AFHRL-TR-75-59(VI)

AIR FORCE HUMAN RESOURCES LABORATORY

AD A022962

ADVANCED SIMULATION IN UNDERGRADUATE PILOT TRAINING: VISUAL DISPLAY DEVELOPMENT

By

Lawrence Nass
Farrand Optical Co., Inc.
Valhalla, New York 10595

Peter Seats
Thomas Electronics, Inc.
Wayne, New Jersey 07470

William B. Albery

ADVANCED SYSTEMS DIVISION
Wright-Patterson Air Force Base, Ohio 45433

December 1975
Final Report for Period March 1971 – October 1975

Approved for public release; distribution unlimited.

DDC
DEGEIVED
APR 14 1976
RESULTS
C

AIR FORCE SYSTEMS COMMAND
BROOKS AIR FORCE BASE, TEXAS 78235

NOTICE

When US Government drawings, specifications, or other data are used for any purpose other than a definitely related Government procurement operation, the Government thereby incurs no responsibility nor any obligation whatsoever, and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data is not to be regarded by implication or otherwise, as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

This final report was submitted by Singer-Simulation Products Division, Binghamton, New York 13902, under contract F33615-71-C-1255, project 1122, with Advanced Systems Division, Air Force Human Resources Laboratory (AFSC), Wright-Patterson Air Force Base, Ohio 45433. Mr William B. Albery, Simulation Techniques Branch, was the contract monitor and co-author.

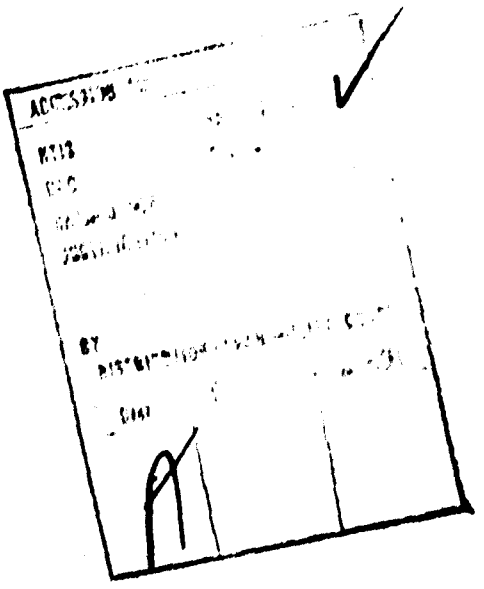
This report has been reviewed and cleared for open publication and/or public release by the appropriate Office of Information (OI) in accordance with AFR 190-17 and DoDD 5230.9. There is no objection to unlimited distribution of this report to the public at large, or by DDC to the National Technical Information Service (NTIS).

This technical report has been reviewed and is approved.

GORDON A. ECKSTRAND, Director
Advanced Systems Division

Approved for publication.

HAROLD E. FISCHER, Colonel, USAF
Commander



Unclassified

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: AFHRL-TR-75-59(II)	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): ADVANCED SIMULATION IN UNDERGRADUATE PILOT TRAINING: VISUAL DISPLAY DEVELOPMENT	5. TYPE OF REPORT & PERIOD COVERED: Final report. Mar 71 – Oct 75
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): Lawrence Nass, Peter Seats, William B. Albery	8. CONTRACT OR GRANT NUMBER(s): F33615-71-C-1255
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Singer-Simulation Products Division (SPD), Binghamton, New York 13902 (16) AF-1192	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 62[illegible] 1192[illegible] (17)
11. CONTROLLING OFFICE NAME AND ADDRESS: Hq Air Force Human Resources Laboratory (AFSC), Brooks Air Force Base Texas 78235	12. REPORT DATE: Dec 1975 (11)
	13. NUMBER OF PAGES: 122
14. MONITORING AGENCY NAME & ADDRESS *(if different from Controlling Office)*: Advanced Systems Division, Air Force Human Resources Laboratory, Wright-Patterson Air Force Base, Ohio 45433	15. SECURITY CLASS. *(of this report)*: Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

(12) 123p.

16. DISTRIBUTION STATEMENT *(of this Report)*

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

18. SUPPLEMENTARY NOTES

Mr. Nass, Farrand Optical, and Mr. Seats, Thomas Electronics, (subcontractors to Singer-Simulation Products Division) contributed to the writing of this report.

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

visual display	cathode ray tube
visual simulation	mosaicked visual channels
infinity optics	transmission efficiency
pancake window	birefringent package
dodecahedron structure	pentagonal channels

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

Visual simulation and its application to flying training is in its infancy. The development of the two visual display systems including the infinity optics, support structures, and 36-inch diameter (the world's largest) cathode ray tubes described in this report has already produced a worthwhile legacy to the state of the art of visual simulation.

The development of the visual display systems for the advanced simulator for undergraduate pilot training (ASUPT) is generally described as three separate efforts: (a) in-line infinity optics, or pancake window development, (b) dodecahedron structure development, and (c) cathode ray tube (CRT) development.

(Over)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

407 886

Item 20 Continued:

The genesis of all three of these efforts represents individual contributions to the state of the art. The pancake windows are the largest of their kind ever developed. The simulator for air-to-air combat employs similar windows, structures, and CRTs but the windows and CRTs are scaled-down versions of the ASUPT designs. The ASUPT visual display structures were tested under dynamic conditions on a motion platform in early 1972; the structural integrity of the dodecahedron design was verified. The CRTs represent, perhaps, the most important element of the ASUPT. For it is the remarkable development of these, the world's largest, hand-crafted TV tubes that not only paced the entire progress of the program, but also provided the ASUPT with its "eyes" and made it the valuable asset that it is today.

SUMMARY

PROBLEM

The advanced simulator for undergraduate pilot training is a research device designed for investigating the role of simulation in the future undergraduate pilot training (UPT) program. For ASUPT to be effective in training research, it must faithfully simulate all aspects of flight, including extra-cockpit visual cues and motion and force cues. Thus, the requirements for ASUPT are very demanding. This report describes the visual display system development including the pancake windows, display structures, and the world's largest cathode ray tubes.

The selection of the ASUPT visual display systems was based on the following key requirements: (a) student pilot field of view; ±120 degrees horizontal, minimum, +120, -40 degrees vertical, minimum, (b) sufficient display channel overlap to allow student pilot to view from all points within a 6-inch radius, forward-facing hemisphere, (c) 6 foot-lamberts minimum highlight brightness, and (d) brightness variation, optical contrast ratio, optical resolution, geometric distortion, linearity error, image discontinuity, collimation, and motion system effects requirements.

APPROACH

The approach to these requirements was one of developing a display system which was not only capable of meeting the optical and brightness

requirements, but also the motion system effects requirements. Whereas the ASUPT computer image generation system, described in Volume V, generated the actual visual simulation imagery, the visual display system was the medium for presentation of that imagery. The approach to developing the visual display system was based on the cockpit size of the T-37B and centered on the geometry of the regular dodecahedron, a solid having 12 equal regular pentagonal faces. The field of view requirements could be met by mosaicking 7 of the 12 sides of a dodecahedron with infinity optics, or pancake windows. The approach to providing 6 foot-lamberts highlight brightness was to develop a cathode ray tube of the magnitude to mate with a pancake window and the brightness to overcome the 100 to 1 reduction of transmission through the 1% efficient optics. The approach to satisfying the optical requirements was to use the best available materials in glass, cements, polaroids, beamsplitter mirrors, and optical coatings. The expertise in this country and England, as well, was tapped to gather together the best materials and techniques available.

RESULTS

The visual display systems were officially accepted in November 1974 after the delivery and installation of the last CRT. In general, the visual displays met all of the requirements. There were no major problems identified with the final visual systems including the performance of the CRT electronics. Transmission efficiencies of

the pancake windows proved to be 50% better than anticipated in some instances when the CRT/pancake window were tested in combination. The spectral response of the PT462 CRT phosphor excellently matched the spectral characteristics of the pancake window. This unanticipated bonus allowed the drive requirements of the CRT electronics to be relaxed which, in turn, significantly improved overall system resolution and tube life. Had a CRT been developed early enough in the program to test with a pancake window, significant savings in CRT electronics and tube design could have been achieved. Because of its hand-crafted nature, the CRT development started from theory and progressed on a vertical learning curve throughout a major portion of the program. The only adverse results of the visual display development are, perhaps, the six windows which have processing problems, and the two CRTs which have burn spots, scratches, or sleeks. The problems show up as regions of small bubbles in the birefringent packages or rings of depression in the case of the windows, and as holes or splotches where there are burn spots or sleeks in the case of the CRTs. One CRT has a long (18") scratch in the phosphor. In lieu of replacing these anomalies at a cost of perhaps $200,000 it was decided to locate these problem channels in "non-critical" locations since they all met their performance requirements. The six pancake windows were split up between the two visual displays and placed at the far left, top, and far right channel locations.

These problem windows were even rotated in their channels to provide the best portions of the optics to the pilot's immediate field of view. The best, aesthetically and performance-wise, windows were placed in the forward-looking channels (Figure 11).

CONCLUSIONS

The ASUPT visual display systems were developed, tested, and accepted during the time period of March 1971 to November 1974. In general, the visual displays met all of the system requirements. Released for research in January 1975, the ASUPT has already answered some of the questions researchers are asking about flying training. As of December 1975, many of the CRTs have over 2,000 hours of use and there have been no major problems with the displays during 1975.

PREFACE

This report is the 6th of seven volumes describing the Advanced Simulation in Undergraduate Pilot Training (ASUPT) system development program. The seven volumes of AFHRL-TR-75-59 are as follows:

Volume I: Advanced Simulation in Undergraduate Pilot Training: An Overview

Volume II: Advanced Simulation in Undergraduate Pilot Training: Motion System Development

Volume III: Advanced Simulation in Undergraduate Pilot Training: G-Seat Development

Volume IV: Advanced Simulation in Undergraduate Pilot Training: Automatic Instructional System

Volume V: Advanced Simulation in Undergraduate Pilot Training: Computer Image Generation

Volume VI: Advanced Simulation in Undergraduate Pilot Training: Visual Display Development

Volume VII: Advanced Simulation in Undergraduate Pilot Training: Systems Integration

This project derived from a DOD Directive to the three Services requesting programs of advanced development in the area of training and education. The purpose was to insure that military training and education make the fullest use of recent innovations and technological advances. In October 1967, a joint Air Training Command/Air Force Human Resources Laboratory effort culminated in a recommendation to establish an advanced simulation system at an undergraduate pilot training base. Hardware development of the ASUPT began in 1971 and the system was released for research in Jan 75.

All members of the ASUPT Program Office and participating organizations who worked on the program contributed to the final system. In addition to the listed contract monitors, they include Don Gum, ASUPT Program Manager, James Basinger, CIG Project Engineer, Israel Guterman, Basic Simulators Project Engineer, William Albery, Systems Integration Project Engineer, Patricia Knoop, Advanced Training Systems Project Engineer, Kenneth Block, Program Controller, and Virginia Lewis, Secretary, all of the Advanced Systems Division, Air Force Human Resources Laboratory, Wright-Patterson AFB OH; Warren Richeson, Capt Frank Bell III, Maj Ray Fuller, Capt John Fuller, Capt Dennis Way, Capt Steve Rust, Capt Mike Cyrus, and Mr. Glenn York, all from the Flying Training Division, Air Force Human Resources Laboratory, Williams AFB AZ.

TABLE OF CONTENTS

	Page
INTRODUCTION	8
GENERAL DESCRIPTION	9
DESIGN CONSIDERATIONS	11
Optical Design	11
Mechanical Design	17
Cathode Ray Tube Design	22
TEST ARTICLE	27
MANUFACTURE AND ASSEMBLY	30
Optical Components	30
Mechanical Structures	35
Assembly	37
Optical Assembly	37
Mechanical Assembly	39
Cathode Ray Tube	41
FIELD INSTALLATION AND INTEGRATION	52
Installation at Singer-SPD, N.Y.	52
Installation at General Electric, Fla.	53
Installation at Williams AFB, Az.	54
TESTS	55
Special Tests	55
Visual Display Maintenance Considerations	57
Final Test Data	59
APPENDIX A	72

LIST OF ILLUSTRATIONS

		Page
Fig. 1	Dodecahedron Support Structure	60
Fig. 2	36 Inch Cathode Ray Tube	61
Fig. 3	Decollimation vs Head Motion Curves	62
Fig. 4	ASUPT Design Collimation Curve	63
Fig. 5	ASUPT Design Mapping Curve	64
Fig. 6	Clearnace Study Mock-Up	65
Fig. 7	CRT Bulb Assembly at Corning	66
Fig. 8	Test Article Assembly	67
Fig. 9	Test Article Dynamic Testing	68
Fig. 10	ASUPT System with Maintenance Platforms	69
Fig. 11	Final Full ASUPT	70

ADVANCED SIMULATION IN UNDERGRADUATE PILOT TRAINING: VISUAL DISPLAY DEVELOPMENT

INTRODUCTION

Singer Simulation Products Division (SPD) was assigned the task of producing a T-37 training simulator for use in the Advanced Simulation for Undergraduate Pilot Training (ASUPT) program by the U.S.A.F. Human Resources Laboratory. This system will be used to investigate the role of simulation in undergraduate pilot training, therefore, simulation of the external visual scene is of particular importance. In order to conduct effective research on training methods and to provide for future needs of an imaginative experimental program, a highly realistic visual system is required.

Farrand Optical Co. (FOCI) was given the responsibility for designing, building, assembling, testing and installing the infinity display windows, the outer support structure and cathode ray tubes for two displays. This included the interfacing with the motion platform, the T-37 cockpit, and the CRT electronics. The Computer Image Generation equipment was not a part of this task; it is discussed in detail in Volume V[1] of this series of technical reports.

In order to evaluate the interface and structural design problems, provisions were made in the contract for the construction of a temporary wooden mock-up and a structural test article. The mock-up was a model of the complete assembly representing the inner surfaces of the window modules and the external envelope of the support structure. This was fitted over a mock-up of the aircraft cockpit provided by SPD in order to establish the optimum orientation of the visual display

so as to minimize the interference between the two units.

The structural test article was a full scale prototype support structure fitted with actual window frames in which the optical elements were replaced with aluminum plates of equivalent weight and center of gravity. The CRT and electronics were replaced by similar dummy weights. The entire test article was mounted on the Singer motion platform, equipped with strain gages, and subjected to dynamic testing as described later.

GENERAL DESCRIPTION

A visual system was required to provide real time images of the outside world for all phases of undergraduate pilot training and evaluation. This system would be installed around and operate with a T-37 aircraft cockpit and Singer Simulation Products Division six-degrees-of-freedom motion platform. Since the T-37 aircraft has side-by-side seating, the system would have to be large enough to accomodate the student pilot's and instructor's bodies. However, the specified optical performance of the system need only be achieved from the pilot's position. The visual system must also be capable of integration with the General Electric Co. provided Computer Image Generation system. Thus it would have to support and maintain in proper focus and alignment the Farrand supplied special 36 inch diameter cathode ray tube and that portion of the G.E. supplied electronics which must be mounted near or close to it. After

considerable study the dodecahedron was selected as the most suitable arrangement. The pentagonal facets are all the same allowing all the windows to be identical. This permits a mosaic of adjacent windows to be created with the smallest gaps. Furthermore, it minimized the number of channels required for a given field of view. In this case seven windows gives a field of view of ±150° horizontally and +75° -20° vertically in the plane of the forward line of sight. The seven window assembly forms an inner dodecahedron which is carried by an outer support structure. This support structure is an open tubular frame work in the form of a larger dodecahedron which surrounds the T-37 cockpit and is fastened directly to the motion base platform. See Fig. 1. At each apex of the structure, means is provided to center the inner assembly and to adjust the position of each window with respect to adjacent windows as well as longitudinally along their respective lines of sight. The outer support structure, Fig. 1, also incorporates provisions for mounting and adjusting the position of the CRT mounting plate. Swivel ended screws with lock nuts are fitted into angle brackets at the center of each tubular member to permit transverse positioning of the CRT with respect to the window optical axis. The cathode ray tube (CRT) Fig. 2 which provides the input to the infinity window, is a specially designed 36 inch diameter tube (the largest made to date) with a spherical

faceplate made to match the focal surface of the window. It has a unique phosphor formulated for highly efficient energy conversion thus giving high brightness in the spectral region where the infinity window has its best transmission. The CRT is discussed in detail later in this report.

The bulb is mounted in a conical housing which incorporates a mu-metal shield. The housing has an integral flange through which the combination mounting and adjusting studs pass. These studs, which have spherical washers at their upper ends, are locked to the CRT mounting plate, which in turn is fastened directly to the outer support structure. The studs are used to locate the CRT phosphor surface at the focal surface of the window.

DESIGN CONSIDERATIONS

OPTICAL DESIGN

The size of the visual display was dictated by the width of T-37 cockpit with its side-by-side seating arrangement. The structure had to be large enough to enclose the cockpit with the student pilot's head located at the nominal eyepoint. This was the lower limit. The upper limit was set by the size of the largest CRT which could be obtained to fill the window with sufficient image to provide some overlap so that no information would be lost when the pilot's head moved to the limits of the specified head motion. (Six inch radius forward facing hemisphere.) Consideration of these factors resulted in

selection of 48 inches as the optimum radius for the spherical beam splitter. This was based on using a 36 inch outside diameter CRT having a useful phosphor screen diameter of 34 inches.

Since the only active image forming element of the pancake window is the mirror surface, the performance characteristics can be determined by considering the optical properties of a 48 inch radius of curvature spherical mirror as used in this application.* If the mirror radius of curvature is 48 inches, the focal length is by definition half of that, or 24 inches. The radius of curvature of the display CRT faceplate is also 24 inches, and the eye position (nominal pilot eyepoint) is located at the center of curvature of the eyepiece mirror, 48 inches from the mirror. These dimensions take full advantage of the mirror's geometric properties as shown by the following discussion of the aberrations of a spherical mirror.

Spherical aberration is the failure of a bundle of rays parallel to the optical axis to come to a focus at a single point. Spherical aberration, the only aberration that exists by definition in the design, manifests itself by the pilot seeing a change in direction of the object as he moves his head. (See the discussion below on decollimation for a full treatment of these effects.) It is important to note that objects in this case cannot appear out of focus due to spherical aberration because the pilot's pupil diameter is only a small percentage of his head motion (the full pupil available). This is shown by a consideration of the f-number of the display, f-number defined as the ratio: $\frac{\text{Focal Length}}{\text{Aperture}}$. Since the pilot's head motion

* See the appendix for an explanation of the theory of operation of the pancake window.

is equivalent to the system aperture, the f-number = $\frac{24 \text{ inches}}{12 \text{ inches}}$ = 2.00 for $\pm$6 inches head motion. However, since the sharpness is determined only by the f-number associated with the pilot's eye, the f-number = $\frac{24 \text{ inches}}{.3 \text{ inches}}$ = 80.0 for an eye pupil diameter of .3 inches (7.6mm).

Coma and astigmatism are aberrations which prevent a bundle of rays parallel to a chief ray from coming to a focus at a single point. A chief ray is any ray (other than the optical axis) that passes through the pupil center (pilot eyepoint). Most optical systems degrade toward the edge of the field because of these aberrations. If a spherical mirror is used with the aperture stop (eyepoint) at the center of curvature, any chief ray can be considered the optical axis of the mirror because of geometric symmetry. Thus coma and astigmatism do not exist in this design. Indeed, because of the geometric symmetry, the optical properties by definition are identical for any field direction. This is most important when the overlapping fields of view of adjacent pancake windows are considered because aberrations at the field edges could cause image smearing, doubling, color changes and positional shift. If convergent decollimation results, a pilot might even become nauseated.

Color errors by definition do not exist because a mirror reflects all wavelengths in the same direction. This is particularly important

because the lateral color that can exist in refractive systems is the only aberration that can cause an image to smear or lose sharpness when viewed by the pilot. The high f-numbers associated with the pilot pupil size do not help here because lateral color would cause a given field point in the image to appear at different angles at the eyepoint depending upon wavelength.

Field curvature describes the departure of the image surface shape from a plane. The difference is evident as a defocussing in most optical systems but represents collimation errors in this application. Whereas the collimation change due to spherical aberration varies across the aperture (pupil), the collimation change due to field curvature varies across the field of view. The field curvature of a spherical mirror is the reciprocal of the image surface radius and is numerically equal to the focal length, in this case 24 inches. Because the CRT image surface has the same radius as the mirror focal surface, field curvature is eliminated by definition so that decollimation effects are a function only of pupil position and not of field position.

Distortion is a lack of correspondence of image shape and object shape, as for example, when a square object is imaged as a barrel or pin-cushion. A unique characteristic of a spherical mirror is that the center of curvature of the mirror is also the center of curvature of the focal surface. If the focal surface is viewed from its

center of curvature, it is clear that the arc length on the surface equals the focal length times the angle in radians; that is, the chordal height at the focal surface equals the focal length times the sine of the angle ($h = F \sin \theta$). Since θ is also the angle at the pilot's eyepoint, the above equation describes the relationship between the image point and field angle when no distortion exists. Since $h = F \sin \theta$ is the correct mapping function of the system, to the degree that the electro-optical chain meets this requirement, the entire system will also be distortion free.

As shown above, the pancake window is essentially free of all aberrations except spherical aberration, which manifests itself as an object exhibiting decollimation or apparent direction change as the pilot moves his head laterally. These motion effects can be evaluated by the following criteria:

1. What is the absolute error in direction as a function of head motion?

2. What happens to the apparent object distance seen with both eyes? Does the object appear closer or further than infinity? Focus is the one system variable that is available for trade-off and optimization of these factors. When the CRT is moved along the optical axis (focused) it has the effect of adding a general divergence or convergence to all of the rays. Divergence is defined as light diverging as it approaches the observer, and convergent light converges at the observer. Divergence corresponds to an

observer using two eyes to view an object closer than infinity and convergence corresponds to viewing an object further than infinity. Any convergence will cause the eyes to diverge in an attempt to fuse the images, resulting in eyestrain or even nausea. If the convergence is large, the image will double. It is obvious then, that convergence should be minimized and avoided if at all possible, especially for central head locations.

