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Final Report to

NAVAL TRAINING SYSTEMS CENTER 12350 Research Parkway Orlando, FL 32826-3224

DISPLAY PROJECTOR TECHNOLOGY

VIA SINGLE CRYSTAL FACEPLATE TECHNOLOGY

Contract N61339-91-C-0052

Presented to:

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Approved for public releases Distribution University

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SECURITY CLASSIFICATION OF THIS PAGE **REPORT DOCUMENTATION PAGE** 1a. REPORT SECURITY CLASSIFICATION 16 RESTRICTIVE MARKINGS Unclassified 3. DISTRIBUTION / AVAILABILITY OF REPORT 2a. SECURITY CLASSIFICATION AUTHORITY Approved for Public Release 26. DECLASSIFICATION / DOWNGRADING SCHEDULE Distribution is Unlimited 4. PERFORMING ORGANIZATION REPORT NUMBER(S) 5. MONITORING ORGANIZATION REPORT NUMBER(S) 7a NAME OF MONITORING ORGANIZATION Naval Training Systems Center 66. OFFICE SYMBOL 6a. NAME OF PERFORMING ORGANIZATION (If applicable) Sensor Simulation Branch, Code 263 Trident International, Inc. 7b. ADDRESS (City, State, and ZIP Code) 6c. ADDRESS (City, State, and ZIP Code) 12350 Research Parkway 3251 D Progress Drive Orlando, FL 32826 Orlando, FL 32826-3224 8a. NAME OF FUNDING / SPONSORING 9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER 8b. OFFICE SYMBOL ORGANIZATION (If applicable) N61339-91-C-0052 Naval Air Systems Command 8c. ADDRESS (City, State, and ZIP Code) 10 SOURCE OF FUNDING NUMBERS PROGRAM PROJECT WORK UNIT TASK ACCESSION NO. ELEMENT NO. NO NO 11. TITLE (Include Security Classification) Display Projector Technology via Single Crystal Faceplate Technology 12. PERSONAL AUTHOR(S) Tucker, A. and Kindl, H. J. 14. DATE OF REPORT (Year, Month, Day) 13b. TIME COVERED 13a. LYPE OF REPORT Final 15. PAGE COUNT FROM Nov. 90 TOAug. 93 93 September 29 16. SUPPLEMENTARY NOTATION **Final Report** Single Crystal Faceplate Evaluation COSATI CODES 18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) 17 Video Projectors, Single Crystal Phosphor, CRTs, Flight FIELD GROUP SUB-GROUP Simulators 19. ABSTRACT (Continue on reverse if necessary and identify by block number) Single crystal phosphor faceplates are epitaxial phosphors grown on crystalline substrates with the potential for high light output, resolution and extended operational life. Single crystal phosphor faceplate industrial technology in the United States is capable of providing faceplates appropriate to the projection industry up to four (4) inches in diameter. This contract continued the evaluation of the use of single crystal phosphor faceplates integrated into CRTs and incorporated into projection display systems. Previous government contractual evaluation of 3" SCFP CRTs (green) lent encouragement to the potential for develop nent of red and blue single crystal faceplate based CRTs; thus, forming the basis for fabrication of a high brightness, long life projection display system for use in government flight simulators. While satisfactory spectral responses were attained for the red and blue colors, mechanical ussembly problems with Ce:Bel (blue) precludes its use as a light source. Abstract continued on reverse side 21. ABSTRACT SECURITY CLASSIFICATION 20. DISTRIBUTION / AVAILABILITY OF ABSTRACT Unclassified UNCLASSIFIED/UNLIMITED UNCLASSIFIED/UNLIMITED DTIC USERS 22a NAME OF RESPONSIBLE INDIVIDUAL 22b. TELEPHONE (Include Area Code) 22c. OFFICE SYMBOL Richard C. Hebb, Code 263 407-280-4578 NTSC/Code 253 UNCLASSIFIED SECURITY CLASSIFICATION OF THIS PAGE DD FORM 1473, 84 MAR 83 APR edition may be used until exhausted. All other editions are obsolete

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1.0 Introduction

Three single crystal faceplates were to be integrated into Cathode Ray Tube (CRT) envelopes with the intent of evaluating the light output from Ce:YAG (Green), modified Ce:Gd,YAG (Orange), Ce:BEL (Blue). These CRT's were to be mounted in the projection test bed developed under Contract N61339-90-C-0047 and furnished G.F.P. to Trident International, Inc. for use and delivery during this contract.

Three 3 inch diameter Ce:YAG faceplates were supplied as GFP from previous contract N61339-90-C-0047. One of these three was to be used for construction of a CRT, the remaining two were to be used for coating tests. During the processing of the CRT's one of the crystals was destroyed. The other two single crystal faceplates were incorporated in test CRT's. An additional Ce:Gd,YAG (Red shifted green) faceplate of 1.5 inches diameter and two Ce:BEL (Blue) crystals of 0.75 inch diameter were obtained from Allied Signal, Inc. by Trident.

Investigations were made to provide optimum optical coupling of the CRT light output into a projection lens. Index matching heat dissipation fluids were used. A wide angle lens was selected and supplied by the contractor. Filtering of the light output of the Ce:YAG, Ce:Gd,YAG and Ce:BEL faceplates was investigated for use in producing green, red and blue light outputs suitable for a full color video projector.

The green (Ce:YAG) and the red shifted (Ce:Gd,YAG) single crystal CRTs were tested, evaluated and demonstrated in the high performance video projection test bed developed under contract N61339-90-C-0047. The blue (Ce:BEL) crystal was not incorporated into a CRT successfully, but tests were performed on them (Ce:BEL) in a demountable vacuum chamber and with an ultraviolet laser to indicate efficiency (lumens/watt) and color spectrum emission. The projection testbed will be delivered with one green (Ce:YAG) 3" CRT installed.

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2.0 Background

Under contract 61339-90-C-0047 an evaluation of single crystal faceplate performance when mounted (integrated) on a cathode ray tube was completed.

Delays in the assembly of the CRTs were encountered; however, initial test results were sufficiently encouraging to warrant proceeding with and evaluating equivalent red and blue faceplates with the goal of generating a full color projected picture. The data obtained was to establish the feasibility of producing a high brightness, long life video projection system for government simulator applications.

The construction of two 3" diameter green (Ce:YAG) CRT's by Hughes Display Products allowed Trident to perform tests on these units under various conditions. Early in the test program cooling was deemed necessary to produce the brightness goals desired. A liquid cooling chamber was designed and adapted to the CRT.

Problems with sealing the SCFP's to the glass proved to be troublesome and were not solved with the Ce:BEL (Blue) crystal material.

Ce:YAG was modified to red shift its spectral luminescence in the form of a 1.5" CRT. The test bed projector was used to evaluate these CRT's.

3.0 Objectives

3.1 Fabrication of red and blue single crystal faceplate cathode ray tubes.

3.2 To evaluate interference coatings to improve optical transmission and anti-reflection capabilities.

3.3 To test filters to shift and utilize the desired spectral output of the crystal faceplates to produce color images.

3.4 To test light output and resolution obtainable from projection test bed developed under Contract 61339-90-C-0047.

3.5 To deliver test bed and remaining CRTs.

4.0 Manufacturing Attempts and Test of Ce:BEL (Blue)

Three Ce:BEL crystal faceplates were made by Allied Signal Corp. for Trident International, Inc. in small 3/4" diameter x Two Ce:BEL crystals were delivered to Hughes .1" thickness. Display Products to assemble in a working CRT for testing by On 15 June 93 Trident was notified that the first CRT Trident. utilizing the Ce:BEL faceplate had failed. It is very difficult to frit seal the small (3/4") Ce:BEL crystal to the larger glass bulb and appears to be impractical. The fractured pieces were mailed to Trident for evaluation. Trident utilized a 2 watt argon laser to perform tests on the fractured Ce:BEL crystal pieces to determine the color temperature and destructibility of the material. Although the laser was capable of reaching very high spot power densities, no noticeable change occurred in the crystal. The color of the light output on the chromatic scale was X=.150, Y=.130. Allied Signal Corp. agreed to deliver It was then decided, Trident one remaining Ce:BEL crystal. because the power density of the laser in comparison with electron beam power could not be readily correlated, to ask Thomas Electronics, Inc. to mount the crystal in their demountable vacuum chamber for testing.

Mr. Thomas St. John and Mr. A. R. Tucker of Trident International, Inc. traveled to Thomas Electronics' facility in Wayne, NJ to run the tests. Thomas Electronics was very cooperative and aluminized the Ce:BEL crystal and placed it in the chamber. Testing revealed the crystal in the vacuum could not dissipate the heat and rapid thermal saturation became immediately apparent. The crystal was allowed to cool for 80 minutes and retested in short current applications allowing the Ce:BEL to cool between measurements. The results indicate that the high temperatures reached in the first attempt did no damage to the crystal.

The test set-up at Thomas was capable of 28 kv @ .600 ma. The crystal had to be held by two clips in the vacuum chamber which apparently caused asymmetrical heat conduction. The crystal broke during a power application of 28 kv @ .450 ma. It was noted that the aluminization was being precipitated off the crystal at those power levels and temperatures. Light outputs projected by Allied Signal, Inc. of up to 1.2 lumens per watt could not be verified.

It has not been determined if the Ce:BEL is the desired chemical composition to produce the optimum blue faceplate at this time. It has not been determined if the CE:BEL can be grown in large enough crystals to be useful or if the structure is stable enough to withstand the mechanical and thermal stresses. The expansion coefficient of Ce:BEL (blue) crystal has not been measured adequately and attempts to seal with gradient frit-toglass techniques have not been successful to date. N61339-91-C-0052

Several attempts have been made to frit seal bond the Ce:BEL (Blue) faceplate onto a ceramic ring which is itself bonded to the glass bulb. On each occasion an apparent expansion rate mismatch occurs between the Ce:BEL faceplate and the ceramic ring.

In order to accelerate the Ce:BEL SCFP evaluation we attempted to replace the frit seal area with a vacuum grade epoxy (Torr Seal epoxy made by Varian Company). The advantage of using this epoxy is that it removes the expansion rate mismatch differentials by joining at room temperature, not 450 degrees C. This material is used for vacuum applications at 10% Torr and below. It is bakeable to 150 degrees C and has a dielectric strength compatible to the frit it replaces. The expansion rate of the Torr Seal epoxy is significantly different from the expansion rate of the Ce:BEL faceplate and ceramic ring; but, ioining and operation of these parts at room temperature development of thermally induced expansion eliminates the The remaining Ce:BEL: crystal fractured before this stresses. seal could be tried. No successful blue (Ce:BEL) CRT was made.

5.0 Tests of Blue Single Crystal Faceplates

The cathodoluminescence of Ce:BEL was characterized in a thin wafer of a Czochralski boule prepared from a melt of 0.5% cerium content. Ce:BEL proved to be an excellent blue phosphor with a peak fluorescence at 485 nm and a fluorescence bandwidth of 80 nm (Fig. #1). Thus, there is significant light energy at the extremely blue wavelength, 445 nm. The measured cathodoluminescent efficiency of the available crystal was 0.1 lumen/watt, weighted according to the C.I.E. photoptic curve. It was found that annealing at 1150 degrees C in a reducing atmosphere of 10% hydrogen in argon doubles the efficiency of Ce:BEL to 0.2 lumens/watt (Fig. #2). Annealing also changes the appearance of the crystals from an orange color to transparent. It was also found that the light output of Ce:BEL does not saturate up to an electron beam power of 19 watt/cm squared if adequately cooled.

Mass spectroscopy of the CE:BEL crystal revealed a cerium content of 3.9×10 to the eighteenth power atoms/cc, as compared with 23×10 to the eighteenth power atoms/cc for YAG. If cerium content of CE:BEL can be increased to the level of cerium in YAG, this six-fold increase in concentration could increase the C.I.E. weighted efficiency of CE:BEL to 1.2 lumens/watt. Since the refractive indices of CE:BEL are about the same value as the refractive index of YAG, reticulation or stippling should yield an increase in external efficiency.

Attempts to incorporate Ce:BEL (Blue) .75" crystals failed by cracking during bakeout or shortly thereafter. No successful blue CRT has been constructed. Blue (CE:BEL) crystal fragments were placed in a vacuum demountable chamber at Thomas Electronics, Inc. and tested. The light output was an excellent blue (420 nm), but because the crystal could not be cooled in the vacuum chamber, saturation was rapidly reached. By pulsing the current and allowing the crystal to cool between tests additional data was obtained (See Figs. #3, 4 and 5).

Methods of matching the CE:BEL crystals' expansion coefficient with the frit seal to a glass envelope or possibly a metal to glass seal need to be tried. Ce:BEL (blue) efficiencies indicated by Allied Signal, Inc.s' study for Trident International, Inc. dated Feb. 1992,), Enclosure #12.1) indicate up to 1.2 lumens per watt are possible. Other blue generating phosphors need tested to fully evaluate their to be possibilities.

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CE: BEL EPITAXIAL CRYSTAL TESTS (UNMOUNTED)

June, 29, 1993 IMAGE SIZE (.5 X .5) INCHES



Figure 3



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EL CRYSTA	·	0.25	19.0	0017		Χ.5	.250	0017		28	00	0.45 12.6	0/30		50.4	0.0 (CRYSTA 470 (PULSED	0.00 0.82	0.06 (STARTE	•
FROM CE:B		0.25	19.0	0.0017 0.		.5 X.5 .5	0.250 0	0.0017 0.		25	00	0.45 11.25	5750/30 1575		45.0	0.0 420	0.00	90.0	
INC.		0.25	0.64	0.0017		.5 X.S	0.250	0.0017		25	00	0.3	5750/30		30.0	0.0 373	0.00	0.09	CRYSTAL
NICS.		0.25	0.64	0.0017		.5 X.5	0.250	0.0017		25	0.2	0.2 5	5750/30 1		20.0	66.0 252	0.11	0.02	V HIGH RRENT TO PH)
ELECTRO		0.25	0.64	0.0017		.5 X.5	0.250	0.0017		25	0.15 3.75	0.15 3.75	15750/30 1		15.0	96.0 175	0.17	0.04 0.08	POWER APPL UST BE VER PULSED CUI G.(SEE GRM
THOMAS	. 110.2	0.25	\$9.0	0.0017		5 X.5	0.250	0.0017		25	0.1 2.5	00	15750/30		9.0	122.0 0	0.21	0.00	NG AS MORE I CHAMBER M SO MIN.THEN M. QUENCHIM
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DAIA) د	0.25	9.64	0.0017		.5 X.5	0.250	0.0017	70	25	0.007	00	15750/30	FOCUSED	0.0	7.60	0.00	0.08	SANPLE AL LA TENP.OF CRYS HO HAY OF NE ALLONED CRYS TO SEE EFFI
	29-JUNE-93 IAL FACEPLATE(NOT MOUNTE	E SIZE(50.°.5 X .5)	: SIZE(SQ.CH.)	EE1	HOR TYPE(COLOR)BLUE	AREA, INCHES	NOD.AREA(PEAK POVER) E SIZE(SQ.INCHES)TES	EET , IEST	(NG (TENP.F)	VOL TAGE (KV.)	CURRENT(AMPS.)TEST#1 5 TO TARGET	CURRENT(AMPS.)TEST12 5 10 TARGET	P FREQ.	SIZE(LINE NIDTH)	.IN.	HTNESS FL. TEST#1 HTNESS FL. TEST#2	TOUTPUT(LUNENS)TESTAL FOUTPUT(LUNENS)TESTA2	NS PER NATT, TESTAL NS PER NATT, TESTAL	ENTS:

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Figure 5

6.0 Tests of Red Single Crystal Faceplates

The fluorescent spectrum of cerium in single crystal faceplates may be shifted toward the red from the green by incorporating gadolinium and grown to Ce:(Y,Gd) on YAG. The spectral peak is approximately 50 um toward the red (580 um) compared to 535 um of green Ce:YAG. Light output at the desired red peak of 650 um is 31% of the spectral peak compared to 19% Using absorption filters such as Schott OG 570 (See for Ce:YAG. Fig. #6) will produce adequate red energy to generate the 29% of total energy of white to produce a white image. A 1.5" SCFP CRT was manufactured by Hughes Display Products from crystals furnished by Trident International, Inc. grown by Allied Signal, Inc. This CRT was tested by Trident International, Inc. The test results as shown in Figs. #7, 8 and 9). The CRT failed during tests, but sufficient data was obtained to determine its relative efficiency and color spectrum. The failure was not related to the crystal composition and the CRT construction techniques developed in 3" green Ce:YAG faceplates and successfully integrated onto a CRT will be used in further manufacturing.



