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OF NAVTRASYSCEN CONTRACT N61339-92-C-0014

Final Report for period 11/1/91 to 3/25/93

HIGH DEFINITION TV PROJECTION
VIA SINGLE CRYSTAL FACEPLATE TECHNOLOGY

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Single crystal phosphor faceplates are epitaxial phosphors grown on crystalline substrates with the advantages of 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.

Projection systems incorporating cathode ray tubes utilizing single crystal phosphor faceplates will produce 1500 lumens of white light with 1000 lines of resolution, non-interlaced. This 1500 lumen projection system will meet all of the currently specified luminance and resolution requirements of Visual Display systems for flight simulators.

Significant logistic advantages accrue from the introduction of single crystal phosphor faceplate CRTs. Specifically, the full performance life of a CRT is expected to increase by a factor of five (5); ie, from 2000 to 10,000 hours of operation. There will be attendant reductions in maintenance time, spare CRT requirements, system down time, etc.

The increased brightness of the projection system will allow use of lower gain, lower cost simulator screen material. Further, picture performance characteristics will be more balanced across the full simulator.

Pending satisfactory completion of in process evaluation testing of 3" SCPF CRTs, it is recommended that a 4" SCPF CRT T2080 R/C projector head assembly be built and evaluated in an operational simulator (UH1N).

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(5) Silicon Field Emitter Arrays for Cathodoluminescent Flat Panel Displays

#N61339-92-C-0014

1.0.0

Introduction

Current technology projection systems utilizing glass, phosphor deposited faceplates have been manufactured in size up to 9" diagonal in both an electrostatic and electromagnetic configuration. With F 1.0 lenses, these projection systems can produce 1000 lumens of light output. The resolution of these projectors, based on the spot sizes possible; ie, .002" to .005", is in excess of 1000 lines, non-interlaced. In addition, these systems can autoscan and autolock in horizontal scan frequency from 15.750 Khz to 80 Khz; thus, bounding any current or projected Imaging Computer operating horizontal scan frequency requirement.

In the areas of light output and useful operational life, conventional CRTs do not optimally meet current simulator system needs.

Research and development to date has demonstrated that Single Crystal Phosphor faceplates (SCPF) could be utilized for producing high resolution, high brightness video projection cathode ray tubes (CRTs) with significantly longer operational life.

The general process of fabricating a SCPF begins with the growth of a single crystal boule of Y3A15012 (YAG)2 or other garnet with a diameter large enough for a projection CRT faceplate. The boule is sliced into wafers about 0.125 inch thick and then ground and polished to optical flat tolerances to form a substrate for epitaxial growth of doped garnet compositions. 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.

A number of cerium doped crystals have been identified as phosphor materials for the red, green and blue faceplate requirements of projection systems. Faceplates of all three colors have been fabricated tested and evaluated. Results of these faceplate evaluations are reported in Enclosure (1).

This report represents a study of the ramifications of the application of SCPF based CRTs to projection systems. For example, projection system performance, physical characteristics, cost, SCPF manufacturability, logistic support, risks; etc. are all addressed in the report and enclosures hereto.

#N61339-92-C-0014

2.0.0

Summary of SBIR Study #92-C-0014; High Definition TV Projection Via Single Crystal Faceplate Technology

1. Single Crystal Faceplate Process technology is currently limited in its ability to produce faceplates appropriate to the projection industry in diameters up to four inches (4").

2. Four (4) inch single crystal faceplate based CRTs will meet all of the currently specified flight simulator brightness and resolution specifications. Specifically, 1500 lumens of white light and 1000 lines of resolution non-interlaced can be displayed at all required brightness levels.

3. Significant logistic advantages accrue from the introduction of single crystal faceplate based CRTs. Specifically, the <u>full</u> performance life of a CRT is expected to increase by a factor of five (5); ie, from 2000 to 10,000 hours of operation. There will be an attendant reduction in maintenance time, spare CRT requirements, system down time, etc.

4. The logistic support cost savings will offset the relatively small increase in product cost by at least a factor of ten (10) to one (1).

5. The weight of the advanced Head Assembly will be equal to or less than 150 lbs. Thus, the overall size and weight will be compatible with existing dome structures currently in operational use and allow a Visual Display System upgrade program to be implemented.

6. The increased brightness of the projection system will allow use of lower gain, lower cost simulator screen material.

7. Simulator picture performance characteristics will be more balanced across the full simulator.

8. Given the performance results realized in engineering testing to date; it is recommended that a 3" - 4" SCPF based CRT T1080 R/C projector head assembly be built and evaluated in an operational simulator (UH1N).

9. It is further recommended that a 4" SCPF based CRT head assembly be developed which utilizes newly developed hybridized video and deflection amplifiers. The weight goal for this development should not exceed 150 lbs.

10. With the exception of increased light output (1500 lumens) and reduced weight (150 lbs), the performance characteristics of the item described under item (9) will be equivalent to the T2080

raster/calligraphic specification (enclosed herewith).

11. The cost to produce and implement the system configuration recommended under paragraph (8) is $450,000. The cost to produce and implement the system configuration recommended under paragraph (9) is $300,000 assuming paragraph (8) has been implemented.

3.0.0

Conclusions and Considerations

1. Brightness

A projection system which will produce 1,500 lumens of white light will encompass all of the luminance needs of currently specified simulators. All other specifications of Enclosure (4) can be met.

2. Projection System Size and Weight

The component dimensions which dictate projection system physical characteristics begin with the CRT faceplate size and length. A standard 9" diagonal tube size will result in a system of approximate size H 12" x W 28" x L 38". The weight of such a system in total approximates 300 to 400 lbs. including power supplies and remote control units. Separate Head Assembly units of these systems currently weight 200 to 250 lbs.

Size and weight reductions to 150 lbs. are possible using a 3" or 4" Single Crystal Phosphor Technology (SCPT) based CRTs.

3. Faceplate Size

While brightness is critical, the selection of the faceplate size (diameter) versus performance was based on a tradeoff of brightness, resolution, projector size and weight, simulator system capability versus current system sunk costs, logistic support costs, problems associated with manufacturing of SCPT based CRTs etc. and the cost and feasibility of manufacture of various size faceplates; ie, 3", 4" or greater. In addition to these considerations, an analysis of the use of electronic surface or hybrid technology was evaluated to optimize projected system size and weight; ie, recommendation 6 of para 6.0.0.

The determinants in specifying single crystal faceplate size are:

1. Luminance and resolution requirements of military flight simulator visual display systems.
2. Manufacturing capability to produce SCPF large diameter faceplates.
3. Compatability of proposed CRT with existing projection systems.
4. Cost.
5. Logistic support impact.

1. As delineated in enclosure 4, a projection system which produces 1500 lumens of white light with 1000 lines of resolution, non-interlaced, will meet all current or projected visual display needs for military flight simulators.

2. The manufacturing capability of U.S. suppliers is currently limited to producing four inch (4") faceplates of acceptable quality levels.

3. A four inch (4") single crystal CRT is logistically interchangeable with existing nine (9) inch conventional CRTs

installed in the T1080 R/C projection system.

4. The cost to productionize the four inch (4") single crystal faceplate would be approximately $350,000.

5. The logistic implications of introducing single crystal faceplate CRTs into simulator projection systems is very favorable because of significant life cycle cost savings, see para.10.0.0.

Given the above consideration, implementation of a four inch (4") single crystal faceplate CRT is recommended.

4. Upgrade of Existing Visual Systems

Existing simulators have motion bases installed that have limited weight handling capacity. The weight of the on-motion base visual display subsystem thus becomes critical to a "Visual Display System Upgrade". A lighter weight, high luminance, high resolution projector, compatible with the existing motion base carrying capacity, would allow a cost effective visual display upgrade program. The separate head assembly projector configuration would be appropriate for this retrofit program.

Design of the projection system proposed has been configured to insure the capability for replacement of existing projection systems and thus incur maximum benefit to existing as well as future visual display systems.

5. Projector Head Assembly Replacement

Simulator installations which currently meet all current system specifications would benefit from SCPF head assembly replacement because of the significant cost savings which would accrue from the improved CRT performance and life over the operational life of the simulator. (See para. 10.0.0).

Currently, CRTs are warranted for 2000 hours of satisfactory operation; satisfactory operation being defined as generating 50% of the original light output. SCPFs have low coulombic degradation, high resistance to burning and good thermal conductance to the faceplate substrate; thus allowing operation of cathode ray tubes at power levels which would destroy a conventional powder phosphor CRT (see Enclosure 1). In addition, the "browning effect" (browning of the faceplate glass as a function of x-rays striking the glass) results in reduced light output. Since the "browning effect" does not take place in single crystal faceplates, the operational life of a SCPF based CRT will be limited by the useful life of the electron gun. An assumed electron gun life of 10,000 hours is considered reasonable. Re-gunning of tubes is an acceptable factory process; thus, from a logistic support point of view, a cost saving factor of 10 can be anticipated by the introduction of SCPF CRT based projection head assemblies into Simulator visual display systems.

6. Recommended Areas of Additional SCPT CRT Development and Evaluation

a. Areas for potential efficiency improvement

   1. Coating of YAG surface to modify critical angle

b. Areas for test and evaluation to delineate operational limitations and failure modes

   1. High voltage limits
   2. Faceplate frit seal heating limits
   3. Life test experiment to establish limiting element; eg, E-gun, etc.
   4. Outgassing
   5. X-ray generation at high power operation
   6. Manufacturability of SCPF CRTs

4.0.0

SBIR SYSTEM CONFIGURATION

EVALUATION

This section (4.0.0) addresses the various approaches and technology options considered in arriving at the most cost effective utilization of SCPF based CRT technology in a timely and meaningful manner.

1. T1080 R/C - Head Assembly
   a. *Replace CRTs only
   b. New lenses
2. T1080 R Projection System
   a. Replace CRTs
   b. Current Technology
   c. Deflection Technology
3. New Projection System
   a. New Video Amplifiers
   b. New Deflection Amplifiers
   c. New Lenses

   Consider for 3" and 4" CRTs
4. Commercial H.D.T.V. Projection System

   **Filmless Theater Application

   15.750 Khz to 80 Khz
   a. New Video Amplifier
   b. New Deflection
   c. Single Unit

*All CRTs are circular, have cooling jackets attached and have appropriate lenses attached. The maximum diameter is determined by the heat sink.

**Also called Electronic Theater

Projectors which are utilized in currently deployed simulators are configured as follows:

1. Integrated (Head assembly with electronics and remote power supply) projector design.

2. Separate Head assembly with remote electronics and low voltage power supplies.

System Configuration Evaluations

CRT type projection systems utilized in simulators are of two (2) functional configurations; ie, raster and raster/calligraphic. Raster projectors may either have integral power supplies or remoted power supplies. Raster/calligraphic projection systems are all of the separate head assembly, remote electronics and remote power supply configuration.

Equivalent units can be fabricated with SCPF based CRTs. The extent of the changes incorporated along with the SCPF based CRTs will determine cost and schedule impact.

The recommendation of this study is incorporation of SCPF based CRTs in an existing operational unit with minimal impact on system configuration; so that, the system performance can be evaluated at minimal overall cost.

Satisfactory system performance would allow an early SCFP based CRT replacement program to be implemented resulting in major logistic cost savings to the national defense simulator program.

4.0.1

I. T1080 R/C

The T1080 R/C (Raster/Calligraphic) projection system is utilized in the UH1N Simulator and compatible with the V22 simulation system and is of the separate head, remote electronics and power supply, computer controlled configuration. Figure 2, graphically shows a CRT assembly from a T1080 R/C production unit. The CRT assembly (less lens) is a spareable, replacement unit. Figure 1, which follows, and figure 3 graphically shows a 4" SCPF CRT assembly which is directly interchangeable with the above T1080 R/C production CRT assembly. Figure 1 is the figure referred to in 6.0.0. Modification of the head assembly by replacement of the 9" CRT assembly with 4" SCPF based CRT assemblies is practical, see figure 1 through 11. All other physical and electrical elements and interfaces would remain the same.

A new lens must be developed to be compatible with the CRT and required fields of view (FOV).

This approach to proving the system performance characteristics of a SCPF based CRT projection system in an operational environment is considered the lowest cost approach with the maximum long term potential benefit.

4.0.2

II. New SCPF based CRT Head Assembly

There are other technical developments which should be pursued in order to take full system advantage of SCPF based CRTs. These developments fall into two (2) areas:

1. Fully hybridized video amplifiers

   Hybridization of existing T1080 video amplifiers would result in broader bandwidth, higher performance units.

2. Smaller, more efficient deflection amplifiers.

   Smaller, more efficient deflection amplifiers can be developed, optimized to the smaller deflection angles required in 3" and 4" SCFP based CRTs.

With these developments assumed, a new head assembly which can also interface with existing remote electronics can be developed. The head assembly would be smaller; (150 lbs.) thus, allowing weight benefits to be considered in new simulator designs.

4.0.3

III. T1080 R

A T1080 R (Raster only) projection system could be fabricated using existing technology deflection amplifiers and integral power supplies. Because of the reduced power requirements, the total system would fall approximately within the physical configuration of an existing T1080 R/C head assembly profile. This unit would have broad application and utility in the simulator visual system retrofit upgrade market.

These units would require development of lenses to be compatible with simulator FOV requirements.

Further, a raster projection system, with integrated power supplies could be upgraded for use in the simulation or "Filmless Theater" market HDTV markets.

5.0.0

IV Commercial Applications

The commercial applications of the single crystal faceplate technology falls into two (2) categories:

1. SCPF based CRT projection systems for "Filmless Theater/Auditorium use with HDTV aspect ratio presentations. Currently projected developments will support this potential.
2. Retail HDTV markets.

   While SCPF based CRTs could be utilized in large, rear screen television sets, the cost would probably be prohibitively high and is thus not recommended. A cold cathode, direct view single crystal faceplate system appears technically feasible and offers promise of superior performance to currently projected technologies at a reasonable cost. Enclosure (6) Silicon Field Emitter Arrays for Cathodoluminescent Flat Panel Displays is a description of the technology state of cold cathode development.

6.0.0

Recommendations

1. The following equipment configurations are recommended for development:

a. Projector Head Assembly using 4" single crystal faceplate based CRTs and existing electronics.

The key development items of this system would be Red, Green and Blue SCPF CRT assemblies as graphically shown in Figures 1 and 3 of paragraph 4.0.1. Development time for these assemblies is estimated to be twelve (12) to fifteen (15) months. Assuming satisfactory completion of these assemblies, incorporation of the assemblies into a T1080 R/C system assembly and subsequent systems evaluation testing will encompass approximately four to six months.

Cost to implement this phase of the recommendation is approximately $450,000. This includes the continued SCPF CRT development and evaluation effort recommended under paragraph 3.0.6.

b. Projector Head Assembly using 4" single crystal faceplate based CRTs and new video and deflection amplifiers based and developments with specifications within the range of currently projected technology advances.

Subsequent to the completion of the development of the red, green and blue SCPF and proof of overall system performance, (evaluation versus requirements of enclosure 4), the development of new wider bandwidth video amplifiers and deflection amplifiers should be initiated. These amplifiers should be of the hybrid technology configuration and be designed to meet specifications which will allow projector operation in the calligraphic mode at a horizontal scan frequency capability of 130 Khz.

Development and evaluation of these amplifiers will take approximately nine (9) months.

In parallel to this development effort, a mechanical projector configuration would be initiated which considers the significant change in amplifier form factor and weight. Preliminary layouts and weight analysis show that a 150 lb. head assembly is feasible.

Cost to complete item (b) after completion of item (a) is estimated to be $300,000.

7.0.0

High Definition TV Projections via Single Crystal Phosphor Faceplate Technology

The standards of HDTV, (1125 lines) will ultimately become the standard for commercial display systems as well as home television. The problem of brightness versus resolution on an adequate screen size can be solved for most commercial uses by a single crystal faceplate CRT based projection system. In addition, with full control of picture intensity across the screen, a uniformly bright picture can be displayed.

Development of single crystal faceplate CRT based projection systems will have broad application to both the simulation and commercial display system markets both nationally and internationally.

8.0.0

CRT Cost

Current CRTs of the electromagnetic 9" type have a unit cost of approximately $2,500 each. At a material cost level, a projector, having three (3) CRTs red, green and blue, would have a systems cost of $7,500.

The projected cost per faceplate based CRT is $5,000 each, resulting in a projector material cost of $15,000; thus showing an increase of approximately $7,500.

The basis for these estimates were quotations solicited from alternate sources; specifically,

1. Allied Signal Corp.
2. Litton Airtron Industries
3. Crystal Systems, Inc.
4. Shanghai Institute of Optics and Fine Mechanics
5. Hughes Display Products
6. Thomas Electronics

9.0.0

Logistic Support Assumptions

All data is based on currently submitted spares pricing data for the T1080 R/C projection system of the UH1N program.

1. CRT replacement assumed at 2000 hours of operation.
2. Simulator use is assumed at 4000 hours per year.
3. SCPF CRT tube life is assumed at 10,000 hours prior to factory regunning.
4. SCPF CRT module assembly cost is assumed to be $11,500.

*5. T1080 R/C CRT module assembly cost is $9,518.

6. Factory CRT module turnaround cost is assumed to be the same.
7. Six (6) simulators are assumed to be developed and operational.

* Based on quoted costs on UH1N contract.

10.0.0

Comparative Logistic Support Costs for Five (5) Year Cycle
Current CRTs vs SCPF/CRTs

T1080 Current CRTs

Initial CRT/Spares (2 sets) $28,554 x 2 = $57,108

Following the logistic support assumptions of paragraph 9.0.0, all three (3) CRTs in one (1) projector are replaced at 2000 hours of operation intervals; ie, five (5) times in 10,000 hours of operation. The replacement and repair cost per CRT is $4,500; thus, cost per projector replacement/repair is 3 x $4,500 = $13,500 (per projector).

Since there are five (5) projectors per simulator; one (1) Simulator replacement cycle would cost 5 x $13,500 or $67,500. This replacement cycle would occur five (5) times in 10,000 hours of simulator operation; thus, the total cost per 10,000 hours would be $337,500. Because operation of the Simulator is assumed to be 4000 hours per year (20,000 hours), this cycle would be repeated twice for a total cost of $675,000 per simulator installation.

Replacement 5 times in 10,000 hrs
* 1 Replacement cost/projector $13,500
5 cycles per 10,000 hours of operation x $13,500 = $67,500
x 5 projectors per simulator = $337,500
x 2 (20,000 hrs of operation) per 5 years = $675,000

Total five year cost per UH1N Program, assuming 6 installations:

6 x $675,000 = **$4,050,00**

T1080 SCPF/CRTs

Initial SCPF/CRTs spares (2 sets) $34,500 x 2 = $69,000

Replacement: 1 time in 10,000 hours.
Replacement cost = $15,500
1 x 15,500 = $15,500
x 5 projectors per simulator system = $77,500
x 2 (20,000 hours of operation) per 5 years = $155,000

Total five year cost per UH1N Program, assuming 6 installations:

6 x 155,000 = **$930,000**

For the SCPF CRT based projector, the CRT replacement cycle would be reduced by a factor of five (5); ie, once every 10,000 hours versus five (5) times. The resultant savings projected would be:

$4,050,000 - $930,000 = **$3,120,000**

11.0.0

Recommended Development Programs

Under paragraph 3.0.6 (Recommended areas of additional SCPF CRT development and evaluation) there was listed areas pertinent to the SCPF CRT which require additional test and evaluation. There follows a brief description of the specific development action required and expected results and benefits of each action.

A1. Coating of YAG surface to modify critical angle should improve the lens system F number. Calculations indicate that the maximum F number possible is 1.145.

B1. Degree of high voltage that can be tolerated with a production version SCPF CRT. The degree of high voltage that can be tolerated is dependent on the frit seal and the high dielectric insulator surrounding it. The effectiveness of the frit seal and dielectric should be at the selected operating high voltage.

2. Faceplate frit seal heating limits. Limits to the extent of heating of the faceplate are a direct function of the difference in the coefficients of expansion of the faceplate to frit seal to CRT glass envelope. Additional testing and evaluation of other materials; eg, ceramic seals and/or ceramic CRTs are recommended to insure optimum materials selection for production CRTs.

3. A life test experiment should be conducted on early production prototype SCPF CRTs; eg, E-gun life, etc. Further, confirmation of the no-browning of YAG faceplates would be obtained.

4. Outgassing. As part of item three (3), extent of or existence of outgassing would be verified.

5. X-Ray Generation As part of item 3, x-ray generation would be measured to verify that the projector shall comply with the US Department of Health and Human Services X-Radiation Safety Rules, 21 CFR, Subchapter J when operated at the normal CRT operating voltage.

6. Manufacturability of SCPF CRTs. As part of any additional production plan, a manufacturing producibility and quality plan must be completed and verified by a pilot production test run and evaluation.

12.0.0

Potential Products

As a result of this contractural study, it appears reasonable to project the following products resulting from the successful demonstration of SCPF based CRTs.

1. A T1080 R/C replacement Head Assembly utilizing four inch (4") SCPF based CRTs.

2. An integrated four inch (4") video (HDTV)/graphics projector which can be used in the simulation industry plus the filmless theater and large auditorium commercial markets.

3. The status of development of the cold cathode for direct viewing is described in Enclosure 6. Coupling of this technology with the single crystal faceplate technology holds significant product potential for both commercial and military projection systems. For example, HDTV retail products could be based on cold cathode single crystal faceplate based direct view panel integrated into an optical viewing system. This product could be marketed worldwide for both the commercial and retail entertainment markets.

All of these actions have broad international competitive implications.

13.0.0

Manufacturability

The manufacturability of SCPF based CRTs at the 4" diameter level is within the capability of U.S. suppliers today. The supplier of faceplates in production would be Litton Airtron, a division of Litton Corp. The CRT manufacturer would be determined as a result of final product configuration and competitive evaluations.

While many process problems were encountered in the CRT assembly process, these problems have been resolved to the extent that projected yields would be satisfactory. A pilot program of limited rate is necessary to confirm this assumption after completion to the additional technical effort described under paragraph 6 of section 3.0.0.

13.0.1

Liquid Phase of epitaxial growth of single crystal phosphors of Ce-Yag on Yag substrates

There appears to be no fundamental size limitation for the liquid phase epitaxy process. (See Enclosure 1).

13.0.2

Photoreticulation

The photoreticulation process will not limit the production of four inch (4") diameter single crystal faceplates. (See Enclosure 1). The need or desirability of incorporation of the photoreticulation process in the final faceplate has yet to be firmly proven.

13.0.3

Current Size Limitations of Growth limitations for Single Crystal Boules

Enclosure 1, discusses current size limitations for Single crystal Boules as projected by Allied-Signal, Inc. Their assumption was that the Czochralski method for producing boules would be used. Additionaly, the Litton Airtron Division of Litton Corp. and the Shanghai Institute for Optics were solicited as was the University of Central Florida, Crystal Growth Laboratory for quotations, opinions, etc. It was unanimously agreed that current technology for growth of Yag crystal boules was limited to four inches (4") of maximum diameter for the forseeable future.

While the Heat Exchanger Method (HEM) is being used to grow sapphire crystals in diameter of ten inches, this method has never produced crystals of equivalent Yag material to the required levels of purity. This technology was discounted by knowledgeable persons solicited.

14.0.0

Performance of Yag Faceplates

Enclosure (3), Study of the Performance of a Yag Faceplate, was conducted by Optical Research Associates under subcontract to Trident under contract N61339-91-C-0052 dated 27 March 1991. This study addressed issues of halation effects, filtering, coupling fluid refractive indics, etc.

As a result of this study, the CRT assembly, liquid cooled, will be configured as shown in Figures 1 & 2.

The cooling liquid is a mixture of 82% Ethylene Glycol and 18% Glycerin, resulting in an index of refraction of 1.60.

Temperature rise from ambient never exceeded 113 degrees F, although a worst case temperature peak of 178 degrees F was projected under maximum operating conditions.

No halation effects were noted under any condition of operation.

15.0.0

Analysis of Simulation System Visual Display Requirements (Enclosure 2)

Enclosure 2, **Final Report, Study and Evaluation of Single Crystal Faceplate CRT Projection Systems for Flight and Weapon System Trainers** summarizes the visual display performance requirements of four (4) operating or in-the-design-stage simulators.

The report concludes that a 1500 lumen projection system will have the greatest use for replacement upgrade and new system applications.

The visual system requirements can be met by a four inch (4") SCPF based CRT projection system. This system can realistically meet the 1500 lumen requirement for light output and with proper developments; ie, video amplifiers and deflection amplifiers, meet the 150 lb. goal for the head assembly. In addition, the anticipated life expectancy 10,000 hours will provide significant cost savings in the logistic support area.

16.0.0

Comparison of T1080 R/C performance versus T2080 R/C performance

As a result of the analysis and extrapolated data recorded on a 2 and 3 inch single crystal CRTs, the Study and Evaluation of Single Crystal Faceplate CRT Projection Display Systems for Flight and Weapon System Trainers (Enclosure 2) and the Comparative Logistic Support Costs Five (5) year cycle, para. 10.0.0, it was concluded that the major gains to simulator visual display systems would accrue if a 1500 lumen, 1000 lines of resolultion, non-interlaced, system were configured. Thus, enclosure (4), Product Performance Specification for the Trident Model T2080 R/C Dual Mode Video Projector, Specification Number 00222107, dated April 5, 1993 has been modified to reflect simulator system performance requirements. Specifically,

1. **LUMINANCE**. The system shall be capable of projecting a full white video field with a center luminance at the screen of no less that four (4) (versus 2) foot Lamberts (FL) for one (1) minute with a design goal of three minutes, and at 3 FL (versus 2 FL) for an indefinite period of time, at a color temperature of 6500 Degrees K.
2. Para. 3.5.1.1 -- **Light Points.** The raster

light point luminance was changed to 4 FL (versus 2 FL).

3. **Resolution.** The 1000 lines of resolution, non-interlaced, will be met and tested by means of the Resolution Test Locations, para. 3.5.2.1.2, test requirements.

4. No other system performance changes were necessary to the specification to insure that all of the simulator display requirements for a Raster/Calligraphic projector are met.

17.0.0

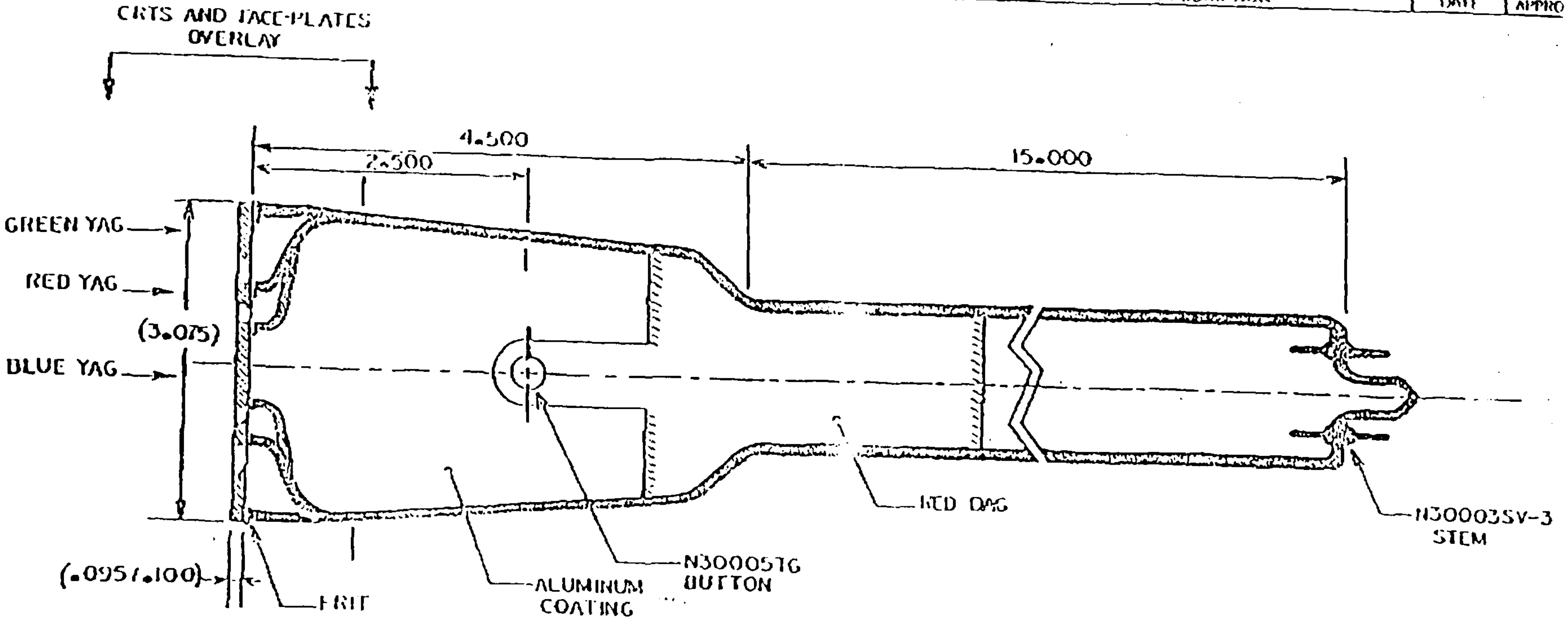
Description of System (Head Assembly) Physical Configurations

Figure 4. SCPF Based CRT (Figure following this page).

During the evaluation of Single Crystal Faceplate based CRTs, a number of manufacturing process problems were encountered.

While the following figure describes the last units manufactured, sufficient data and knowledge has been gathered to lend a high probability of success to manufacture of a four inch (4") CRT. The final configuration will be a variant of configurations already evaluated.

FIGURE 1



NOTES.

1. CRTS WILL USE "PROJECTRON'S" HIGH RESOLUTION GUN

QTY REQD	FSCM NO	PART NO OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION

PARTS LIST

EXCEPT AS NOTED DIM ARE IN INCHES AND PERCENTAGES XXX XX ANGLES

MATERIAL NA

CONTRACT

DR Onde Dotte

CHK 4/14/76

APPD

HUGHES

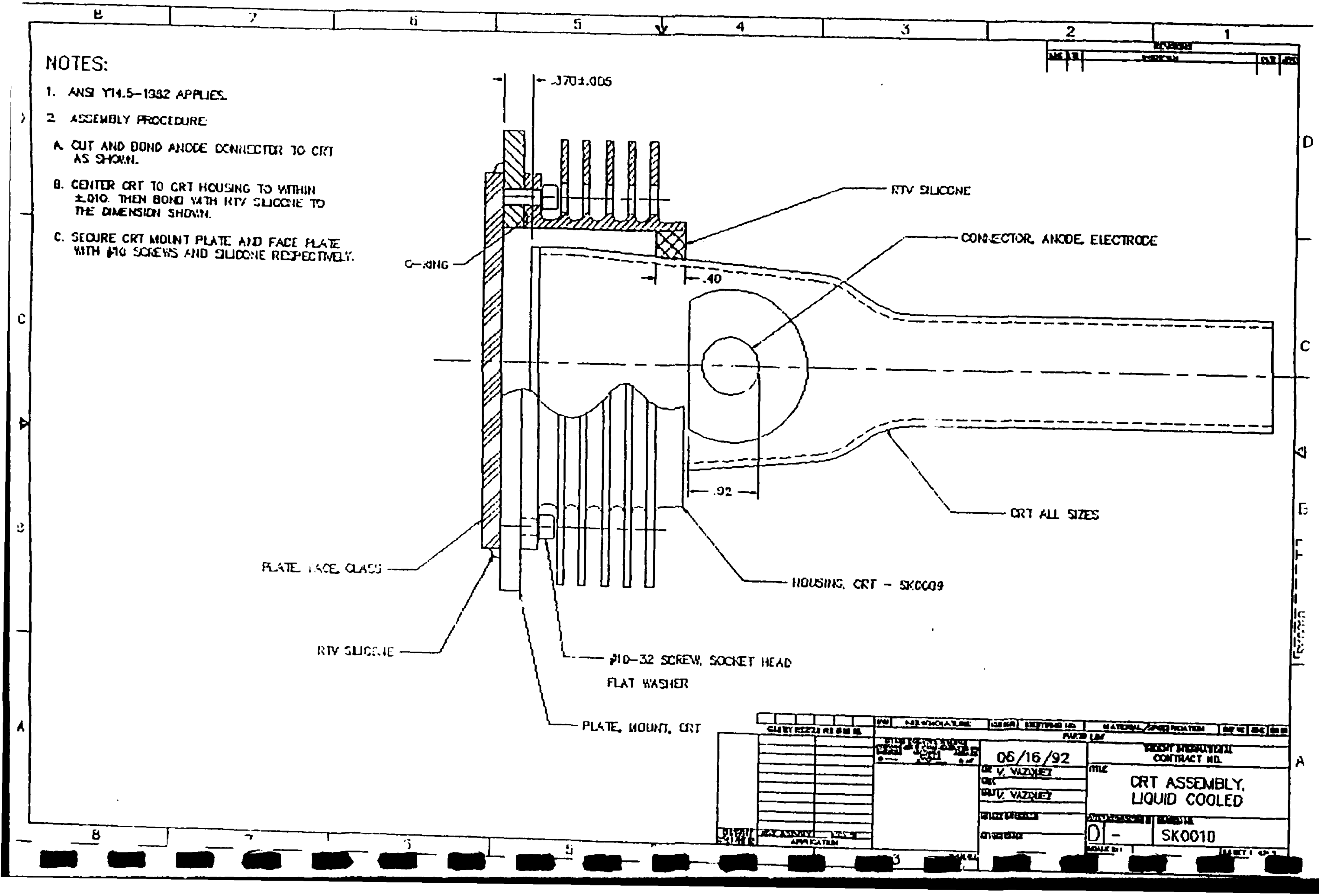
HUGHES AIRCRAFT COMPANY

CRT DESIGN FOR COOLING SCHEME (CROSS SECTION)

SIZE | FSCM NO | DWG NO

Figure 2. Single Crystal Faceplate CRT Assembly Liquid Cooled: The CRT is secured to the CRT housing by a .40 inch thick ring of structural silicone adhesive. The ring isolates the faceplate laminants from shock and vibration loads. Optical fluid surrounding the CRT provides both enhanced optical performance and transfers heat to the CRT housing. Heat from the CRT is convected to circulating air by the fins at a rate of 50 watts. Thus, this keeps the CRT at a stable temperature. (Figure 2 following this page).

