7502	.4640
*6BB	-.016	.002	-.38	.5050	-.2770	.0534	.5508	-.7583	.3332
*6CC	-.019	-.025	-.20	.3600	-.3128	.1789	.2736	-.7497	.5990
7A	-.021	-.015	-.38	.3650	-.2188	.1115	.3494	-.6050	.4132
7B	-.046	.010	-.50	.4120	-.1650	.0667	.4713	-.6170	.3065
7C	-.050	-.031	-.33	.3000	-.2347	.1521	.2301	-.5905	.5201
8A	-.003	-.010	-.35	.4150	-.2450	.1179	.4030	.6833	.4555
8B	-.054	.002	-.40	.5000	-.2194	.0603	.5416	-.6930	.3277
8C	-.053	-.025	-.24	.3600	-.2710	.1816	.2717	-.6969	.5951
10A	.057	-.005	-.11	.4000	-.2534	.0964	.3588	-.6639	.3935
10B	.016	.003	-.14	.4520	-.2319	.0082	.4830	-.6736	.2782
10C	.010	-.013	-.10	.3450	-.3087	.1490	.2398	-.6675	.5138
11A	.009	-.009	-.22	.3480	-.2170	.0993	.3197	-.5860	.3658
11B	-.020	.006	-.31	.4000	-.2013	.0262	.4303	-.5957	.2654
11C	-.022	-.023	-.19	.3050	-.2558	.1474	.2160	-.5997	.4772
13A	.004	-.010	-.25	.3580	-.2153	.1014	.3316	-.5858	.3796
13B	-.029	.003	-.35	.4250	-.1922	.0386	.4490	-.6014	.2771
13C	-.029	-.024	-.22	.3130	-.2523	.1504	.2245	-.6014	.4961
14A	.027	-.006	-.16	.3500	-.2319	.0828	.3191	-.5954	.3578
14B	-.007	.001	-.18	.4180	-.1769	.0340	.4272	-.5952	.2537
14C	-.012	-.014	-.14	.3130	-.2651	.1346	.2111	-.5833	.4582

Table 10.6- Thin lens triplet (third order solution). Sheet 4 of 5

System No.	Vertex of Parabola $_3Y_k$	FD for c_2 at Vertex	Slope of FD Curve	c_2 at Vertex $_3Y_k$	c_4 at Vertex $_3Y_k$	c_6 at Vertex $_3Y_k$	c_a	c_b	c_c
15A	.059	-.003	-.09	.3800	-.2544	.0655	.3339	-.6334	.3633
15B	.025	.003	-.13	.4350	-.2117	-.0043	.4516	-.6488	.2574
15C	.021	-.010	-.08	.3350	-.3162	.1252	.2258	-.6488	.4812
16A	.016	-.008	-.15	.3380	-.2057	.0780	.2984	-.5589	.3380
16B	-.013	-.002	-.20	.4000	-.1578	.0463	.4000	-.5643	.2428
16C	-.014	-.017	-.13	.2900	-.2563	.1271	.2000	-.5643	.4387
17A	.013	-.009	-.20	.3360	-.2028	.0911	.2968	-.5591	.3388
17B	-.015	.004	-.24	.3960	-.1571	.0548	.3968	-.5617	.2437
17C	-.020	-.018	-.19	.2880	-.2430	.1278	.1952	-.5440	.4296
19A	.014	-.007	-.20	.3400	-.2157	.0832	.3113	-.5648	.3533
19B	-.016	.001	-.28	.4100	-.1674	.0423	.4177	-.5716	.2544
19C	-.019	-.020	-.17	.3050	-.2480	.1390	.2097	-.5753	.4606
21A	.034	-.004	-.10	.3480	-.2170	.0601	.2938	-.5624	.3232
21B	.004	.001	-.18	.4050	-.1541	.0122	.3927	-.5652	.2276
21C	.000	-.010	-.09	.3000	-.2816	.1024	.1963	-.5652	.4216
22A	.005	-.010	-.18	.3200	-.1693	.0873	.2679	-.5022	.3075
22B	-.015	.003	-.27	.3620	-.1468	.0270	.3623	-.5161	.2252
22C	-.017	-.020	-.16	.2750	-.2273	.1192	.1811	-.5161	.4015
25A	.014	-.006	-.13	.3200	-.1792	.0612	.2605	-.4954	.2915
25B	-.007	.001	-.17	.3680	-.1278	.0300	.3502	-.5033	.2087
25C	-.011	-.014	-.13	.2800	-.2410	.0992	.1751	-.5033	.3807
29A	.015	-.006	-.13	.3200	-.1710	.0607	.2611	-.4812	.2928
29B	-.012	.002	-.20	.3650	-.1136	.0130	.3444	-.4742	.2060
29C	-.010	-.016	-.11	.2950	-.2118	.1084	.1736	-.4789	.3778
29D	.008	-.002	-.18	.3520	-.1417	.0261	.3167	-.4879	.2436

Table 10.6-Thin lens triplet (third order solution). Sheet 5 of 5

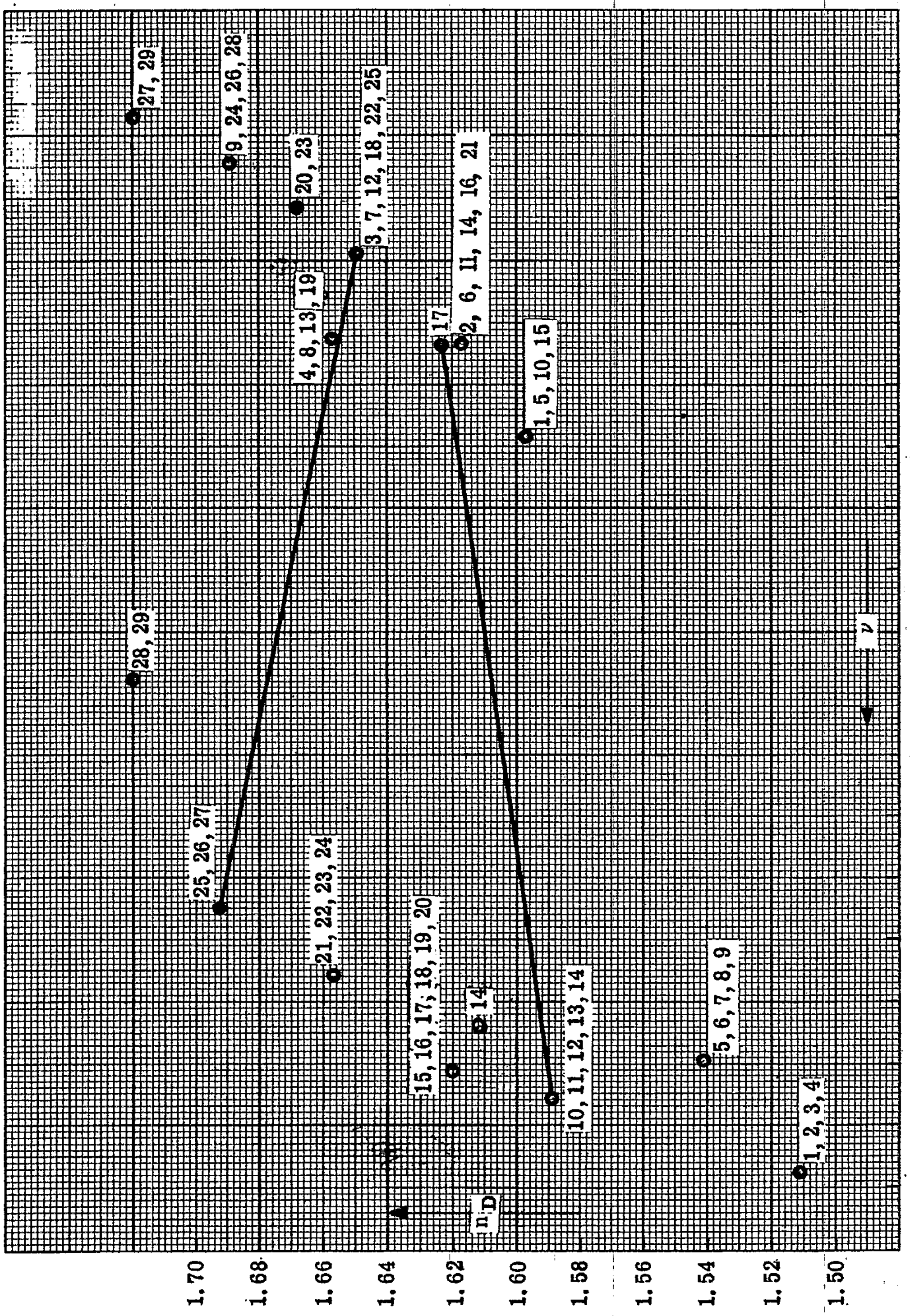

Figure 10.3 - Plot of n_D versus ν for glasses used in triplet study.