Yellow, Orange and Red Sharp Cut-Off Glass Filters

		Correction	
Schott Glass	$\overline{7y}$	Factor	PRODUCT
Туре		$(t_i t_2)$	NUMBER
GG 400	0.07	0.91	03 FCG 057
GG 420	0.07	0.91	03 FCG 059
GG 435	0.07	0.91	03 FCG 061
GG 455	0.08	0.915	03 FCG 063
GG 475	0.09	0.915	03 FCG 065
GG 495	0.10	0.915	03 FCG 067
OG 515	0.11	0.915	03 FCG 083
OG 530	0.12	0.915	03 FCG 085
OG 550	0.13	0.915	03 FCG 087
OG 570	0.14	0.915	03 FCG 089
OG 590	0.15	0.915	03 FCG 098
RG 610	0.16	0.915	03 FCG 101
RG 630	0.17	0.915	03 FCG 103
RG 645	0.17	0.915	03 FCG 105
RG 665	0.17	0.915	03 FCG 107

 $\frac{\Delta\lambda}{\Delta T}$ is the temperature coefficient of half-power point position shift, in nm' $\frac{\Delta\lambda}{\Delta T}$ °C. See text.



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Fig. 8. Cathodoluminescent spectrum (detail) of a Ce:Y2Gd1Al5O12 phosphor layer grown on a YAG substrate.

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Red Shifted Ce:Y,Gd,YAG 1.5" Single Crystal Faceplate CRT #11-114-2-1 Test Date 17 August 1992

Raster Size .6417 sq in (.9055" X .7087") Aluminized, Non-Reticulated

High Volt (KV)	Beam "I" (ma)	Light Output (fl)	Power (W)	Lumens	L/W	Coolant Temp o/F
30.28	.048	269	1 45	1 1097		
30.34	.051	304	1 547	1 2547	.02	70
30.34	.055	359	1.54,	1.5547	.0/	78
30.35	.062	465	1 88	2.0	.90	78
30.36	.085	786	2 59	2.0	1.1	78
30.36	. 124	1294	2.30	J.J E 76	1.30	/8
30.37	103	2100	5.70	5.70	1.53	78
30.38	301	2540	D.00	9.70	1.00	78
30.38		5340	9.14 42 E	15.//	1.72	78
30.39	408	551U A000	13.5	23.00	1./5	78
30 42	502	4300	12.4	22.2	1.79	78
30.42	·303 557	01/U 6700	15.32	27.5	1.79	79
20.42	.007	0780	16.97	30.16	1.78	79
20.43	.000	8050 .	20.95	35.9	1.71	81
30.43	•/54	8/00	12.00	38.77	1.68	82
30.44	.142	1600	4.30	7.13	1.65	82
30.4/	./00	8200	21.00	36.54	1.74	83
30.40	1.08	11240	30.46	50.	1.64	83

Figure 9

7.0 Test Results of Deliverable Monochrome Projector (Green)

The raster line width measurement was measured by projecting on a screen. The green (CE:YAG) SCFP projector had an HD6 (U.S. Precision, Inc.) wide angle lens installed and a square image projected. The image size on the SCFP CRT was 1.626" square. The projected image was 28.625".

28.625"

 1.626^{H} = 17.6 X magnification

The line width at various beam currents and high voltages were measured. Faceplate brightness was taken using a Tektronix luminous probe J6523 1 degree spot brightness meter. The CRT brightness was measured through the lens looking at the CRT. This measurement does include all the losses of the lens, X-ray glass, fluid and YAG faceplate. Measurements were then taken at A standard magnesium flashed block was used at the the screen. screen surface to measure foot lamberts. The test results are shown in Figs. 10 through 13. Considerable crystal edge illumination was noted and also there was noticeable halation on the highlights. The test setup did not have liquid coupling to the lens but did have fluid to the X-ray window. The lens was coated for first surface reflections, but the X-ray window was not.

The graphs in Figures 10 and 11 were derived from data shown on Page 17, Figures 12 and 13. The test results shown by Figure 12 were run to measure spot (line width) growth at constant power with high voltage change. The line width decreased from .0046" to .0034" with high voltage increase from 20 kv to 30 kv indicating improved resolution possible with higher anode voltages. The line width measurements were taken by projecting the image on a screen to enable the individual scan lines to be observed. A micrometer was used to measure from skirt to skirt. Several lines were measured in the center of the image. This method will give larger line width readings than those normally quoted when a slit scanner is used. Measurements shown in Figure 13 were an attempt to verify losses through the optical system. Discrepancies occur because of the poor measurement ability in taking the faceplate brightness through the projection optics. The Tektronix one (1) degree spot brightness probe's subtense is not accurate under these conditions, but the screen measurements are correct.

Example pertaining to data in Figure 13: The transmission should be as follows: (HD6 lens .91)(X-ray glass .894)(Fluid .99) = Total .8054 F:1 lens efficiency .2 113.80 lu at the CRT face should generate 3.5 fl at the screen. (113.8)(.8054)(.2) = 18.60 divided by screen area 5.3166 sq.ft. = 3.5 fl.





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Figure 11

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Ce:YAG Single Crystal Faceplate Resolution (Line Width) Versus High Voltage @ Constant Power Epitaxial Thickness 17 um

<u>Watts</u>	Beam Current	H.V. <u>(kv)</u>	Line Width @ Screen	Line Width 0 CRT
1.8	.09 ma	20	.081"	.0046"
1.8	.08 ma	22.5	.079"	.0045"
1.8	.072 ma	25	.068"	.0039"
1.8	.065 ma	27.5	.060"	.0035"
1.8	.060 ma	30	.059"	.0034"

Figure 12

Ce:YAG Single Crystal Faceplate CRT Mounted in Trident Test Bed Projector CRT Crystal #10212-1-2 3" Epitaxial Thickness 17 um

Brightness Measurements

Faceplate Image Size:	1.25" Wide x 1.98" High 2.475 sa. in0172 sa. ft.
Screen Image Size:	22" Wide x 34.8" High 5.3166 sq. ft.

H.V. (kv)	Faceplate Lumens*	<u>Watts</u>	Faceplate Brightness (fl)	Lu/W**	Screen Brightness	Screen Lumens*
27	6.88	3.10	400	2.22	.21 FL	1.11 Lu
27	10.32	4.43	600	2.33	.32 FL	1.70 Lu
27	16.03	5.67	932	2.83	.50 FL	2.66 Lu
27	22.36	6.92	1300	3.23	.70 FL	3.72 Lu
27	29.24	9.69	1700	3.01	.90 FL	4.78 Lu
27	58.48	19.84	3400	2.95	1.80 FL	9.56 Lu
30	19.51	6.21	1134***	3.14	.60 FL	3.19 Lu
30	45.50	14.40	2645***	3.25	1.40 FL	7.44 Lu
30	81.30	26.10	4726***	3.11	2.50 FL	13.29 Lu
34	25.90	6.80	1511***	3.80	.80 FL	4.25 Lu
34	59.80	17.00	3488***	3.52	1.85 FL	9.80 Lu
34	113.80	32.00	6616***	3.55	3.50 FL	18.60 Lu

* Lumen calculation: Brightness X sq. ft. screen image area
** Lu/W calculation: Lumens divided by watts
*** Calculated number based on optical efficiency of .1635

Figure 13

8.0 Study of Optical Coupling and Anti-Reflective Coatings

A study was contracted from Optical Research Associates in Pasadena, CA. (Enclosure #12.2), to determine the optical effects of using single crystal faceplates for CRT's in projection. The study compared the effects of the high refractive index of YAG crystal (1.832) to the existing glass faceplate (1.537) used in powder phosphor CRT's.

The goals were to minimize losses at the refractive index change boundaries and minimizing the incident reflected ray causing halation effects and to determine the optimum index matching fluid as well as optically coupling the faceplate to the optical system.

Trident International, Inc. has used liquid optical coupling in its high power, high resolution projectors for many years. The practicability of this cooling and coupling approach has been proven.

To accommodate the increased "light piping" (total internal reflection due to the critical angle effects), a thicker liquid chamber with black walls (See Fig. #14) is recommended to minimize internal scattering and contrast reduction. Interference coatings at the first highly concave element of the projection lens will aid in collection of energy from the SCFP CRT. Figure #1 in Optical Research Associate's study shows such a lens.

Graphs showing selected absorption filters to trim the spectral output of Ce:YAG, Ce:Gd,YAG and Ce:BEL single crystal faceplates and peak output versus NTSC standard points are shown in Figures 15 through 18 from tests taken by Trident International, Inc.



VIEW A



Figure 14



Figure 15

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Figure 16



Figure 17



Figure 18

9.0 <u>Comparison of a Contemporary Powder Phosphor Versus Single</u> Crystal Faceplate CRT Projectors

The following is an analysis and a comparison of the power requirements of a contemporary powder phosphor versus single crystal faceplate CRT projector with a 2046 faceplate lumen output as a constant.

A. A typical powder phosphor projector using a CRT with a 6.15" X 4.87" raster (so called 9" CRT) has the following:

31.68 sq.in. area or .022 sq.ft. per tube.

High voltage is 35 kv at an average beam current of 1.5 ma per tube.

The Trident projector is capable of reaching approximately three times the average power in small scene highlights. Using the powder phosphor efficiencies of 23 to 30 lu/watt green, 13 to 15 lu/W red and 6 to 8 lu/W blue

			Watts	Lumens
Green	P53	23 Lu/w	52.5	1207
Red	P22R	13 Lu/w	52.5	682.5
Blue	P22B	8 Lu/w	52.5	420

To obtain white balance the energy needs to be distributed as follows:

59% Green	1207 lu	52.5 Watts
26% Red	532 lu	41.0 Watts
15% Blue	307 lu	38.4 Watts
Total	2046 Lu	132.0 Watts

or white efficiency of 15.5 lumen/watt. If we use an F:1 lens system, the optical efficiency will be:

F:1 lambertion cone = 20% of energy collected.

A typical coated lens will have a transmission of 88% or (.2)(T.88) = .1760.

The light available at the screen with average power will be 2046 lu (.1760) = 361 lumens. The peak brightness that is usually quoted on CRT projectors then can approach 1,000 lumens equivalent brightness (2.88 X 361 lumens).

B. Using the efficiencies of single crystal faceplate CRT's determined by testing and reported in Allied Signal's report to Naval Training Systems Center Contract N61339-90-C-0046, August, 1991 and AT&T Bell Laboratories' Report AFWAL-TR-84-1185, dated July, 1984 and Trident International, Inc.'s report under Contract N61339-90-C-0047 and tests run during this contract, we can assume that reasonable efficiency expectations are:

	Ce:YAG (Green)) 4	- 5 1	u/W	
(Ce:Gd,Ag (Red)	2.5	5 - 3.5 1	u/W	
(Ce:BEL (Blue)	.7	7 - 1.2 1	u/W;	
therefore,	to generate t	he equ	ivalent	light output	we need:
	•	Eff	iciency	Watts	Lumens
	Green	@4.5	lu/w	268	1207
	Red	3	lu/w *	177	532
	Blue	1	lu/w	307	307
			-	752	2046

(* includes absorption filter)

This above comparison concludes that 2.72 lumens per watt for white balance in single crystal faceplate efficiency versus 15.5 lumens per watt for powder phosphor efficiency.

The possible advantage that single crystal faceplate CRT;s would have is their ruggedness against electron beam damage and practically infinite particle resolution versus powder phosphor grain size. Any image that is repeatedly scanned over the same screen area will cause reduction of light output in powder phosphor within a few hours particularly at the phosphor loading used in high power projectors. This is particularly true if the deflection system uses calligraphic or stroke writing to generate small bright lines or spots.

To generate the higher electron beam power necessary to overcome the 5.5 to 1 difference in efficiencies, the electron beam spot size will increase. To conserve resolution the high voltage to beam current ratio would have to be changed; such as, 50 kv vs 25 kv. The increase in high voltage will require additional X-ray shielding as well as increasing the absorption properties of the optical system.

Nothing in the above discussion precludes the use of single crystal faceplate projectors in lower light output application where images require prolonged stationary lines or spots; such as, maps, rail routes, communication lines or status boards of reasonable dimensions.

10.0 Conclusions

A. Powder phosphor faceplates are approximately five (5) times more efficient per input power than Ce:YAG single crystal faceplates.

B. Single crystal faceplates appear impervious to high beam power densities when adequately cooled.

C. Manufacturing problems associated with integrating single crystal faceplates onto CRT envelopes are not solved to the extent that practical fabrication processes are available. While some success was achieved with the Ce:YAG (Green), integration for the Ce:BEL was not achieved. Extensive materials and manufacturing process research would be necessary prior to any further initiatives in the projector application area.

D. The electron beam power requirements to produce equivalent light output to a powder phosphor based CRT system are so great that the electron beam spot size resulting from the high power input will limit the resolution on the maximum available faceplate size; therefore, the 1,000 line resolution specification cannot be met at required brightness levels.

E. Satisfactory spectral responses are attainable in all three colors (red, green and blue); however, mechanical problems with Ce:BEL currently preclude its use as a light source.

F. Early data taken indicating the ability to obtain high levels of brightness without saturation and coulombic destruction of the phosphor was confirmed; however, scaling of the power required for obtaining desired light output resulted in an unacceptable loss in resolution due to electron beam spot size growth.

11.0 Recommendations

In view of the problems remaining to be solved and the limited potential for their solution, further development effort on application of Single Crystal Faceplates to projection cathode ray tubes is not recommended.

12.0 Enclosures

12.1	Single	Crystal	Phosphor	Face	plates	for	High
Resolution,	High	Intensity	Cathode Ra	y Tubes	by All	ied-Si	gnal,
Inc., Morri	stown,	NJ., P.O.	#9166 for	Trident	Internat	ional,	Inc.

12.2 The Study of the Performance of a YAG Faceplate, dated February 3, 1992, by Optical Research Associates, Pasadena, CA. for Trident International, Inc. Final Report

SINGLE CRYSTAL PHOSPHOR FACEPLATES FOR HIGH RESOLUTION, HIGH INTENSITY CATHODE RAY TUBES

Purchase Order No. 9166

Submitted By

Applied Physics Laboratory ALLIED-SIGNAL INC. Research and Technology P.O. Box 1021 Morristown, New Jersey 07962-1021

Submitted To: Trident International Inc. Central Florida Research Park 3290 Progress Drive Suite 155 Orlando, Florida 32826



Single Crystal Phosphor Faceplates for High Resolution High Intensity Cathode Ray Tubes

a study for

Trident International, Inc. Central Florida Research Park 3290 Progress Drive, Suite 155 Orlando, Florida 32826

by

D.M. Gualtieri Allied-Signal, Inc. Research and Technology P.O. Box 1021 Morristown, NJ 07962-1021

February 1992

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1.0.0 INTRODUCTION

Conventional CRT faceplates are formed by the deposition of phosphor powder on the inside of a glass envelope of limited thermal conductivity. The image resolution and power capabilities of these faceplates are limited, and many applications now require CRT performance at the limits of phosphor faceplate technology. For example, sunlightreadable head-up displays (HUDs) for aircraft require a brightness of 10,000 footlamberts, a performance just achieved by conventional CRTs in stroke mode, and a factor of ten beyond that achieved in raster mode. The resolution of conventional faceplates is limited by phosphor particle size to twenty micrometers. High intensity operation is limited by a decomposition threshold of about 1 watt/cm². The phosphor particles will actually melt at about 5 watts/cm². High intensity operation also limits phosphor lifetime by a process called coulombic degradation. This failure mode reduces the intensity of P53, a standard phosphor, to 50% of its initial value after an electron dosage of 140 coulombs/cm². This leads to a CRT lifetime in a high luminance application of about 1000 hours under the best conditions. Garnets are crystalline materials with many technologically useful properties. Garnets are oxides of the general composition R3T5O12 (R and T are large and small metal or metalloid elements) which are resistant to chemical attack and high temperatures. There is much diversity in garnet composition since R and T can be combinations of one or several elements cohabiting a crystal sublattice, and R and T range over much of the Periodic Table. As an example, the yttrium in Y3Al5O12 (YAG) can be partially replaced with neodymium to form the useful laser crystal Nd-YAG. YAG is used not only as a laser material, but as a substrate for the deposition of other garnet compositions. In particular, YAG doped with rare-earth elements, when grown as epitaxial layers on YAG substrates, is a cathodoluminescent material. Such layers can be used as phosphor faceplates in cathode ray tubes with significant advantages over standard, powder phosphor, faceplates. The single crystal nature of such epitaxial faceplates allows a higher resolution, and the intimate thermal contact between the epitaxial phosphor and the thermally conductive substrate allows operation of cathode ray tubes at power levels which would destroy a conventional powder phosphor.