Figure 3 illustrates the changes in collimation with focusing. Curve 1 of Figure 3 (marked paraxial) shows the normal undercorrected spherical aberration curve for the nominal (paraxial) focus location. Criterion Number 1, absolute error, can be read off directly as angular error in milliradians versus head motion. Criterion Number 2, convergence or divergence, must be evaluated by comparing the angular error between any two pupil points corresponding to the interocular separation (2-1/2 inches). For example, at the 6 inch pupil point for the paraxial curve, the ray converges toward the eye by 2 milliradians while at the 3-1/2 inch pupil point the value is 4.8 milliradians convergent. Subtracting the 3-1/2 inch value from the 6 inch value, the net effect is 1.6 mils convergence, or 5.5 arc minutes. Other curves on the graph illustrate the improvement in both criteria as the CRT is focused toward the pancake window, allowing a trade-off to be made between absolute error, convergence and divergence, and head motion. Curve Number 4 depicts the case

for zero convergence.

The actual pancake window contains finite thicknesses. The spherical mirror/beamsplitter is approximately one inch thick. Therefore an optical degree of freedom is the second surface of the mirror. This surface is manipulated, within limits, to effect correction of the off-axis meridional rays, which are important in the area of points. In addition, during fabrication of these mirrors, the second surface is left adjustable until the finished ground radius of the mirror is ascertained. Then the second radius is optimized through ray tracing analysis. The nominal ASUPT collimation and mapping are displayed in Figures 4 and 5.

Since the pancake window in effect places the pilot eyepoint at the center of curvature of the CRT faceplate, correct mapping is assured when $h_1 = R \sin \theta$ where h_1 is the chordal height on the CRT phosphor surface, R is the radius of the CRT phosphor surface and is the real world field angle at the pilot eyepoint. In addition, each CRT has provision for magnification adjustment to compensate for small changes in focal length due to fabrication tolerance in the spherical mirror/beamsplitter.

MECHANICAL DESIGN

The basic requirement for the pancake window frame is to support the optical elements firmly and accurately in their predetermined positions, while avoiding the imposition of strains due to the linear and

angular accelerations of the motion system. This is a prime consideration since the first and last elements contain polarizing materials which exhibit undesirable colors when strained. This requirement was met by designing a pentagonal steel structure having a modified box section arranged for minimum deflection under load. The birefringent assembly and the spherical mirror are hard mounted to the frame and located by individually fitted retainers. The loads are carried on the large flat edges of the glass elements with care taken to provide clearance at the points.

The linear polarizer is a circular element carried in a separate housing bolted to the rear of the main window frame. This arrangement permits adjustment of the polarizing axis to achieve optimum performance. Provisions are also incorporated to adjust and maintain uniform clamping pressure to avoid the introduction of color fringing. The outer support structure was designed to carry the inner assembly of pancake windows with a minimum transfer of loads to the window frames. It consists of an open tubular dodecahedral frame bolted directly to the top of the motion platform. At each apex, the three tubes are joined in a three part aluminum forged joint into which they are clamped and doweled. This results in an extremely rigid structure. Through each joint assembly, there is provided a heavy threaded stud which passes through thick retaining plates and is held in place by inner and outer nuts. The inner end of the stud carries a large ball joint,

the cap of which is arranged to carry the corner brackets of three adjacent windows. The center lines of all the studs intersect at the geometric center of the structure. Therefore the adjustment of the studs makes it possible to accurately center the assembly of windows within the outer support structure. The balls permit the windows to be aligned with respect to each other. The adjusting screws permit movement of the individual windows along their respective optical axes to vary the space between windows as well as to tilt them so that the optical axes pass through the geometric center of the support structure. The attitude and mounting of the support structure was determined by the size and shape of the cockpit structure, the wind screen and canopy, clearance requirements for ingress and egress, and the location of motion platform structural members. Joint studies by SPD and FOCI resulted in a position achieved by yawing left 20°, pitching upward 35° and rolling left 15° in that order about the eyepoint. In addition, it was necessary to cut off the lower portion of the No. 5 (R.H. front) window and modifying the support structure accordingly. This attitude also brought the lower corner of the No. 4 (L.H. front) window close to the motion platform, requiring further structure modification. Since the clearances between the visual display and the cockpit were so close, a wooden full scale mock-up (Fig. 6) of the structure and the windows was constructed. This was installed

over a mock-up of the cockpit. A joint HRL, SPD and FOCI design review was conducted and the final attitude and clearance were established. This formed the basis for the final configuration of the visual system. See Fig. 9, for example.

The primary purpose of the mechanical structure is to support the optical elements in proper alignment during dynamic operation of the motion base and still subject them to as little strain as possible. Therefore, it was necessary to design for minimum deflection rather than to a selected value of stress or safety factor. This suggested the utilization of steel members rather than aluminum to take advantage of the higher modulus of elasticity. Since it was also necessary to limit the weight of the display in order not to exceed the capacity of the motion system, an efficient design was required. Since the analysis of the loads and deflections of the total support structure-window-module assembly represented a large and complex problem, it was evident that it could only be done in a reasonable time by utilization of a high speed computer. Accordingly an investigation disclosed that the "Structural Engineering System Solver" program (STRESS) for the IBM 1130 computer was suitable. The use of this program made it possible to determine the axial and shear loads and moments in each member as well as the displacement of every joint, for any loading condition or combination of loading

conditions. The applied loads and the physical properties of each member were calculated manually and were inserted by means of punched cards, thus it was relatively easy (but time consuming) to change member sizes, wall thicknesses and/or materials in order to optimize the design. The basic applied loads were calculated with the display static on a horizontal motion base. These were established by distributing the weight of the structural members, the window modules, and the CRT assemblies to the joints which supported them. Additional sets of applied loads were calculated for the inertial forces generated by the maximum accelerations encountered during the linear and rotational motions of the motion system. These loads were then combined to represent the worst conditions which could be encountered during actual motion base operations. The resulting computer print-outs were examined to find the worst loads imposed on individual members and the maximum joint displacements. The corresponding stresses and deflections were calculated and member sizes or physical properties were adjusted in order to achieve the most desirable overall structure.

The above described method resulted in a support structure consisting of 5 inch O.D. steel tubing with a wall thickness of 1/4 inch, supported by legs of 7 inch diameter aluminum tubing with a wall thickness of 1/2 inch. The apex joints are three aluminum

forgings bolted and machined together. The radial struts which carry the window modules are high strength steel 1 1/4 inches in diameter. The complete outer support structure weighs 3100 pounds and supports a total load of 7900 pounds.

CATHODE RAY TUBE DESIGN

The responsibility for the design, development production and testing of the 36 inch diameter cathode ray tube was given to Thomas Electronics, Inc. (TEI) of Wayne, N.J.

The development of 36" diameter CRTs for the ASUPT program required the solutions to many unique problems. The envelopement requirement above for the 34" useful screen faceplate put it outside the technology of any established production technique. No one has ever attempted to fabricate a CRT of such magnitude and power requirements. In addition to the envelope problems created by the size which, in turn, posed unique problems of safety in tube processing, the faceplate also interfaced with an optical system and presented critical tolerance problems with respect to glass quality and radius. The power in the electron beam required to produce the brightness level over such a large screen raised unprecedented electron design questions. Finally, the application of internal coatings and the vacuum processing of the tube raised questions concerning the applicability of established techniques.

Due to these primarily and many associated design questions, a study program was performed to investigate design and performance feasibility. Following the completion of this study phase which successfully predicted the practicality of building tubes which met the required performance criteria, procurement of materials and equipment was initiated and the first production prototype was completed. Completion of the prototype lead to the final confirmation of production specifications and a total of 14 production tubes were built and shipped over a 1 1/2 year period including the reworking of the original prototype.

The copy of the Final Technical Report covering the initial design study under Contract #036-H59002-61329 is in Appendix A. In brief, the study was successful in establishing the feasibility of achieving the required brightness level of 1000 ft. lamberts at the ASUPT writing rate of 1.6 million inches/sec at a 6 milli-ampere beam current and 38,000 volts acceleration level. In view of the risks involved in extrapolation of conventional analytical design data, it was considered necessary to construct a special CRT in the study phase which essentially duplicated the mechanical and deflection parameters of the ASUPT tube. By specific operation of this experimental tube with respect to the essential requirements of the electron optics as well as with respect to magnetic coil designs, data was obtained which provided a very firm basis for predicting

ultimate performance. The study also considered various alternatives in envelope design including a metal funnel approach as well as that of a fully sagged, or concave, envelope comprising a hemispherical funnel and faceplate combination. The choice of an optimum phosphor screen was considered and finally a brief life test study was conducted to confirm that the operational requirements of ASUPT CRTs would not result in excessively short tube life.

However, it was necessary to continue certain developmental activities following the successful completion of the design study and these engineering activities continued through the materials and equipment procurement phase. The additional engineering developments which followed the design study included:

1. Completion of the envelope investigations leading to the decision to employ an all-glass approach which consisted of a two-part glass funnel produced by Corning Glass Wo·ks, Corning, N.Y. (see Fig. 7); a sagged non-browning glass faceplate produced by United Lens; and a custom 1.9" diameter neck and yoke reference area. This latter design requirement was the result of deflection and focus coil studies performed by Syntronic Instruments, the subcontractor for magnetic components. It was further decided that the funnel of the CRT should be bonded to a metal housing which incorporated mumetal shielding and forward and rear flanges for optical and magnetic coil alignment.

2. Electron Gun:

In order to provide maximum possible tube life, it was decided to incorporate a dispenser cathode in the CRT if this were feasible. A program of investigation of available cathodes was conducted and the successful adoption of a Metalonix type cathode was achieved. The use of a dispenser cathode, which incorporates a very large reservoir of available barium for continuation of the emission process, resulted in a small increase in filament power but virtually no other adverse trade-offs were involved. Associated with the life of the tube from the cathode standpoint, it was also realized that outgassing of internal phosphor surfaces caused by the high energy beam would most probably shorten tube life if special precautions were not taken. Accordingly, life tests were conducted in order to investigate the optimum getter yields. Consideration was also given to the high voltage gradient isolation in the gun which was accomplished through the use of a large diameter metal flange placed above the low voltage triode region. It was further considered necessary in the gun design to provide means for independently varying the divergence angle of the beam through the focus and deflection fields in order to provide for optimum center-to-edge spot size uniformity. Without this prefocus control, the operation of the tube and the inherent variations that would be present from tube to tube would present many difficult alignment problems. Finally, a design effort was also conducted with a goal of reducing the grid swing

required for the video amplifier. A series of high transconductance guns were designed and tested but although it was found that peak video voltage could be reduced by a factor of at least 10 with such guns, the penalty of spot size increase was too severe for acceptance.

A further refinement in the performance of the gun involved the solution of a difficult video problem associated with the motion of the CRT beam crossover with drive. In view of the very wide dynamic range of the ASUPT CRT, the beam cannot remain in focus over the entire video swing and the implication was that video modulation of focus would be required. This is a difficult and expensive thing to do. By analysis however, it was shown that an introduction of a field shaping element just above the beam crossover location will provide essentially automatic compensation. Such an element was constructed and was found to be effective. This improvement was then incorporated in all ASUPT electron guns.

3. Phosphor Screen:

The original design study suggested the use of narrow band, rare earth phosphors which might assist in solving certain ghost* emission problems inherent in the associated optical system. However, the conversion efficiency of such phosphors is significantly lower than highly optimized phosphors in the sulphide family similar to P31 and P22G. Accordingly, an investigation was made to obtain a

* See discussion of optical ghosts in appendix.

highly efficient green television phosphor whose output peaked at the maximum transmission for the optical system. A most suitable phosphor was located in England, and evaluated, designated PT462; throughout the program, phosphor efficiencies in the 50-60 lumen per watt range have been attained with this material despite the extremely high beam currents employed in the ASUPT tube.

TEST ARTICLE

Since the outer support structure and related window module assembly make up a complex, indeterminate structure, the accuracy of the load and stress analysis could not be evaluated. Furthermore, the maximum accelerations which might be encountered during emergency stop conditions were unknown. The physical strength characteristics of the laminated birefringent optical assembly also were unknown. Since the student and instructor pilots are both surrounded by these large glass elements, it was deemed advisable in the interest of safety to test a full size prototype display assembly fitted with simulated optical elements and simulated loads representing the CRT's and electronic models under real and extreme operating conditions. Accordingly, the first support structure was designated the test article. A full complement of window frames was also fabricated. These were fitted with aluminum plates having the same weight as the optical elements they represent and installed so as to have their

centers of gravity in the proper locations. The CRTs and CRT electronic modules were also replaced by dummy loads. The test article was assembled on the motion system at Singer-SPD Binghamton, N.Y. and prepared for dynamic testing.

Brewer Engineering Labs, Inc. of Marion, Mass. was engaged to conduct a dynamic strain gage analysis of the visual display under the supervision of FOCI personnel. Brewer Engineering Labs supplied the labor, material and instrumentation to measure and record the strains occurring during the six modes of linear and angular motion and six modes of buffet or vibration. An examination of computer stress analysis was made to determine the points of highest loading. A total of 103 strain gages were installed on nine tubes, four radial studs, six legs, eight triple joints and seven window frames. Accelerometers were also installed on the motion base to measure acceleration about all axes. These were all recorded during every test run in the event that unwanted components about other axes were encountered. See Fig. 8. After installation of all the strain gages, wiring and recording equipment, the dynamic tests were run on February 24 and 25, 1972. See Fig. 9. The motion system was operated by Singer personnel manually (rather than by computer control). The acceleration tests about each axis was performed in three or four increments up to the maximum specified value. Each test was run

twice in each direction to insure against loss of data. The details of strain gage installation, recording instrumentation and test results are given in Brewer Engineering Labs Report[2] No. 478 dated May 5, 1972. After examination of test results it was decided that additional testing be performed to evaluate the effects of simultaneous acceleration about two axes, and accelerations starting from attitudes other than horizontal. In addition, it was desired to investigate the effect on the birefringent assembly being hit by a large piece of spherical beamsplitter in the event that it fractured. Accordingly a weight of 100 pounds was attached to the plate simulating the birefringent sandwich and strain gages were attached to the plate. The acceleration tests were run and the data recorded on March 21, 1972. The test method details and test results are contained in the Supplement dated June 14, to Brewer Engineering Labs Report 478.

In summary, the results of the dynamic testing confirmed that the computed factors of safety were conservative. The lowest factor of safety under one axis acceleration test was 13.9 during yaw. The lowest factor of safety under combined acceleration about two axes was 8.9 during combined roll and pitch. The highest strain recorded on the simulated birefringent assembly occurred during vertical heave of 2.27 g. When extrapolated to the maximum of 4.3 g this resulted in a factor of safety of 3.9 based on a modulus of rupture of 6500

p.s.i. for polished plate glass. Since the actual birefringent is a seven layer laminated sandwich, the true factor of safety will be significantly high.

The above conclusions were subsequently confirmed when the first windows containing the real optics were installed. The motion system was operated manually with accelerations increased to a maximum by simulating an emergency power failure. A careful examination revealed no damage or any signs of strain. The two deliverable systems were subsequently assembled and put into full operation with no incident.

MANUFACTURE AND ASSEMBLY

OPTICAL COMPONENTS

The manufacture of the optical components required the solution of a unique set of problems due to the large size of parts, the precision required and the light polarizing processes involved. For instance any residual strain in any sheet of glass would produce undesirable colors in the finished product.

The spherical beamsplitters part No. 138279 required blanks of 60 inches in diameter and 1 25 inches thick. Since these are used in transmission as well as reflection the blanks had to be free of visible defects. Suitable material was not available in the U.S. and was finally procured in England.

The first operation to produce the desired shape was to sag

the blanks to the proper radius of curvature. This task was given to United Lens Co. in Sturbridge, Mass. who has ovens of the required size. However, special molds had to be designed and built, and heating and annealing cycles had to be developed. A number of blanks were lost during the testing of the molds and the annealing cycle. Since these problems had been anticipated a sufficient number of blanks had been procured. The length of the annealing cycle to remove all strains as finally adopted turned out to be one of the pacing processes of the program.

Since the sagging operation results in the blank changing thickness, the original blanks as procured had to be much thicker than the finished dimension. The removal of this excess material before grinding and polishing necessitated the design and construction of special curve generators. Two such units were required in order to meet the program schedule requirements. One was used for the concave side and the other for the convex side. This work was assigned to the Delta Development Corp. of Nyack, N.Y. who are specialists in these operations. The same firm also performed the grinding and polishing operations which also required special rotary tables because of the size and weight of these pieces. This equipment was designed and built and was successfully used throughout the program.

The last shaping operation was to cut these beamsplitters to the required pentagonal shape. These cuts had to be made at 31°-43'

to conform to the frame angle. They also required extreme precision so that the dynamic loads would be evenly distributed on the bearing surfaces. This task was also delegated to Delta Development who set up special diamond impregnated saws for this purpose.

The last operation needed to complete the spherical beamsplitter was the application of the reflecting coating on the concave side and the anti-reflection coating on the convex side. No vacuum facilities large enough to evaporate these coatings were available. Since the performance of these coatings are crucial to the proper performance of the pancake window, the Optical Coating Labs. Inc. of Santa Rosa, Calif. was authorized under a subcontract to install and/or modify the vacuum chambers and heating ovens required for applying these coatings. O.C.L.I. has the proprietory rights to the HEA anti-reflection coating which was applied to a number of surfaces of various optical elements to reduce the brightness of unwanted ghost images to minimum levels.

The birefringent package, Part No. 139912 was the most difficult element to make. This consists of several layers of glass plates laminated with sheets of polaroid and quarter wave retarders. The angular alignment of the various elements is critical. The problem was compounded by the fact that the glass parts were 58.75 inches in diameter but the maximum width of the polaroid available was only 18

inches; the maximum width of the quarter wave material was only 28 inches. Thus three pieces of polaroid had to be joined and two pieces of quarter wave plate had to be joined. The lack of materials of adequate size made it necessary to carefully match adjoining pieces both for color uniformity and angle of retardation. This problem was greatly complicated by the fact that both materials were not usable out to the edges because of non-uniformity and had to be slit to remove the edges. The slitting process was very difficult since ordinary cutting produced residual strains in the material which resulted in undesirable color fringing. An air-abrasive cutting process was devised to overcome this problem.

The situation involving the quarter wave material was even more difficult because it is supplied in very large rolls of several thousand feet long and is only a few thousandths of an inch thick. Its angle of retardation varied considerably across its width as well as its length. This made it necessary to set up large rewinding facilities and instrumentation for analyzing retardation as well as light tables to inspect for defects. Thus the process of selecting sections for correct matching was difficult and time consuming. After complete sets of materials were selected they had to be cemented into a final assembly. This had to be done in two operations because of the difficulty of maintaining angular alignment between the quarter wave retarder

and the polaroid sheets while at the same time attempting to avoid gaps between adjacent sections. The relatively high viscosity of the optical cement and the large areas involved made it extremely difficult to eliminate entrapped air bubbles. Elaborate positioning fixtures which permitted control of each section were developed. These were extremely difficult to use because the materials tended to float in the cement until it started to set. Various clamping techniques were evolved during the program until a satisfactory method was arrived at. While some of the first assemblies made were not entirely satisfactory, the later ones were much improved and quite good.

The finished birefringent assembly also required precision cutting to pentagonal shape to accurately fit the frame. This cutting presented a new problem since it was feared that the plastic layers would clog the diamond saws required to cut the glass. After considerable experimentation and consultation with the saw manufacturers, a satisfactory method was developed which resulted in clean, precise cuts with no chipping or flaking of the glass.

The last element of the pancake window is the linear polarizer part No. 139915. This consists of a set of polaroid sheets sandwiched between two pieces of glass coated with HEA anti-reflection coating on the outer surfaces. This part was somewhat easier to fabricate since it is only 48" in diameter and only three pieces of polaroid

had to be matched and positioned during cementing. This part remained circular to facilitate alignment of the axis of polarization.

MECHANICAL STRUCTURES

WINDOW FRAMES

The fabrication of the window frames part No. 139905 was particularly difficult because of the tight requirements for precision and straightness on a complex, heavy weldment. The basic frame member is cut from a 10x4x3/16 wall, steel structural tube with a piece of 1/8 inch thick, high strength steel plate welded across the cut opening to carry the glass elements. An elaborate welding fixture was developed to position all the component parts in proper relationship and a welding schedule was designed to control distortion. The inner and outer stiffening braces at each apex were bolted on to avoid deforming the critical frame angles. All through the fabricating process and final inspection every frame was checked by fitting in guage plate part No. 139929-A. The entire task of fabricating the 16 window frames was entrusted to Skyline Products, Inc. of Deer Park, New York.

OUTER SUPPORT STRUCTURE

The fabrication of the components of the outer support structure part No. 141200 was carefully controlled to insure easy and accurate assembly in spite of all the compound angles involved. The pipe struts

part No. 139907 were ordered as drawn-over-mandrel tubing in order to get the best straightness and smallest tolerance on out-of-roundness. Both ends were then turned to provide concentricity and proper fit in the forged yokes. The yokes are aluminum forgings which were faced and drilled and then bolted together in sets of three with suitable spacers. These sets were numbered and always kept together for final boring of the strut sockets and the stud seats. These operations required extensive tooling to provide the accuracy required for complete interchangeability. After installation of the ball stud and associated parts this became the joint assembly part No. 141150. The most difficult components of the support structure to fabricate were the joint assemblies on top of the legs due to the complex angles. Each joint has different angles due to the nature of the dodecahedron geometry and the asymetric orientation of the structure. See Fig. 1. These joints consist of a yoke forging welded to an adapter to support it in the position. Spacers were provided between the joint assemblies and leg weldments in the event a leg had to be shortened or an angle had to be adjusted. None of the changes proved to be necessary. This task was done by National Welding and Manufacturing Co. of Newington, Conn.

The last major component required was the CRT mounting plate, part No. 139906. This is a pentagonal piece with each apex joggled

and bored and drilled to support the 36 inch CRT at the proper focal plane of the pancake window. The fabrication of these plates presented considerable difficulties to Skyline Products, Inc. in keeping the bent sections in the same plane within the specified tolerance.

