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RESEARCH INVESTIGATIONS ON PHOTO FACSIMILE TRANSMISSION TECHNIQUES

REPORT NO. 2
SECOND QUARTERLY PROGRESS REPORT
1 OCTOBER 1962 THRU 31 DECEMBER 1962
CONTRACT NO. DA36-039 SC-90862
DEPARTMENT OF ARMY PROJECT NO. 3A99-12-001

U.S. ARMY SIGNAL RESEARCH AND DEVELOPMENT LABORATORY
FORT MONMOUTH, NEW JERSEY

THE MARQUARDT CORPORATION
16555 SATICOY STREET  VAN NUYS, CALIFORNIA
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Gentlemen:

Subject: Photo Facsimile Transmission Techniques
Contract No. DA 36-039 SC-90862
Second Quarterly Progress Report

1. In accordance with Contract No. DA 36-039 SC-90862 the Second Quarterly Progress Report is being forwarded to you.

2. This report covers the period from 1 October 1962 through 31 December 1962.

THE MARQUARDT CORPORATION

Thomas G. Bek, Manager
V. N. Contract Administration Section

TGB:WHH:bg
RESEARCH INVESTIGATIONS ON
PHOTO FACSIMILE TRANSMISSION TECHNIQUES

Report No. 2
Second Quarterly Progress Report
1 October 1962 thru 31 December 1962
Contract No. DA 36-039 SC-90862
Signal Corps Technical Requirements No. SCL-4362A
dated 2 February 1962
Department of Army No. 3A99-12-001

Objective: A research investigation leading to the development of techniques useful in the design of a facsimile scanner which shall be capable, upon command, of capturing an optical image, scanning it with high resolution and storing it or directly transmitting it via radio to a facsimile recorder.

Report prepared by
W. H. Hell
B. Case
J. A. Howard
R. M. Ransier
C. Schuppe
J. A. Widmer

THE MARQUARDT CORPORATION
VAN NUYS, CALIFORNIA

Report No. 25069
TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>PURPOSE</td>
<td>iv</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>v</td>
</tr>
<tr>
<td>PUBLICATIONS, LECTURES, REPORTS, AND CONFERENCES</td>
<td>v-i</td>
</tr>
<tr>
<td>I INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>II SYSTEM ANALYSIS</td>
<td>4</td>
</tr>
<tr>
<td>A. Summary</td>
<td>4</td>
</tr>
<tr>
<td>B. Scene Composition Physical Basis</td>
<td>5</td>
</tr>
<tr>
<td>C. Image Transducing Parameters - An Image Transducer Survey</td>
<td>30</td>
</tr>
<tr>
<td>D. Recommendations</td>
<td>69</td>
</tr>
<tr>
<td>E. References</td>
<td>70</td>
</tr>
<tr>
<td>III COMPONENT RESEARCH</td>
<td>74</td>
</tr>
<tr>
<td>A. Summary</td>
<td>76</td>
</tr>
<tr>
<td>B. Component Techniques - Readout Methods</td>
<td>86</td>
</tr>
<tr>
<td>C. Image Retention Services</td>
<td>96</td>
</tr>
<tr>
<td>D. Fiber Optic Arrays</td>
<td>101</td>
</tr>
<tr>
<td>E. Recommendations</td>
<td>102</td>
</tr>
<tr>
<td>IV MATERIAL STUDY</td>
<td>103</td>
</tr>
<tr>
<td>A. Summary</td>
<td>103</td>
</tr>
<tr>
<td>B. Literature Survey</td>
<td>105</td>
</tr>
<tr>
<td>C. Experimental Investigation</td>
<td>149</td>
</tr>
<tr>
<td>D. Recommendations</td>
<td>156</td>
</tr>
<tr>
<td>E. References</td>
<td>157</td>
</tr>
<tr>
<td>V CONCLUSIONS</td>
<td>158</td>
</tr>
<tr>
<td>VI PROGRAM FOR NEXT INTERVAL</td>
<td>159</td>
</tr>
</tbody>
</table>
LIST OF FIGURES AND TABLES

<table>
<thead>
<tr>
<th>FIGURES</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Proposed Standard Solar Irradiance Curves</td>
<td>9</td>
</tr>
<tr>
<td>2.</td>
<td>Direct Solar Illuminance at the Earth's Surface on a Plane Normal to the Sun's Rays</td>
<td>10</td>
</tr>
<tr>
<td>3.</td>
<td>Illuminance on the Horizontal Plane Due to Light from the Clear Sky as a Function of Solar Altitude</td>
<td>13</td>
</tr>
<tr>
<td>4.</td>
<td>Illuminance Due to Sunlight as a Function of Solar Altitude</td>
<td>15</td>
</tr>
<tr>
<td>5.</td>
<td>Illuminance Due to Skylight as a Function of Solar Altitude</td>
<td>16</td>
</tr>
<tr>
<td>6.</td>
<td>Spectral Composition at Various Radiant Energies</td>
<td>24</td>
</tr>
<tr>
<td>7.</td>
<td>Spectral Response Characteristics of Typical Emissive Surfaces</td>
<td>52</td>
</tr>
<tr>
<td>8.</td>
<td>Space Frequency Response Characteristics of Typical Image Transducing Tubes</td>
<td>55</td>
</tr>
<tr>
<td>9.</td>
<td>Degradation of Resolution Due to Lateral Charge Leakage For a Specific Target as a Function of Integration Time</td>
<td>57</td>
</tr>
<tr>
<td>10.</td>
<td>Theoretical Variation of Resolution with Wavelength Which Might Be Obtained in a Target</td>
<td>58</td>
</tr>
<tr>
<td>11.</td>
<td>Response Characteristics of Some Standard Image Tubes as a Function of Scan Rate</td>
<td>62</td>
</tr>
<tr>
<td>12.</td>
<td>Salient Characteristics of Various Image Transducers</td>
<td>64</td>
</tr>
<tr>
<td>13.</td>
<td>Resolution As a Function of Photocathode Illumination For Several Sensors</td>
<td>66</td>
</tr>
<tr>
<td>14.</td>
<td>Signal to Noise Ratio (S/N) As a Function of Photocathode Illumination For Several Sensors</td>
<td>67</td>
</tr>
<tr>
<td>15.</td>
<td>Spectral Irradiance Required at Entrance Aperture of 1 cm² For Detection of Minimum Number of Photons With Different Integration Times</td>
<td>68</td>
</tr>
</tbody>
</table>
16. Kaiser-Aiken Facsimile Tube 81
17. Moving Lens Scanning System 83
18. Single Mirror Scanner 84
19. Cross Section Thru Mirror Light Collecting System 85
20. Optron Storage Element 87
21. Multi Mode Optron Storage Element 89
22. Optron Matrix 91
23. Light Storage Element (Ferrotron) 92
24. Multi-Element Image Storage Screen 94
25. Insulated Fiber Drawing Machine 97
26. Methods of Fiber Fabrication 100
27. Electron Transition Processes 135
28. Ultraviolet Exposing Unit 151
29. Graphite Layer Pressing Equipment - Overall 152
30. Graphite Layer Pressing Equipment - Closeup 153
31. Potassium Bromide Wafers 155

TABLES
I Luminance of the Clear Sky, Winter and Summer Values 12
II Luminance Values For Various Atmospheric Conditions 18
III Luminance Characteristics of 126 Outdoor Scenes Under Daylight Conditions 28
IV Some Typical Facsimile Equipment 46
V Summary of Properties of Typical Electroluminors 103
VI Summary of Properties of Typical Photoconductors 122
VII Summary of Properties of Typical Double Activated Phosphors 132
PURPOSE

The theoretical and experimental research study under this contract is directed toward investigating pertinent materials and components with the purpose of evolving a new design concept for an advanced image transducer. Major emphasis in the study is on (1) photosensitive material having the properties of storage and erasure, (2) component techniques for achieving high resolution, fast and accurate readout of the stored information and (3) image transducer system analyses. The ideas, techniques and data evolved in the study will be applied to the generation of a design recommendation for the construction of a feasibility model of an advanced image transducer.
ABSTRACT

The major effort during the second quarterly period on advanced photofacsimile transmission techniques has been directed toward a comprehensive survey of image transducing materials. In addition, work was continued on system analysis and component technique investigations.

Representative data for describing scenes was acquired. While no attempt was made to classify all possible scenes, sufficient examples are presented to establish guide-lines for transducer requirements as functions of active scene irradiance and of geometry and spectral properties of scene elements. The image transducing parameter study was continued. Data on performance characteristics and practical parametric interrelationships of most types of image transducing techniques is presented.

Several line scanning techniques for the optical readout of a stored image have been investigated. These techniques include a programmed matrix light source with a fiber optic converter to provide a line scan, a flying spot scanner employing a fiber optic line converter, and the Kaiser Electronic special line scan facsimile tube. Furthermore, a number of novel mechanical scanner configurations have been conceived.

Two image storage techniques were studied: (1) The optron (a photoconductor-electroluminophor combination); (2) the ferrotron (a photoconductor-ferroelectric combination). The former has achieved 80 lines per inch resolution and 0.1
foot candle sec. sensitivity, while the latter has achieved 250 lines per inch under an illumination of 0.001 foot candles, and appears more promising as a component for an advanced photo facsimile transmission system.

Methods of automatic fabrication of an ordered fiber optic array for high resolution image dissection were investigated. The evolution of a device capable of providing fibers in vast numbers and of the small diameter required for the array contemplated would entail a prohibitively costly development, at least in the near future.

An extensive literature search was made to uncover materials displaying properties which may make them useful in an image transducing device. As a result of this search, material characteristics associated with the phenomena of photoconductivity, electroluminescence, double-activated phosphorescence, and phototropism are listed. Materials exhibiting properties associated with the ferro-electric phenomenon have yet to be investigated in the literature search.

Experiments were made to develop a transparent synthetic form of hackmanite. In these experiments, a novel approach using elevated temperatures and pressures in the forming process was employed.
PUBLICATIONS, LECTURES, REPORTS AND CONFERENCES

A. Publications:
None

B. Lectures:
None

C. Reports:


C. Conferences:

Date: 1 October 1962
Location: Polacoat, Inc., Blue Ash, Ohio
Subject: Research on Phototropic Materials
Present: John F. Dryer, Polacoat, Inc.
        Robert W. Harries, "  "
        J. A. Widmer, The Marquardt Corporation

Resume: The use of hackmanite as a phototropic information storage medium is feasible. Theoretical and experimental research should be continued to determine methods of practical application.

The use of photochromic dyes as storage media is less promising than the use of hackmanite because of the gradual deterioration of the phototropic material due to unwanted side reactions.

Date: 2 October 1962
Location: Horizons, Inc., Cleveland, Ohio
Subject: Possible application of photochromic dyes as a high density information storage medium.

Present: Robert Sprague, Horizons, Inc.
         Eugene Wainer, " "
         J. A. Widmer, The Marquardt Corporation

Resume: The research program at Horizons, Inc. has uncovered many interesting photochromic dyes oriented toward photo recording and picture formation. At the current stage of development, none are applicable to use in the image transducer on the subject contract as a consequence of lack of erasure capability.

Date: 10 October 1962
Location: Bureau of Standards, Washington, D. C.
Subject: Instrumentation for measuring characteristics of phosphors.
Present: Dr. Telle, NBS
         J. A. Widmer, The Marquardt Corporation

Resume: Instrumentation for measuring the photometric characteristics of phosphors was discussed.

Date: 19 December 1962
Location: Optics Technology, Belmont, Calif.
Subject: Fiber Optics fabrication
Present: Dr. Kapony, Optics Technology Incorporated
         B. Case, The Marquardt Corporation
         R. Ransier, The Marquardt Corporation

Resume: The state-of-the-art in fabricating fiber optics does not now permit the automatic and economical construction of an ordered fiber optics array employing the vast number of fibers necessitated by the application as a readout component of the image transducer for the subject contract.
I. INTRODUCTION

In order to improve on the present state-of-the-art in image transducing, broad research work to develop new approaches was outlined in the First Quarterly Report in three areas: (1) system analysis; (2) component research; (3) materials study. As the work progressed, the least promising materials and techniques were to be eliminated, resulting in a systematic narrowing of the possible approaches.

In the area of system analysis, the two fundamental problems are: (a) defining desirable image transducer performance characteristics; (b) defining their theoretical and practical limitations. During the first quarter, scene composition studies were effected and a study of parametric interrelationships was initiated. In order to provide insight into the performance characteristics and practical limitations of image transducers, a survey of the state-of-the-art in existing systems was needed. This survey would also be useful in establishing design criteria for the advanced system.

Under the category of component research, it was pointed out in the First Quarterly Report that an image transducer system requires components capable of image retention and readout. One of the requirements of a system is that the storage medium for image retention be capable of erasure. Only recently have new developments along this line been made. These developments (thermoplastic and photostatic tapes, optron and ferrotron) should be investigated to determine their applicability to the
problem at hand. If they are not suitable, an entirely new approach based on the findings of the material study may be required. For image readout, the matrix switching method and the line or raster scan method are considered. Evaluation of the former awaits the outcome of the material survey. Raster scan suffers from a basic limitation on resolution capability which is a function of the ratio of scan length to beam width. Improved resolution of electronic scanning techniques can be achieved through the use of an ordered fiber optic array. Another possible method for improving the resolution of electronic scanning techniques consists of converting the elements of a raster into a single line, with orthogonal scanning accomplished by moving the image with respect to the line.