10.3 STEP THREE - THE THIRD ORDER THIN LENS SOLUTION

10.3.1 Evaluation of third order coefficients.

10.3.1.1 With the thin lens first order equations worked out so that ϕ_a , ϕ_b , ϕ_c , t_3 and t_5 are known, it is now possible to evaluate the coefficients in Equations 8-(36) through 8-(39) for each lens. In order to simplify the equations, the chief ray is again chosen to pass through the center of the (b) lens. Then the problem is to solve the following equations:

$$B_a^* + B_b + B_c^* = \Sigma B = 0 \quad (1)$$

$$F_a^* + F_b + F_c^* = \Sigma F = 0 \quad (2)$$

$$C_a^* + C_b + C_c^* = \Sigma C = -\frac{1}{3} \Sigma P \Phi^2 \quad (3)$$

$$E_a^* + 0 + E_b^* = \Sigma E = 0 \quad (4)$$

10.3.1.2 The value of ΣC was not set equal to zero because ΣP is not zero. Instead the value of ΣC is chosen to make $t_{kT} = 0$, as it is defined in Equation 8-(9). For these equations,

$$B_a^* = \alpha_1^* + \alpha_2^* c_2 + \alpha_3^* c_2^2 \quad (5)$$

$$B_b = \alpha_1 + \alpha_2 c_4 + \alpha_3 c_4^2 \quad \text{Note: The } \alpha\text{'s are} \quad (6)$$

$$B_c^* = \alpha_1^* + \alpha_2^* c_6 + \alpha_3^* c_6^2 \quad \text{different for each lens.} \quad (7)$$

$$F_a^* = \beta_1^* + \beta_2^* c_2 + \beta_3^* c_2^2 \quad (8)$$

$$F_b = \beta_1 + \beta_2 c_4 \quad \text{The } \beta\text{'s are different} \quad (9)$$

$$F_c^* = \beta_1^* + \beta_2^* c_6 + \beta_3^* c_6^2 \quad \text{for each lens.} \quad (10)$$

$$C_a^* = \gamma_1^* + \gamma_2^* c_2 + \gamma_3^* c_2^2 \quad (11)$$

$$C_b = -\phi_b \Phi^2 \quad \text{The } \gamma\text{'s are different} \quad (12)$$

$$C_c^* = \gamma_1^* + \gamma_2^* c_6 + \gamma_3^* c_6^2 \quad \text{for each lens.} \quad (13)$$

$$E_a^* = \delta_1^* + \delta_2^* c_2 + \delta_3^* c_2^2 \quad (14)$$

$$E_b = 0 \quad \text{The } \delta\text{'s are different} \quad (15)$$

$$E_c^* = \delta_1^* + \delta_2^* c_6 + \delta_3^* c_6^2 \quad \text{for each lens.} \quad (16)$$

This appears like a rather formidable array of equations to solve. But the problem can be tackled by a combination of algebraic and graphical solutions, and enough common sense to realize that there really is little point in trying to find an exact solution for thin lenses anyway. Any solution for thin lenses will be changed as soon as thicknesses are added.

10.3.1.3 The problem is approached by noting that the astigmatism of the (b) lens, C_b , is constant and does not depend on the bending of the lens. This means that Equation (3) in this section can be written in two variables, c_2 and c_6 . By using c_2 as a free variable, and choosing a numerical value of c_2 , c_6 may be found by solving a quadratic equation. If there are two real solutions one must choose between the positive or negative sign before the square root. In all the work to follow, the positive sign has been taken for the solution. The solutions provided by the negative root are not promising optical systems, because the lens surfaces have too high a curvature.

10.3.1.4 With c_2 and c_6 determined, Equation (2) becomes a linear equation which can be solved for a single value of c_4 . Now c_2 , c_4 , c_6 are determined, so Equations (1) and (4) determine ΣB and ΣE. This procedure may then be repeated for several values of c_2 . The values of ΣB and ΣE should then be plotted on a graph with c_2 as the abscissa. A plot of this type is illustrated in Figure 10.4. The ordinates of this graph are $\Sigma B/2\ (n_{k-1}\ u_{k-1}) = {}_3Y_k$ and $\Sigma E/2\Phi$ = F.D., which are the actual transverse third order spherical aberration and the fractional distortion. The thin lens coefficients were computed using $y_1 = 1$ and $\bar{u}_1 = 0.3$. Therefore, the graph in Figure 10.4 shows the spherical aberration and fractional distortion for an $f/5$ system with an image height of 3.0. The graphs in Figure 10.4 show that there are two solutions where the spherical aberration is zero, while the fractional