FIGURE 2



NOTES:

1. ANSI Y14.5-1982 APPLIES.
2. ASSEMBLY PROCEDURE:
   - A. CUT AND BOND ANODE CONNECTOR TO CRT AS SHOWN.
   - B. CENTER CRT TO CRT HOUSING TO WITHIN ±.010. THEN BOND WITH RTV SILICONE TO THE DIMENSION SHOWN.
   - C. SECURE CRT MOUNT PLATE AND FACE PLATE WITH #10 SCREWS AND SILICONE RESPECTIVELY.

Figure 3. <u>Head Assembly -- T1080 R/C Compatible 3" and 4" Single Crystal Faceplate Based CRTS</u>

A conventional T1080 R/C projector head is fitted with a 4" crystal faceplate CRTs. The CRT assemblies are longer than the conventional phosphor CRTs by four inches. Therefore the lens assembly and CRT image plane has been moved forward 3.1 inches. To obtain the original image area a new lens design is needed or the projector needs to be placed further away from the screen. (Figure 3 on following page).

FIGURE 3

HEAD ASSEBLY TOP VIEW - T1080 R/C COMPATIBLE
3" AND 4" SINGLE CRYSTAL FACE PLATE
BASED CRTS

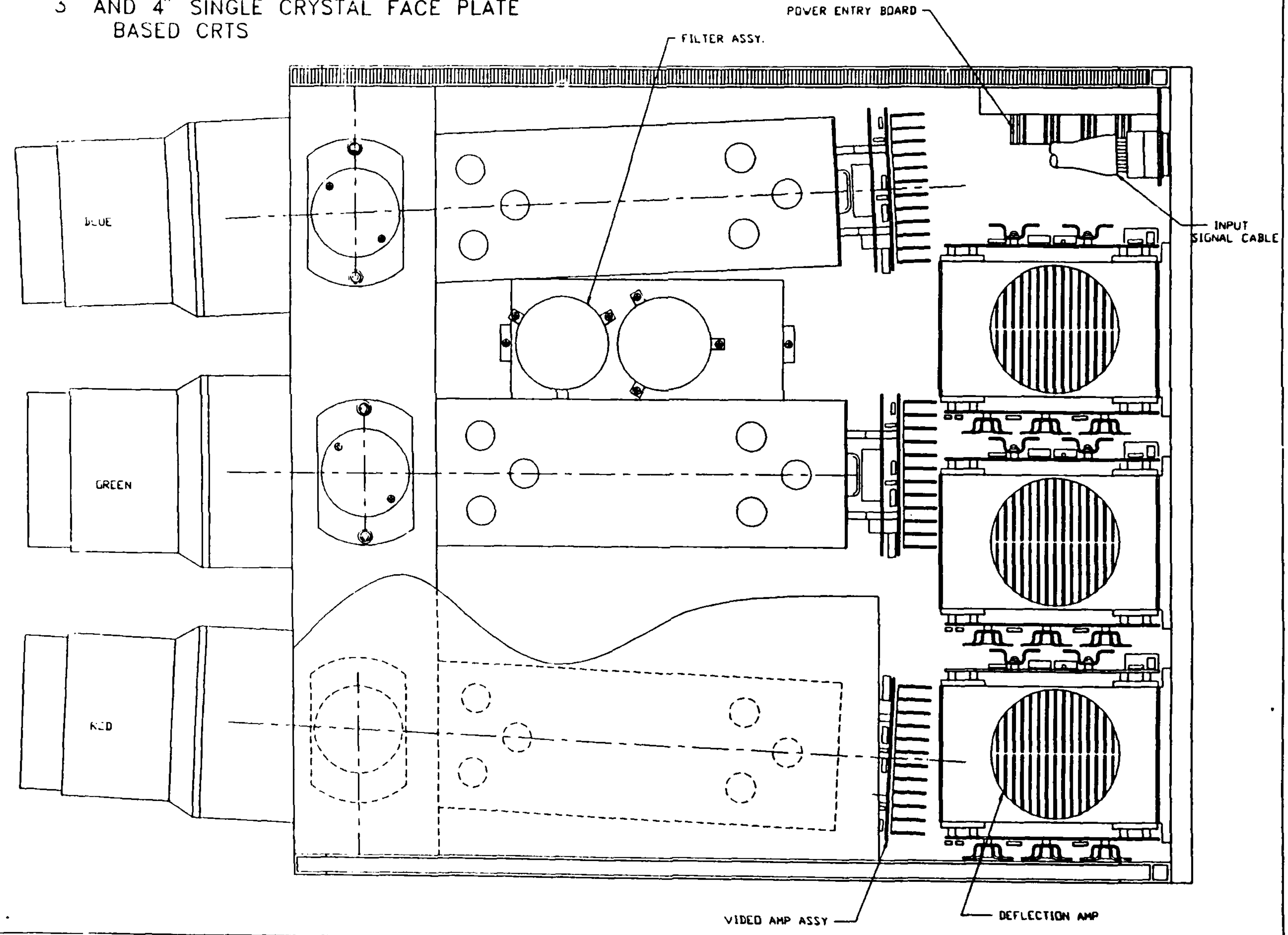


Figure 4. Head Assembly -- T1080 R/C Compatible 4" Single Crystal Faceplate Based CRTs

The CRT assemblies are secured to the projector head by a trunion mount which interfaces with existing support structure. Eight cap screws attach the trunion mount to the CRT assembly via the rear of the CRT housing. Optical coupling fluid surrounds the CRT and "C" element. The fluid increases optical performance and at the same time effectively transfers heat from the CRT faceplate laminants. The lens assembly mounts in the traditional manner with four captive screws. This configuration results in a weight reduction a CRT assembly from 37 to 29 pounds. (Figure 4 following this page).

FIGURE 4

HEAD ASSEMBLY – T1080 R/C COMPATIBLE
4" SINGLE CRYSTAL FACE PLATE
BASED CRTS

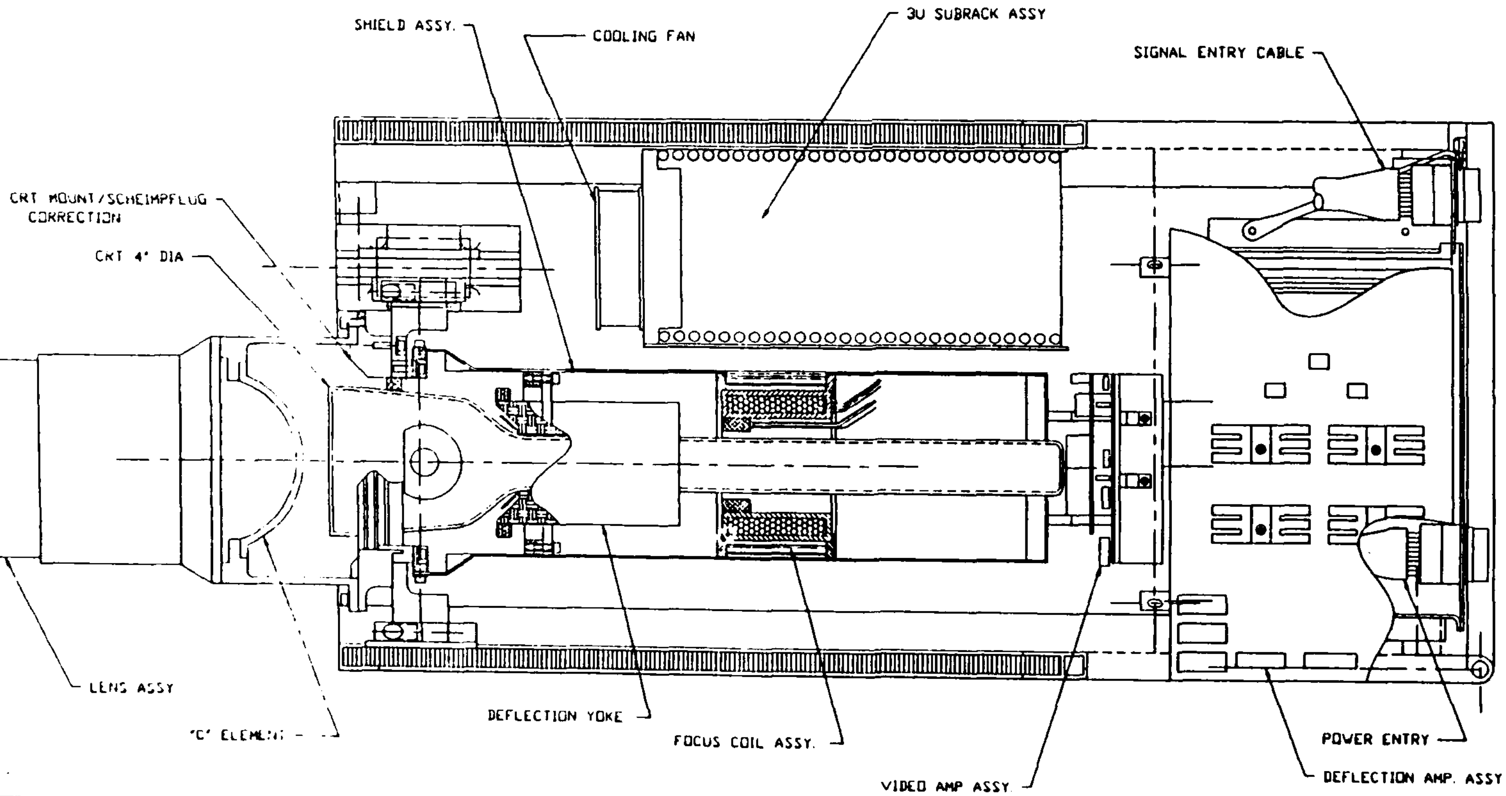
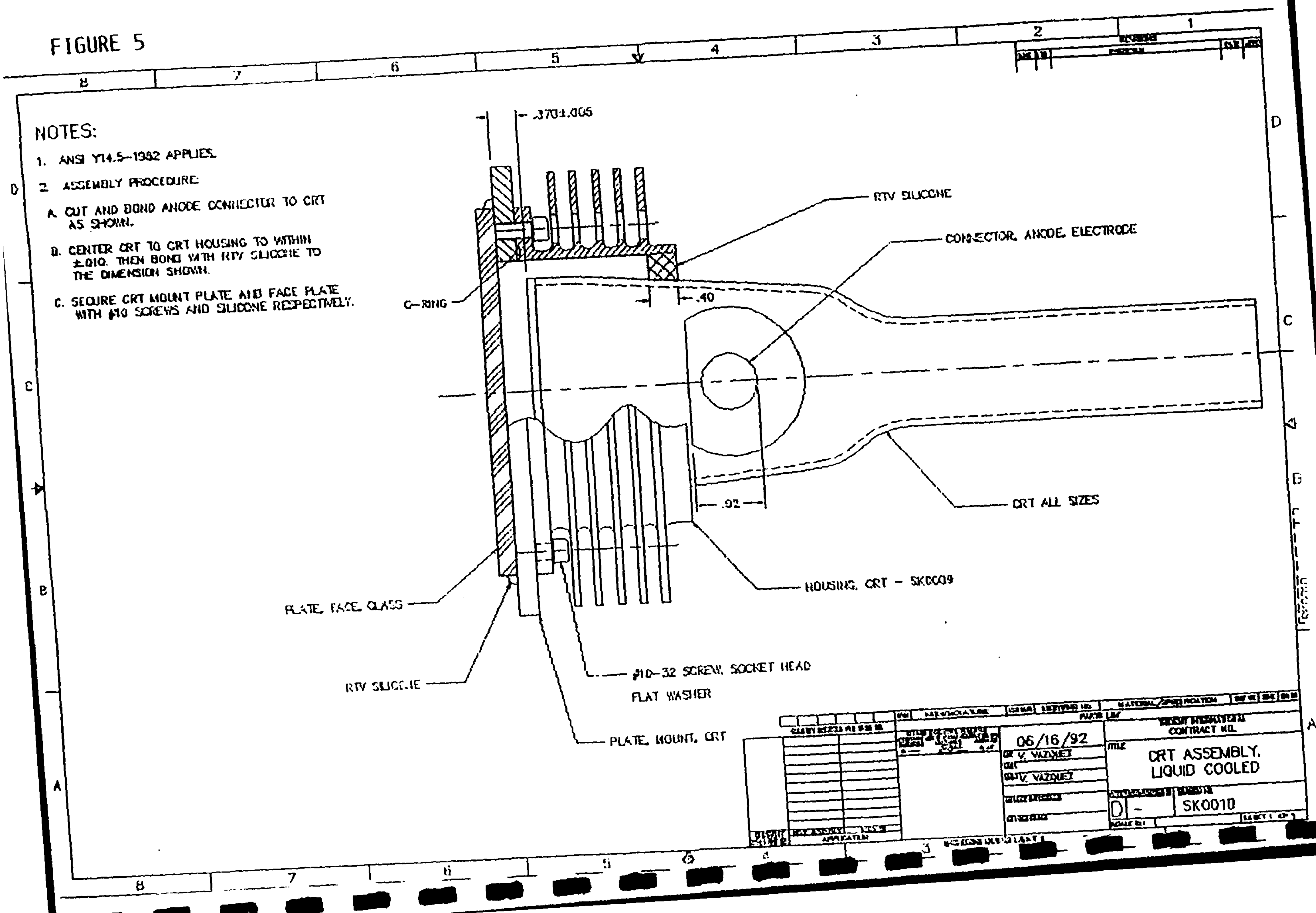


Figure 5. Single Crystal Faceplate CRT Assembly Liquid Cooled: The CRT is secured to the CRT housing by a .40 inch thick ring of structural silicone adhesive. The ring isolates the faceplate laminants from shock and vibration loads. Optical fluid surrounding the CRT provides both enhanced optical performance and transfers heat to the CRT housing. Heat from the CRT is convected to circulating air by the fins at a rate of 50 watts. Thus, this keeps the CRT at a stable temperature. (Figure 5 following this page).

FIGURE 5



NOTES:

1. ANSI Y14.5-1982 APPLIES.
2. ASSEMBLY PROCEDURE:
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Figure 6. Head Assembly -- T1080 R/C Compatible 3" and 4" Single Crystal Faceplate Based CRTS

A conventional T1080 R/C projector head is fitted with a 4" crystal faceplate CRTs. The CRT assemblies are longer than the conventional phosphor CRTs by four inches. Therefore the lens assembly and CRT image plane has been moved forward 3.1 inches. To obtain the original image area a new lens design is needed or the projector needs to be placed further away from the screen. (Figure 6 on following page).

FIGURE 6

HEAD ASSEBLY TOP VIEW - T1080 R/C COMPATIBLE
3" AND 4" SINGLE CRYSTAL FACE PLATE
BASED CRTS

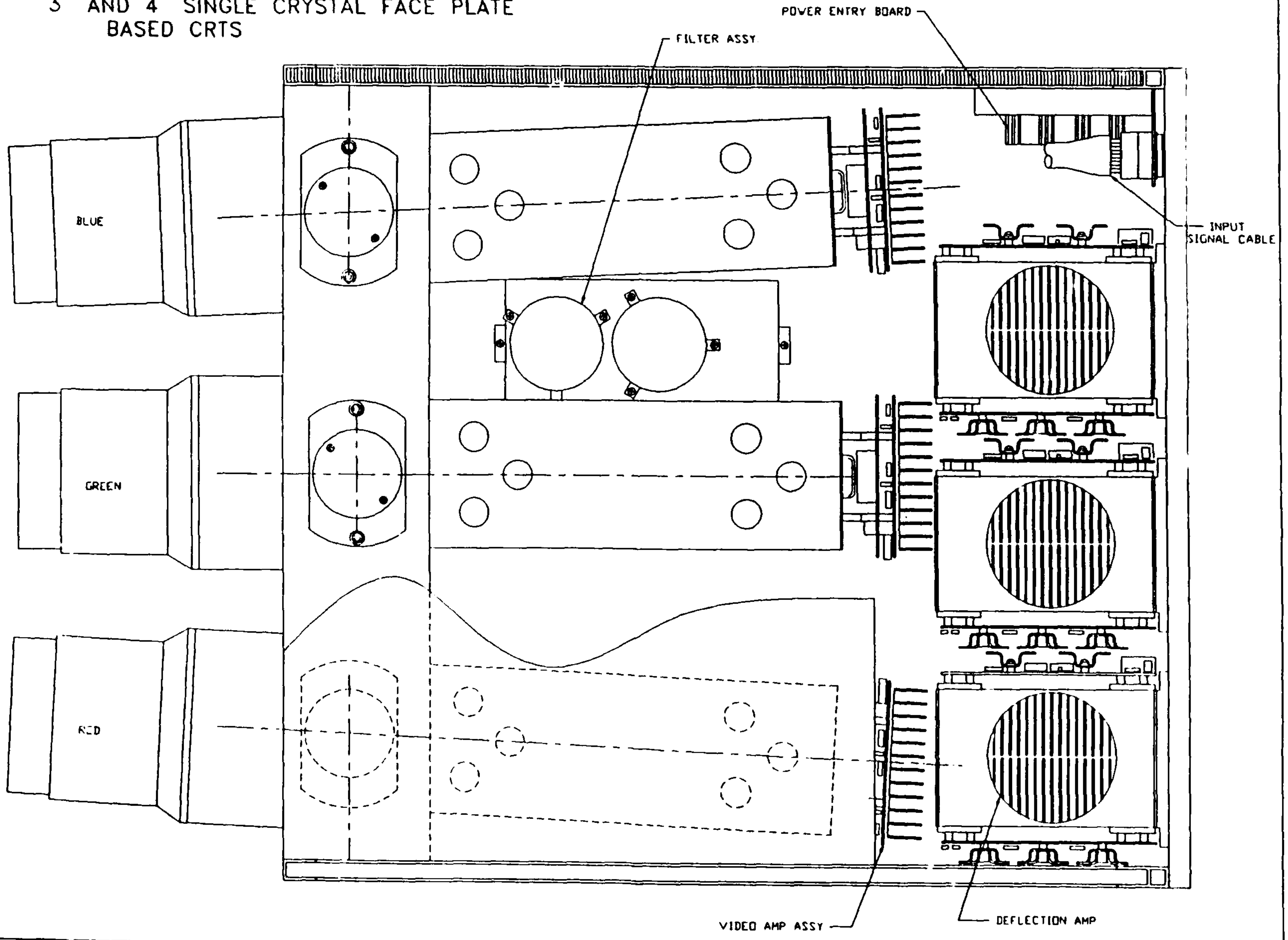


Figure 7. Head Assembly -- T1080 R/C Compatible 4" Single Crystal Faceplate Based CRTs

The CRT assemblies are secured to the projector head by a trunion mount which interfaces with existing support structure. Eight cap screws attach the trunion mount to the CRT assembly via the rear of the CRT housing. Optical coupling fluid surrounds the CRT and "C" element. The fluid increases optical performance and at the same time effectively transfers heat from the CRT faceplate laminants. The lens assembly mounts in the traditional manner with four captive screws. This configuration results in a weight reduction a CRT assembly from 37 to 29 pounds. (Figure 7 following this page).

FIGURE 7

HEAD ASSEMBLY - T1080 R/C COMPATIBLE
4" SINGLE CRYSTAL FACE PLATE
BASED CRTS

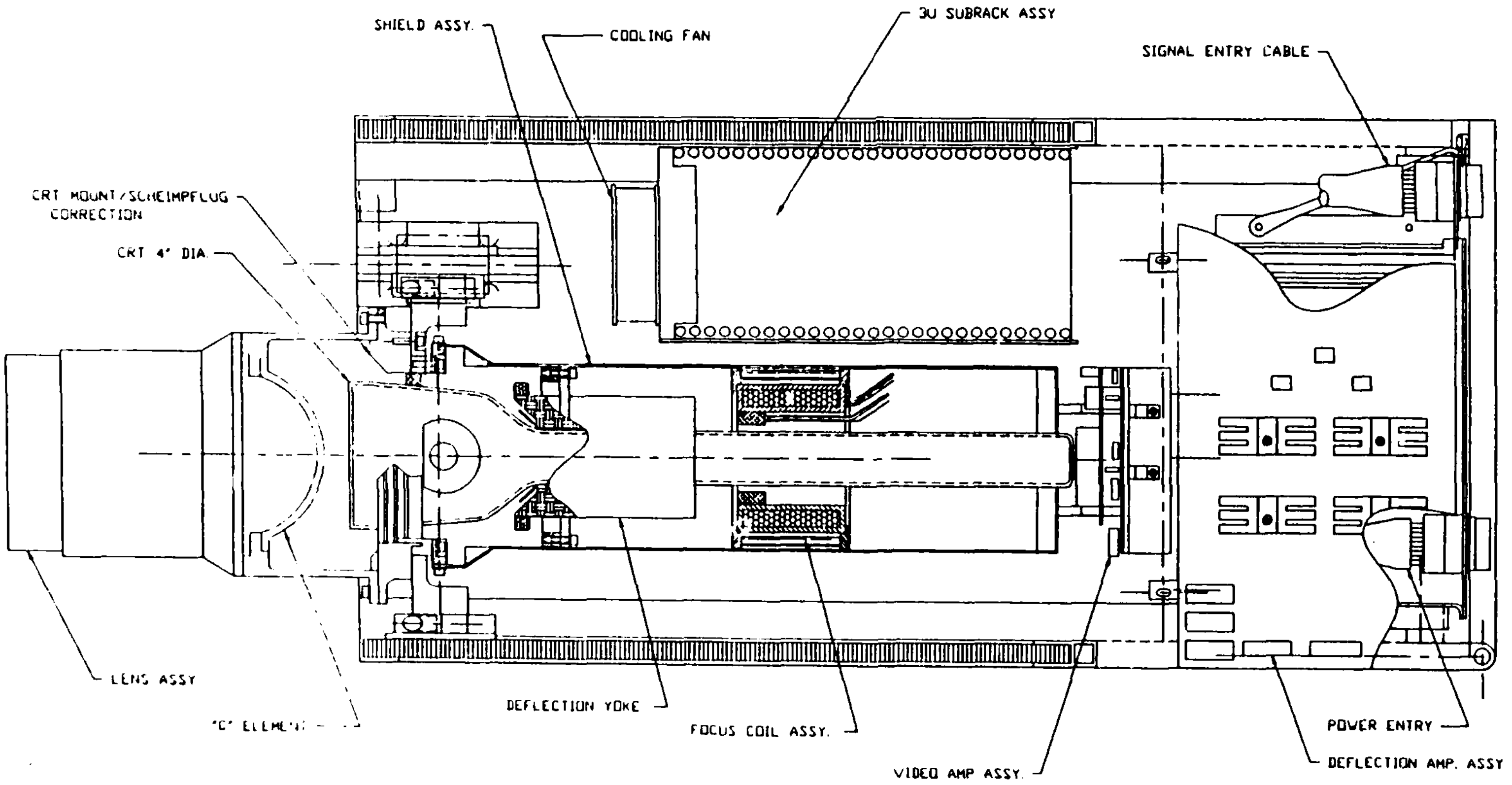


Figure 8. Head Assembly -- T1080 R/C Compatible 3" Single Crystal Faceplate Based CRTs

The CRT assemblies are secured to the projector head by a trunion mount which interfaces with existing support structure. Eight cap screws attach the trunion mount to the CRT assembly via the rear of the CRT housing. Optical coupling fluid surrounds the CRT and "C" element. The fluid increases optical performance and at the same time effectively transfers heat from the CRT faceplate laminants. The lens assembly mounts in the traditional manner with four captive screws. This configuration results in a weight reduction a CRT assembly from 37 to 29 pounds. (Figure 8 following this page).

FIGURE 8

HEAD ASSEMBLY - T1080 R/C COMPATIBLE
3" SINGLE CRYSTAL FACE PLATE
BASED CRTS

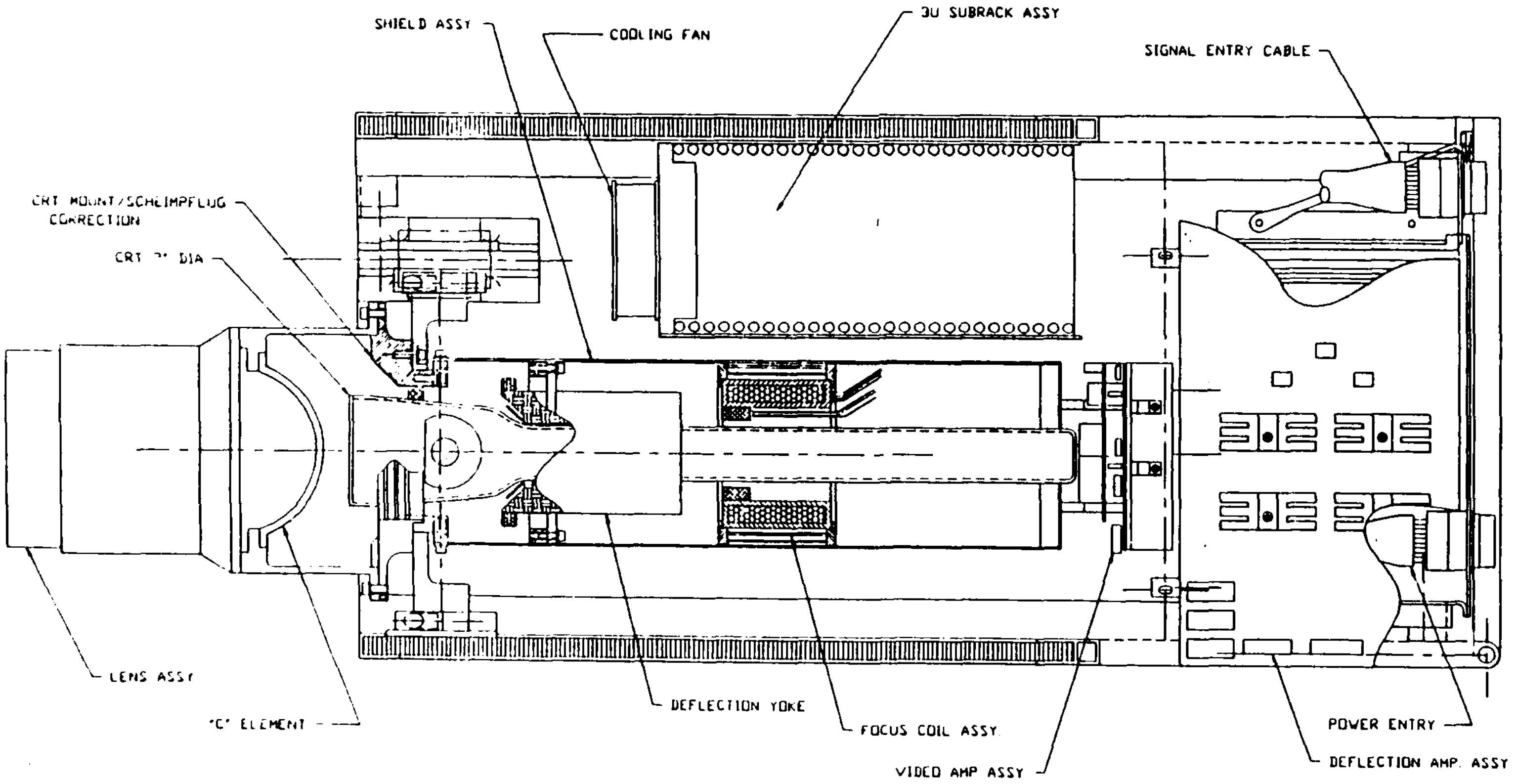


Figure 9. Head Assembly 4" Single Crystal Faceplate Based CRTs Advanced Projector

Top View

A broken section from the top illustrates the location of the CRT assemblies to the filter and 3U subrack assembly. The 3U subrack contains the focus amps and cpu control boards. Two fans push cooling air through the unit. A third fan provides the main cooling for the electronics on the underside of the head assembly. The width of the projector head has been reduced by three inches. This can be used to the advantage of the simulator configuration engineer by placing the projectors closer together. The effective use of this property can reduce the simulator pitch and role inertia, (Ixx) and (Izz), of a UH1N five projector head system from 1605 slug-ft^2 and 1552 slug-ft^2 to 918 slug-ft^2 and 874 slug-ft^2 respectively. These inertia estimates result by placing the first and second zone projectors at the same height above the dome center and then dropping the third zone projector to the previous level of the second zone projectors. (Figure 9 on the following page).

HEAD ASSEMBLY TOP VIEW
4" SINGLE CRYSTAL FACE PLATE BASED CRTS
ADVANCED PROJECTOR

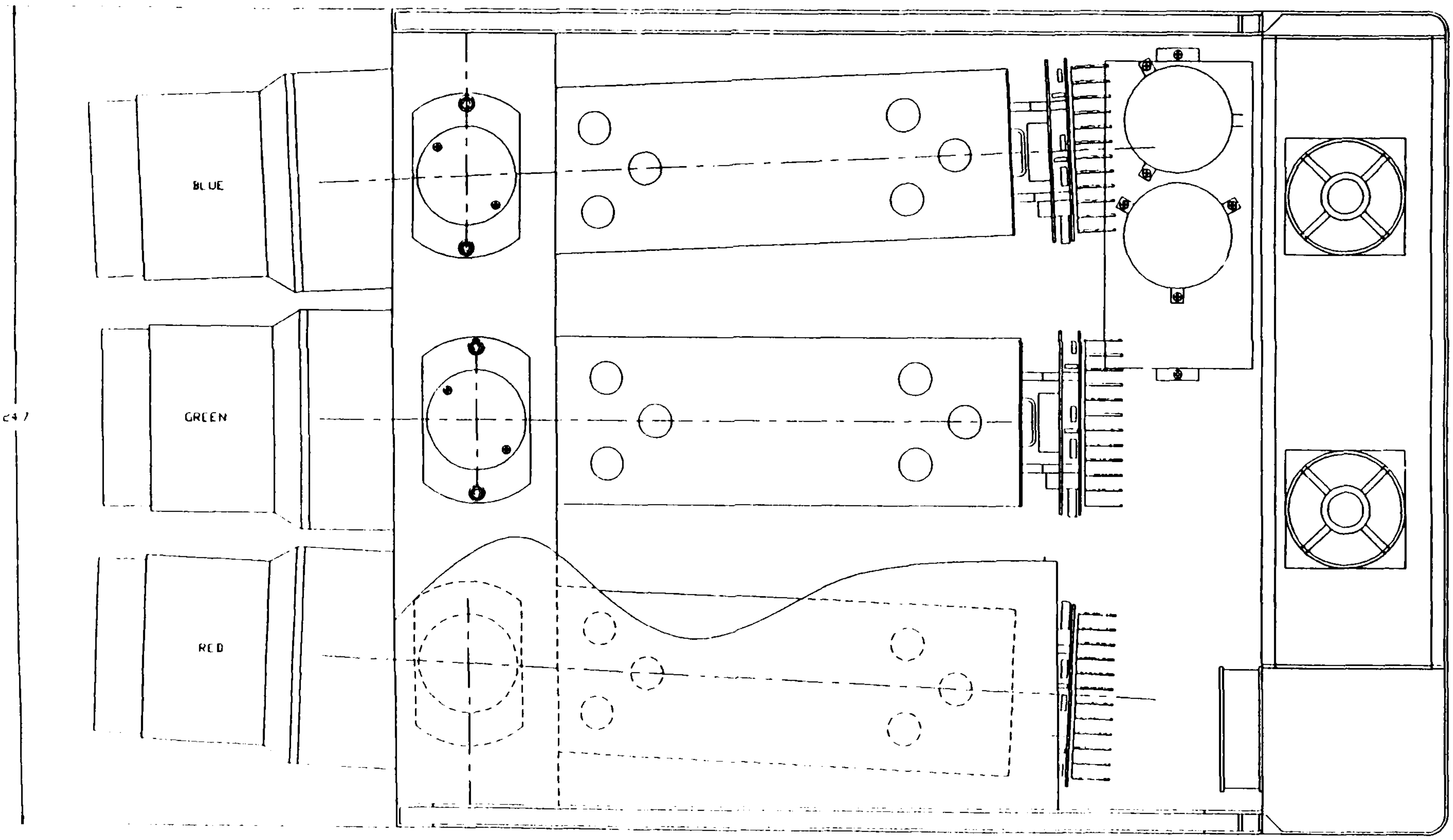


Figure 10. **Head Assembly 4" Single Crystal Faceplate Based CRTs Advanced Projector**

Side View

A broken section of the side illustrates the separation of the CRT assemblies and the electronics that control the head assembly. Maintenance of all control electronics is performed by removing the bottom cover. This cover swings way from the projector. It is made of fiber composite material and weighs approximately 7 pounds. Removal of a CRT assembly is accomplished by detaching the trunion clamps and sliding the assembly out the front.

The main structure surrounds the CRT assemblies and all the controlling electronics is either mounted to the rear or below the CRT assemblies. As a result of this configuration weight has been reduced from a maximum of 213 to 183 pounds. A second benefit is that mechanical stabilization form vibration is easily obtained since the CRT assemblies are close to the mounting locations. (Figure 10 is on the following page).