The selection of materials is based upon material characteristics and upon the configuration of the entire image transducing system. It was found during the first quarter that the available literature on materials often contained data of a descriptive nature, devoid of information required for application to an image transducer (e.g., quantum efficiency). For this reason, experiments are required in order to obtain the needed parameters. Experiments are time-consuming, however, and must be limited to the most promising materials. It was indicated in the First Quarterly Report that hackmanite in its natural form is not suitable for use in the contemplated image transducer. Therefore, a decision was made to investigate the possibility of fabricating a synthetic form of the material.
Since no specific material has been selected for use in an image transducer, the approach was to initially consider all materials exhibiting suitable properties associated with the image transducing phenomena. In the previous report the number of suitable phenomena has been narrowed, thereby reducing the materials that can be considered for evaluation. Ultimately, as a result of this process of elimination, the most promising of the many materials will be selected for consideration in an advanced image transducer system.
II SYSTEM ANALYSIS

A. SUMMARY

During the last quarter, the following has been accomplished in the area of systems analysis:

(1) Completion of scene composition studies
(2) Continuation of image transducer parameter studies

The specific requirements for defining the composition of a scene were detailed in the First Quarterly Progress Report. During this quarter, specific data were gathered to allow a full description of the scene and completion of the analytical research study in line with the original objectives. This information consists of representative data for evaluating the irradiance in many active scenes and an expanded study of the relative importance of the geometry and spectral properties of the scene elements. It is shown that these data used in conjunction with the scene categorization method reported in the First Quarterly Progress Report allow the complete specification of many representative scenes. No attempt was made to completely classify all scenes since this is beyond the scope of the present study. However, several representative examples of scene categorization are given.

During the past quarter, the transducer parameter study has been concerned with: (1) establishing ranges for the several parameters based on practical transducer limitations; and (2) obtaining a more comprehensive picture of the relative importance of the parameters as a function of transducer mission in order that trade-off possibilities can be delineated. To meet these objectives, a survey of the present state-of-the-art of image transducers has been conducted. The results of this survey briefly summarize the characteristics of image transducer systems and discuss the interrelation of the various parameters from a practical viewpoint.
B. SCENE COMPOSITION PHYSICAL BASIS

The specific requirements for a more extensive review and presentation of radiometric data describing a range of passive and active scenes was made clear in the First Quarterly Progress Report. Although some average or representative data for active (transient luminance pattern) and passive (steady state) scenes were reported, the very large literature of this technical area was hardly touched. During the past quarter, this analytical research study has been continued and been brought to effective completion in the light of the objectives of the preliminary study. Scenes were defined in the context of a flow diagram in the last report. In review, the scene characteristics are:

a. **Radiant excitation** - Quantity, directional character (collimated to perfectly diffused) temporal variation and spectral distribution of the radiant flux incident on the scene elements.

b. **Geometric Detail** - angular size, shape, and orientation of significant detail (dictated by the acuity of the read-out instrumentation) in the scene in terms of scene aspect (distant, semi-distant, etc.)

c. **Spectral Properties of Scene Elements** - the spectral reflectance, absorptance, and transmittance of significant detail in the scene; classification in terms of gray (non-selective) and spectral range (selective or variant in wavelength).
Additional specific data identified with the above scene properties are reported here to allow further development of the unique classification system reported earlier. This physical data for ranges of scenes with various G (Geometry), E (Excitation), and S (Spectral) characteristics provides the input information necessary for the evaluation of a variety of image transducing effects. In this section, the required G, E, and S data is reported. This is, of course, a preliminary study that cannot include all available data but the presentation is so structured that additional significant data can be introduced as it becomes available.

1. Radiant Excitation

Multiple, highly variable radiant sources are characteristic of outdoor active reconnaissance scenes while passive scenes (e.g., the photographic image) are generally illuminated with controlled sources of well-known spectral, temporal, and directional properties. For this reason, the more demanding aspects of illuminants for the active scene are treated here. When direct solar irradiation is available to a scene within the earth's atmosphere, both the collimated sunlight and the scattered skylight contribute to the luminance pattern viewed by the image transducer. In addition to differences in quantity and quality (spectral distribution), direct solar illumination and scattered skylight are most strikingly distinguished by their directional aspects. Direct sunlight is effectively collimated (sun subtends an angle of 0.5 degrees) and thus produces strong shadows in a typical scene. Differently, the sky is a source of effectively infinite dimensions (occupies half space with respect to the horizontal plane) and is thus a diffuse illuminant capable of producing only weak, poorly defined shadows.
Objects of scene elements that receive no direct sunlight are often largely illuminated by the diffuse skylight of a strongly blue character relative to the effectively white direct sunlight.

Direct sunlight and skylight are strongly affected by the atmosphere. Although the effective height of the earth's atmosphere is about 60 miles, the path length through the atmosphere in the direction of the zenith is equivalent to only about 5 miles with the same gases compressed to sea-level conditions. At directions away from the zenith, the effective path length through the atmosphere increases and the direct sunlight reaching the earth's surface is diminished. Water vapor, condensed water vapor, dust particles, smoke, etc., are the principal contaminants of the atmosphere that influence the sunlight and scattered skylight on the scene. Rayleigh scattering in the atmosphere gases accounts for the blue sky while the Mie scattering function describes the skylight scattered by particles.

a. Direct Sunlight

As suggested above, the direct solar illumination at the scene within the earth's atmosphere is dependent on:

(1) Variations in solar emission with time
(2) Seasonal differences in the earth-sun distance (7% difference in flux intensity from January to July)
(3) Amount of water vapor as a function of latitude, altitude, distance from the oceans and gaseous temperature.
(4) Dustiness or haziness of the atmosphere
(5) The zenith distance of the sun for a particular location which is a well defined function of the latitude, time of day, and time of year.

(6) The altitude above sea level. Taking all these factors into account, the data of Figure 1 contain proposed standard solar irradiance curves.

In Figure 2, the spectral solar irradiance on a plane normal to the sun's rays is shown with the number of air masses through which the flux has passed as the parameter. Zero air mass ($m = 0$) corresponds to a location outside the earth's atmosphere. When the sun is at the zenith, the air mass is taken as unity. These curves are applicable to a scene at sea level with some condensed water vapor present and a relatively small amount of dust. The change in curve shape with increasing air mass (atmospheric path length) is related to increased scattering.

Using the standard photopic response function, the spectral curves of Figure 1 can be converted to illumination curves by an integration process. The results are plotted in Figure 2 which depicts the direct solar illumination at the earth's surface (sea level) as a function of air mass through which the sun is viewed. As shown in Figure 2, the experimental values vary somewhat with the time of year but the average is in good agreement with the computed solid line. Note that the ordinate of Figure 2 is expressed in terms of "lumens/sq. meter" which is approximately equivalent to foot-candles or lumens/ft$^2$ by divided by 10. Thus, at air mass zero or outside the earth's atmosphere, the illuminance is about 12,000 lumens/ft$^2$ and at the earth's surface with an air mass of unity (sun at the zenith) the value is about 9800 lumens/ft$^2$. 
PROPOSED STANDARD SOLAR IRRADIANCE CURVES (WATTS/m²/µ),
ON A PLANE NORMAL TO THE SUN'S RAYS, OUTSIDE THE EARTH'S
ATMOSPHERE (m=0), AND AT THE EARTH'S SURFACE FOR AIR
MASSES OF 1, 2, 3, 4, AND 5.

CONDITIONS: ATMOSPHERIC PRESSURE = 760mm
PRECIPITABLE WATER = 20mm
DUST = 300 PARTICLES/cm³
OZONE = 2.8 mm

R-14,560 REF: JOSA, VOLUME 38, NO. 2, FEBRUARY, 1948 FIGURE 1
DIRECT SOLAR ILLUMINANCE (LUMENS/m²) AT THE EARTH'S SURFACE ON A PLANE NORMAL TO THE SUN'S RAYS

DIRECTLY DETERMINED EXPERIMENTAL VALUES ARE REPRESENTED BY THE PLOTTED POINTS

REF: JOSA, VOLUME 38, NO. 2, FEBRUARY 1948

FIGURE 2
b. **Clear Atmosphere Skylight**

Great variability in the skylight conditions makes a generalized representation of the data much more difficult than the case of direct sunlight. The most useful set of data describing the directional aspect of skylight as a time of year is shown in Table I. The data of Table I show that the sky is far from uniform in luminance with the maximum values in the direction of the sun and with the minimum values found about 90° in azimuth from the sun's direction. Integration of the variable luminance over the entire sky vault produces the illuminance on a horizontal plane. This integration process performed numerically for a variety of sky luminance distributions measured on a world-wide basis results in a range of curves around the single curve shown in Figure 3. Obviously, "clear sky" is judged visually in terms of luminance distribution at various locations (latitudes, propinquity to the sea, and altitude above sea level). The averaged values of illuminance on a horizontal plane from a clear sky as shown in Figure 3 are regarded as a suitable standard for input to various daytime reconnaissance scenes. The total illuminance of the scene is obtained from the sum of the values presented in Figures 2 and 3. For example, the total illuminance of a horizontal plane on a clear day with sun at the zenith is 9570 lumens/ft² (direct sunlight) plus 1480 lumens/ft² (skylight) equal to 11,050 lumens/ft². It does not seem probable that the departure of the values represented in the Figures 2 and 3 from the extreme conditions termed "clear day" is of sufficient magnitude to be of any appreciable importance in the relative evaluation of image transducers.
TABLE I

LUMINANCE OF THE CLEAR SKY
WINTER AND SUMMER VALUES

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<td>344</td>
<td>334</td>
<td>380</td>
<td></td>
</tr>
<tr>
<td>180</td>
<td>1400</td>
<td>729</td>
<td></td>
<td>410</td>
<td>304</td>
<td>293</td>
<td>349</td>
<td></td>
</tr>
</tbody>
</table>

Clear Sky, Summer

| 20°   | 0°    | 7850     |           | 4040      | 1510      | 870       | 521       | 372       |
| 45    | 2870  | 2190     |           | 1450      | 1020      | 722       | 487       |           |
| 90    | 1330  | 1050     |           | 662       | 502       | 398       | 424       |           |
| 135   | 923   | 692      |           | 458       | 309       | 268       | 305       |           |
| 180   | 1060  | 792      |           | 443       | 316       | 275       | 283       |           |
| 40°   | 0°    | 5480     |           | 4620      | 6290      | 2050      | 1180      | 746       |
| 45    | 3100  | 2330     |           | 2010      | 1830      | 1400      | 1060      |           |
| 90    | 1590  | 1050     |           | 843       | 724       | 739       | 776       |           |
| 135   | 1300  | 843      |           | 552       | 448       | 463       | 552       |           |
| 180   | 1370  | 828      |           | 507       | 403       | 395       | 507       |           |
| 60°   | 0°    | 3180     |           | 2660      | 2820      | 3840      |           | 1530      |
| 45    | 2660  | 2340     |           | 1990      | 2340      | 2560      | 2160      |           |
| 90    | 1770  | 1350     |           | 1100      | 1130      | 1350      | 1510      |           |
| 135   | 1450  | 933      |           | 719       | 765       | 887       | 1150      |           |
| 180   | 1530  | 979      |           | 719       | 765       | 826       | 1100      |           |
| 70°   | 0°    | 3100     |           | 2760      | 2420      | 3420      | 7060      | 2140      |
| 45    | 2680  | 1930     |           | 1900      | 2290      | 2850      | 3270      |           |
| 90    | 1650  | 1390     |           | 1200      | 1160      | 1330      | 1900      |           |
| 135   | 1330  | 899      |           | 792       | 813       | 942       | 1410      |           |
| 180   | 1240  | 835      |           | 663       | 663       | 877       | 1310      |           |

1 - Solar altitude
2 - Azimuth from sun
ILLUMINANCE (FOOT-CANDLES) ON THE HORIZONTAL PLANE DUE TO LIGHT FROM THE CLEAR SKY AS A FUNCTION OF SOLAR ALTITUDE.

REF: JOSA, VOLUME 38, NO. 2, FEBRUARY 1948
c. Total Clear Sky Illuminance on Scene Elements

Thus far only the total illuminance on a horizontal scene element has been reported as in Figures 2 and 3. Scene surface elements in other orientation must also be treated to establish a realistic range of conditions. Well known relationships involving solar azimuth and altitude are available to compute the direct sunlight on planes of various orientations. The clear skylight on planes of various orientation is obtained by an integration process that recognizes the distribution of sky luminance as a function of solar altitude. Normal, perpendicular (facing the sun) and horizontal planes are selected as representative of typical scene element orientations. The component illuminances of these various surfaces are defined as:

\[ I_{nd} \] - illuminance on a plane normal (n) to the sun's rays caused by direct (d) sunlight.

\[ I_{hd} \] - illuminance on a horizontal (h) plane caused by direct (d) sunlight.

\[ I_{pd} \] - illuminance of a perpendicular (p) (facing the sun) plane caused by direct (d) sunlight.

\[ I_{ns}, I_{hs}, \text{ and } I_{ps} \] - illuminances on the planes defined above but caused by skylight (s).

In Figures 4 and 5, the sunlight and skylight illuminances, respectively, of the three representative planes are plotted as a function of solar altitude. Suppose, for example, that the total illuminance at noon on a vertical plane facing south at Los Angeles, California, on March 31 (clear day conditions) is required for prediction of the luminance of a reconnaissance scene element.
ILLUMINANCE (FOOT-CANDLES) DUE TO SUNLIGHT (ON THE NORMAL, HORIZONTAL, AND PERPENDICULAR PLANES) AS A FUNCTION OF SOLAR ALTITUDE.

REF: JOSA, VOLUME 38, NO. 2, FEBRUARY 1948

Figure 4
ILLUMINANCE (FOOT-CANDLES) DUE TO SKYLIGHT (ON THE NORMAL, HORIZONTAL, AND PERPENDICULAR PLANES) AS A FUNCTION OF SOLAR ALTITUDE.