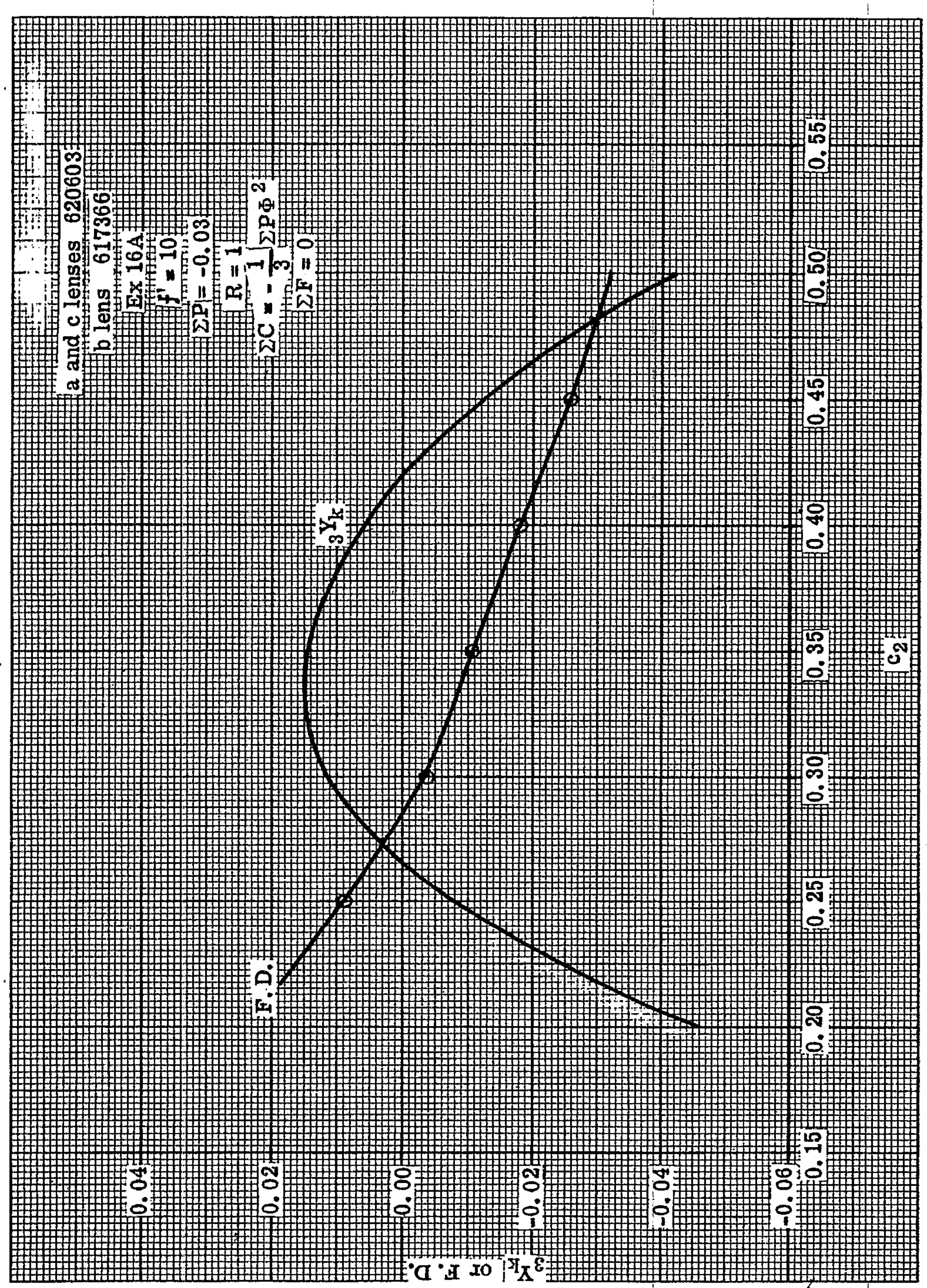

Figure 10.4 - Variation of distortion and spherical aberration with curvature c_2.

distortion is positive for one and negative at the other. The solution with the smaller value of c_2 has the least amount of distortion.

10.3.1.5 Curves of the type shown in Figure 10.4 have been worked out for all the systems included in sheets 1, 2, and 3 of Table 10.6. An attempt to summarize the data is included in Table 10.6, sheets 4 and 5. In nearly every case, the curve for spherical aberration can be represented by a parabola, while the distortion curve can be approximated by a straight line. The data in Table 10.6, sheets 4 and 5, give the information defining the constants of the parabola and the slope of the straight line. For practical purposes, all the parabolas and straight lines can be fitted to the same constants. Therefore,

$$_3Y_k = -2.0\ (c_i - c_{i\ vertex})^2 + {_3Y_{k\ vertex}}\ .$$

In the tables, c_2, c_4, and c_6 are given for the vertex of the parabola. Therefore one can calculate c_2, c_4, and c_6 for any desired $_3Y_k$ from the above equation. Using example 16A in Table 10.6, sheet 5, the values for c_2, c_4, and c_6 for $_3Y_k = 0$ are given by

$$0 = -2.0\ (c_2 - 0.3380)^2 + 0.016, \quad c_2 = 0.249 \text{ and } .427$$

$$0 = -2.0\ (c_4 + 0.2057)^2 + 0.016, \quad c_4 = -0.295 \text{ and } -.116$$

$$0 = -2.0\ (c_6 - 0.0780)^2 + 0.016, \quad c_6 = -0.011 \text{ and } .167$$

10.3.2 Analysis of the data.

10.3.2.1 Notice that the c_2 values for $_3Y_k = 0$, calculated above, do not agree with the data in Figure 10.4, where $c_2 = 0.262$ and 0.416. This is because the equation of the parabola has been simplified to meet all the cases. The slight discrepancy is of little concern at this step of the design, for introducing the thicknesses will change conditions anyway. These figures, therefore, give adequate starting data for the next step of the design. However, before proceeding, the following features of the data in Table 10.6, sheets 4 and 5, should be observed.

(1) Changing the value of R from 1 to 2.0, or from 1 to 0.5, has the effect of moving the parabola downward, with a horizontal vertex shift towards increased c_2 values for $R = 2.0$, and toward decreased c_2 values for $R = 0.5$.

(2) Changing R from 1.0 to 2.0, or from 1 to 0.5, has the effect of moving the F.D. versus c_2 curves upward for $R = 2.0$, and downward for $R = 0.5$ with no appreciable change in slope.

(3) Decreasing ΣP from -0.03 to -0.02 has the effect of moving the parabolas upward, with little effect on the F.D. curves.

10.3.2.2 The $_3Y_k$ and F.D. curves for the same solution for values of $R = 2$ and 0.5, are shown in Figure 10.5. At some value of R (about $R = 0.80$), the distortion curve and the spherical aberration parabola will intersect each other at 0.0 for a c_2 value around 0.27. For an R about 1.5, the curves cross again at 0.0 for a value of $c_2 = 0.35$. This means that if R is variable, there are two solutions corrected for both spherical aberration and distortion. Since ΣP, ΣC, and ΣF are specified for all the curves, these two solutions are then completely corrected to the desired third order aberrations. The solution with the smaller value of c_2 will be referred to as the left hand triplet solution, while the other solution will be called the right hand solution.

10.3.2.3 If glasses with larger $\Delta\nu$ are used, the parabolas are lowered and the two solutions approach each other on the c_2 plot, the final single solutions tend towards a value of R slightly greater than 1.0. The indices of the elements seem to have only a secondary effect on the design while the $\Delta\nu$ difference has a very significant effect.

10.3.3 Ray trace analysis. The designer cannot be sure from the thin lens data how to choose from all the possible choices of glass. There are a very large number of triplets for which the third order distortion and spherical aberration are zero; and the number, of course, is unlimited if distortion residuals are allowed. The only way to really check on the advantage of one design over another is to ray trace the various possibilities. One instinctively feels, however, that if the left hand and right hand solutions can be made to come together that this design will be a good solution. Under this condition the spherical aberration para-