Epitaxial phosphors are fluorescent crystalline layers which are grown on crystalline substrates. The usual case is homoepitaxial growth, in which a fluorescent ion is substituted for another ion in a host composition epitaxially grown onto a substrate of the host composition. An example is Ce:YAG epitaxially grown on YAG substrates, where cerium is incorporated into the layer on yttrium sites. The more unusual case is heteroepitaxy, in which a layer is grown on a substrate of different crystal structure; for example, zinc sulphide deposited on sapphire. Since electrons penetrate only a few microns into epitaxial phosphors, the epitaxial layer need not be very thick, 5-20 microns are usually sufficient. Epitaxial layers can be grown on top of other epitaxial layers to form penetration phosphors, in which different colors are excited at different anode potentials.

Epitaxial phosphor faceplates (EPF) have several significant advantages, which are summarized below:

- 1) Ultra-High Resolution. Resolution is limited only by electron beam size.
- 2) Fast Decay Time. Fluorescence decay of Ce:YAG (10 nsec), a standard epitaxial phosphor, is an order of magnitude faster than conventional powder phosphors.
- 3) High Power Operation. Epitaxial phosphors will not decompose at high power levels. There is no "burn". Thermal quench temperature is much higher than for powder phosphors.
- 4) Superior Ageing Characteristics. No coulombic degradation.
- 5) Superior Mechanical Properties. Single crystals have high strength. Faceplates resist scratching.

Since epitaxial phosphors are single crystals with no granulation, resolution is limited only by the dimension of the electron beam. Prof. Albert Crewe of the Fermi Institute, University of Chicago, has tested a Ce: YAG epitaxial phosphor faceplate fabricated by Allied-Signal, Inc. in a high resolution electron microscope and found no granulation to 0.1 μ m spot size. This Ce: YAG epitaxial phosphor faceplate was further tested to a current density of 1000 A/cm² at 5 kV without permanent damage. M.W. van Tol and J. van Esdonk operated epitaxial phosphor faceplates at power levels of 10 W/cm² [1]. J.M. Robertson and M.W. van Tol tested epitaxial phosphor faceplates of Ce: YAG,
Tb:YAG, and Eu:YAG at power levels to 10^4 W/cm² [2]. They found that Ce:YAG is linear to the highest power levels, but that the light output of Tb:YAG and Eu:YAG saturates at power levels above 1 W/cm². Thus, Ce:YAG is preferred as a high intensity monochrome phosphor. The saturation in Tb:YAG arises from excited state absorption and cross-relaxation processes and it is a general feature of many phosphors, for example Mn:BaAl12O19 [3,4]. AT&T Bell Laboratories has developed a modified terbium composition, Tb0.2Y0.1Lu2.7Al3Ga2O12, with improved saturation characteristic [5]. Such a phosphor has shown a peak line brightness of 28,000 fL at a 25,000 inch/sec writing speed when excited with a 25 kV, 2 mA beam. This is equivalent to 594 lumens in a 2.75 inch diagonal raster.

Levy and Yaffe have shown that the thermal quenching temperature of Ce:YAG is about 400°C, and that a decrease in light output is first evident at 200°C [6]. They determined that it is safe to operate an EFP at thermal gradients up to 150°C/inch, and that a three inch diameter epitaxial phosphor faceplate can be operated at 25 watts excitation with no cooling. Since the thermal conductivity of YAG is high, forced-air cooling is very effective at higher excitation levels. Forced-air cooling can extract about 60% of the heat, radiation can dissipate about 20% of the heat, and conduction down the neck can dissipate the remaining 20%. Coulombic degradation does not occur in epitaxial phosphor faceplates, whereas 0.5 W/cm² is the conventional limit for projection CRTs. Operation of P53 at 0.5 W/cm² results in an extremely short lifetime.

The fluorescent spectrum of cerium in garnet crystals is a function of the atomic spacing in the crystal which is reflected in the lattice constant. It is possible to red-shift the green emission of Ce:YAG by incorporation of gadolinium. In the extreme case, Ce:Gd3Al5O12 can be grown as the analog of Ce:Y3Al5O12, and the spectral peak is shifted almost 50 nm towards the red. A blue-shift is possible, by using a small rare-earth ion in place of yttrium, but the magnitude of such a blue-shift is not sufficient to produce much energy at blue wavelengths suitable for color CRTs. Although other activators in YAG, notably thulium, are blue emitters, cerium seems to be the only activator which will not saturate at high power levels. Two blue cerium emitters, Ce:La2Be2O5 (Ce:BEL) and Ce: Y2SiO5 (cerium orthosilicate), are candidates for blue faceplates. Ce: Y2SiO5 has emission extending below blue, so that much of its light output is not visible. Its performance in CRTs has been investigated by AT&T Bell Laboratories and elsewhere, and saturation has been observed in this phosphor. Ce:BEL, however, emits prominently in the blue, and does not appear to saturate. Thus, Ce:Gd3Al5O12 (Ce:GdAG, red), Ce:Y3Al5O12 (Ce:YAG, green), and Ce:La2Be2O5 (Ce:BEL, blue), appear to be an appropriate trio of epitaxial phosphors for a high intensity color projection display. Figure 1.0.0.1 shows the spectra of these phosphors.



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Fig. 1.0.0.1 Spectra of Ce:BEL (blue), Ce:YAG (green) and Ce:GdAG (red) phosphors.

2.0.0 PROCESS

Table 2.0.0.1 shows the major stages of the process for the production of epitaxial phosphor faceplates.



Epitaxial Phosphor Faceplate Process



5

2.1.0 Crystal Growth Process of Substrate Wafers

There are presently two processes which are suitable for the growth of the substrate wafers used in epitaxial phosphor faceplates. These are the Czochralski method, which has produced large single crystals of YAG up to three inches in diameter; and the Heat Exchanger Method. The Heat Exchanger Method (HEMTM) is being used for the commercial production of 10-inch diameter sapphire crystals of very high quality. It is possible to grow sapphire by HEM free of scattering centers for stringent optical applications. HEM is used also for commercial production of multi-crystalline silicon ingots for photovoltaic and optical applications. Titanium-doped sapphire (Ti:Sapphire) boules are grown routinely for cw and pulsed laser applications. A number of mixed oxides, fluorides and compound semiconductors has also been grown by HEM.

2.1.1 Undoped Crystal Boule

Substrate wafer crystal for epitaxial phosphor faceplates of YAG have been produced up to three inches in diameter by the Czochralski process. In the Czochralski process, a melt is produced in a crucible by induction heating. A "seed" crystal is dipped into the melt and withdrawn with rotation at a slow rate as the melt is cooled. This produces solidified crystal on the seed with the same crystallographic orientation as the seed. Usually crystal weight is used as a process variable to control the growth in a feedback loop.

There are difficulties involved in the growth of large diameter Czochralski crystals. The crystal is in contact with the liquid melt, and in the case of YAG it is actually immersed in liquid. This leads to considerable thermal stress on the crystal which can cause cracking. Also, scale-up from one diameter to a larger diameter is troublesome, since the exact parameters for stable crystal growth depend critically on the thermal environment of the crystal. There is a steep "learning curve."

In the HEM method, he crucible with the seed positioned at the bottom is loaded with a material charge and placed on top of a heat exchanger. After evacuation, heat is supplied by the graphite heater and the material charge is melted. The seed is prevented from melting by forcing gaseous helium through the heat exchanger. Growth is started after sufficient meltback of the seed is achieved by increasing the flow of helium and thereby decreasing the heat exchanger temperature. The liquid temperature gradients are controlled by the furnace temperature, while the temperature gradient in the solid is controlled by the heat exchanger temperature. Crystal growth is achieved by controlling the heat input as well as the heat extraction. After solidification is complete, the gas flow through the heat exchanger is decreased to equilibrate the temperature throughout the crystal during the annealing and cooldown stage.

HEM is the only crystal growth process in which both the heat input and heat extraction are controlled. The heat flow is set up such that the heat input is from the sides and top of the crucible and the heat extraction is primarily through the heat exchanger at the bottom of the crucible. Under these conditions a convex solid-liquid interface is set up so that core-free crystals can be grown. The convexity of the solid-liquid interface can be controlled by changing the ratio of heat input and heat extraction. The independent liquid and solid temperature gradients are achieved without movement of the crucible, heat zone or crystal. After the crystal is grown, it is still in the heat zone and can be cooled at a controlled rate to relieve solidification stresses. This unique capability allows the growth of sapphire up to 32 cm diameter and weighing about 50 kg without cracking due to thermal stresses associated with such large sizes.

A distinguishing feature of HEM, as compared with the Czochralski, top-seeded process, is that the solid-liquid interface is submerged beneath the surface and is surrounded by the melt. Under these conditions the thermal and mechanical perturbations are damped out by the surrounding molten mass before reaching the interface. This results in uniform temperature gradients at the interface. In the Czochralski process, growth occurs at the melt surface where the local gradients vary sufficiently to cause solidification and remelting of the crystal. Precise control of the furnace and heat exchanger temperatures, combined with minimized thermal perturbations resulting from the submerged interface, gives HEM an advantage over the Czochralski techniques for growing high-quality crystals.

In HEM growth, after the crystal is grown, the temperature of the furnace is reduced to just below the solidification temperature and the helium flow is reduced at a desired rate. The whole crystal can, therefore, be brought to high temperatures to anneal the solidification stresses, followed by uniform cooling at a controlled rate to room temperature. Because *in situ* annealing is part of the solidification cycle, HEM can reduce the defect density. Further the last and most impure material to solidify is along the crucible walls, where it can be removed. These features of HEM produce uniform, growth and the only sapphire free of light scatter. In the case of sapphire and silicon, it has been demonstrated that once crystal growth parameters are established, large crystals can be grown. The HEM has been adapted for the growth of Ti:A12O3. HEM is cost competitive with Czochralski. The furnace is uncomplicated, automated, and well insulated, which results in low equipment, labor and energy costs.

2.1.2 Doped Crystal Boule

Single crystal boule may be produced with the activator ion grown into the crystal. There are both advantages and disadvantages to this technique. The principal advantage is that the subsequent deposition of the phosphor by liquid phase epitaxy is not required. The disadvantages relate to the difficulty in achieving as high an activator concentration as desired, maintaining the proper charge state of the activator, and the usually lower growth rate required for doped crystals.

One of the problems with doped crystals is the segregation coefficient of dopant in the host crystal. The segregation coefficient is the ratio of the concentration of a species in the crystal to that in the melt. If the segregation coefficient is low, there is a gradation in dopant concentration along the length of the crystal and it is necessary to grow crystals at low growth rates in order to maintain high quality. These problems are minimized as the segregation coefficient is higher and essentially there are minimal problems when the segregation coefficient is unity. For example, the segregation coefficient of Ti in A1203 and Nd in YAG is rather low, approximately 0.16. The growth of Nd-doped YAG for laser applications proceeds at about one-fifth the rate as for undoped YAG.

Ce-doped BEL has been produced in boule form, so that subsequent epitaxy of a phosphor layer is not required, but an anneal in a hydrogen atmosphere is required to bring the cerium into its reduced Ce³⁺ charge state. Likewise, the blue phosphor Ce:Y2SiO5 has been produced by AT&T Bell Laboratories as doped boule one-inch in diameter.

Researchers from Hitachi Chemical Co. [17] have reported growth of the similar crystal Ce:Gd2SiO5 in diameters to two-inch.

2.1.3 Current Size Limitations

The Czochralski method has produced YAG crystal up to three inches in diameter. Experience indicates that four inch crystal is a possibility, but only by a flat interface technique pioneered at Allied-Signal. However, a considerable development effort would be required to attain a process for the Czochralski growth of four inch YAG.

The Heat Exchanger Method (HEMTM) is being used for the commercial production of 10-inch diameter sapphire crystals of very high quality. The growth of YAG crystal to this diameter appears possible. These melting point of YAG (1950°C) is lower than that for A1₂O₃ (2040°C): therefore, current HEMTM furnaces are adequate for growing this crystal. In the case of sapphire (Al₂O₃) crystals grown by HEMTM, the processing is carried out under vacuum; however, it is expected that even though the host phosphor materials may be stable under vacuum, it may be necessary to control the atmosphere during growth of doped crystals. The candidate phosphor materials are compatible with using a molybdenum crucible and graphite resistance heat zone of the HEMTM furnace so that these crystals can be grown with existing HEMTM furnaces. In the case of BEL, it would be necessary to set up additional safety procedures for handling BeO raw material and BEL crystals because of their toxic nature.

2.2.0 Optical Fabrication of Wafer Faceplates

Fabrication of wafer faceplates from crystal boule is accomplished by standard techniques available in most optical shops. This involves centerless grinding of the crystal boule to diameter, xray orientation, wafer slicing with an ID saw, lapping and polishing. The requirement of the final polish is severe. This "epi" grade polish involves the use of a chemical-mechanical colloidal silica polish on a soft pad to produce a surface free of defects which would interfere with the subsequent epitaxial phosphor growth stage.

2.2.1 Grind and Slice Wafers

The crystal boule is first ground to the required diameter using a centerless grinding technique. After alignment of the crystal by xray diffraction, wafers are sliced by the type of saw ("ID" saw) used in processing of semiconductor wafers.

2.2.2 Lap and Polish

The sliced wafers are polished using finer grit until the saw damage has been removed (about 0.005 inch in the case of YAG) and the required flatness of about 1 μ m/inch has been achieved. A final polish ("epi" polish) is done with a colloidal silica suspension to achieve a polish beyond an optical polish into the regime of a polish on an atomic scale.

2.2.3 Current Size Limitations

Since the semiconductor industry is now fabricating wafers up to ten and twelve inches in diameter, it is concluded that wafer fabrication will not constrain the development of large diameter single crystal faceplates.

2.3.0 Liquid Phase Epitaxy Process

The following is a general procedure for the growth of epitaxial layers of Ce:YAG on YAG substrates. A YAG wafer, prepared by the processes in the previous sections, is carefully cleaned and mounted in a substrate holder which allows rotation and translation. Epitaxy is achieved by dipping the substrate into a platinum crucible holding the molten constituent oxides of the Ce:YAG composition in the proportions listed in Table 2.3.0.1.

Mole Fraction	Moles	Grams	
0.90282	3.44684	769.299	
0.01737	0.06632	6.762	
0.07524	0.28724	19.998	
0.00457	0.01745	3.941	
	0.00581	1.000	
1.00000	3.82367	801.000	
	Mole Fraction 0.90282 0.01737 0.07524 0.00457 1.00000	Mole Fraction Moles 0.90282 3.44684 0.01737 0.06632 0.07524 0.28724 0.00457 0.01745 0.00581	Mole Fraction Moles Grams 0.90282 3.44684 769.299 0.01737 0.06632 6.762 0.07524 0.28724 19.998 0.00457 0.01745 3.941 0.00581 1.000 1.00000 3.82367 801.000

The platinum crucible, 3-inches high by 2.25-inch diameter for epitaxial growth on one-inch diameter wafers, is placed in a vertical furnace. These powders are heated to 1050 °C, a temperature well above the melting point of the mixture, and allowed to "soak" for 24 hours. The melt is stirred for one hour at 1050 °C and 200 rev/min just before each layer growth. After stirring, the melt is cooled to the growth temperature of about 980°C in 45 minutes (melt saturation occurs at about 990°C).

The YAG faceplate wafers are thermally equilibrated above the melt surface for ten minutes, dipped to the melt surface, and rotated at 200 rev/min. for about ten minutes. The Ce:YAG epitaxial phosphor layer grows at a rate of about 1.5 μ m/min. After growth, the substrate with the epitaxial layer is raised above the melt, and the residual flux is spun-off by rapid rotation of 500 rev/min. Removal of the faceplate from the furnace to room temperature proceeds over the course of 90 minutes. This slow exit rate prevents thermal shock and cracking of the wafers. This entire process is done in a class 100 laminar flow hood. Remaining traces of solidified growth solution on the wafers are removed in a 40% solution of nitric acid at 90 °C. Layer thickness is measured by weight, using a density of 4.565 g/cc, the density of pure Y3Al5O12. Optical thickness measurement is not possible since there is no refractive index difference between the layer and the substrate.