REF: JOSA, VOLUME 38, NO. 2, FEBRUARY 1948

R-14,534
Under these conditions of

Los Angeles: latitude = 34° North
March 31: solar declination = 0°
Noon: solar altitude = 90°-34°-56°

the sunlight $I_{pd}$ is read from Figure 4 and the skylight $I_{ps}$ is read from Figure 5 as follows:

$$I_{pd} = 5000 \text{ lumens/ft}^2$$
$$I_{ps} = 1150 \text{ lumens/ft}^2$$

The total illumination on the vertical scene element is then the sum of the two component values or $6150 \text{ lumens/ft}^2$.

d. Illuminance Under Non-Clear Atmospheric Conditions

In the preceding sections, the evaluation of the amount of sunlight and skylight available to a scene at the earth's surface has been based on the assumption of an atmospheric condition which, as appraised by visual inspection, is designated as "clear". Such an atmosphere contains no clouds but a small amount of condensed water vapor and some dust. The chief cause of atmospheric non-clarity is the presence of significant amounts of condensed water vapor, clouds, fog, haze, ice crystals and dust which reduce the quantity of lumen flux at the scene and alter its directional characteristics. A range of atmospheric conditions from clear to dense cloud is defined in Table II in terms of the apparent brightness $B$ of the sun and the luminance of the sky as viewed in three representative locations. In a medium haze, for example, the sun's apparent brightness is reduced to one half the value under clear conditions but the position of the sun is still clearly discernable. In addition, the average sky
TABLE II

LUMINANCE VALUES FOR VARIOUS ATMOSPHERIC CONDITIONS

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Perfectly clear</td>
<td>500X10^6</td>
<td>(3) 1,400</td>
<td>740</td>
<td>(2) 400</td>
</tr>
<tr>
<td></td>
<td>450X10^6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clear</td>
<td>450X10^6</td>
<td>(1) 6,000</td>
<td>1500</td>
<td>(4) 650</td>
</tr>
<tr>
<td>Light Haze</td>
<td>14X10^6</td>
<td>(1) 100,000</td>
<td>4300</td>
<td>(4) 1800</td>
</tr>
<tr>
<td>Medium Haze</td>
<td>450X10^3</td>
<td>(1) 25,000</td>
<td>3150</td>
<td>1500</td>
</tr>
<tr>
<td>Heavy Haze</td>
<td>15X10^3</td>
<td>(1) 8,000</td>
<td>2150</td>
<td>1200</td>
</tr>
<tr>
<td>Light Cloud</td>
<td>0</td>
<td>(1) 4,000</td>
<td>1750</td>
<td>1000</td>
</tr>
<tr>
<td>Medium Cloud</td>
<td>0</td>
<td>(2) 2,500</td>
<td>1300</td>
<td>(3) 650</td>
</tr>
<tr>
<td>Heavy Cloud</td>
<td>0</td>
<td>(2) 1,200</td>
<td>640</td>
<td>(3) 400</td>
</tr>
<tr>
<td>Dense Cloud</td>
<td>0</td>
<td>(2) 400</td>
<td>200</td>
<td>(3) 150</td>
</tr>
</tbody>
</table>

(1) near sun
(2) near zenith
(3) near horizon
(4) approximately 90° from sun, measured through zenith

Note: Numerical values which characterize the atmospheric conditions indicated in column 1.
luminance under a medium haze is twice the value under clear conditions and thus the illuminance \( I_{hs} \) on a horizontal plane from the sky is also double the clear conditions. Thus the data of Table II allow the easy evaluation of the luminous input conditions to the scene under various non-clear atmospheric conditions.

e. Night Illuminance

Moonlight and the "lights of the night sky" are the principal sources of illumination in the absence of sunlight. The illumination received from the moon depends on the phase angle of the moon cycle, declination of the moon and sun, and the time of night. Full moonlight is about 0.01 to 0.04 foot-candles but illumination from the half-moon is only 10 percent of the full moon value. The portion of night time during which illumination from the half-moon or greater is available is about 30 percent. Sun and moon provide an illuminance greater than 0.002 foot-candles about 75 percent of the total time. During the remaining 25 percent of the time, illumination is provided mostly by starlight, zodiacal light (scattered sunlight in space) and galactic light. The total of these three components of the lights of the night sky is about 0.00005 foot-candles. The permanent aurora and the airglow provide an equal or greater illuminance so that the total lights of the night sky amount to about \( 10^{-4} \) foot-candles on a horizontal plane on a clear night.

2. Geometric Detail

The apparent luminance of scene elements represents the input to the image transducer. This luminance is determined by the radiant flux (excitation) on the element, the geometrical properties of the scene, and the spectral reflectance of the scene element. The
significant geometrical detail within the scene and its influence on the scene luminance is described in this section.

Surfaces of the scene that are directly illuminated by sunlight or skylight, even if they are relatively low reflectances, exhibit luminances which are high compared with other surfaces situated such that they do not receive direct input. Thus directly illuminated scene elements from the highlights (maximum luminance of the scene) are often less significant than the shadowed areas in terms of the information content (in the reconnaissance sense). The surface elements of lowest luminance are usually illuminated either by (a) multiple reflections (interreflections) of sunlight among adjacent surfaces or (b) light coming from small sky areas seen through intervening objects of (c) mixtures of (a) and (b) in various proportions. The illuminance of these darker scene elements is given by the relationship

\[ E_{\text{surfaces + sky}, dA} = F_{dA, \text{surfaces}} L_{\text{surfaces}} + F_{dA, \text{sky}} L_{\text{sky}} \]

where:

- \( E_{\text{surfaces + sky}, dA} \) - the illuminance on the scene element \( dA \) from surfaces in the half space with respect to \( dA \) and from the small sky area seen.

- \( F_{dA, \text{surfaces}} \) - the total shape modulus or configuration factor from the element \( dA \) to the surfaces.

- \( F_{dA, \text{sky}} \) - shape modulus from the element \( dA \) to the sky.
\( L_{\text{surfaces}} \) - total luminous emittance of the surfaces after multiple reflections.

\( L_{\text{sky}} \) - luminous emittance of the sky.

As an example of the use of the above equation, consider a military vehicle in the shade of several large trees on an overcast (Medium clouds of Table II) day. The vertical surface of the vehicle will see leaf surfaces, ground cover, and some part of the sky. The sky luminance or luminous emittance \( L_{\text{sky}} \) is read from Table II as 1300 foot-lamberts. A reasonable estimate of the leaf surface emittance \( L_{\text{surface}} \) is 50 foot-lamberts and with a 10% shape modulus to the sky, the vehicle luminance is

\[
E (\text{tree surfaces + sky, vehicle}) = (0.9 \times 50) + (0.1 \times 1300) = 175 \text{ foot-candles}
\]

The amount of luminous flux available to the scene elements of lowest luminance also depends on the spatial distribution and orientation of these elements. That is, some estimate of the mean direction of the normals to the scene elements relative to the direction of view (axis of the image transducer) should be attempted. The scene elements (terrestrial objects) are located at an infinite variety of positions in the three-dimensional space in front of the image transducer. The scene appears to consist of a plane mosaic made up of many two-dimensional elements varying in size and shape, the plane of the mosaic being normal to the line of sight. No predominant orientation of surface elements is found in natural scenes so that it is not productive to select a plane with some particular orientation as being more significant than another plane having one of many possible orientations.
A resume of the geometrical aspects of scene elements is:

(a) The illuminance of scene elements in shadowed locations is not related in any simple way to the illuminance of surfaces that see direct sunlight and skylight before multiple reflections.
(b) There is little justification for choosing a plane of any particular orientation as representative of the entire natural scene.
(c) The integral of all luminous flux incident on the scene without regard to initial direction seems most significant in terms of scene evaluation by the image transducer.

3. Spectral Properties of Scene Elements

The study of the spectral emittances of natural scene elements suggests that on the average the spectral characteristics of the flux incident on the element is more significant than the spectral reflectance or transmittance of the material. It should be understood that this condition of effectively gray or neutral reflectances of the scene elements is a correct representation only on the average (the statistical average of a large number of scenes covering the entire gamut of all possible geometrical variations).

In the scene elements (particularly those which receive multiple reflected flux) are postulated to be gray, the spectral composition of the radiant energy reflected or transmitted by these elements is practically identical with that of the incident radiant energy. Because of the multiple reflection process, the radiant energy
incident on the scene elements of minimum luminance is a very thorough mixture of that present in direct sunlight with that of the radiant energy coming from the entire sky hemisphere. The mixture proportion of the two components is approximately the same as the ratio of the two fluxes incident on a horizontal plane.

The spectral composition of the radiant energies reaching the earth in various phases of sunlight and skylight will now be considered. In Figure 6, the solid line A is the spectroradiometric emission curve for the international photographic unit of intensity. The dashed curve B represents the spectral composition of annual mean noon sunlight with a clear atmosphere at latitude 40° N.

Mean noon sunlight on clear days at latitude 40° has been assigned a color temperature of 5400°K, but color temperature is an index of the visual appearance of light and not of a physical characteristic such as spectral distribution. Experience with the detailed analysis of the relative capabilities of non-gray image transducer responses suggests that color temperature is not a useful measure of the spectral composition of the radiant energy.

The mixture of direct sunlight and skylight on a horizontal plane on a clear day is depicted by Curve D in Figure 6. Curve C of the same figure represents the spectral composition of the radiant energy on a horizontal plane under a completely overcast sky (heavy cloud condition of Table II).

Radiant data that define the physical basis of scene composition are reported and discussed in this section.
SPECTRAL COMPOSITION AT VARIOUS RADIANT ENERGIES

CURVE A -- SPECTRAL COMPOSITION OF RADIANT ENERGY EMITTED BY THE INTERNATIONAL PHOTOGRAPHIC UNIT OF INTENSITY.

CURVE B -- SPECTRAL COMPOSITION OF RADIANT ENERGY IN MEAN NOON SUNLIGHT AT LATITUDE 40° (CLEAR ATMOSPHERE).

CURVE C -- SPECTRAL COMPOSITION OF RADIANT ENERGY FROM COMpletely OVERCAST SKY, DOTTED PORTION EXTRAPOLATED.

CURVE D -- SPECTRAL COMPOSITION OF RADIANT ENERGY REFLECTED FROM A NON-SELECTIVELY ABSORBING HORIZONTAL PLANE ILLUMINATED BY SUNLIGHT AND SKY LIGHT (CLEAR ATMOSPHERE).

WAVE-LENGTH, \( \mu \mu \)
Representative values of direct sunlight, skylight, total illuminance, and night illuminance are presented as the necessary input to any scene evaluation approach. In addition, the importance of geometric detail and spectral properties of scene elements are discussed. The data of this section used in conjunction with the scene categorization method reported in the First Quarterly Progress Report allow the complete specification of representative scenes. The response of a variety of image transducing systems to these representative scenes is related to the broad objectives of this study.

Some specific conclusions to be drawn from this section are:

(a) A standard set of curves describing the spectral distribution of direct sunlight to scene elements as a function of atmosphere path length (air mass) is available (Figure 1).

(b) The total illuminance on the outdoor scene under clear conditions is obtained as the sum of the data for sunlight (Figure 2) and skylight (Figure 3).

(c) Luminous conditions associated with the extremes of atmospheres designated as "clear" do not depart from the average value (Figures 2 and 3) enough to be of any appreciable importance in the relative evaluation of image transducers.

(d) Direct and skylight illuminances on normal, perpendicular (facing the sun) and horizontal scene elements can be obtained from Figures 4 and 5.
(e) The data of Table II allow the evaluation of the luminous excitation of the active scene under various non-clear atmospheric conditions.

(f) The illuminance of scene elements in shadowed locations is not simply related to the illuminance of surfaces in direct sunlight because of the multiple reflection process that conveys flux to the shadows is described by a complicated integral equation.

(g) A useful and reasonable postulate is that scene elements, on the average, are effectively gray in reflectance and transmittance so that the spectral character of the flux streaming from the scene element toward the transducer is identical to the spectral distribution of the illuminant.

4. Scene Categorization

The data of the preceding sections used in conjunction with the scene categorization method reported in the First Quarterly Progress Report allow the complete specification of many representative scenes. It has been pointed out that the geometry, excitation, and spectral properties of scenes are extremely complicated. In view of this, a complete classification of all scenes into specific groups and subsequent establishment of the image transducer parameters for these groups is beyond the scope of this present study.

The important point to note is that the study does present a scene evaluation approach. This approach coupled with the data presented with the study of similar data can be utilized to define the image transducer parameters for a specific transducer mission.
For example, consider the case of specifying the image transducer parameters for a low level (i.e., altitude) drone reconnaissance mission under daylight conditions. Luminance characteristics of 126 outdoor scenes under daylight conditions which are applicable to the drone mission are given in Table III.

126 scenes have been categorized into the four geometry groups discussed earlier, plus a fifth group. Excitation conditions for each of these four groups varied but in most cases consisted of the excitation categories described in E-3 through E-6. Also included in Table III is a fifth group of scenes consisting of a combination of scenes from groups G-1 through G-4 where the excitation was a low illuminance large area diffuse source.

Table III shows the average and extreme values of the maximum and minimum luminance for each group of scenes. In addition, the maximum, minimum, and average luminance ranges for each scene in both arithmetic and log units are given. The logarithmic form of expressing luminance range is included since it offers a convenient means of discussing tonal reproduction. A study of the table shows that the average for the minimum luminance decreases progressively in the first four groups. The average maximum luminance behaves in the same fashion but decreases at a slower rate. The luminance range increases for the first four groups. In the section at the bottom of the table under "Summary of All Scenes" are given the averages applying to all 126 scenes.

---

**TABLE III**

LUMINANCE CHARACTERISTICS OF 126 OUTDOOR SCENES UNDER DAYLIGHT CONDITIONS

<table>
<thead>
<tr>
<th></th>
<th>Minimum Luminance</th>
<th>Maximum Luminance</th>
<th>Luminance Range</th>
<th>Luminance Range</th>
<th>Detectable Tonal States</th>
</tr>
</thead>
<tbody>
<tr>
<td>B Min</td>
<td>B Max</td>
<td>Log</td>
<td>Arithmetic</td>
<td>Density Step</td>
<td></td>
</tr>
</tbody>
</table>

(1) Group G-1 - Distant Scenes - 28 Scenes

| Min.  | 20    | 1500 | 1.43 | 27   | 24 |
| Max.  | 160   | 11500| 2.45 | 285  | 49 |
| Avg.  | 55    | 4500 | 1.90 | 81   | 36 |

(2) Group G-2 - Semidistant Scenes - 30 Scenes

| Min.  | 8.4   | 820  | 1.54 | 35   | 31 |
| Max.  | 76    | 9200 | 2.53 | 340  | 50 |
| Avg.  | 24.5  | 3150 | 2.11 | 130  | 42 |

(3) Group G-3 - Near Scenes - 38 Scenes

| Min.  | 5.6   | 620  | 1.62 | 42   | 32 |
| Max.  | 31.0  | 8000 | 2.79 | 620  | 56 |
| Avg.  | 12.5  | 2400 | 2.27 | 190  | 45 |

(4) Group G-4 - Close Up Scenes - 19 Scenes

| Min.  | 2.0   | 710  | 2.06 | 115  | 41 |
| Max.  | 11.6  | 4000 | 2.87 | 750  | 56 |
| Avg.  | 4.6   | 1600 | 2.53 | 345  | 50 |

(5) Combination of Groups G-1 to G-4 Under Low Level Diffuse Excitation - 22 Scenes

| Min.  | .82   | 55   | 1.43 | 27   | 28 |
| Max.  | 50.0  | 3700 | 2.80 | 640  | 56 |
| Avg.  | 6.3   | 1050 | 2.21 | 165  | 44 |

Summary of All Scenes - 126 Scenes

| Min.  | 0.82  | 55   | 1.43 | 27   | 28 |
| Max.  | 160.0 | 11500| 2.87 | 750  | 57 |
| Avg.  | 14.5  | 2300 | 2.20 | 160  | 44 |

* Luminance Values are in Foot Lamberts.
It is apparent from these data that on the average the minimum luminance is 14.5 foot-lamberts, the maximum luminance is 2300 foot-lamberts giving the average luminance scale of 160.