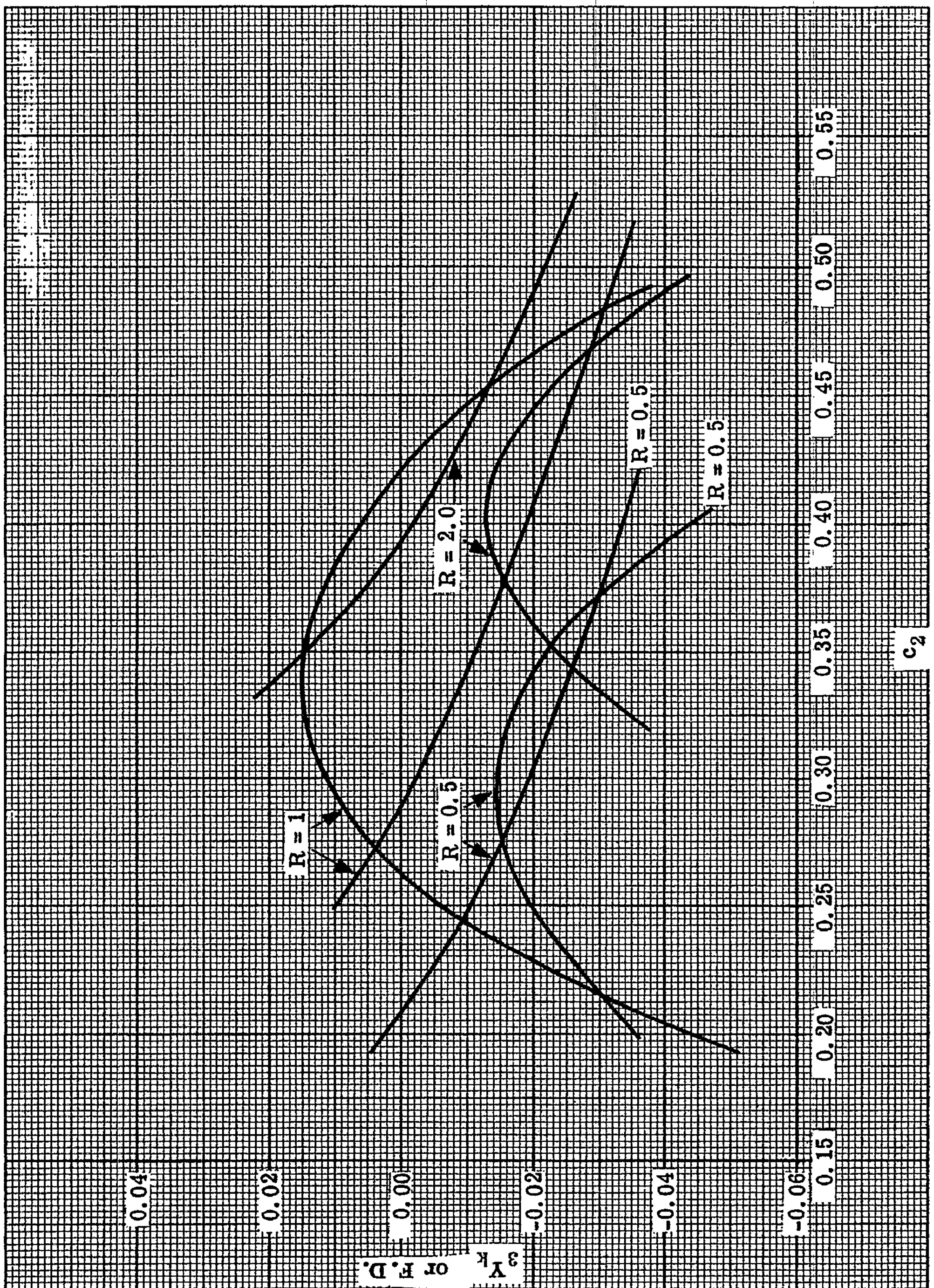

Figure 10.5 - Same plot as in Figure 10.4 with different values of R.

bola and the distortion curve intersect at the maximum of the parabola. Therefore the solution will be somewhat insensitive to changes in curvature, and consequently should be less sensitive to errors in manufacture. Later work on ray trace results will also substantiate that these solutions are preferred to others.

10.3.4 Summary of thin lens design for a triplet objective.

(1) There are two main solutions for $B = F = E = 0$ and $C^{*} = -\frac{1}{3} P \Phi^2$. One solution is called the left hand solution, $(R < 1)$. The other is the right hand solution, $(R > 1)$.

(2) These solutions are brought together to form a single solution, by increasing the $\Delta \nu$ between the positive elements and the negative element. The R values also converge to a value slightly greater than 1. It is believed that this provides a near optimum solution.

(3) If the $\Delta \nu$ is made too large, there is no solution.

(4) If the value of ΣP is made more positive, the two solutions (if they exist) separate, and in order to bring them together again, the $\Delta \nu$ must be made greater.

10.4 STEP FOUR - THE THICK LENS FIRST ORDER AND THIRD ORDER ABERRATIONS

10.4.1 Lens thickness.

10.4.1.1 Introducing the proper thicknesses in a lens system is also a problem. One has to be sure the positive lenses are of large enough aperture to pass the necessary rays, and the negative lenses have to be made thick enough to resist warping during manufacture. The thickness of the negative lenses can be usually assigned quite easily by adopting the rule that a negative lens should not be thinner than 1/10 its diameter. This usually provides a lens with sufficient strength. In special cases thinner lenses can be made if there is a real need for it; hence this rule is merely a guide.

10.4.1.2 The positive lens thickness is more difficult to ascertain because it depends on the system. It is necessary that the system be almost completely designed before deciding on the diameters of the positive lenses. The designer usually vignettes the oblique beams by cutting the clear aperture of some of the positive lenses. He seldom makes the positive elements with clear apertures large enough to pass the complete oblique beams. Drawings of the lens with pictures of the rays passing through it are very useful in visualizing the thickness required. After the clear apertures of a lens are determined it is still necessary for the diameter to be somewhat larger in order to take care of the edge thickness and mounting rims. When the maximum diameter is known, the thickness is calculated using the thin lens curvatures.

10.4.1.3 Rules for the increased diameter needed to mount the lens vary from shop to shop; thus the problem of lens mounting is a subject in itself and will not be treated here. A designer will have to learn these things through experience, although a shop practice manual may help. The designer must remember, however, that shop people have a natural tendency to resist doing things differently. A designer can miss some good designs if he lets shop people talk him out of a very thin lens, or a glass that is difficult to handle. Formerly designers also had a tendency to resist change, insisting on sticking with their design simply because it was so difficult to recalculate. Today, with modern computing machines, there is no excuse for this. It is now very inexpensive to redesign a system completely just to provide a bit more thickness if it is required by the shop people. There are, however, times when the designer needs a thin element for the reduction of weight or to fit into a tight spot, or an expensive hard-to-handle glass may be required to optimize the design. The designer today can back up his design with proof, so he should be able to violate some shop rules.

10.4.1.4 In order to proceed with the thick lens system, the problem of assignment of thickness will not be discussed further. For the present example thicknesses will be inserted without further explanation.

10.4.1.5 The thin lens first order study of the triplet was started using the glasses 620603 for the crowns, and 617366 for the flint, System No. 16. The thin lens third order study shows that the spherical aberration parabola for these glasses extends far above the zero axis. The two solutions are therefore widely separated. For this reason, it appears that the parabola should probably be lowered. This can be done by choosing a flint with a lower ν value. The thick lens set-up is, therefore, System No. 17 in Table 10.6, sheet 2, with 621362 glass for the negative lens. Using the data from Table 10.6, sheet 5, and the parabolic equation, it is possible to compute the first curvatures for the two solutions with $R = 1$ for zero spherical aberration. These thin lens solutions are as follows:

Left Hand Solution	Right Hand Solution
$c_2 = 0.26$	$c_2 = 0.41$
$c_4 = -0.28$	$c_4 = -0.13$
$c_6 = 0.016$	$c_6 = 0.22$
$t_3 = 1.28$	$t_3 = 1.28$
$t_5 = 1.28$	$t_5 = 1.28$

10.4.1.6 The angle the axial ray makes with the optical axis may be computed from the data in Table 10.6, sheet 2, by setting up a table as in Table 10.4. The values of ϕ_a and t_3 are known; therefore the table is completely determined.

10.4.1.7 As soon as it is necessary to assign thicknesses, the designer has to decide on the f-number and the focal length of the lens. For the following study, it will therefore be assumed that the diameter of the entrance pupil will be 3 and the focal length 10. It is also important to assign a maximum field of obliquity for the lens. Let this (object field) be 20° half angle.

10.4.1.8 The axial paraxial ray should therefore be traced through the system as follows:

$$y_1 = 1.5$$

$$u_o = 0$$

The thin lens axial ray trace for this example then appears as in Table 10.7.

SURFACE	1	2,3	4,5	6,7
$-\phi$	0	-0.184	0.347	-0.210
t		1.24	1.24	
y	1.5	1.5	1.158	1.314
u	0	-0.276	0.126	-0.15

Table 10.7 – Thin lens solution for example 17A in Table 10.6.

10.4.2 Computing the thick lens solution.

10.4.2.1 The thick lens is then set up using the values c_2, c_4, c_6, t_3 and t_5 for either the right hand or the left hand solution with the thicknesses of the lenses inserted. For this example the positive lenses are assigned thicknesses of 0.6 and the negative lens a thickness of 0.25.

10.4.2.2 The second curvatures of the lenses are then computed to maintain the paraxial angles, shown in Table 10.7, between the lenses. The spaces between the lenses may at this time be set at about 1.0.

10.4.2.3 With this initial system, the first order and third order contributions are calculated as shown in Table 8.2.

10.4.3 Iterative analysis and adjustment.

10.4.3.1 As the formalized step-by-step procedure of Section 9 is followed through the remaining steps, it is necessary to examine results and repeat, with changes, earlier steps in order to balance the higher order aberrations. This iterative appraisal and recomputation is the means by which the design can be refined and developed to the desired degree. The mechanics of computation are well described in the foregoing sections and will not be repeated in detail.

10.4.3.2 This discussion, then, will be devoted only to the examination and interpretation of results and to the analytical processes which dictate the iterative changes as design refinement proceeds. With this orientation in mind, and also remembering that by properly programming an automatic computer, the results of one run will produce much of the data necessary for analysis, the discussion will proceed.