ASSEMBLY

OPTICAL ASSEMBLY

The installation of the optical components into the window frame required the precise fitting of each part to assure uniform bearing on all sides. It further required that both the birefringent assembly and the spherical beamsplitter be aligned so that the optical axis was square to the frame mounting surfaces. The shape of the frame weldment made it necessary to install the birefringement assembly part No. 139912 first. This was done with the frame suspended with the small face down. It was found that resting the frame on any support introduced enough distortion to affect the fit. With the birefringent assembly in place, the fit at each apex was checked for uniform clearance to avoid chipping or flaking the glass. After the birefringent was properly set in the frame, the retainers part No. 139897 were individually fitted and clamped in place while the holes for the mounting screws were transferred from the holes in the frame. The retainers were then

removed and the holes tapped. The retainers were then reinstalled and the clamping screws were removed.

The installation of the spherical mirror part No. 138272, was particularly difficult because the birefringent sandwich precluded access to the front of the frame to guide it over the mirror. The method finally used involved the use of a stand fitted with a hydraulic jack and a heavily padded table to carry the mirror which was carefully leveled. The frame with the birefringent sandwich in place was suspended from a hoist, face up and also carefully leveled. The frame was then slowly lowered over the mirror while being guided to keep it centered until it was within one inch of the edges. The hoist was then secured and the mirror jacked up until it was snugly in place. While in this position the retainers were individually fitted, and installed to secure the mirror in its final location.

The last item to be installed was the linear polarizer, part No. 139915.. This was lightly clamped by the retainer to permit rotation of the polarizer to correct alignment with the birefringent sandwich. After completion of the alignment, the retainer screws were carefully tightened while observing the window with diffused light to detect unwanted color fringing in the event the polarizer was strained. In this case the retainer was shimmed with corkprene.

MECHANICAL ASSEMBLY

All three outer support structures, part No. 141200 were shop assembled in order to check the fit and alignment of all parts and to locate the holes for dowels which lock the tubes into the joint forgings. In order to provide a flat and level surface to simulate the top of the motion platform, a floor made up of two layers of crossed sheets of plywood bolted together was prepared. Pads of several layers of plywood were screwed on to provide the proper elevations for the legs. This floor was then leveled on the shop floor using shims and a surveyors optical level. The eyepoint and locations of the legs were laid out on the wooden floor using steel tapes and squares. Since the bolt hole pattern and orientation of each leg was different, sets of coordinates were computed to insure proper location of every base plate. This data is given on Dwg. No 139936 along with the height of each leg. The legs were mounted on the floor and the heights were determined by using a theodolite. Adjustments were made by shimming where required. The structure erection continued with the mounting of joint assemblies on the legs using the nominal 1/2 inch thick spacers. The pipe struts and joints for the first tier were put in place and loosely clamped. The joints were accurately spaced and the tubes located longitudinally and angularly by the use of a set of gages adjusted to the nominal drawing dimensions. This

process was continued until the entire structure was completed by closing the last joint. All the joint spacings and strut locations were rechecked, and the clamping bolts on the yokes were tightened to the specified torque value to hold the pipe struts. A portable drill was fitted with a special clamping fixture to position it on the forged yokes to drill the pilot holes for the 3/4 inch diameter high tensile shoulder bolts. These holes were then reamed for a push fit with the bolts. The bolts and nuts were then installed to lock the structure. After installation of the ball end screws and associated parts, a set of empty window frames was put in place to check the fit. The first assembly was designated the test article so the window frames were fitted with the metal dummy optical components. After inspection by Singer-SPD representatives, the whole unit was dismantled and shipped to Singer-Binghamton.

The procedure outlined above was repeated with the following two support structures. The second unit was fitted with a full complement of deliverable pancake windows. Plastic screens were installed in place of the CRTs and the optical tests were performed. The third support structure was completely assembled, less windows, and after inspection it was dismantled and stored until required for installation at the using facility. The pancake windows for the second system were delivered to General Electric Co., Daytona Beach,

Florida to be installed in support structure No. 1 which was shipped after completion of the dynamic stress testing.

CATHODE RAY TUBE MANUFACTURE AND ASSEMBLY

Following the decision to proceed with an all-glass CRT envelope resulting from the preliminary design studies, and while further detailed CRT design studies were being conducted and a CRT processing facility was being established, procurement of the CRT envelope was initiated with Corning Glass Works having the primary responsibility of designing a glass CRT funnel which, after sealing to a sagged faceplate, would be capable of being processed into a finished CRT.

The production of the CRT envelopes involved a complex sequence of steps performed by Schott, Penn Optical, United Lens, Corning Glass and Optical Coating Labs. The steps performed were essentially in sequence and consequently difficult management problems were presented in maintaining schedule conformance due to the successive slippages resulting from difficulties in any preceding step. Jenaer Glaswerk Schott in Duryea, Pa. was the contractor for melting boules, or large blocks of glass, in non-browning glass. After annealing, the boules were sliced into large discs for delivery to the grinding and polishing subcontractor. The technique for slicing the glass discs involved the use of a diamond loaded fine wire some one mile

in length looped throughout the complex of buildings. This wire length was necessary in order to prevent premature reduction of cutting efficiency due to the loss of abrasive.

After disc production, the ground surfaces were polished by Penn Optical, Reading, Pa. and the discs then forwarded to United Lens, Southbridge, Mass., which performed the faceplate sagging step. Wherever possible, the CRT faceplate was sagged together with a second glass disc of thinner glass which comprised the implosion plate. This item was obtained from conventional glass plate sources and after sagging was dispatched to OCLI in Santa Rosa, Calif. for the application of a highly efficient anti-reflective coating.

In the meantime, the sagged faceplate was dispatched again to Penn Optical for a second grinding and polishing operation. Following this step, the faceplate was delivered to Corning Glass Works, Corning, New York.

At Corning the CRT funnel was produced by a combination of pouring and spinning using equipment and techniques developed for the production of missile nosecones. Following the production of the major funnel portion by this technique, a second specially tooled, conical section was then sealed to the minor diameter of the main funnel. This funnel subassembly was then delivered to the frit

sealing department of Corning where the sagged and ground and polished faceplate was ground to match the flange on the major diameter of the funnel and the two ground surfaces frit sealed in a special kiln. Following successful sealing and annealing, the completed assembly in this form was delivered to Thomas Electronics in Wayne, N. J. Specification and procurement of the metal housing for the CRT bulb proceeded essentially without developmental problems.

Early in the design study phase of the program, it was apparent that the processing steps in tube manufacture would present unique processing problems. In the first place, the weight of the CRT bulb, approximately 160 lbs., obviously made it impossible to hand carry the tube from station to station as with conventional tubes. It was therefore concluded that it would be necessary to have a portable hoist which could convey the tube through the various processing stations and to devise special supports over the processing stations to safely hold the CRT funnel. The processing steps involved are as follows:

1. Acid wash and water rinse after Quality Control inspection
2. Dry, place in special holding ring, and apply graphite conducting coatings across frit seal at faceplate/funnel
3. Bake at 420° C.
4. Apply phosphor screen
5. Decant and dry
6. Rewet screen, apply lacquer solution, rinse bulb walls and dry

7. Apply graphite wall coating to funnel and anode; dry
8. Aluminize
9. Screen bake in air at 420° C.
10. Remove original neck and splice new neck prior to gun seal
11. Gun seal
12. Exhaust including electrical gun processing and tip-off
13. Cathode aged and getter flashed
14. Pretest
15. Encapsulation - implosion plate housing, anode lead and flying base leads
16. Final test
17. ATP and ship.

The first approach to the transportation problem was to consider the use of a hoist and overhead rail. For flexibility however, it was considered more suitable to employ a wheeled vehicle and the selection of a battery powered hydraulic hoist was finally made. At first it was suggested that the CRT bulb be moved from station to station and left at each position until the processing sequence was complete. It was quickly found much more suitable however to permanently secure the CRT bulb to a platform on the hoist and adapt the platform to rotate, rilt and perform all other maneuvers while remaining attached to the hoist, rather than to frequently remove and reattach the bulb.

Through the use of the holding ring, the CRT remains attached to the hoist throughout all processing steps prior to screen bake. The concept was particularly effective during the aluminization step where the tube is placed under high vacuum for the first time. This is the first step involving the substantial implosion hazard and although guards were employed around the CRT envelope during this step, the face that the tube was constrained in a holding ring provided substantial added protection. The two most hazardous steps were however:

1. The removal of the evacuated bulb from the exhaust oven.

2. Removal of safety guards from the CRT prior to encapsulation.

During these steps, technicians who were required to handle the bulb wore heavy duty safety helmets and leather crash suits.

By February 1972, the first sagged faceplate had been frit sealed to a glass funnel designed and produced at the main Corning Glass Works in Corning, New York. A strain gauge test program was then conducted on this first faceplate/funnel assembly. After completion of these strain gauge tests, it was concluded that the design was not adequate for CRT processing. Accordingly at a meeting at Corning Glass Works on March 16, it was decided to redesign the glass funnel with a view to increasing the overall

pressure strength of the assembly. Tentatively, no faceplate changes were suggested. On June 9, 1972, Corning completed the production of a redesigned funnel which essentially employed a thicker wall section for the first 2" below the frit seal. The first new funnel was sealed to a faceplate and strain gauge tests predicted that the complete assembly would withstand a pressure of 42 psi, which was considered satisfactory. However, during the week of June 19th, a severe flood occurred in Corning, New York which destroyed the first bulb assembly and additional inventory, and rescheduling was required. It was further agreed, following consultations with GE and Syntronic Instruments, the selected vendor for the CRT magnetic coils, that a redesigned yoke reference line contour would be required to facilitate optimum beam deflection. Accordingly, Corning was instructed to proceed with the tooling of a new lower funnel design for subsequent incorporation in the main assembly.

The first bulb delivered to Thomas by Corning was on September 20, 1972. This bulb incorporated the new funnel design but not the final tooled version of the yoke reference line section. However, it was deemed acceptable for prototype purposes and tube processing was commenced. During the course of the preliminary processing of the bulb, the CRT neck was accidentally broken and processing had to be discontinued and the bulb returned to Corning for salvage. The second bulb was then delivered to Thomas on September 27, 1972.

Processing was commenced with this bulb and progress was made in applying the phosphor screen and lacquer layers. However, following a routine inspection step, it was noted that the bulb had developed many small axial cracks across the funnel/faceplate frit seal. Corning's examination of this bulb resulted in a recommendation to handle the envelope by means of a circular peripheral clamp in order to evenly distribute the stresses around the entire CRT circumference. Accordingly, a split ring was designed and was employed in conjunction with the hydraulic lift to perform all operational steps in the processing of the tube.

Following successful completion of the lacquering step with the third CRT envelope, the bulb was placed on the vacuum aluminizing equipment. It imploded after several minutes of evacuation.

An examination of the failed bulb confirmed the presence of severe radial cracks and after the bulb was examined in detail in the CGW laboratories, it was concluded that improvements in the frit sealing thermal cycle should solve the cracking problem. Accordingly, Corning redesigned the thermal controls in their frit sealing kiln and the first new assembly was sealed on January 19, 1973. This bulb was then subjected to a full hydrastatic pressure test to 31.5 psi without failure. On careful inspection following the pressure test, no defects could be detected and the envelope was then released to Thomas Electronics for processing. All processing

steps on this envelope were successfully concluded and the tube was finally tested electrically on March 7, 1973 and shipped to GE, Daytona. Considerable apprehension was felt during the first high voltage testing of the tube both at Thomas and Daytona due to the inevitable occurrence of initial high voltage arcing. At some risk to envelope puncture, Thomas engineers applied an 80 kV discharge to the neck of the tube to successfully clear stray emission paths. However, on delivery to Daytona the tube arced intermittently for the first few days or week. Fortunately the development of protective circuit techniques by GE engineers resulted in no catastrophic sweep losses and in the subsequent course of the program, high voltage stability was never a serious problem.

PRODUCTION PHASE

Fifteen production tubes have been fabricated for the ASUPT since 7 Mar 73. It required 24 bulbs and 3 implosions in the process. Following the completion of the prototype tubes, the production of subsequent tubes from 7 Mar 73 to 6 Dec 73 continued without undue conflicts until the processing of tube No. 6 (M12). This tube, following the completion of all coating and bake steps, imploded violently during exhaust on 7 Dec 73. Further production on two bulbs at Thomas was halted until Corning Glass engineers completed an analysis of the problem. Oven temperature gradients at both Thomas and Corning were re-checked, compatability of glass

components checked, and Corning's final verdict was that the implosion was an unexplained failure. Early in 1974 production was started again and on 25 January, a brightness output problem in tube No. 7 was discovered in pre-tests. The first six CRTs had no brightness efficiency problems as outputs of 50 lumens/watt were achieved. Tube No. 7 was measured at about 40 lumens/watt. Thomas tried different phosphor processes and in late Feb 74 the phosphor weight was reduced 12% and the water/air temperature differential was reduced to 15° F. This change resulted in an increase in output efficiency of 68 lumens/watt in CRT No. 10, for example. Tubes 8 and 9 had been held at Thomas until GE determined whether or not they could drive the "low efficiency" tube No. 7. GE had no problem and CRTs 8 and 9 were shipped to GE.

PRODUCTION

CGW Bulb #	ASUPT CRT No.	Date Shipped	Ship #	Remarks
#1		--	--	neck cracked
#2		--	--	fractures in frit seal
#3		--	--	imploded
#4	Prototype	3/7/73	M5	prototype; reshipped 9/4/74
#5	1	4/20/73	M6	first production tube
#6		--	--	neck perpendicular out of spec
#7	2	6/18/73	M7	second production tube
#8	3	7/17/73	M8	third production tube

CGW Bulb #	ASUPT CRT No.	Date Shipped	Ship #	Remarks
#9	4	8/27/73	M9	fourth production tube
#10	5	9/26/73	M10	fifth production tube
#11	8	4/11/74	M16	eighth production tube
#12	9	4/11/74	M11	sixth production tube
#13	6	11/30/73	M12	seventh production tube
#14		--	--	imploded 12/7/73
#15	7	3/27/74	M17	ninth production tube
#16	10	4/19/74	M18	tenth production tube
#17		--	M19	imploded 4/11/74
#18		--	--	returned to CGW 4/12/74
#19		--	--	returned to CGW 4/12/74
#20	11	7/23/74	M20	eleventh production tube
#21	12	7/23/74	M21	twelfth production tube -- imploded 4 Nov 74
#22	13	9/4/74	M22A	thirteenth production tube
#23	14	9/20/74	M23	fourteenth production tube
#24	15	10/13/75	M24	first spare CRT

The next CRT was shipped in March 74. The following CRT imploded in the oven at Thomas several weeks later, 11 Apr 74. This was quite a blow to the program. When it appeared that the bulb manufacturing problems at Corning had been resolved and that processing skills at Thomas had been nearly optimized, another CRT implosion was plaguing

the program. The two bulbs currently at Thomas were returned immediately to Corning for analysis. Although Corning felt that this failure was, again, an exclusive incident, they modified their fritting procedures (frit is the tooth paste-like material which is heated, melts, and bonds the faceplate to the funnel section of the tube), and returned these bulbs 16 May to Thomas. Corning considered "armour guarding" (a process by which vaporized frit is sprayed on and around the frit seal region under the heat of a flame), or strengthening the frit seal but eventually grounded the seal down and pressure tested the bulbs before sending them back to Thomas. Tubes 11 through 14 proceeded without disaster and the schedule of 27 Sep 74 for CIG acceptance was met with all fourteen CRTs installed in both visual displays. The prototype CRT was reworked in the Fall of 1974 and used in the final system with the 14th production CRT serving as a spare.

The third CRT implosion in the program occured at Williams AFB on 4 Nov 74. CRT No. M21, which was installed in channel B-6 on the ASUPT, suddenly, and inexplicably cracked. The implosion panel preserved the glass bulb and prevented the tube from total self-destruction. An Air Force evaluation team investigated the incidents surrounding this failure and reported their findings. See Appendix A. The damaged tube was returned to Thomas, who in turn had the CRT

sliced apart at the frit seal by Schott Optical. Corning analyzed fragments and pieces of the damaged CRT and published their findings 26 Jun 75. Although their analysis did not conclude that the frit seal was the cause, they could not blame structural defects in the faceplate or funnel sections. See Appendix A.

The first spare ASUPT CRT was fabricated in Sep 75 and shipped to Williams AFB 13 Oct 75. This tube was the best performing CRT fabricated and its test report is included in Appendix A. Three to six spare CRTs are projected with spares #2 through #6 being fabricated at Thomas in 1976. Thomas is currently investigating plastic, or LEXAN, implosion panels for the 36" CRTs.

FIELD INSTALLATION & INTEGRATION

INSTALLATION AT SINGER-SPD

The first unit to be installed at Singer-SPD at Binghamton was the test article. This was delivered on February 9, 1972. The locations of leg base-plates and bolt holes had been laid out previously on the motion platform so the assembly was started as soon as the parts were unloaded from the truck. The assembly of the entire structure including the window frames, CRT mounting plates and all the dummy loads required for dynamic testing was completed on February 22, 1972.

The installation of the strain gages was started on February 11. The wiring of strain gages to the signal conditioners and recorders

was completed on February 23, 1972. The dynamic testing was started on February 24, and completed on February 25, 1972. The second series of dynamic tests using combined motions was conducted on March 21, 1972. As was previously noted the results of the tests are given in the Brewer[2] report. A motion picture record was made of all motion tests.

The second outer support structure frame was delivered to Singer-SPD on October 27, 1972 and erection was started on October 30, 1972 and completed on November 2. The installation and alignment of all seven pancake windows was completed on December 15, 1972.

The third support structure assembly was completed on November 20, 1972, then dismantled and put into storage.

INTEGRATION SUPPORT AT G.E.

After completion of the dynamic testing, the outer support structure of the test article was dismantled and shipped to the General Electric Co. in Daytona Beach, Florida. Erection of the frame was started on March 26, 1973 and was completed on March 29, 1973. The pancake window modules were shipped to G.E. on March 28, 1973. Installation of the windows started on March 30 and was completed on April 13. The optical alignment was started on April 30, 1973 and the preliminary acceptance tests using screens instead

of CRTs was completed on May 3, 1973.

The first production CRT was delivered to G.E. on June 12, 1973. Installation and alignment was completed on June 15, 1973. The remainder of the tubes were installed and aligned between December 3, 1973 and December 11, 1973.

Since the electronics for the CRTs was not available when alignment was started on December 3, 1973 no test pattern could be illuminated. Specially calibrated test strips with holes accurately located at known angles were attached to the faces of the tubes. These strips were then used to properly focus and center the CRTs utilizing a theodolite and parallel telescopes to check mapping and collimation respectively. The adjusting screws in the CRT mounting plates and the CRT mounting studs were locked in position with jam nuts to permit G.E. personnel to remove and replace the CRTs without changing the optical alignment. This system was left at G.E. until July 1, 1974 for use in integrating the electronics after which time the windows were removed, crated and shipped to Williams AFB, Arizona. The support structure was dismantled and shipped to Wright-Patterson AFB where it is now stored.

INSTALLATION AT WILLIAMS AFB

The first outer support structure which was previously installed at SPD Binghamton, N.Y. was shipped to Williams AFB and erected on

motion platform B. This was completed by October 1, 1973. The installation of the window modules was started on October 3 and was completed on October 9, 1973.

The second outer support structure was delivered to Williams AFB on June 21, 1974 and was erected on motion platform A. The window modules for this system arrived from G.E., Daytona Beach, Florida on July 9, 1974, and installation was started. This was completed on July 26, 1974 including the alignment of the CRTs. Work was then resumed on the installation and alignment of the CRTs for platform A. The CRTs were installed as they were delivered. In the interim the maintenance platforms and ladders were fitted to both platforms and the mounting brackets were installed to permit use of the platforms on both motion systems. See Fig. 10. All work was completed on July 31, 1974.

TESTING

The testing of all component parts of the visual display was carried out at Farrand for the window assemblies, at Thomas in the case of the CRTs, and at SPD in the case of the test article. Nevertheless, there were additional, special tests conducted on the visual display and its components. These test reports are not documented here but include the following:

(1) ASUPT CRT motion/electrical test at Singer, 1973 -

purpose: to determine whether or not a powered CRT could withstand normal and emergency motion platform accelerations.

(2) ASUPT CRT coil mounting flange deflection test at Farrand, 1973 - purpose: to determine whether or not the 50 lbs. of coils would deflect the coil mounting flange enough to cause coil/glass neck interference (damage) under motion platform accelerations.

(3) Simulated T-37 wing study, 1973 at Farrand - purpose: to determine whether or not wings could be somehow simulated in the visual displays realistically and economically. Farrand proved the feasibility and General Electric implemented wings in the visual displays in 1975 at Williams AFB.

(4) Contrast ratio performance through the ASUPT pancake window, 1973, at Farrand - purpose: to determine whether or not the system specification of a 20:1 contrast ratio could be met.

(5) Integrated testing at General Electric, 1973 - purpose: to determine whether or not the first ASUPT CRT/CRT electronics and pancake window combination would meet design goals.

(6) Simulated CRT mapping test at General Electric, 1973 - purpose: to establish the range of system discontinuities and/or mapping errors to be anticipated with a complete set of aligned CRTs (specially designed plastic screens were used to simulate CRT faceplates).

VISUAL DISPLAY MAINTENANCE CONSIDERATIONS

The maintenance of the ASUPT visual displays, including CRT electronics, CRTs, and pancake windows presented a unique problem. The ASUPT was the first simulator developed with a dodecahedron shaped visual display structure and CRTs mounted to each of seven channels. Commercial maintenance platforms could be considered for the lower channels, but special consideration had to be made for the upper and top channels of the displays. In April, 1974, General Electric sent to the Air Force and Singer an Engineering Memorandum (GE-051) stating some necessary requirements for the maintenance platforms. This memo included the following: (1) The design of upper platforms should account for the CRT electronics and allow 30" clearance, (2) The upper platforms should be independent of the lower platforms, i.e., they should be mountable without the lower platforms being installed, (3) Installation and removal of the platforms should take no longer than 30 minutes, (4) All maintenance ladders should have wide steps and a moderate incline angle, (5) There should be 4' high railings on all platforms, and (6) The upper platforms should be 30" x 7 1/2' to allow a minimum working area. Farrand Optical considered these suggestions in their design of the two upper platforms, since GE was contracted to maintain the visual displays including electronics, CRTs, and optics after final systems installation. Fig. 10 depicts the two maintenance platforms in their final form. The platform at the top of the figure services channel 3

primarily, whereas the platform at the left, behind the man holding onto the railing, services channel 2. The commercial scaffolding, located at the left of the figure and consisting of aluminum tubing, services the lower channels, including 1, 4, 6, and 7. Channels 1, 5 are available for maintenance from the motion platform, to some extent. The wooden, pentagonal frame at the bottom of figure 11 is used to hold CRT assemblies as they are transported from the alignment bench area to the display by fork lift. After one year of visual display maintenance, the visual display platforms have worked well.