The foregoing conditions represent the complete range of luminance that an image transducer would be expected to encounter on a drone type mission. From these data, parameters such as number of detectable tonal states, sensor sensitivity, resolution and similar parameters can be determined. For example, the number of detectable tonal steps based on a .05 density step assumption is shown in Table III. On the average, the transducer would be expected to resolve 44 tonal states as indicated.
C. IMAGE TRANSDUCING PARAMETERS - AN IMAGE TRANSDUCER SURVEY

1. General

As pointed out in the First Quarterly Progress Report, the study of image transducing parameters had progressed to the point of defining five parameters characterizing the performance of image transducing and deriving a parametric expression interrelating these parameters. In addition, initial ranges were established for the parameters based on theoretical considerations. It was indicated that a logical continuation of the parameter study would encompass the following items:

(1) Establish practical ranges for the several parameters based on practical transducer limitations such as granularity, noise, and so forth.
(2) Develop a suitable method for displaying the information content of the parametric expression interrelating the parameters.
(3) Obtain a more comprehensive picture of the relative importance of the parameters as a function of transducer mission in order that parameter trade-off possibilities can be delineated.
(4) Establish the desired performance parameters of an advanced image transducer and translate these into the appropriate design criteria.

During the past Quarter Period this study has continued in the light of the above objectives. In particular, Items (1) and (3) above have received the major emphasis by the conduction and completion of a cursory survey of the present state-of-the-art of
image transducers. This survey briefly summarizes the characteristics of image transducer systems and discusses the interrelation of the various parameters from a practical viewpoint.

The results of this survey coupled with a continued effort which has taken place during this quarter on the objectives mentioned in (2) and (4) above should bring an effective conclusion to this study during the third quarter.

Although work has been accomplished in all defined areas of the study, only the image transducer survey is included as part of this report.

For the most part, these developments have been clustered around the Television and Graphic Arts or Film industries since these industries today represent the largest markets. However, in recent years, military and industrial requirements have demanded an extension of image transducer parametric limits — more sensitivity in pickup tubes — greater speed or capacity in graphic art or image processing, or recording — more environmental restrictions (12, 17)°. There has been a correspondingly large outcropping of new devices to meet these special requirements. New devices are ruggedized, have new spectral ranges (ultraviolet, infrared), very low sensitivities, much higher resolution, different frame or scan times, are lighter in weight, simpler and more reliable. Other potentially interesting storage, display, and transducing devices are also under development which, in many applications, may replace or supplement the use of the very versatile conventional image tube transducers.

° Numbers in parenthesis refer to references in Section II E.
A brief review of image storage and transducer devices, their component limitations and parametric tradeoffs are described in the following pages. Section IV contains a graphical summary of the more significant image transducer devices, their salient parameters and their theoretical limits.

2. Image Transducer Types

a. The Iconoscope (35)

The iconoscope is an early pickup tube development. It has largely been replaced in use by the image orthicon (which is more than 100 times more sensitive) or the vidicon, which is simpler. However, the iconoscope is still useful when high definition and good storage properties are desired and sensitivity is not too important.

The iconoscope uses a photo-emissive surface constructed in an electrically isolated mosaic pattern. Light from a scene projected on this photo-sensitive surface emits electrons. The electrons accumulate at each image point during the frame time. Once, during each frame, a high velocity electron beam scans over this mosaic surface restoring the charge to its original value. A capacitive pickup senses the current flow to a wire mesh adjacent to the mosaic surface.

The beam electrons rarely require energies in excess of 1000 electron volts. Beam currents are typically .1 to .5 micro-amperes.

The sensitivity of an iconoscope, can, in principle, be increased by image amplification. Image iconoscopes.
have been built which enhance the stored charge on the mosaic target by using secondary emission multiplication of the electrons emitted by a photoemissive cathode. The photo electrons are refocused by an electron lens onto the target element which provides multiple secondary emissions. The remaining signal detection process of the image iconoscope is similar to the ordinary iconoscope.

Typical examples of the image iconoscope include the Multicon, Superemitron, Eriscope.

b. The Orthicon (35, 36)

The orthicon, in contrast to the iconoscope, uses a low velocity scanning beam. The electron beam is slowed by a decelerator just before reaching the target. The beam current may typically be .02 micro-ampere. The scanning beam is reflected from the target by the presence of a stored charge on the first mesh screen. The amount of reflection provides signal indication.

The electron emission from the target is collected on an adjacent wire mesh. This emission leaves the target at a positive potential. The scanning beam neutralizes the target charge and returns it to its original potential. The number of electrons repelled by the charge is amplified by a secondary emission electron multiplier in the base of the orthicon tube.

The commonly used photo-emissive surface and target provide a sensitivity gain of 5 in electron emission. The secondary emission multiplier is typically a five stage device which
introduces negligible noise compared to that generated by the scanning electron beam (shot noise).

**Typical examples of the image orthicon are**

the type 7198 and the 5820. New developments have included the use of a more sensitive S-20 tri-alkali photo-cathode and high resistivity thin film target (e.g. Westinghouse's WL22722). Larger area photocathodes have also recently been reintroduced (4½ vs. 3" tube) (2,12). The thin film target provides an increase of 10-15 times and the S-20 photo-cathode 5 times in sensitivity over conventional image orthicons.

Image intensifier sections have also been added to these tubes to provide more than 1 stage electron image amplification before integration on the target (25d, h). Typical development tubes are RCA's C73477, C74093A and Westinghouse's WX4299. The intensifier section increases sensitivity by as much as 10 to 20 times. In combination with an S-20 surface and thin film target, new image intensifier orthicons are 500 to 1000 times more sensitive than image orthicons of a few years ago. The image intensifier orthicon is the most sensitive of any image transducer today.

c. **The Isocon (35c)**

Shot noise in the returned scanning beam is the principle limitation of the normal orthicon. At low light levels, essentially the entire beam is returned. It is precisely at these low light levels that random shot noise in the returned beam is greatest (i.e. the noise is greatest when the signal is weakest (6, 25)).
The isocon tends to provide the smallest shot noise when the signal is weakest. The detection principle involves the use of the scattered electrons which do penetrate to the target, and hence, there will be a small returned beam current when the scene or signal is the darkest. The electron beam shot noise is greatest when the signal is greatest.

The principal problem in the development of this tube has been the separation of returned electrons from scattered electrons. Nonetheless, this development potentially offers greater sensitivity, and signal to noise, at low threshold signals than other transducers.

The developmental RCA C74060 is an image intensifier isocon (25d). The use of image intensifier stages ahead of conventional image orthicon permits a sufficient charge buildup in the target itself that the signal will override its own beam noise at low signal levels.

d. The Vidicon (35, 36)

The foregoing devices use a photoemissive cathode. Light striking a photocathode emits electrons which are then amplified through secondary emission multiplication and finally collected and refocused in a stored charge pattern on a target. The electrostatic charge pattern is then read from the target by a scanning electron beam.

Another photon to electrical characteristic phenomena is one of photo conductivity. A photon, incident upon a photoconductor, forms charge carriers at a rate proportional to the
incident light intensity. If the photoconductor is located in a bridge circuit with a constant potential balance, the change in free carriers will change the current through this photoconductor. The change can be detected in the bridge.

The vidicon uses a photoconductive target. The target has, on one side, a conductive coating, (high resistance R) and a dielectric substrate (which acts as a capacitor C). Initially, the capacitor is charged to a fixed potential, which then leaks off, due to the presence of the RC combination, at a rate proportional to the illumination. One side of the glass, or MgO, acts as a capacitor charged to a fixed potential. At the readout time, the capacitor is partly discharged. The amount of electrical charge imparted to each element by the electron scanning beam is then detected at the conductive coating itself through a video amplifier.

The vidicon is a very simple device. It is small and light weight. Typical tubes include 6326 or 6198.

Recent developments include larger photocathode surfaces (3/5 x 4/5 inches vs. standard 1/2 x 3/8 inches, RCA 8051), the use of higher resistivity thin film targets for longer time constants (Westinghouse 7290 which employs longer integration and slow scans), and new photoconductive surfaces with different spectral characteristics favoring long wavelength radiation thus being more sensitive to 2870°K tungsten source illuminated scenes (Westinghouse 4915). The vidicon attains the largest tonal range or signal-to-noise ratio of any other imaging device (approximately 200:1).
e. **The Ebicon (36, 37)**

The ebicon is a modified form of vidicon which uses an image section. A photoemissive cathode emits electrons which are then refocused on a photoconductive surface. The target is a thin electron permeable aluminum layer on a high resistance semiconductor. The bombarding electrons induce conductivity in a thin film of selenium. The remainder of the Ebicon tube operates as a conventional vidicon. Another version, The Uvicon operates on the Ebicon principle but uses an ultra violet photoemissive cathode.

f. **Thermoplastic Recording (3, 4, 23)**

Thermoplastic recording utilizes a reusable storage and recording process. The film consists of a heat resistant base film coated with a thin film of thermoplastic material which is readily deformed by heat. An electron beam images an electrical charge pattern on the film. Heat is then applied to the film. The thermoplastic material melts, and electrical and electrostatic forces deform the thermoplastic film — the displacement is a function of the charge interaction and the surface tension of the film. The film is cooled and the data stored. For reuse, the film is reheated to the melting point of the thermoplastic material.

Thermoplastic recording was developed by General Electric in recent years. The electrical time constant must be 50 to 100 times the thermal time constant. For example, if 1/2 second is used for exposure, 1/2 minute is needed for cooling. The cooling technique presents the greatest problem. Presumably thermoplastic material has an ASA 10 equivalent photo speed, can record 40 lines/mm, and 8 shades of gray. It is expected to attain
100 lines/mm resolution, a tonal range 15 shades of gray, and attain a recording density of $1.5 \times 10^7$ elements/square inch. As a reusable device, it has the longest storage time ability of any other sensing material.

g. Phototape (11)

Phototape is another recent development in reusable image storage. This technique has been developed by Radio Corporation of America. A transparent polystyrene base has overlaid on it a transparent thin gold conducting layer, a photoconductor, and a dielectric insulator. With simultaneous image exposure and electronic beam contact across this film, a charge pattern is introduced on the insulator proportional to the light intensity. The charge may be stored for several days. Readout is accomplished by an electron beam readout in a manner analogous to the readout of the vidicon.

Resolution of the tape is expected to approach 1200 lines/mm. However, electron beam spot size presently limits this to 40 lines/mm on a 2-¾ inch format. Normal gray scale rendition of 8 to 10 levels has been obtained. The readout is, at present, only partially destructive, but usable pictures can still be obtained after 2 or 3 readouts. Phototape has the highest resolution of any other short term non-destructive, storage mechanism.

h. Film (19, 38)

Film has, for many years, enjoyed widespread use for high quality recording of high density data. Automatic film processing, however, is messy. The film is radiation-sensitive
and, in the past, has not been reusable. Basic film resolution is quite high. Poor film resolution occurs occasionally due to camera or shutter motion, or the film not being flattened against the plates.

Present films obtain 150 lines/mm resolution with ASA 3 ratings (bright targets) or 25 lines/mm with weak targets (ASA 650). The quantum efficiency of the film is high, basic film resolution being limited ultimately by the clumping of silver halide grains.

Present developments favor the use of vacuum evaporated monomolecular silver bromide and single crystal silver bromide. These developments may lead to 200-300 lines/mm resolution with reusable, radiation resistant film having an ASA rating 10-25. Film has the highest resolution and tonal range of any other recording or storage medium.

i. **Image Intensifiers and Image Converters (14, 25 a,b,c,i, 27, 30, 31, 33, 34)**

Many image intensifier and image converters employ a photo-emissive cathode surface, an accelerating electron multiplication, and a phosphor target which emits radiant energy when struck by electrons. The phosphor radiant image is in general, more intense than the image focused on the photocathode. A light amplification factor of many hundred is possible. Image intensifiers have recently been used on the front end of image orthicons for improved sensitivity.

Image intensifiers operate continuously. Their integration time is solely a function of the build up and decay time.
of the phosphor. Electrons incident upon a phosphor area excite certain phosphors. If more electrons impinge, more phosphors will be excited and the spot size will, in poor resolution systems, appear brighter until saturation occurs. This accumulation or reciprocity effect is not exact and exists only over times which are short compared to the decay time of the phosphor and are well below the saturation current of the phosphor.

Two types of image intensifiers currently under development are Westinghouse's transmission secondary emission intensifier (TSEM with accelerating dynodes and RCA's two or three stage cascaded electrostatically or magnetically focused image tube. Other solid state image intensifiers are also under development. These intensifiers combine electroluminescent layers with photoconductive layers to form imaging panels.

j. Storage Tubes (26)

There are many types of image and scan conversion tubes which store different tonal or gray levels at each image point. The tubes generally employ charge restoration or some form of charge modulation.

Most of the tubes have separate read and write guns -- and may have three or four guns. (Two read, one erase, and one write gun, etc.). Readout may occur at nominal television frequencies (i.e., 1/30 second --) or the picture may be stored for minutes or hours before readout (generally with some image quality degradation). Tonal range is a problem. In storage devices which retain information up to 5 minutes, 8 to 10 gray scale is
possible. For the longer time storage tubes (hours or days) almost all gray scale information is lost.