10.4.3.3 Next comes the problem of ray tracing, analyzing, and readjusting the lens to the desired third order aberrations. The recommended procedure for doing this is to make small changes in the system and solve Equations 9-(1) through 9-(7). A procedure of this type has been programmed for the I.B.M. 650 computer, and with this program the foregoing triplet system has been studied extensively. A brief account of this study is presented below.

10.4.3.4 First it was decided that the quantities c_2, t_3, c_4, t_5, c_6 would be used as variables. This provided only five variables so it was necessary to provide another variable in order to correct the six quantities B, F, C, P, a, and b. c_5 was used as the extra variable, meaning that the solution departed from $R = 1$. It was possible with three iterations to find the left and right hand solutions, but neither of these solutions were ray traced because it was not possible to tell what value of R the final solution would have. Therefore, it was decided to let c_3 also vary. This provided an extra degree of freedom so the distortion was corrected. In other words, R was allowed to be a variable for the purposes of correcting distortion. In other words, with the seven variables c_2, c_3, t_3, c_4, t_5, c_6, and R, the seven aberration coefficients, B, F, C, P, E, a, and b could be specified. As one would predict from the graphs in Figure 10.5, two solutions were found. This same technique was used in the further study of this lens; hence all the solutions are corrected to exactly zero third order distortion. It was thus possible to compare several designs by varying single parameters, and the third order aberrations could be brought to precisely the required values.

10.5 STEP FIVE - TRACING A FEW SELECTED RAYS

10.5.1 Analysis of the ray tracing results. One finds immediately upon ray tracing that the first and third order aberrations should not be set to zero. The reason for this is that high order aberrations are always present and the third order aberrations have to be set to compensate for them. For example, if the triplet is corrected with $\Sigma B = 0$, the rays traced at $Y = 1.5$ will strike the paraxial image plane at large positive values indicating that the high order aberrations have over-corrected the lens. This is also the reason why ΣP was made equal to -0.03 instead of zero. The same is true with respect to color aberrations. In the triplet it turns out that ΣF, ΣE, and Σb can be set at zero, but the remaining ones, ΣB, ΣC, ΣP, and a have to be set at negative values.

10.5.2 Target values and solutions.

10.5.2.1 Early in the study of this system it was found that the value for ΣP had to be changed from -0.03 to = -0.035 and the spherical aberration had to be under-corrected to $\Sigma B = -0.006$. The first solutions showing interest were computed with the following target values for the third order coefficients:

$$\Sigma B = -0.006$$

$$\Sigma F = 0$$

$$\Sigma C = -\frac{1}{3} P \Phi^2$$

$$\Sigma E = 0$$

$$\Sigma P = -0.035$$

$$\Sigma a = -0.0004$$

$$\Sigma b = 0$$

The chromatic aberrations were left small and unchanged throughout, since the study was done primarily to show how the monochromatic aberrations are corrected.

10.5.2.2 With these target values, two solutions were found. The lens data are included in Table 10.8. The data include the overall thickness T of the lens. Aberration plots similar to Figure 9.1 are shown in Figures 10.6 and 10.7 for the two solutions.

Left Hand Solution c	t	Right Hand Solution c	t
0.2209		0.3116	
	0.600		0.600
-0.0124		-0.0282	
	1.3949		0.8572
-0.2407		-0.1734	
	0.2500		0.2500
0.2606		0.3319	
	0.9631		1.628
0.0777		0.0683	
	0.600		0.600
-0.2822		-0.1891	
	8.453		7.599
R = 0.7685		R = 1.82	
T = 3.808		T = 3.935	

Table 10.8 - Left and right hand solutions for a triplet with $\Sigma P = -0.035$.

10.6 STEP SIX - READJUSTING THE THIRD ORDER ABERRATIONS

10.6.1 Analysis of the aberration curves.

10.6.1.1 The aberration curves show that the meridional rays depart from third order drastically at 20°. In the lens designer's language, the tangential field has pulled in rapidly. On the other hand, the sagittal field has moved back relative to the third order field by a much smaller amount. These lenses cannot perform well beyond a 15° half angle. The sagittal rays tend to follow the third order curve much more closely than the meridional rays. Notice also how the skew fan appears similar to the axial fan, but over-corrects in spherical aberration as the field angle increases. The left hand solution appears to be somewhat better than the right hand solution at 20°, but there is little to choose between them at the smaller field angles.

10.6.1.2 It can be seen from Table 10.8 that the left and right hand solutions are widely separated on the c_2 scale. This means the spherical aberration parabola should be lowered. Now this can be done by many methods. One way is to increase $\Delta\nu$ by changing the glass in the flint element. The 649338 glass could be used. However, as the thin lens data indicate (System No. 18), this would lengthen the system and the result would be that the tangential field pulls in even faster. An additional disadvantage is that the 649338 glass lowers the parabola so far that there is no solution with the present glass thicknesses. A second method of lowering the parabola is to make the Petzval sum more negative. One might think at first that this would make the system longer, which is likely to make the tangential field pull in even more, but if the parabola is lowered, the R values will be closer to 1, and the thin lens study showed that for this value of R, the systems are the shortest. Therefore, making $\Sigma P = -0.040$ probably will not make the system much longer.

10.6.2 Readjustment procedure.

10.6.2.1 The value of ΣP was therefore changed to -0.040, and solutions were found with all the other aberrations identically the same. The two solutions and the aberration plots are shown in Table 10.9, and Figures 10.8 and 10.9.

10.6.2.2 The aberration curves now show real improvement. The skew ray fans for the two solutions are quite similar. However the left hand solution appears more symmetrical than the right hand solution, and at 20° it is definitely superior. The R values are now closer together and the barrel length, T, is actually shortened. Notice that the left hand solution is shorter than the right. This may be the reason why the tangential field pulls in further with the right hand solution. Notice also that the left hand solution has a value of R closer to 1.0 than the right. If the parabola were lowered still further, the two solutions would converge to a single solution with $R > 1$ as predicted from the thin lens system.