FINAL TEST DATA

The final optical alignment of both systems was measured after adjustment of the window modules and the respective CRTs. Since the driving electronics were still not operable the measurements were made with the calibrated tapes on the outer surface of the CRT implosion caps. A suitable correction was made for the glass thickness between the tapes and the phosphor surface when checking collimation. The final test results are included in Appendix A.

Only collimation measurements were made to insure that the system was focused at infinity within tolerance. It was not necessary to take mapping measurements since the local distortions had been determined previously. The distortions in the optics remain constant but the magnification can be varied by changing the image size electronically on the CRT thus making the images on all windows match.

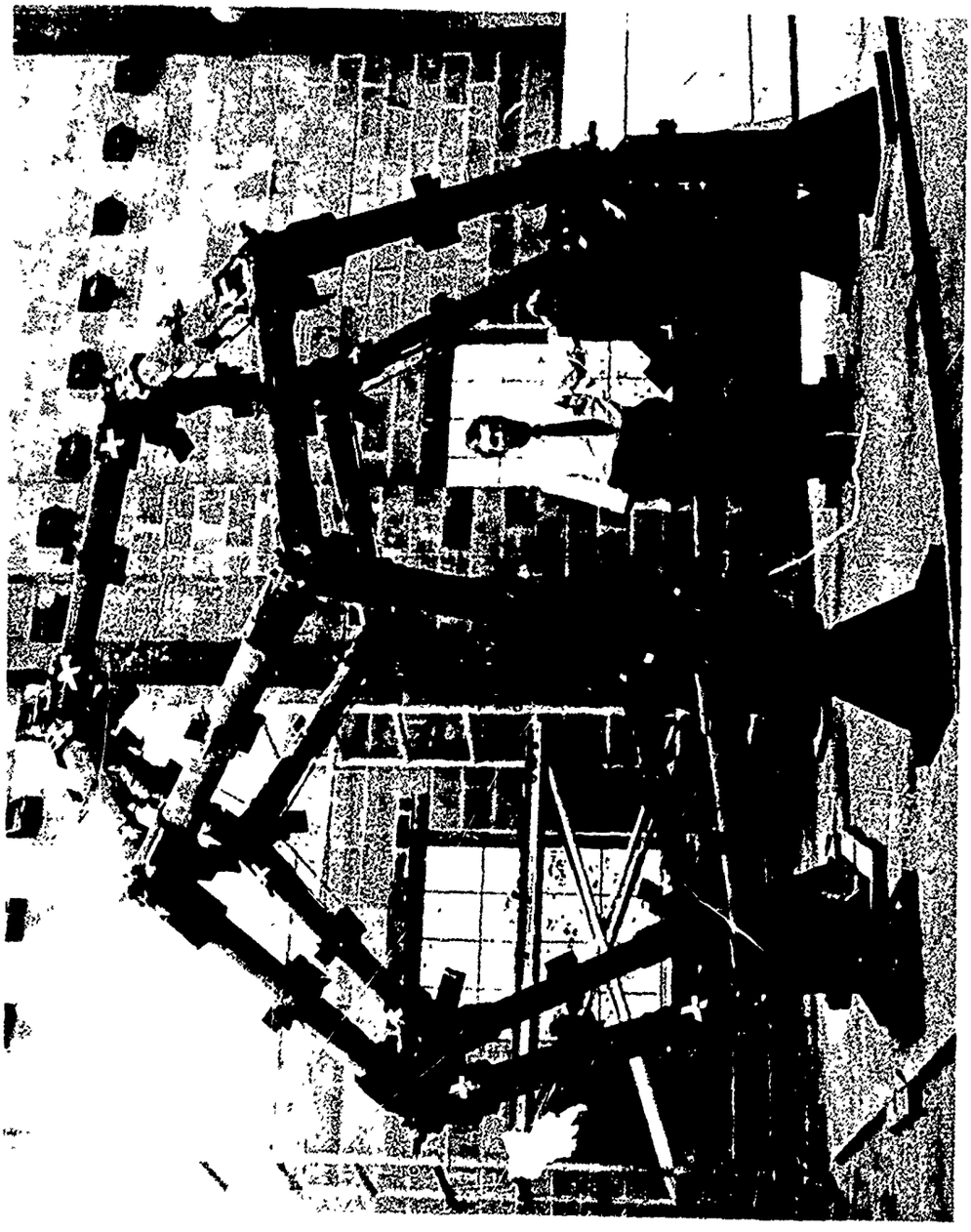
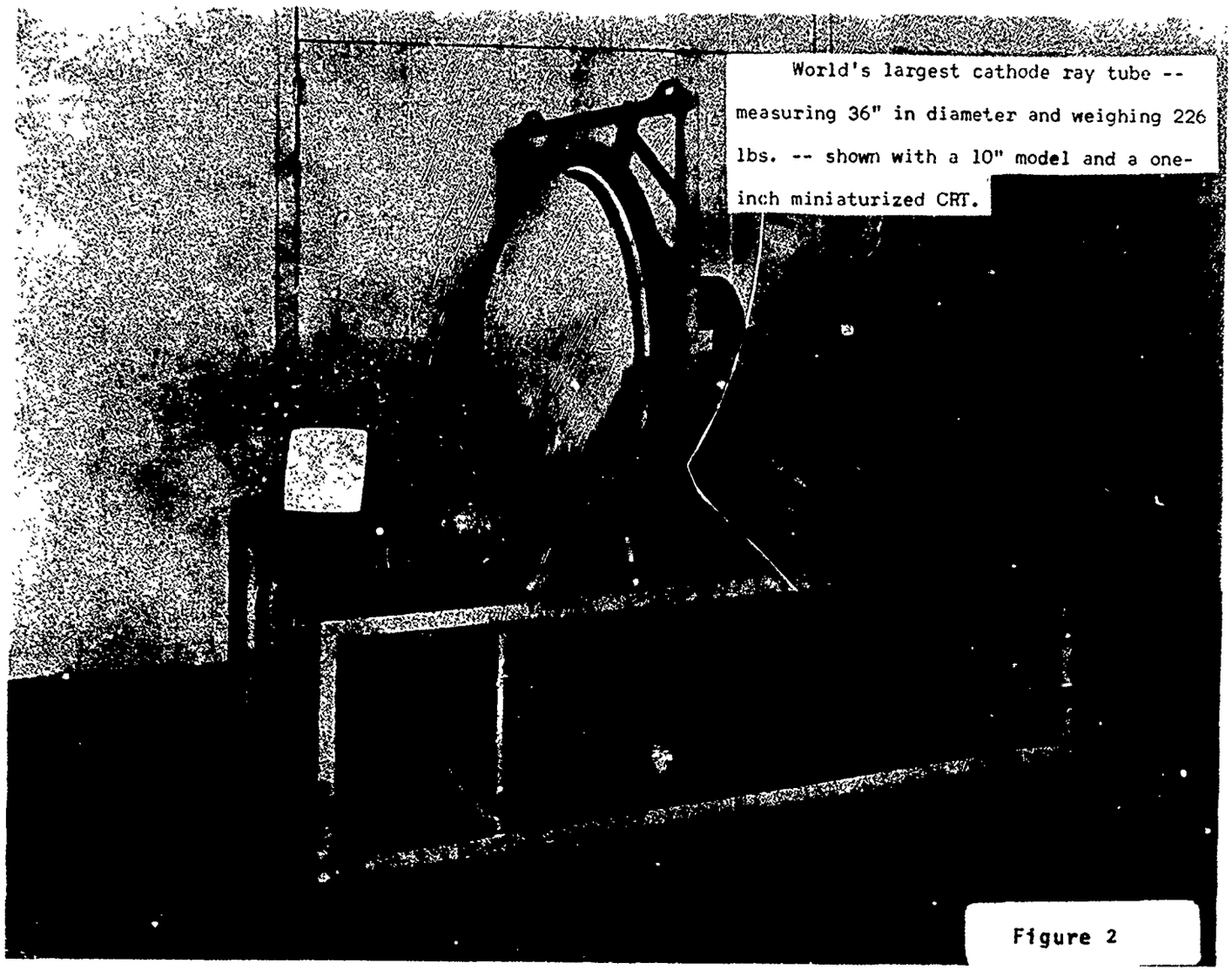
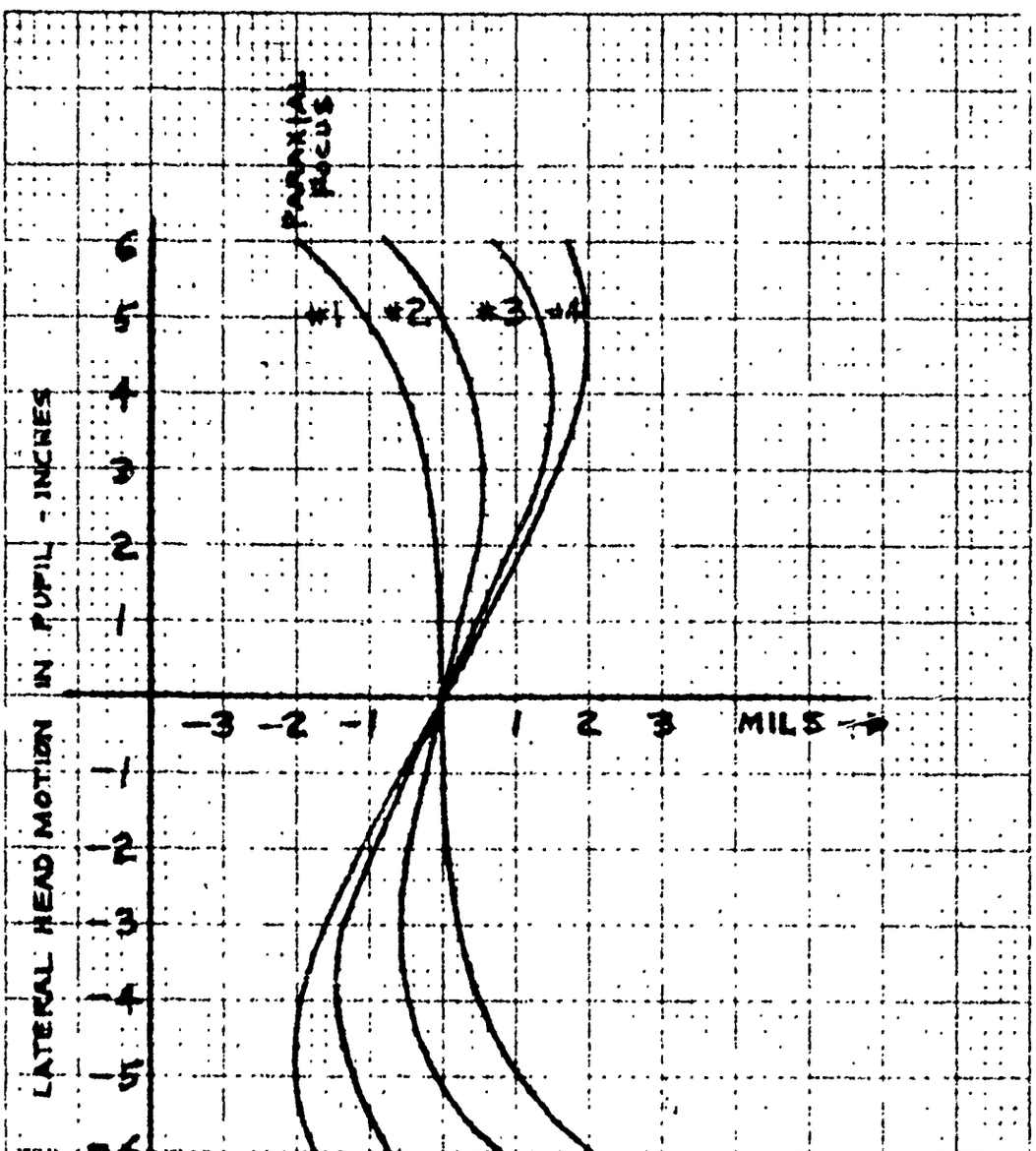


Figure 1



World's largest cathode ray tube -- measuring 36" in diameter and weighing 226 lbs. -- shown with a 10" model and a one-inch miniaturized CRT.

Figure 2



DECOLLIMATION VS. HEAD MOTION
FOR VARIOUS FOCUS CURVES - MILS

Figure 3

OWG No. 136948

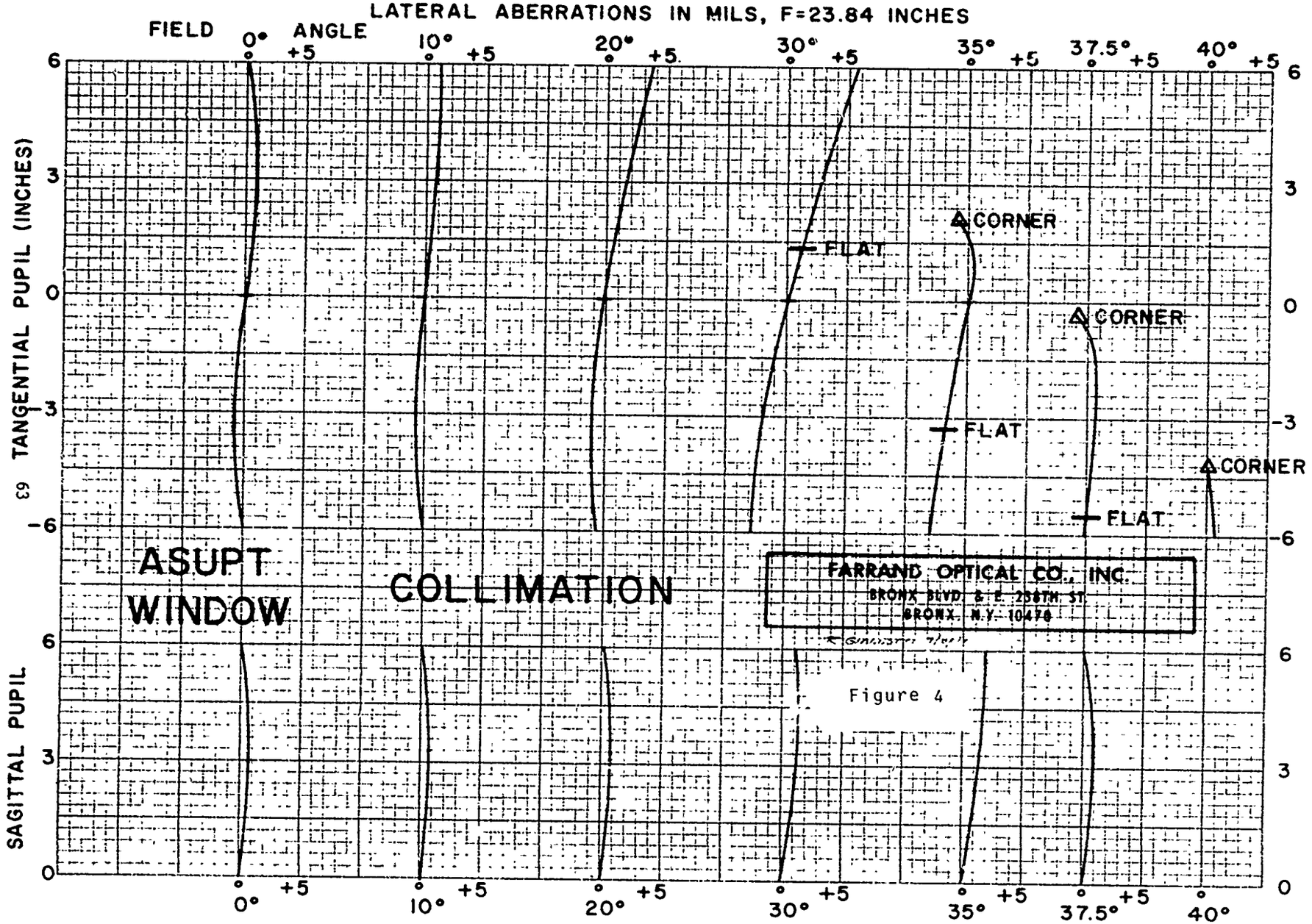

LATERAL ABERRATIONS IN MILS, F=23.84 INCHES
FIELD ANGLE
0° +5
10° +5
20° +5
30° +5
35° +5
37.5° +5
40° +5
TANGENTIAL PUPIL (INCHES)
SAGITTAL PUPIL
6
3
0
-3
-6
CORNER
FLAT
CORNER
FLAT
CORNER
FLAT
ASUPT
WINDOW
COLLIMATION
FARRAND OPTICAL CO., INC.
BRONX BLVD. & E. 238TH ST.
BRONX, N.Y. 10470

Figure 4

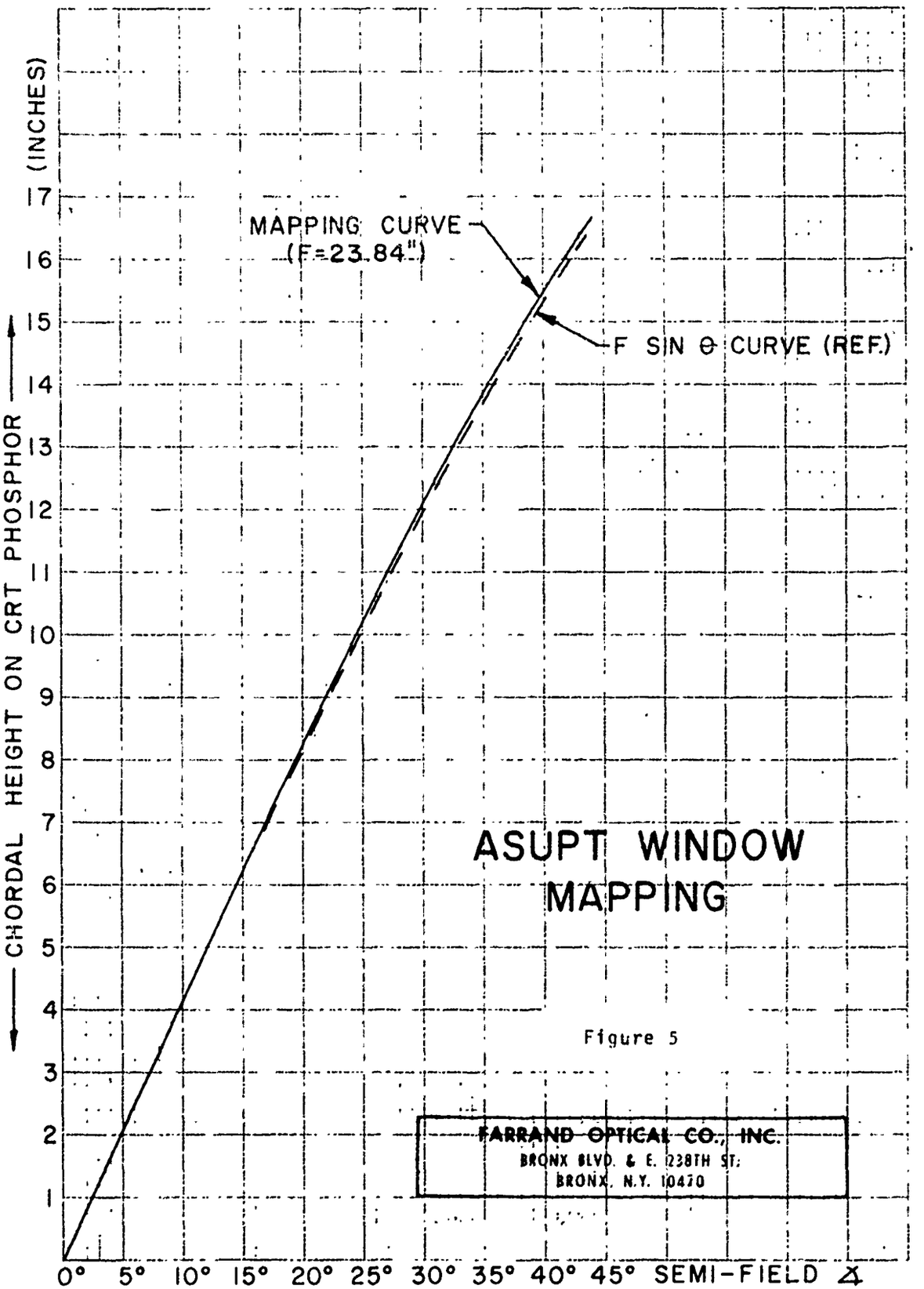

CHORDAL HEIGHT ON CRT PHOSPHOR (INCHES)
MAPPING CURVE
(F=23.84")
F SIN θ CURVE (REF.)
ASUPT WINDOW
MAPPING
FARRAND OPTICAL CO., INC.
BRONX BLVD. & E. 238TH ST.
BRONX, N.Y. 10470
0° 5° 10° 15° 20° 25° 30° 35° 40° 45° SEMI-FIELD ∠