The charge restoration tubes include the storage orthicon (photoemissive) CBS emitron; a Grapherhon (electron bombardment induced conductivity); VCR X 350; a Metrechon; numerous direct view storage tubes such as Westinghouse's 7268, 7356, 7682, WX 4584, and RCA's C73922, 31, 38, 59, 83, or 6866, Dumont's Storatron, ITT's Iatron, Hughes' Tonotron and Memotron. A vidicon type storage tube, the Permachon; uses charge modulation. It is a direct pickup storage device (5 min.). There are several scan conversion tubes which readin information at one rate and pattern and readout at different rates, Intercontinental Electronics Corporation TMA-403X, RCA's barrier grid-storage Radechon (also ITT), or Intec's TCM-154.

k. **Flying Spot Scanner (No Integration)**

Historically speaking, mechanical flying spot scanners antedate all of the foregoing image storing and scanning techniques. A very large number of devices have been built, invented and discussed. All such devices suffer from the same limitation; lack of integration of light during the frame time.

The Nipkow scanning disk is an early example. A number of mirror drum devices have also been built. Most facsimile and wire photo equipment use the sequential readout, non-integration type mechanical scan. Examples of this are the Electronic Communication, Standard Products Division facsimile equipment used by Western Union, the Westrex FAXWRITER or PRESSFAX (with a 16" x 22" format used for the Stewart Warner's DATAFAX used widely by the telephone company, and Fairchild Camera's continuous strip recorder.
Infrared scanning and reconnaissance devices have also used strip scanning with mirror or drum rotation at high speeds. Haller, Raymond and Brown's AAD 2 or AAR 2 (Reconofax), and Texas Instruments' line scanner are recent developments.

The above scanners, by and large, use a fixed photo sensitive cell and some image, mirror, lens or drum rotation mechanism. Another way of obtaining line scan motion is by use of electronic deflecting plates in a photomultiplier type imaging tube. Such a device was developed by Farnsworth (ITT) and is known as an Image Dissector. Again, as in all of these flying spot scanning devices, no integration is performed. Also, scan motion can be obtained electronically without requiring the use of moving mechanisms.

3. Mechanical Scanning Sensor and Recording System

Mechanical scanners employ (1) a physically moving scanning mechanism, (2) an optical condenser or projection system, and (3) a photon sensitive detector for image to electrical transducers, or a light source and modulator for electrical to image transducing. The scanning mechanism most often consists of a rotating disk or drum upon which (1) optical imaging rays are deflected in a predetermined way, (2) upon which a series of limiting field stop apertures are sequentially brought into use, or (3) upon which the picture itself is brought past a stationary pinhole and sensor or light source.

The frequencies or time rate with which information is gathered is an important parameter for measuring the inherent capacity of the overall system. If the bandwidth is large, then the
intermediate electrical transmission system must have adequate capacity
to handle this wide band information. Facsimile systems for example,
have, until recently, limited their communication system to telephone
lines. This results in a low frequency (<200 cps) data rate. More
recently, however, due to the greater availability of radio and
microwave links, newer systems have been and are being developed with
much greater capacity. Stewart Warner has a new 10 KC bandwidth
system for example, Westrex has just recently introduced a 47 KC
bandwidth system capable of 300 scan/min (400 lines/in. resolution)
and before the end of the year hopes to bring out a 935 KC system
with 3000 scan/min. Fairchild Camera, Facsimile Division, also
has some new wide bandwidth systems in development that may shortly
be brought out.

The higher frequencies require sensors that can respond at this rate, and lights or light modulators that can record at this rate. The sensor is not a problem. Photomultiplier and photo-emissive detectors have bandwidths comparable to $10^8$ cps. Conventional TV pickup devices normally operate at $4.5 \times 10^6$ cps and could, in principle, approach the bandwidths of a photomultiplier tube.

Light modulators at these frequencies present more of a problem. Glow lamps for the most part have been used in the low frequency bandwidth system. The intensity of the light source has been directly controlled by varying the exciter current through the tube. Frequencies to 10 or 20 KC are perfectly feasible with this technique. At much higher frequencies some recent developments, such as the GaAs infrared source, may prove to open a much broader range to the direct modulation of source illumination.
High frequency light modulators have most often used an intermediate attenuating or polarizing material. The Kerr cell is a prime example. A beam of polarized light, passing through a birefringent material is affected by the direction of the incident light. The incident polarized light is broken into two components which traverse the medium at different velocities dependent on the material, and the applied voltage on the material -- an organic liquid.

Another light modulation technique is that of diffraction, which scatters light. The diffraction phenomena arises when supersonic waves are introduced into some liquid by a piezo electric crystal. This technique has been used in recording systems for some years by Fairchild Camera.

The transmission of wideband frequencies without distortion introduces problems in the fidelity of reproduction. It is necessary that the recording system be synchronized with the transmitting system. This takes the form of a synchronizing signal between receiving and transmitting stations. Even so, the relative "flatness" of the frequency bandwidth, and delay distortion are problems which may vary slightly with different frequencies.

Some of these difficulties can be overcome by use of frequency or pulse code modulation in the transmitting system (instead of more conventional amplitude modulation (39)). Frequency modulation is substantially unaffected by small variations in relative amplitude of the transmission band -- and hence the bandwidth need not be flat (to ± 2 db as is frequently cited).

Pulse code modulation or digital systems obtain the same objective. Here, in addition, the amplitude, or tone level
of the transmitted signal can be encoded in bits to reduce the needed bandwidth. The pulses so transmitted each occupy the entire band and lack of distortion or uniformity of response across this band is unimportant. (42,43).

The mechanical scan methods are very numerous. The Nipkow disc, a series of perforated holes on a disc -- all stepped down in progressively smaller radii, can, in one rotation sweep out a number of lines in an image equal to the number of holes in the disk. This scan mechanism is extremely simple. However, it requires an extended light source which encompasses the whole field.

Another mechanism employs a series of mirrors on a drum, each mirror serving to deflect the converging beam from a light source down another line, and the rotation of the drum sweeping the projected light across the width of the image.

Another technique uses a large stationary drum with many mirrors and a small rotating mirror in the center which progressively employs each separate external mirror.

Another common technique is to fix the light source or sensor, but instead rotate the copy. A synchronous motor drives the drum at the line scan frequency, and a geared down translating mechanism drives the pickup, recording lamp, or drum itself slowly in a direction normal to the rotation of the drum.

Table I following lists a few of the facsimile recording and transmitting equipments which are currently available. They each individually possess some unique feature or advantage in certain applications. The Western Union TELEX or WIREFAX for example,
## SOME TYPICAL FACSIMILE EQUIPMENT

<table>
<thead>
<tr>
<th>TRADE NAME</th>
<th>MANUFACTURER</th>
<th>COPY SIZE</th>
<th>Transmission Time/In/min</th>
<th>Resolution Lines/inch</th>
<th>SCANS MIN</th>
<th>BANDWIDTH</th>
<th>CARRIER</th>
<th>Signal Contract</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAXWRITER</td>
<td>Westrex</td>
<td>8.5&quot; x 13&quot;</td>
<td>1.86</td>
<td>96</td>
<td>180</td>
<td>1.2-3.6 KC</td>
<td>2.4 KC</td>
<td>16 db</td>
</tr>
<tr>
<td>1. PRESSFAX</td>
<td>&quot;</td>
<td>16&quot; x 22&quot;</td>
<td>400</td>
<td>300</td>
<td>47 KC</td>
<td>25 db</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. PRESSFAX(Wall St.)</td>
<td>&quot;</td>
<td>16&quot; x 22&quot;</td>
<td>800</td>
<td>3000</td>
<td>935 KC</td>
<td>25 db</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AN/GXC-4 (XC-2)</td>
<td>&quot;</td>
<td>4-3/16&quot; x 3¾&quot;</td>
<td>0.40</td>
<td>300</td>
<td>120</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(70 mm cont. on RCR) (with Polaroid Film)</td>
<td>&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AN/GXC-5</td>
<td>&quot;</td>
<td>8¾&quot; x 11&quot;</td>
<td>12.5(12 min)</td>
<td>90</td>
<td>90</td>
<td>.5-5 KC</td>
<td>20 db</td>
<td></td>
</tr>
<tr>
<td>WEATHERFAX</td>
<td>&quot;</td>
<td></td>
<td>25 (6 min)</td>
<td>96</td>
<td>180</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;</td>
<td>18&quot; x 36&quot;</td>
<td>96</td>
<td>60</td>
<td>1.8 KC</td>
<td>15 db</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;</td>
<td></td>
<td>96</td>
<td>90</td>
<td>.6-4.2 KC</td>
<td>2.4 KC</td>
<td>15 db</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;</td>
<td></td>
<td>(29 min)</td>
<td>96</td>
<td>120</td>
<td>24.4 KC</td>
<td>15 db</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CF/RF Photofacsimile</td>
<td>&quot;</td>
<td>8&quot; x 11&quot;</td>
<td>(11 min)</td>
<td>96</td>
<td>90</td>
<td>1.2-2.4 KC</td>
<td>1.8 KC</td>
<td></td>
</tr>
<tr>
<td>DATAPAX</td>
<td>Stewart Warner</td>
<td>8¾&quot; x any</td>
<td>1.875</td>
<td>96</td>
<td>180</td>
<td>1.2-2.4 KC</td>
<td>2.4 KC</td>
<td></td>
</tr>
<tr>
<td>DATAPAX</td>
<td>&quot;</td>
<td>3.75</td>
<td>96</td>
<td>360</td>
<td></td>
<td>.3-2.3 KC</td>
<td>4.5 KC</td>
<td></td>
</tr>
<tr>
<td>3. DATAPAX</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SCANAFAX</td>
<td>Fairchild</td>
<td>8¾&quot; x any</td>
<td>(3-6 min)</td>
<td>100</td>
<td>180-360</td>
<td>1.2-2.7 KC</td>
<td>2.4 KC</td>
<td>27 db</td>
</tr>
<tr>
<td>INTRAPAX</td>
<td>Western Union</td>
<td>8¾&quot; x 11&quot;</td>
<td>(3-6 min)</td>
<td>100</td>
<td>180-360</td>
<td>Voice</td>
<td>20 db</td>
<td></td>
</tr>
<tr>
<td>ELECTRONIC MESSENGER</td>
<td>&quot;</td>
<td>8¾&quot; x 14&quot;</td>
<td>(1-2 min)</td>
<td>85</td>
<td>180-360</td>
<td>.8-4.1 KC</td>
<td>3.6 KC</td>
<td>20 db</td>
</tr>
</tbody>
</table>

**NOTE:** 1,2 and 3 to be introduced in near future.
is reputedly better adapted to the transmission line type delays and distortion occurring over long transcontinental transmissions, Westrex has some high capacity developments, (47 KC and 935 KC which will soon be out) and have further reduced to military form and field use, some equipments which are adaptable to transmission of Polaroid 3 x 4 in. snapshots, AN/GXC-4 (XC-2), or larger copy AN/GXC-5. This latter development advantageously employs FM modulation in contrast to most other equipments in use.

Stewart Warner, DATAFAX and Fairchild Camera both have facsimile devices which can use copy of any length on a roll but of limited width (8-1/2 or 11 in.). Westrex has a PRESSFAX and WEATHERFAX which can transmit large width copy; 16" x 22" and 18" x 36" respectively.

4. Component Limitations and Parametric Tradeoffs

a. Photon Noise Limits (10, 18, 29, 35, 38)

Ultimately, photon noise always limits the performance of any image sensor or transducer. Photons are little packets of discrete energy equal to hv, where h is Planck's constant, and ν is the frequency of oscillation (c/λ). Near the visible spectrum, the wavelength λ, is short, and the photon energy is large. The emission, and reception of photon energy in discrete units must be considered at low light levels or at high data rates. There must be at least one photon received in a discrete area during a given detection interval to provide indication of intelligence.

Photons are neither emitted nor received at a constant rate. The ν is a statistical fluctuation of individual quanta.
The distribution is Poissonian. Thus, if an average of 1 quanta is received per unit time, the probability of actually receiving a photon in a particular time interval is only 68%. If the average rate of arrival is 5 quanta per unit time, then there is better than a 99% probability that at least one quanta will be received in any particular time interval.

A random arrival of photons introduces unpredictable noise. With the arrival of large numbers of photons in a bandwidth limited system, the noise fluctuation is found to vary with the square root of the number of photons arriving in a unit time (the law of large numbers). If an average of 100 photons are present, there will be a 10% ripple.

The photon noise limit can be simply calculated. The number of photons received per resolution element in one frame or integration period from an ambient intensity is:

$$M_a = N_o N_B n A_i T_F (f/#)^{-2} = H_a n A T_F \sqrt{n(f/#)}^{-2} N_o$$

and the number of photons from a change in average intensity (contrast) focused on a single resolution element is:

$$M_s = H_s n A_o T_F N_o$$

where:

- $M_a$ = number of average background photons
- $M_s$ = number of average signal photons
- $N_B$ = background radiance watts/cm^2 steradian (at entrance aperture)
A photoemissive surface does not emit an electron with every incident photon. It has a quantum efficiency, \( \eta_q \), which is a measure of the average number of received photons necessary to emit one electron. Typically the quantum efficiency may be 10 to 20% for some surfaces (see following sections). The signal to noise then becomes:

\[
(S/N)_{\text{theor}} = \frac{M_s \eta_q}{(M_{\text{env}} \eta_q)^{1/2}}
\]

\[
(S/N)_{\text{theor}} = \frac{(f/#) H_s A_o N \eta_q \eta \eta n T_F}{(N_B A_c)^{1/2}}
\]

(see conditions below)
This signal to noise is only a theoretical ratio. In a real system, one must also impose the additional constraint that at least 1 photon be received, (although 5 is a more realistic figure).

\[ M_t q^* \gtrsim 1 \]

\[ H_s n A T q^* \eta \eta_q = 1 \]

If one wishes to determine tonal range exactly, then photon noise in the limit is contributed by signal irradiance, \( H_s \) itself. In these circumstances the signal becomes \( \Delta H_s \) instead of \( H_s \) and the uncertainty, or photon noise from this background \( N_B \) must include \( H_s \) itself. The S/N can be increased by:

1) Larger Collector area \( A_0 \)
2) Greater resolution \( N \)
3) Longer integration time \( T_F \)
4) Slower optics (but this reduces capacity of the system)
5) Smaller photocathode area \( A_c \) (but this reduces capacity of the system)
6) Better optical or quantum efficiencies \( \eta_c, \eta_q \)
7) Brighter illumination \( H_s/(N_B)^{1/2} \)

If the limit on performance is the arrival of a single photon, then this can be obtained only with:

1) Larger optical collecting area \( A_0 \)
2) Longer integration time \( T_F \)
3) Better optical or quantum efficiencies \( \eta_c \eta_q \)
4) Brighter object irradiance \( H_s \)
b. Spectral Sensitivity

The spectral selectivity and quantum efficiencies of presently known photo-emissive, photoconductive, and photo-chemical transducers vary over very wide limits. Figure 7 shows the spectral sensitivity of typical emissive surfaces.