2.3.1 Equipment

Fig. 2.3.1.1 shows the equipment involved in the liquid phase epitaxy process. There are motor assemblies to "dip" and rotate the wafers in the solution, but the major piece of equipment is the large-bore vertical tube furnace which heats and maintains the solution at about $1100^{\circ}C \pm 1^{\circ}C$.





2.3.2 Current Size Limitations

Liquid phase epitaxy is routinely carried out for wafers up to three inches in diameter in the preparation of magneto-optical materials. These wafers, however, are thin (0.020 inch) compared with YAG faceplate wafers (0.125 inch). Generally, a slower withdrawal rate from the epitaxy furnace is required for these thick wafers. Liquid phase epitaxy has been demonstrated on four-inch diameter by 0.020 inch thick wafers. There appears to be no fundamental size limitation for the liquid phase epitaxy process.

2.4.0 Photoreticulation

The major factor limiting the external efficiency of Ce:YAG phosphors is the high refractive index of the YAG substrate (1.84), which allows only rays less than a critical angle of 33° to be emitted from the faceplate. The remaining rays are waveguided to the

edges, so that only 16% of the cathodoluminescence is emitted from the faceplate. Higher external efficiencies can be expected from Ce:YAG through reticulation, a texturing of the epitaxial phosphor into structures which will focus the cathodoluminescence towards the observer. Non-reticulated epitaxial phosphors have low external efficiencies, since the cathodoluminescence is waveguided by the high refractive index of YAG to the edge of the faceplate.

P.F. Bongers, et al., [12] have etched grooves in the phosphor to increase the external efficiency. D.M. Gualtieri, et al. [13] have used a faceted epitaxial layer for the same purpose. D.T.C. Huo and T.W. Hou [14], have used photolithographic techniques to pattern a Ce:YAG epitaxial phosphor faceplate with an array of rectangular mesas. They were able to increase the external efficiency by a factor of three. A truncated cone geometry can increase the external efficiency by a factor of 5.5, if such a shape can be formed in the phosphor layer. Such reticulation will not limit the faceplate resolution if a small mesa size is used. The reticulation concept is shown schematically in fig. 2.4.0.1

Non-reticulated faceplates of Ce:YAG have an NTSC raster efficiency at 25 kV of 1.9 - 2.0 lumens/watt, when measured in our characterization station, so that at a beam power of 10 watts/cm² an NTSC raster of 2.75-inch diagonal on a *non-reticulated* Ce:YAG faceplate will have a luminance of 450 lumens. The best *reticulated* faceplate was found to give 5.38 lumens/watt at a beam power of 5 watt/cm². A beam power of 16 watt/cm² will be required for 2000 lumen output at such an efficiency. Fig. 2.4.0.2 shows the results of cathodoluminescent measurements on a reticulated faceplate.



Non-Reticulated Faceplate

Faceted or Reticulated Faceplate

Fig. 2.4.0.1. Schematic illustration of waveguiding effect in epitaxial faceplates, and the role of reticulation in directing light into the critical cone.



Fig. 2.4.0.2. Cathodoluminescent measurements on a reticulated faceplate.

2.4.1 Equipment

Photoreticulation is done by techniques common to fabrication of semiconductor devices. A mask aligner of micron resolution is required, typically a contact printer as distinct from a projector. A typical resist coater/developer/stripper line is required. Either a metallizer, such as an electron beam evaporator, or a plasma reactor for silica deposition are required to coat the wafers with an acid resisting mask for the etching stage. A phosphoric acid etcher is required. All this equipment must be sited in a class 100 clean room.

2.4.2 Current Size Limitations

Since the semiconductor industry is now fabricating wafers up to ten and twelve inches in diameter, it is concluded that this processing step will not constrain the development of large diameter single crystal faceplates.

3.0.0 FACEPLATE AND PHOSPHOR MATERIALS

3.1.0 Cerium Activators

Cerium seems to be the only activator which will not saturate at high power levels. Two blue cerium emitters, Ce:La2Be2O5 (Ce:BEL) and Ce:Y2SiO5 (cerium orthosilicate), are candidates for blue faceplates. Ce:Y2SiO5 has emission extending below blue, peaking at about 390 nm, so that much of its light output is not visible. A similar phosphor Ce:Gd2SiO5 has a better spectral overlap with the visible, peaking at 430 nm. The performance of Ce:Y2SiO5 has been investigated by AT&T Bell Laboratories and elsewhere, and saturation has been observed in this phosphor. Ce:BEL, however, emits prominently in the blue, and does not appear to saturate. Thus, Ce:Gd3Al5O12 (Ce:GdAG, red), Ce:Y3Al5O12 (Ce:YAG, green), and Ce:La2Be2O5 (Ce:BEL, blue), appear to be an appropriate trio of epitaxial phosphors for a high intensity color projection display.

3.2.0 Red Phosphors

3.2.1 Ce:(Y,Gd)AG on YAG

It is possible to epitaxially grow a red-shifted garnet composition on YAG wafer substrates. This garnet composition, Ce:Y2Gd1Al5O12, is strained with respect to the YAG wafer, and its red-shift is only about a third as large as that of Ce:Gd3Al5O12. This composition has a lattice constant (measured perpendicularly at the (444) reflection) about 0.4% greater than YAG, which is just under the typical facet limit of 0.5%. Figs. 3.2.1.1 and 3.2.1.2 show cathodoluminescence measurements for this composition. There is a red-shift of 20 nm, and, most importantly, almost a two-fold increase in the luminance at the red wavelength of 650 nm. The light output at 650 nm was 31% of the spectral peak for this composition, as compared to 19% for Ce:YAG. The cerium emission in the fully substituted garnet, Gd3Al5O12, would exhibit a larger red-shift, but it cannot be grown as an epitaxial layer on YAG.



Fig. 3.2.1.1 Cathodoluminescent spectrum of a Ce:Y2Gd1Al5O12 phosphor layer grown on a YAG substrate.



Fig. 3.2.1.2. Cathodoluminescent spectrum (detail) of a Ce:Y2Gd1Al5O12 phosphor layer grown on a YAG substrate.

3.2.2 Ce:GdAG on GdAG

Epitaxial layers of Ce:Gd3Al5O12 could be grown on Gd3Al5O12, and they would be good red faceplates in color projection systems since they would have a red-shift of about 50 nm.



Fig. 3.2.2.1. Calculated spectrum of Ce:Gd3Al5O12.

3.3.0 Green Phosphors

3.3.1 Ce:YAG

Cerium YAG is the material of choice for green epitaxial phosphors. Its cathodoluminescent spectrum appears as fig. 3.3.1.1.





Non-reticulated faceplates of Ce:YAG have an NTSC raster efficiency at 25 kV of 1.9 - 2.0 lumens/watt, when measured in our characterization station, so that at a beam power of 10 watts/cm² an NTSC raster of 2.75-inch diagonal on a *non-reticulated* Ce:YAG faceplate will have a luminance of 450 lumens. The best *reticulated* faceplate was found to give 5.38 lumens/watt at a beam power of 5 watt/cm². A beam power of 16 watt/cm² will be required for 2000 lumen output at such an efficiency.

3.4.0 Blue Phosphors

3.4.1 Ce:BEL

The cathodoluminescence of Ce:BEL was characterized in a thin wafer of a Czochralski boule prepared from a melt of 0.5% cerium content [16]. Ce:BEL proved to be an excellent blue phosphor with a peak fluorescence at 485 nm and a fluorescence bandwidth (FWHM) of 80 nm (fig. 3.4.1.1). Thus, there is significant light energy at the extremely blue wavelength 445 nm. The measured cathodoluminescent efficiency of the available, as-grown Czochralkski crystal was 0.1 lumen/watt, weighted according to the C.I.E. photoptic curve. It was found that annealing at 1150 °C in a reducing atmosphere of 10% hydrogen in argon doubles the efficiency of Ce:BEL to 0.2 lumens/watt (fig. 3.4.1.2). Annealing also changes the appearance of the crystals from an orange color to transparent. It was also found that the light output of Ce:BEL does not saturate up to an electron beam power of 19 watt/cm².

Mass spectroscopy of the Ce:BEL crystal revealed a cerium content of 3.9×10^{18} atoms/cc, as compared with 23×10^{18} atoms/cc for YAG. If the cerium content of Ce:BEL can be increased to the level of cerium in YAG, this six-fold increase in concentration could increase the C.I.E. weighted efficiency of Ce:BEL to 1.2 lumens/watt. Since the refractive indices of Ce:BEL are about the same value as the refractive index of YAG, reticulation will yield the same increase in external efficiency.



Fig. 3.4.1.1. Cathodoluminescence spectrum of Ce:BEL.



Fig. 3.4.1.2. Cathodoluminescent efficiency of Ce:BEL after hydrogen anneal.

3.4.2 Ce:Y2SiO5 and Ce:Gd2SiO5

Fig. 3.4.2.1 shows the cathodoluminescent spectrum of the blue emitting cerium activated phosphor Ce:Y2SiO5. Since the spectrum of Ce:Y2SiO5 peaks at about 390 nm, much of its light output is not visible, reducing its efficiency. The similar phosphor Ce:Gd2SiO5 has a spectrum which peaks at 430 nm.



Fig. 3.4.2.1. Cathodoluminescent spectrum of the blue emitting cerium activated phosphor Ce:Y2SiO5.

4.0.0 SCALE-UP CONSIDERATIONS

Table 4.0.0.1 summarizes the actual performance of two inch Ce:YAG faceplates and the predicted performance of three and four inch faceplates.

Table 4.0.0.1. Performance data for Ce:YAG faceplates.

	Demonstrated (2")	Predicted (3")	Predicted (4")	
Faceplate Luminance, fL	· 62,700	86,750	86,750	
Faceplate Efficiency, L/W	4.84	4.84	4.84	
Raster Size, in ² (cm ²)	1 (6.45)	3.63 (23.4)	5.88 (37.9)	
Beam Power, W	90	413	413	
Beam Power Density, W/cm	2 14	18	10.9	
Faceplate Output, L	435	2000	2000	

4.1.0 Crystal Growth Process of Substrate Wafers

The Czochralski method has produced YAG crystal up to three inches in diameter. Experience indicates that four inch crystal is a possibility, but only by a flat interface technique pioneered at Allied-Signal. However, a considerable development effort would be required to attain a process for the Czochralski growth of four inch YAG.

The Heat Exchanger Method (HEMTM) is being used for the commercial production of 10" diameter sapphire crystals of very high quality. The growth of YAG crystal to this diameter appears possible. These melting point of YAG (1950°C) is lower than that for A12O3 (2040°C): therefore, current HEMTM furnaces are adequate for growing this crystal. In the case of sapphire (A12O3) crystals grown by HEMTM, the processing is carried out under vacuum; however, it is expected that even though the host phosphor materials may be stable under vacuum, it may be necessary to control the atmosphere during growth of doped crystals. The candidate phosphor materials are compatible with using a moybdenum crucible and graphite resistance heat zone of the HEMTM furnace so that these crystals can be grown with existing HEMTM furnaces. In the case of BEL, it would be necessary to set up additional safety procedures for handling BeO raw material and BEL crystals because of their toxic nature.

Crystal Systems Inc. (Dr. Chandra P. Khattak, 27 Congress Street, Salem, MA 01970, Telephone (508)-744-5059) is proposing a program for development of the HEMTM method for crystal growth of candidate phosphor materials. The first phase is a feasibility phase followed by the development phase. During the feasibility stage it is intended to develop procedures so that the growth characteristics of these materials can be established. Crucibles approximately two inches in diameter would be utilized for this effort. It is expected that single crystal material samples would be available for testing for high resolution, high brightness video projection CRT applications. Close cooperation would be maintained with the user so that optimization of this material for the application can be achieved. The problems involved with growth of larger crystals would also be identified during this phase. The development phase will be undertaken depending upon the results of the feasibility phase. Crystal Systems Inc. expects that the feasibility phase could be completed in approximately a six-month time frame. The cost of their effort would be \$50,000 per candidate phosphor material. This cost does not include the raw materials, installation of additional safety features required for beryllium crystal growth, or crystal characterization.

4.2.0 Optical Fabrication

Since the semiconductor industry is now fabricating wafers up to ten and twelve inches in diameter, it is concluded that wafer fabrication will not constrain the development of large diameter single crystal faceplates.

4.3.0 Liquid Phase Epitaxy

Liquid phase epitaxy is routinely carried out for wafers up to three inches in diameter in the preparation of magneto-optical materials. These wafers, however, are thin (0.020 inch) compared with YAG faceplate wafers (0.125 inch). Generally, a slower withdrawal rate from the epitaxy furnace is required for these thick wafers. Liquid phase epitaxy has been demonstrated on four-inch diameter by 0.020 inch thick wafers. There appears to be no fundamental size limitation for the liquid phase epitaxy process.

4.4.0 Photoreticulation

Since the semiconductor industry is now fabricating wafers up to ten and twelve inches in diameter, it is concluded that this processing step will not constrain the development of large diameter single crystal faceplates.

5.0.0 COST ESTIMATES

The following cost estimates for the production of 100 and 200 faceplates per year are calculated on the basis of minimal dedicated facilities being constructed to accomplish each step necessary for the production of faceplates at these quantities. At the 100 and 200 faceplate per year levels, such minimal facilities would still be significantly under-utilized, and the cost per faceplate is high. Section 5.5.0 below contains estimates of faceplate cost with the assumption of 100% utilization of facilities. These costs for 100% utilization will be lower that those which can be anticipated from tolling these steps to outside vendors, perhaps by as much as 25%.

5.1.0 Crystal Growth Process of Substrate Wafers

The following table is an estimate of cost per wafer of substrate wafer growth for three inch and four inch diameter wafers at a 100 and 200 wafer per year production level. Note that the facility is not fully utilized at even the 200/year level.

Cost of YAG Substrate Wafer Crystal Growth at 100% and 80% Yield for Dedicated Facility (maximum facility utilization at 400 faceplates/year)

	Three-Inch Wafers		Four-Inch Waf	ers
	100/year	200/year	100/year	200/year
Capital Equipment (5 yr. amort.)	500	250	700	350
Laboratory Facility	600	300	600	300
Materials	150	150	300	300
Fabrication & Maintenance	35	35	50	50
Labor & Employee Overhead	175	175	225	225
Electrical Power	25	25	30	30
Environmental/Toxic Disposal	20	20	30	30
Cost per Wafer at 100% Yield	1505	955	1935	1285
Cost per Wafer at 80% Yield	1881.25	1193.75	2418.75	1606.25

5.2.0 Fabrication

The following table is an estimate of cost per wafer of substrate wafer polishing for three inch and four inch diameter wafers at a 100 and 200 wafer per year production level. Note that the facility is not fully utilized at even the 200/year level.

Cost of Wafer Polishing at 100% and 80% Yield for Dedicated Facility (maximum facility utilization at 800 faceplates/year)

	Three-Inch Wafers		Four-Inch Wat	iers
	100/year	2 0 0/year	100/year	200/year
Capital Equipment (5 yr. amort.)	400	200	450	225
Laboratory Facility	600	300	600	300
Supplies	20	20	25	25
Maintenance	5	5	5	5
Labor & Employee Overhead	50	50	50	50
Environmental/Toxic Disposal	10	10	15	15
Cost per Wafer at 100% Yield	1085	585	1145	620
Cost per Wafer at 80% Yield	1356.25	731.25	1431.25	775

5.3.0 Liquid Phase Epitaxy

The following table is an estimate of cost per wafer of phosphor epitaxy for three inch and four inch diameter wafers at a 100 and 200 wafer per year production level.

Cost of Unreticulated Epitaxial Phosphor Faceplates at 100% and 50% Yield for Dedicated Facility (maximum facility utilization at 200 faceplates/year)

	Three-Inch Wafers		Four-Inch Waf	lers
	100/year	200/уеаг	100/year	200/year
Capital Equipment (5 yr. amort.)	600	300	750	375
Laboratory Facility	600	300	600	300
Materials (less substrate wafer)	160	180	220	245
Fabrication & Maintenance	15	15	20	20
Substrate Wafer	1115	1115	1485	1485
Labor & Employee Overhead	175	175	225	225
Electrical Power	40	20	60	30
Environmental/Toxic Disposal	20	15	25	20
Cost per Wafer at 100% Yield	2725	2120	3385	2700
Cost per Wafer at 50% Yield	5450	4240	6770	5400

5.4.0 Photoreticulation

The following table is an estimate of cost per wafer of wafer reticulation for three inch and four inch diameter wafers at a 100 and 200 wafer per year production level. Note that the facility is not fully utilized at even the 200/year level.