Figure 5

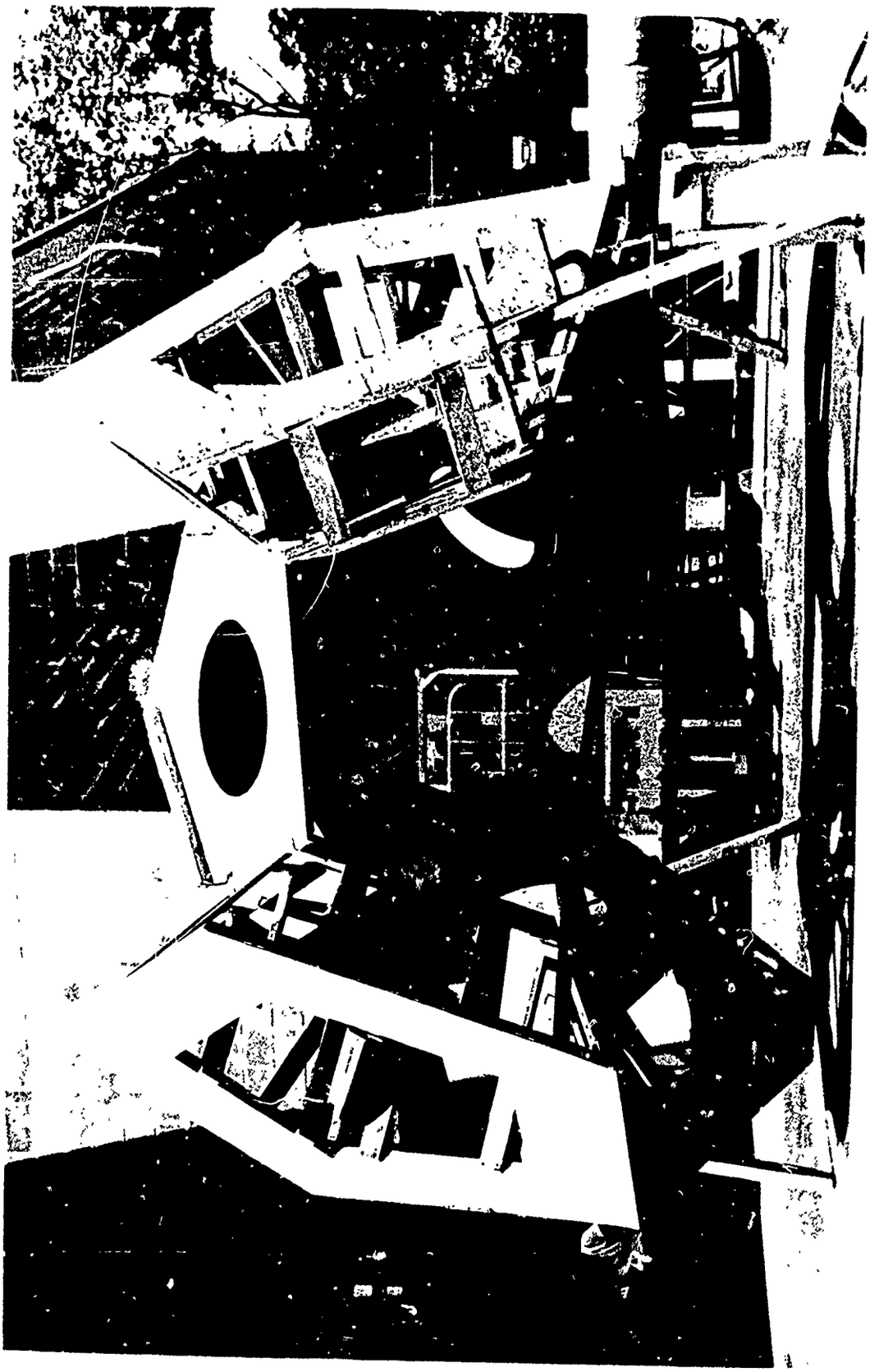


Figure 6

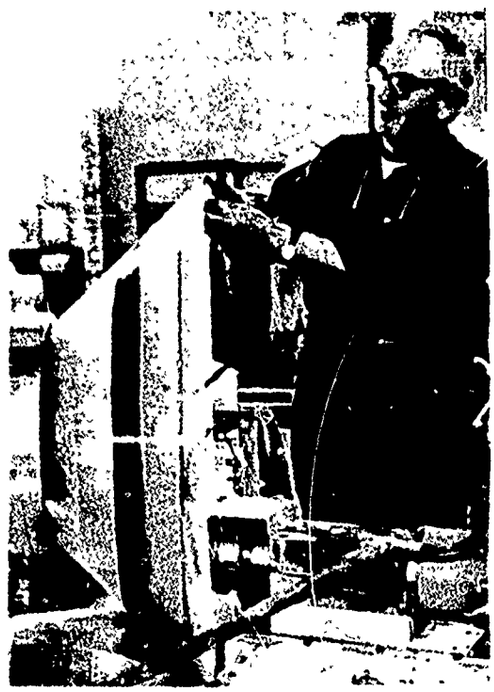


Fig. 7 Workers at Corning Glass assemble the glass bulb. At the left, measurements of the funnel section are made. Above, the funnel section, actually two pieces, is set on top of a faceplate to show the relative size. Below, workers are preparing to remove a faceplate from the grinding jig.

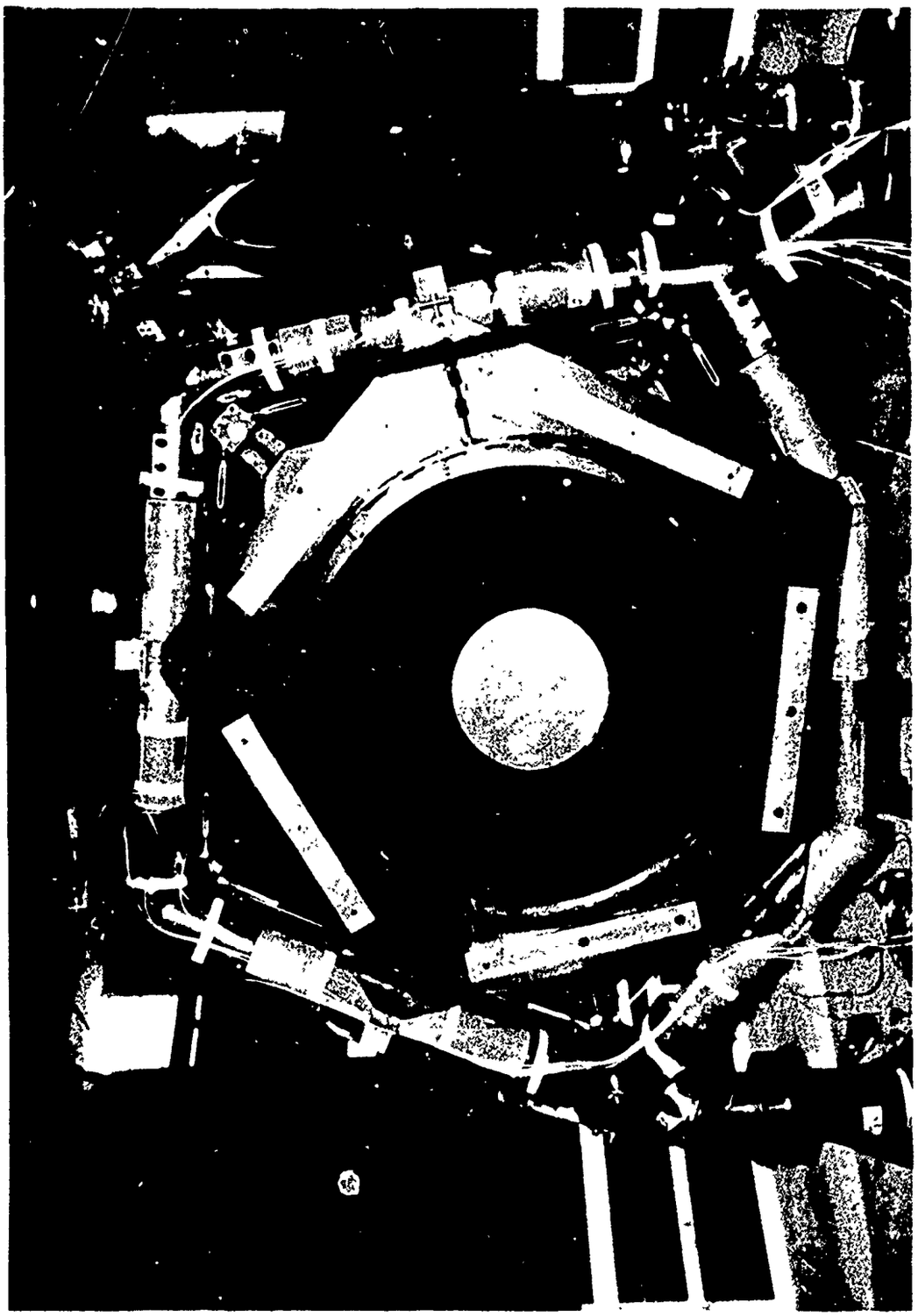


Figure 8

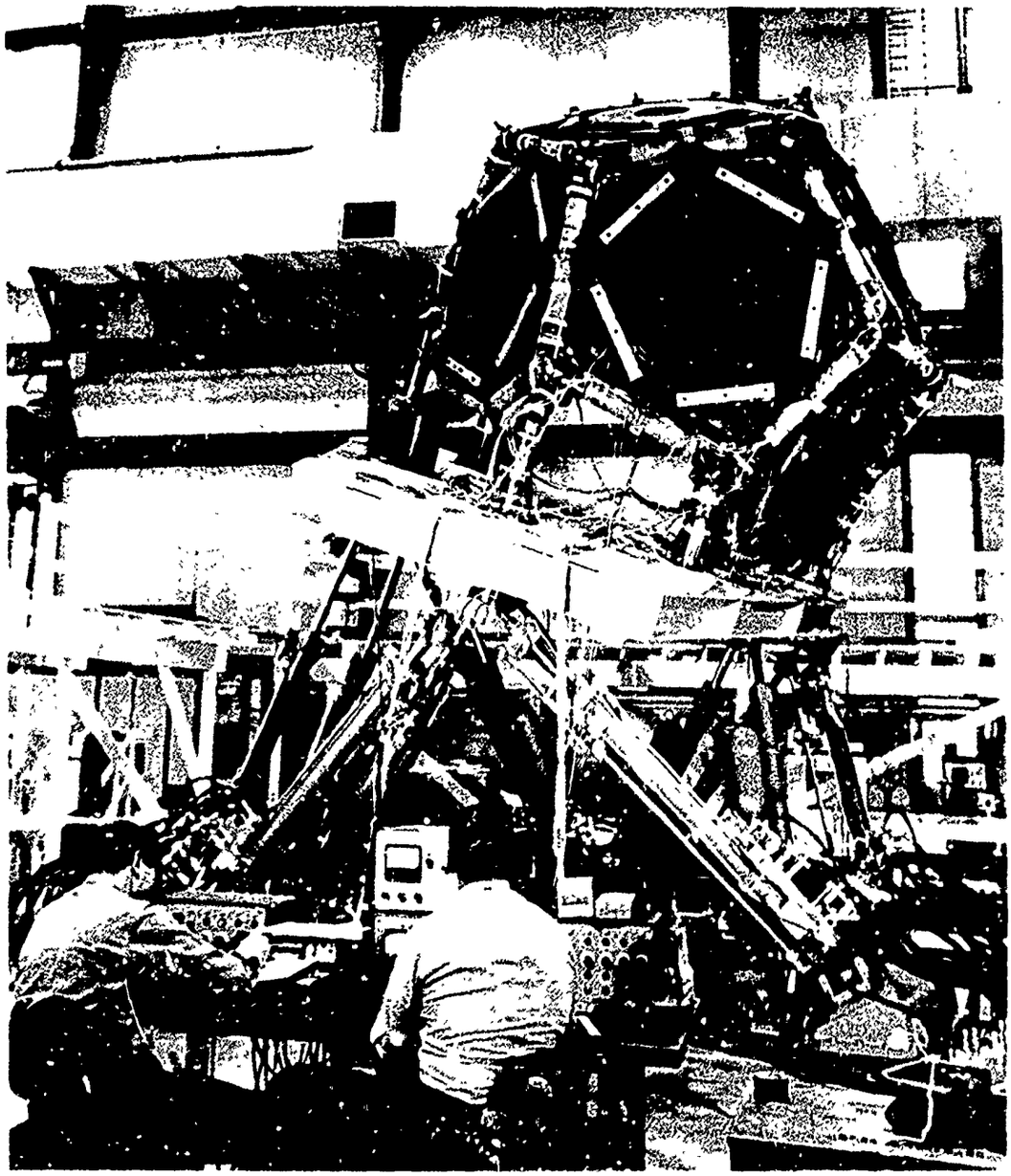


Figure 9

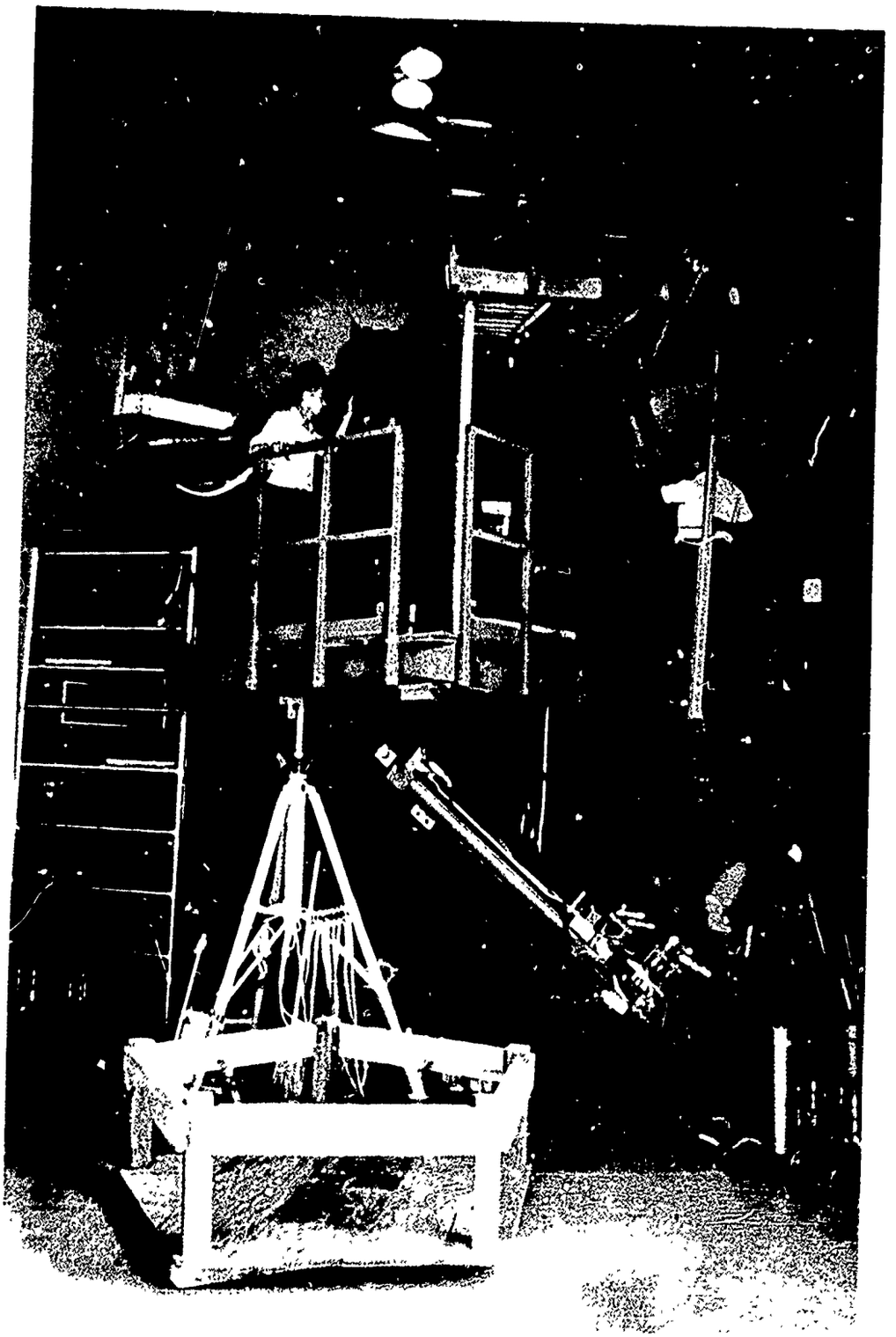


Figure 10

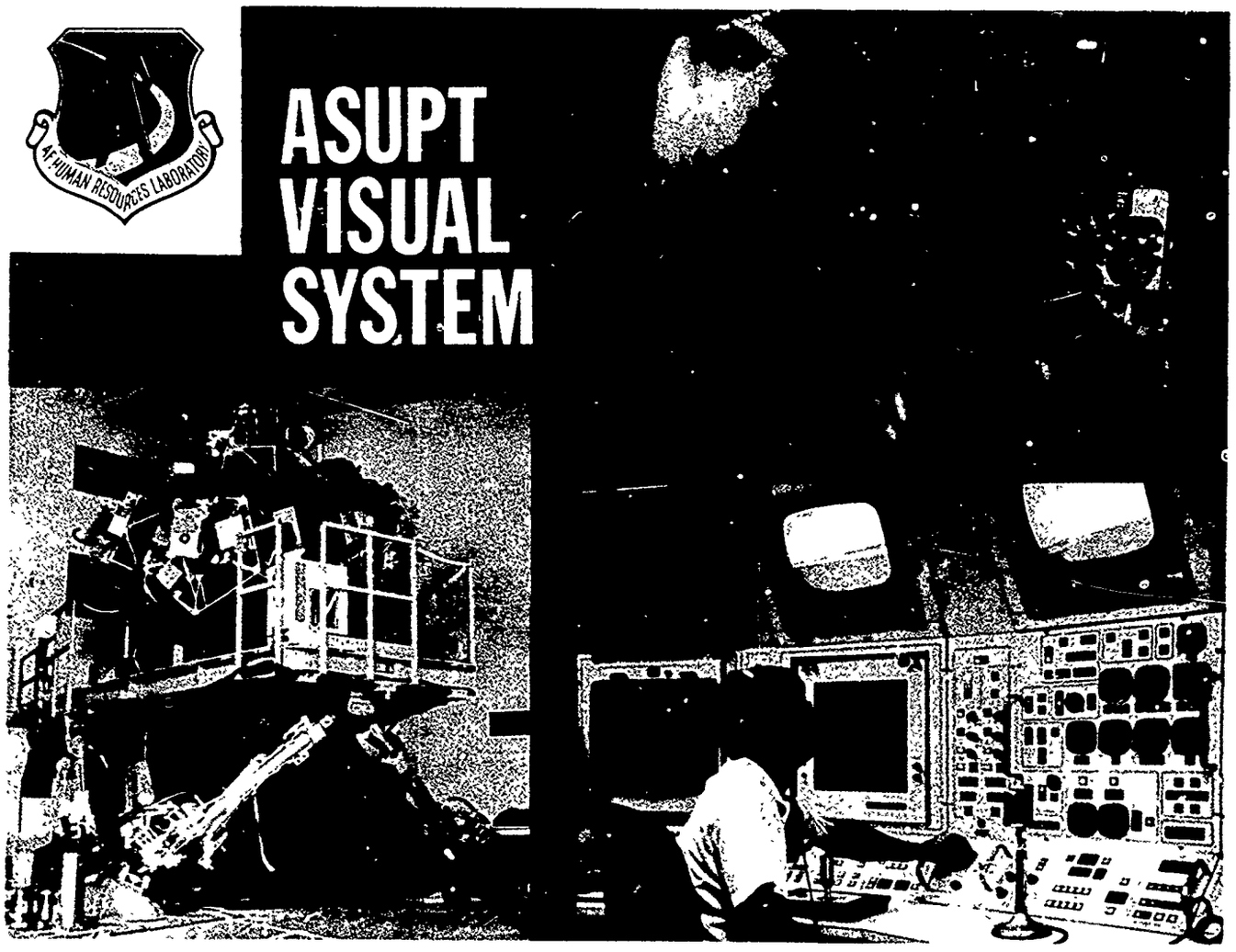


Figure 11

REFERENCES

1. Beardsley, H., Bunker, W., Eibeck, A., Juhlin, J., Kelly, W., Page, J., & Shaffer, L. Advanced Simulation in Undergraduate Pilot Training: Computer Image Generation. AFHRL-TR-75-59(V). Wright-Patterson AFB, OH: Advanced Systems Division, Air Force Human Resources Laboratory, November 1975.
2. Dynamic Stresses on Dodecahedral Support Structure, Report No. 478, Brewer Engineering Laboratories, Inc., Marion, Mass. 02738.
3. System Definition Study for the Primary Visual Simulation System for the ASUPT Program, Report for Contract F33615-69-C-1883, Apollo Systems, Space Division, General Electric Co., Daytona Beach, Florida, 30 Jan 70.

APPENDIX A

1. Initial Thomas technical report on the feasibility of a 36" CRT.
2. Imploded CRT #M-21 report.
3. CRT #15 acceptance test report.
4. Final window test data.
5. Theory of operation of Farrand infinity in-line optical system and ghost images.

April 30, 1971

1. Initial Thomas Technical Report

An all-glass envelope design and corresponding bill of material was anticipated at the commencement of the CRT Study and confirmation of vendor sources has been established. Non-browning faceplate glass in the form of ground and polished discs to satisfactory blemish specifications is available both from Schott Optical Glass Company (Glass No. 3459) and Corning Glass Works (Glass No. 9025). A two-piece spun glass funnel in 0120 glass can be produced in the Radome facility of Corning to satisfactory mechanical and quality specifications. The faceplate and funnel can be sealed by the frit technique as proven in crts for earlier Air-to-Air and Apollo visual simulator programs.

However, continued investigations into cost, lead time and safety factors have resulted in two alternative approaches to envelope fabrication.

It appears feasible to sag the rear funnel section from plate glass by the same technique employed for faceplate sagging. By employing a commercial plate glass for both faceplate and funnel, together with an appropriate conical neck and flare section sealed to the sagged funnel component, it is possible that the entire crt envelope could be produced at substantially lower cost and within a 90-day delivery period. Further investigation into the availability and properties of commercial plate glass is underway to confirm feasibility of this envelope fabrication approach.

An important consideration in producing an all-glass envelope employing either a spun or sagged funnel component relates to the potential implosion hazard presented during the crt processing operations. A particularly vulnerable phase of processing

occurs between the crt evacuation step and the application of implosion cap and funnel shields. Implosion precautions necessary during this phase would be greatly simplified through the use of a metal funnel envelope component. The feasibility of adopting a metal funnel design has therefore been re-examined.

Prior practice with metal funnel crts has involved the use of a hot sealing technique for the faceplate. This technique is highly critical and requires special annealing equipment. The use of a pyroceramic frit technique for sealing faceplate to a spun metal funnel appears quite feasible and could result in substantial cost and time savings, in addition to providing a crt envelope which is inherently less hazardous during both processing and end use. Further study is underway with respect to detailed seal design.