Most optical sensor characteristics are measured, for convenience, in foot-candles against a 2870°K standard tungsten source. This is an unfortunate choice for a source unless one is using the sensor with this type of illumination. Thus, long wavelength spectral sensitivity may look apparently like a "more sensitive" photocathode in 2870°K light. (This is the case of S-20 photocathode now widely used in the more sensitive image orthicon -- or the newer "sensitive" vidicon). However the quantum efficiency may be no better than shorter wavelength sensors, and, if short wavelength illumination is used (solar illuminated, moonlight, or arc or plasma lamps), then these apparently more sensitive sensors may, in operation, be no more sensitive than shorter wavelength sensitive sensors with poorer apparent 2870°K luminous sensitivity. (An S-5 or S-17 surface may be better under these conditions than an S-20 although the S-20 can quote a lower luminous sensitivity).

There are 621 lumens/watt of monochromatic .556 micron radiation. Integrating the number of lumens in a 2870°K source and comparing it with total black body radiation, the luminous efficiency is:

\[
\frac{\int k \lambda F(2870°K) \, d\lambda}{\int F(2870°K) \, d\lambda} = \frac{9.75 \text{ w/cm}^2}{400 \text{ w/cm}^2} = 2.4\%
\]
FIGURE 7
where:

\[ K_\lambda = \text{The relative spectral response characteristics of the eye (dimensionless)} \]
\[ F_\lambda = \text{Spectral radiation characteristics of the 2870^\circ K source (watts per unit area per unit wave length)} \]

The luminous efficiency in lumens/watt is

\[
\text{Luminous} = \frac{9.75 \times 621}{400} = 15 \text{ lumens/watt (2870^\circ K)}
\]

\[
\text{Efficiency} \quad \frac{2870^\circ L \text{ source}}
\]

An S-20 tri-alkali surface represents one of the most sensitive photocathodes presently available. The total percentage of 2870^\circ K radiation sensed by an S-20 surface is:

\[
\int \frac{K_{S-20} F_\lambda (2870^\circ K) d\lambda}{F_\lambda (2870^\circ K) d\lambda} = \frac{18.6}{400} = 4.65\%
\]

or, the number of lumens per watt sensed by the S-20 surface.

\[
\int K_{S-20} F_\lambda (2870^\circ K) d\lambda = \frac{9.65 \times 621}{18.6} = 322 \text{ lumens/S-20 watt of 2870^\circ K}
\]

The luminosity response of the S-20 is 150 microamps/lumen. A conventional image orthicon (5820 or 6649) has a response of 36.6 microamps/lumen, a sensitivity of .0173 amps/watt or a luminous conversion of 2870^\circ K radiation equal to 473 lumens/watt. The standard vidicon (6826 for example) has a response of 520 lumen/watt.
An experimental long wavelength sensitive vidicon developed by Westinghouse (WX4915) has a much lower visibility threshold.

\[
\frac{\int_{k} F(2870K) d\lambda}{\int F(2870K) d\lambda} = \frac{21.2}{400} = 5.3\%
\]

WX4815 vidicon = 330 lumen/watt

c. Resolution (5, 7, 8, 9, 13, 2, 1, etc.)

Resolution is affected by many factors. A periodicity of line number is often used as a measure of the apparent resolution. This is a repetitive pattern, of equally spaced black and white bars called a space frequency response.

The resolution limit is the periodicity which is just barely detectable. Thus, if a target has initial high contrast (i.e., with large signal to noise factor) the resolution limit occurs with minimum detectable signal (i.e., a very low signal to noise factor). The signal has been subjected to a very large attenuation factor, and only very bright targets can be detected at this maximum resolution limit.

Figure 8 shows the space frequency response characteristic of a typical tube. The attenuation characteristic of a tube is a measure of signal attenuation at a particular line frequency. Sometimes an "effective" line number is used, \( N_e \), which occurs when the response just equals in intensity the square wave input at one point.

The space frequency response characteristics of an image transducer are dependent on several factors. These are:
SPACE FREQUENCY RESPONSE CHARACTERISTICS
OF TYPICAL IMAGE TRANSDUCING TUBES

<table>
<thead>
<tr>
<th>OBJECT TEST PATTERN</th>
<th>IMAGE RESPONSE</th>
<th>RATIO a/b</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a</td>
<td>(a/b)_fund.</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td></td>
</tr>
</tbody>
</table>

"IDEAL" RESOLUTION

EFFECTIVE RESOLUTION

THRESHOLD RESOLUTION

RELATIVE AMPLITUDE

- "HIGH RESOLUTION" VIDICON
- IMAGE ORTHICON 0°C
- VIDICON 10°C, 35°C

TV LINES RESOLUTION

FIGURE 8
1) The diffraction limit of the collector.

2) Aberrations and imperfections in the imaging lens.

3) Granularity in the photo sensitive surface -- grain sizes may be 10 microns or smaller -- however clumping and side scattering diffuses effective spots to 100 microns or so.

4) Lateral charge leakage in the target of integration type sensors (Vidicon, Orthicon) due to insufficiently high resistivity or small interelectrode capacitance.

5) Imperfect electrostatic or magnetic focusing.

6) Velocity differences in scanning electron beams emitted by filament.

7) Velocity differences in photo emitted electrons due to differences in incident photon energy occurring with non-monochromatic spectral source radiances.

Figure 9, for example, shows the degradation in resolution due to finite leakage with target thickness of .0002 inches, target mesh spacing of .002 inches and target glass resistivity of 10 ohm-cm. for various integration times (36). Figure 10 shows the theoretical resolution due to velocity differences (i.e., Item 7 above) which might be obtained in a target as a function of the upper wavelength cutoff of source illumination. This latter figure assumes an upper wavelength cutoff at 7000 Å of an S-10 surface, where the photon energy of 7000 Å is just able to overcome the work function of the photo emissive cathode.

d. Granularity

The projection, recording, or display of an image is ultimately limited by the granularity of the surface itself.
DEGRADATION OF RESOLUTION DUE TO LATERAL CHARGE LEAKAGE FOR A SPECIFIC TARGET AS A FUNCTION OF INTEGRATION TIME

FIGURE 9

THEORETICAL
MEASURED
CATALOGUE

RELATIVE AMPLITUDE

RESOLUTION TV LINES

R-14,566
THEORETICAL VARIATION OF RESOLUTION WITH WAVELENGTH WHICH MIGHT BE OBTAINED IN A TARGET

![Graph showing theoretical variation of resolution with wavelength. The graph includes two curves representing 20% and 50% contrast, with the x-axis labeled WAVELENGTH Å (7000 Å WORK FUNCTION CUTOFF) and the y-axis labeled RESOLUTION TV LINES.]

R-14,565

FIGURE 10
Photographic emulsions, for example, have grain sizes of 10 to 40 microns for high sensitivity film -- which may be reduced to only a few microns with film having poorer sensitivity. Assuming a typical grain size of 20 microns, then a film size of 1.6 inches is required to record 2000 lines. In addition to the basic grain size there is another phenomena which degrades resolution -- clumping. This is the characteristic behavior of grains to show more affinity to other grains than to stand alone.

An image orthicon has even larger minimum resolution. It is of the order of 80\(\mu\). Thus, a 6" photocathode would be necessary to record 2000 lines if there were no other deteriorating effects such as the difference in wavelength dispersion discussed earlier. An image intensifier orthicon with an additional accelerating-electron lens, source of "spread", obtains typically 100 \(\mu\) and an 8" photocathode would be necessary. These photocathode areas are much larger than have been developed to date.

Simply increasing the size of the scanned areas alone does not necessarily increase the resolution. Beam spread, electronic or magnetic focusing and velocity differences in electron emission, all tend to increase proportionately with image transducer size.

That some improvement in resolution can be obtained with larger size tubes however is attested to by the development of the RCA 8051 Vidicon, which has obtained a threshold 1200 line resolution and uses a 3/5 x 4/5 inch photocathode (22). It has a 60% response at 400 lines resolution. This compares with conventional Vidicons having a 1/2 x 3/8 inch photocathode which
obtains only 700 to 750 line resolution and whose response at 400 lines is only 30%. Similarly Marconi Wireless Telegraph Co. reintroduced the 4-1/2 inch image orthicon in Europe in 1958 and RCA in the U. S. in 1960. These tubes obtain better resolution than the more widely used 3 inch image orthicons (2, 12, 24, 40). RCA's tubes are the 7295 and 7389. At 400 lines resolution, for example, their response is 60% instead of the more conventional 40 or 50% of 3 inch image orthicons.

Large diameter Kinescopes are also able to attain 2000 to 3000 line resolution which is better than that obtained by the ordinary pickup tubes or smaller display devices.

There are techniques for reducing the granularity effect and thereby improving resolution. A striking example of this is the work by Dr. Feldman at N. R. L. (41). Phosphors were evaporated upon a transparent substrate and then refired to reintroduce certain contaminants lost in the evaporation process. The result was a much thinner layer of phosphor. In addition, the heavy scattering normally associated with Fresnel reflections from particulate matter is missing. Very high contrast and resolution was obtained by this technique with very little halo or ghost effect (certain films also have antihalation coatings and RCA's 7293A has an antighost). A similar technique is under development for high resolution film using evaporated monomolecular silver bromide and single crystal silver bromide.

e. Integration Time (7, 9, 25)

If long integration times are allowed the transducer has more time in which to collect photons. For this
condition the lateral charge leakages of the targets described above must be reduced in order to attain a better sensitivity. This reduction may be accomplished by specially designed high resistivity thin film targets or by cooling the tube to increase the surface resistivity of the target (i.e., decrease the free electron mobility).

Figure 11, for example, shows the improved response of some standard type image tubes when scanned at slower scanning rates. The threshold is noticeably lowered with longer frame times (25h). Some tubes have been specially designed with thin film, high resistivity targets for slow scan operations. The Westinghouse 7290 and \( \times \) 4384 Vidicons and the WL2724 (or 22723, 22722) image orthicon are examples.

Slow scan rates and long integration mean, of course, that rapidly changing scenes, or target motion cannot be readily resolved. The blurring effects of image motion with slow scan speeds are described in Reference 8 and 25h.

5. **Graphical and Tabular Summary**

Some of the more salient features and typical characteristics of image transducers in existence today are set forth in tabular and graphical form immediately following. The data have been gathered from manufacturer's articles and numerous technical papers. Data have been extrapolated where necessary to form some sort of comparative norm. As such, the data cannot be regarded as final, but only indicate present limits of difficulty.
RESPONSE CHARACTERISTICS OF SOME STANDARD IMAGE TUBES AS A FUNCTION OF SCAN RATE

**IMAGE ORTHICON**

```
<table>
<thead>
<tr>
<th>VERTICAL SCAN RATES (frames/sec)</th>
<th>.001</th>
<th>.01</th>
<th>.1</th>
<th>1.0</th>
<th>10.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHOTOCATHODE ILLUMIN (foot-candles)</td>
<td>.001</td>
<td>.01</td>
<td>.1</td>
<td>1.0</td>
<td>10.0</td>
</tr>
</tbody>
</table>
```

**VIDICON**

```
<table>
<thead>
<tr>
<th>VERTICAL FRAME RATE (frames/sec)</th>
<th>.01</th>
<th>.1</th>
<th>1.0</th>
<th>10</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHOTOCATHODE ILLUMIN (foot-candles)</td>
<td>.01</td>
<td>.1</td>
<td>1.0</td>
<td>10</td>
<td>100</td>
</tr>
</tbody>
</table>
```

FIGURE 11

R-14,564
and trends beyond which substantial development effort is necessary to extend the limits of these particular devices.

In many instances, the performance limits or parameters quoted are for the limiting or maximum value assuming all other parameters are optimized. Actually, the parameters interact with each other so that a limit on one value will not occur with a limit on another. This is particularly true of signal to noise ratio (S/N) resolution, sensitivity, and scan time. Wherever possible, the interactions are noted.

An examination of all existing transducers covers a wide range of physical principles. Moreover, it is difficult to establish meaningful parameters which can serve as a common denominator for a basis of comparison. For example, with a cathode ray type image transducer, resolution is commonly expressed as "number of TV lines". This expression is a complicated function of such items as bandwidth, line scan spot size ratio, and vertical linearity of the specific deflection circuits. An indication of resolution for silver halide film, on the other hand, is more specifically related to the media itself and would be expressed in "lines per millimeter". In the graphical presentations that follow, the parameters and units have been chosen to conveniently express relationships and do not conform, in all cases, to common usage.

Figure 12 presents the relationship between the resolution of an image transducer and time. The independent variable of time spans the interval necessary for exposure, processing, storage, and readout. In this fashion, the ranges of operation of existing transducers are related.
SALIENT CHARACTERISTICS OF VARIOUS IMAGE TRANSUCERS

These curves are approximate. They indicate general limitations of existing devices.
In Figure 13 resolution is shown as a function of photo cathode irradiance. This graph is intended to show how this relationship, for representative transducers, compares with the theoretical limit.

Figure 14 describes the variation of the signal to noise ratio photo cathode irradiance. A comparison between representative image transducers is possible.

The variation of necessary integration time for minimum detection as a function of signal irradiance is shown in Figure 15. This function for various transducers can be compared with the theoretical limit.