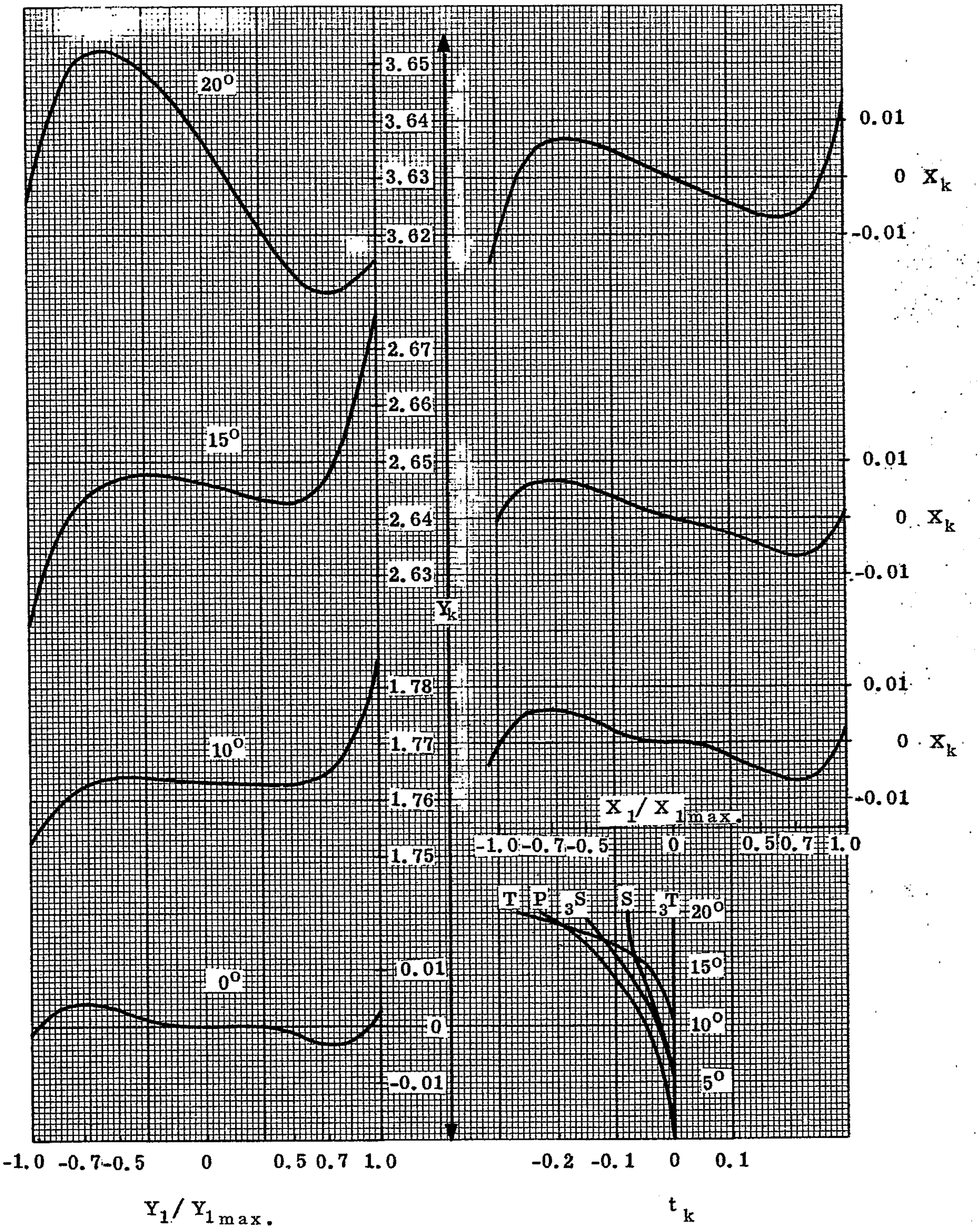

Figure 10.6 - Aberration plots for left hand solution of lenses in Table 10.8.

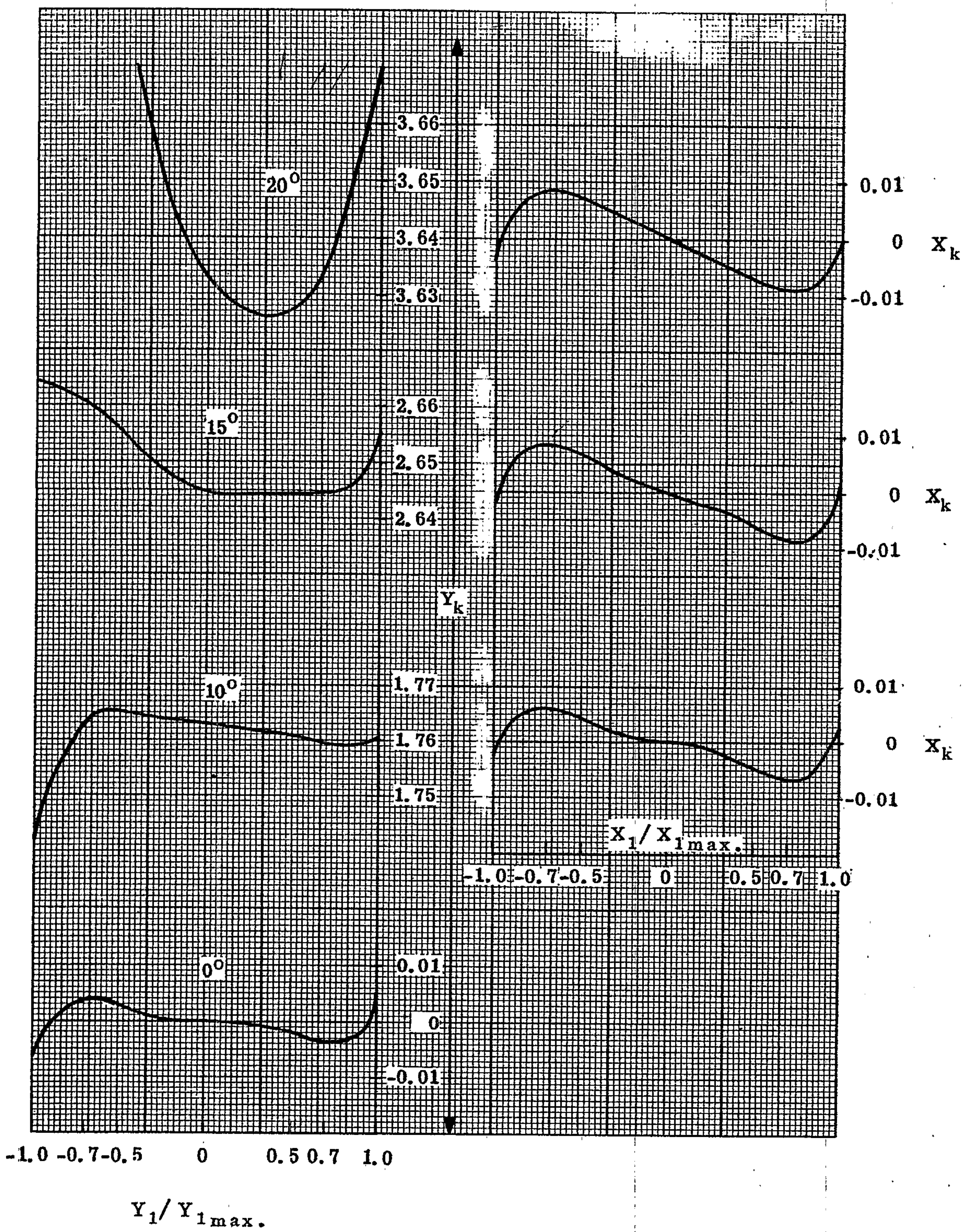

Figure 10.7- Aberration plots for right hand solution of lenses in Table 10.8.