A final decision to select one of the three fabrication approaches will be made following the completion of strength analyses and design tests currently underway.

Thomas Electronics, Inc. 100 Riverview Drive, Wayne, New Jersey 07470 · Telephone: 201-633-6000

April 30, 1971

2. CRT Electrical Parameters

Two special crts have been constructed and evaluated to provide electrical performance data. Both tubes employed a 19" diameter faceplate sealed to a low deflection angle funnel similar to tube type 19M34 which closely approximates the funnel length of the 36M10 ASUPT crt. The first tube employed a conventional on-axis gun/neck assembly. At 35 Kv, it exhibited the following characteristics on-axis:

Modulation Voltage	Anode Current	Line Width Inches
Volts-DC	Micro-Amperes	Inches
20	17	0.010
40	130	0.012
60	390	0.018
80	900	0.020
100	1830	0.022
120	3300	0.030

The second tube was fabricated with the gun/neck assembly inclined to result in undeflected spot landing at the crt screen edge. Deflection of the beam across the crt screen results in a 40° deflection angle as in the 36M10 ASUPT tube. Off-axis line width data is therefore fully representative of that obtainable in the final crt. At 35 Kv, the following data was obtained:

Mod. Voltage	Anode Current	Off-Axis (35°) Line Width (Merged)	Brightness
VDC	UA	Inches	Ft. L.
20	22	0.010	6.5
60	250	0.018	145
100	1050	0.024	530
120	1600	0.026	700
140	2600	0.028	970

*At 600,000 IPS with 20 lines per inch.

The deflection coil employed was a Syntronics type Y66EFGS. The focus coil was type JEDEC Standard No. 122 manufactured by Rola Corporation. The writing rate was 600,000"/sec. with a line spacing of 20 LPI.

It will be noted that the off-axis line width is essentially comparable to the on-axis performance within the limitations of the modulation level of 140 v, which in the case of the second crt resulted in a 2.8 mA beam current. Due to video pulse amplifier limitations, it was not possible to operate the off-axis crt at modulation levels above 140 v. To determine, therefore, whether line width increased sharply at the 4 mA level, a brief visual observation of raster lines was made with the grid setting adjusted to provide a 4 mA beam current at DC level. No excessive line width growth was observed during this subjective evaluation.

The Syntronics Y66EFGS deflection coil is a high inductance type and in general, deflection defocusing is increased with the low inductance coil designs. However, Dr. H. O. Marcy, the deflection coil consultant in this Study, states that comparable performance should be obtainable from a deflection coil with reduced inductance, on the order of 100 uH, suitable for the crt electronics design.

The deflection coil diameter of the Y66 yoke is 2.125". The excellent off-axis line width readings can be partially attributed to this larger-than-normal yoke diameter. The favorable readings, however, suggest a possibility that a standard 1.5" yoke may be feasible, thus simplfying deflection amplifier design. The off-axis crt will be retained for future yoke testing.

The x-radiation emerging from the crt faceplate during operation of the on-axis

crt at 38 Kv and with 1 MA DC beam was 18 milliroentgens per hour at a 6" distance from the faceplate. However, the insertion of a 3/16" thick implosion panel between the crt faceplate and the radiation survey meter reduced the x-radiation to less than 0.1 mR. It should be further noted that the anticipated faceplate thickness of the 36M10 ASUIT crt is 0.6" minimum, which is approximately twice that of the 19M34 crt.

3. Optical Characteristics and Screen Brightness

The selection of an optimum phosphor screen with emission characteristics matching the transmission properties of the pancake window has been investigated in the light of current progress in pancake window construction. A recent window spectral transmission curve exhibits a peak zone over 5,000 to 5,800 Å, with a particularly sharp fall-off below 5,000 Å. The use of a white P-4 screen consisting of a blend of blue and yellow phosphors would appear to be most inefficient, and even the choice of a high-efficiency P-31 would appear questionable in view of the significant portion of P-31 energy emitted below 5,000 Å. The best choice at present appears to be a P-20, peaking at approximately 5,450 Å.

In addition to the direct transmission match requirement, there are, however, other considerations in the pancake window design which raise further phosphor selection questions. For example, the use of a very narrow band phosphor such as P-44 would assist in the accurate alignment of pancake window components but, on the other hand, may accentuate transmission uniformity problems associated with quarter waveplate uniformity. It is probable that the intensity and color of ghost images could be affected, and possibly minimized, by the use of a phosphor with low side band emissions. It would appear that blue emission content or side band peaks would be particularly objectionable since most bleed-through appears to be in the blue portion of the spectrum. All of the above questions, of course, must be considered in relation to both on-axis and off-axis properties of the phosphor/pancake window match.

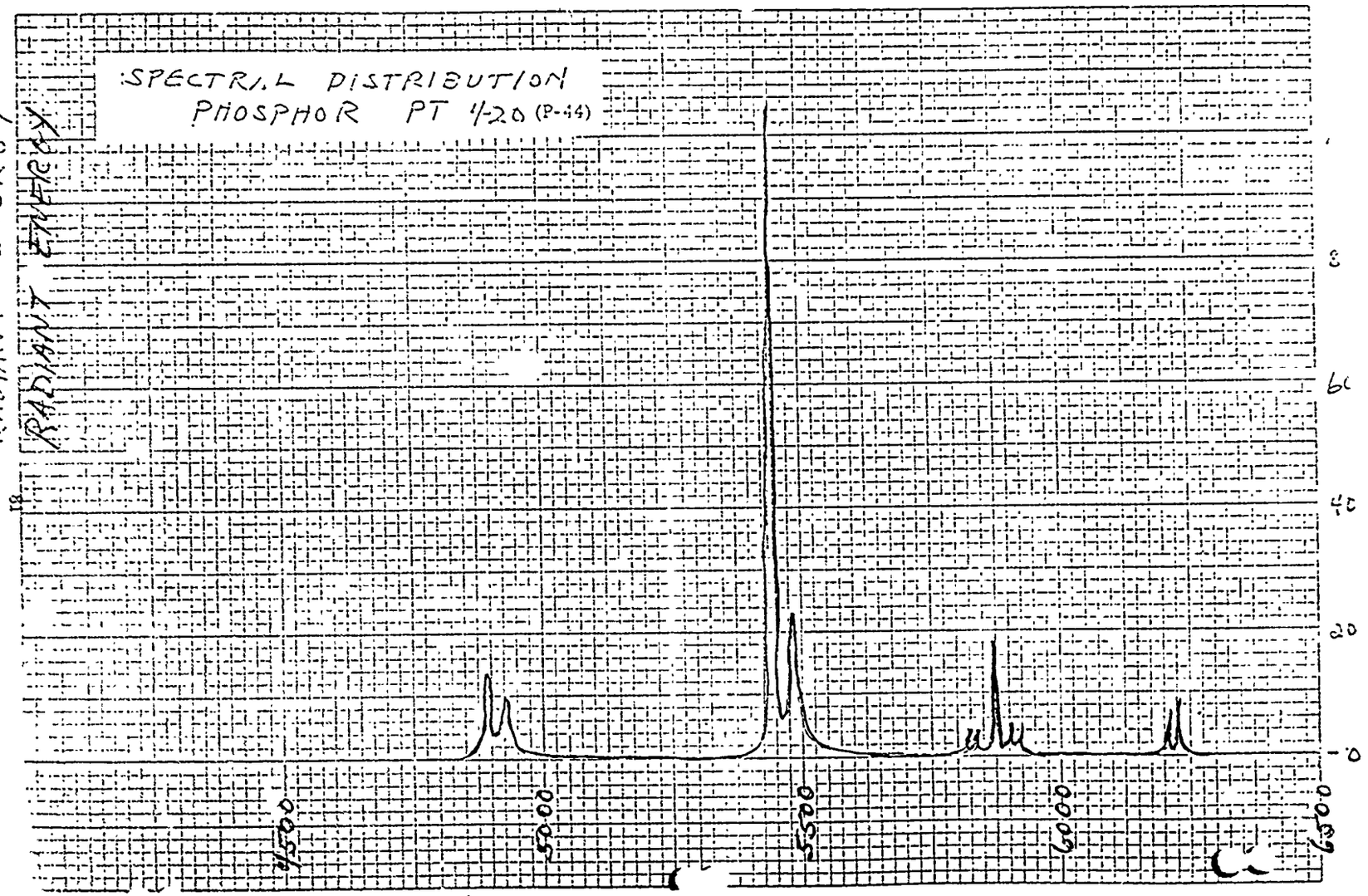
At the present time, it would be premature to suggest a specific phosphor in view of detailed material and design factors concerning the construction of pancake windows currently underway. Close liaison with Farrand Optical engineers is recommended in order to arrive at an optimum selection, as final pancake window characteristics are established.

It will be noted from Section 2 above that an area brightness of 970 Ft. L. was measured on the off-axis experimental crt under the conditions specified. This measured brightness reading corresponds very closely with the calculated screen brightness assuming a phosphor efficiency of 40 lumens/watt, which is a typical figure for high efficiency sulfide phosphors operating at high brightness levels. Assuming that a high-efficiency sulfide phosphor similar to P-20 will be acceptable as an optimum transmission match, it will be noted that an increase in beam current of up to 6 mA, or a corresponding power increase in beam current and high voltage ratio, will be required in order to provide for a field brightness of 1,000 Ft. L. at a writing rate of [illegible] million inches/second. The actual writing rate may be somewhat faster than this, but on the other hand the line spacing of 20 lines per inch may be only a worst case condition at the extreme center, with a substantially increased average line density over most of the screen area. A precise calculation of beam power required for sufficient screen brightness is not practical until further details are available concerning the non-linear raster characteristics and retrace blanking ratios. It is also not possible to state at this time the net pancake window transmission with its matching phosphor screen. It would appear, however, that the use of the most efficient sulfide type phosphor would be highly desirable in view of the high beam power requirement.

In the testing of the off-axis crt, no subjective variation in color of the P-20 phosphor screen was apparent up to the 970 Ft. L. level attained. Since P-20 is a single peak phosphor, in comparison with the double peak characteristic of P-31 for example, it is not anticipated that significant color variations will occur either initially or during the life of the phosphor screen. To establish repeatability of color on successive crts, it is recommended that a substantial quantity of the P-20 phosphor be procured and stocked for use over the anticipated life of the program, since this class of phosphor is both inexpensive and has

an extremely stable shelf life.

In view of the favorable line width results reported in Section 2 above, small area contract ratio, or MTF, should be relatively high but quantitative measurement is not practical without a more detailed definition of raster design. Large area contrast ratio at 1,000 Ft. L. was 200:1 on the off-axis crt (from a measured background value of 4.9 Ft L. 1" away from edge of raster at 1,000 Ft. L. of area brightness).


SPECTRAL DISTRIBUTION
PHOSPHOR PT 1-20 (P-44)
RADIANT ENERGY
RELATIVE ENERGY
.8
.6
.4
.2
.0
.450
.500
.550
.600
.650

4. Anticipated Tube Life

As tabulated in the Third Monthly Report, the final life test results were as follows:

Tube #:		1	2	3	4	5
D/C Beam Current:		1.0 mA	2.0 mA	1.0 mA	1.5 mA	2.0 mA
% of Original Emission at:	477 hrs	96	113	86	92	92
	1009	128	70	57	51	-- *
	1491	96	51	38	51	--

* CRT total loss

The tubes fabricated for life test incorporated 19" 90° envelopes, since life test equipment was readily available for this CRT size. The guns employed were similar to the 27M23P-type (Air-to-Air CRT) which, in turn, were derived from the 27M18P-design, which has demonstrated an average life of 12,000 hours in use on the Apollo Mission Simulator. The 27M23P-gun design was also employed in the 19" low deflection angle CRTs in the line-width and brightness studies above. It was anticipated that this design would be suitable for the proposed 36M10P-CRT, with a cut-off adjustment to provide a 4 mA capability. The cathode loading factor in the gun triode section is approximately 1 Amp/cm^2. No special processing steps were taken in the fabrication of the 19" life test tubes; 75 mgm: S.A.E.S. exothermic getters were employed. The phosphor screen was P-31; the acceleration voltage employed during the test was 15 Kv. The tubes were operated on a DC basis with a fully scanned raster and were monitored once weekly. Six tubes were originally fabricated but one tube exhibited a leakage path during initial test and was, therefore, unusable. Due to the fixed time available for the life test study,

it was not practicable to build an additional tube to replace the reject. It will also be noted that Tube No. 5 was lost after the first 477 hour test measurement. This tube developed a neck crack resulting in loss of vacuum. The origin of the crack was ascribed to a handling bruise which occurred during removal and insertion of the crt in the test equipment associated with the life test rack.

It will be noted that all five tubes exhibited a satisfactory emission level at the 477 hour test point (nominal 500 hours). One tube in the group continued to operate at a high efficiency level throughout the 1491 hours of test (nominal 1500 hours).

The tubes were examined at the completion of the test period with the following results:

Tube #	Serial #	Getter Mirror	Cathode Condition
1	34523	Darkened but intact	white (normal)
2	34529	Non-metallic	white (thinned)
3	34530	Non-metallic	greyish (thinned)
4	34521	Non-metallic	white (normal)

General comment: Cathode ceramic - no sublimation.

The depletion of the getter mirror in an electron tube is a strong indication of excessive outgassing of tube coatings or electrodes in operation. It would appear that the degree of outgassing, presumably from the phosphor screen at the high DC beam current levels in the test CRTs, was substantially higher than normal, resulting in early getter depletion in three of the tubes during the test period. In order to provide an operational life time for the proposed 36M10 CRT more nearly comparable to that of a conventional tube, it would appear necessary to incorporate getters with larger yields and to extend the outgassing time temperature cycles during final crt evacuation. This latter requirement

Thomas Electronics, Inc. 100 Riverside Drive, Wayne, New Jersey 07470 Tel. [illegible]

will be fulfilled as a matter of course during the processing of the 36M10 bulb, since a 24-hour time-temperature cycle similar to that employed in the 27M23 and 27M18 CRTs will be necessary for thermal gradient requirements.

The calculated life of a sulfide phosphor screen such as P-20 or P-31, assuming a 20 coulombs/cm.^{2} half brightness characteristic, is 40,000 hours at a DC beam current of 1 mA. A final prediction of tube life limitation due to phosphor screen aging cannot be made until the phosphor choice in known and operational brightness levels established. However, it would appear that a substantial margin is available.

Thomas Electronics, Inc. 100 Riverview Drive, Wayne, New Jersey 07470 Telephone: 201-696-5200

6. Conclusion and Recommendations

The results of the CRT Study appear to be most encouraging and confirm the "Anticipated Results" in that an acceptable minimum performance level has been demonstrated. The envelope design aspects are especially favorable in view of the options and alternatives which are now available. With the choices now established, there appears no doubt that satisfactory envelopes can be fabricated.

Screen brightness and resolution results indicate that with an increase in beam current of up to a maximum of 6 mA, adequate resolution should be available at a 1,000 Ft. L. area brightness level. However, if additional development and study confirms the need for 6 mA peak currents, it would appear highly desirable to develop a gun design which would require reduced video drive, since to achieve a 6 mA beam current with a conventional triode section a minimum of 200 volts of video signal would be required. High transconductance techniques exist which could probably reduce video requirements by a factor of between 2 and 5, and it is recommended that additional study and development be conducted to verify the feasibility of such designs in this application, with particular reference to preservation of adequate resolution.

Adequate options appear to exist with regard to selection of an optimum phosphor screen. A final choice is unlikely to require any new materials development.

The results of the life test study suggest that a continuation of study and development is required in order to confirm the tentative conclusions. Additional tubes should be built employing the largest available envelopes and incorporating increased getter yields and extended exhaust processing. With this additional development work, it is considered probable that the 36MP10 life can be predicted at between 5,000 and 10,000 hours.

2. Imploded CRT #M-21 Report

36" BULB FRACTURE ANALYSIS

Performed for

Thomas Electronics, Inc.

by

Corning Glass Works

Thomas J. Larkin, Jr.
Corning Glass Works
June 26, 1975

I. Bulb History

Corning Glass Works 36" bulb #21 was manufactured in June 1974 from all new parts. No salvaged parts were used and none had been exposed to any previous firing cycle other than normal anneal. Manufacturing notes made during the bulb assembly indicate nothing unusual about the parts themselves, preparation for sealing, or the actual frit sealing cycle.

It should be noted here that in May 1974 it was determined that the frit firing cycle for two bulbs shipped previous to May, 1974 was not the recommended, optimum cycle. At that time these two 36" bulbs were returned to Corning for possible salvage. Subsequently, extensive work was done on the firing kiln with new thermocouples, new controllers, and recut cams being installed. Three loaded test firings were carried out prior to actual frit sealing. Bulb number 21 was the first bulb frit sealed after completion of kiln repair and testing.

II. Initial Findings

Brian Gray and T. Larkin of Corning Glass Works visited Thomas Electronics on January 9, 1975 for the purpose of inspecting the cracked 36" tube which had been returned from Williams Air Force Base. At that time the tube was at air. The laminated implosion panel was in place and the bulb faceplate maintained its original geometry. The funnel portion of the bulb, except for two inches below the faceplate-funnel seal remained potted in the RTV-funnel housing combination. Photographs of the exposed breakage were taken at the time. (See fig.1.)

The following additional observations were made at that time:

1. The exposed cracking extended from some where in the funnel through the frit seal extending towards the panel centerface.
2. Several cracking propagations were evident all showing similar patterns.
3. A visual frit seal inspection showed a good frit fillet both outside and inside of the seal area.
4. No conclusive break source was visible with the bulb in this state.

III. Program

After initial inspection on January 9, 1975 a review of findings and a discussion of a possible program was held. Participants included P. Seats and B. Waxenbaum of Thomas Electronics; B. Gray and T. Larkin of Corning Glass Works; W. Alberry from Wright Patterson Air Force Base. It was determined that the primary objective of the investigation was to determine the break source and cause of the tube breakage. In order to maximize the probability of determining the source and cause of breakage several courses of action were discussed:

III. Program (Con't)

1. The glass funnel could not be separated from the RTV potting without damage, and therefore, a physical separation of panel and funnel would be necessary.
2. Two methods of separation were proposed:
   A. Separation by scoring and spot heating an area 1½" below seal area.
   B. Separation by contracting Schott Glass to cut using the same method to cut large boules of glass.

The separation by Schott was preferred due to the toxic nature of hot RTV. Thomas Electronics agreed to contact Schott to discuss separation feasibility and timing.

3. It was agreed that the breakage analysis would be accomplished by Corning Glass Works at Thomas Electronics and at Corning's TV Laboratory in Corning, N.Y.

IV. Analysis & Results

B. Gray and T. Larkin of Corning Glass Works visited Thomas Electronics on April 11, 1975 to begin analysis of the 36" tube after panel-funnel separation by Schott. The Schott cutting operation was successful leaving both panel and funnel sections intact. The following observations were made:

1. Three areas of the frit seal, each approximately 6" in length, were removed as a result of saw binding and not cutting perpendicular to the bulb axis.
2. The exposed frit surface appeared clean, evenly applied, and well fired.
3. Excluding the missing seal area, the remainder of the seal exhibited a good, continuous frit fillet on both the inside and outside seal edges.
4. The break did not appear to originate in the lower funnel section.
5. One crack in the funnel, 180° from the major breakage, occurred during the panel-funnel separation.

During the April 11, 1975 visit T. Larkin numbered broken portions which were suspect for containing the break source. Polaroid photographs were taken and panel sections were numbered 1-7 (see figure 2). Funnel sections were numbered 8-15 (see figures 3 & 4). It was requested that pieces numbered 1-14 be removed from the total panel and funnel sections, be wrapped individually, and shipped to the TV Development Laboratory in Corning, N.Y. for futher analysis. The piece numbered 15 was felt to have broken during panel funnel separation and it was not

IV. Analysis & Results (Con't)

felt to be of any investigative value. On April 21, 1975 pieces numbered 1-7 and 9-13 were received in Corning. The sections numbered 8 and 14 were damaged during removal of the laminate panel and RTV-funnel. Upon initial examination of these parts Corning's TV Lab personnel requested that the remaining protions of the bulb be sent to Corning. On May 13, 1975 the remainder of the 36" faceplate was received in Corning from Thomas Electronics. Thomas Electronics advised that no remaining funnel pieces existed.

With all available pieces TV Lab personnel began a study of the flow of the Wallner lines (break propagation). The purpose of this type of study is to trace propagation backwards to a flow interface which has a glass irregularity indicative of the actual origin of the break. Figure 5 shows a sketch of the location and direction of the panel and funnel break propagation relative to the seal area. The following are results of the Wallner line study.

1. All portions of the bulb faceplate were present and no break source was found.
2. All flow patterns on the funnel sections received are short in comparison to those shown on the panel pieces. The dotted, circled area shown in figure 5, indicates that possibly this area was damaged in delamination of the funnel, since a segment is missing at the intersection of sections 10 and 13. In addition, Wallner lines flow only to the edge of section 13 on the left and terminate at the cut seal line in section 9. These are outside flow lines indicating damage during delamination of the potted funnel. No actual break source was found on any of the funnel pieces.
3. The longest continuous flow pattern of Wallner lines originate somewhere in the seal area at the left of section 1, and flow generally to the left along sections 2, 3, 5 and 6 and ending at the cut seal to the left of section 6.

V. Conclusions

From an analysis of the available parts, no conclusive source or reason for failure can be made. However, the following statements may be made.

1. Since all faceplate pieces are accounted for, and no break source found, there is no possible source in the faceplate.

2. Although not all funnel pieces were available for Wallner line study, those that were available were positioned in the area of major breakage. The relatively short Wallner line paths present in this funnel section tends to remove suspicion from the funnel as containing the break source.

V. Conclusions (Con't)

3. The position of the longest continuous flow pattern of Wallner lines described in 3. under results may indicate a possible source in the area of the frit interface with the panel glass at section number 1. However, since the actual frit seal and fillet is missing any speculation as to the source or cause is purely conjecture.

4. The thermal history of the bulb and tube gives confidence in the tubes structural integrity. Structural defects would tend to be exposed during the bulb and tube thermal manufacturing processes.