The above material is intended as background material; it is intended to characterize the range of certain transducer parameters for comparison only. The ideal transducer (or the proposed transducer) cannot be related within such a frame of reference at this point in the study program. The ideal transducer must be more specifically defined by its physical properties before a full correlation can have meaning. However, the graphical summaries do serve the purpose of classifying the range of limitations of existing image transducer systems.
RESOLUTION AS A FUNCTION OF PHOTOCATHODE ILLUMINATION FOR SEVERAL SENSORS
SIGNAL TO NOISE RATIO (S/N) AS A FUNCTION OF PHOTOCATHODE ILLUMINATION FOR SEVERAL SENSORS

*INDICATES MAXIMUM (S/N)

1P21 PHOTOMULTIPLIER TO $10^4$

FILM $\rightarrow$ 1000

IMAGE ORTHICON 5820 $\rightarrow$ 40

IMAGE INTENSIFIER ORTHICON $\rightarrow$ 10

VIDICON $\rightarrow$ 200

ISOCON $\rightarrow$ 100

IMAGE ORTHICON 6849 $\rightarrow$ 20

PHOTOCATHODE ILLUMINATION (LUMENS-sec/cm²)

SIGNAL TO NOISE-(S/N), (TONE RANGE)²
SPECTRAL IRRADIANCE Hs REQUIRED AT ENTRANCE APERTURE OF 1 cm² FOR DETECTION OF MINIMUM NUMBER OF PHOTONS 
\( \frac{S}{N} = 1 \) WITH DIFFERENT INTEGRATION TIMES

- Image Intensifier Orthicon
- Image Orthicon
- Film
- Eye
- Theoretical Limit \( \eta = 1, \bar{N} = 1, \lambda = 556 \mu \)

\[ \eta_0 = 1 \]
\[ A_c = \text{Photocathode Area} \]
\[ \lambda_{\text{theo}} = 556 \mu \]

Irradiance \( H_s \) (Lumens/cm²) = Photocathode Illumination \( \times A_c/N^2 \)

Time, sec

FIGURE 15
D. **RECOMMENDATIONS**

The systems analysis work has been concerned with:

1. completion of the scene composition study;
2. continued analysis of image transducing parameters; and
3. a preliminary study of read-out systems. During the next quarter, the following areas should be accented.

1. **Completion of image transducer parameter studies**
2. **Utilization of parameter and scene analysis to establish the desired performance parameters of an advanced image transducer and translate these into appropriate design criteria.**
E. REFERENCES FOR IMAGE TRANSDUCER SURVEY


Papers:

a. Solid-State Image Intensifiers, by F. H. Nicoll, p. 9

b. RCA Developmental Cascade Image Converter Tubes, by R. G. Stoudenheimer, p. 35

c. The Isocon: A Low Noise, Wide Signal Range Camera Tube, by A. D. Cope, p. 43
d. Image Intensifier Orthicon Tubes, by F. David Marschka, p. 51


f. Limitations to Resolving Power in Electronic Imaging, by A. E. Anderson and R. J. Schneeberger, p. 73

g. Low Contrast Threshold Imaging, by G. A. Morton, p. 79

h. Performance of Image Orthicon Type Intensifier Tubes, by James S. Parton and John C. Moody, p. 85

i. Gain and Resolution of Fiber Optic Intensifier, by Paul J. Dolon and Wilfrid F. Niklas, p. 93

j. The Characteristics of Photocathodes Under High Light Levels, by Marshall P. Wilder and Bernard R. Linden, p. 113

k. Special Phosphor Screens for Image Tubes, by D. A. Cusano, p. 119


28. Meier Sadowsky, "The Preparation of Luminescent Screens".


III. COMPONENT RESEARCH

A. SUMMARY

Recognizing that the read-out operation is of major importance in image transducing, a preliminary study of the various methods of read-out was initiated and completed during this quarter. Three promising read-out methods are:

(1) Programmed matrix light source with a fiber optic geometry converter to provide a line scan
(2) Flying spot scanner employing fiber optic conversion
(3) Kaiser Electronics special line scan facsimile tube.

It is shown that the read-out method which will ultimately be employed in the image transducer is largely dependent on the storage medium. As the storage medium has not been selected, the foregoing methods will only be considered in more detail as they become applicable.

Further analytical investigations and the suggested experimental program for electroluminescent matrix light sources requires the knowledge of the use of the light source in conjunction with other components. This investigation therefore has been postponed until the next quarter.

In the present reporting period two devices were investigated for possible use as image storage components. The optron consists of a photoconductor - electroluminophor combination. Half-tone operation of this device has been achieved for periods as long as one minute. Resolutions of 80 lines per inch have been achieved in practice with much
higher resolutions possible in theory. Response time - sensitivity products of 0.1 foot candle second have been achieved using CdS as the photoconductor. Considerable improvement on this parameter should be possible by using faster and more sensitive photoconducting materials.

The ferrotron can also be used for purposes of image retention. It consists of a photoconductor - ferroelectric combination. A breadboard version of this device has been operated at readout speeds of 50kc. A resolution of 200 lines per inch with a sensitivity of 0.001 foot-candies has been reported. Further investigation of this device for possible application in the proposed image transducer should prove fruitful.

In the previous reporting period it was suggested that an ordered fiber optic array offered a possible method of high resolution image dissection. In this reporting period the possible fabrication of such a device was investigated. Several methods capable of automatically fabricating the desired ordered array were evolved. The extremely large size of the ordered array required for the present system suggests that the cost of developing such a device would be prohibitive for the near future.
B. COMPONENT TECHNIQUES — READ OUT METHODS

1. General

Consideration of the functional breakdown of an image transducer system indicates that the read-out operation is of major importance. This section will be concerned with several read-out systems and their respective components.

The read-out system employed will necessarily depend upon the characteristics of the storage medium. Many storage media will store the input optical image in a form which can be interrogated with a beam of light. However, the optical image could be stored in a form which could be read-out in correspondence with the light input level. This storage medium would require only a sensor and a moving aperture for read-out. This discussion will consider only these storage media which employ a beam of light or an electron beam and a photo sensor for interrogation and read-out of the storage medium.

A scan in both X and Y coordinates is necessary to interrogate the complete area of the storage medium. Scan generation can be accomplished by use of either a raster scan or line scan with coincident movement of either the light source or of the storage medium to provide the other scan dimension. The line scan coupled with movement of the medium requires a more complex mechanical arrangement but offers better positioning accuracy.

The methods of generating a scanning light beam include:

a) A programmed matrix light source
b) A flying spot scanner

c) Special line scan tubes such as those developed by CBS and Kaiser Electronics

d) Mechanical scanning.

Read-out systems employing the above methods are discussed in the subsequent sections.

2. Programmed Matrix Light Sources

A matrix light source consists of a large number of individually energized light elements. As pointed out in the First Quarterly Progress Report, this light source can achieve very high positional accuracies; is not limited in its scan length capability; can produce a reasonable light output; and, it appears, can yield high scanning speeds. If, however, a 10,000 line resolution is desired and a single light source is required per image element, $10^8$ light sources would be needed. Two major problems associated with a matrix light source of such a high packing density are:

1) Fabrication problems

2) Switching configuration

The fabrication of a matrix light source with a packing density in the order of $10^8$ elements in a reasonably small area would require an extensive research and development program.

High speed commutators provide the most basic method of successfully switching each element of a matrix light source. In practice, two commutators would be used, one commutator to switch the
lines of the matrix and the other to switch the columns. The voltage is applied sequentially to each element of the matrix by allowing the column commutator to complete a full cycle of operation for each successive position of the line commutator. With this basic arrangement, a total of 20,000 switch positions would be necessary to achieve a resolution of 10,000 lines and 4,000 switch positions for 2,000 line resolution.

The commutation or switching process may be accomplished mechanically or electronically. The mechanical method, utilizing a rotating switch, suffers disadvantages in operating life and limited operating speed. Straight-forward electronic switching, employing some form of counter driving a diode switching matrix, would demand an excessive number of circuit elements to provide 10,000 discrete outputs for each axis.

A more sophisticated method of switching might be achieved by the use of a line scan in conjunction with movement of the storage medium. A square matrix light source of 10,000 elements, programmed by two 100 position electronic commutators, would provide a sequentially switched light source. The line scan is obtained by using fiber optic conversion to change the elements of the square matrix to a line of 10,000 positions.

The method of switching proposed above overcomes the two major problems associated with the use of a programmed matrix light source for read-out. The packing density of the source is reduced by a factor of $10^4$ and the number of switching elements is greatly reduced. A 10,000 element matrix light source and the proposed fiber optics converter can both be realized by present state-of-the-art techniques. In
view of this, a more thorough analysis of this read-out method should be undertaken in order to determine its feasibility.

3. Flying Spot Scanner Read-Out

A flying spot scanner could be used to generate the scanning light beam for interrogating the storage medium. This scanner could generate either a raster or a line scan pattern. This system, however, has several major problems. First, its line scan to spot size ratio, a measure of its read-out resolution capability, is limited. Secondly, the intensity and spectral distribution of its light output is also limited. Beam positioning accuracy, the uniformity of its light output, and light spot "halo" and "trailing" effects are other problem areas that must be considered with the flying spot scanning system.

Some present day flying spot scanners are capable of achieving .003 inch spots over an approximately 4" scan in a 5" CRT tube. This would represent a read-out resolution capability of approximately 4/.003 or 1,330 lines, which is far short of the 10,000 lines desired. These scanners can achieve positioning accuracies of 1% which is considerably poorer than the .01% desired.

The desired resolution and accuracy could, however, be achieved in a flying-spot scanner system by using fiber-optic geometry converter and a line scanning read-out system. In this case, the fiber-optic scan converter would convert a ten-line, 1000 element/line, raster scan pattern on the flying spot scanner into a single 10,000 element horizontal scan at the storage medium. As conical fibers would be employed, the read-out beam positioning accuracy would be considerably higher than that of the C. R. T. By embedding these fibers into the
face-plate of the flying spot scanner, considerable improvements in optical efficiency can also be obtained.

4. **Special Line Scan Tubes**

Special modifications of the flying spot scanner could be employed to yield higher scan length/spot size ratios. One such device, the CBS line scan tube, has phosphor coating on a rotating drum, inside of a CRT, thus alleviating problems in phosphor burn-out and fatigue. It also utilizes the light spot generated on the electron beam side of the phosphor. On conventional CRT's, the light spot on the outside of the phosphor is employed. This light spot is larger than that on the inside because of light and electron beam spreading through the phosphor.

Kaiser Electronics of San Jose has proposed a special line facsimile read-out tube (see Figure 16) which deflects and focuses the scanning electron beam in a unique manner. The use of a line scan read-out allows the use of a compact cylindrical tube with deflection in only one axis. The spot size may be independent of scan length, an advantage which is not realized by conventional flying spot scanner systems.

5. **Mechanical Scanning**

The scanning light spot can be generated mechanically. In general, mechanical scanning methods are limited in scanning velocity but realize advantages in spectral range, scan length, spot size ratios, intensity, and lack of after-glow. The generation may be accomplished by rotating lenses, a rotating mirror, or rotating glass fibers.
A moving light spot can be generated mechanically by means of pinholes in rotating discs, drums, or belts. Each of these methods, however, requires a uniform light source of high intensity extending over a large surface area which is difficult to achieve.

In the moving-lens scanning system, such as shown in Figure 17, the scanning dot is produced by means of a number of lenses mounted to a common rotor. Three lenses focus light from the light sources onto the storage medium and the motion of the rotor produces a line scan. Information is obtained from the moving storage medium. The transmitted light is collected and relayed to a photomultiplier.

A typical moving-mirror scanning system is shown in Figure 18. The pinhole is located at the axis of rotation. Its light is collected by a rotating elliptical mirror and projected onto the storage medium. Multi-surface mirrors could be employed for producing several scan lines per mirror revolution.

The scanning spots can also be generated by means of moving glass fibers. A typical system is shown in Figure 19. The fibers, one for each scanning spot, are mounted in a rotor. The entrance ends are located at the axis of rotation and are illuminated by means of a small, intense light source and lens. The light output ends move in a circle very close to the storage medium. That light which passes through the storage medium is collected and sent to the photomultiplier.
NOTE: THE LENS IS SHOWN SCHEMATICALLY ONLY THE RADII ARE NOT CALCULATED

MOVING LENS SCANNING SYSTEM

FIGURE 17
C. IMAGE RETENTION DEVICES

An important function to accomplish in the proposed image transducing system is that of image retention. The reason for this is that the scene exposure time is only 10 milliseconds while transmission of the image may require considerably longer times. Thus, to have the scene available for transmission operations longer than the 10 millisecond exposure time, it is necessary to provide for temporary image storage.

In the present report period two devices capable of image retention were investigated. These devices (the optron and ferrotron) are discussed in this section.

1. Optron Matrix

Materials such as double activated phosphors and those exhibiting phototropism are capable of retaining a latent optical image. It is also possible to retain an active optical image by combination of certain types of materials. One possible device, consisting of a combination of an electroluminophor and a photoconductor, called an optron, will be discussed here. A matrix of optron elements could be employed to store an optical image. The cell construction of an optron element is shown in Figure 20. The light emitted from a light source (image) strikes the photoconductor, thus increasing its conductivity and simultaneously increasing the voltage across the electroluminor. The electroluminor is thus excited and emits light. A part of this light serves as the output signal (retained image) and part is fed back to the photoconductor to sustain the excitation when the input light source is extinguished. Such panels have already been
OPTRON STORAGE ELEMENT

LIGHT OUTPUT

LIGHT INPUT

ELECTROLUMINOR

PHOTOCONDUCTOR

TRANSPARENT ELECTRODES
extensively discussed in the literature and several such devices have been constructed. The resolution of existing devices is a little below that desired in this application. However, this appears to be a matter of improvement on the state-of-the-art as no fundamental limitations prevent reaching the desired resolution.

With sufficiently high level inputs the optron unit shown in Figure 20 can be operated in a bistable mode. Operated in this way the unit is essentially a storage element with two states, dark (off) and fully lit (on). For present purposes this is undesirable since several shades of gray are required. If the unit is operated below this critical input level, it no longer acts as a stable memory. However, the closer to the critical level the device is operated the longer it takes for the image to decay. Half tone operation\(^2\) for such panels has already been achieved for times greater than one minute.