FIGURE 10

HEAD ASSEMBLY
4" SINGLE CRYSTAL FACE PLATE BASED CRTS
ADVANCED PROJECTOR

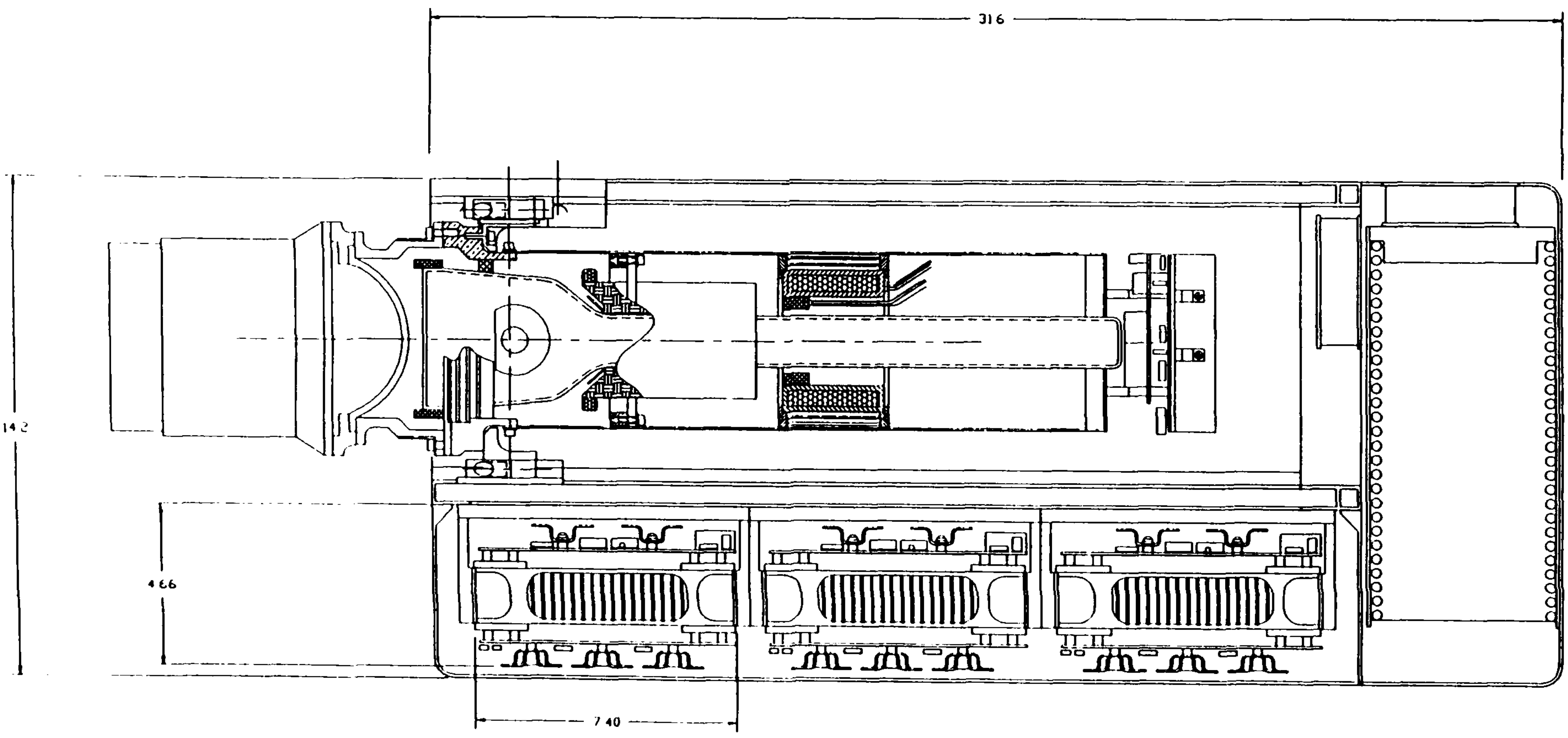
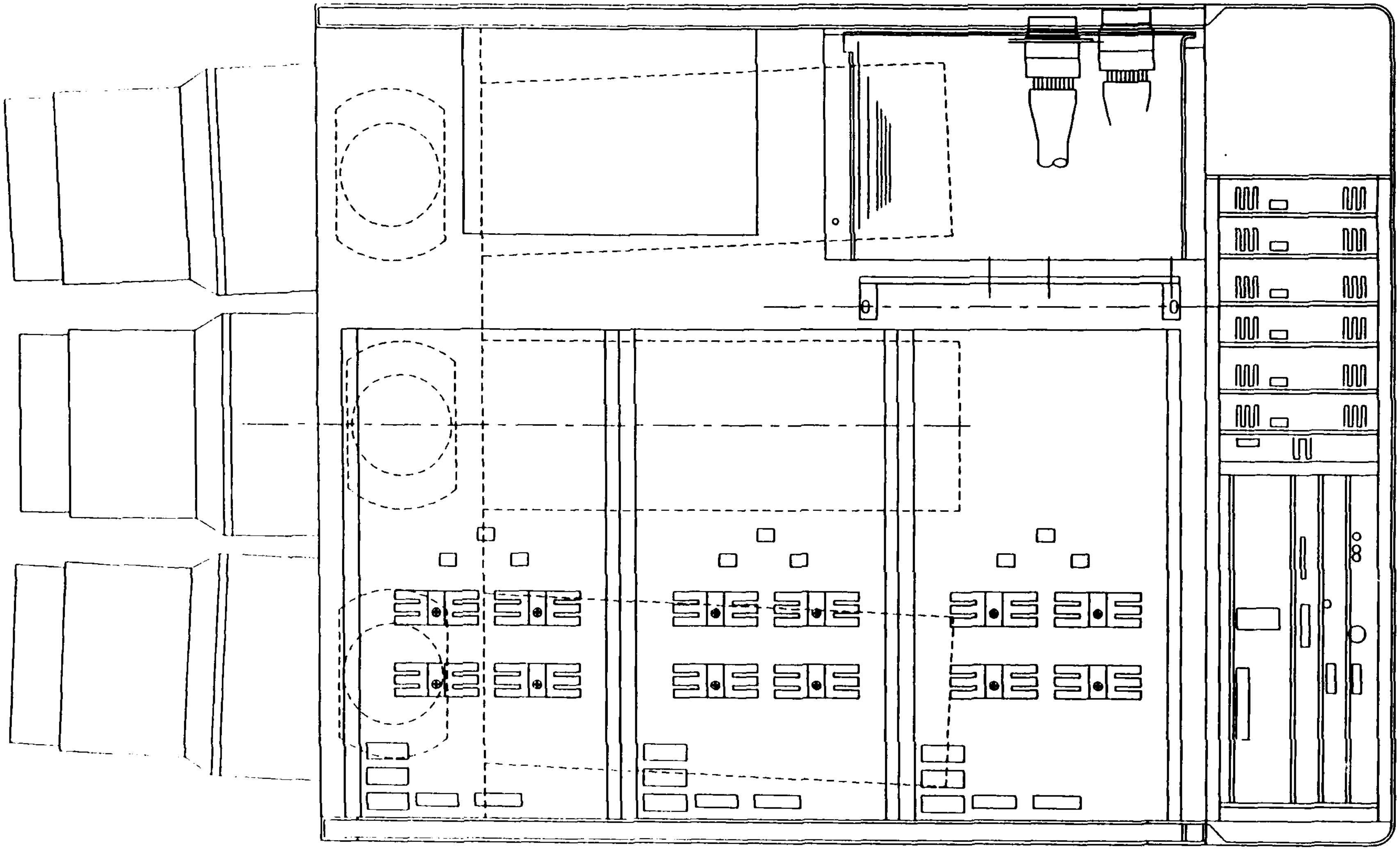


Figure 11. **Head Assembly 4" Single Crystal Faceplate Based CRTs Advanced Projector**

Bottom View

This view illustrates that with the electronics cover stowed the deflection amplifiers, high voltage power supply, input power board, and 3U subrack control electronics are all accessible for maintenance. The electronic components on the underside of the deflection amplifiers are accessed by incorporating a deflection amp mount that pivots. Thus the deflection amplifiers are easily removed or tested in place. (Figure 11 is on the following page).

HEAD ASSEMBLY BOTTOM VIEW
4" SINGLE CRYSTAL FACE PLATE BASED CRTS
ADVANCED PROJECTOR



Final Report

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

Purchase Order No. 9166

Submitted By

Applied Physics Laboratory
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P.O. Box 1021
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Submitted To:
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Allied Signal

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

a study for

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Central Florida Research Park
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Orlando, Florida 32826

by

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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, sunlight-readable head-up displays (HUDs) for aircraft require a brightness of 10,000 foot-lamberts, 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/cm^2. The phosphor particles will actually melt at about 5 watts/cm^2. 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/cm^2. 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 $R_3T_5O_{12}$ (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 $Y_3Al_5O_{12}$ (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 μm spot size. This Ce:YAG epitaxial phosphor faceplate was further tested to a current density of 1000 A/cm^2 at 5 kV without permanent damage. M.W. van Tol and J. van Esdonk operated epitaxial phosphor faceplates at power levels of 10 W/cm^2 [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/cm^2 [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/cm^2. 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:$BaAl_{12}O_{19}$ [3,4]. AT&T Bell Laboratories has developed a modified terbium composition, $Tb_{0.2}Y_{0.1}Lu_{2.7}Al_3Ga_2O_{12}$, 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/cm^2 is the conventional limit for projection CRTs. Operation of P53 at 0.5 W/cm^2 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:$Gd_3Al_5O_{12}$ can be grown as the analog of Ce:$Y_3Al_5O_{12}$, 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:$La_2Be_2O_5$ (Ce:BEL) and Ce:Y_2SiO_5 (cerium orthosilicate), are candidates for blue faceplates. Ce:Y_2SiO_5 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:$Gd_3Al_5O_{12}$ (Ce:GdAG, red), Ce:$Y_3Al_5O_{12}$ (Ce:YAG, green), and Ce:$La_2Be_2O_5$ (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.

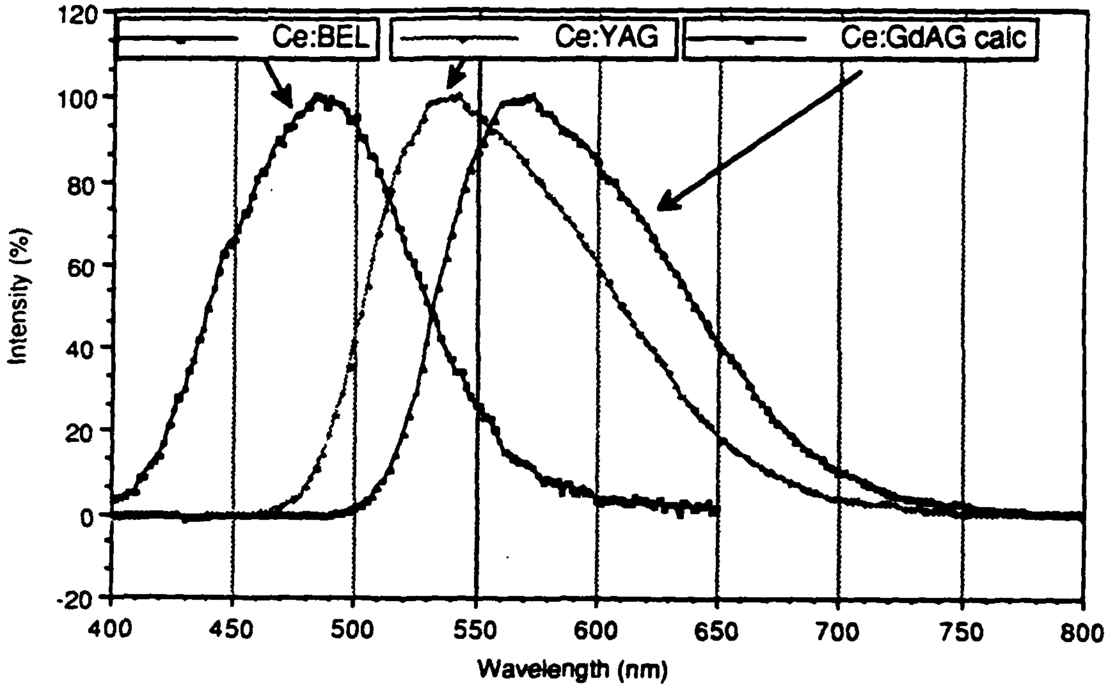

Fig. 1.0.0.1 Spectra of Ce:BEL (blue), Ce:YAG (green) and Ce:GdAG (red) phosphors.

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

Stage	Example
Grow Cylindrical Crystal by Czochralski Technique	YAG Crystal Boule 3-1/4 inch diameter by 10 inch length
Grind and Slice Wafers	YAG wafers 3 inch diameter by 0.125 inch thickness
Lap and Polish Wafers	Rough polish to remove saw damage (0.005 inch); fine polish to flatness 1 µm/inch; final polish (epi polish) with silica colloid
Liquid Phase Epitaxial Coating with Phosphor	Ce:YAG phosphor layer 20 µm thickness deposited from PbO-based flux
Reticulation	Photolithography of hexagonal array 25 µm centers, followed by etching in phosphoric acid to give frustrated pyramids
Test	Demountable faceplate test station with 1 inch square NTSC raster at 25 kV, up to 20 Watt per square cm beam power

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

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 (HEM™) 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 $Ti:Al_2O_3$. 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 Al_2O_3 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 Ce^{3+} charge state. Likewise, the blue phosphor $Ce:Y_2SiO_5$ 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:Gd_2SiO_5 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 (HEM™) 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 Al_2O_3 (2040°C): therefore, current HEM™ furnaces are adequate for growing this crystal. In the case of sapphire (Al_2O_3) crystals grown by HEM™, 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 HEM™ furnace so that these crystals can be grown with existing HEM™ 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 µm/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.

Table 2.3.0.1. Melt for the growth of epitaxial layers of Ce:YAG on YAG substrates at 980 °C. Note that cerium oxide, the dopant, is not included in the mole fraction calculation.

Oxide	Mole Fraction	Moles	Grams
PbO	0.90282	3.44684	769.299
Al_2O_3	0.01737	0.06632	6.762
B_2O_3	0.07524	0.28724	19.998
Y_2O_3	0.00457	0.01745	3.941
CeO_2		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 µm/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 $Y_3Al_5O_{12}$. 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°C ± 1°C.

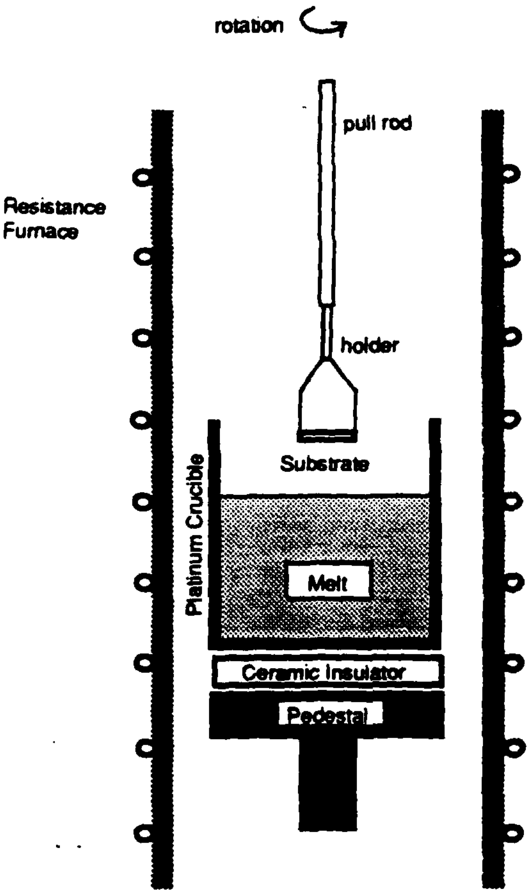

Fig. 2.3.1.1. Schematic diagram of system for liquid phase epitaxial growth of single crystal phosphors of Ce-YAG on YAG substrates.

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/cm^2 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/cm^2. A beam power of 16 watt/cm^2 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.

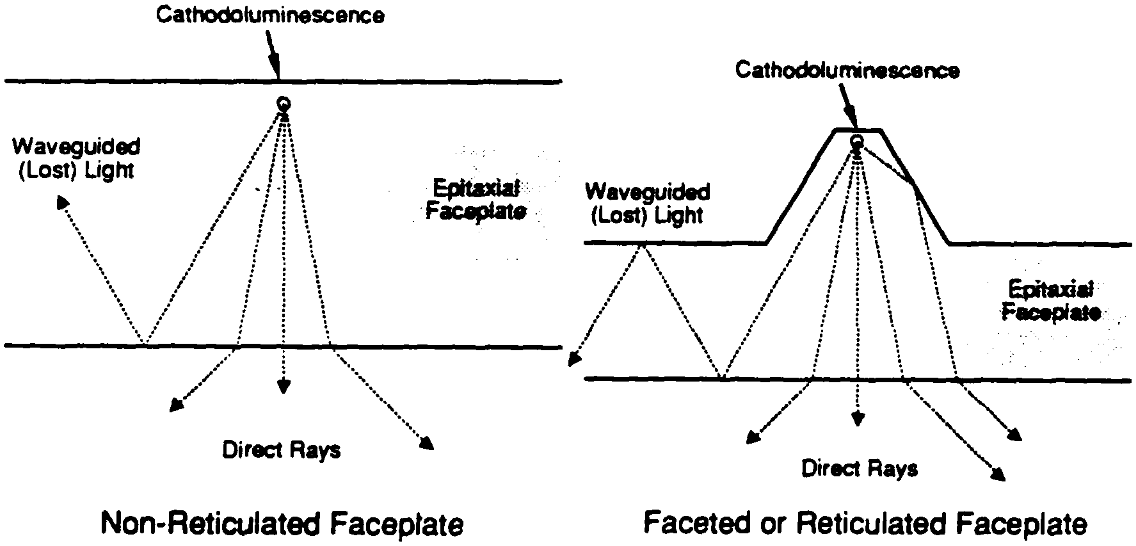

Fig. 2.4.0.1. Schematic illustration of waveguiding effect in epitaxial faceplates, and the role of reticulation in directing light into the critical cone.

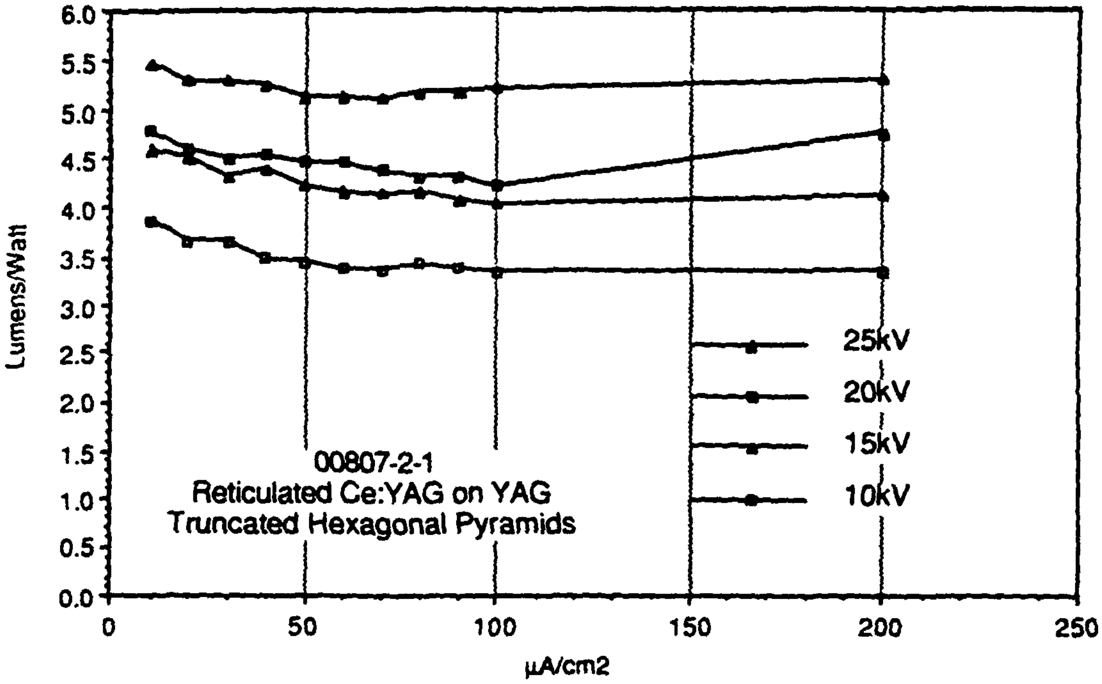

Fig. 2.4.0.2. Cathodoluminescent measurements on a reticulated faceplate.

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, $Ce:La_2Be_2O_5$ (Ce:BEL) and $Ce:Y_2SiO_5$ (cerium orthosilicate), are candidates for blue faceplates. $Ce:Y_2SiO_5$ has emission extending below blue, peaking at about 390 nm, so that much of its light output is not visible. A similar phosphor $Ce:Gd_2SiO_5$ has a better spectral overlap with the visible, peaking at 430 nm. The performance of $Ce:Y_2SiO_5$ 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, $Ce:Gd_3Al_5O_{12}$ (Ce:GdAG, red), $Ce:Y_3Al_5O_{12}$ (Ce:YAG, green), and $Ce:La_2Be_2O_5$ (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, $Ce:Y_2Gd_1Al_5O_{12}$, is strained with respect to the YAG wafer, and its red-shift is only about a third as large as that of $Ce:Gd_3Al_5O_{12}$. 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, $Gd_3Al_5O_{12}$, would exhibit a larger red-shift, but it cannot be grown as an epitaxial layer on YAG.

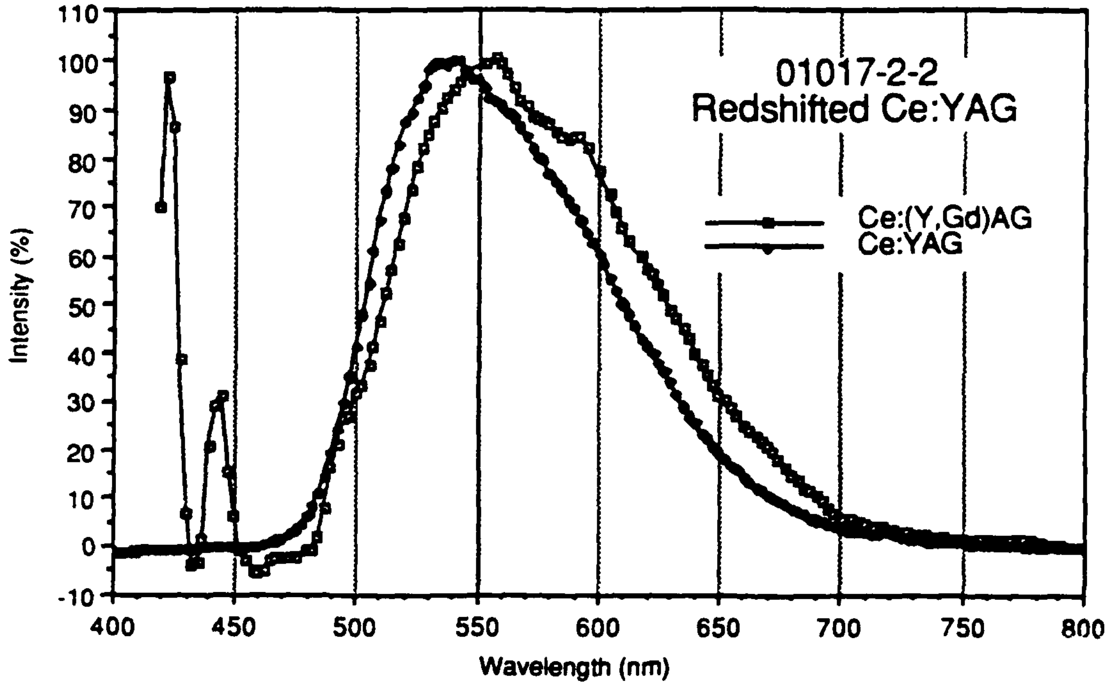

Fig. 3.2.1.1 Cathodoluminescent spectrum of a Ce:$Y_2Gd_1Al_5O_{12}$ phosphor layer grown on a YAG substrate.

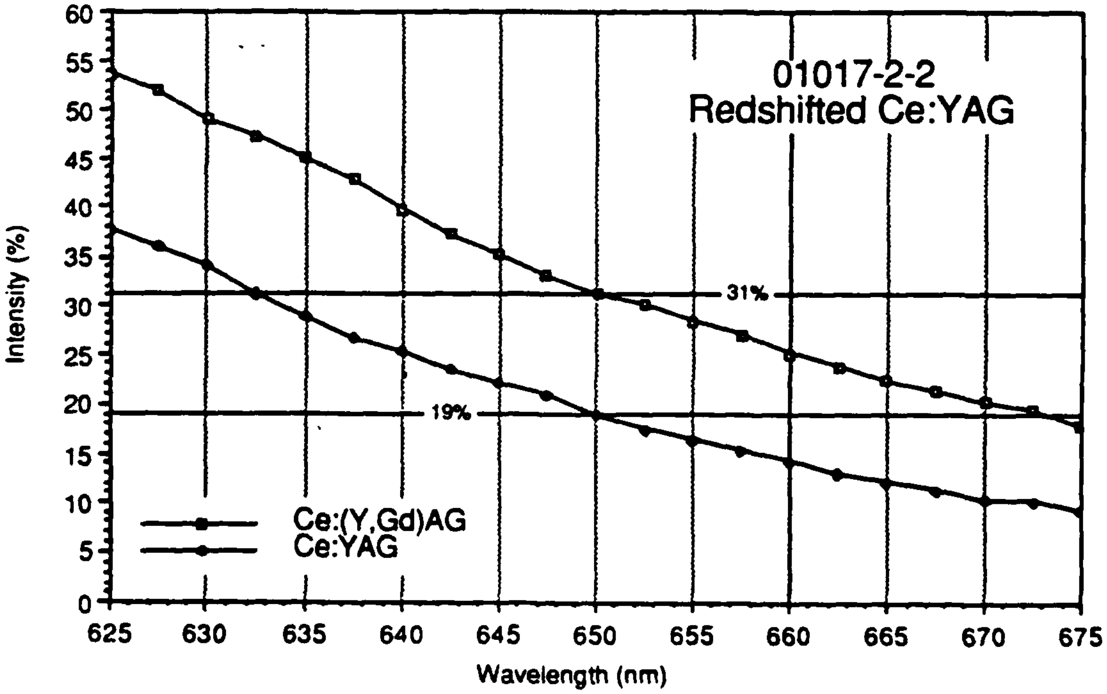

Fig. 3.2.1.2. Cathodoluminescent spectrum (detail) of a Ce:$Y_2Gd_1Al_5O_{12}$ phosphor layer grown on a YAG substrate.

3.2.2 Ce:GdAG on GdAG

Epitaxial layers of Ce:$Gd_3Al_5O_{12}$ could be grown on $Gd_3Al_5O_{12}$, and they would be good red faceplates in color projection systems since they would have a red-shift of about 50 nm.

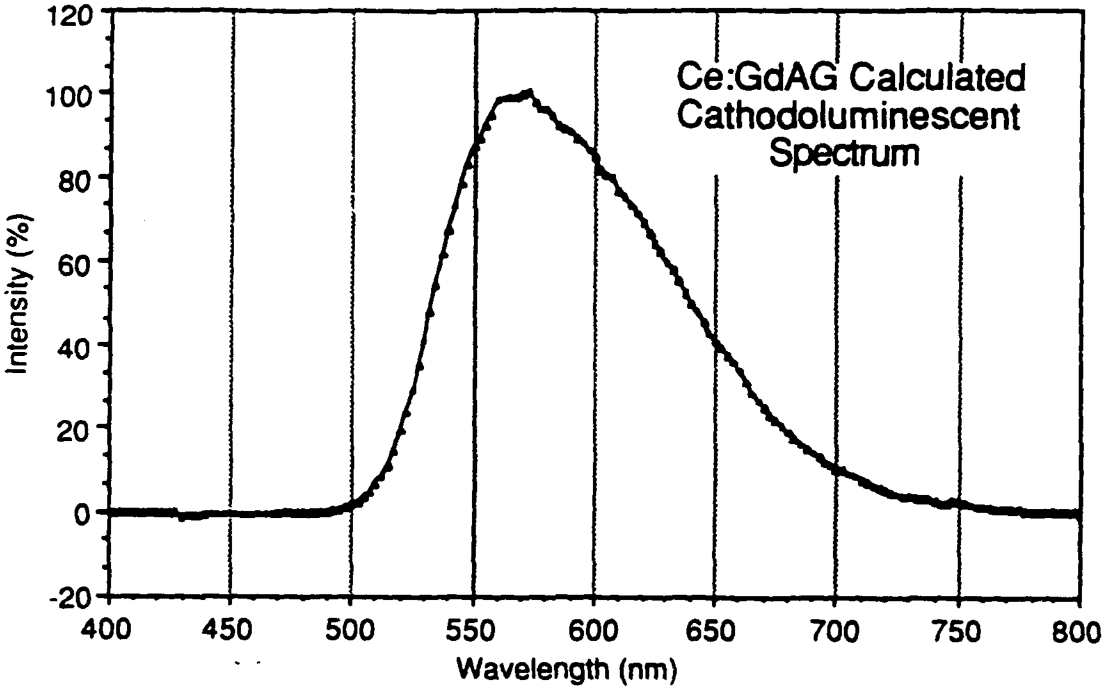

Fig. 3.2.2.1. Calculated spectrum of Ce:$Gd_3Al_5O_{12}$.

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.

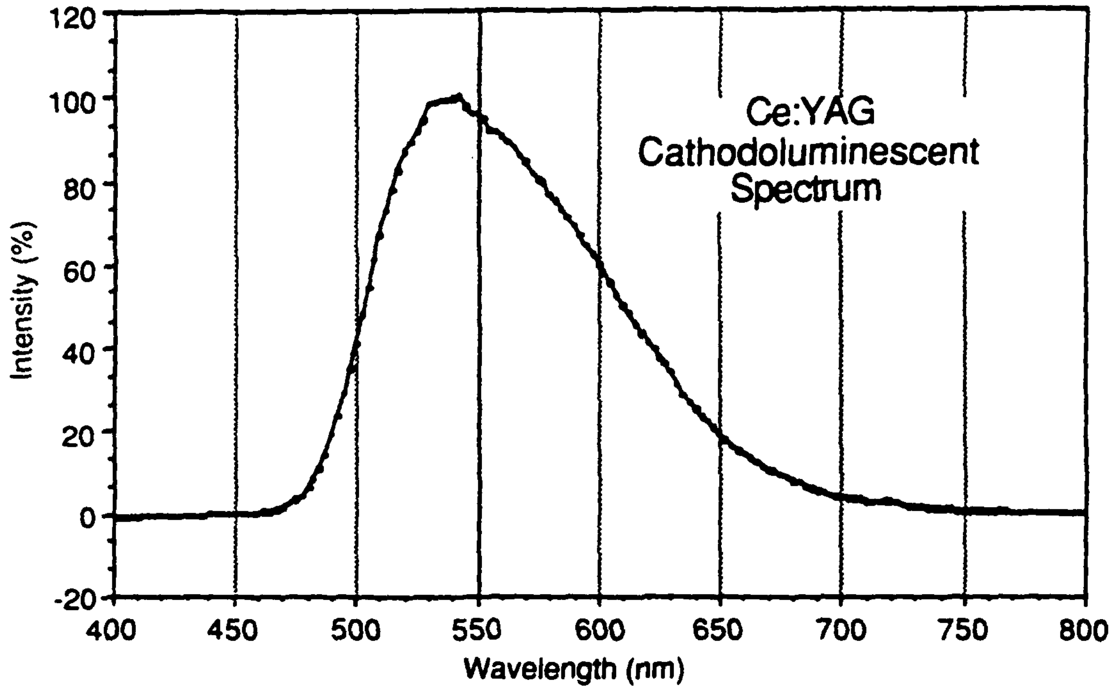

Fig. 3.3.1.1. Spectrum of Ce:$Y_3Al_5O_{12}$.

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/cm^2 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/cm^2. A beam power of 16 watt/cm^2 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/cm^2.

Mass spectroscopy of the Ce:BEL crystal revealed a cerium content of 3.9 x 10^{18} atoms/cc, as compared with 23 x 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.

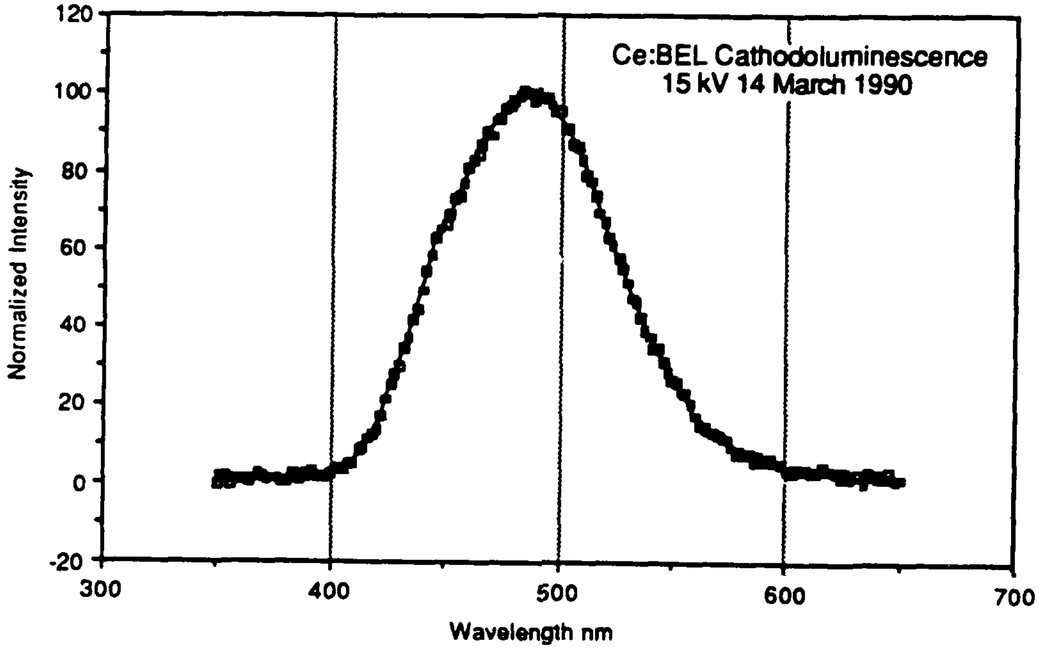

Fig. 3.4.1.1. Cathodoluminescence spectrum of Ce:BEL.