TJL/jem

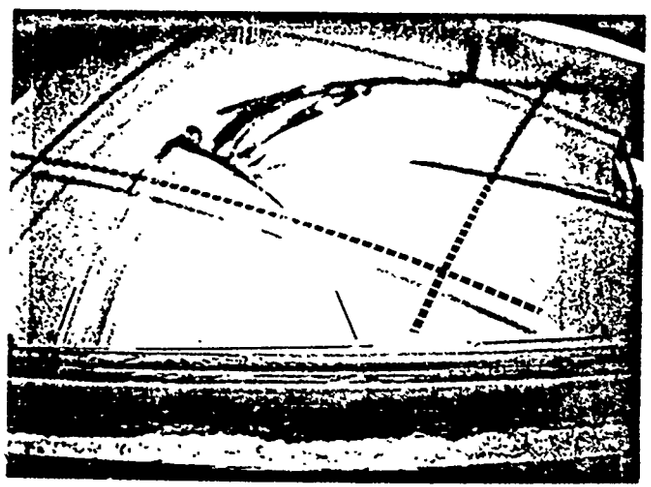


FIG. 1.

PANEL BREAKAGE PATTERN
BEFORE SEPARATION

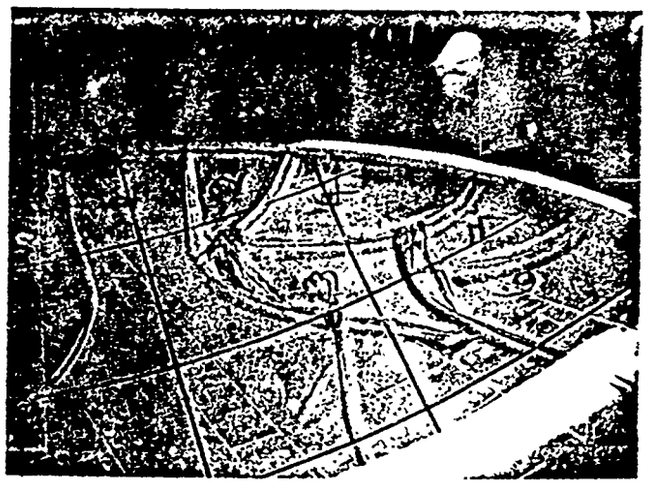


FIG. 2.

PANEL BREAKAGE PATTERN
AFTER SEPARATION

FIG 3

FUNNEL BREAKAGE
AFTER SEPARATION

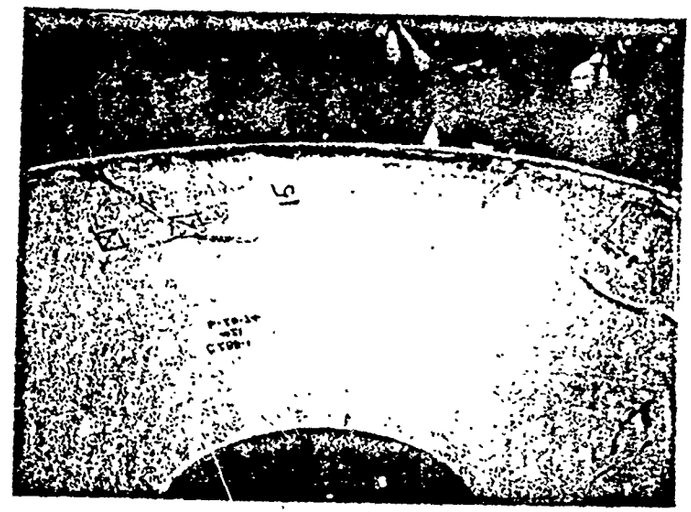


FIG 4

FUNNEL BREAKAGE
AFTER SEPARATION

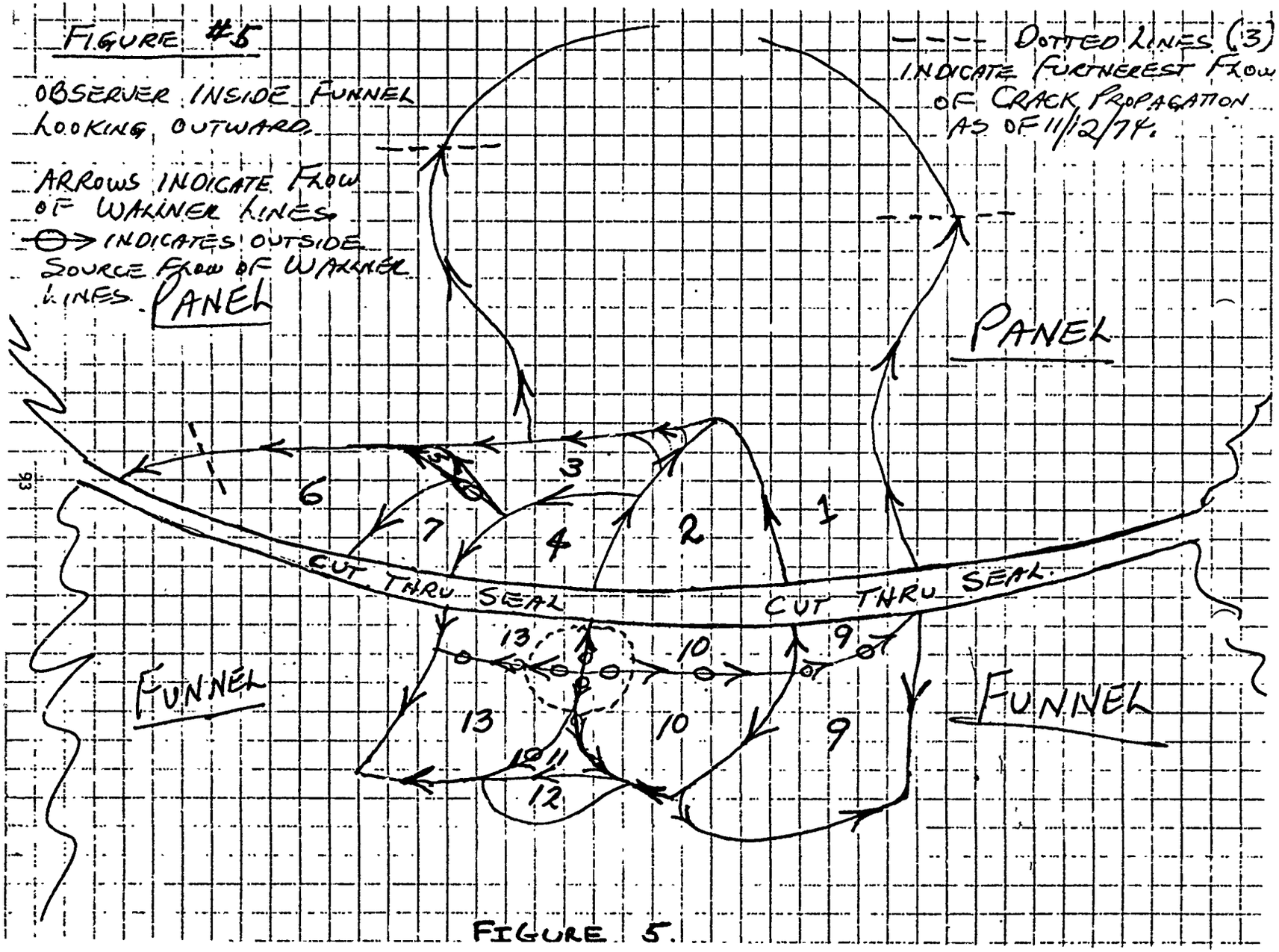


FIGURE #5
OBSERVER INSIDE FUNNEL LOOKING OUTWARD.
ARROWS INDICATE FLOW OF WALINER LINES.
INDICATES OUTSIDE SOURCE FLOW OF WALINER LINES.
PANEL
---- DOTTED LINES (3) INDICATE FURTHEREST FLOW OF CRACK PROPAGATION AS OF 11/12/74.
PANEL
CUT THRU SEAL
CUT THRU SEAL
FUNNEL
FUNNEL
1
2
3
4
6
7
9
10
11
12
13

FIGURE 5.

FARRAND OPTICAL ES-1128 Rev. D
THOMAS TUBE TYPE 36M10PT462M
Serial Number M-24

Revision C
Sheet 24
Test Date 10-9-75
Test Operator S. FOSTER / S. VELGER

PARAMETER	SPECIFICATION REFERENCE FARRAND ES-1128 PARA.	MIL-STD-1311 METHOD	LIMITS MIN	LIMITS MAX	UNITS	TEST
Blemishes	3.3.2.4	5106	---	---	---	S S/US
Gas Ratio		5205.6	---	0.25	Ratio	.01
Voltage Breakdown		5201 Para 4	---	None	---	S S/US
Undeflected Spot Position		5231 Para 1	---	1.0	Inch	.98 Inch
Cathode Cutoff Voltage		5241	---	---	VDC	+162 Volts
Ec2 for cathode cutoff			---	---	VDC	420 Volts
Leakages		5251 Para 1 H-K	---	±10	uA.	7.5 uA
		5251 Para 2 G1	---	±3	uA	0 uA
		5251 Para 3 G2	---	±5	uA	0 uA
		5251 Para 4 G3	---	±5	uA	0 uA
		5251 Para 5 A2	---	±5	uA	4. uA
Heater Current	@ 7.5	1301	---	1.2	A	.78 A
Stray Emission		5216 Para 2	---	---	---	S S/US
Assembly Cutoff Voltage			---	---	VDC	-122 VDC
Zero Bias Anode Current for assembly cutoff voltage		5236	---	---	uA	[illegible] uA
Inter-electrode Capacitance*	3.3.7.1.1	1331				
	a. K to all other electrodes		---	16	pf	14 pf
	b. G1 to all other electrodes		---	20	pf	12 pf
	c. G2 to all other electrodes.		---	100	pf	72 pf
	d. G3 to all other electrodes		---	100	pf	4.5 pf
	e. A2 to housing		---	8,000	pf	[illegible] pf
Contrast Ratio	3.3.2.5.4		100	---	Ratio	107 Ratio
X-Radiation Measurements on axis						
At 5CM			---	---	---	mR/h
At 12 "			---	---	---	mR/h
At 24 "			---	---	---	mR/h
At 30 "			---	---	---	mR/h
Max. Reading at Rear of crt			---	---	---	mR/h

*See Page 25

FARRAND OPTICAL
THOMAS TUBE TYPE 36M10PT462M
Serial Number M-24

Revision C
Sheet 25
Test Date 10-9-74
Test Operator S. FOSTER / A. VELEBIR

PARAMETER	SPECIFICATION REFERENCE FARRAND ES-1128 PARA.	MIL-STD-1311 METHOD	LIMITS MIN	MAX	UNITS	TEST
Brightness & Resolution Modulation	3.5.1					
	Condition A					
	Brightness		630	---	Ft.L.	630 Ft.L.
	Cathode Current		---	---	mA	[illegible] mA
	Cathode Modulation		---	---	VDC	14 VDC
	Resolution		---	0.0434	Inches	[illegible] S/US
	Focus Coil Current		---	---	mA	320 mA
	Condition B					
	Brightness.		840	---	Ft.L.	840 Ft.L.
	Cathode Current		---	---	mA	[illegible] mA
	Cathode Modulation		---	---	VDC	14 VDC
	Resolution		---	0.0345	Inches	[illegible] S/US
	Focus Coil Current		---	---	mA	370 mA
	Condition C					
	Brightness		840	---	Ft.L.	840 Ft.L.
	Cathode Current		---	---	mA	[illegible] mA
	Cathode Modulation		---	---	VDC	14 VDC
	Resolution		---	0.0274	Inches	[illegible] S/US
	Focus Coil Current		---	---	mA	370 mA
Mechanical Dimensions & Marking			---	---	---	5 S/US

GAMMA

BRIGHTNESS CONDITION A

FT.L.(LO)	K VOLTAGE	KIb
630	15	5.0
600	17	4.7
500	26	3.7
400	35	3.0
300	50	2.1
200	62	1.4
100	92	.65
60	105	.30

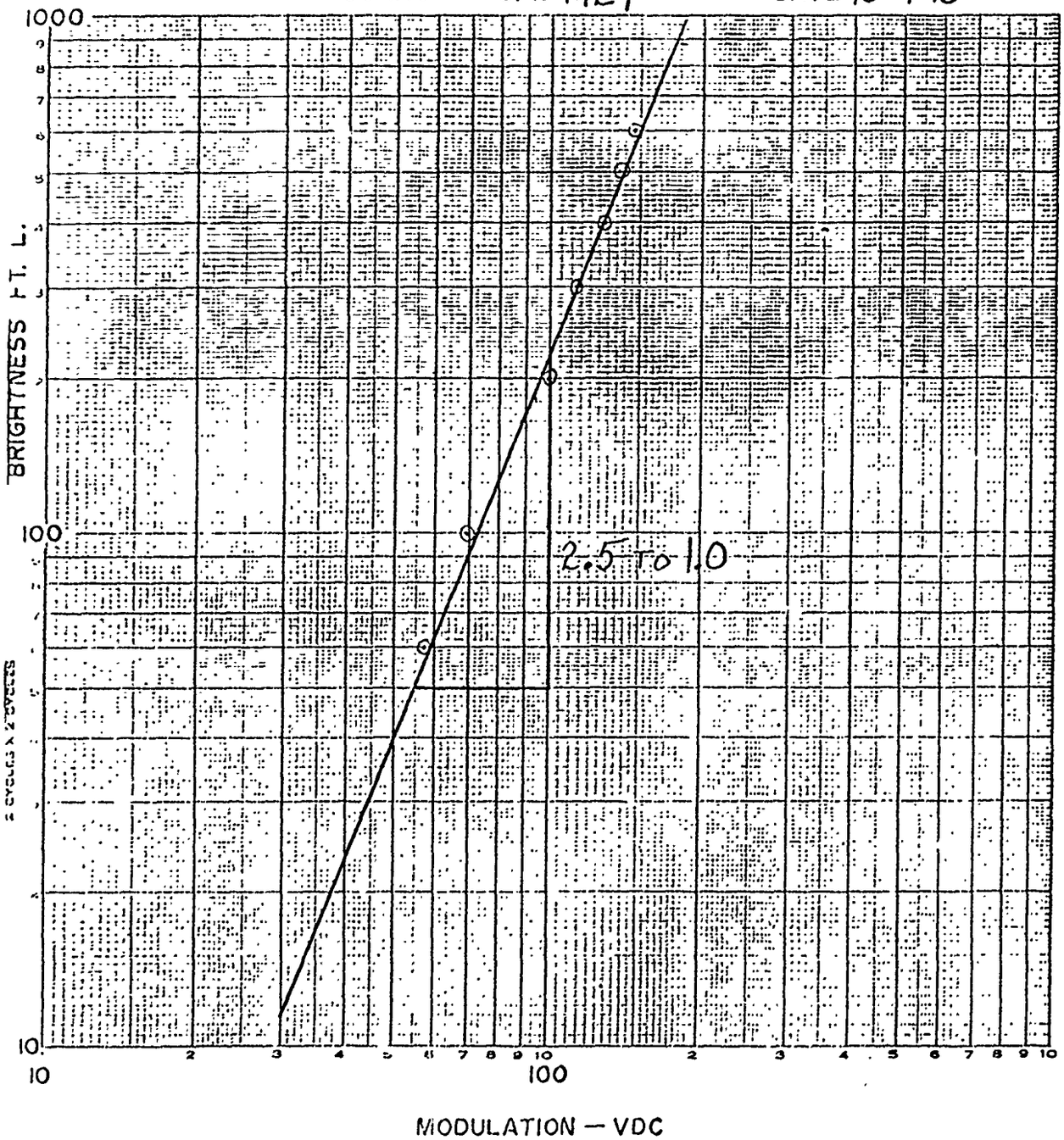
Screen Brightness Uniformity — In between 20% Nom. Ft.L.

C	30	FT.L.
L	[illegible]	FT.L.
R	24	FT.L.
U	[illegible]	FT.L.
D	25	FT.L.

*All measurements for Condition "A" are taken with Ec2 at the voltage measured as described on sheet 13 and 13A.

GAMMA CURVE PAGE 24C

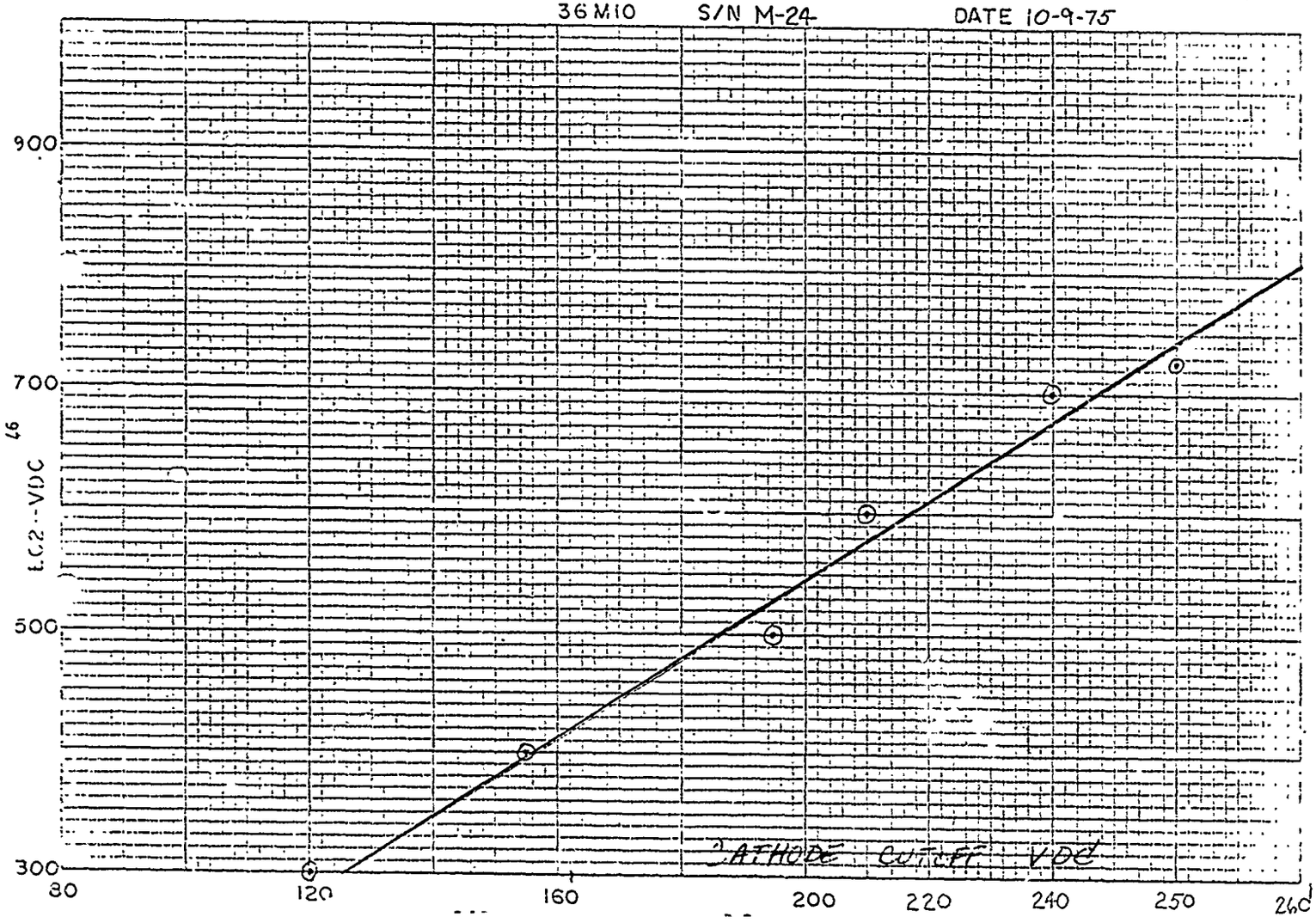
36 M10 S/N M24 DATE 10-9-75



NO 340R-10 DIETZGEN GRAPH PAPER
10 X 10 PER INCH
EUGENE DIETZGEN CO.
MADE IN U. S. A.

EC2 VS CATHODE CUT-OFF

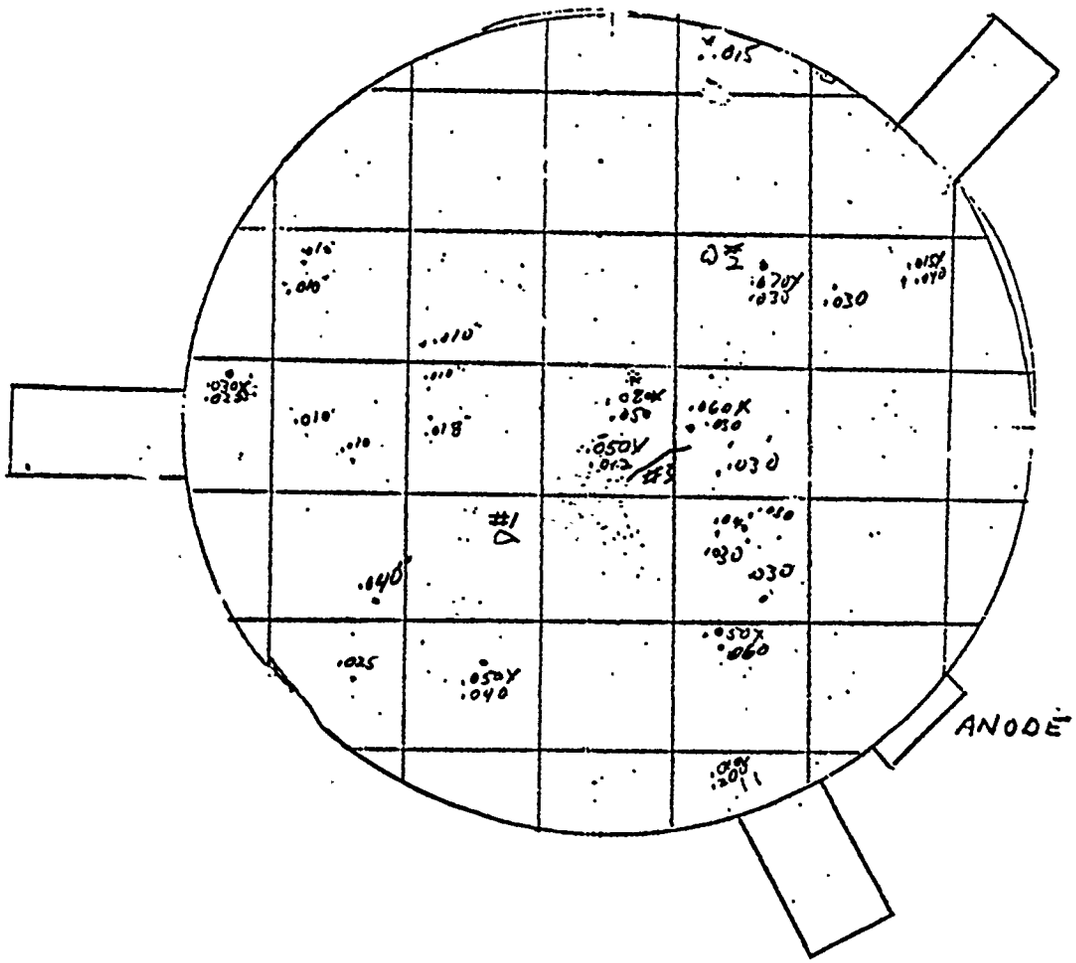
36M10 S/N M-24 DATE 10-9-75



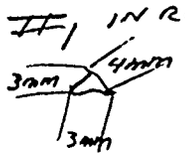
BLEMISH MAP

S/N M24

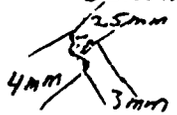
DATE 10-8-75



#1 BLEMISH IN RESIN



#2 BLEMISH IN SCREEN



#3 SCRATCH ON INSIDE OF FACEPLATE .006" WIDE X 2.4" LONG

SEE OTHER SIDE

4. Final Window Alignment Test Data

Date July 24, 1974

FINAL TEST DATA

ASUPT SYSTEM A

Williams Air Force Base, Ariz.