Cost of Faceplate Reticulation at 100% and 80% Yield for Dedicated Facility (maximum facility utilization at 1000 faceplates/year)

	Three-Inch Wafers		Four-Inch Wafers	
	100/year	200/year	100/year	200/year
Capital Equipment (5 yr. amort.)	1150	575	1150	575
Laboratory Facility	800	400	800	400
Supplies (Chemicals, Photomasks)	400	200	450	225
Labor & Employee Overhead	60	60	75	75
Environmental/Toxic Disposal	20	15	25	20
Cost per Wafer at 100% Yield	2430	1250	2500	1295
Cost per Wafer at 80% Yield	3037.5	1562.5	3125	1618.75

5.5.0 Cost Summary

The following table is an estimate of cost per wafer of fully processed faceplates of three inch and four inch diameter at a 100 and 200 wafer per year production level. Note that these cost include idle equipment/workspace expenses at even the 200/year level.

Summary Costs of Epitaxial Phosphor Faceplates for Dedicated Facility

	Thr ee -Inch 100/year	Wafers 200/year	Four-Inch 100/year	Wafers 200/year
Cost per Unreticulated Faceplate	5450	4240	677() 5400
Cost of Reticulation	3037.5	1562.5	312	5 1618.75
Cost per Reticulated Faceplate	8487.5	5802.5	989	5 7018.75

The following table is an estimate of cost per wafer of fully processed faceplates of three inch and four inch diameter at a 100% utilization of facilities.

Summary Costs of Epitaxial Phosphor Faceplates for 100% Facility Utilization

	Three Inch	Four Inch
YAG Wafer Crystal Growth	850	1200
YAG Wafer Polishing	265	285
Bare YAG Wafer Ready for Epitaxy	1115	1485
Epitaxial Phosphor Faceplate (Unreticulated)	4240	5400
Photoreticulation	600	650
Reticulated Epitaxial Phosphor Faceplate	4840	6050

6.0.0 **RECOMMENDATIONS AND CONCLUSIONS**

Ce: YAG epitaxial phosphor faceplates are capable of 2000 lumens light output in either their reticulated or facet-textured form in a 2.75-inch diagonal raster. Higher light outputs can be obtained from larger diameter faceplates, but the largest available YAG crystals are presently three-inches in diameter. Single crystals of YAG greater than three inches in diameter can be obtained only after a further development of either the Czochralski or HEMTM techniques.

Wafer flatness is a requirement for photolithographic reticulation over a large diameter faceplate. Epitaxy requires a surface which is free of even the smallest scratch or defect. Thus, polishing of YAG wafers to higher flatness and perfection would be a suitable area for research.

The reticulation process involves etching in hot phosphoric acid. A rapid etching rate has to be used to effect the reticulation before the etching mask is dissolved. This technique is marginally successful, and defects are introduced into the faceplate as the mask is undercut in some areas. Further research on alternative masking materials and etching methods is necessary.

Reticulation is most effective when there is a minimum in the ratio of the mesa top to bottom area, but this pointed reticulation gives "ghost" images of the raster in the sixfold symmetry of the reticulation. This "ghosting" effect must still be quantified.

Ce:Gd3A15O12 (Ce:GdAG, red), Ce:Y3A15O12 (Ce:YAG, green), and Ce:La2Be2O5 (Ce:BEL, blue), appear to be an appropriate trio of epitaxial phosphors for a high intensity color projection display. Ce:BEL has not as yet been bonded to a CRT neck assembly, so that its suitability as a faceplate material is still unknown. Research on such bonding would be appropriate.

The growth of large crystals of Gd3Al5O12 as substrates for epitaxial red phosphor faceplates would be a suitable area for research.

Further research on alternative masking materials and etching methods, and quantification of the reticulation "ghosting effect, is also required.

Ce:Gd3Al5O12 (Ce:GdAG, red), Ce:Y3Al5O12 (Ce:YAG, green), and Ce:La2Be2O5 (Ce:BEL, blue), appear to be an appropriate trio of epitaxial phosphors for a high intensity color projection display. The growth of large crystals of Gd3Al5O12 as substrates for epitaxial red phosphor faceplates would be a suitable area for research.

The HEM[™] method seems to be the most appropriate path to large diameter crystals. This would require further development, as proposed by Crystal Systems, Inc.

Prepared for:

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TRIDENT INTERNATIONAL, INC. Orlando, Florida

Final Report

THE STUDY OF THE PERFORMANCE OF A YAG FACEPLATE

February 3, 1992

Prepared by:

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1.0 BACKGROUND

Trident International, Inc (TII) has funded Optical Research Associates (ORA) to undertake a study to determine the effects on the performance of a CRT of a change in faceplate material from a relatively low index of refraction glass (Nd = 1.537) to Yttrium Aluminum Garnet (YAG) crystal with relatively high index (1.832). The two primary goals of the study are to (1) evaluate the effect of anti-reflection coatings in reducing reflection losses at the glass boundaries and halation effects and (2) to determine the optimum index matching fluid and analyze its effectiveness in producing an optically coupled system. Since ORA's primary area of expertise is optical design and optical system engineering, and not coating design, ORA sub-contracted the services of Bruce Reinbolt of Santa Barbara Applied Optics (SBAO) to perform the coating portion of the study.

2.0 PROJECTION SYSTEM CHARACTERISTICS

Since the phosphor is deposited or grown directly on the faceplate material, it is in optical contact with the faceplate, eliminating most of the losses in injecting the emitted energy into the faceplate material. However, since the phosphor emits over a wide angular range, a significant portion of the energy can fall outside of the critical angle of the faceplate material. For the older faceplate materials (index = 1.537), the critical angle is 40.6° into air. Energy at angles greater than 40.6° is "waveguided" (totally internally reflected through multiple bounces) radially out to the edge of the faceplate and lost to the system.

CRT projection systems commonly are designed for f numbers approaching F/1.0, and possibly faster. In addition, due to the geometry of typical projection systems, the required field of view is often 25° -30° half-angle, with an aperture stop location central to the projection lens to reduce distortion and aid field correction. As a result, chief ray angles (the "central" ray of the optical bundle) are often steep at the focal plane (phosphor surface). It is normal for the chief ray angle at the faceplate to exceed the object field chief ray angle for air-coupled systems, and for optically coupled systems, for the chief ray angle to be nearly twice as steep as the object field chief ray angle. Thus, for CRT projection systems with a half field projection angle of 25°, the chief ray angle at the phosphor would be greater than 50°, if it were in air, and is reduced to between 30° and 40° in the faceplate material. To this must be added the angle due to the f number of the lens system, bringing the steepest ray angle to greater than 70° equivalent in air or nearly 40° in the faceplate glass.

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From this quick analysis, it can be seen that the CRT projection system works at very steep angles, and that air-glass boundaries can have a profound effect on the system performance. It also indicates the reason why optically coupled or fluid coupled systems are in use for projection systems. Fluids are often used to cool the CRT faceplate when very high luminous output is required. In order to reduce the angles at which rays enter the faceplatecoolant-window assembly, the strongly negative, rearmost field lens is used as the window of the coolant chamber. The steepest bundles from the edge of the field are incident upon the curved front surface of the field lens at an incidence angle much closer to normal than is the case with a flat coolant window. This benefits the transfer of energy, as the fluid then reduces the index difference between the faceplate and the adjacent lens (no glass to air boundary).

Several effects take place at the boundary of the faceplate and coolant fluid which affect system performance. These are all related to the reflection and scattering losses at the interface. Energy scattered or reflected at the faceplate/coolant boundary are manifested as halation of the image or as contrast decrease due to broad angle scattering. Halation is probably due to the first reflection from the boundary to the phosphor surface and back to the boundary, where it is mostly transmitted as a defocused image of the source. Optimization of the characteristics of this boundary is discussed in section 5.0.

3.0 OPTICAL EFFECTS OF YAG FACEPLATES

When the index of the faceplate is increased from the original 1.537 to that of YAG (1.832), the critical angle becomes approximately 33°. This would imply that a YAG faceplate in air would tend to put out significantly less power than a lower index faceplate, since the angular distribution of the energy inside the faceplate is similar, but the part which can pass through into the air is limited to 33° instead of the 40°+ of the lower index faceplate. Stating it differently, for the same f number optical system, the solid angle in the faceplate is smaller for the higher index material, and therefore, a smaller cone of the emitted energy is injected into the optical system. The magnitude of this decrease in screen irradiance is $N1^2/N_2^2 \approx 0.70$, or a drop of 30%.

This would only hold true if the source in both faceplates were perfectly matched to the faceplate index, so that no boundary was encountered in passing from the phosphor into the faceplate. However, if a boundary (differential index) exists, then the difference in screen irradiance would not be seen, as the source output characteristics would be modified equivalently to the lens f number, cancelling the effect.

It would seem that this effect is independent of whether the lens system is optically coupled or not and this would indicate that the optimum faceplate material is the one with the lowest possible index, in order to maximize the collected energy.

The effectiveness of fluids in coupling the faceplate to the optical system is also dependent on the faceplate index, with higher index fluids required to efficiently couple higher index faceplates. This will be discussed in more depth later in this report.

4.0 PROJECTION LENS SYSTEMS

In order to evaluate the effects of the high index faceplate material on the optical system, ORA requested that TII supply a typical lens system from an existing projection system to use for the analysis. TII forwarded a patent supplied by US Precision Lens Corporation to be used for this purpose. TII expressed interest primarily in optically coupled systems, in which the CRT faceplate is coupled to the lens system through the use of a index matching fluid.

ORA used the patent (U.S. Patent 4,900,139, included as Appendix A) to generate models of lens systems for analysis. Two different configuration were modeled: one with an air gap between the field lens and the flat faceplate/coolant assembly, and the other with the field lens in optical contact (through a fluid) with the faceplate. Both lenses from the patent were poorly corrected from the patent data, but were reoptimized by releasing the aspheric coefficients and several variable airspaces to hold first order properties (focus and magnification).

Figure 1 shows the optically coupled model and Figure 2 shows a projection lens with a flat window on the coolant chamber and an air gap to the field lens. Correction is significantly better with the second, air-spaced design due to the fact that it has three aspheric, plastic elements and an additional degree of freedom in the bending of the field lens. However, both are representative of types of lenses used in fast CRT projection systems. Ray angles are steeper in the faceplate for the optically coupled system, but incidence angles are shallower at the coolant window interface. These designs are used in the analysis which follows.

5.0 ANALYSIS OF YAG FACEPLATE PERFORMANCE

In order to reduce reflection loss at the YAG faceplate fluid interface, two approaches were investigated. This involved (1) varying the refractive index of the coolant fluid, or (2) coating the faceplate with a matching layer. It will be seen that either adding a matching

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layer or increasing the index of the cooling fluid can reduce the reflection losses to that of the current 1.537 index faceplate systems or better.

The spectral performance of the original faceplates are calculated, as well as the performance of the YAG faceplates with various index fluids and coatings. The nomenclature used is as shown below:

where R1 is the reflection at the faceplate/fluid boundary, and R2 is the reflection at the fluid/window boundary.

The index of the current phosphor faceplate is 1.537 used with a fluid of index 1.41 and a front panel of 1.572. The reflections at the interfaces for this system are R1 = 0.2% and R2 = 0.3%. Changing the faceplate to YAG increases the index to about 1.83, which results in an R1 = 1.6%. By changing the index of the fluid, the value of R1 can be reduced as shown in Figure 3. An index of at least 1.6 would be required to restore the R1 values of the current system. The reflection losses for the YAG system become worse with angle as shown in Figure 4, but again can be improved with increasing fluid index. An alpha 1 of 33° was used as the incidence angle at the faceplate fluid interface based on information from Trident.

Since it may be difficult to attain an appropriate fluid with the proper index, the other option is to coat the faceplate with a single layer matching film. A film of index nf would be positioned as shown below:



where nf is the matching single layer coating.

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Choosing an index of approximately 1.6 will reduce the reflection at one wavelength as shown in Figure 5 and 6. The performance of a thin film interference coating varies as a function of wavelength, which is shown in Figure 7 for nf = 1.6 at 0 and 33° incidence on the YAG/film interface. A film of this type is normally deposited at temperatures of 200°C to 300°C to improve its durability. It would be more efficient to deposit this film prior to bonding the faceplate if processing conditions are not hostile to the coating. A possible candidate for the film would be Al203. There are other materials between 1.5 and 1.7 which may also be possibilities. For instance, the performance of SiO, which has an index of 1.7 and is very durable, is shown in Figure 8. This material may be even more appropriate for the optically coupled systems with steeper angles than those modeled here.

6.0 CHROMATIC FILTERS

An additional question was raised as to whether thin film spectral filters could be used to modify the performance of the YAG faceplate, shown in Figure 9 (provided by Trident via fax on 10/09/91), to an F-53 (green) or a P-22 (red). Figure 10 shows the spectral distribution of the the current, lower index faceplate, also provided by Trident (fax, 10/11/91).

It is possible to produce distributions similar to the P-23 (blue) in Figure 10 for the red and green filters. This would require that the spectral range performance for the green and red filters be defined with wavelength and transmittance tolerances for system-to-system variation. Filter glasses would, however, be the best choice for this application, as they would not suffer from the angular dependence of this film filters. They would also be measurably less expensive to produce in the required 4 inch diameters than their thin film counterparts.

Using optical thin film filters, it is possible to divide and/or isolate certain portions of the YAG spectral response. Shown as sketched lines on the Figure 9 YAG spectral distribution curve are two edge filters. These are simple thin film designs, but they have several drawbacks in this application. The incidence angles on filters with current designs will range over at least 30°. The cut-off edge of any thin film filter shifts toward shorter wavelength as the angle increases, resulting in a color variation of the output. This phenomenon does not occur with filter glass.

The surface to be coated would be at least 4 inches in diameter, and if a narrow spectral spike is required, such as that shown in Figure 10 for the P-22 (red) band, with rigid spectral requirements, it would result in a low volume, low yield (expensive) part.

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To reduce non-uniformity in the coating thickness, it is desirable that the filter be coated on a flat surface. If the optical design requires that the coating be placed on a strongly curved surface, cost can be expected to increase. Coating yields for multilayer filters are are typically lower than those for anti-reflection coatings.

7.0 CONCLUSIONS

ORA, with the help of Bruce Reinbolt of SBAO, has analyzed the characteristics of CRT faceplates to evaluate the effects of using a high index YAG material. Uncoated and with poorly index-matched fluids, reflection losses at the faceplate/fluid interface are nearly an order of magnitude greater than for current, low index faceplates.

From an optical performance viewpoint, low index faceplates may perform better than high index faceplates in energy collection, if the phosphor is index matched to the faceplate.

The halation effects that were seen in the original test plates were probably caused by the high reflection losses at the YAG/fluid (or YAG/air, if observed) interface. Reduction of this reflection can be accomplished by increasing the fluid index from 1.41 to between 1.58 and 1.75. It can also be improved by using the existing fluid if a film of index 1.5 to 1.7 is placed on the YAG faceplate. Implementing either of these solutions will increase the efficiency of the system to some degree by reducing reflection losses and decreasing halation effects.

Chromatic filtering of the spectral output of the phosphor is probably accomplished most effectively by filter glass materials, which are much less angularly sensitive than thin film filters.