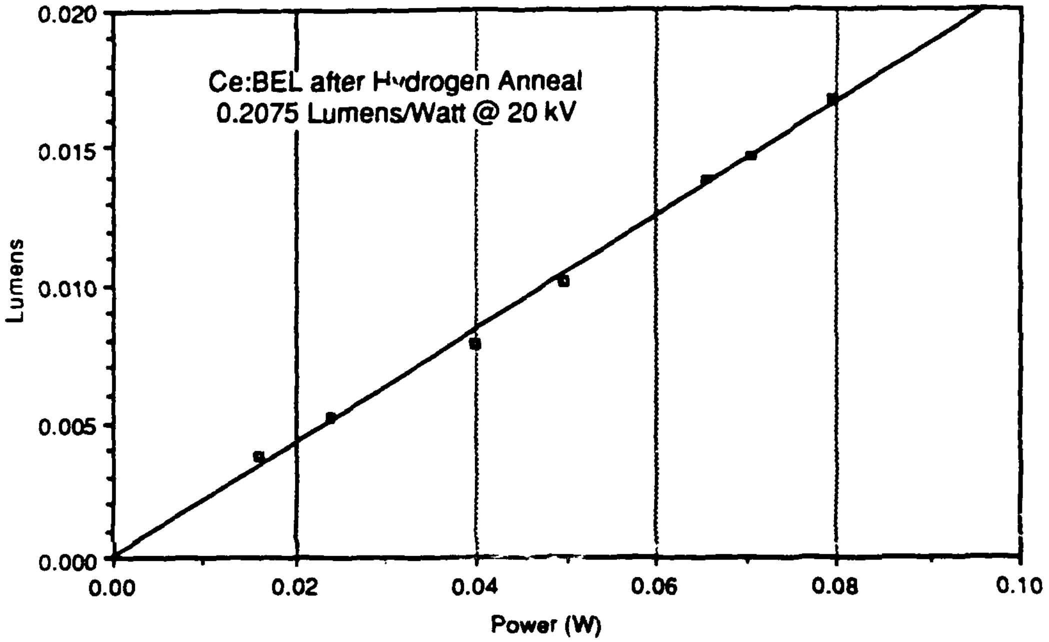

Fig. 3.4.1.2. Cathodoluminescent efficiency of Ce:BEL after hydrogen anneal.

3.4.2 Ce:Y_2SiO_5 and Ce:Gd_2SiO_5

Fig. 3.4.2.1 shows the cathodoluminescent spectrum of the blue emitting cerium activated phosphor Ce:Y_2SiO_5. Since the spectrum of Ce:Y_2SiO_5 peaks at about 390 nm, much of its light output is not visible, reducing its efficiency. The similar phosphor Ce:Gd_2SiO_5 has a spectrum which peaks at 430 nm.

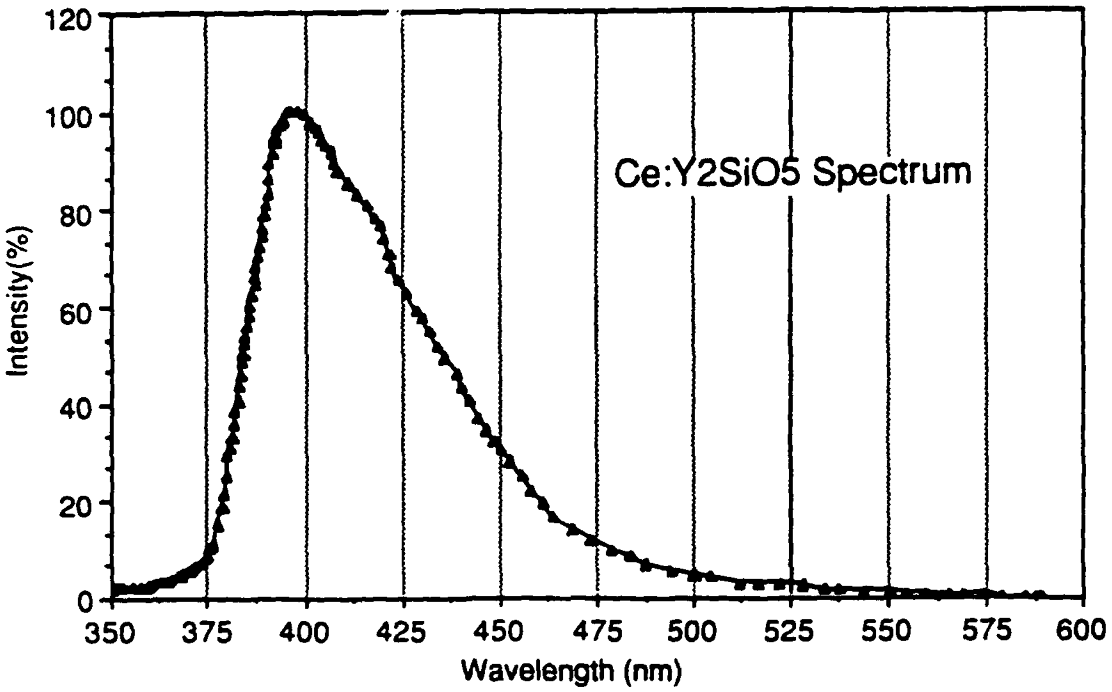

Fig. 3.4.2.1. Cathodoluminescent spectrum of the blue emitting cerium activated phosphor Ce:Y_2SiO_5.

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 (HEM™) 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 Al_2O_3 (2040°C): therefore, current HEM™ furnaces are adequate for growing this crystal. In the case of sapphire (Al_2O_3) crystals grown by HEM™, 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 HEM™ furnace so that these crystals can be grown with existing HEM™ 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 HEM™ 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 Wafers**	
	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 Wafers	
	100/year	**200/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 Wafers	
	100/year	**200/year**	**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

	Three-Inch Wafers		Four-Inch Wafers	
	100/year	200/year	100/year	200/year
Cost per Unreticulated Faceplate	**5450**	**4240**	**6770**	**5400**
Cost of Reticulation	3037.5	1562.5	3125	1618.75
Cost per Reticulated Faceplate	**8487.5**	**5802.5**	**9895**	**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 HEM™ 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 six-fold symmetry of the reticulation. This "ghosting" effect must still be quantified.

$Ce:Gd_3Al_5O_{12}$ (Ce:GdAG, red), $Ce:Y_3Al_5O_{12}$ (Ce:YAG, green), and $Ce:La_2Be_2O_5$ (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 $Gd_3Al_5O_{12}$ 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.

$Ce:Gd_3Al_5O_{12}$ (Ce:GdAG, red), $Ce:Y_3Al_5O_{12}$ (Ce:YAG, green), and $Ce:La_2Be_2O_5$ (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 $Gd_3Al_5O_{12}$ 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.

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JBM SIMULATION SYSTEMS, INC.

Enclosure (1)
24 February 1992
JBM/SSI 92-12A
Revision A
6 May 1992

FINAL REPORT

Study and Evaluation of Single Crystal Faceplate CRT Projection Display Systems for Flight and Weapon System Trainers

Prepared By
JBM SIMULATION SYSTEMS, INC.

for

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PREFACE

This document has been prepared for Trident International under Purchase Order #9174 dated 11 November 1991. The objective of the study effort is to determine which size CRT projection system using a Single Crystal Faceplate would yield the maximum utility to the existing family of installed flight and weapon system trainers and simulators and also have the greatest impact on the design of future trainers.

Revision A has been prepared to incorporate Government comments and to correct errors. Changes to the following pages have been made and annotated by a vertical mark on the right hand margin of the modified page:

Title Page
Pages 1-5
Pages 7-10
Page 12
Appendix B Title Page
A fifth page of backup data has been added to Appendix B

JBM SIMULATION SYSTEMS, INC.

Enclosure (1)
24 February 1992
JBM/SSI 92-12
Page 1 of 13
Revision A
6 May 1992

FINAL REPORT

Study and Evaluation
of
Single Crystal Faceplate
CRT Projection Display Systems
for
Flight and Weapon System Trainers

1.0 Scope

The objective of the study-evaluation was to determine the optimum size Single Crystal Faceplate (SCF) CRT Projection System which would provide maximum utility to existing installed Operational Flight Simulators (OFTs) and Weapon System Trainers (WSTs) and to determine their impact on the design of future motion-based visual system displays.

2.0 Background

The application of high brightness, high resolution, digitally controlled CRT projectors in Visual System Display subsystems of current Operational Flight Simulators (OFTs), Mission Flight Trainers (MFTs), and Weapon System trainers (WSTs), has extended the training effectiveness of the devices by their ability to provide realistic out-the-window visual scenes duplicating real-world conditions of day night and dusk visibility and brightness.

In order to create the illusion of flight and motion duplicating the aircraft environment it is essential that Visual Systems provide maximum fields of view both horizontally and vertically. To achieve the desired realism, Visual Systems currently in use or under development use multiple projector systems to display the scenes on large spherical surfaces mounted on computer driven electro-hydraulic motion systems.

The mounting of the domes, projectors and associated optics on the motion platforms imposes severe design complications on the Visual System Display elements. Similarly, the need for mounting the projectors at sufficient heights to avoid interference of cockpit structural elements with the line of site from the projectors to the spherical dome results in high moments of inertia of the projectors and their mounting structure thereby imposing severe conditions on the motion bases.

The performance characteristics of currently available CRT projectors in terms of brightness of displayed images on large diameter spherical domes limit their ability to provide fully acceptable wide fields of view of out-the-window displays.

The limitation in brightness or luminance capabilities of current CRT projectors not only limits the brightness of the projected scenes over large fields of view, but also limits the ability for edge blending and edge matching of adjacent images projected by multiple projector installations. Attempts to increase the scene brightness as viewed by the trainee include special high gain screen materials which introduce a new set of problems.

The physical size and weight of the display system elements also generate additional concerns due to their impact on motion system performance. These concerns relate to the ability of existing fielded motion bases to withstand the additional weights and high moments of inertias imposed by the newer dome/projector display systems required in Visual System upgrades.

Essentially, if CRT projectors can be produced having increased luminance capabilities by several orders of magnitude greater than the luminance provided by current state of the art projectors, the ability to provide higher brightness, fully blended and continuous images over large fields of view for use on existing systems would be achievable. Reducing their size and weight with resulting reduction in moments of inertia loads imposed on existing motion systems will also be beneficial.

Accordingly, the emphasis of this study-evaluation is to establish the optimum size, weight and brightness performance characteristics of Single Crystal Face Plate CRT Projectors for use in trainer and simulator applications.

3.0 Study-Evaluation Approach

To establish the optimum physical and brightness performance characteristics of a Single Crystal Faceplate CRT Projector needed to cost effectively meet Visual System Display System requirements for typical OFTs, MFTs, and WSTs, the study-evaluation has been conducted in several steps.

Firstly, a review of several typical OFTs, MFTs and WSTs (both existing and under development), was conducted to determine their display system design parameters. Secondly, the dome/screen surface area illuminated by a projector located at the center of a dome was computed based upon the Zone characteristics specified for each of the Visual Systems for the simulators reviewed in the first step.

Thirdly, the anticipated luminance one could expect at the screen surface of a Lambertian surface dome screen was computed for each of the three Single Crystal Faceplate projector designs being considered.

The final analysis conducted concerned the impact on computed moments of inertia of the weight of the SCF projectors in typical multiple projector installations compared to those imposed by typical currently available CRT projectors.

The results of each of the above listed analyses are presented in the following paragraphs.

4.0 Results of Analyses Conducted

4.1 Summary of Display Requirements for Typical Flight Simulator Systems

The review of the display requirements of several existing and/or currently under development OFTs, MFTs, and WSTs was conducted in terms of the following display system design parameters:

- Number of projectors/zones required to cover the specified fields of view
- Specified Fields-of-View (FOV) of each zone
- Peak luminance specification requirements

The Visual System requirements for the following trainers were evaluated:

- UH-1N WST - Device 2F161
- A6E WST- Device 2F114
- SH-60 B/F Devices 2F135/2F146
- F-14D MFT-Device 2F153

The above listed trainers include both fixed base and motion base mounted display systems and the Visual System requirements for the trainers/simulators reviewed represent the current state-of-the-art in large dome/projector type display systems.

The requirements for the Display Systems for each of the above trainers were obtained from references (a) through (d) listed in Appendix A, which are the best data available to Trident International at the time the study was conducted. It is to be noted that the display requirements obtained from the references may not represent the delivered and/or current configurations of the trainers.

The Specified Field of View data available in the referenced documents are presented in Table 4-1 while the requirements for luminance for each of the specified display zones of the trainers are presented in Table 4-2.

The following additional information is provided:

(1) The number of zones shown for each display system represents the number of projectors used in each trainer.
(2) The UH-1N and SH-60 Display Systems use 24 foot diameter Domes mounted on six degree-of-freedom (6 DOF) motion bases.
(3) The A6E WST Display System uses a 24 foot diameter dome mounted on a deactivated 6 DOF Motion base.
(4) The F14D MFT Display System is a fixed base trainer using a 30 foot diameter dome. Although the trainer uses Light Valve Projectors the luminance analysis has been conducted based upon the use of CRT projectors. Also, the F14D MFT has a servoed Area of Interest (AOI) projector zone which was not used in these analyses.

SPECIFIED FIELDS OF VIEW
FOR
ZONES

	I	II	III	IV	V
1. UH 1N/CH 53/CH46	-20 to +20H -30 to +20V	-20 to -60H -40 to +20V	+20 to +60H -40 to +20V	-60 to -110H -50 to + 20V	+60 to +110H -50 to + 20V
2. A6E WST	-50 to +10 H -30 to + 20 V	-50 to -110H -40 to +20V	+10 to +70H -40 to +20V	-20 to -110H +20 to + 70V	-20 to + 70H +20 to + 70V
3. SH60B/F	-20 to +20H -30 to +20V	-20 to -60H -40 to +20V	+20 to +60H -40 to +20V	-60 to -110H -50 to + 20V	+60 to +110H -50 to + 20V
4. F14D MFT	-12.5 to +12.5H 15 to +17V	-12.5 to -50H -12 to + 33V	+12.5 to +50H -12 to +33V	-50 to -100H -12 to +33	None

Note: Fields of View in degrees

Table 4-1. Display System Field of View Requirements
Typical Flight Simulators and Weapon System Trainers

SPECIFIED LUMINANCE
FOR
CENTER OF ZONES

	I	II	III	IV	V
1. UH 1N/CH 53/CH46	6.0	5.0	5.0	4.0	4.0
2. A6EWST	4.0	4.0	4.0	3.5	3.5
3. SH60B/F WSTs	5.0	4.0	4.0	3.5	3.5
4. F14D MFT	2.0 minimum/ 6 .0 preferred specified for zones I-IV.				None

Note: (1) Luminance in ft-Lamberts
(2) Values specified for 100% screen illumination
(3) All values for 24 foot diameter domes

Table 4-2. Display System Luminance Requirements -
Typical Flight Simulators and Weapon System Trainers

4.2 Summary of Performance Parameters Investigated

A. Impact of Dome Size on Projector Performance

To illustrate the impact of dome size on projector performance, the area illuminated on the inside of the dome surface has been computed as a function of the required zone parameters as defined in each of the trainer specifications . The Field of View areas obtained for three dome sizes (20.24, and 30 fot diameters) have been computed. To simplify the computations, it has been assumed that the projectors are mounted at the center of the dome.

The area of the illuminated surface has been computed as follows:

$$(1)\quad SA = R^2 * (\sin X - \sin Y) * (B-A)$$

where:
SA = Area illuminated on the surface of the dome (sq ft)
R = Radius of the Dome (ft)
X = Vertical Angle to the top of the area
Y = Vertical Angle to the bottom of the area
A = Horizontal Angle to the left side of the area
B = Horizontal Angle to the right side of the area

Note: All angles are in radians.

The results of the computations of the zone areas for each of the three dome sizes and for each of the trainers investigated are presented in Table 4-3.

B. Predicted Luminance Based Upon Current CRT Projectors

In order to determine the Luminance to be obtained at the screen surface when measured at the center of each of the zones, the following expression was used:

$$(2)\quad fL = L * K * G / SA$$

where:
fL = Luminance in ft Lamberts
L = Projector Light Output in Lumens
K = Optics efficiency factor
G = Screen Gain
SA = Surface Area of Dome Illuminated in sq ft

COMPUTED AREA OF FOV
FOR
ZONES

	I			II			III			IV			V		
DOME DIAMETER(ft)	20	24	30	20	24	30	20	24	30	20	24	30	20	24	30
1. UH-1N/CH-53/CH46	59	85	132	69	99	155	69	99	155	97	139	218	97	139	218
2. A6EWST	88	127	198	103	149	232	103	149	232	94	135	211	94	135	211
3. SH60B/F	59	85	132	69	99	155	69	99	155	97	139	218	97	139	218
4. F14D MFT	24	35	54	49	71	111	49	71	111	66	95	148	--		

Note: (1) Areas in square feet

(2) Projector located at center of dome

Table 4-3. Display System Computed Zone Areas
Various Dome Sizes
Typical Flight Simulators and Weapon System Trainers

For this investigation, the light output for the projector was 300 lumens which is a nominal value for typical projectors currently used in existing systems. To provide a baseline for the computations, a Lambertian screen surface has been assumed; hence a Gain of 1.0 has been used. Typical lenses and optical efficiency of 0.85 was used in all computations. Accordingly, the area of the zone and the projector light output primarily determine the luminance obtained at the screen surface at the center of the zone area. A 100% screen illumination of the area was also assumed. The results of the computations are presented in Appendix B and they are summarized in Table 4-4.

COMPUTED FOV AREAS
AND
PREDICTED LUMINANCE
FOR
CENTER OF ZONES

	I	II	III	IV	V
1. UH 1N/CH 53/CH46					
ZONE AREA (sq ft)	85	99	99	139	139
LUMINANCE (fL)	3.0	2.6	2.6	1.8	1.8
2. A6E WST					
ZONE AREA (sq ft)	127	149	149	135	135
LUMINANCE (fL)	2.0	1.7	1.7	1.9	1.9
3. SH60 B/F WSTs					
ZONE AREA (sq ft)	85	99	99	139	139
LUMINANCE (fL)	3.0	2.6	2.6	1.8	1.8
4. F14D MFT					
ZONE AREA (sq ft)	35 / 54	71 / 111	71 / 111	95 / 148	
LUMINANCE (fL)	7.4 / 4.7	3.6 / 2.3	3.6 / 2.3	2.7 / 1.7	

Note: (1) Based upon Typical Projector Output of 300 Lumens
(2) Luminance Values are for 100% screen illumination
(3) All values for 24 foot diameter domes except F14D which includes values for 24'/30' D domes

Table 4-4. Computed Areas of Fields of View and Predicted Luminance Values for Typical Flight Simulators and Weapon System Trainer Zones Using Current 300 Lumen Projector with Lambertian Screen

C. Luminance Performance Prediction for SFP Projectors

A prediction of the luminance attainable with SFP CRT Projectors can be computed using Equation No. (2) by substituting the Light output expected for each of the three designs of the SFP projectors under development for the 300 Lumens used for typical existing projectors.

The Light Output performance for the three potential designs for the SFP CRT Projectors are as follows:

CRT Size	Light Output
Type 1. Three inch (3")	1500 Lumens
Type 2. Four inch (4")	2500 Lumens
Type 3. Five inch (5")	3000 Lumens

The predicted Luminance values using the above light outputs to illuminate the same zone areas required for the trainers examined are presented in Table 4-5.

PREDICTED LUMINANCE
FOR
ZONES

	I			II			III			IV			V		
Projector Type	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1. UH-1N/CH-53/CH46	15	25	30	12.9	21.5	25.8	12.9	21.5	25.8	9.2	15.3	18.3	9.2	15.3	18.3
2. A6EWST	10	16.7	20	8.6	14.2	17.2	8.6	14.2	17.2	9.4	15.7	18.8	9.4	15.7	18.8
3. SH60B/F WSTs	15	25	30	12.9	21.5	25.8	12.9	21.5	25.8	9.2	15.3	18.3	9.2	15.3	18.3
4. F14D MFT (24' D)	36.8	61.3	73.6	18.0	30.0	36.0	18.0	30.0	36.0	13.5	22.5	27.0		---	
(30' D)	23.6	39.3	47.1	11.5	19.2	23.0	11.5	19.2	23.0	8.6	14.4	17.3		-- --	

Note: (1) Luminance in ft Lamberts
(2) Projector located at center of dome

Table 4-5. Predicted Luminance for SFP Projectors
Typical Flight Simulators and Weapon System Trainers

A review of the luminance figures presented in Table 4-5 clearly indicates the ability of the three SFP projector designs to provide more than enough scene brightness capability to meet all current and in-development trainer display system luminance requirements.

The 1500 lumen projector is comparable to existing light valve projectors in terms of light output capability and has the further advantage of its ability to be used in motion base mounted applications without the pitch and roll limitations noted on the light valve manufacturer's data sheets.

The selection of the optimum design for trainer applications requiring motion base mounting must be based on size and weight considerations as well as technical performance considerations. The study results indicate all three will easily meet the luminance requirements. The final selection will therefore be primarily a function of the costs of developing and producing the projector face plates capable of providing the 1500, 2500 and 3000 lumen light outputs.

D. Impact of Projector Weight on Motion Base Installations

The weight and dimensions of the projector head and the size and weight of the associated el;ectronics equipment package which must be mounted within approximately 25 feet fof the projector have a considerable impact on the dynamic loads imposed by a display system mounted on a motion system.

Current CRT projectors have projector heads weighing approximately 150 pounds and most have 250-300 pond associated electronics equipment which must be located within 25 feet of the projector head thereby requiring both packages to be mounted on the motion platform.

For a five-zone display system, the total weight of the projector systems alone add a load of 2000 - 2250 pounds to the total payload to be moved by the motion system. The weight alone is not the total problem however due to the fact that, for a 24 food diameter dome installation, the projector heads have to be mounted approximately 12-18 feet above the center of rotation of the motion base system which increases the moments of inertia of the loads considerably depending upon the position of the projector head relative to each axis of rotation.

The electronics packages associated with each projector impose there own respective moments of inertia depending upon their location relative to each axis of rotation.

The equations [see reference (e)], used to determine the Mass Moment of inertia for each package are as follows:

(3) $Iox = 1/12 * M *(b^2 + c^2)$
(4) $Ioy = 1/12 * M *(a^2 + c^2)$
(5) $Ioz = 1/12 * M *(a^2 + b^2)$

Where: Iox,Ioy,Ioz = The mass moment of Inertia of the unit about its own x,y,z axes
M = Mass of the unit (Weight/g)
a,b,c = Dimensions of unit along x,y,z, axes

The equations [see reference (e)], used to determine the moment of inertia of each package relative to the center of rotation of the motion base are as follows:

(6) $Ix = Iox + M*D^2$
(7) $Iy = Ioy + M*D^2$
(8) $Iz = Ioz + M*D^2$

Where: Ix,Iy,Iz = Mass Moment of Inertia of the unit about the axis of rotation of the motion base (slug ft^2)
M = Mass of the unit (Weight/g)
D = Distance of the center of mass of the unit from the center of rotation of the motion base

Using the above equations, the Moments of Inertia values for a 100 pound projector head unit having the dimensions of x=2 feet; y=3 feet and z=1 foot and mounted 15 feet high and 2 feet left and 2 feet aft of the center of rotation of the motion base are as follows:

$Ix = 718.2$ slug-ft^2
$Iy = 26.3$ slug-ft^2
$Iz = 719.0$ slug-ft^2

For a 200 pound projector located similarly, the Moments of Inerta are as follows:

Ix = 1436.2 slug-ft^2
Iy = 52.6 slug-ft^2
Iz = 1438.0 slug-ft^2

By increasing the distance by 3 feet to 18 feet and leaving other distances the same, the Moments of Inertias for the two projector weights are as follows:

Weight		100 lbs	200 lbs
Ix	=	1027.6 slug-ft^2	2052.6 slug-ft^2
Iy	=	26.3 slug-ft^2	52.6 slug-ft^2
Iz	=	1028.4 slug-ft^2	2056.8 slug-ft^2

The examples given above clearly show the impact of weight and height above center of rotation on the Moments of Inertia of the projectors in a motion-based installation. To summarize the results of the above examples,:-doubling the weight doubles the moment of inertia. However, a 20% increase in the distance to the center of rotation results in a 43% increase in the moment of inertia.

5.0 Conclusions

As indicated by a comparison of the 1500 lumen/3" faceplate projector predicted luminance values (see Table 4-5), with the required values for each zone of the trainers evaluated, (see Table 4-3), it is quite evident that the 1500 lumen/3" faceplate projector is a suitable replacement for existing CRT projectors. It is assummed that the other required major performance parameters, such as resolution, contrast ratio, etc. meet the minimum requirements.

The impact on motion bases in terms of moments of inertia as a result of having the lowest weight and size, further points to the selection of the 1500 lumen/3" faceplate projector as the optimum design for a replacement projector. Potential savings in avoiding the costs of replacement of existing motion bases would be substantial.

APPENDIX A

LIST OF REFERENCES

(a) NTSC Specification 881111 dated 21 March 1990 for UH-1N Weapon System Trainer and Visual Systems for CH53/CH46 Weapon System Trainers.

(b) Grumman Specification TS/A6-300-SP-88-001 Rev B dated 13 June 1989 for Visual System for A6-E Weapon System Trainer, Device 2F114.

(c) NTSC Specification 910013 dated 19 December 1990 for Visual Upgrade for Device 2F 106, SH-2F, Device 2F135, SH-60B, and Device 2F146, SH-60F Weapon System Trainers.

(d) NTSC Specification 881103 dated 22 September 1989 for F-14D Mission Flight Trainer (MFT).

(e) Engineering Mechanics:Dynamics-Joseph F. Shelley

JBM SIMULATION SYSTEMS, INC.

Enclosure (1)
24 February 1992
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6 May 1992

Appendix B

Supporting Data
for
Table 4-4
(5 sheets)

```
UH-1N ZONE I
Angle to Top of Zone = 20
Angle to Bottom of Zone in degrees =-30
Angle to Left Side of Zone in degrees =-20
Angle to Right Side of Zone in degrees = 20
Zone Area in square feet = 84.64947
Projector Light Output in Lumens = 300
Optics Loss Factor = .85
Screen Gain = 1
Luminence in Foot Lamberts = 3.012423

UH-1N ZONE II
Angle to Top of Zone = 20
Angle to Bottom of Zone in degrees =-40
Angle to Left Side of Zone in degrees =-60
Angle to Right Side of Zone in degrees =-20
Zone Area in square feet = 99.00411
Projector Light Output in Lumens = 300
Optics Loss Factor = .85
Screen Gain = 1
Luminence in Foot Lamberts = 2.575651

UH-1N ZONE III
Angle to Top of Zone = 20
Angle to Bottom of Zone in degrees =-40
Angle to Left Side of Zone in degrees = 20
Angle to Right Side of Zone in degrees = 60
Zone Area in square feet = 99.00411
Projector Light Output in Lumens = 300
Optics Loss Factor = .85
Screen Gain = 1
Luminence in Foot Lamberts = 2.575651

UH-1N ZONE IV
Angle to Top of Zone = 20
Angle to Bottom of Zone in degrees =-50
Angle to Left Side of Zone in degrees =-110
Angle to Right Side of Zone in degrees =-60
Zone Area in square feet = 139.2441
Projector Light Output in Lumens = 300
Optics Loss Factor = .85
Screen Gain = 1
Luminence in Foot Lamberts = 1.831317

UH-1N ZONE V
Angle to Top of Zone = 20
Angle to Bottom of Zone in degrees =-50
Angle to Left Side of Zone in degrees = 60
Angle to Right Side of Zone in degrees = 110
Zone Area in square feet = 139.2441
Projector Light Output in Lumens = 300
Optics Loss Factor = .85
Screen Gain = 1
Luminence in Foot Lamberts = 1.831317
```

```
A6-E ZONE I
Angle to Top of Zone = 20
Angle to Bottom of Zone in degrees =-30
Angle to Left Side of Zone in degrees =-50
Angle to Right Side of Zone in degrees = 10
Zone Area in square feet = 126.9742
Projector Light Output in Lumens = 300
Optics Loss Factor = .85
Screen Gain = 1
Luminence in Foot Lamberts = 2.008282

A6-E ZONE II
Angle to Top of Zone = 20
Angle to Bottom of Zone in degrees =-40
Angle to Left Side of Zone in degrees =-110
Angle to Right Side of Zone in degrees =-50
Zone Area in square feet = 148.5062
Projector Light Output in Lumens = 300
Optics Loss Factor = .85
Screen Gain = 1
Luminence in Foot Lamberts = 1.717101

A6-E ZONE III
Angle to Top of Zone = 20
Angle to Bottom of Zone in degrees =-40
Angle to Left Side of Zone in degrees = 10
Angle to Right Side of Zone in degrees = 70
Zone Area in square feet = 148.5062
Projector Light Output in Lumens = 300
Optics Loss Factor = .85
Screen Gain = 1
Luminence in Foot Lamberts = 1.717101

A6-E ZONE IV
Angle to Top of Zone = 70
Angle to Bottom of Zone in degrees = 20
Angle to Left Side of Zone in degrees =-110
Angle to Right Side of Zone in degrees =-20
Zone Area in square feet = 135.1907
Projector Light Output in Lumens = 300
Optics Loss Factor = .85
Screen Gain = 1
Luminence in Foot Lamberts = 1.886225

A6-E ZONE V
Angle to Top of Zone = 70
Angle to Bottom of Zone in degrees = 20
Angle to Left Side of Zone in degrees =-20
Angle to Right Side of Zone in degrees = 70
Zone Area in square feet = 135.1907
Projector Light Output in Lumens = 300
Optics Loss Factor = .85
Screen Gain = 1
Luminence in Foot Lamberts = 1.886225
```

```
SH-60 ZONE I
Angle to Top of Zone = 20
Angle to Bottom of Zone in degrees =-30
Angle to Left Side of Zone in degrees =-20
Angle to Right Side of Zone in degrees = 20
Zone Area in square feet = 84.64947
Projector Light Output in Lumens = 300
Optics Loss Factor = .85
Screen Gain = 1
Luminence in Foot Lamberts = 3.012423

SH-60 ZONE II
Angle to Top of Zone = 20
Angle to Bottom of Zone in degrees =-40
Angle to Left Side of Zone in degrees =-60
Angle to Right Side of Zone in degrees =-20
Zone Area in square feet = 99.00411
Projector Light Output in Lumens = 300
Optics Loss Factor = .85
Screen Gain = 1
Luminence in Foot Lamberts = 2.575651

SH-60 ZONE III
Angle to Top of Zone = 20
Angle to Bottom of Zone in degrees =-40
Angle to Left Side of Zone in degrees = 20
Angle to Right Side of Zone in degrees = 60
Zone Area in square feet = 99.00411
Projector Light Output in Lumens = 300
Optics Loss Factor = .85
Screen Gain = 1
Luminence in Foot Lamberts = 2.575651

SH-60 ZONE IV
Angle to Top of Zone = 20
Angle to Bottom of Zone in degrees =-50
Angle to Left Side of Zone in degrees =-110
Angle to Right Side of Zone in degrees =-60
Zone Area in square feet = 139.2441
Projector Light Output in Lumens = 300
Optics Loss Factor = .85
Screen Gain = 1
Luminence in Foot Lamberts = 1.831317

SH-60 ZONE V
Angle to Top of Zone = 20
Angle to Bottom of Zone in degrees =-50
Angle to Left Side of Zone in degrees = 60
Angle to Right Side of Zone in degrees = 110
Zone Area in square feet = 139.2441
Projector Light Output in Lumens = 300
Optics Loss Factor = .85
Screen Gain = 1
Luminence in Foot Lamberts = 1.831317
```

```
F14D ZONE I
Angle to Top of Zone = 17
Angle to Bottom of Zone in degrees =-15
Angle to Left Side of Zone in degrees =-12.5
Angle to Right Side of Zone in degrees = 12.5
Zone Area in square feet = 34.6325
Projector Light Output in Lumens = 300
Optics Loss Factor = .85
Screen Gain = 1
Luminence in Foot Lamberts = 7.363027


F14D ZONE II
Angle to Top of Zone = 33
Angle to Bottom of Zone in degrees =-12
Angle to Left Side of Zone in degrees =-50
Angle to Right Side of Zone in degrees =-12.5
Zone Area in square feet = 70.92655
Projector Light Output in Lumens = 300
Optics Loss Factor = .85
Screen Gain = 1
Luminence in Foot Lamberts = 3.595269


F-14D ZONE III
Angle to Top of Zone = 33
Angle to Bottom of Zone in degrees =-12
Angle to Left Side of Zone in degrees = 12.5
Angle to Right Side of Zone in degrees = 50
Zone Area in square feet = 70.92655
Projector Light Output in Lumens = 300
Optics Loss Factor = .85
Screen Gain = 1
Luminence in Foot Lamberts = 3.595269

F-14D ZONE IV
Angle to Top of Zone = 33
Angle to Bottom of Zone in degrees =-12
Angle to Left Side of Zone in degrees =-100
Angle to Right Side of Zone in degrees =-50
Zone Area in square feet = 94.56873
Projector Light Output in Lumens = 300
Optics Loss Factor = .85
Screen Gain = 1
Luminence in Foot Lamberts = 2.696452
```

Revision A
6 May 1992

```
F-14D ZONE I
Angle to Top of Zone = 17
Angle to Bottom of Zone in degrees =-15
Angle to Left Side of Zone in degrees =-12.5
Angle to Right Side of Zone in degrees = 12.5
Zone Area in square feet = 54.11328
Projector Light Output in Lumens = 300
Optics Loss Factor = .85
Screen Gain = 1
Luminence in Foot Lamberts = 4.712338


F-14D ZONE II
Angle to Top of Zone = 33
Angle to Bottom of Zone in degrees =-12
Angle to Left Side of Zone in degrees =-50
Angle to Right Side of Zone in degrees =-12.5
Zone Area in square feet = 110.8227
Projector Light Output in Lumens = 300
Optics Loss Factor = .85
Screen Gain = 1
Luminence in Foot Lamberts = 2.300972


F-14D ZONE III
Angle to Top of Zone = 33
Angle to Bottom of Zone in degrees =-12
Angle to Left Side of Zone in degrees = 12.5
Angle to Right Side of Zone in degrees = 50
Zone Area in square feet = 110.8227
Projector Light Output in Lumens = 300
Optics Loss Factor = .85
Screen Gain = 1
Luminence in Foot Lamberts = 2.300972


F-14D ZONE IV
Angle to Top of Zone = 33
Angle to Bottom of Zone in degrees =-12
Angle to Left Side of Zone in degrees =-100
Angle to Right Side of Zone in degrees =-50
Zone Area in square feet = 147.7636
Projector Light Output in Lumens = 300
Optics Loss Factor = .85
Screen Gain = 1
Luminence in Foot Lamberts = 1.725729
```

Optical Research Associates

550 NORTH ROSEMEAD BOULEVARD
PASADENA, CALIFORNIA 91107
TELEPHONE (818) 795-9101
FAX (818) 795-9102

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

Eric H. Ford, Director
of Optical Engineering Services

EHF:cmn:R04:fed ex

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

enc: Final Report

Prepared for:

TRIDENT INTERNATIONAL, INC.
Orlando, Florida

Final Report

THE STUDY OF THE PERFORMANCE OF A YAG FACEPLATE

February 3, 1992

Prepared by:

Eric H. Ford

OPTICAL RESEARCH ASSOCIATES
550 N. Rosemead Boulevard
Pasadena, California 91107
(818) 795-9101

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.