COLLIMATION

Window Ser. No. 102 Position No. 3

Location	Reading		Error
	Divisions	Minutes	
Center			
10^{o} Right	3 1/2 L	17.5	+3.5
10^{o} Up	3 1/2 L	17.5	+3.5
10^{o} Down	3 1/2 L	17.5	+3.5
10^{o} Left	3 1/2 L	17.5	+3.5

1 div. = 5 arc minutes

Left = Divergent

Right = Convergent

Correction Factor for CRT face plate thickness = 2.8 div. = 14 arc minutes
Tolerance + 6 arc minutes

Date July 25, 1974

FINAL TEST DATA

ASUPT SYSTEM A

Williams Air Force Base, Ariz.

COLLIMATION

Window Ser. No. 108 Position No. 4

Location	Reading		Error
	Divisions	Minutes	
Center			
10^{o} Right	3 1/2 L	17.5	+3.5
10^{o} Left	3 1/4 L	16.25	+2.25
10^{o} Up	3 1/2 L	17.5	+3.5
10^{o} Down	3 1/2 L	17.5	+3.5

1 div. = 5 arc minutes

Left = Divergent

Right = Convergent

Correction Factor for CRT face plate thickness = 2.8 div. = 14 arc minutes
Tolerance + 6 arc minutes

Date July 24, 1974

FINAL TEST DATA

ASUPT SYSTEM A

Williams Air Force Base, Ariz.

COLLIMATION

Window Ser. No. 104 Position No. 7

Location	Reading		Error
	Divisions	Minutes	
Center			
15^{o} Right	3 1/2 L	17.5	+3.5
15^{o} Up	3 1/2 L	17.5	+3.5
15^{o} Down	3 1/2 L	17.5	+3.5
15^{o} Left	3 1/2 L	17.5	+3.5

1 div. = 5 arc minutes

Left = Divergent

Right = Convergent

Correction Factor for CRT face plate thickness = 2.8 div. = 14 arc minutes
Tolerance + 6 arc minutes

Date July 24, 1974

FINAL TEST DATA

ASUPT SYSTEM_____

Williams Air Force Base, Ariz.

COLLIMATION

Window Ser. No. 110 Position No. 2

Location	Reading		Error
	Divisions	Minutes	
Center	3 L	15	+1.0
10^{o} Right	4 L	20	+6.0
10^{o} Left	4 L	20	+6.0
10^{o} Up	3 1/2 L	17.5	+3.5
10^{o} Down	3 1/2 L	17.5	+3.5

1 div. = 5 arc minutes

Left = Divergent

Right = Convergent

Correction Factor for CRT face plate thickness = 2.8 div. = 14 arc minutes
Tolerance + 6 arc minutes

Date July 18, 1974

FINAL TEST DATA

ASUPT SYSTEM A

Williams Air Force Base, Ariz.

COLLIMATION

Window Ser. No. 111 Position No. 6

Location	Reading		Error
	Divisions	Minutes	
Center	2.75 L	13.75	-0.25
10^{o} Right	4.0 L	20.0	+6.0
10^{o} Up	3.8 L	19.0	+5.0
10^{o} Down	3.9 L	19.5	+5.5

1 div. = 5 arc minutes

Left = Divergent

Right = Convergent

Correction Factor for CRT face plate thickness = 2.8 div. = 14 arc minutes
Tolerance + 6 arc minutes

Date July 18, 1974

FINAL TEST DATA

ASUPT SYSTEM A

Williams Air Force Base, Ariz.

COLLIMATION

Window Ser. No. 112 Position No. 1

Location	Reading		Error
	Divisions	Minutes	
Center	3L	15	+1.0
5° Right	3 1/2L	17.5	+3.5
5° Up	3 1/2L	17.5	+3.5
5° Down	3 1/2 L	17.5	+3.5
5° Left	3 1/2 L	17.5	+3.5

1 div. = 5 arc minutes

Left = Divergent

Right = Convergent

Correction Factor for CRT face plate thickness = 2.8 div. = 14 arc minutes
Tolerance + 6 arc minutes

Date July 25, 1974

FINAL TEST DATA

ASUPT SYSTEM A

Williams Air Force Base, Ariz.

COLLIMATION

Window Ser. No. 202 Position No. 5

Location	Reading		Error
	Divisions	Minutes	
Center	2.8 L	14	0
15° Up	4 L	20	+6
15° Right	3 3/4 L	18.75	+4.75
15° Left	4 L	20	+6
15° Down			

1 div. = 5 arc minutes

Left = Divergent

Right = Convergent

Correction Factor for CRT face plate thickness = 2.8 div. = 14 arc minutes
Tolerance + 6 arc minutes

Date July 30, 1974

FINAL TEST DATA

ASUPT SYSTEM B

Williams Air Force Base, Ariz.

COLLIMATION

Window Ser. No. 103 Position No. 6

Location	Reading		Error
	Divisions	Minutes	
Center	2 3/4 L	13.75	-0.25
10^{o} Up	3 1/2 L	17.5	+3.5
10^{o} Down	3 1/2 L	17.5	+3.5
10^{o} Left	4 L	20.0	+4.0
10^{o} Right	4 L	20.0	+4.0

1 div. = 5 arc minutes

Left = Divergent

Right = Convergent

Correction Factor for CRT face plate thickness = 2.8 div. = 14 arc minutes
Tolerance + 6 arc minutes

Date July 9, 1974

FINAL TEST DATA

ASUPT SYSTEM B

Williams Air Force Base, Ariz.

COLLIMATION

Window Ser. No. 105 Position No. 4

Location	Reading		Error
	Divisions	Minutes	
Center	2 3/4 L	13.75	-0.25
5^0 Right	3 1/4 L	16.25	+2.25
5^0 Up	3 L	15	+1.0
5^0 Left	3 1/4 L	16.25	+2.25
5^0 Down	3 L	15	+1.0

1 div. = 5 arc minutes

Left = Divergent

Right = Convergent

Correction Factor for CRT face plate thickness = 2.8 div. = 14 arc minutes
Tolerance + 6 arc minutes

Date July 30, 1974

FINAL TEST DATA

ASUPT SYSTEM B

Williams Air Force Base, Ariz.

COLLIMATION

Window Ser. No. 106 Position No. 1

Location	Reading		Error
	Divisions	Minutes	
Center	3L	15	+1.0
10^{o} Up	3 1/4L	16.25	+2.25
10^{o} Down	3 1/2 L	17.5	+3.5
10^{o} Left	3 1/2 L	17.5	+3.5
10^{o} Right	3 1/2 L	17.5	+3.5

1 div. = 5 arc minutes

Left = Divergent

Right = Convergent

Correction Factor for CRT face plate thickness = 2.8 div. = 14 arc minutes
Tolerance + 6 arc minutes

Date July 9, 1974

FINAL TEST DATA

ASUPT SYSTEM B

Williams Air Force Base, Ariz.

COLLIMATION

Window Ser. No. 109 Position No. 2

Location	Reading		Error
	Divisions	Minutes	
Center	3 1/2 L	17.5	+3.5
5° Right	3 1/4 L	16.25	+2.25
5° Down	3 L	15	+1.0
5° Left	3 1/2 L	17.5	+3.5
5° Up	3 L	15	+1.0

1 div. = 5 arc minutes

Left = Divergent

Right = Convergent

Correction Factor for CRT face plate thickness = 2.8 div. = 14 arc minutes
Tolerance + 6 arc minutes

Date July 30, 1974

FINAL TEST DATA

ASUPT SYSTEM B

Williams Air Force Base, Ariz.

COLLIMATION

Window Ser. No. 201 Position No. 5

Location	Reading		Error
	Divisions	Minutes	
Center	2 3/4 L	13.75	-0.25
10^{o} Up	3 1/2 L	17.5	+3.5
10^{o} Down	3 L	15	+1.0
10^{o} Right	3 1/2 L	17.5	+3.5
10^{o} Left	3 1/2 L	17.5	+3.5

1 div. = 5 arc minutes

Left = Divergent

Right = Convergent

Correction Factor for CRT face plate thickness = 2.8 div. = 14 arc minutes
Tolerance + 6 arc minutes

5. Theory of Operation of Farrand Infinity In-Line Optical System and Ghost Images.[3]

Ray Trace

The system consists of a single image forming element, a spherical mirror. The observor's viewpoint is at the center of curvature of this mirror. The object surface is spherical and is concentric with the spherical mirror and one half this mirror's radius of curvature. This surface is then the focal surface of the spherical mirror and is projected to infinity. The size of the object surface determines the field of view the observer will see.

This elementary system is shown in Figure A. This is the theoretical imaging condition for a spherical mirror, but is impractical with a large object surface (large field of view) because the object surface obscures the observer's view so that even moving his viewpoint outward from the center of curvature he cannot see the object surface. It is necessary to remove the object from the position shown. This is done with a plane beam splitter in Figure B. Rays from the object proceed through the spherical mirror which must in this case be semi-transparent - thus a beamsplitter also - and reflect from the plane beam splitter. A virtual object surface is thus formed in the position of the real object surface of part (a) of the figure and the system functions as it did before, but now the observer can see the field of view with no obscuration. He can also see some grossly undesirable things such as the object surf directly and unwanted

images or ghosts arising from multiple reflections between the plane and spherical beam splitters. The Farrand Infinity In-line Optical Display System uses a unique method of suppressing unwanted images and the direct view of the object surface. This is done by the use of plane and rotational polarizing elements so that ideally only the wanted infinity image emerges from the display and is seen by the observer.

Practically, this is not a completely achievable condition and dome light from the ghost images and the direct view of the object surface emerge as well. This will be quantitively discussed later. The operation of the system will be explained with the aid of Figure C.

Four polarizing elements are added to the basic geometrical optical system of Figure B. These are two plane polarizers and two quarter wave plates, and these elements function in the following manner to transmit the infinity image and suppress unwanted images. A ray from a point, O_1, on the object surface enters the display system passing through the entrance plane polarizer, P_1. The ray now polarized is incident on the spherical mirror beam splitter. Part of the ray is reflected back toward the object surface and part is transmitted through the spherical beam splitter. We are concerned principally with the part that is transmitted through the spherical beam splitter. The part that is reflected by this element returns to the object surface, and since

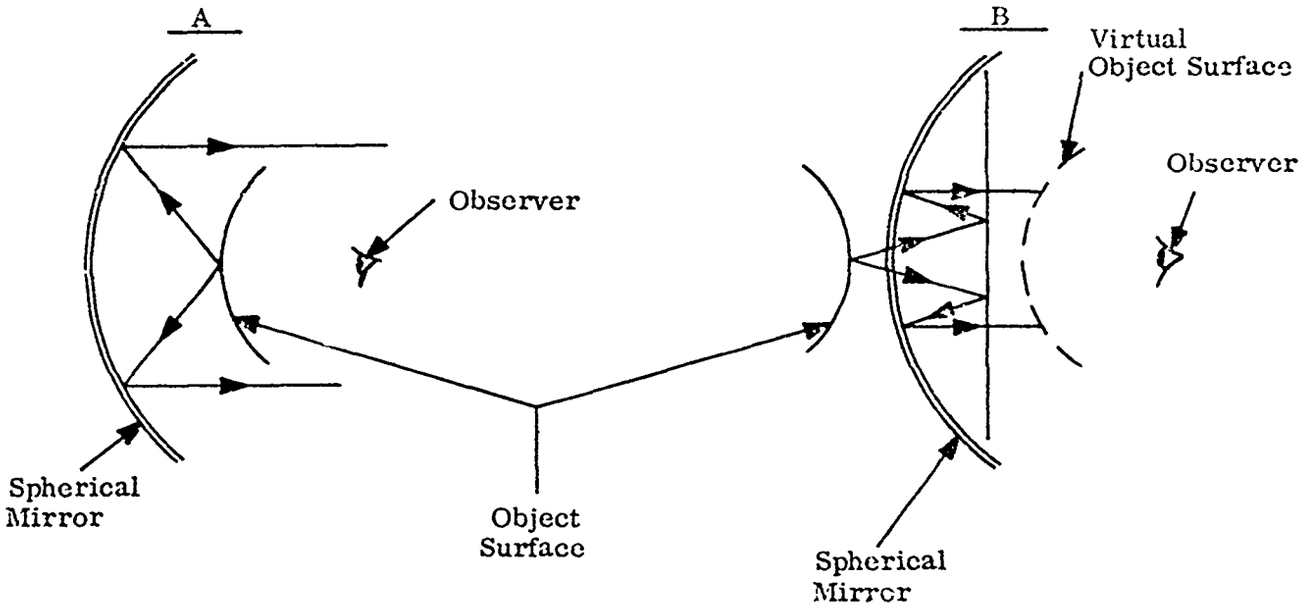
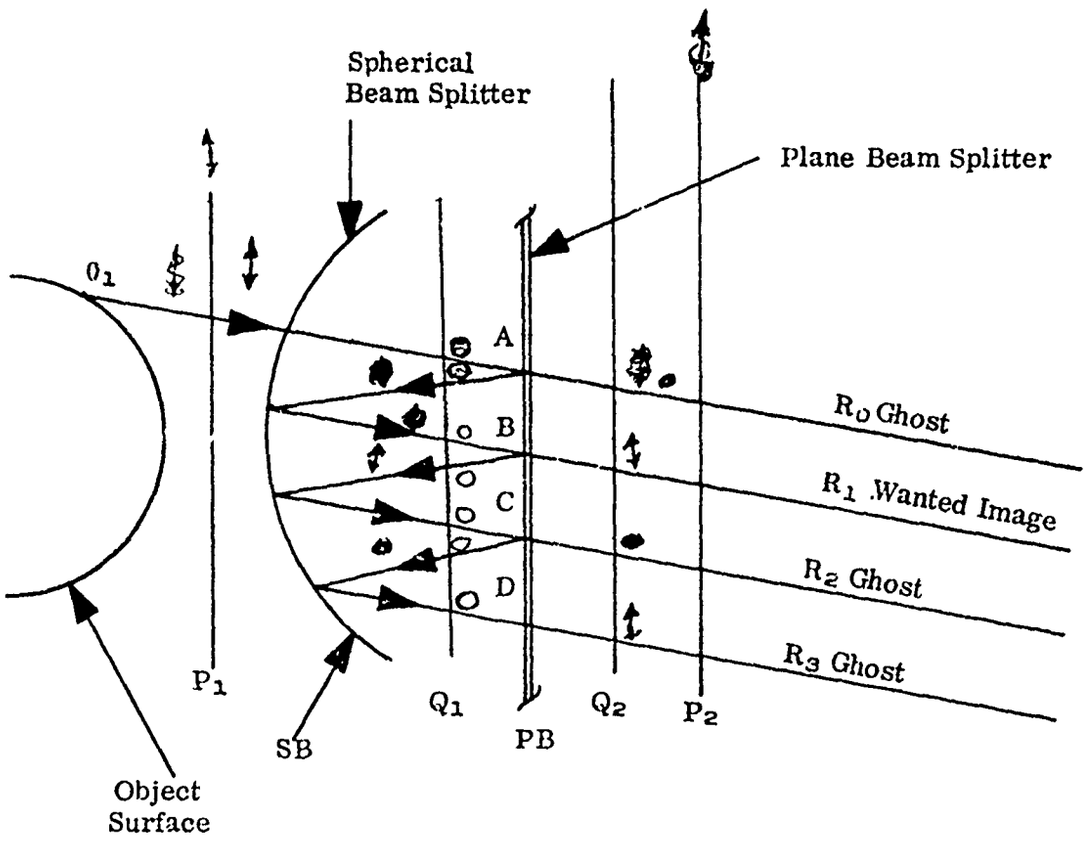


Figure A,B Folded Concentric Spherical Optical System



P_1, P_2 Plane Polariziers

Q_1, Q_2 Quarter Wave Plates

Schematic Illustration of Farrand Infinity
In-Line Optical Display

Figure C.

it returns to a different point than O_1, it causes a contrast reduction. In general, the spherically convex surface of the beam splitter diverges this reflected light so the contrast reduction is greatest at the center of the object surface. This, as will later be shown, is a contributing cause of reduced modulation transfer function at the center of the display.

The light transmitted through the spherical beam splitter proceeds through the quarter wave plate and emerges circularly polarized. It is both reflected and transmitted by the plane beam splitter at A, and we are concerned principally with the reflected ray. The transmitted ray proceeds through the second quarter wave plate, Q_2, emerges plane polarized 90 degrees to its former plane of polarization, and is absorbed in the second plane polarizer which is aligned parallel to P_1. This absorption is incomplete causing the observer to see the object surface directly. This artifact of the optical system is called the R_o ghost. The ray reflected from PB at A first passes through Q_1 a second time and is then reflected from the spherical beam splitter, SB. It is now plane polarized 90 degrees to its former direction having passed through Q_1 twice. After reflection from SB, it again passes through Q_1 and is circularly polarized in the opposite direction. It proceeds thence to plane beam splitter PB, and part is reflected and part transmitted at B. We are concerned principally

with the transmitted part and will return to trace the reflected ray subsequently. The transmitted ray goes through quarter wave plate, Q_2, and emerges plane polarized parallel to its original plane of polarization. It is therefore transmitted by P_2 which is aligned with P_1. This ray is one of the rays forming an infinite image of object point O_1. It has, in addition to being focused by the spherical mirror folded optical system, been plane polarized, then returned a full wave length by passing four times through quarter wave plates, and finally transmitted by a plane polarizer aligned with the plane polarizer that initially polarized it. It is the only ray that can traverse the system without suffering extinction by the polarizing elements or severe attenuation by multiple reflection. Of course there are many such rays from each object point, but all must travel through an equivalent combination of reflecting and polarizing optics to contribute to the infinity image. All other possible paths of rays reflected by the beam splitters are extinguished by the exit polarizer or severely attenuated by multiple reflections.

We return to the component of the ray reflected from PB at B. It passes through Q_1 to become plane polarized parallel to its initial direction. It is both transmitted and reflected by SB, the transmitted part passing through P_1 to illuminate the object surface, although it is so attenuated by multiple reflections that its

reduction of contrast is minimal. The part reflected by SB is passed through Q_1 a fifth time and strikes PB at C. The portion transmitted goes through Q_2. This ray has now made six passes through quarter wave plates so it is polarized 90 degrees from its initial direction. It is extinguished by P_2. The extinction is not complete so some light emerges to form ghost image, R_2. Since this light has reflected twice from the spherical mirror, it is being focused by an optical system having approximately twice the power of that focusing the wanted image, and consequently the ghost image, R_2, is formed half the distance between the spherical mirror and the observer.

The ray reflected from PB at C is again reflected by SB to intersect PB at D. It is transmitted through Q_2 and having passed eight times through quarter wave plates is aligned with P_2 and is transmitted. It has been severely attenuated by multiple reflections from the beam splitters but nonetheless forms ghost image, R_3, which is approximately equal to R_2 in brightness. Each of the In-line Infinity Optical Display Systems is compactly folded on its own optical axis. This compactness, as compared to other reflective optical displays, has earned them the name of "Pancake Window" since they are comparatively flat, and the observer looks through them at the simulated world as he would look through a window at the real world. In the ASUPT displays, the In-line Infinity Optical Systems are indeed assembled as windows having contiguous fields of view.

These windows are assembled as facets of a dodecahedron which enclose an observer located at the intersection of their optical axes. The dodecahedron array is inscribed in a 48-inch radius sphere. This sphere is the spherical mirror (beam splitter) of the Farrand In-line Infinity Image Display. Each of these displays is a facet of the dodecahedron, and each has its own segment of the spherical mirror. When the facets are aligned with respect to each other, they have a common center point and the individual spherical mirror segments are parts of the same spherical surface.

Ghost Images

The three ghost images whose origin was explained previously are superimposed on the wanted infinity image and reduce its contrast. These ghosts are all closer to the observer than the infinity image and are not perceived as having structure when the eye is accommodated to the infinity image. They appear as a haze or veiling glare superimposed on the wanted infinity image and reduce its contrast.

Only when an image point is on axis are ghosts of that point superimposed on it. When the image point moves from the display axis toward the edge of its field, the ghost images all move at different rates and separate from the wanted image point. The R_2 and R_3 ghosts of the image point move at higher angular rates than the wanted image so they leave the field of view before it reaches the edge of the field. The R_0 ghost moves at a slower angular rate than the wanted image so it always remains in the field. Thus in the usual viewing situation

when the image point is other than on the display axis, it is surrounded by a combination of ghosts from other image points rather than its own ghosts.

☆U S GOVERNMENT PRINTING OFFICE: 1976-671-623/6