FIGURE 4








RUHHROHQXOR

FIGURE 7

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RUHUROHGSOR

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	Nazimen	Useful Bi	17863	Sacus Tune	tathada /	Seresa Panel	Liquid	Frant Panel
	H (ma)	V (ma)	8 (mm)			t (mm) (Nd-1.537)	k (mm) (Nf-1.41)	t (mm) (H4=1.872)
T	82	64	104	E'ectro Stat.c	Ox.ce	<u> </u>		·
-1	112	87	141.8	Esciro Static	1 Oxice	575	·	•
	112	87	141.8	Euctro Static	Cxide	5.75		
]	155	116	194.4	Electro Static	Cxte	7.0		
1	156	116	194.4	Napreus	Impregnated	7.0	·	in an aite agus dharmann
Ţ	82	64	1 104	Electro Static	Oxide	2.5	32	4.0
.1	1:2	87	141.8	Electro Stalic	Oxice	5.75	5.0 1	5.75
	112	87	-418	Electro Static	Oxice	575	50 1	5.75
	155	116	194.4	Electro Static	CXIDE	7.0	4.3	7.0
	156	116	194.4	Magnetic	be: srgaremi	7.0	4.3:	7.0
_	82	64	104	L'ectro Static	Oxice	4.0	For 36" &	41" system
ļ	112	87	141.8	Electro Static	Oxice	5.75	For 41" &	46" system
T	112	87	141.8	Liectro Statuc	Oxce	5.75	For 46"	system

Specific Energy Distribution Curyps













APPENDIX A

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Projection Lens Patent

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United S	states Patent [19]
Kreitzer	
[54] COLOR C	ORRECTED PROJECTION LENS
[75] Inventor:	Melvya H. Kreitzer, Cincinnati. Ohio
[73] Assignee:	U. S. Precision Lens, Inc., Cincinnati, Ohio
Tall Appl. No.:	266,234
[22] Filed:	Oct. 28, 1988
Reint	ed U.S. Application Data
dend.	a of Ser. No. 48,026, May 11, 1987, aban-
[51] Int. CL4	
	G02B 3/00
[52] U.S. Cl	
	350/412
[58] Field of Sea	rce JJU/412, 432, 403, 403
[56]	References Cited
U.S. P.	ATENT DOCUMENTS
3,446,547 5/19 4,620,773 11/19	69 Jeffree

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[11] Patent Number: 4,900,139

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[45] Date of Patent: Feb. 13, 1990

4.682.862	7/1987	Moskovich	350/432
4.776.681	10/1988	Moskovich	350/432
4.810.075	3/1989	Fukuda	350/432
4,824,224	4/1989	Fukuda et al.	350/432

FOREIGN PATENT DOCUMENTS

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[57] ABSTRACT

A lens comprising from the image side a first lens unit which is a positive element with at least one aspheric surface; a three element lens unit consisting of a biconcave element, a biconvex element and another positive component, in that order: a third lens unit having a strongly concave image side surface and which serves as a field flattener and to correct the Petzval sum of the lens.

59 Claims, 2 Drawing Sheets





FIG-1





COLOR CORRECTED PROJECTION LENS

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RELATED APPLICATION

This is a continuation of application Ser. No. 5 07/048,026 filed May 11, 1987 now abandoned.

FIELD OF THE INVENTION

This invention relates to projection lenses for cathode ray tubes and, more particularly, relates to such lenses 10 which are color corrected.

BACKGROUND OF THE INVENTION

In projection television systems, it is common practice to utilize three cathode ray tubes (CRTs) of differ- 15 ent colors, namely, red, blue and green. Utilizing three monochromatic CRT's does not require a color corrected lens for normal usage. Examples of such lenses are shown in U.S. Pat. Nos. 4,300,817, 4,348,081 and 20 4,526,442.

In practice, the phosphors of the three differently colored CRT's emit polychromatically with the green phosphor having significant side bands in blue and red. This chromatic spread can effect the image quality, particularly in situations where high resolution is of 25 prime concern. Where there is to be a data display or large magnification, this color spread manifests itself as lowered image contrast and visible color fringing.

The degree of color correction required in the lenses for these applications depends on the intended applica- 30 tion of the lenses.

In general, for lower resolution systems, such as for the projection of typical broadcast television, good color optical performance out to three cycles per millimeter as measured by the modulation transfer function 35 (MTF) is adequate. In these cases, partial color correction may be adequate. For data display via red, green and blue inputs (RGB), and for high definition television, good performance out to ten cycles per millimeter. as measured by the MTF, may be required, and total 40 image to the object end. Surfaces of the lens elements color correction then becomes necessary.

The requirement for partial or total color correction always complicates an optical design problem. In projection television, it is of vital concern not to alleviate this difficulty by relaxing important system specifica- 45 tion, such as field coverage, lens speed, and relative illumination. Additionally, it is often desirable that the lenses be capable of high performance over a significant range of magnifications. A typical front projection requirement might be from a magnification of 10× to 50 power and has at least one aspheric surface defined by 60x. This further complicates the optical design.

Accordingly, the present invention provides a new and improved projection lens for a cathode ray tube of high definition while maintaining a wide field angle and large relative aperture. The invention also provides a 55 CRT projection lens that maintains a high level of image quality over a wide range of magnifications, for example. 10×10 60 × or greater.

SUMMARY OF THE INVENTION

Briefly stated, a lens embodying the invention in one form thereof consists from the image side a first lens unit which is a positive element with at least one aspheric surface: a three element lens unit consisting of a biconcave element. a biconvex element and another positive of lens embodying the invention. The lens of FIG. 1 comcomponent, in that order: a third lens unit having a . strongly concave image side surface and which serves as a field flattener and to correct the Petzval sum of the

lens: and a weak power corrector lens element having at least one aspheric surface that significantly improves the higher order saginal flare aberration is positioned between the second and third lens units.

The first two elements of the second lens unit form a color correcting doublet of overall menicus shape concave to the image side.

An object of this invention is to provide a new and improved color corrected lens for cathode ray tube projection which provides enhanced image quality while maintaining a large relative aperture and wide field.

Another object of this invention is to provide a new and improved color corrected lens for cathode ray tube projection which maintains enhanced image quality thoughout a wide range of magnifications.

The features of the invention which are believed to be novel are particularly pointed out and distinctly claimed in the concluding portion of the specification. The invention, however, together with further objects and advantages thereof, may best be appreciated by reference to the following detailed description taken in conjunction with the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. 1-4 are schematic side elevations of lenses which may embody the invention.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS OF THE INVENTION

Different projection lenses embodying the invention are set forth in Tables I-X and exemplified in the drawings.

In the drawings, the lens units are identified by the reference G followed by successive arabic numerals. except that a corrector lens unit is designated by the reference CR: lens elements are identified by the reference L followed by successive arabic numerals from the are identified by the reference S followed by successive arabic numerals from the image to the object end. The reference SC denotes the screen of a cathode ray tube. while the reference C denotes a liquid optical coupler. between the screen SC and the overall lens. In the embodiments of FIGS. 1 and 2, the coupler C contributes optical power as hereinafter explained.

In all disclosed embodiments of the invention, the first lens unit G1 comprises an element L1 of positive the equation:

$$\frac{C_{1}^{2}}{1-(1-(1-K)C_{1}^{2})^{2}}=D_{1}^{2}-$$

 $Ey^{a} - Fy^{a} + Gy^{10} - Hy^{12} - Iy^{14}$

where x is the surface sag at a semi-aperture distance y from the axis A of the lens. C is the curvature of a lens 60 surface at the optical axis A equal to the reciprocal of the radius at the optical axis. K is a conic constant and D. E. F. G. H and I are aspheric coefficients of correspondingly fourth through fourteenth order.

Reference is now made to FIG. 1, which discloses a prises three lens units, G1, G2, and G3, as seen from the image side or the projection screen (not shown). Lens unit G1 consists of a single element L1 having two

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aspheric surfaces. Lens unit G2 consists of a color correcting doublet L2 and L3 of weak total optical power which is closely spaced to a biconvex element L4. Lens unit G3 comprises an element having a concave image side surface, and a liquid coupler which optically cou- 5 ples the lens to the faceplate CS of a cathode ray tube The construction of the coupler is disclosed and claimed in co-pending U.S. application Ser. No. 820.266 filed Jan. 17, 1986. The coupler C comprises a housing CRT faceplate CS. The housing has a window at the other side which is closed by a meniscus element L6 having a strongly concave image side surface. Lens unit G3 provides correction for field curvature and contributes to reduction of Petzval sum. Coupler C is filled 11 with a liquid having an index of refraction close to the index of refraction of element L6 and the CRT faceplate. Thus, surface S12 of element L6 does not have to be highly finished. The material of element L6 may be a plastic material such as acrylic or, as specified in Table 20 I, may be glass having spherical surfaces. Element L5 is a corrector, which is positioned between lens units G2 and G3 and as exemplified in Table 1, has two aspheric surfaces.

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Corrector element L5 is positioned with respect to 25 lens unit G2 such that the marginal axial rays OA intersect surface S9 thereof at a height substantially less than the clear aperture of the lens, while allowing the dimension above the height H to be configures to correct for aberrations due to off-axis rays. In FIG. 1, the marginal 30 axial rays AR are indicated in full line, while the off-axis rays OA are indicated in short broken line. The corrector element L5 is configured and spaced from lens unit G2 to permit the central portion thereof up to the height H to be utilized to aid in correction of aperture depen- 35 dent aberrations and for this reason. L5 should be within a distance D_{2C}/F_0 where D_{2C} is the axial spacing between lens unit G2 and corrector element L5, and F0 is the equivalent focal length (EFL) of the lens.

In all cases. The corrector lens unit CR where used is 40 shaped to contribute to correction of spherical aberration in the center and to contribute to correction of off-axis aberrations toward the ends. These off-axis aberrations are sagittal oblique spherical, coma and astigmatism.

Lenses as shown in FIG. 1 are described in the prescriptions of Tables I and II. The lens of Table III has the same form but is not optically coupled to the CRT screen SC.

Lenses as shown in FIG. 2 are described in the pre- 50 scriptions of Tables IV, V, VI, VII and VIII. In the lenses of Tables VI and VII the coupler C has no optical DOWET.

Lenses as shown in FIG. 3 are described in the prescriptions of Tables IX and X. These lenses are air 55 spaced from the CRT screen SC. The screen SC is shown as comprising two outer plates with a coolant therebetween.

A lens as shown in FIG. 4 is described in the prescription of Table XI. Here, there is no corrector CR, and 60 the second biconvex element of the second lens unit is split into two elements.

In the following tables, the lens elements are identified from the image end to the object end by the reference L followed successively by an arabic numeral. 65 Lens surfaces are identified by the reference S followed by an arabic numeral successively from the image to the object end. The index of refraction of each lens element

is given under the heading N_D . The dispersion of each lens element as measured by its Abbe number is given by Vo. EFL is the equivalent focal length of the lens and the semi-field angle is set forth. F/No. is the relative aperture of the lens, and the aperture stop is indicated in relation to a surface. The aspheric surfaces of the lens elements are in accordance with the coefficients set forth in the foregoing aspheric equation

The following Tables also set forth the magnification which defines a peripheral wall which is sealed against 10 (M) of the image as an inverse function of the object. and the diagonal of the CRT for which the lens is designed. The dimension for the diagonal is for the phosphor raster of the CRT screen. The raster may vary for different CRT's having a nominal diagonal

5			TA	BLE 1		
	LENS		SURFACE RADII (mm)	ANIAL DISTANCE BETWEEN SURFACES (mm -	_	、
)	LI	S :	283 5*)	21 100	1493	• :
		5:	- 1050 203	10 á(s.		
	L:	S 3	- 329 768	T 4000	: • • •	12.15
		54	137 724	·بد" ۱		
	L 3	50	142 246	30 G++		et 24
)		5°	133 114	0.250		
	L4	58	- 253 947	32 40 Y	1.517	₩ :"
		S٩	- 1569 033	62 100		
ş	L ?	S 10	3665.023	10 (000)	1 201	<u>.</u>
	Lo	S 11	- 69 434	500 B 000	: • ! •	N4 1"
	c	S 12	- 70:013	18.000	1410	!! 0
)		S 13	Plane		_	
	{/N EF Ser Asi	io = 1 L = 10 ni-field phenc S	2 0 9 9 mm N = 24° A 500ríaces S1. S2.	IRT Diagonai = 161 Magnification = - 00 Aperture stop is 6 00 p 59. 510	mm yis mm atter !	5.
ş		Si		<u>\$2</u>	Sc	
	D -0 E -0. F 0.1	.2310 × 3115 × 117 ×	10 ⁻¹ -0.1 10 ⁻¹⁰ -0.2 10 ⁻¹⁴ 0.19	1901 ≠ 10 ⁻¹ =0 372 + 10 ⁻¹ =0. 40 ≠ 10 ⁻¹¹ =0	.2135 - 1 3129 - 1 1604 - 1	0- 0- 0-
	G -0. H 0.7	4454 x 641 x	10-14 -0.3 10-22 0.0	978 × 10" ·* 0.2 061 × 10" 0.2	514 × 10 123 × 10	- 1. - 20
,		3878 2	1003	eve : 10 -0	iner i	

	\$10	
D	0.1728 × 10-*	
E	-0.6890 - 10-10	
F	0.1558 × 10-14	
G	0.1647 x 10-1"	
н	0.1056×10^{-20}	
1	-0.1015×10^{-24}	

		TAE	BLE II		
LENS		SURFACE RADILIUMM)	AXIAL DISTANCE BETWEEN SURFACE (mm)	Ν.	<u> </u>
	\$1	195.212	17.100		
51	S 2	- 1341.860	17.300	1 441	•
	\$3	- 255.343	نەر .رە		
12			5.890	1.689	31.16

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			5		7,2	00,	,,			6		
		TAB	LE II-continued						TABLE	Ill-continued		
	54	:23 1	1 030			-	с -	0 1943 -	10-1 -0 10-1 01	101 - 101 140 - 101 -	0 10+4 - 10	p-:
	S !	131 0	1) 28 04 0	1 ***	61 25	4	<u> </u>	0.30-1 -	10-10	H11 101-1 -	0	
1.	Se	- 1-7 9	4) 0.200						<u> </u>	5 04413 + 101		
	5-	109 64	lt in the						Ē	-01300 - 10		
La	5.	- 205 35	30 240	1.51	64 20				G	-0611-		
	59	- 127.29	Di 19			10			H 1	0.2021 10-	- : '	
15	S 10	- 211 49	7 46) 16 1010	1 491	:::							
	\$11	- 58 67	3 • • • • •	1.170	-0.01					BLE IV		
L. C	\$12	- 60.20	11 7 000	10		13	LENG		SURFACE	DISTANCE		
	\$13	Plano	CRT Disease	174 mm		•	LENG	S I	ALUIT MAL	JURFALES		<u> </u>
1	/No == EFL == 1	1 35.0 mm	Aperture stop is (00 mm aiter	S!	20	Li		184 805	10 00+	1 441	•• :
5	iem-field Lapheric) = 23° Surfaces S1	. 52. 59. 510					3.	4,54,5UA	• 031		
	S)		S:	59			L2	53	- 58 724	0 (K)	1.620	••
D -	0.3078	10-10	-0.2154 - 10-7	01115 - 10	0- ' 10- '			S4	88 724	· · · · · · ·		
F O	4895	10-14	0 8120 + 10-14	-01773 • 1	n- ::	25		S !	133 545			
G - H 0	04066 × (8615 ×	10-10-	07248 10-21	0 1932 - 10	- •		63	50	- 6 1 130	17 (0)	17:	·⊷ _
<u> </u>	0.6304 -	10	-0 \$796 - 10	-07320 - 3		•		s-	12 eff	0.105		
	\$10	EF	L (mm) D\$ (mm)	DIUImmi	M	10	L÷	Sk	- 145 278	20 û +	1.517	o⊷ :
D 0.	1483 × 1	10-:				0				[]]89		
E -0 F -0 G -0	1.3031 × 18927 × 13316 ×	10-4 10-14 10-14	130.3 44.87 135.0 48.22 138.2 51.78	39.69 - 30.09 - 22.12 -	0992 0500 0165		L5	510	- 65 972	6 00 0	40	57 2 0
H 0.3	663 × 1	0-19				••		LU	- 15.209	30 003		
	30 32 X	10. 0.				35	Lo		134.000	3.200	1.620	36.30
		1					c	312	- 123.000	7.530	1 410	60 00
_			AXIAL			•		<u>S1.</u>	Planc	CRT Discossi e		
		SURFAC	DISTANC E BETWEE	E N		40	Ē	FL = 6	7.5 mm	Aperture stop is 11	L25 mm afte	or \$5
LENS		RADII IS	m) SURFACES	mm) Ne	N.d	•		spheric	Surfaces S1. 59	. \$10		
LI	\$1	258.72*	21.700	1 491	57.2			\$1		S¢.	\$16	
	S :	- 1207.840	47 750			48	D E	0.1074	k 10-1 0.1 k 10-1 0.1	209 - 10-1 361 x 10-5	0.2701 + 1	0-:
••	\$3	329.761	47.7 4 0			43	F 0	1340 ×	10-12 0.1	851 • 10 ⁻¹¹	01395 - 1	n- ::
12	54	137.720	7400	1,673	32.1-		H O	6780 ×	10-11 -0.	3643 - 10-	-0.2834	10-
	55	142.596	0.740					0.2118 >	101 0.1	561 × 10-20	0.1130 1	0"
D			30.000	1.589	61.26	50		EFL (m	m) [Dig teten :	м	
	30	- 211.134	0.250					67.94		29.55	0831	
L4	S 7	133.114	32.400	1.517	64.20			67.46	·	29.96	0935	
	34	- 233.94	57.490			55			Т	RIEV		
LS	5 7	396.343	10.00	1.491	57.2		<u> </u>			AXIAL		
	\$10	479.403			-				\$119 ±	DISTANC	E	
• •	\$11	- 69.734	31.447				LENS		RADII Imm	SURFACES	nmi Ny	_ V.;
LO	\$12	Plano	4.760] 49]	27.2	60		S 1	76.197	11.000	1 481	
ŝ	ie. = 1.	2	CRT Disponal =	131.8 mm			F 1	\$2	-472.688	13.000	[4¥]	
EF Sei	L = 16 m-field (6. sam m 24*	Aperture stop # 2	0314 2.5 mm after	\$ 5			S 3	- 81.639	10.334		
A.	phenc S	urfaces SI.	\$2. \$9. \$10		·	•	12		60.841	4.000	1.620	36.34
	\$1		\$2	59		65		34	79.043	0.066		
0	13401 × 2852 ×	10-* -	0.1956 × 10	0.2561 × 10 -0.4838 × 1	,-+ D-10		ப	\$5	91.468	21.100	1.51	7 64.1
· -0	1414 x	10-15 0	1560 × 10-14	0.4407 × 10	- 15			56	- 91.468			