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 faceplate-coolant-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 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:

```
      Faceplate            Fluid              Window
                     |                  |
          n1         |      n2          |       n3
                     |                  |
              R1<--  |          R2<---  |
                     |                  |
        alpha 1 ---> |      alpha 2 --> |
```

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:

```
      Faceplate            Fluid              Window
                  |    |                 |
          n1      | nf |    n2           |       n3
                  |    |                 |
          R1<---- |    |         R2<---  |
                  |    |                 |
      alpha 1 --> |    |     alpha 2 --> |
```

where nf is the matching single layer coating.

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).

Grn 450 - 520
Rx 490 - 610

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 thin 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.

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

CRA, 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 1

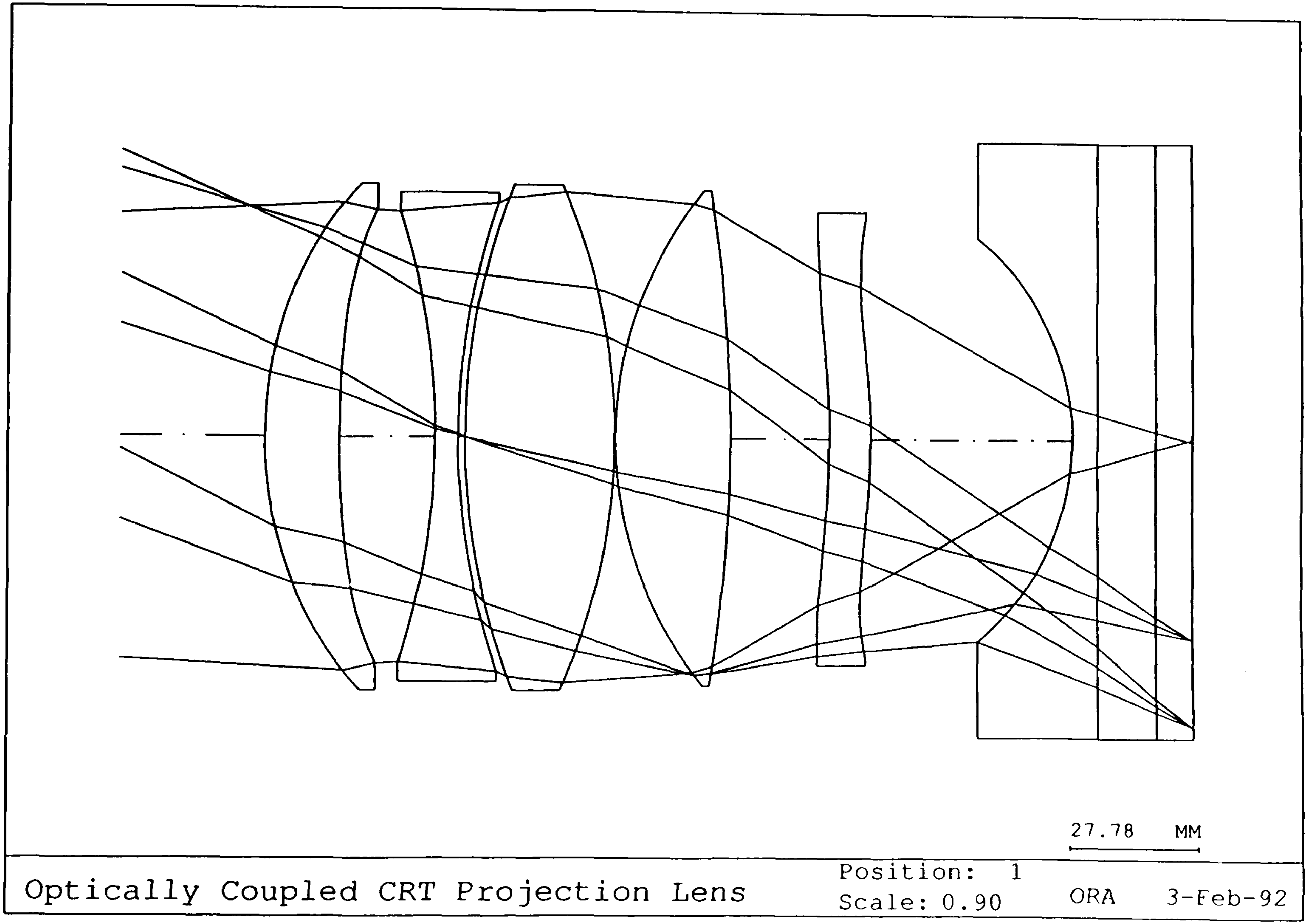

27.78 MM
Optically Coupled CRT Projection Lens
Position: 1
Scale: 0.90
ORA
3-Feb-92

FIGURE 2

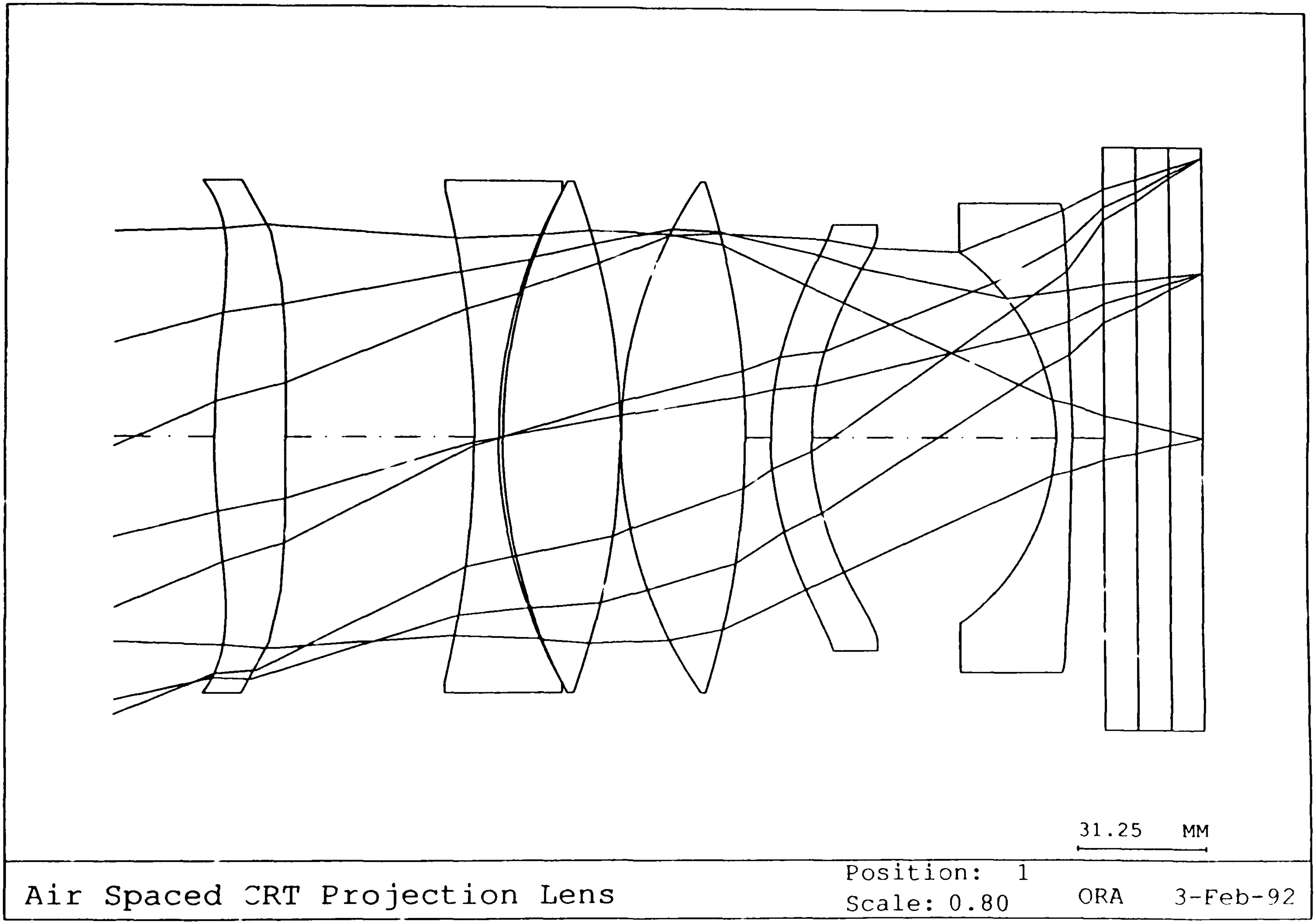

31.25 MM
Air Spaced CRT Projection Lens
Position: 1
Scale: 0.80
ORA
3-Feb-92

FIGURE 3

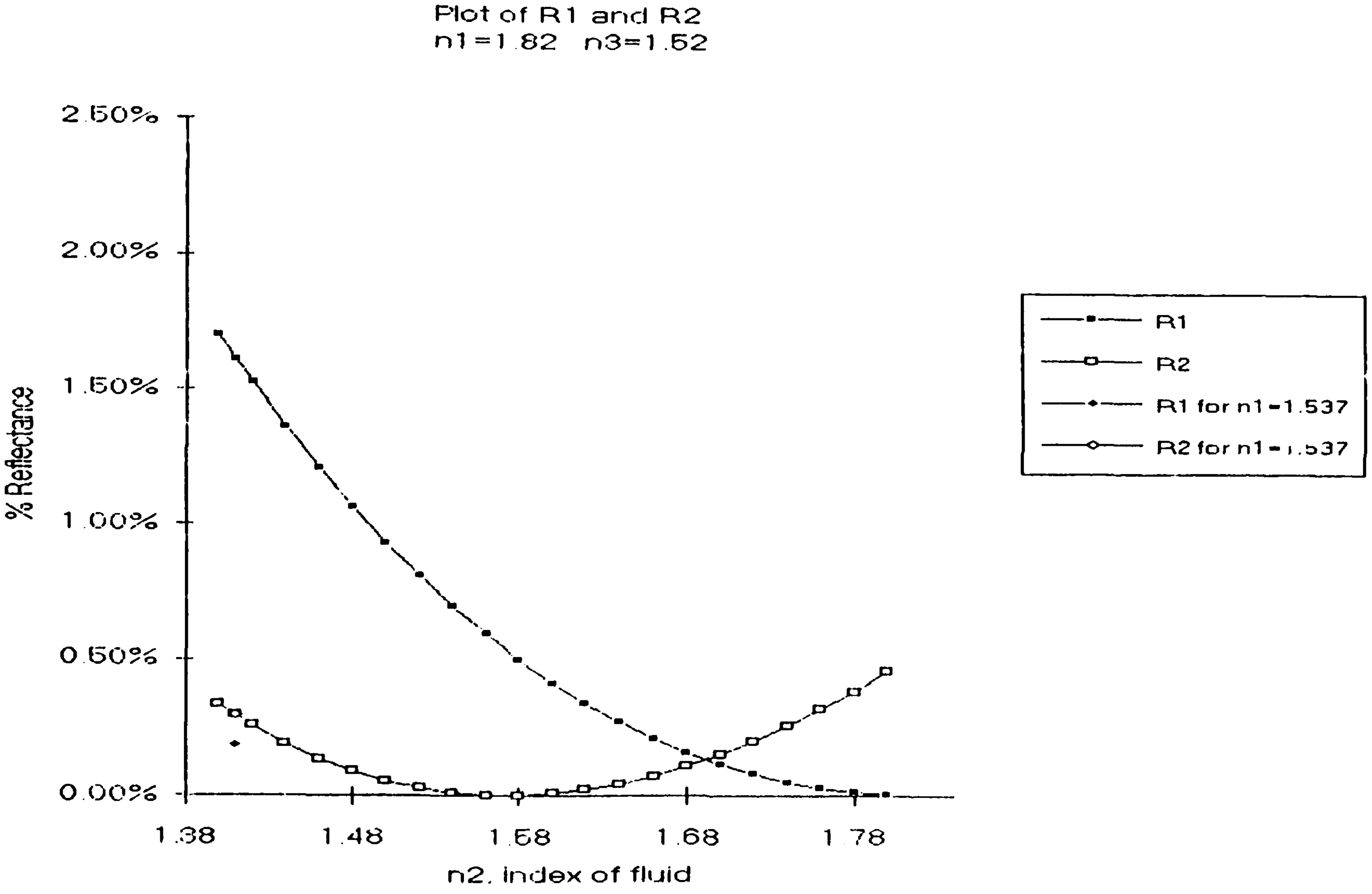

Plot of R1 and R2
n1=1.82 n3=1.52
% Reflectance
2.50%
2.00%
1.50%
1.00%
0.50%
0.00%
1.38
1.48
1.58
1.68
1.78
n2, index of fluid
R1
R2
R1 for n1=1.537
R2 for n1=1.537

FIGURE 4

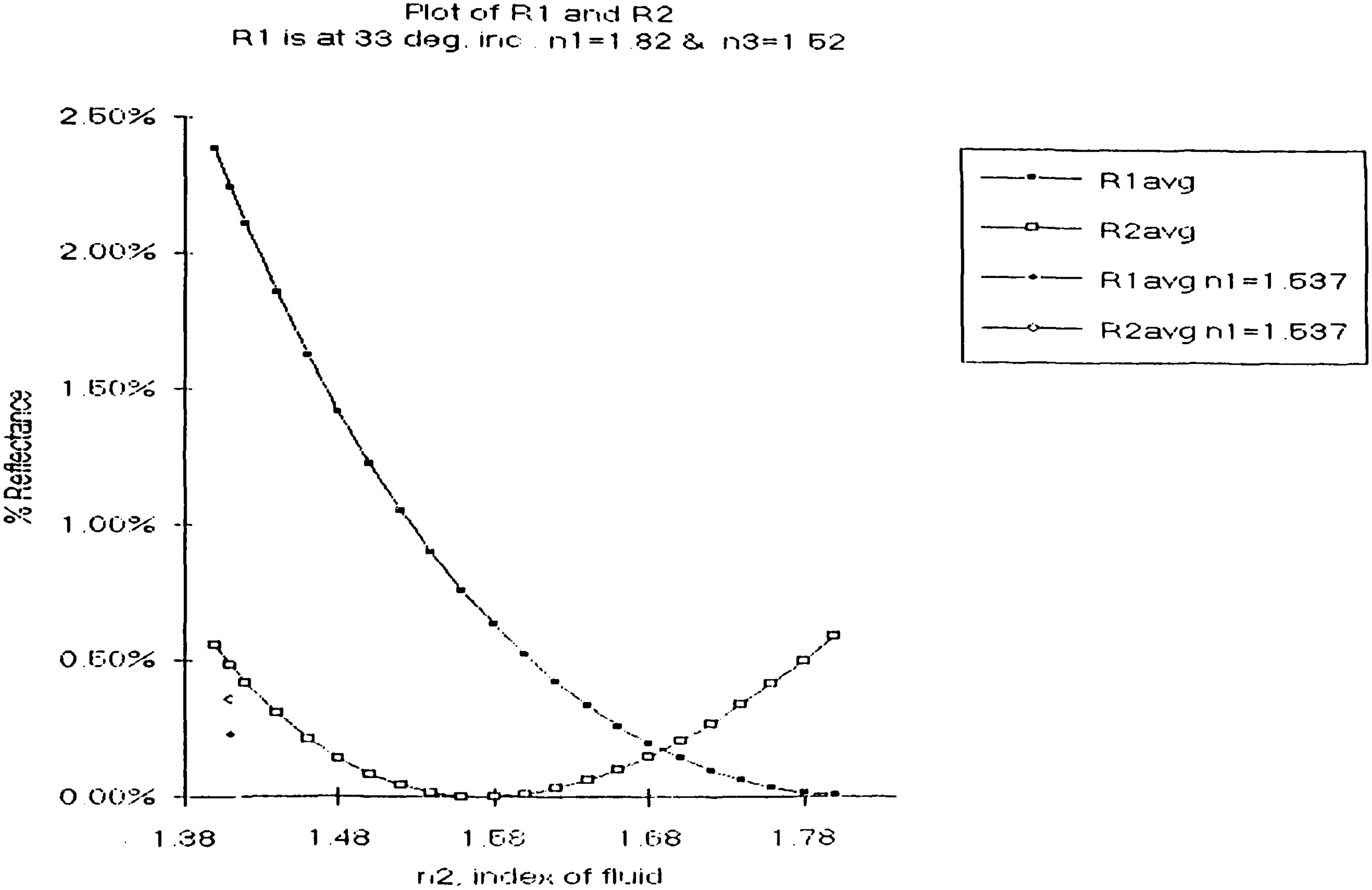

Plot of R1 and R2
R1 is at 33 deg. inc . n1=1.82 & n3=1.52
% Reflectance
2.50%
2.00%
1.50%
1.00%
0.50%
0.00%
1.38
1.48
1.58
1.68
1.78
n2, index of fluid
R1avg
R2avg
R1avg n1=1.537
R2avg n1=1.537

FIGURE 5

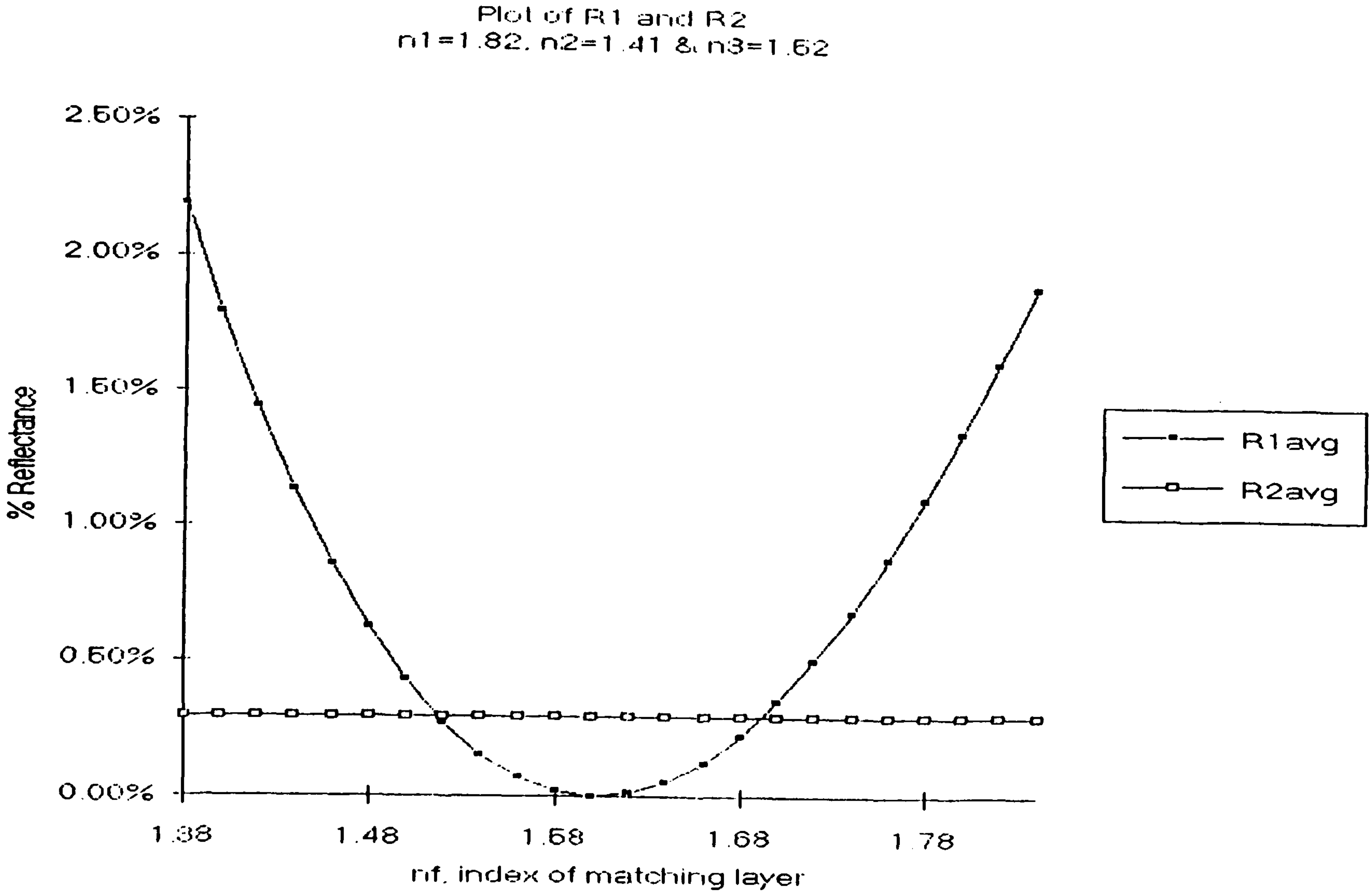
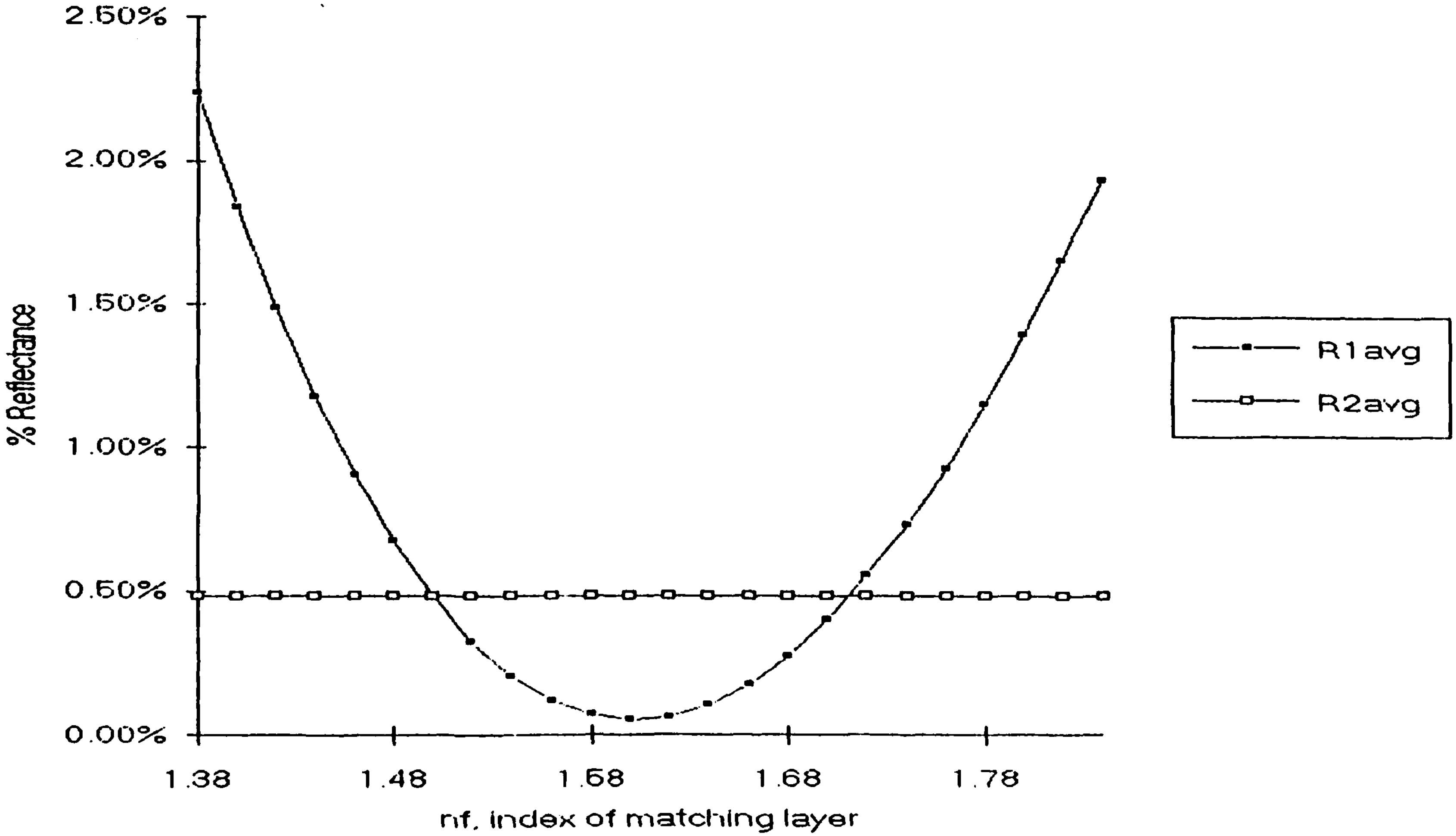

Plot of R1 and R2
n1=1.82, n2=1.41 & n3=1.62
% Reflectance
2.50%
2.00%
1.50%
1.00%
0.50%
0.00%
1.38
1.48
1.58
1.68
1.78
nf. index of matching layer
R1avg
R2avg

FIGURE 6



Plot of R1 and R2
R1 is at 33 deg. inc. n1=1.82, n2=1.41 & n3=1.52

FIGURE 7

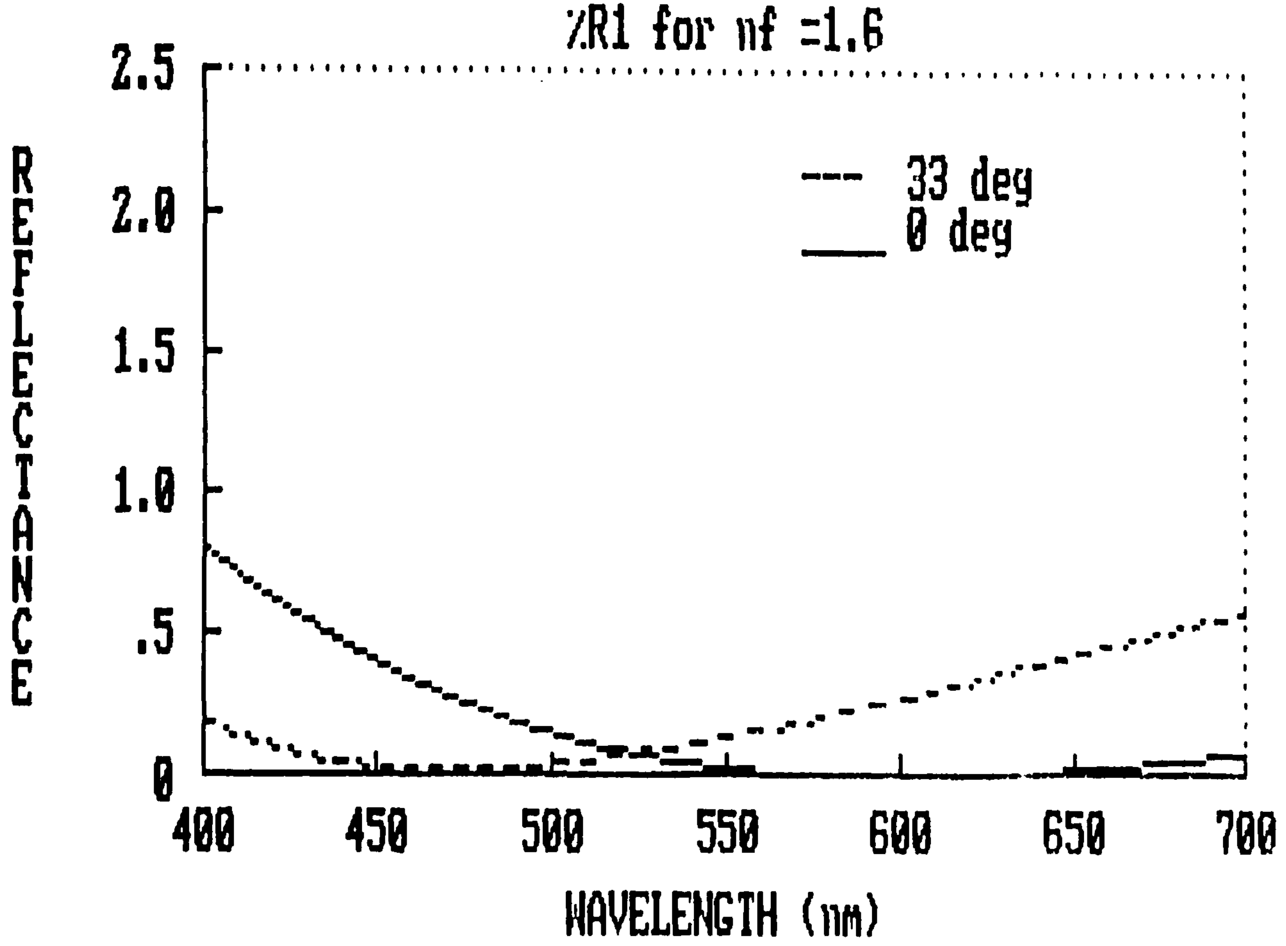

%R1 for nf =1.6
--- 33 deg
___ 0 deg
REFLECTANCE
2.5
2.0
1.5
1.0
.5
0
400
450
500
550
600
650
700
WAVELENGTH (nm)

FIGURE 8

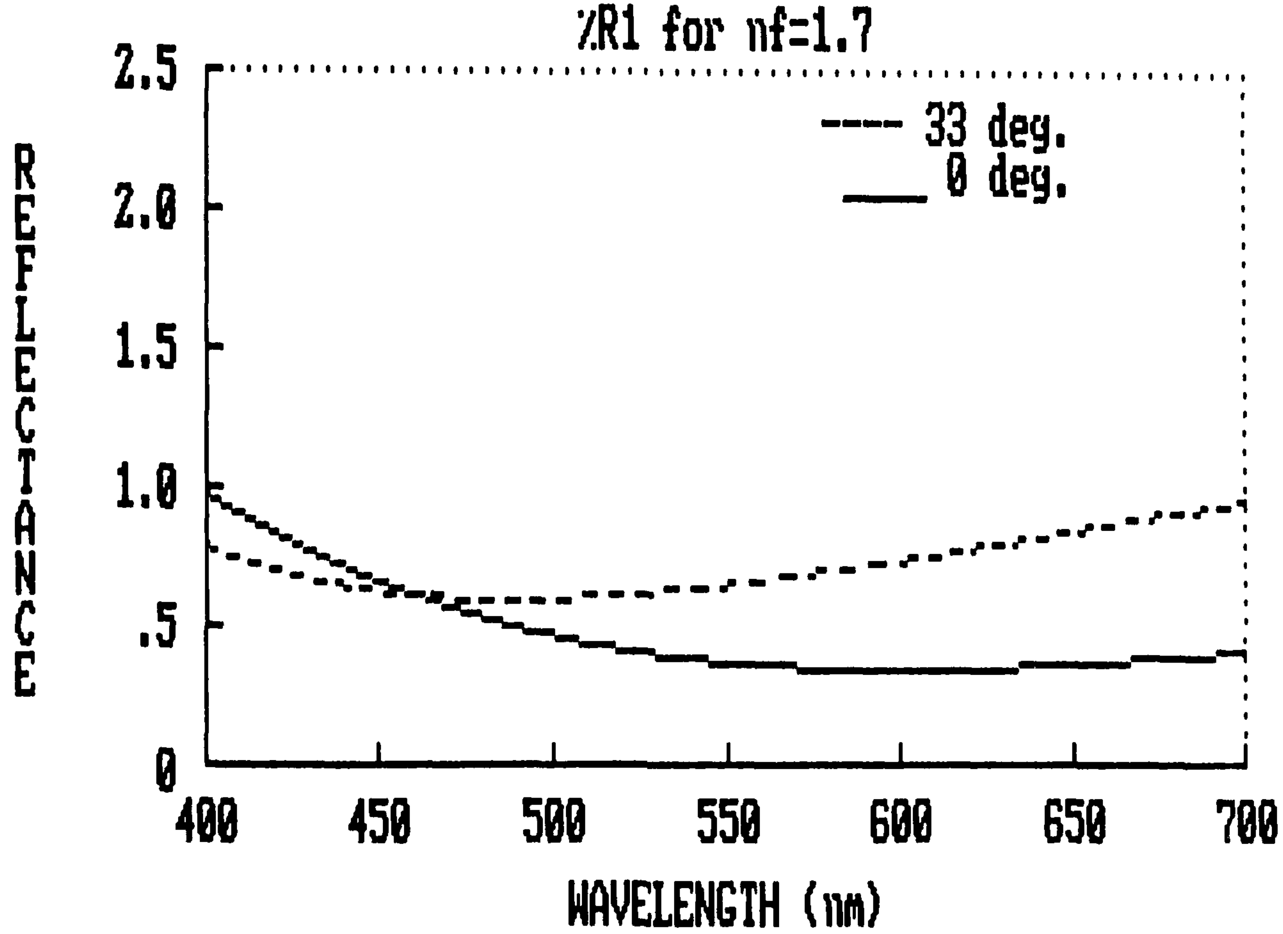

%R1 for nf=1.7
---- 33 deg.
___ 0 deg.
REFLECTANCE
2.5
2.0
1.5
1.0
.5
0
400
450
500
550
600
650
700
WAVELENGTH (nm)