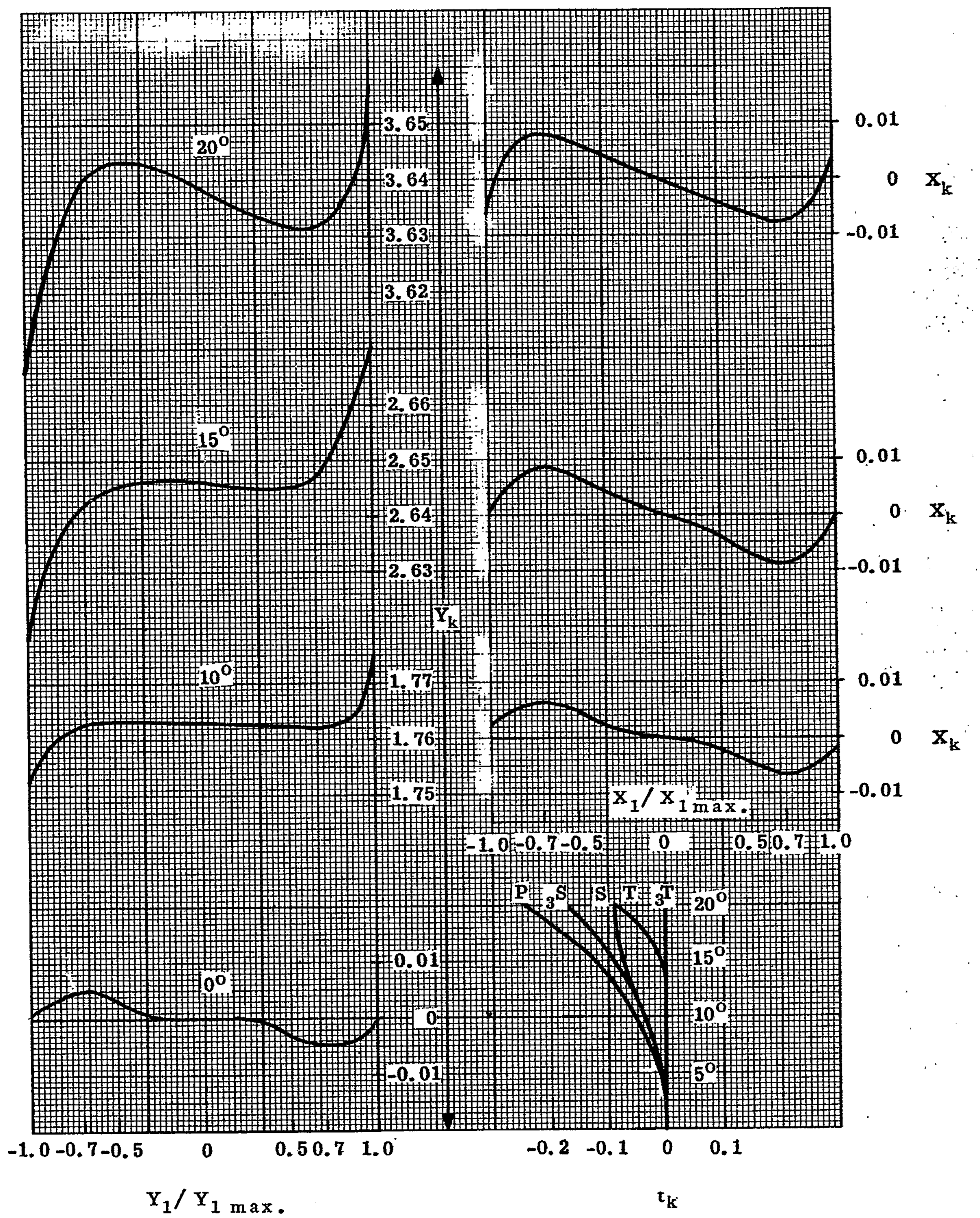

Figure 10.8- Aberration plots for left hand solution of lenses in Table 10.9.

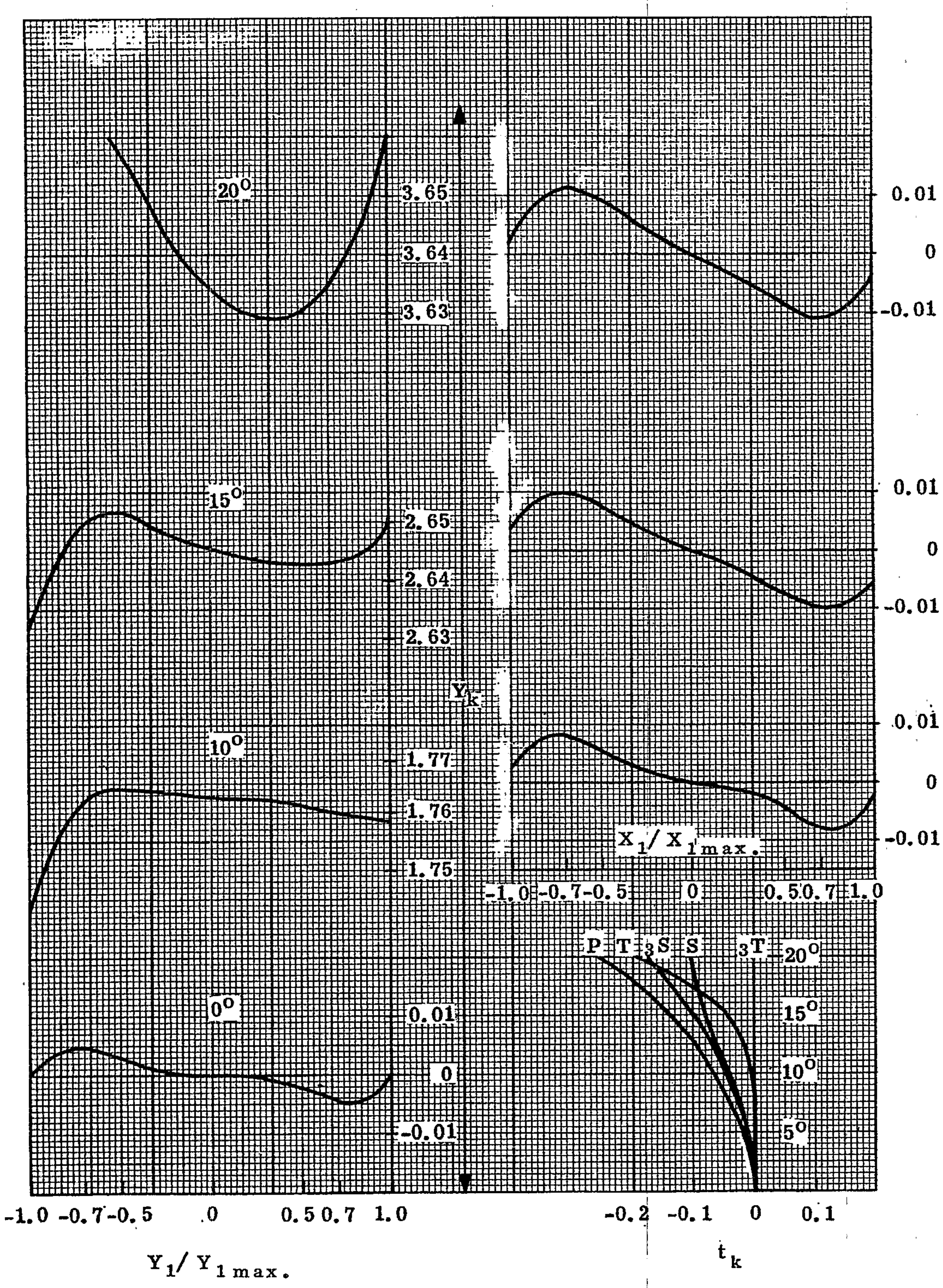

Figure 10.9- Aberration plots for right hand solution of lenses in Table 10.9.

Left Hand Solution		Right Hand Solution	
c	t	c	t
0. 2339		0. 2882	
	0. 60		0. 60
-0. 0098		-0. 0193	
	1. 211		0. 8900
-0. 2107		-0. 1641	
	0. 25		0. 25
0. 2516		0. 2998	
	1. 016		1. 426
0. 06799		0. 0650	
	0. 60		0. 60
-0. 2556		-0. 1963	
	8. 363		7. 847
R = 0. 9003		R = 1. 493	
T = 3. 677		T = 3. 766	

Table 10. 9 - Left and right hand solutions for ΣP = -0. 040.

10. 6. 2. 3 At this point, it was noticed that the system still was not as good as that described in Table 8. 2. It was finally apparent that the thickness of the negative lens was 0. 15, instead of 0. 25. This indicated that the aberration parabola was lowered in this solution because of the decreased thickness of the negative lens. Then a new solution was found and the only change was to make t_b = 0. 15. The result is that left and right hand solutions have R values 0. 987 and 1. 363. They are drawing closer together and the tangential field does not pull in as rapidly. The surface data for these solutions are included in Table 10. 10 (step seven). Figures 10. 10 and 10. 11 show spot diagrams for these two solutions. In these diagrams only half of the symmetrical image is shown. The diagrams include the appearance of the images as the focal plane is shifted, clearly showing how a shift towards the lens provides a better concentration of light than in the paraxial focus. These diagrams show that there are only slight differences between the imagery in the left and right solutions, out to a half field angle of 15°. However, beyond 15° the left hand solution definitely is superior to that of the right hand. Notice how it shows better concentration and is more symmetrical.

Left Hand Solution		Right Hand Solution	
c	t	c	t
0. 2469		0. 283	
	0. 60		0. 60
-0. 00775		-0. 01227	
	1. 128		0. 9289
-0. 2024		-0. 1692	
	0. 15		0. 15
0. 2568		0. 2911	
	1. 0738		1. 3209
0. 0608		0. 05869	
	0. 60		0. 60
-0. 2487		-0. 2113	
	8. 346		8. 033
R = 0. 987		R = 1. 363	
T = 3. 552		T = 3. 5998	

Table 10. 10 - Left and right hand solution for ΣP = -0. 040.