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		TA	BLE V-continu	ed					T				
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	1.4	5- 14	10r 19 3	00 11	-9 a!	••	G H	-0.6250	- 10	0 1553	10-440	0 er -	-14
		5 × - 120	*24		•	•	<u>:</u>	- 0 -	10	0.3482	10-23	<u>-9154</u>	
	:	5 80	143 743	6H.							hocusor	5 D.J.	
1	L! 5	10 - 105 (6 i 033	40 14	0] ș.	:			510	EFLIM	n≕ Div	4 mr	<u>M</u>
	-		Dic	i i			E	0 4129	10-7	105	4 C :	: -	: •
l	L0 _		40	00 14	41 <u>5</u> *.	: "	J F G	0.0202 0.1104	+ 10 ⁻¹⁺	106 -	34 9 38 9	-	.:
1	c s	12 44 0	rox 3.0	يد و	43 30	U	<u>н</u>	0.3025	- 10-14			-	
-	5	13 Plan	m				<u> </u>						
	EFL =	= 1.0 77.2 mm	CRT Diagonal Aperture stop i	. m. 121 n s 6.33 mm aft	er S!	15	L .				1/11		
	Semi-fie	nici = 33° In Surfaces S	1 57 59 510 511							ABLE	ANIAL		
		SI	S2	<u>ę</u> u		-			61'BE -	~~	DISTANC	F.	
D	-0.491	3 2 10-1	-0.3031 - 10-*	0.3387	10-5	-	LE	<u>NS</u>	RADII I	immi St	BETWEE		ι
E F	-0.3240	× 10 ⁻¹	-0.1899 - 10-*	-01011 -	10-1	20		Si	90 44	101			
5	-0.3111	> 10- in	0 0000 - 10-"	01:45	10-11		L.	s:	<u>99</u> 1 7	10	17 (8)	1.45	** ***
1	-0.2346	. 10- 22	0 0000 - 10-"	0.064	10-22			\$3	- 148 33	20	19.81-		
	5	10	S	.1:		- 35	L	:	1100.00		6 () ,1	i e:	: •• ÷
•	0.3964	• 10 ⁻¹	- 0 6421	• 10 .				34	100 44		0.50		
	-0.5484	10-12	0 1142	• 10-			L	5 ٩	102 82	::	30 cm •		•
ι.	-0.7876	10-14	0.2151 0.2972	• 10-				Sr	— 134 3e	. *			·
_	-0.6164	. 10-22	-0.1386	· 10-2		30	-	5-	85 07	.e	0 200		
	EFL/=		Dig (mm)	N			L	51	- 309.65	•	24 5(8)	: ! !	•
	78.25	,	34.06	- 0944		-		20	_ 144		25 364		
	77.10)	25.29	- 1170			L	24	- 123 43	+1	9 (). #1	144	1 57 2
	11.9	; 		- 1000		_ 35		\$10	- 112 10	7			• •
		-					1 4	SII	- 57.39	1			
			ADLE VI			-		\$12	plano		4 0(1)	1 62	0.364
			DISTANC	E		مد		[/No = 1		CRT D	cagonal - 1	2 mm	
				N		~~							
ENS	i	SURFAC RADII (m	E BETWEE m) SURFACES (¥₫.			Semi-field	= 25°	Apenar	e stop is vi	0 mm 2116	r 5:
	; Si	SURFAC RADII (m 89.851	E BETWEE m) SURFACES ((mm) N ₂	V _d	-		Semi-field Aspheric 1	= 28" Surfaces 51.	52. 59. 51	()		r 5 <u>*</u>
<u>ENS</u> _1	51 52	SURFAC RADII (m 89.851 452.287	E BETWEE m) SURFACES (16.000	(mm) Ne 491	V _d 57.2	-		Semi-field Asphene S S1	= 25" Surfaces 51.	52. 59. 51 52		0 mm aire 5-	
<u>INS</u> .1	51 52 51	SURFAC RADII (m 89.85) 452.287	E BETWEE m) SURFACES ie.000 13.205	(mm) N _e 49]	V _d 57.2	- 45	DE	Semi-field Aspheric 1 -0.2355 x -0.1505 x	= 28' Surfaces 51. 10-*	52, 59, 51 52 0 1469 + 1 -0.1695 +	10~* 10~*	0 mm aite 5- 0.2639 . 0.4973 .	r St 10
	51 52 53	SURFAC RADII (m 89.851 452.287 - 141 472	E BETWEE m) SURFACES 16.000 15.205 5.000	(mm) N _C 491 .620	V _d 57.2 36.30	45	D E F G	Semi-field Aspheric S -0.2355 x -0.1505 x 0.7536 x -0.3857 x	= 25' Surfaces S1. 10-0 10-13 10-10	S2. S9. S1 S2. S9. S1 S2 0 1469 - 1 -0.1695 - 0.3153 - 1 0.5871 - 1	10~* 10~* 10~ ''' 0~ 13 _	5- 0.26:0 0.40=3 .0 \$\$=0	r S* 10 10
<u>ENS</u>	5) 52 53 54	SURFAC RADII (m 89.851 452.287 - 141.472 111.221	E BETWEE m) SURFACES (14.000 13.205 5.000 1.205	1 491	Va 57.2 36.30	45	DEFGH!	EFL = 10 Semi-field Aspheric S = 0.2355 x = 0.1505 x 0.7536 x = 0.3857 x 0.9174 x	= 25° jouriaces 51. 10-0 10-1 10-10 10-20 10-21	52. 59. 51 52 0 1469 - 1 -0.1695 - 0.3153 - 1 0.5873 - 1 -0.7355 -	10-13 0-13 10-14 10-14 10-14 10-14	5- 0.26:9 0.40*3 .0 85*9 .0 10*5 .0 10*5	r S* 10 10 10 10
ENS _1 _2	51 52 53 54 55	SURFAC RADII (m 89,85) 452,287 - 141,472 111,221 113,348	E BETWEE m) SURFACES (16.000 15.205 5.000 1.200	<u>mm) Ne</u> 49 1.620	<u>Va</u> 57.2 36.30	45	D E F G H I K	ErL = 10 Semi-field Asphene 5 -0.1505 x -0.1505 x -0.3857 x 0.9174 x -0.1059 x 1.326	- 25° 5007(aces \$1. 10-0 10-1 10-1 10-1 10-1 10-1 10-20 10-23 10-23	S2, S9, S1 S2 0 1460 - 1 -0.1695 - 0.3153 - 1 -0.7355 - 0.1920 - 1	10-13 0-13 0-13 10-23 0-23	5- 0.2010 - 0.4010 - 0.4010 - 0.445" - 0.01734 -	10
ENS	51 52 53 54 55 56	SURFAC RADII (m 89.55) - 141.472 111.221 113.348 - 113.348	E BETWEE m) SURFACES (i&000 15.205 5.000 1.200 32.500	<u>mm) Ne</u> 1 491 1.620 1.517	V _d 57.2 36.30 64.29	- 45 50	DEFGHIK	EFL = 10 Semi-field Aspheric S1 = 0.2355 x = 0.1505 x = 0.3857 x 0.9174 x = 0.1059 x 1.326	10-1 10-1 10-1 10-1 10-2 10-2 10-2 10-2 10-2 10-2 10-2 10-2 10-2 10-2 10-2 10-2 10-2 10-2 10-2 10-2 10-4	S2. S ⁰ . S1 S2 0 146 ⁰ - 1 -0.1695 - 1 0.3153 - 1 0.3153 - 1 0.7355 - 0 0.1920 - 1	10-11 0-13 0-13 10-21 10-21 Focusing	5- 0.2639 . 0.4973 . 0.4973 . 0.4879 . 0.4467 . 0.1095 . 0.1095 . 0.1734 .	r St 10 10 10 10 10
ENS LI	51 52 53 54 55 56	SURFAC RADII (m 89.851 452.287 - 141.472 111.221 113.348 - 113.348 84.350	E BETWEE m) SURFACES (14.000 13.205 5.000 1.200 32.500 0.200	<u>mm) Ne</u> 49] 1.620 1.517	V _d 57.2 36.30 64.29	45 50	DEFGHIK	EFL = 16 Semi-field Aspheric S -0.1505 x -0.1505 x -0.3857 x 0.9174 x -0.1059 x 1.326 S10	- 25" 5007150005 51. 10-0 10-1 10-1 10-10 10-20 10-23 10-23	S2. S9. S1 S2 0 146° - 1 0.1495 - 0.3153 - 1 0.5873 - 1 -0.7355 - 0.1920 - 1 EFL (mm	10	5- 0.2639 . 0.4973 . 0.9879 . 0.9279 . 0.1055 . 0.1055 . 0.1734 . Data	r S* 10
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Table XII sets forth the powers K_{G1} , K_{G2} , K_{G3} , and K_{CR} of the iens units of each of the examples as a ratio of the power of the overall lens.

		TABLE X	II		
TABLE	Kgi/Ko	KG7/KO	Kgi/Ko	KCR/KO	
1	.373	.449	~ 1.017	- 064	-
11	.392	1.000	- 1.149	203	
111	.387	.948	~ 1.189	.174	
IV	.452	-836	- 1.021	011	9
v	.574	.838	131	106	
VI	.479	.755	838	212	
VII	.488	.803	1.080	.139	
VIII	.478	.789		.063	
IX	.340	1.000	- 1.149	004	
X	377	.947	- 1.099	095	
XI	.355	1.009	- 1.013		

It will be seen that the corrector element CR has little optical power. Its primary purpose is to provide aspheric surfaces for correction of aberrations. 65

In all embodiments, except that of Table XI, all elements of lens unit G2 are glass with spherical surfaces, and thus avoid focus drift with temperature. The optical power of the doublet consisting of L2 and L3 is all embodiments is very weak

The axial spacing between L3 and the power element L4 is very small, less than one tenth of one per cent of the EFL of the lens

The power of the corrector element CR as a ratio to the power of the lens is weak and

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Thus any change in index of refraction of the corrector element due to temperature does not adversily affect the focus of the lens.

Table XIII sets forth the spacing of element L1 and L2. $D_{12}/F_{0.}$ and also the spacing of the corrector element from the second lens unit $D_{2C}/F_{0.}$ together with the ratio of the powers of L2 and L3 to the power of the lens.

TABLE XIII

TABLE	Deg F	Dir I	Kr K	N N
1	244	245	-114.	
11	314	16-	-1133	
111	284	342	- 1150	
11	117	100	- 96.1	
N.	154	160	- 40	
- VI	145	20-	- 990	
VII	151	242	-101	
VIII	14*	1-5	1	
1X	323		- 1 1	
X	.302	050	-1433	
XI	181	- 13		

The color correcting doublet of the second lens unit 40 is designed to provide the necessary color correction without introducing uncorrectable aberrations. The lenses of Tables I. II. VII and VIII provide modulation transfer functions of ten cycles/millimeter over most of the field. In these examples, the absolute optical 45 power of the biconcave element L2 and the first biconvex element L3 are greater than the optical power of the overall lens.

The lens of Table XI provides an MTF of 0.3 cycles/millimeter and the embodiments of Tables IV-VIII 50 provide 5.0 cycles/millimeter.

The lens of Table XI and FIG. 4 utilizes a two element power component L4 and L5 where L4 is acrylic and has two aspheric surfaces, and has an axial power which is about 21% of L5. The EFL's of the lenses as 55 set forth in the prescriptions may vary as the lens is focused for various projection distances and magnifications.

The lenses of Tables I and III are designed for front projection at predetermined distances and provide $160 \text{ image/object magnifications of } 16.4 \times \text{ and } 31.5 < \text{ re$ $spectively.}$

The lens of Table II is also designed for front projection and has a range of magnifications $10 \times 10.60 \dots$ To focus for varying image distances elements L1-L5 move in the same direction with the corrector L5 moving differentially to correct for aberrations introduced by movement of lens units G1 and G2. In FIG. 1, the focusing movement of elements L1-L4 is shown by the tł

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arrow F and the focusing movement of element L5 is shown by the arrow Fr.

The lenses of Tables IN and N are also designed and have magnifications of 10 - 10 60 - Here elements L1-L5 move axially for focusing with L1 moving dife 5 ferentially at a lesser rate. This differential movement corrects for aberrations introduced by the focusing movement of elements L1-L5. In FIG. 3, the focusing movement of elements L2-L5 is shown by the arrow F while the differential movement of element L1 is shown 10. by the arrow FD

The lenses of Table IV-VIII are designed for rear projection and in some cases are provided with focusing capability dependent on the magnification required for the size of the viewing screen. That is, the same lens 15 tween said first lens unit and said second lens unit is may be used for a forty or fifty inch diagonal viewing screen.

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The lens of Table XI does not use a corrector element CR as shown in the other embodiments, but does include a weak meniscus L4 having two aspheric surfaces 20 as a part of the second lens unit G2.

It may thus be seen that the objects of the invention set forth as well as those made apparent from the forcgoing description are efficiently attained. While preferred embodiments of the invention have been set forth 25 for purposes of disclosure, modification of the disclosed embodiments of the invention as well as other embodiments thereof may occur to those skilled in the art Accordingly, the appended claims are intended to cover all of the embodiments of the invention and modi- 30 fications to the disclosed embodiments which do not depart from the spirit and scope of the invention.

Having described the invention, what is claimed is: 1. A projection lens for use in combination with a cathode ray tube where the projection lens is closely 35 coupled to the cathode ray tube, said lens comprising from the image end a first lens unit of positive optical power having at least one aspheric surface and contributing to correction of aperture dependent abertations, a second lens unit providing a majority of the positive 40 power of said lens. and a third lens unit having a strongly concave image side surface which provides correction for field curvature and Petzval sum of other units of said lens. said second lens unit consisting from the image end of a biconcave element, a biconvex ele- 45 ment and a positive component, said biconcave element and said biconvex element forming a color correcting doublet and being of overall meniscus shape concave to the image end, said color correcting doublet being axially spaced from said positive component a distance less 50 than 0.01 of the equivalent focal length of said lens.

2. The lens of claim 1 where said doublet is axially spaced from said first lens unit at least 0.1 of the equivalent focal length of said lens.

iens unit of weak optical power having two aspheric surfaces positioned between said second and third lens units, said corrector lens unit being axially spaced from said second lens unit a distance

04>D:c/Fo>0.15

where D2C is the axial spacing distance between said second lens unit and said corrector element and Fois the equivalent focal length of said lens.

4. The lens of claim 3 where said lens has a variable magnification, said first and said second lens units move axially in fixed relation to focus said lens and said corrector lens unit moves axially in the same direction but at a differential rate

5 The lens of claim 3 where said element of said first lens unit has two aspheric surfaces

6. The lens of claim 3 where the axial marginal rave traced from the iong conjugate intersect a surface of said corrector lens unit substantially below the clear aperture of said image side surface

7 The lens of claim 1 where said element of said first lens unit has two aspheric surfaces

8 The lens of claim 1 where said first and second lens units move axially in the same direction at differential rates to vary the focus of said lens.

9. The lens of claim 8 where the axial spacing be-

04>D-+ F->01

where D12 is the distance between the first and second lens units and Foils the equivalent focal length of said iens.