FIGURE 9

OL-D

104

Maximum Useful Screen			Focus Type	Cathode	Screen Panel t (mm) (Nd=1.537)	Liquid t (mm) (Nd=1.41)	Front Panel t (mm) (Nd=1.572)
H (mm)	V (mm)	D (mm)					
82	64	104	Electro Static	Oxide	4.0		
112	87	141.8	Electro Static	Oxide	5.75		
112	87	141.8	Electro Static	Oxide	5.75		
156	116	194.4	Electro Static	Oxide	7.0		
156	116	194.4	Magnetic	Impregnated	7.0		
82	64	104	Electro Static	Oxide	4.0	3.2	4.0
112	87	141.8	Electro Static	Oxide	5.75	5.0	5.75
112	87	141.8	Electro Static	Oxide	5.75	5.0	5.75
156	116	194.4	Electro Static	Oxide	7.0	4.3	7.0
156	116	194.4	Magnetic	Impregnated	7.0	4.3	7.0
82	64	104	Electro Static	Oxide	4.0	For 36" & 41" system	
112	87	141.8	Electro Static	Oxide	5.75	For 41" & 46" system	
112	87	141.8	Electro Static	Oxide	5.75	For 46" system	

Spectral Energy Distribution Curves

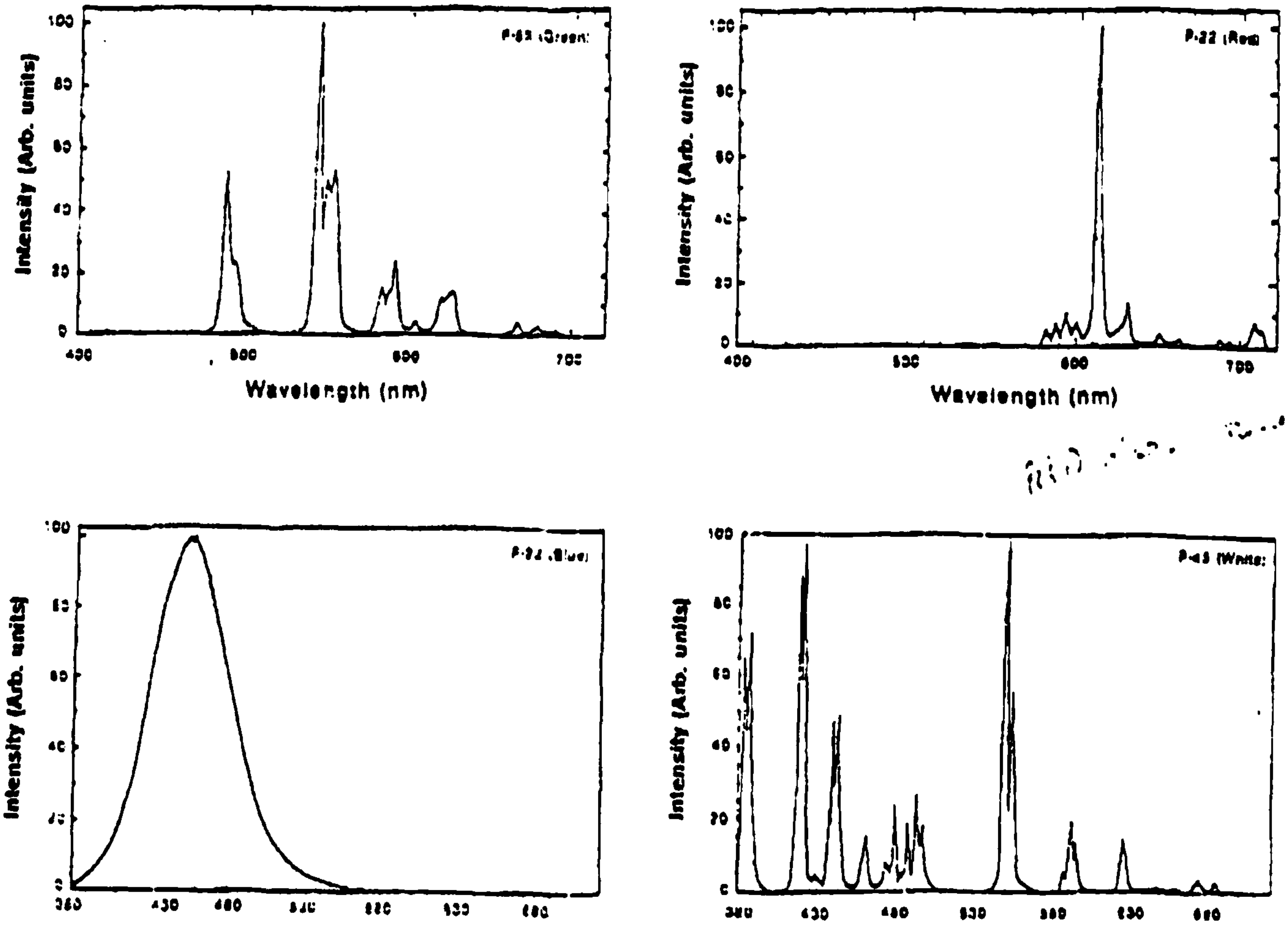
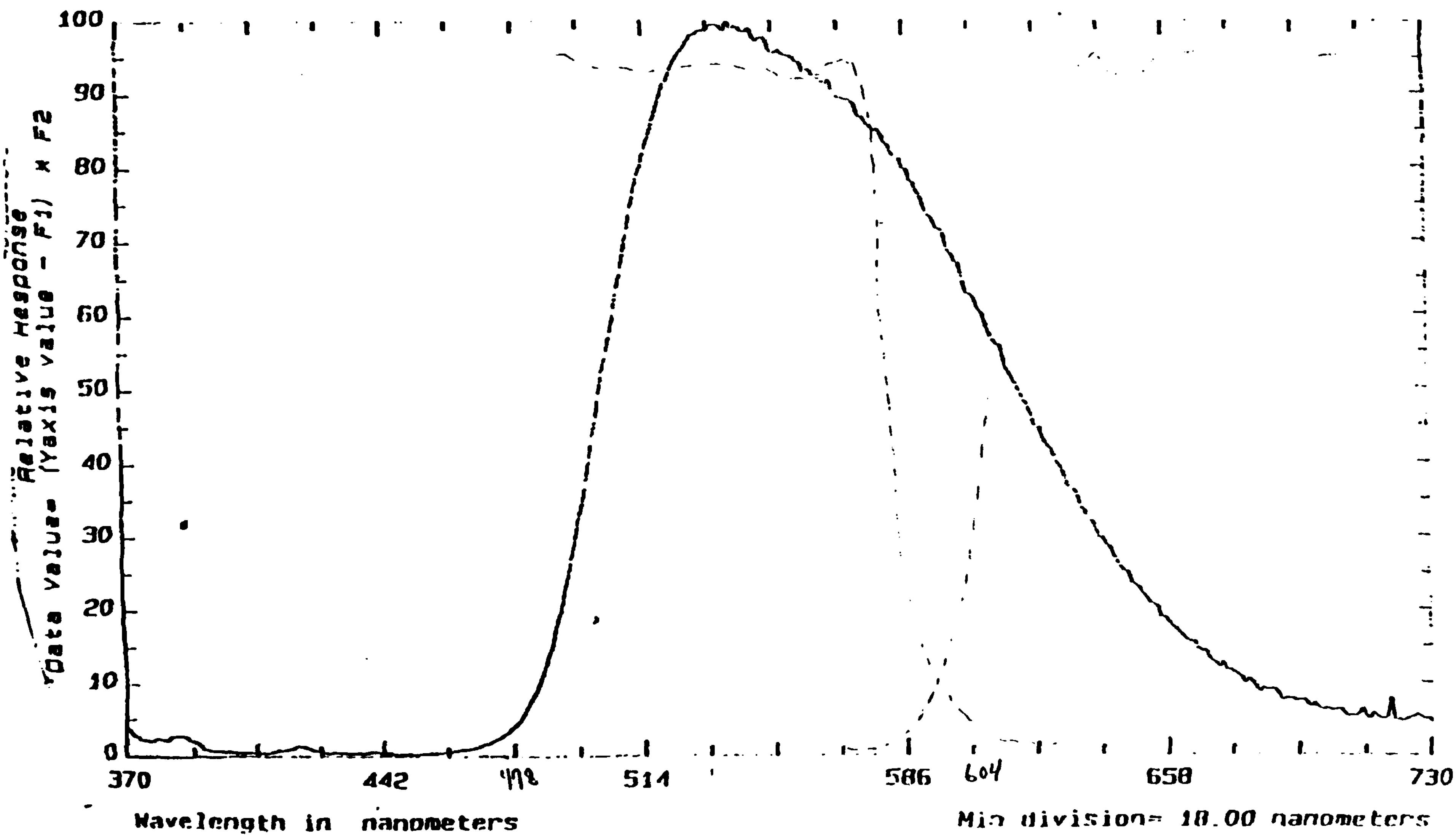


FIGURE 10

19808/SS S.N.S-1668 Date: 9/21/90 Photo Research Mod VI Multiplot

File #	Description (one line)	Date	Max.	Min.	F1	F2
27	3M320YAG-154871 P25KV-25UA (1"X1" SIZE)	9/21/90	3.720e-02	1.001e-04	0	3.720e-04



APPENDIX A

Projection Lens Patent

United States Patent [19]

Kreitzer

[11] Patent Number: 4,900,139

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

[54] COLOR CORRECTED PROJECTION LENS

[75] Inventor: Melvyn H. Kreitzer, Cincinnati, Ohio

[73] Assignee: U. S. Precision Lens, Inc., Cincinnati, Ohio

[21] Appl. No.: 266,234

[22] Filed: Oct. 28, 1988

Related U.S. Application Data

[63] Continuation of Ser. No. 48,026, May 11, 1987, abandoned.

[51] Int. Cl.^{4} G02B 13/18; G02B 9/00; G02B 3/00

[52] U.S. Cl. 350/432; 350/463; 350/412

[58] Field of Search 350/412, 432, 463, 465

[56] References Cited

U.S. PATENT DOCUMENTS

3,446,547	5/1969	Jeffree	350/465
4,620,773	11/1986	Fukuda	350/432
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

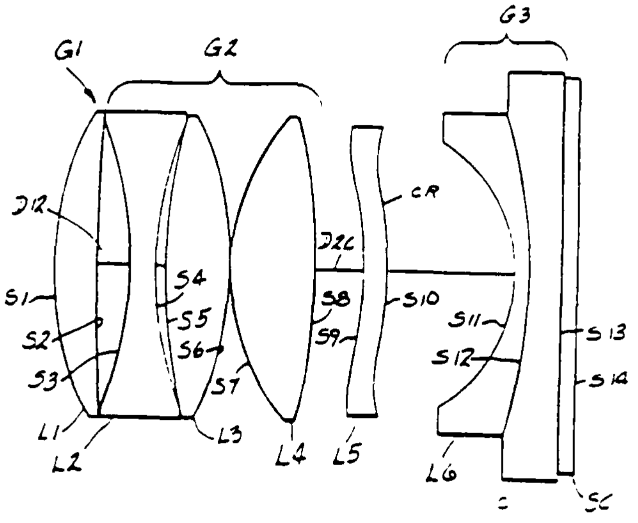
0198016	11/1983	Japan	350/432

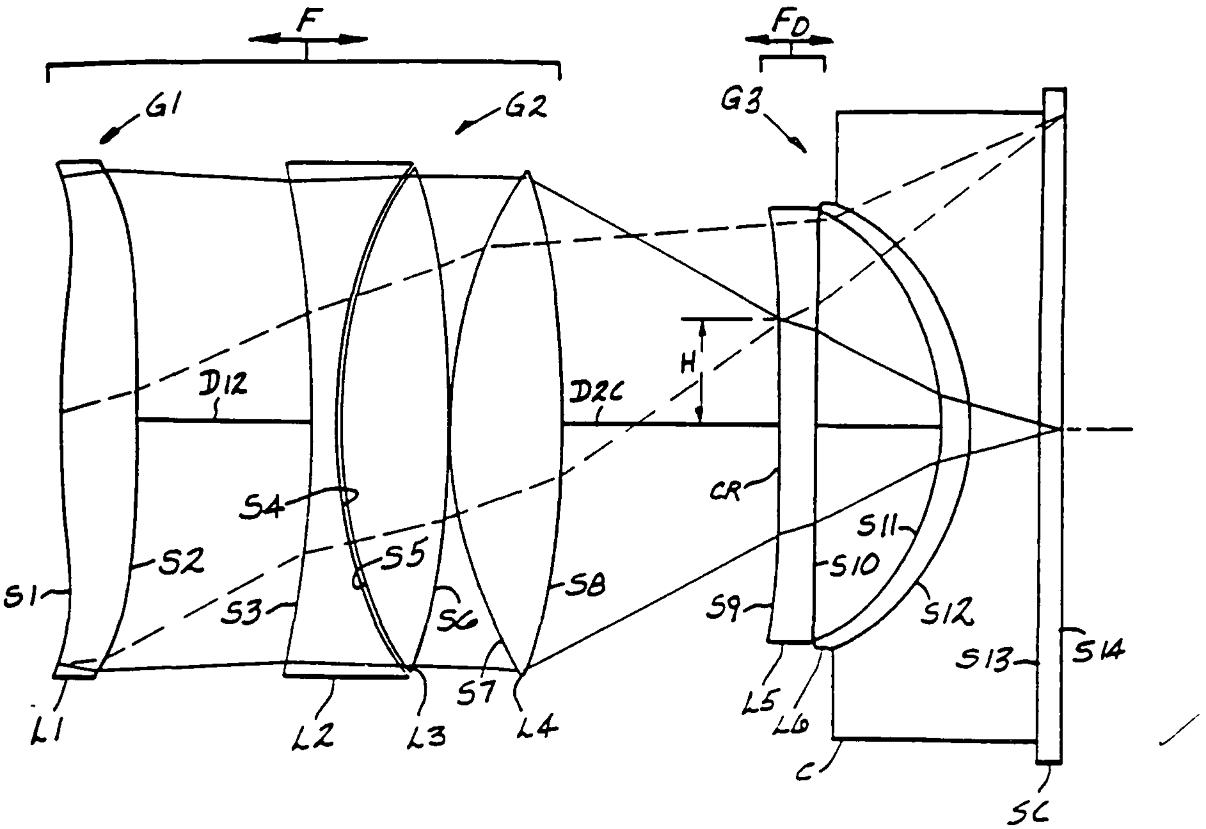
Primary Examiner—Bruce Y. Arnold
Assistant Examiner—Ronald M. Kachmarik
Attorney, Agent, or Firm—Robert H. Montgomery

[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




F
FD
G1
G2
G3
D12
D2C
H
CR
S1
S2
S3
S4
S5
S6
S7
S8
S9
S10
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S12
S13
S14
L1
L2
L3
L4
L5
L6
C
SC

FIG-1

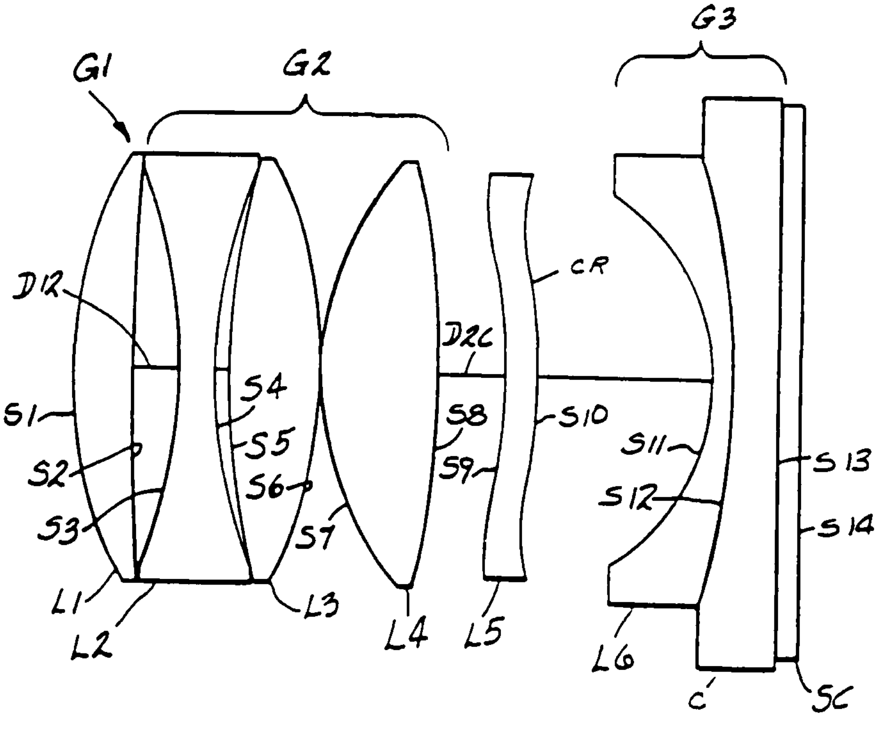
G1
G2
G3
D12
D2C
CR
S1
S2
S3
S4
S5
S6
S7
S8
S9
S10
S11
S12
S13
S14
L1
L2
L3
L4
L5
L6
C
SC

FIG-2

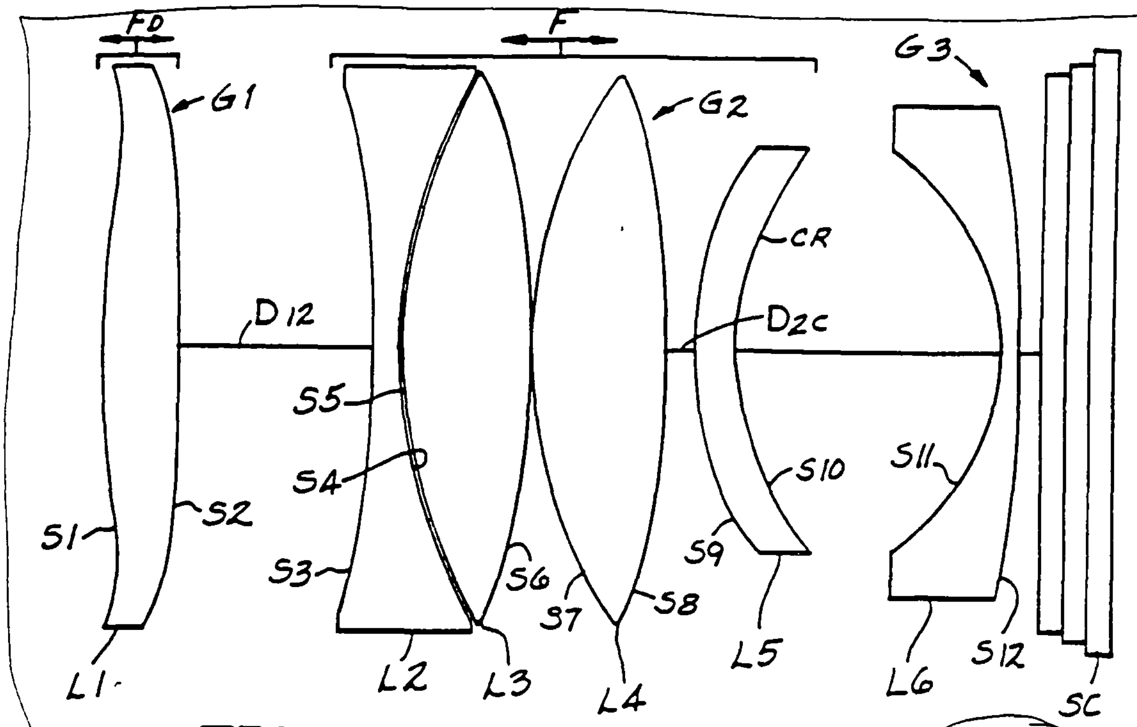

FIG-3

HD6

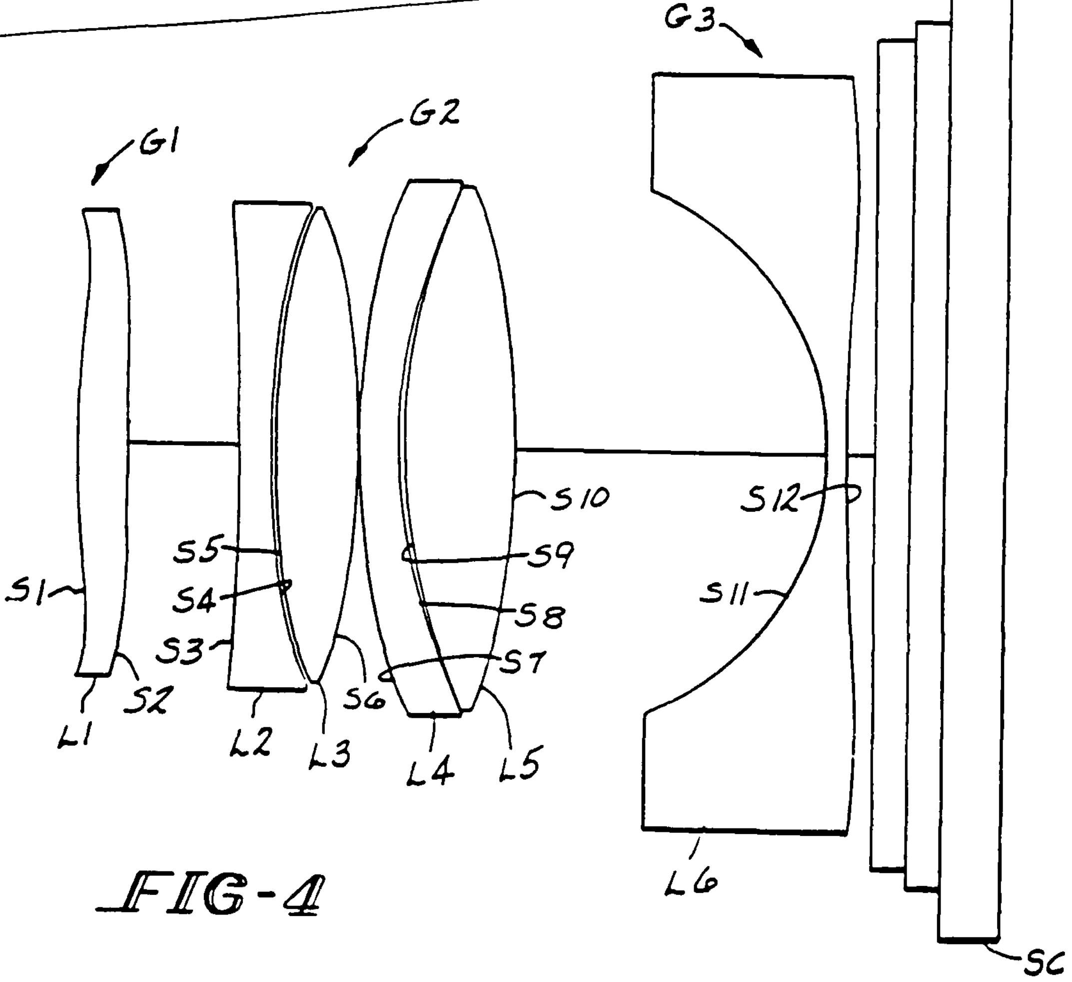

FIG-4

COLOR CORRECTED PROJECTION LENS

RELATED APPLICATION

This is a continuation of application Ser. No. 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 which are color corrected.

BACKGROUND OF THE INVENTION

In projection television systems, it is common practice to utilize three cathode ray tubes (CRT's) of different 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 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 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 application 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 (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 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 specification, 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 60×. 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 CRT projection lens that maintains a high level of image quality over a wide range of magnifications, for example, 10× to 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 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; and a weak power corrector lens element having at least one aspheric surface that significantly improves the higher order sagittal 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 meniscus 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 image to the object end. Surfaces of the lens elements 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 power and has at least one aspheric surface defined by the equation:

$$x = \frac{Cy^2}{1 + [1 - (1 + K)C^2y^2]^{1/2}} + Dy^4 + Ey^6 + Fy^8 + Gy^{10} + Hy^{12} + Iy^{14}$$

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 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 lens embodying the invention. The lens of FIG. 1 comprises 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 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 couples 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 which defines a peripheral wall which is sealed against 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 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 1, 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 I, has two aspheric surfaces.

Corrector element L5 is positioned with respect to 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 configured to correct for aberrations due to off-axis rays. In FIG. 1, the marginal 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 dependent 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 F_0 is the equivalent focal length (EFL) of the lens.

In all cases, the corrector lens unit CR where used is 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 prescriptions of Tables IV, V, VI, VII and VIII. In the lenses of Tables VI and VII the coupler C has no optical power.

Lenses as shown in FIG. 3 are described in the prescriptions of Tables IX and X. These lenses are air 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 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. 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 V_D. 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 (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.

TABLE I

LENS		SURFACE RADII (mm)	AXIAL DISTANCE BETWEEN SURFACES (mm)	N_D	V_D
	S1	283.571			
L1			21.700	1.491	57.2
	S2	−1056.263			
			49.8[illegible]		
	S3	−329.768			
L2			7.400	[illegible]	[illegible]
	S4	13[illegible]			
			0.740		
	S5	142.596			
L3			30.000	[illegible]	61.25
	S6	−2[illegible]			
			0.25		
	S7	133.119			
L4			32.4[illegible]	1.517	64.17
	S8	−253.947			
			62.100		
	S9	−1569.033			
L5			10.000	1.491	57.2
	S10	3665.023			
			36.420		
	S11	−69.434			
L6			8.000	1.517	64.17
	S12	−70.013			
C			18.000	1.410	55.0
	S13	Plano			

f/No = 1.2
EFL = 169.6 mm
Semi-field = 24°
CRT Diagonal = 161 mm
Magnification = −.06[illegible]
Aperture stop is 6.00 mm after S[illegible]
Aspheric Surfaces S1, S2, S9, S10

	S1	S2	S9
D	-0.2310×10^{-6}	$-0.1901 \times 10^{-}$[illegible]	$-0.2135 \times 10^{-}$[illegible]
E	-0.3115×10^{-10}	$-0.2372 \times 10^{-}$[illegible]	$-0.3129 \times 10^{-}$[illegible]
F	0.1117×10^{-14}	0.1940×10^{-14}	$-0.1604 \times 10^{-}$[illegible]
G	-0.4454×10^{-18}	$-0.3978 \times 10^{-}$[illegible]	0.2514×10^{-1}[illegible]
H	0.7641×10^{-22}	$0.6081 \times 10^{-}$[illegible]	0.2123×10^{-20}
I	-0.3878×10^{-26}	-0.3494×10^{-26}	-0.2994×10^{-24}

	S10
D	0.1728×10^{-6}
E	-0.6890×10^{-10}
F	0.1558×10^{-14}
G	0.1647×10^{-17}
H	0.1056×10^{-20}
I	-0.1015×10^{-24}

TABLE II

LENS		SURFACE RADII (mm)	AXIAL DISTANCE BETWEEN SURFACE (mm)	N_D	V_D
	S1	195.212			
L1			17.300	1.491	57.2
	S2	−1341.860			
			43.340		
	S3	−255.343			
L2			5.890	1.689	31.16

TABLE II-continued

	S4	123.557			
			1.030		
	S5	131.041			
L3			26.640	1.589	61.25
	S6	−177.996			
			0.200		
	S7	109.648			
L4			30.280	1.517	64.20
	S8	−205.352			
			D8		
	S9	127.299			
L5			7.961	1.491	57.2
	S10	−211.498			
			D10		
	S11	−58.675			
L6			6.000	1.526	60.03
	S12	−60.201			
C			7.000		
	S13	Plano			

f/No = 1.1
EFL = 135.0 mm
Semi-field = 23°
Aspheric Surfaces S1, S2, S9, S10

CRT Diagonal = 124 mm
Aperture stop is 0.00 mm after S5

	S1	S2	S9
D	-0.3078×10^{-6}	-0.2154×10^{-6}	0.1118×10^{-5}
E	-0.8541×10^{-10}	-0.7388×10^{-10}	-0.2040×10^{-9}
F	0.4895×10^{-14}	0.8120×10^{-14}	-0.1373×10^{-12}
G	-0.4086×10^{-17}	-0.3506×10^{-17}	0.4412×10^{-16}
H	0.8618×10^{-21}	0.7248×10^{-21}	0.1932×10^{-19}
I	-0.6304×10^{-25}	-0.5796×10^{-25}	-0.7326×10^{-23}

		Focusing Data			
	S10	EFL (mm)	D8 (mm)	D10 (mm)	M
D	0.1483×10^{-5}				
E	-0.3031×10^{-9}	130.3	44.87	39.69	−.0992
F	-0.8927×10^{-14}	135.0	48.22	30.09	−.0500
G	-0.3316×10^{-16}	138.2	51.78	22.12	−.0165
H	0.3663×10^{-19}				
I	-0.8052×10^{-23}				

TABLE III

LENS		SURFACE RADII (mm)	AXIAL DISTANCE BETWEEN SURFACES (mm)	N_e	V_e
	S1	258.727			
L1			21.700	1.491	57.2
	S2	−1207.846			
			47.750		
	S3	−329.768			
L2			7.400	1.673	32.17
	S4	137.720			
			0.740		
	S5	142.596			
L3			30.000	1.589	61.26
	S6	−277.752			
			0.250		
	S7	133.119			
L4			32.400	1.517	64.20
	S8	−253.948			
			57.490		
	S9	396.343			
L5			10.00	1.491	57.2
	S10	479.403			
			31.400		
	S11	−69.734			
L6			4.760	1.491	57.2
	S12	Plano			

f/No. = 1.2
EFL = 168. mm
Semi-field = 24°
Aspheric Surfaces S1, S2, S9, S10

CRT Diagonal = 131.8 mm
Magnification = −.0314
Aperture stop is 22.5 mm after S5

	S1	S2	S9
D	-0.2401×10^{-6}	-0.1956×10^{-6}	0.2561×10^{-6}
E	-0.2852×10^{-10}	-0.2302×10^{-10}	-0.4838×10^{-10}
F	-0.8694×10^{-15}	0.1560×10^{-14}	0.4407×10^{-15}

TABLE III-continued

G	$-0.1953 \times 10^{-\text{[illegible]}}$	$-0.6604 \times 10^{-\text{[illegible]}}$	[illegible]
H	0.4700×10^{-22}	$0.1746 \times 10^{-\text{[illegible]}}$	$0.1974 \times 10^{-\text{[illegible]}}$
I	$-0.3071 \times 10^{-\text{[illegible]}}$	$-0.8422 \times 10^{-\text{[illegible]}}$	[illegible]

	S
D	$0.4413 \times 10^{-\text{[illegible]}}$
E	$-0.1266 \times 10^{-\text{[illegible]}}$
F	$0.1106 \times 10^{-\text{[illegible]}}$
G	$-0.6174 \times 10^{-\text{[illegible]}}$
H	$0.2027 \times 10^{-\text{[illegible]}}$
I	$-0.2456 \times 10^{-\text{[illegible]}}$

TABLE IV

LENS		SURFACE RADII (mm)	AXIAL DISTANCE BETWEEN SURFACES (mm)	N_e	V_e
	S1	64.117			
L1			10.000	1.491	57.2
	S2	454.508			
			7.933		
	S3	−88.724			
L2			6.000	1.620	36.3
	S4	88.724			
			2.290		
	S5	133.595			
L3			15.000	1.517	64.2
	S6	−81.130			
			0.100		
	S7	52.655			
L4			20.000	1.517	64.2
	S8	−145.278			
			11.189		
	S9	−81.119			
L5			6.000	1.491	57.2
	S10	−65.972			
			29.963		
	L11	−35.209			
L6			3.200	1.620	36.30
	S12	−125.000			
C			7.530	1.410	60.00
	S13	Plano			

f/No = 1.0
EFL = 67.5 mm
Semi-field = 29°
Aspheric Surfaces S1, S9, S10

CRT Diagonal = 56.5 mm
Aperture stop is 11.25 mm after S5

	S1	S9	S10
D	-0.1074×10^{-5}	0.1299×10^{-5}	0.2701×10^{-5}
E	-0.1105×10^{-8}	0.1361×10^{-8}	0.2393×10^{-8}
F	0.8360×10^{-12}	0.1851×10^{-11}	$0.1395 \times 10^{-\text{[illegible]}}$
G	-0.1195×10^{-14}	0.6225×10^{-15}	$0.9554 \times 10^{-\text{[illegible]}}$
H	0.6780×10^{-18}	-0.3643×10^{-17}	$-0.2834 \times 10^{-\text{[illegible]}}$
I	-0.2118×10^{-21}	0.1561×10^{-20}	0.1139×10^{-20}

Focusing Data		
EFL (mm)	D10 (mm)	M
67.94	29.55	−.0831
67.46	29.96	−.0935

TABLE V

LENS		SURFACE RADII (mm)	AXIAL DISTANCE BETWEEN SURFACES (mm)	N_e	V_e
	S1	76.197			
L1			13.000	1.491	57.2
	S2	−472.688			
			10.334		
	S3	−81.639			
L2			4.000	1.620	36.30
	S4	90.843			
			0.066		
	S5	91.468			
L3			21.100	1.517	64.17
	S6	−91.468			

TABLE V-continued

			0.[illegible]		
	S7	84.10[illegible]			
L4			19.200	1.5[illegible]	6[illegible]
	S8	−120.724			
			12.3[illegible]		
	S9	−80.743			
L5			6.140	1.491	57.2
	S10	−105.033			
			D10		
	S11	−40.818			
L6			4.000	1.491	57.2
	S12	−44.000			
C			3.000	1.443	50.0
	S13	Plano			

f/No = 1.0 CRT Diagonal = 121.[illegible]
EFL = 77.2 mm Aperture stop is 6.33 mm after S5
Semi-field = 33°
Aspheric Surfaces S1, S2, S9, S10, S11

	S1	S2	S9
D	$-0.6915 \times 10^{-\text{[illegible]}}$	$-0.3031 \times 10^{-\text{[illegible]}}$	$0.3387 \times 10^{-\text{[illegible]}}$
E	$-0.3240 \times 10^{-\text{[illegible]}}$	$-0.1899 \times 10^{-\text{[illegible]}}$	$-0.1011 \times 10^{-\text{[illegible]}}$
F	-0.1245×10^{-12}	$0.0000 \times 10^{-\text{[illegible]}}$	-0.1141×10^{-12}
G	-0.3111×10^{-16}	$0.0000 \times 10^{-\text{[illegible]}}$	0.1345×10^{-15}
H	0.4997×10^{-19}	$0.0000 \times 10^{-\text{[illegible]}}$	-0.2762×10^{-19}
I	-0.2346×10^{-22}	$0.0000 \times 10^{-\text{[illegible]}}$	0.9852×10^{-22}