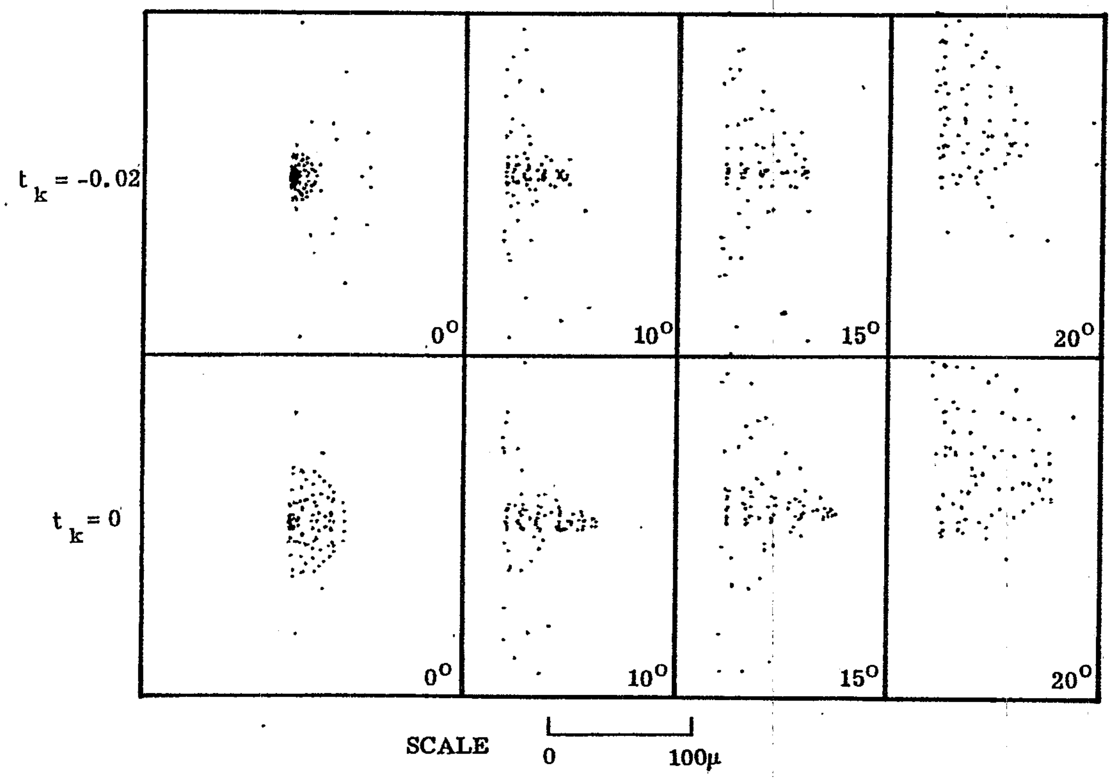

Figure 10.10 - Spot diagrams for left hand solution in Table 10.10.

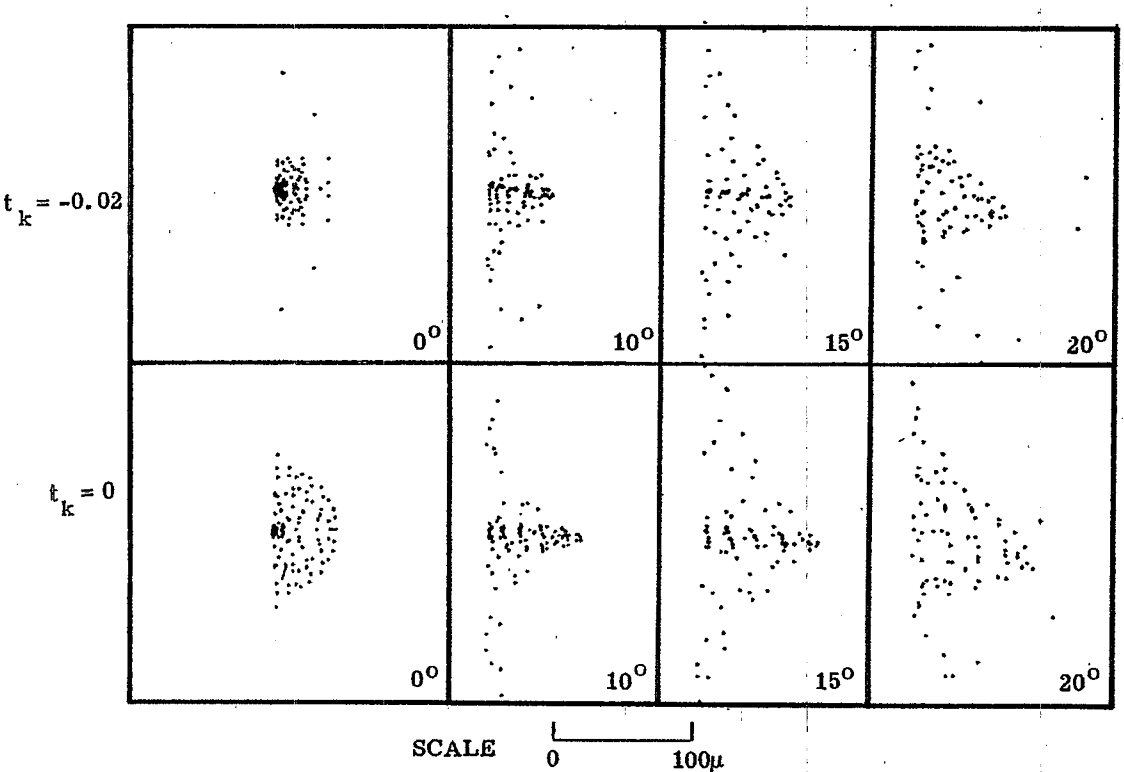

Figure 10.11 - Spot diagrams for right hand solution in Table 10.10.

10.6.3 Analysis of the readjustment procedure.

10.6.3.1 This study showed that reducing the thickness of the negative lens lowers the spherical aberration parabola. This effect then suggested investigating the effect of varying the thicknesses of the positive lenses. The effect is the same, namely lowering the parabola, but not as marked as in the case of the negative lens. This technique of changing the thicknesses of the lenses can be a useful way to compensate for the fact that the parabola is not quite where it should be. The parabola could be lowered still further by reducing the thicknesses, for the case of $\Sigma P = -0.040$, but this is not practical.

10.6.3.2 It is interesting to notice, that in these solutions for the triplet, c_2 is close in value to c_5, and c_4 is close to c_7. For the left hand solution these four surfaces have approximately equal curvatures. It would be very interesting if a solution could be found where all these four curves are identical.

10.7 EVALUATION OF OVER-ALL PERFORMANCE

The design of the optimum triplet is still far from complete, for one must investigate these images carefully by calculating the spot diagrams and energy distributions to be sure the best values for ΣP, ΣC, ΣF and ΣB have been chosen. To do this in detail is an enormous task which realistically can only be done on a very large computer. However with patience and judgment it is possible for designers to arrive at very good solutions.

10.8 SUMMARY

10.8.1 Guide lines. This study has indicated a few guide lines to follow in designing a triplet.

(1) One should always try to design as short a lens as possible to cover a given field.

(2) The spherical aberration parabola can be raised or lowered by the choice of ΣP, thicknesses of lenses, or glass.

(3) It appears that near optimum solutions occur with an R value slightly greater than 1.

10.8.2 Unsolved problems. The study made on this lens merely initiates the reader to the possibilities which need further clarification. A few of the problems are:

(1) What happens as the index of the crown element is increased?

(2) What kinds of solutions can be obtained by first lowering the parabola by glass choice so that there is no solution and then raising the parabola by thickness choice?

(3) What effect has raising the index of the negative lens if $\Delta\nu$ is maintained constant?

(4) When the parabola is too high, is it beneficial to lower it by using aspheric surfaces?

(5) What happens if the number of elements is increased beyond three, and at the same time two or more are cemented together? What happens if the negative element is cemented to either or both positive elements?

(6) If the lens is to cover a wider field, how does one choose the glass?

(7) At finite conjugate will the effect of glass choice and lens thicknesses be the same as at infinite conjugate?