10. The lens of claim 1 where said positive lens component is also biconvex.

11. The lens of claim 1 where all elements of said second lens unit have spherical surfaces

12. The lens of claim 1 wherein said corrector lens has two aspheric surfaces, said corrector lens unit being axially spaced from said second lens unit a distance

04>D:C.H.>015

where D_{2C} is the axial distance between said biconvex element and said biconvex iens and Fois the equivalent foal length of said lens.

13. A projection lens for use in combination with a cathode ray tube where the projection lens is closely coupled to the cathode ray tube, said lens comprising from the image end a first lens unit of positive optical power having at least one aspheric surface and contributing to correction of aperture dependent aberrations. J second lens unit providing a majority of the positive power of said lens, and a third lens unit having a strongly concave image side surface which provides correction for field curvature and Petzval sum of other units of said lens, said second lens unit consisting from the image end of a biconcave element, a biconvex element and a positive component, said biconcave element and said first biconvex element forming a color correcting doublet and being of overall meniscus shape concave to the image end, said positive component comprising two elements, one of said elements of said positive component having two aspheric surfaces and being of meniscus shape.

14. The lens of claim 13 where said doublet is spaced 3. The lens of claim 1 further including a corrector 55 from said first lens unit at least 0.1 of the focal length of said lens.

15. A projection lens for use in combination with a cathode ray tube where the projection lens is closely coupled to the cathode ray tube, said lens comprising 60 from the image end a first lens unit of positive optical power having at least one aspheric surface and contributing to correction of aperture dependent aberrations. said first lens unit consisting of a single element, a second lens unit providing a majority of the positive power of said lens, and a third lens unit having a strongly 65 concave image side surface which provides correction for field curvature and Petzval sum of other units of said lens, said second lens unit comprising from the image

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end a biconcave element. a biconvex element and a positive element, said biconcave element and said biconvex element forming a color correcting doublet and being of overall meniscus snape concave to the image end, and a corrector lens unit of weak optical power 5 having at least one aspneric surface positioned between said second and third lens units, said corrector lens unit being axially spaced from said second lens unit a dis-LADCE

04> D:c Fn>01"

where D2C is the axial spacing distance between said second iens unit and said corrector element and F0 is the equivalent focal length of said lens

16. The iens of claim 15 where said element of said first lens unit has two aspheric surfaces.

17. The lens of claim 15 where said lens has a variable magnification, said first and said second lens units move axially in fixed relation to focus said lens and said corrector lens element moves axially in the same direction but at a differential rate.

18. The lens of claim 15 where said first and second lens units move axially in the same direction at differen-25 tial rates to vary the focus of said lens

19. The lens of claim 15 where said positive element is also biconves.

20. The iens of claim 15 where all elements of said second lens unit have spherical surfaces.

21. The iens of claim 15 where the axial marginal rays traced from the long conjugate intersect the image side surface of said corrector lens unit substantially below the clear aperture of said image side surface.

22. A projection lens for use in combination with a cathode ray tube where the projection lens is closely coupled to the cathode ray tube, said lens comprising from the image end a first lens unit of postive optical power having at least one aspheric surface and contributing to correction of aperture dependent aberrations. a 40 faces. second lens unit providing a majority of the positive power of said lens, and a third lens unit having a strongly concave image side surface which provides correction for field curvature and Petzval sum of the other units of said iens, said second iens unit comprising 45 from the image end a biconcave element. a biconvex element and a positive lens element, said biconcave element and said biconvex element forming a color correcting doublet and being of overall meniscus shape concave to the image end, a corrector lens unit posi- 50 tioned between said second and third lens units, said lens having a variable focus and said first lens unit, said second lens unit, and said corrector lens unit being movable axially in the same direction to change the focus of said lens, one of said first lens unit and said corrector 55 lens unit moving differentially with respect to the other movable lens units.

23. The lens of claim 22 where said biconcave element has an absolute optical power greater than the power of said lens.

24. The lens of claim 22 where said first lens unit consists of a single element having two aspheric surfaces.

25. The lens of claim 22 where the axial spacing between said first lens unit and said second lens unit is

 $0.4 > D_{12}/F_0 > 0.1$

where Dig is the distance between the first and second lens units and Foils the equivalent focal length of said lens

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26. The lens of claim 22 where said positive component is also biconvex

27 The iens of claim 22 where all elements of said second lens unit have spherical surfaces

28. The iens of claim 22 where said first iens unit moves differentially

29. The lens of claim 22 where said corrector lens unit moves differentially

30. A projection lens for use in combination with a cathode ray tube where the projection lens is closely coupled to the cathode ray tube, said lens comprising 15 from the image end a first lens unit of positive optical power having at least one aspheric surface and contributing to correction of aperture dependent aberrations. a second lens unit providing a majority of the positive power of said iens, and a third iens unit having a strongly concave image side surface which provides correction for field curvature and Petzval sum of other units of said lens, said second lens unit comprising from the image end a biconcave element, a biconvex element and a positive element, said biconcave element and said biconvex element forming a color correcting double: and being of overall meniscus shape concave to the image end, and a corrector lens unit of weak optical power having at least one aspheric surface positioned between said second and third lens units, said corrector lens unit being axially spaced from said second lens unit a distance

04>D:c Fo>015

35 where D_{2C} is the axial spacing distance between said second lens unit and said corrector element and Fais the equivalent focal length of said lens.

31. The lens of claim 30 where said first lens unit consists of a single element having two aspheric sur-

32. The lens of claim 30 where said positive element is also biconvex.

33. The lens of claim 30 where all elements of said second lens unit have spherical surfaces.

34. A projection lens for use in combination with a cathode ray tube where the projection lens is closely coupled to the cathode ray tube, said lens comprising from the image end a first lens unit of weak optical power having at least one aspheric surface and contributing to correction of aperture dependent aberrations. a second lens unit providing a majority of the positive power of said lens, said second lens unit being spaced from said first lens unit at least 0.1 of the equivalent focal length of the lens, and a third lens unit having a strongly concave image side surface which provides correction for field curvature and Petzval sum of other units of said lens, said second lens unit comprising from the image end a biconcave element, a biconvex element and a positive element, said biconcave element and said 60 biconvex element forming a color correcting doublet and being of overall meniscus shape concave to the image end, and a corrector lens unit of weak optical power positioned between said second and third lens. said corrector lens unit having at least one aspheric 65 surface, the configuration and the positioning of said corrector lens element from said second lens unit being such that the axial marginal rays from said second lens unit as traced from the long conjugate intersect a sur-

face of said corrector iens unit at a height H from the optical axis of said lens that is less than the clear aperture of said surface of said corrector lens unit, said corrector lens surface being configured to contribute to correction of aperture dependent aberrations within 5 said height H. said surface of said corrector iens beyond said height H being configured to contribute to correct tion of aberrations due to off-axis rays

35. The lens of claim 34 wherein said positive element of said second lens unit is biconvex. 10

36. The lens of claim 34 where said corrector lens unit consists of a single element.

37. The lens of claim 34 where all elements of said second lens unit have spherical surfaces.

38. A projection lens for use in combination with a 15 cathode ray tube where the projection lens is closely coupled to the cathode ray tube, said lens comprising from the image end a first lens unit of positive optical power having at least one aspheric surface and contributing to correction of aperture dependent aberrations. 20 said first lens unit comprising a front meniscus element convex toward the image end, a second lens unit providing a majority of the positive power of said lens, said second lens unit being spaced from said meniscus element at least 0.1 of the equivalent focal length of the 25 iens, and a third lens unit having a strongly concave image side surface which provides correction for field curvature and Petzval sum of other units of said lens. said second lens unit consisting from the image end of a biconcave element, a biconvex element and a positive 30 element, said biconcave element and said biconvex element forming a color correcting doublet and being of overall meniscus shape concave to the image end, and a corrector lens unit of weak optical power positioned between said second and third lens, the configuration 35 rector lens element moves axially in the same direction and the positioning of said corrector lens element from said second lens unit being such that the axial marginal rays from said second lens unit as traced from the long conjugate intersect a surface of said corrector lens unit at a height H from the optical axis of said lens that is less 40 than the clear aperture of said surface of said corrector lens unit, said corrector lens surface being configured to contribute to correction of aperture dependent aberrations within said height H. said surface of said corrector lens beyond said height H being configured to contrib- 45 ute to correction of aberrations due to off-axis rays.

39. The lens of claim 38 wherein said positive element of said second lens unit is biconvex.

40. The lens of claim 38 where said corrector lens unit consists of a single element. 50

41. A projection lens for use in combination with a cathode ray tube where the projection lens is closely coupled to the cathode ray tube, said lens comprising from the image end a first lens unit of weak positive optical power having at least one aspheric surface and 55 contributing to correction of aperture dependent aberrations, a second lens unit providing a majority of the positive power of said lens, and a third lens unit having a strongly concave image side surface which provides correction for field curvature and Petzval sum of other 60 units of said lens. said second lens unit comprising from the image end a biconcave element, a biconvex element and a positive element, said biconcave element and said biconvex element forming a color correcting doublet and being of overall menuscus shape concave to the 65 color correcting doublet and said biconvex lens are image end, and a corrector lens unit of weak optical power positioned between said second and third lens, the configuration and the positioning of said corrector

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lens unit from said second iens unit being such that the axial marginal rays from said second lens unit as traced from the long conjugate intersect a surface of said conrector lens unit at a height H from the optical axis of said iens that is less than the clear aperture of suid surface of said corrector iens unit, said corrector iens surface being configured to contribute to correction of aperiure dependent aberrations within said height H. said surface of said corrector lens beyond said height H being configured to contribute to correction of aberrations due to off-axis ravs

42. The lens of claim 41 wherein said positive element of said second lens unit is biconvex.

43. The lens of claim 41 where said corrector lens unit consists of a single element.

44. The lens of claim 41 where said biconcave element has an absolute optical power greater than the power of said lens and said biconvex element has an optical power greater than the optical power of sale lens

45. The lens of claim 41 where said biconcave element has an absolute optical power greater than the power of said lens

46. The lens of claim 41 where all elements or said second iens unit nave spherical surfaces

47. The lens of claim 41 where said color correcting doublet is of weak negative optical power

48 The lens of claim 41 where the absolute optical power of said biconcave element is greater than the optical power of said biconvex element

49. The lens of claim 41 where said lens has a variable magnification, said first and said second lens units move axially in fixed relation to focus said lens and said corbut at a differential rate.

50. The lens of claim 41 where said first and second lens units move axially in the same direction at differential rates to vary the focus of said lens.

51. A projection lens system for use in combination with a cathode ray tube comprising:

- (a) a first lens at the image end of said lens system wherein the surface of said first lens on the image side is convex to the image on the axis of said first iens and is concave to the image at and near the clear aperture of said first lens and the other surface of said first lens is concave to the image.
- (b) a second lens adapted to be closely coupled to a cathode ray tube, said second lens having a concave image side surface:
- (c) a color correcting doublet located between said first and second lenses, said color correcting doublet being comprised of a biconcave lens and a biconvex lens:
- (d) a biconvex lens located between said color correcting doublet and said second lens; and
- (e) a corrector lens located between said biconvex lens and said second lens. said corrector lens being shaped and positioned to contribute to correction of spherical aberrations in the central portion thereof and to contribute to the correction of aberrations due to off axis rays beyond said central portion.

52. The lens of claim 51 where both elements of said glass having spheric surfaces.

53. The lens of claim 51 where said color correcting doublet is of weak negative optical power.

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54. The iens of claim 51 where said doublet is spaced from said first iens unit at least 0.1 of the equivalent focal length of said lens

55. The lens of claim 51 where said first lens has two aspheric surfaces.

56. The lens of claim 51 where said color correcting doublet is axially spaced from said biconvex element no more than 0.01 of the equivalent focal length of said lens.

57. The lens of claim 51 where said doublet is con- 10 cave to the images.

58. A projection lens system for use in combination with a cathode ray tube comprising

(a) a first lens at the image end of said lens system wherein the surface of said first lens on the image 15 side is convex to the image on the axis of said first lens and is concave to the image at and near the clear aperture of said first lens and the other surface of said first lens is concave to the image.

- (b) a second lens adapted to be closely coupled to the cathode ray tube, said second lens having a concave image side aspheric surface:
- (c) a color correcting doublet located between said first and second lenses, the color correcting doublet being comprised of a biconcave lens and a biconvex lens;
- (d) a biconvex lens located between said color correcting doublet and said biconvex lens: and
- (e) a meniscus lens convex to the image located between said doublet and said biconvex lens.

59. The lens system of claim 58 wherein both surfaces of said second lens are aspheric.

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HUGHES DISPLAY PRODUCTS subsidiary of Hughes Aircraft Company

PACSINILE LEAD PAGE

Following our telephone conversation, we are attaching the first breakdown of tasks and estimated costs to develop YAG faceplate CRT's with delivery of 5 samples as described in the paragraph "Goal".

These costs are a first estimate which may be subject to revision up or down according to our findings. We have thought it much safer to attack the basic CRT envelope problems prior to making sample tubes.

Sincerely yours,

Utto

André Martin Manager, Color Programs

> 1501 Newtown Rd., Lexington, KY 40511 (606) 243-5500 • FAX (606) 243-5555

TRIDENT DEVELOPMENT PROGRAM (ROM PRICING)

<u>GOAL</u>: Manufacture five (5) sample tubes with YAG or BEL faceplates supplied by Trident International.

3 - 3" CRT's with YAG green faceplate

1 - 1.5" CRT with YAG red faceplate

1 - 3/4" CRT with BEL faceplate

Development Program Projected:

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Because of the nature of the faceplates, whose expansion coefficients are 75.10^{-7} for YAG and 80.10^{-7} for BEL, the color television $94X^{10-7}$ expansion standard frit sealing materials and glass cannot be used. As these tubes have to be operated at 35 KV 4mA beam current, 140 watts have to be dissipated in the faceplate. The faceplate to bulb frit seal, if not properly cooled, may develop a conductive path through the seal. Breakdown will occur with the corresponding loss of vacuum in the tube. Another difficulty lies in the anode to faceplate contact, because of the nature of the materials required to make a glass to metal seal, and of the 4mA current. Last thing is the graded glass seals needed to accommodate a glass neck whose expansion coefficient is in the 90.10⁻⁷ range.

All these problems need to find a solution before even a CRT is built. We hence propose the following program.

1. Study of a frit material compatible with the materials of funnel and faceplate.

Manufacture of full size samples for high temperature high voltage testing.

This study has to be made in close touch with Trident for the cooling system to be used.

2. Anode contact development

This will require experimentation of various metal glass seals and of faceplate to anode contact, with temperature testing.

- 3. When 1 and 2 are complete, start the manufacture of ten (10) bulbs with the final configuration decided.
- 4. Using part of these 40 bulbs, build first 3 3" YAG faceplate. CRT's seal.

TRIDENT DEVELOPMENT PROGRAM (RON PRICING)

Page 2 of 2

5. Make guns and seal, exhaust and test 3 each, 3" YAG CRT's.

6. Make the same steps than 4 and 5 for the 1.5" YAG red tube.

7. Make the same steps than 4 and 5 for the 3/4" BEL CRT.

Budgetary Costs, Estimated:

1	\$ 23,000	8 Weeks
2	13,000	+ 3
3	12,000	(10 X 1200) + 3
4	8,100	$(3 \times 2700) + 2$
5	11,000	+ 3
6	5,000	+ 3
7	4,000	+ 3
	\$ 76,100	25 Weeks

HDP Q:92057

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Optical Research Associates

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February 3, 1992

Mr. Tom St. John TRIDENT INTERNATIONAL, INC Central Florida Research Park 3280 Progress Drive Orlando, FL 32826

Subject: Final Report for the Study of the Performance of a YAG Faceplate.

Reference: Trident International, Inc. Purchase Order 9159, Fax Copy Received 11/15/91.

Dear Tom:

Enclosed is the final report on the YAG Faceplate Study. I am still investigating the source coupling efficiency as a function of faceplate index, and will forward any new information that I can find. At this point in time, a majority of our engineers take the position that the phosphor index of refraction is the determining factor, and that if the same phosphor is used for both faceplates, the same brightness will be observed.

If I can confirm the source issue either way, I will contact you. I have enjoyed the opportunity to help in your CRT faceplate development project. If the opportunity comes to develop a new CRT projection lens design, we would be pleased to help. If you have any questions or suggestion, please feel free to contact me.

This completes Optical Research Associates' efforts on the Referenced purchase order.

Sincerely,

OPTICAL RESEARCH ASSOCIATES

Eric H. Ford, Director of Optical Engineering Services

EHF:cmn:R04:fed ex

cc: B. Reinbolt/SBAO K. Thompson/ORA

enc: Final Report