	S10	S11
D	$0.3964 \times 10^{-\text{[illegible]}}$	$-0.6488 \times 10^{-\text{[illegible]}}$
E	$0.4331 \times 10^{-\text{[illegible]}}$	$0.1265 \times 10^{-\text{[illegible]}}$
F	-0.5884×10^{-12}	$0.1142 \times 10^{-\text{[illegible]}}$
G	0.3546×10^{-15}	$0.2151 \times 10^{-\text{[illegible]}}$
H	-0.7876×10^{-19}	$0.2972 \times 10^{-\text{[illegible]}}$
I	-0.6164×10^{-22}	$-0.1388 \times 10^{-\text{[illegible]}}$

Focusing Data

EFL(mm)	D10 (mm)	M
78.25	34.06	−.0944
77.16	25.29	−.1170
77.95	34.40	−.1000

TABLE VI

LENS		SURFACE RADII (mm)	AXIAL DISTANCE BETWEEN SURFACES (mm)	N_d	V_d
	S1	89.851			
L1			16.000	1.491	57.2
	S2	452.287			
			15.205		
	S3	−141.472			
L2			5.000	1.620	36.30
	S4	111.221			
			1.200		
	S5	113.348			
L3			32.500	1.517	64.20
	S6	−113.348			
			0.200		
	S7	84.350			
L4			25.000	1.517	64.20
	S8	−1933.295			
			21.747		
	S9	−205.505			
L5			9.000	1.491	57.2
	S10	−112.793			
			D10		
	S11	−57.034			
L6			5.500	1.620	36.30
	S12	plano			

f/No = 1.0
EFL = 105.0
Semi-field = 30°
Aperture stop is 6.50 mm after S5
Aspheric Surfaces S1, S2, S9, S10

	S1	S2	S9
D	-0.1719×10^{-6}	0.2117×10^{-6}	0.2250×10^{-6}
E	-0.2179×10^{-9}	-0.4171×10^{-10}	0.4005×10^{-9}

TABLE VI-continued

F	$0.1416 \times 10^{-\text{[illegible]}}$	0.4646×10^{-13}	$-\text{[illegible]} \times 10^{-13}$
G	$-0.6286 \times 10^{-\text{[illegible]}}$	0.1553×10^{-16}	$0.667\text{[illegible]} \times 10^{-16}$
H	$0.1324 \times 10^{-\text{[illegible]}}$	-0.1450×10^{-19}	-0.1334×10^{-19}
I	$-0.9909 \times 10^{-\text{[illegible]}}$	0.3482×10^{-23}	$-\text{[illegible]} \times 10^{-23}$

		Focusing Data		
	S10	EFL(mm)	D10(mm)	M
D	$0.7114 \times 10^{-\text{[illegible]}}$			
E	$0.4129 \times 10^{-\text{[illegible]}}$	105	40.[illegible]	−[illegible]
F	$0.6262 \times 10^{-\text{[illegible]}}$	106.3	[illegible]	−[illegible]
G	0.1164×10^{-16}	107.2	[illegible]	−[illegible]
H	0.3025×10^{-19}			
I	$-0.9399 \times 10^{-\text{[illegible]}}$			

TABLE VII

LENS		SURFACE RADII (mm)	AXIAL DISTANCE BETWEEN SURFACES (mm)	N_d	V_d
	S1	90.401			
L1			17.0[illegible]	1.491	57.2
	S2	551.710			
			15.6[illegible]		
	S3	−148.320			
L2			6.0[illegible]	1.620	36.4
	S4	100.990			
			0.30[illegible]		
	S5	102.622			
L3			30.0[illegible]	1.517	64.2
	S6	−134.365			
			0.200		
	S7	85.095			
L4			24.500	1.517	64.2
	S8	−309.659			
			25.369		
	S9	−155.451			
L5			9.000	1.491	57.2
	S10	−112.107			
			D10		
	S11	−57.391			
L6			4.000	1.620	36.4
	S12	plano			

f/No = 1.2 CRT Deagonal - 122 mm
EFL = 104.7 mm Aperture stop is 9.90 mm after S5
Semi-field = 28°
Aspheric Surfaces S1, S2, S9, S10

	S1	S2	S9
D	-0.2355×10^{-6}	$0.1469 \times 10^{-\text{[illegible]}}$	$0.2639 \times 10^{-\text{[illegible]}}$
E	-0.1505×10^{-9}	-0.1695×10^{-10}	$0.4973 \times 10^{-\text{[illegible]}}$
F	0.7536×10^{-13}	0.3153×10^{-13}	$-0.8579 \times 10^{-\text{[illegible]}}$
G	-0.3857×10^{-16}	0.5873×10^{-17}	$0.4467 \times 10^{-\text{[illegible]}}$
H	0.9174×10^{-20}	$-0.7355 \times 10^{-\text{[illegible]}}$	$-0.1095 \times 10^{-\text{[illegible]}}$
I	-0.1059×10^{-23}	0.1920×10^{-23}	$-0.1734 \times 10^{-\text{[illegible]}}$
K	1.326		

		Focusing Data		
	S10	EFL (mm)	D10 (mm)	M
D	0.8827×10^{-6}			
E	0.4826×10^{-9}	104.8	36.40	−.11[illegible]
F	0.6637×10^{-14}	105.7	35.55	−.09[illegible]
G	-0.8763×10^{-17}	103.6	37.30	−.123
H	0.2104×10^{-19}			
I	-0.6838×10^{-23}			

TABLE VIII

LENS		SURFACE RADII (mm)	AXIAL DISTANCE BETWEEN SURFACES (mm)	N_d	V_d
	S1	79.527			
L1			14.000	1.491	57.2
	S2	380.482			
			14.450		
	S3	−116.430			
L2			4.500	1.620	36.4

TABLE VIII-continued

	S4	93.7[illegible]			
			0.10		
	S5	93.126			
L3			31.000	1.517	64.2
	S6	−93.126			
			0.200		
	S7	73.005			
L4			20.000	1.517	64.2
	S8	−7706.288			
			16.870		
	S9	−94.045			
L5			8.000	1.491	57.2
	S10	−83.071			
			D10		
	S11	−53.241			
L6			5.75	1.620	36.4
	S12	−130.000			
C			8.000	1.435	50.0
	S13	plano			

f/No = 1.2 CRT Diagonal = 126.6 mm
EFL = 96.9 Aperture stop is 6.20 mm after S5
Semi-field = 29°
Aspheric Surfaces S1, S2, S9, S10

	S1	S2	S9
D	-0.2013×10^{-6}	0.2663×10^{-6}	0.9194×10^{-5}
E	-0.4457×10^{-9}	-0.1806×10^{-9}	0.9549×10^{-9}
F	0.3147×10^{-12}	0.1593×10^{-12}	-0.2721×10^{-12}
G	-0.1513×10^{-15}	0.4444×10^{-16}	0.1107×10^{-15}
H	0.3487×10^{-19}	-0.6001×10^{-19}	-0.4843×10^{-19}
I	-0.2575×10^{-23}	0.1777×10^{-22}	0.5510×10^{-23}
K	1.326		

		Focusing Data		
	S10	EFL (mm)	D10 (mm)	M
D	0.1532×10^{-5}			
E	0.8778×10^{-9}	96.87	45.21	−.109
F	0.3840×10^{-14}	95.96	46.12	−.123
G	-0.9903×10^{-16}	98.07	44.05	−.092
H	0.6608×10^{-19}			
I	-0.1801×10^{-22}			

TABLE IX

LENS		SURFACE RADII (mm)	AXIAL DISTANCE BETWEEN SURFACES (mm)	N_d	V_d
	S1	178.554			
L1			13.000	1.491	57.2
	S2	2078.521			
			D2		
	S3	−255.343			
L2			5.890	1.689	31.2
	S4	123.551			
			1.030		
	S5	131.041			
L3			28.640	1.589	61.3
	S6	−177.989			
			0.200		
	S7	109.648			
L4			30.280	1.517	64.2
	S8	−205.352			
			0.210		
	S9	100.488			
L5			8.830	1.491	57.2
	S10	92.312			
			70.634		
	S11	−50.216			
L6			4.000	1.491	57.2
	S12	−368.024			
			D12		
	S13	Plano			

f/No = 1.1 CRT Diagonal = 124 mm
EFL = 134.3 mm Aperture stop is 0.00 mm after S5
Semi-field = 23°
Aspheric Surfaces S1, S2, S9, S10, S11, S12

TABLE IX-continued

	S1	S2	S9
D	−0.1388 [illegible]	0.6554 [illegible]	[illegible]
E	0.2155 × [illegible]	−0.3886 × [illegible]	0.1204 [illegible]
F	−0.9592 × [illegible]	−0.1774 × [illegible]	−0.9276 [illegible]
G	−0.3269 × [illegible]	−0.2621 [illegible]	[illegible]
H	−0.1475 × [illegible]	−0.4365 × [illegible]	−0.1022 [illegible]
I	0.2055 × [illegible]	0.7236 × [illegible]	[illegible]

	S10	S11	S12
D	0.4364 × [illegible]	[illegible]	[illegible]
E	−0.1594 × [illegible]	0.6758 × [illegible]	[illegible]
F	0.1444×10^{-12}	0.4601 × [illegible]	[illegible]
G	−0.1501 × [illegible]	0.7441 × [illegible]	[illegible]
H	0.6239×10^{-19}	−0.4504 × [illegible]	[illegible]
I	-0.1204×10^{-22}	0.5755 × [illegible]	[illegible]

Focusing Data			
EFL (mm)	D2 (mm)	D12 (mm)	M
135.05	50.3[illegible]	[illegible]	[illegible]
134.33	46.4[illegible]	4.[illegible]	−.05[illegible]
133.74	43.3[illegible]	[illegible]	[illegible]

TABLE X

LENS		SURFACE RADII (mm)	AXIAL DISTANCE BETWEEN DISTANCES (mm)	N	V
	S1	164.3[illegible]			
L1			17.3[illegible]	1.49[illegible]	57.2
	S2	−4893.612			
			D2		
	S3	−255.343			
L2			5.89[illegible]	1.689	31.1[illegible]
	S4	123.551			
			1.030		
	S5	131.041			
L3			28.64[illegible]	1.589	61.25
	S6	−177.989			
			0.200		
	S7	109.648			
L4			30.280	1.517	64.2
	S8	−205.352			
			6.260		
	S9	78.134			
L5			10.00[illegible]	1.491	57.2
	S10	67.389			
			60.21[illegible]		
	S11	−48.559			
L6			4.000	1.491	57.2
	S12	−252.989			
			1.302		
	S13	Plano			
			D12		

f/No = 1.1 CRT Diagonal = 124 mm
EFL = 135.7 mm Aperture stop is 0.00 mm after S5
Semi-field = 23°
Aspheric Surfaces S1, S2, S9, S10, S11, S12

	S1	S2	S9
D	-0.2911×10^{-6}	-0.1945×10^{-6}	-0.3015×10^{-7}
E	-0.7792×10^{-10}	-0.5934×10^{-10}	0.8356×10^{-10}
F	0.7366×10^{-14}	0.7111×10^{-14}	-0.1079×10^{-12}
G	-0.4384×10^{-17}	-0.3414×10^{-17}	0.4778×10^{-16}
H	0.7916×10^{-21}	0.7097×10^{-21}	-0.1167×10^{-19}
I	-0.3500×10^{-25}	-0.4415×10^{-25}	-0.8726×10^{-23}

	S10	S11	S12
D	0.2618×10^{-7}	0.1161×10^{-5}	0.7359×10^{-7}
E	-0.3268×10^{-10}	-0.6628×10^{-9}	-0.5860×10^{-9}
F	0.9906×10^{-13}	0.4292×10^{-12}	0.2597×10^{-12}
G	-0.1459×10^{-15}	0.9961×10^{-17}	-0.4923×10^{-17}
H	0.7475×10^{-19}	-0.5969×10^{-19}	0.1168×10^{-21}
I	-0.1894×10^{-22}	0.1511×10^{-22}	0.6336×10^{-24}

Focusing Data			
EFL (mm)	D2 (mm)	D12 (mm)	M
135.71	48.71	11.73	−.1000
134.97	44.80	5.42	−.0500

TABLE X-continued

134.3[illegible]	41.5	1.3	−.0[illegible]

TABLE XI

LENS		SURFACE RADII (mm)	AXIAL DISTANCE BETWEEN SURFACES (mm)	N_d	V_d
L1	S1	166.333			
			9.000	1.491	57.2
	S2	−14321.09			
			20.1000		
L2	S3	−600.536			
			6.000	1.785	25.7
	S4	132.672			
			0.080		
L3	S5	134.262			
			15.350	1.589	61.3
	S6	−132.733			
			0.200		
L4	S7	171.215			
			7.000	1.491	57.2
	S8	100.514			
			1.200		
L5	S9	111.209			
			19.450	1.589	61.3
	S10	−142.661			
			55.750		
L6	S11	−68.465			
			4.000	1.491	57.2
	S12	269.673			

f/No = 1.4　　CRT Diagonal = 125.8 mm
EFL = 111.6　　Magnification = .0263
Semi-field = 34°　　Aperture stop is 5.05 mm after S5
Aspheric Surfaces S1, S2, S7, S8, S11, S12

	S1	S2	S7
D	-0.9964×10^{-6}	-0.3034×10^{-6}	0.6027×10^{-6}
E	-0.4344×10^{-9}	-0.3497×10^{-9}	-0.1651×10^{-10}
F	-0.1037×10^{-12}	-0.3718×10^{-13}	0.5166×10^{-14}
G	0.1695×10^{-16}	-0.1261×10^{-16}	-0.6497×10^{-17}
H	0.1831×10^{-19}	0.2801×10^{-19}	0.6405×10^{-21}
I	0.2021×10^{-21}	-0.1241×10^{-23}	-0.7613×10^{-24}

	S8	S11	S12
D	0.1130×10^{-6}	-0.3187×10^{-6}	-0.8632×10^{-6}
E	0.3713×10^{-12}	0.2489×10^{-9}	0.1616×10^{-9}
F	-0.1677×10^{-13}	-0.2606×10^{-12}	-0.1755×10^{-13}
G	-0.8127×10^{-18}	0.1321×10^{-15}	0.2955×10^{-17}
H	0.6405×10^{-21}	0.7036×10^{-19}	0.1630×10^{-21}
I	-0.9106×10^{-24}	-0.4831×10^{-22}	-0.1388×10^{-24}

Table XII sets forth the powers K_{G1}, K_{G2}, K_{G3}, and K_{CR} of the lens units of each of the examples as a ratio of the power of the overall lens.

TABLE XII

TABLE	K_{G1}/K_O	K_{G2}/K_O	K_{G3}/K_O	K_{CR}/K_O
I	.373	.949	−1.032	−.068
II	.392	1.000	−1.149	−.203
III	.387	.948	−1.189	.124
IV	.452	.838	−1.021	−.011
V	.574	.838	−.838	−.108
VI	.479	.755	−.838	−.212
VII	.488	.803	−1.080	.139
VIII	.478	.789	−.975	.083
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.

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.

In the examples of Tables IV–VIII the optical power of the first lens unit K_1/K_0 is greater than 0.4. This is permissable in view of the spacing D_{12}/F_0 which is less than 0.2. Thus the spacing D_{12}/F_0 will be a function of the axial optical power of the first lens unit. The lesser the optical power of the first lens unit, the greater the spacing D_{12}/F_0 may be.

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

$$0.1 > K_{CR}/K_0\ 0.3$$

Thus any change in index of refraction of the corrector element due to temperature does not adversly 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	D_{12}/F	D_{2C}/F	K_2/K	K_3/K
I	.264	.245	−1.19[illegible]	[illegible]
II	.314	.397	−1.133	[illegible]
III	.264	.342	−1.180	[illegible]
IV	.117	.166	−.962	[illegible]
V	.134	.160	−.962	[illegible]
VI	.148	.207	−.990	[illegible]
VII	.151	.242	−1.031	[illegible]
VIII	.147	.175	−1.327	[illegible]
IX	.321	— —	−1.127	[illegible]
X	.302	.050	−1.133	[illegible]
XI	.181	−.13	−.817	[illegible]

The color correcting doublet of the second lens unit is designed to provide the necessary color correction without introducing uncorrectable aberrations. The lenses of Tables I, II, II, VII and VIII provide modulation transfer functions of ten cycles/millimeter over most of the field. In these examples, the absolute optical 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 6.3 cycles/millimeter and the embodiments of Tables IV-VIII 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 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 image/object magnifications of 16.4× and 31.5× respectively.

The lens of Table II is also designed for front projection and has a range of magnifications 10× to 60×. 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 arrow F and the focusing movement of element L5 is shown by the arrow F_L.

The lenses of Tables IX and X are also designed and have magnifications of 10× to 60×. Here elements L1-L5 move axially for focusing with L1 moving differentially 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 by the arrow F_D

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 may be used for a forty or fifty inch diagonal viewing screen.

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 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 foregoing description are efficiently attained. While preferred embodiments of the invention have been set forth 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 modifications 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 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, 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 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 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 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.

3. The lens of claim 1 further including a corrector lens 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

$$0.4 > D_{2C}/F_0 > 0.15$$

where D_{2C} is the axial spacing distance between said second lens unit and said corrector element and F_0 is 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 rays traced from the long 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 between said first lens unit and said second lens unit is

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

where D_{12} is the distance between the first and second lens units and F_0 is the equivalent focal length of said lens.

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

$$0.4 > D_{2C}/F_0 > 0.15$$

where D_{2C} is the axial distance between said biconvex element and said biconvex lens and F_0 is 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, 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 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 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 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 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 doublet 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

$$0.4 > D_{2C}/F_0 > 0.15$$

where D_{2C} is the axial spacing distance between said second lens unit and said corrector element and F0 is the equivalent focal length of said lens.

16. The lens 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 differential rates to vary the focus of said lens.

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

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

21. The lens 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 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 lens, said second lens unit comprising 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 positioned 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 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 D_{12} is the distance between the first and second lens units and F_0 is the equivalent focal length of said lens.

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

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

28. The lens of claim 22 where said first lens 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 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 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 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 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

$$0.4 > D_{2C}/F_0 > 0.15$$

where D_{2C} is the axial spacing distance between said second lens unit and said corrector element and F_0 is 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 surfaces.

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 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 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-

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face of said corrector lens 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 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 rays.

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

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 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, 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 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 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 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 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 contribute 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.

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 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 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 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 and the positioning of said corrector lens unit 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 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 contribute to correction of aberrations due to off-axis rays

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 said 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 of said second lens unit have 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 corrector lens element moves axially in the same direction but 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 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 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 color correcting doublet and said biconvex lens are glass having spheric surfaces.

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

54. The lens of claim 51 where said doublet is spaced from said first lens 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 concave 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 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.

* * * * *

HUGHES

HUGHES DISPLAY PRODUCTS
subsidiary of Hughes Aircraft Company

FACSIMILE LEAD PAGE

TO: Thomas St. John

FROM: Chuck Martino

COMPANY: Trident International

DIRECT DIAL: (606) 243-5519
FAX: (606) 243-5555

FAX NO.: 407-282-3343

DATE: February 13, 1992

NUMBER OF PAGES (INCLUDING COVER PAGE)__________

SUBJECT: Estimation of Costs for the Development of YAG CRTs

In Reply Refer to 92AM085:

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,

for
André Martin
Manager, Color Programs

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

TRIDENT DEVELOPMENT PROGRAM
(ROM PRICING)

GOAL: 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:

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 10 bulbs, build first 3 3" YAG faceplate. CRT's seal.

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 X 2700)	+ 2
5	11,000		+ 3
6	5,000		+ 3
7	4,000		+ 3
	$ 76,100		25 Weeks

PRODUCT PERFORMANCE SPECIFICATION
FOR THE
THE TRIDENT MODEL T-2080-R/C
DUAL MODE VIDEO PROJECTOR

Specification Number 002107

April 5, 1993

1.0. SCOPE

1.1. SCOPE OF SPECIFICATION DOCUMENT

This specification defines the performance, design, test, manufacturing and acceptance requirements of a full color CRT video projector system, Model T-2080-R/C, capable of operating in the raster mode as well as in an X-Y calligraphic mode.

1.2. APPLICATION DESCRIPTION

The projector is intended to meet a variety of applications including simulator visual system displays.

Operational mode changes shall be made in real-time with no perceptible degradation of system performance or loss of data. The projector shall be capable of operating in a pure raster mode and a mixed mode in which calligraphic data is displayed during an extended vertical retrace interval between fields/frames of an otherwise raster based display.

The projector will include three monochrome cathode ray tubes as image sources. The outputs of the CRTs will be passed through a passive optical lens system and will be converged to form a full color image on either flat or curved screens.

The projector may be used in front or rear projection installations.

The projector shall be capable of operating over the line rate spectrum from fifteen to eighty Kilohertz (15KHz - 80KHz).

The projector shall be designed to meet normal environmental conditions in the field environment including simulator motion platform stresses.

The projector shall have the capability to be employed in an array of projectors and shall have the correction capabilities to achieve full image edge matching between adjacent projected images. Therefore, the capability for channel to channel edge matching in both the horizontal and vertical directions will include intensity blending, color blending and all necessary geometric corrections to effect a proper match. The projector head shall be designed to operate in any orientation without altering the display characteristics or degrading or damaging the projector or its performance.

2.0. APPLICABLE DOCUMENTS

The following documents, of the exact date of issue shown, shall form a part of this specification only to the extent specified. In the event of conflict between the referenced documents and the content of this specification, the specification shall supersede.

Department of Health and Human Services - X-Radiation Safety Rules, 21 CFR, Subchapter J.

EIA Standard RS-232-D, Interface Between Terminal Equipment Employing Serial Binary Interchange, '87

EIA Standard RS-343-A, Electrical Performance Standards, Closed Circuit Television Camera, Sept '89

EIA Standard RS-422-A, Electrical Characteristics of Balanced Voltage Digital Interface Circuits, Dec '78

3.0. REQUIREMENTS

3.1. PROJECTOR REQUIREMENTS

The following paragraphs define the performance requirements of the CRT projector. Unless otherwise specified, performance for these paragraphs shall be measured under the following conditions:

Screen Radius of Curvature - 144 inches or greater
Screen Gain - 1.0
Projection Distance - 144 inches
Image Aspect Ratio - 3 X 4
Image Angular Subtense - 45 degrees X 60 degrees
Image Color - White/ Black/ Full Color
Color Temperature (White) - Approximately 6500 Degrees Kelvin

3.2. PROJECTION MODES

The projector shall be capable of being used in a front or rear projection installation.

3.3. OPERATING MODES

The projector shall be capable of operating in two (2) modes.

3.3.1. RASTER MODE

In the raster mode, the projector shall accept video signals conforming to EIA Standard RS-343-A as input at the line rates identified elsewhere in this specification. In addition the projector shall be able to accept separate Horizontal and Vertical sync signals and composite sync or sync on green.

3.3.2. MIXED MODE

In the mixed mode, the projector shall accept raster field/frame data as in the raster mode above. However, during an extended vertical retrace interval, operation shall switch to the calligraphic mode and light points shall be drawn during the time available before the next raster field/frame is drawn.

Switching between the raster and calligraphic mode, as well as the number of active raster lines and the number of light points to be drawn, shall be under the control of the external video signal generator.

3.4. SCREEN AREAS OF PERFORMANCE

For purposes of defining areas of performance, the screen image shall be divided into two areas as follows.

Area 1: A circle centered on the image center having a diameter equal to 0.6 of the diagonal.

Area 2: The remaining area not within Area 1.

3.5. PERFORMANCE CHARACTERISTICS

3.5.1. LUMINANCE

The system shall be capable of projecting a full white video field with a center luminance at the screen of no less than four (4) foot Lamberts (FL) for up to one (1) minute with a design goal of three (3) minutes, and at 3 FL for an indefinite period of time, at a color temperature of 6500 Degrees K.

The minimum black level shall be 0.1% of the white level.

Measurements shall be made using a raster and related Field of View of 45 Degrees by 60 degrees and at a projection distance of twelve (12) feet. Raster duty cycle and timing parameters shall be as dictated by specific application requirements.

Table 3.5.1. presents a set of typical timing parameters for mixed mode operation.

Table 3.5.1. MIXED MODE TIMING PARAMETERS

RASTER PARAMETERS	
FIELD RATE (HZ)	60
FRAME RATE (HZ)	30
INTERLACE	2:1
LINE FREQUENCY (KHZ)	30.69

TOTAL LINE TIME (MICRO SEC)	32.58
ACTIVE LINE TIME (MICRO SEC)	25.34
HORIZONTAL BLANKING (MICRO SEC)	7.24
PIXEL FREQUENCY (MHZ)	39.77
ACIVE ELEMENTS PER LINE	1126
TOTAL H SYNC PULSES PER FRAME	1023
ACTIVE LINES PER FRAME	799

RASTER SYNC PARAMETERS

H. SYNC PULSE WIDTH (MICRO SEC)	2.92
H. FRONT PORCH (MICRO SEC)	1.01
H. BACK PORCH (MICRO SEC)	3.32
V. SYNC PULSE WIDTH, MIN	3 H PERIODS
V. FRONT PORCH (H PERIODS)	0
V. BACK PORCH (H PERIODS)	3 H

FIELD TIME PARTITIONING

ACTIVE RASTER TIME (MICRO SEC)	13,016
ACTIVE POINT LIGHT TIME	
MINIMUM (MICRO SEC)	3,553
MAXIMUM (MICRO SEC)	20,219
CAL TO RASTER SWITH	98
TOTAL FIELD TIME (MIN)	16,667
TOTAL FIELD TIME (MAX)	33,333

The light output shall be measured at five (5) points within the full field. One of these points shall be on-axis. The other four points shall be in four quadrature directions at one-fourth the radius of the Area 1 circle as defined above.

3.5.1.1. LIGHT POINTS

Raster light points shall be projected at a maximum luminance of the 2 FL.

Calligraphic light points shall be projected at a maximum luminance of 4 FL.

3.5.1.2. LUMINANCE VARIATION AND SHADING

The illuminance over the raster shall not drop below 65% of the center brightness while meeting the reference luminance requirements of paragraph 3.5.1.. Sufficient shading correction shall be provided to meet this requirement regardless of the final electro-mechanical configuration adopted.

Luminance variations between adjacent areas, 36 total, of the raster shall not exceed +/- 20%, with a design goal of +/- 10%.

3.5.1.3. EDGE BLENDING ILLUMINANCE

The projector shall provide a means of luminance and color blending for multi-channel systems. This blending shall be achievable along all sides of the active raster area in a region adjustable from 0 to 5% of the image diameters as perceived from the eye position.

3.5.2. RESOLUTION

3.5.2.1. RASTER RESOLUTION

Raster resolution requirements are defined in terms of a minimum value of Modulation Transfer Function (MTF) for the specific spatial frequency of a projected high contrast bar pattern. The MTF value is defined as the maximum luminance minus the minimum luminance divided by the sum of the maximum and minimum luminance values in adjacent black/white bars in the projected bar test pattern. The minimum luminance of the test bars shall be equivalent to 1.0 Foot Lambert for the center luminance of a flat field pattern after adjustment for the allowed luminance variations defined above have been made.

Resolution requirements are as follows.

	Within Area 1.	Outside Area 1.
Arc Minutes subtended per Optical Line Pair as seen from the Eye Point	7	7
Minimum Horizontal and Vertical Average MTF.	0.10	0.10

Vertical resolution shall be measured by employing a raster bar pattern consisting of a known number of line pairs and shrinking the projected image until the line structure is just discernible at the eye point.

3.5.2.1.1. RESOLUTION TEST CONDITIONS

Measurements are to be made for the geometry and projected Field of View of the applicable application. Prior to resolution testing, shading compensation shall be adjusted for an acceptable luminance variation across the projected flat field.

Modulation shall be measured along the fast axis (cross pixel) by adjusting the frequency of the square wave test input signal to yield the correct spatial frquency at the eye point.

Modulation shall be measured along the slow axis (cross line) by adjusting the raster spacing of the slow axis to obtain the correct bar pattern spatial frequency. Two lines on and two lines off are acceptable.

3.5.2.1.2. RESOLUTION TEST LOCATIONS

The Modulation Transfer Function shall be measured at the center of the display, at four (4) points on the major axes located 85% out from the center, and at four (4) points on the diagonals located 85% out from the center.

Minimum resolution requirements shall be met at the center and for the average of all test points. No single MTF measurement shall be less than 80% of the performance specified above.

3.5.2.2. LIGHT POINT RESOLUTION

Calligraphic light point resolution shall be measured at locations as specified in the raster MTF test paragraphs above.

The average light point diameter of all the measurement points shall be less than 4.5 arc minutes with a design goal of 3 arc minutes. No single measurement shall be greater than 6 arc minutes.

Light point diameter shall be measured as the subtended horizontal and vertical angle of an almost merged mosaic of light points divided by the number of light points in each row and column. Separate measurements shall be made for both horizontal and vertical resolution. The array shall be reduced in size until the light points are almost merged, corresponding to approximately 10% MTF.

3.5.2.3. CALLIGRAPHIC ADDRESS RESOLUTION

The minimum address resolution (digital X and Y positioning resolution) for vector endpoints and light points shall be one part in 8000.

3.5.2.4. CONTRAST RATIO

The contrast ratio measured at the screen shall not be less than 15 : 1 when measured between a maximum illuminance white surface and an adjacent black area of a 4 X 4 checkerboard board pattern covering the entire projected image. Measurements shall be made with the white area brightness adjusted for a 2 FL flat field.

3.5.3. SYSTEM GEOMETRY AND RASTER PREDISTORTION

The projector shall provide the capability to correct for the geometric distortion caused by offsets between the projector axis, the viewer and the screen surface. The capability must be provided to permit creation of a rectilinear image as observed at

the eyepoint.
Maximum deviation from the predistorted image shall be less than +/-1% of the Area 1 diameter, including cases where the required deflection is non-symmetric with respect to its beginning and end.

3.5.4. EDGE MATCHING

The projector's horizontal and vertical edge matching accuracy on the projected image shall be within +/-0.2% of the Area 1 circle diameter in the overlap region.

3.5.5. CONVERGENCE

The images of any two CRTs shall meet the following convergence requirements, measured at the screen.

0.06% of Area 1 diameter within Area 1.
0.10% of Area 1 diameter Outside Area 1.

3.5.6. TIMING

Timing performance of the projector shall be a function of the mode of operation.

3.5.6.1. RASTER MODE TIMING

The projector shall have the capability to automatically sense and lock on to any horizontal sweep frequency in the range from 15 KHz to 80 KHz.

3.5.6.2. MIXED MODE TIMING

The projector shall have the capability to switch between raster format and calligraphic format in real time.

Two display formats shall alternate, raster and calligraphic, as follows. First the raster phase shall display approximately 400 lines of data at a sweep frequency of approximately 30 KHz. Next, a calligraphic phase begins during which point light information will be displayed. Then the projector will switch back to raster mode and display approximately 400 interlaced raster lines. Finally, the calligraphic phase will update point lights based upon new input data.

Two different methods of handling calligraphic data shall be supported in the mixed mode -- these are the normal and the field extension method.

In the normal method, the projector will display calligraphic data until either the incoming data has been exhausted or the time allotted for calligraphic mode has been exhausted. In the first case, the electron beam shall be blanked and means employed to preclude damage from the undeflected beam and overheating of the deflection system, until such time as the raster mode restarts. Additionally, provisions shall be employed to ensure that sync lock is not lost during the calligraphic phase. In the second case, the projector will display calligraphic data until it is commanded to restart raster mode and will discard any calligraphic data still in the queue.

In the field extension method, the projector will display input calligraphic data, regardless of raster restart requirements, until all calligraphic data has been displayed. It will then blank the electron beam and return to the raster mode.

The projector shall have a First In First Out (FIFO) priority system for displaying calligraphic data. The FIFO shall have sufficient depth to store up to 1000 calligraphic data packets.

Appropriate delay and synchronization mechanisms shall be incorporated in the projector to enable it to perform all necessary geometric, convergence and color shading corrections, as well as interchannel edge matching calculations, on the incoming stream of X-Y deflection and intensity data.

3.5.7. FOCUS AND DEFOCUS

The projector shall incorporate static and dynamic focusing capabilities. Dynamic focus shall be provided to minimize spot size variations across the projected image. Spot size shall be consistent with the system resolution requirements.

In the mixed mode, the projector shall be capable of defocusing light points and vectors by a factor of four. That is, light points shall be defocused to up to four times their focused diameter.

3.5.8. ASTIGMATISM

The ratio of minor axis to major axis spot diameters shall not be less than 0.8 for any calligraphic light point in the Area 1 circle and not less than 0.5 for any line width over the entire useful screen area.

Measurements shall be taken at 1.5 FL luminance.

3.5.9. VIDEO AMPLIFIERS

3.5.9.1. SIGNAL TO NOISE RATIO

The video amplifiers shall have a signal to noise ratio of greater than 54 dB relative to a maximum white video signal measured at the CRT drive points. Noise shall be measured with all input signals disconnected and the amplifier input terminated in 75 Ohms.

3.5.9.2. FREQUENCY AND TRANSIENT RESPONSE

The video amplifier frequency response, measured from full minimum black to maximum white video drive levels , shall be flat within +/- 3 dB to 110 MHz, measured at the CRT drive points. Full scale 10% to 90% rise and fall times shall be five (5) nanoseconds or less. Overshoot at any drive level down to visible threshold shall produce no discernible effects on the screen. There shall be no objectionable ringing or long time constant decay after pulses falling from maximum white to 5% white.

3.5.9.3. AMPLIFIER LINEARITY

Video amplifier linearity shall be within +/- 1% with a design goal of +/- 0.5%, input to output, over the full video range.

3.5.9.4. DYNAMIC RANGE

Video amplifier dynamic range shall be sufficient to drive the CRTs from full maximum white to full black without compromising frequency and transient responses.

3.5.9.5. VIDEO BLACK LEVEL

Black level shift, as measured at the video amplifier output, shall be less than 1% of the white level pulse amplitude when the width of a vertical peak white bar is increased from 5% to 80% of the width of the raster in the cross pixel (fast scan) direction.

3.5.10. BLANKING

The projector shall be capable of accepting composite sync signals and generating the internal blanking signals required by the projector.

3.5.11. DEFLECTION SYSTEM

The projector shall generate the necessary beam deflection waveforms for normal beam deflection and any special waveforms required for geometric and convergence corrections in all three modes of operation.

3.5.11.1. SETTLING TIME

The maximum deflection slew and settling time to within 0.05% of final value shall be as follows.

DISPLAY SCAN PROPORTION	SETTLING TIME
FULL SCALE	20 micro seconds
1/32 PART	2.85 micro seconds

3.5.11.2. DEFLECTIONS SYSTEM BANDWIDTH

In the raster mode, the deflection system shall be able to produce a fully corrected raster image at a line rate of 80 KHz.

3.5.12. PICTURE QUALITY

There shall be no perceptible noise or ringing visible in a uniform raster field having a light output adjustable from 0.01 to 2.0 foot Lamberts at the screen.

Following alignment, there shall be no visible effects in a flat grey pattern caused by insufficient resolution of any digitally generated correction signals. Digital correction signals shall have sufficient address and data resolution to avoid visible effects in all three modes of operation.

3.5.13. HIGH VOLTAGE POWER SUPPLY REGULATION

The CRT anode supply shall have sufficient regulation so that points near the edge of the raster shall not move more than 0.05% as the total lumen output is changed from 1.5 FC down to less than 0.01 FC. The edge of the raster shall not "bounce" more than 0.05% for switched changes of the same magnitude.

3.6. CONTROL AND ALIGNMENT FEATURES

3.6.1. PROJECTOR CONTROLS

All necessary operator controls and switches shall be provided to enable alignment of the projector system to within the performance limits defined in this specification and to allow periodic realignment of the projector system by means of a Remote Control Unit (RCU). The number, type, location and method of activation of the controls and switches shall be based on good human factors engineering practices.

3.6.2. TEST SIGNAL GENERATION

A video and sync test pattern generator shall be incorporated in the projector. Test pattern selection shall be accomplished from the RCU.

The following test patterns, at a minimum, shall be selectable.

Cross Hatch
Flat Field
Grey Scale
Calligraphic Light Points - Colocated with the intersections of the Cross Hatch Generator.
Other Raster and Calligraphic Test Patterns - Off-line programmable and recallable on command.
On-Line Intensity control of all test patterns.

3.6.3. PROJECTOR HEAD ADJUSTMENT REQUIREMENTS

The projector head assembly shall include provisions to perform adjustments of the image position, size and orientation on the face of the CRTs and on the screen. These adjustments, when made with the RCU controls zeroed out, shall serve as preliminary image adjustments to reduce the range and resolution requirements of the RCU controls. It is anticipated that the projector head controls will be mechanical and analog electrical.

3.6.4. REMOTE CONTROL ADJUSTMENT REQUIREMENTS

The projector shall be equipped with a Remote Control Unit (RCU) which may be located up to 60 feet from the projector and shall enable an operator to make adjustments to the display to correct for geometric distortion, convergence, color balance, edge matching and video to provide an acceptable display.

Only one RCU shall be required to control up to eight projectors in a system. The individual projectors in a system may operate on a mixture of timing standards.

Once corrections and adjustments are made, they shall be maintained in each projector computer system until additional corrections are required.

The RCU shall be designed to be disconnectable without disturbing the adjustment parameters or the operation of the projector system.

The RCU adjustments shall operate over two different adjustment ranges - a coarse, or predistortion, range and a fine adjustment range.

The following adjustments, at a minimum, shall be included as part of the RCU. Other adjustments may be incorporated.

3.6.4.1. COARSE ADJUSTMENTS

The RCU coarse adjustments shall consist of the following, at a minimum.

Position

Size
Skew
Bow
Pin Cushion/Barrel
Keystone

Individual and simultaneous red, green and blue adjustments shall be provided in the X and Y directions with a range of +/- 30% of the X and Y dimensions.

3.6.4.2. FINE ADJUSTMENTS

3.6.4.2.1. SIZE

Individual and simultaneous red, green and blue size adjustments shall be provided in both X and Y directions.

3.6.4.2.2. POSITION

Individual and simultaneous red, green and blue position adjustments shall be provided in both X and Y directions.

3.6.4.2.3. DISTORTION

Individual and simultaneous red, green and blue distortion adjustments shall be provided in both X and Y directions.

3.6.4.2.4. ADJUSTMENT RANGE AND RESOLUTION

The adjustment range shall be sufficient to adjust to the final raster configuration with at least 10% adjustment range remaining.

Adjustment resolution shall be fine enough to allow the display to be corrected for distortion to the degree that the edges of two projector images can be matched to within +/- 0.1% of the Area 1 diameter.

3.6.4.3. CONVERGENCE

Convergence controls shall be provided to meet the specified convergence requirements. The control range shall be sufficient to accommodate the size, position and distortion controls.

3.6.4.4. LUMINANCE AND COLOR TEMPERATURE

Adjustments shall be provided to allow luminance and color temperature requirements of this specification to be met.

3.6.4.5. VISIBLE THRESHOLD

Separate CRT cut-off voltage adjustments shall be provided for all 13 three CRTs. A brightness control shall be provided to adjust the low light level simultaneously for all three colors.

3.6.4.6. VIDEO GAIN AND CONTRAST

The gain of each video amplifier chain shall be variable over at least 50% of the maximum CRT drive range. A contrast control shall be provided to adjust the highlights simultaneously for all three colors.

3.6.4.7. FOCUS

Both static and dynamic focus adjustments shall be provided for all three CRTs. Focus adjustment range shall be at least 40% of the focused spot size in the raster mode.

3.6.4.8. DEFOCUS

Dynamic defocusing control shall be provided in the calligraphic mode having a range such that a light point may be defocused up to four (4) times its focused diameter.

3.6.4.9. INTENSITY SHADING

Adjustments shall be provided for all three CRTs to minimize luminance variations across the screen area and to allow luminance matching of adjacent projectors in a multi-projector system. The adjustment range and resolution shall be sufficient to satisfy the illumination variation requirements of this specification.

3.6.4.10. EDGE BLENDING

Adjustments shall be provided to obtain smooth illumination and color transition between adjacent projectors. This capability shall include edge tilt, blending, slope and position to allow parallel edge matching of adjacent displays.

Adjustment capability shall be provided for all edges of the displays. Provisions shall be made to easily modify the locus of the blend region to align curved blend regions.

3.6.4.11. GUN ON/OFF CONTROL

On/Off control shall be provided for each CRT and for all three CRTs in a projector.

3.7. STABILITY

With the exception of the specific requirements of paragraphs 3.7.1., 3.7.3. and 3.7.4., the performance requirements listed in this specification shall be met after 45 minutes warm-up time from a minimum 8 hour standby mode, and shall be maintained for a minimum of 8 hours over an ambient temperature change of +/- 4 degrees Celsius. Warm up time is 45 minutes and test time is 21 hours for the three cited paragraphs.

3.7.1. POSITIONAL STABILITY

With an ambient temperature variation of less than +/- 4 degrees Celsius, the 21 hour drift of any point in the projected image, in all modes of operation, shall not exceed 0.06% of the Area 1 diameter, with a design goal of 0.03%.

3.7.2. JITTER

Raster, vector and light point jitter shall not exceed +/- 0.04% of Area 1 diameter.

3.7.3. CONVERGENCE STABILITY

After initial warm-up and when operated at an ambient temperature of +/- 4 degrees Celsius of the set-up temperature, the red, green and blue convergence error shall not exceed 0.1% of Area 1 diameter in Area 1 and 0.15% outside Area 1 during the following 21 hours. This requirement applies to all three modes of operation.

3.7.4. LUMINANCE AND COLOR HUE STABILITY

After the warm-up period and when operated at an ambient temperature +/- 4 degrees Celsius, the individual red, green and blue brightness corresponding to peak white and 1% of peak white shall be stable such that no perceptible color hue variation is observable in any part of a grey-scale pattern or flat field covering this range over a 21 hour period of displaying low to medium intensity video data.

In a multi-projector system, this performance shall be reverified after the system is aligned, using adjacent juxtaposed projectors as the color reference.

An equal mixture of day, dusk and night scenes shall be displayed during the 21 hour test period.

3.8. PROTECTION

3.8.1. PHOSPHOR PROTECTION

Phosphor protection shall be provided to minimize CRT damage in all modes of operation. The protection system shall utilize information derived from instantaneous beam currents, electron beam deflection rates, light point dwell and defocusing information to extinguish a potentially damaging video spot. When a potentially damaging set of parameters is detected by the system, the video shall be blanked and sufficient CRT voltages removed to protect the system.

The system shall be designed so that undeflected beams following normal turn-off shall not damage the CRTs.

Full operational recovery of the phosphor protection system following power fluctuations, momentary sync loss or other 15 triggering circumstances, shall be no more than 30 seconds.

3.8.2. SYNC SIGNAL PROTECTION

No circuit or component in the projector shall be damaged by either the absence of a sync signal input, wrong frequency sync signal or a noisy sync signal.

3.8.3. OVER TEMPERATURE PROTECTION

Circuitry shall be provided to shut down the projector in the event of major components exceeding their safe operating temperatures.

3.8.4. POWER-UP SEQUENCE

The projector shall be designed such that any power-up or power-down sequence, whether normal or abnormal, is permitted without causing system damage.

3.8.5. CRT PROTECTION AGAINST ARCING

Suitable means shall be incorporated in the projector to minimize the probability of CRT or circuit damage in the event of CRT arcing.

3.8.6. TRANSIENT PROTECTION

The projector shall be protected from over-voltage, under-voltage and power line transients. Power line spikes up to 3 KV in common mode and up to 1 KV in differential mode, both containing up to 2 Joules of energy, shall not damage the projector system.

3.9. INTERFACES

The projector shall be equipped with the necessary data and control interfaces to support all modes of operation. In addition, communication interfaces shall be provided to support communications with the RCU, BIT functions.

3.10. OPTICAL SYSTEM PERFORMANCE

The optical system design shall be such that the combined optical, electronic and mechanical system shall meet all of the requirements of this specification. Lenses shall be designed/selected to meet the requirements of specific projector applications as required.

3.10.1. OPTICAL FOCUS

The lenses shall have adjustable optical focus with provisions for locking the focus adjustment.

3.10.2. DEPTH OF FIELD

The lens depth of field shall be sufficient to provide uniform 16 focus over the screen and at the offsets for which the system is designed.

3.10.3. THROW DISTANCE

Lens design/selection shall take into account throw distance requirements so as to meet application and system performance requirements.

3.10.4. SCREEN RADIUS OF CURVATURE

The projector shall meet all requirements of this specification for screens having a radius of curvature of 144 inches and greater.

3.11. CATHODE RAY TUBES

The CRTs shall be high resolution, high brightness, non-browning, red, green and blue projection CRTs.

3.11.1. TUBE LIFE

Under conditions of average light output, the operating life of the CRTs shall be at least 2000 hours. End of life shall be defined as that time at which performance has declined to the point that light output of the CRT has dropped to 50% of the original light output. Failed tubes shall be individually replaceable without adversely affecting the display.

3.12. ELECTRO-MECHANICAL PROPERTIES

3.12.1. MECHANICAL CONFIGURATION

The major mechanical subassemblies of the projector shall consist of the following components.

3.12.1.1. PROJECTION HEAD ASSEMBLY

This assembly shall contain the three projection CRTs with associated coils, lenses, and selected drive electronics as well as the deflection and focus systems.

3.12.1.2. LOW VOLTAGE POWER SUPPLY ASSEMBLY

This assembly shall contain the Low Voltage Power Supply(ies) and may be combined with other assemblies such as the High Voltage Power Supply Assembly.

This assembly must be capable of being located remotely from the projection head assembly and other assemblies by a distance of at least one hundred and fifty (150) feet.

3.12.1.3. PROJECTOR CONTROL ASSEMBLY

This assembly contains the Controller circuitry required to effect control and remote adjustment capability of the projector.

This assembly must be capable of being located remotely from the projection head assembly by a distance of at least twenty (20) feet.

3.12.1.4. REMOTE CONTROL UNIT ASSEMBLY

This assembly contains the circuitry and operator interface controls to provide control and adjustment capabilities of the projector by the operator.

This assembly must be capable of being located remotely from the projector control assembly by a distance of at least sixty (60) feet.

3.12.2. INPUT POWER

Power consumption shall be less than 3800 watts at a power factor not less than 0.7.

The projector shall meet all performance requirements with input power of 110 volts +/-10% AC, or 240 volts +/-10% AC, 47 to 63 Hertz.

3.12.3. ENVIRONMENTAL REQUIREMENTS

3.12.3.1. ACCELERATION

The projector or subsystem shall operate within specifications after exposure to 2G acceleration in any direction. No perceptible visual anomalies shall be present during acceleration.

No damage shall occur for accelerations of 5G in any direction.

3.12.3.2. SHOCK

The projector or subsystem shall operate within specifications after exposure to a shock of 6G for 100 milliseconds in any direction.

3.12.3.3. VIBRATION

The projector or subsystem, when mounted moving platform, shall operate within specifications:

1. After exposure to vibration of 2.5G amplitude over a 5Hz to 10Hz frequency spectrum in any direction.

2. Without discernible anomalies, during exposure to vibrations of 1.5G amplitude in a 5Hz to 10Hz frequency range in any direction.

Vibration frequencies below 5 Hz shall not affect the performance of the projector.

The lowest natural frequency of the projector or subsystem shall be greater than 15 Hz.

3.12.3.4. TEMPERATURE, HUMIDITY AND ALTITUDE

The projector shall operate within specifications over a temperature range of 10 to 30 degrees Celsius, a relative humidity 18 range of 30 to 80%, non-condensing, and up to an altitude of 8000 feet.

The projector shall withstand the following non-operating conditions without damage: Temperatures of -20 to +60 degrees Celsius and relative humidity of 0 to 85%, non-condensing.

4.0. RELIABILITY, MAINTAINABILITY AND SAFETY

4.1. SAFETY

4.1.1. X-RAY RADIATION

The projector shall comply with the U.S. Department of Health and Human Services X-Radiation Safety Rules, 21 CFR, Subchapter J when operated in accordance with these specifications and at the normal CRT operating voltage.

4.1.2. TOUCH TEMPERATURE

Exposed parts of the projector, with cover plates installed, shall not reach temperatures in excess of 140 degrees Fahrenheit at an 80 degree F ambient temperature.

4.2. RELIABILITY

As a design goal, the Mean Time Between Failures (MTBF) for the projector shall be greater than 4500 hours, excluding the CRTs, but including the power supplies.

4.3. MAINTAINABILITY

The projector shall be designed and constructed to permit ease of assembly, disassembly, trouble shooting and maintenance.

Mean Time To Repair shall be less than 30 minutes. CRT replacement shall take less than one hour.

The Maximum Mean Preventive Maintenance Time shall not exceed 40 minutes per day.

An elapsed operating time meter shall be provided with each projector.

4.3.1. BUILT-IN TEST (BIT)

Built-In-Test (BIT) features shall be provided to verify the status of selected critical projector elements during power-up, system readiness tests and normal operation. Diagnostic fault isolation capability shall also be provided.

Test status shall be reported to the RCU from the individual projector control modules.

4.3.1.1. POWER-UP TESTS

The power-up test will be conducted each time AC power is applied to the system. The results of normal power-up tests and system states shall be reported in the form of a go/no-go bit for each parameter of each projector.

All critical projector parameters shall be tested sequentially. The projector shall shut down automatically when any critical parameter falls outside normal operating bounds to avoid projector damage.

4.3.1.2. SYSTEM READINESS TESTS

Provisions shall be made to call up test patterns to determine contrast, geometry, edge match, convergence and resolution. The patterns may originate either from the projectors' built in test generators or from the external image generator. Test pattern selection shall be made from the RCU or from the image generator.

4.3.1.3. CONTINUOUS TESTS

The same tests, at a minimum, executed during power-up shall be repeated continuously during normal system operation. Only malfunctions shall be reported to the operator via the RCU. Test status shall be reported to the image generator on a demand basis.

4.3.1.4. FAULT ISOLATION TESTS

Part of the data needed for diagnostic tests and fault isolation is contained in the tests described in the preceding paragraphs. Additional off-line fault isolation tests shall be provided. At a minimum, these shall include:

1. Digital data integrity (Read/Write Tests)

2. Outputs from subsystem modules

3. Critical signals within subsystems

Using projector controller software and hardware, these tests shall isolate faults to the single circuit card level at a minimum.

4.3.2. DATA INTERFACE

An RS-232 interface shall be provided to support BIT and fault isolation test reporting.

4.3.3. TEST POINTS

Test points shall be provided on circuit cards and terminal strips and shall be accessible without major disassembly of the projector.

5.0. QUALITY ASSURANCE

A quality assurance program shall be established covering all phases of design documentation, manufacturing, procurement, parts control, configuration control and testing. The program will be based upon and utilize Best Commercial Practices used in the electronic manufacturing industry.

Silicon Field-Emitter Arrays
for Cathodoluminescent Flat-Panel Displays

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Abstract

Cathodoluminescent flat-panel displays can be made with field-emitter arrays (FEAs). Using orientation-dependent etching and a linear thermal-oxidation process, we have fabricated uniform and reproducible FEAs which yield more than 10 microamperes/tip with less than 140 VDC extraction voltages. Modulation voltages are in the 40 volt region. These FEAs can be the basis for a simple and inexpensive cathodoluminescent flat-panel display.

I. INTRODUCTION

A number of flat-panel-display technologies are being developed worldwide including liquid-crystal displays (LCDs), plasma displays (PDs), and electroluminescent displays (ELDs). Each of these display technologies has inferior display characteristics in comparison to the CRT. Hence, the search for a flat-panel CRT continues to draw attention.

Recently, a new cathodoluminescent flat-panel television display based on field-emitter arrays (FEAs) has been reported.[1] Each pixel in that display is composed of hundreds of FEA cells working in parallel in order to minimize noise and to insure that non-uniformity in emission from individual emitters is inconsequential. The FEAs in that flat-panel display were made with a modified e-beam metal-deposition technique [2,3], a process which is both non-standard in the microelectronics fabrication community and is hard to control.

In this paper we report the fabrication of silicon FEAs[4] using a modified orientation-dependent etching (ODE) process [5] and a linear thermal-oxidation process which yields uniform and reproducible silicon-field emitters. The current-voltage characteristics of these FEAs are also presented.

II. FABRICATION PROCEDURES

The silicon FEAs reported here were fabricated on 4" n-type, <100> substrates. Figure 1 shows the schematic diagram of the fabrication process. A thermal oxide was grown at 1000C in wet oxygen ambient to a thickness of 150 nm, then patterned photolithographically and RIE etched to form a mask (Fig. 1(a)). A proprietary ODE etch was used to create square vertical pyramidal structures which are shown in Fig. 1(b). This pyramidal structure, bounded by silicon <111> planes, possessed a 200 nm flat top which retained its silicon-dioxide cap up to this point. This pyramid was then sharpened by a linear oxidation at 850C in a dry oxygen ambient to half the thickness of the flat top of the pyramid. (This makes a pointed silicon pyramid.) An insulator was then directionally evaporated onto the substrate by electron-beam evaporation and annealed at 850C in an oxygen environment for 16 hours to enhance the oxide-breakdown field (up to ~ 5 MV/cm) (Fig. 1(c)).

A liftoff process[6] was used to form the extraction electrode. First, a photoresist pattern with a sloped sidewall was formed, followed by directional metal deposition (Fig.

1(d)). Metal deposited on top of the photoresist was then removed in acetone (Fig.1(e)). This metal was self-aligned to the silicon pyramid. The oxide cap on the top of the oxidized pyramid, as well as the layer on the pyramidal sidewall, were then etched away in buffered-HF solution leaving the gated-diode structure shown in Fig. 1(f). Further linear oxidation of the <111> planes results in uniformly sharp field emitters.

Figure 2(a) is a SEM picture of a single field emitter. The radius of curvature of the field emitter is about 100 Å. Figure 2(b) shows a SEM picture of 2x2 FEA. The number of masks and processing steps is small and relatively simple to implement with standard processing and fabrication equipment. In fact, the basic process has one mask (plus a crude mask to define the extraction electrode) and is self-aligned. The density of FEA cells using this process can be 10^6 - 10^7 emitters/cm^2. Since the FEAs in each pixel operate in parallel, one obtains redundancy and low flicker noise. (Flicker noise decreases as the square root of the number of field emitters.) Because the basic FEA cell is very small, extremely high spatial resolution and high brightness are expected. Low cost and high resolution of FEAs may be obtainable.

III. RESULTS AND DISCUSSION

Emission currents from a single field emitter have exceed 10 microamperes with extraction-bias voltages (voltage between gate and emitter) less than 140 VDC as shown Fig. 3. Fig.3(a) shows the I-V characteristics of a single field emitter. The Fowler-Nordheim plot of these data, shown in Fig. 3(b), demonstrates that the emission is indeed field emission as opposed to Frankle-Poole emission. The normalized emission current characteristics of a 3x3 tip FEA is shown in Fig. 4 (normalized to 8.223 x 10^{-5} A/V^2) which demonstrates that similar tip characteristics are observed with both single and multiple tip arrays. These silicon FEAs have been operated in a non-baked vacuum system for several weeks with no observable change in their current-voltage characteristics [7]. Extensive life tests have not been performed.

More than 99% of the current flowing in this device structure is emission current to a free-standing collector (which could be replaced by phosphors). Consequently, the drive-power requirement for flat-panel displays based on this technology is expected to be minimal. The forecasted power consumption for different types of flat-panel displays, including displays based on FEAs, [8], indicates that low-power displays based on this technology appear attractive. Furthermore, the device capacitance for these structures can be made very small [9], thereby permitting fast gating and refresh. High screen voltage, or high screen current density, can be employed to take advantage of various phosphor characteristics. The signal-drive modulation voltage, in the 40 volt region, is attractive and commercially obtainable. The pixel addressing methodology is row-column thereby eliminating the need for active matrix technology. [1,2,10]

IV. CONCLUSIONS

Low-voltage, high-current-density, uniform, and stable silicon FEAs have been fabricated and characterized. We suggested that silicon based FEAs promised to be the basis of a new, inexpensive, flat-panel-display technology, including TV and HDTV screens. In additional, this FEA technology promises the possibility of an inexpensive, monolithic cold electron-gun replacement for thermionic cathode based electron guns in CRTs.

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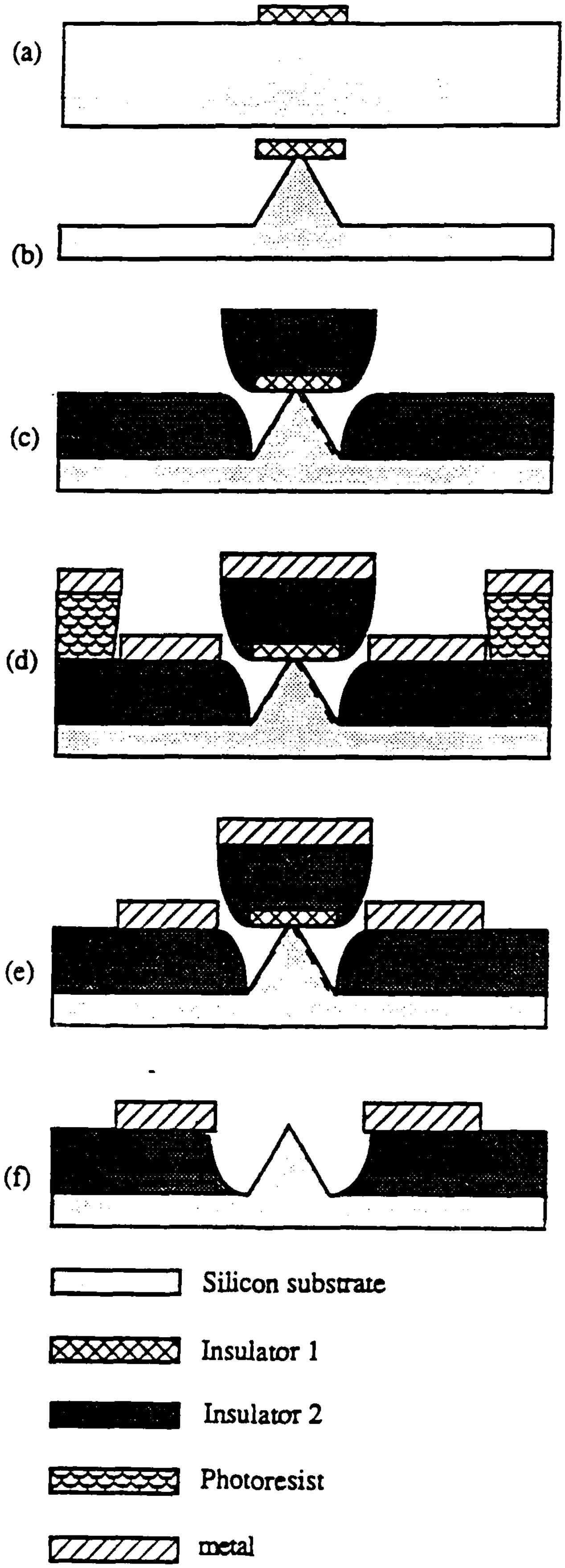
Figure Captions

Fig.1 Schematic diagram of fabrication process of field emitters.

Fig. 2 (a) SEM picture of single field emitter. (b) SEM picture of a 2x2 array field emitter.

Fig.3 Current-voltage characteristics of a singe field emitter. (b) Fowler-Nordheim plot for a single field emitter.

Fig.4 Normalized Fowler-Nordheim plot for one 3x3 array of point-like field emitters.


(a)
(b)
(c)
(d)
(e)
(f)
Silicon substrate
Insulator 1
Insulator 2
Photoresist
metal

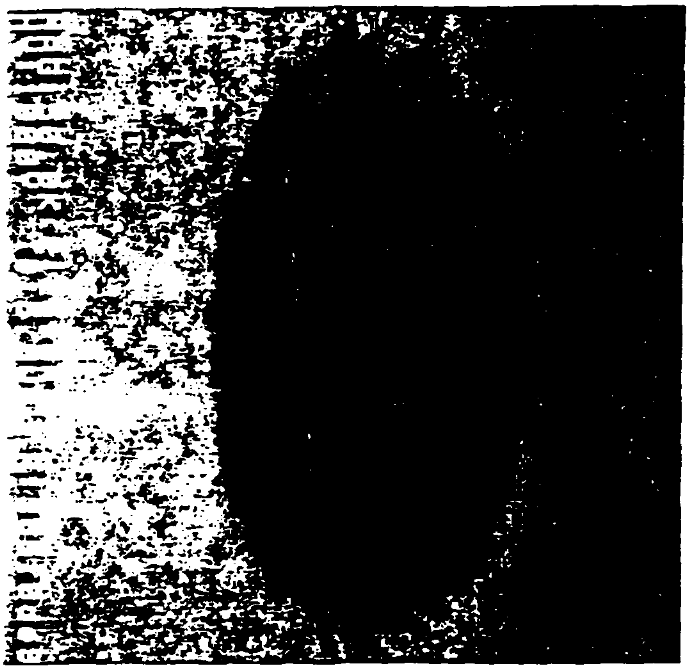


Fig 2(a)

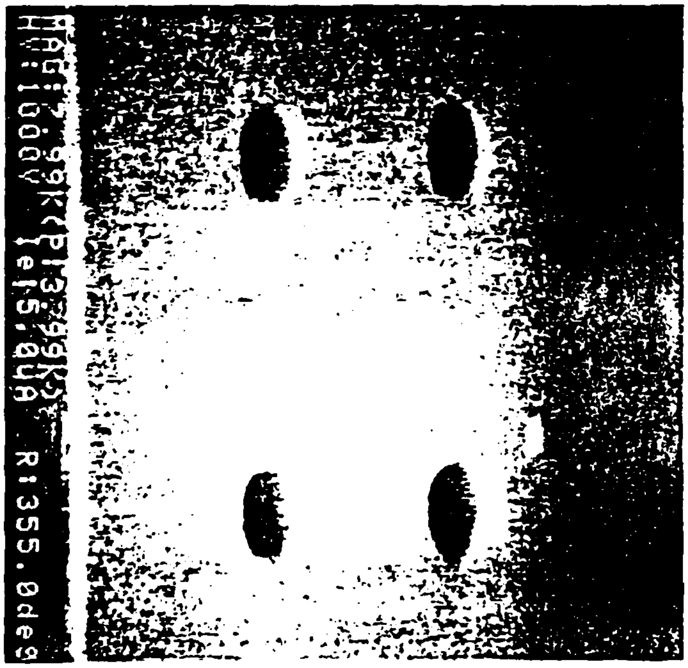


Fig 2(b)

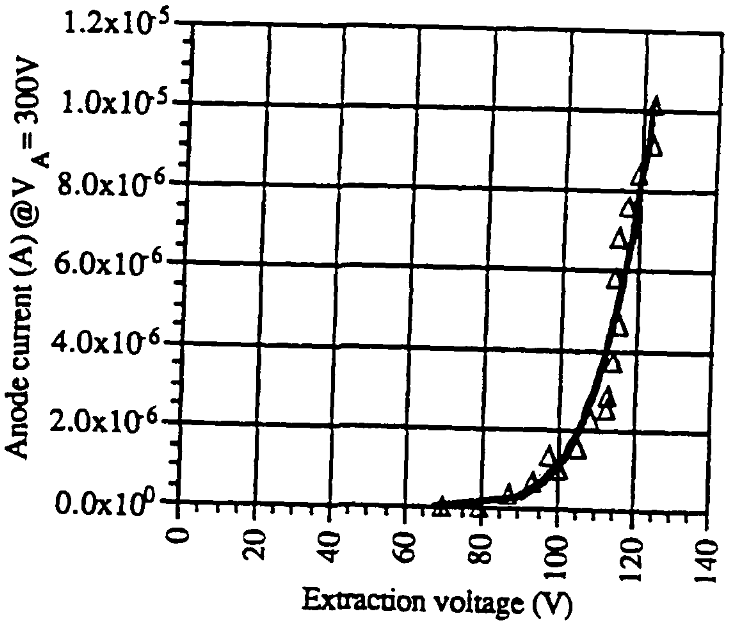

1.2x10-5
1.0x10-5
8.0x10-6
6.0x10-6
4.0x10-6
2.0x10-6
0.0x100
Anode current (A) @ V_A = 300V
0
20
40
60
80
100
120
140
Extraction voltage (V)

Fig. 3(a)

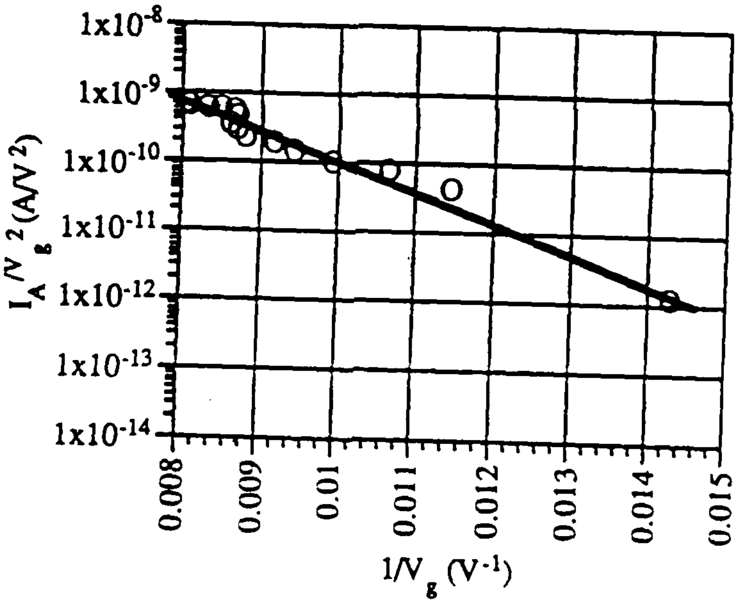
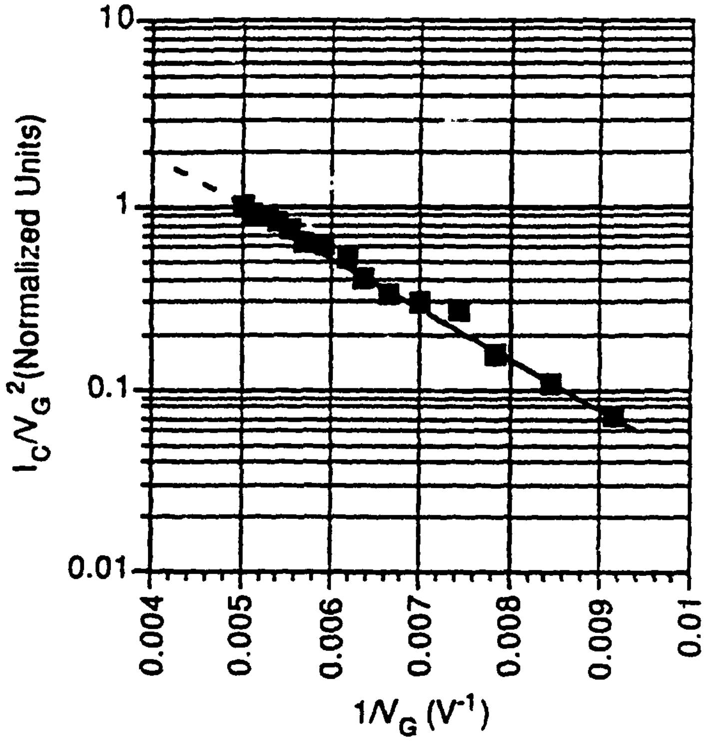

1x10-8
1x10-9
1x10-10
1x10-11
1x10-12
1x10-13
1x10-14
I_A/V_g^2 (A/V^2)
0.008
0.009
0.01
0.011
0.012
0.013
0.014
0.015
1/V_g (V-1)

Fig. 3(b)



10
1
0.1
0.01
$I_C/V_G{}^2$(Normalized Units)
0.004
0.005
0.006
0.007
0.008
0.009
0.01
$1/V_G$ (V^{-1})

Fig. 4