A possible modification of the optron storage element is shown in Figure 21. Here several layers of different photoconducting materials are used rather than one. The photoconductors are chosen such that different light levels are required to trigger them. In this way one layer after another is rendered conducting by increasing the input light level, resulting in multimode storage operation. In theory any number of layers could be used and hence any number or modes obtained. In practice, of course, the number of layers will be limited by thickness considerations as absorption of the light energy increases rapidly with increasing thickness. Preliminary experiments would be essential to determine the limitation on the number of usable layers. The memory time of such a device is essentially infinite since it operates in a multi-stable mode.
MULTIMODE OPTRON STORAGE ELEMENT

FIGURE 21
An optron matrix is shown schematically in Figure 22. The individual cells are optically insulated to prevent crosstalk. Existing optrons trigger at input light levels of the order of 0.1 foot candle second. This sensitivity can be improved greatly by employing photoconductors other than those presently used. Existing devices tend to contain materials which are both insensitive and have long response times. Proper choice of the photoconducting material should improve this situation considerably.

2. **Ferrotron**

Photoconductors, which detect light, and ferroelectric materials, which store information, have been wed together to store light images. This section describes the operation of this light storage device in an image storage and retrieval system. This device will be referred to as a ferrotron.

The light storage element consists of the necessary electrodes and layers of photoconductive and ferroelectric material (Fig. 23). In operation the incident light decreases the resistance of the photoconductor while simultaneously the programmer momentarily closes switch X permitting a voltage to be applied which polarizes the ferroelectric. The degree of polarization of the ferroelectric cell is determined by the applied voltage, the length of time the switch is closed and the resistance of the photoconductor (which is a function of the incident light level). The ferroelectric material can store amplitude levels, providing the storage element with a tone range capability.

It is thus seen that the switch "on" time "t" can be varied to establish the sensitivity of the storage device. Where the average light level is high, the pulse duration will be short.
OPTRON MATRIX

OPAQUE CELL SEPARATORS

LIGHT OUTPUT

OPTRON CELL

TRANSPARENT ELECTRODES

TRANSPARENT BASE

LIGHT INPUT

FIGURE 22
LIGHT STORAGE ELEMENT

![Diagram of light storage element](image)

**FIGURE 23**
When operating at night (low light levels), the duration time can be increased to provide higher image storage sensitivity.

Multi-element image storage screens can be prepared by depositing layers of photoconductive (such as cadmium sulfide) and electrode material (gold) on a ferroelectric slab similar to the arrangement shown in Fig. 2. In operation, the image side of the screen is exposed to the incident image light which changes the resistivity pattern of the photoconductor in accordance with the incident light level at each point. Switch "I" is then momentarily closed for a time "t" (determined by the average ambient light level) polarizing the ferroelectric in correspondence with the resistivity (and thus light) pattern on the read-in photoconductor layer.

Readout of the stored image can be accomplished either optically or electrically. For optical readout a voltage is continuously applied across the ferroelectric layer and a pin-point beam of light scans the stored image line by line. The incident light lowers the resistance of the photoconductive layer sufficiently to result in a voltage pulse being applied to the ferroelectric material. This voltage pulse depolarizes the ferroelectric material, the resultant current being sensed for readout. This readout method, however, depending upon the speed of the photoconduction is relatively slow. Readout could also be accomplished electrically by laying a grid of conductors on either side of the ferroelectric layer in the form of a matrix. Each matrix position could then be sampled sequentially by application of a voltage pulse.
MULTI-ELEMENT IMAGE STORAGE SCREEN

INCIDENT IMAGE LIGHT

SWITCH I

VOLTAGE SUPPLY

ELECTRODE GRID

TRANSPARENT ELECTRODE

READ IN PHOTOCONDUCTOR

FERRO-ELECTRIC

READ OUT PHOTOCONDUCTOR

TRANSPARENT ELECTRODE

READ OUT LIGHT SOURCE

LEADS TO ELECTRODE GRID

COMMUTATOR SWITCH

INTERROGATOR

FIGURE 24
In Fig. 24 is shown a complete image retention and readout technique employing a line of light together with electrical line commutation to accomplish readout. The interrogation and depolarization of all points of the ferroelectric storage layer is accomplished by moving the light line in incremental steps and sampling all the conductors of the electrode grid at each of the light line positions.
D. FIBER OPTIC ARRAYS

The analysis appearing in the first image transducer quarterly report indicated that a fiber optic array of five micron fibers would theoretically dissect a 5" x 5" image with a resolution of 10,000 lines and a method was shown for separating the image elements for achieving this high resolution with conventional readout techniques. However, this would necessitate the construction of an ordered array of $6.45 \times 10^6$ five micron coated fibers (or $2.59 \times 10^6$ fibers for a 2,000 line resolution system), posing a formidable fabrication problem. A method for simplifying the fabrication process was presented. This method would consist of automatically arranging 100 fibers in small coded sections, the final array being made by mosaicking these sections together. The fibers in each section would be interwoven to separate the image elements in the output plane for high resolution readout. This section discusses the present state-of-the-art of producing coated fibers and unordered fiber bundles and suggests several methods which might be employed to automatically fabricate ordered fiber arrays.

Methods of drawing lengths of high refractive index glass fibers with a thin coating of low refractive index glass and methods for drawing multiple unordered fibers have been developed. The insulated fiber drawing machine is illustrated in Figure 25. The rod and its tubing are fed, at constant speed, into a hollow cylindrical furnace. Here they are heated sufficiently to cause fusion of the two materials and tapering of the fiber down to very

INSULATED FIBER DRAWING MACHINE

HIGH REFRACTIVE INDEX ROD

LOW REFRACTIVE INDEX TUBING

FEED MECHANISM

HOLLOW CYLINDRICAL FURNACE

FIBER WINDING DRUM

METAL COATING UNIT

MOTOR

INSERT

FIGURE 25
small diameters (see insert). The resultant fiber diameter is determined by the size of the original rod and tube, the rate of feed, the furnace temperature and the speed of the winding drum. A second metal insulating coating can simultaneously be deposited on the fiber by the metal coating unit shown in Figure 25. This is accomplished by passing the fiber through molten metal such as aluminum or indium, which deposits a continuous and uniform metal coating around the fiber.

A method of producing a new type of fiber consisting of a large number of very small diameter fibers has been developed. These "multiple fibers" are made in the same manner as the single coated fiber described above. However, in this case a large number of coated rods are bundled together and passed through the drawing machine. Multiple fibers consisting of as many as 275 fibers having 2 micron diameters have been drawn by this method but these fibers were not ordered.

Two methods of automatically arranging a fiber bundle are described below. In the system shown in Figure 26a the fiber ends would be sequentially directed to their desired locations by air flow. Individual fibers would be fed into the air chamber. A programmed valve would uncover the appropriate hole in the acceptor plate, permitting air to flow only through it. The air flow would direct the fiber to the uncovered hole where it would be captured and held. The next fiber would then be fed into the chamber and similarly directed to its desired end position on the acceptor plate. The process would be repeated until the entire fiber section is formed. The fiber ends would then be cut and stacked and cemented together to form the ordered section. The sections, in turn, would be stacked together to form the final fiber array.
Another method would utilize holes which can be positioned in the acceptor plate to arrange the fibers in the desired pattern. In the initial step of the operation, the acceptor plate would be adjacent to the feeder plate (Figure 26b), the holes in the two plates being in alignment at this time.

The fibers would then be fed into the holes of the acceptor plate, at which time the holes in this plate would contract, locking the fibers. It then would move away from the feeder plate into the position shown in Figure 26c. These holes would then be repositioned into the desired arrangement (Fig. 26d), both ends cut and the fibers bundled and cemented together to form the 100 fiber ordered section. Such machines are highly complex, and, because of the fragility of the fibers, would require a large amount of experimental research and development. Furthermore, assuming the cost of ten fibers to be one cent, the cost of the fibers alone ($645,000 for 10,000 line resolution) makes them impractical for this application.

The inter-leaving of 100 five micron fibers to form one ordered fiber section is a formidable task. As \[6.5 \times 10^6\] of these sections would be required in a complete 10,000 line resolution fiber optic system, the fabrication cannot be done manually. The small fibers are extremely fragile, making any mechanical manipulations very difficult. Machines and techniques have been developed for drawing fine insulated fibers and unordered multiple fibers, consisting of as many as 275, \(2 \mu\) diameter fibers. However, these techniques are not directly applicable to the solution of the present problem. It appears that the solution would require a large advancement in the state-of-the-art of fiber handling and weaving. This, together with the high cost of producing the required fiber array renders this approach impractical at this time.
METHODS OF FIBER FABRICATION

A

FEEDER PLATE

AIR CHAMBER

ACCEPTOR PLATE

VALVING SYSTEM

VACUUM SUPPLY

B

FEEDER PLATE

ACCEPTOR PLATE

C

FEEDER PLATE

POSITIONING HOLES

ACCEPTOR PLATE

D

FIGURE 26
E. RECOMMENDATIONS

During the next report period investigations should be carried out in the following areas.

(1) The compatibility of various components used in combination to form an image transducing system should be studied to determine an optimum performance system.

(2) The investigation and study of solid state light storage elements should be placed on determining the operating parameters such as sensitivity, resolution, noise characteristics, dynamic range, response times and other pertinent parameters.

(3) Analytical and experimental investigations should be carried out leading up to the design and construction of a breadboard matrix electroluminescent light source. The performance parameters should be ascertained to determine the feasibility of this type device as a matrix light source.
F. REFERENCES

IV MATERIAL STUDY

A. SUMMARY

During the past quarter an extensive survey of the literature was carried out to determine the capabilities of materials exhibiting phenomena which could be useful in an image transducing device. These phenomena had been identified as electroluminescence, double activated phosphorescence, photoconductivity and phototropism in the previous Quarterly Report. This aspect of the literature survey is essentially complete. The data obtained will be analyzed and a selection of a material (or materials) for the contemplated image transducer made. The complete survey will also include a full understanding of the image retention capabilities of ferroelectric materials.

The electroluminescent materials have band widths typically of the order of one to two thousand Angstroms centered in any part of the entire visible spectrum, the near ultra-violet, or the near infrared. Injection electroluminescence has the advantage of low excitation voltages, ranging from 10 to hundreds of volts, and short decay times, of the order of microseconds or less. These properties make the electroluminescent materials useful as a cold light source of small size capable of being turned on and off rapidly.

The information available on double-activated phosphors is somewhat limited, although information on infrared stimulable phosphors is more abundant. Standard VI and VII appear to be the best available infrared stimulable phosphors at this time. Standard VI is excited in the blue-green and emits in the orange-red whereas Standard VII is excited in the near ultra-violet and emits in the green. The double activated phosphors are of special importance...
for image retention devices.

Photoconductors can be obtained with a great range of thresholds. Normally the response is found to peak at a wavelength corresponding to the energy gap of the photoconductor. Consequently, photoconductors can be obtained with peak responses ranging from the near ultra-violet to the far infrared. The more sensitive photoconductors tend to have the longer response times although lead selenide and lead telluride appear to be exceptions. A sensitivity of $10^{-11}$ to $10^{-12}$ watts with a response time of ten microseconds is possible in the infrared. Photoconductors are of fundamental importance in devices which convert an optical image into an electrical image.

The phototropic materials by and large do not appear to hold as much promise for image storage as do the electroluminesphors, photoconductors, and double activated phosphors. The best available phototropic material is pink hackmanite although the sensitivity is rather low. In addition the problem of fabrication in a suitable form exists.

Experiments were made to develop a transparent synthetic form of hackmanite through a novel approach employing elevated temperatures and pressures in the forming process. Fourteen attempts at producing suitable wafers were made. While complete success was not achieved, steady improvement in the results was noted. Further experiments along these lines will be made.
B. LITERATURE SURVEY

In the previous quarterly report it was pointed out that an image transducer requires materials having suitable properties to convert photon into electron energy or electron into photon energy and for the retention of the image whether in optical or electrical form.

Materials can accomplish the above objectives through either physical or chemical processes. The most promising phenomena associated with these reactions for image transducing have been determined as follows:

<table>
<thead>
<tr>
<th>Phenomena</th>
<th>Photon to Electron</th>
<th>Electron to Photon</th>
<th>Image Retention</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electroluminescence*</td>
<td>- - x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photoconductivity*</td>
<td>- x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(and associated phenomena)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Double Activated phosphorescence</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Phototropism</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Ferroelectricity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemical:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phototropism</td>
<td></td>
<td></td>
<td>x</td>
</tr>
</tbody>
</table>

* These phenomena often occur together.

The research for literature and the examination of materials has been conducted in consideration of the foregoing table.
1. Electroluminescence

Light may be generated by the direct action of an electric field (AC or DC) on various solid materials by a number of different mechanisms. These phenomena are called electroluminescence and materials which exhibit these phenomena are called electroluminophors or electroluminors. Electroluminescence may be subdivided into (1) intrinsic electroluminescence (Destriau effect), (2) injection electroluminescence (Lossev effect), and (3) photo-electroluminescence. Intrinsic electroluminescence covers chiefly light emission of suitable phosphor powders embedded in an insulator and subjected only to the action of an alternating electric field. Injection electroluminescence covers light emitted by the sole action of an electric field on crystals or particles in contact with conducting electrodes so that current injection can occur. Photoelectroluminescence covers electroluminescent phenomena which are enhanced through the action of incident radiation. Related to these three classes of phenomena is a fourth referred to generally as (4) electrophotoluminescence. Electrophotoluminescence covers photoluminescent phenomena (i.e., light stimulation by photons) which are enhanced (or quenched) through the action of an applied electric field. The characteristics of this phenomenon render it less difficult than those mentioned above for application in an image transducer.

The literature on various aspects of these phenomena is vast with over 500 references occurring since 1955. H. K. Henisch in a book entitled Electroluminescence, published by Pergamon Press in 1962, lists 810 references dating back to 1891. It should be noted that many of the papers appearing in 1961 and most of those appearing in 1962 are not included in Henisch's
compilation. The field is extremely active at the present time, both from the research and application points of view. Confronted with such a huge amount of literature, no attempt has been made to complete an exhaustive study, but rather it was decided to make a selective study in order to determine the present state of knowledge of the phenomena and the materials concerned.

Electroluminescence is normally observed only in solids. However, certain liquids behave electrically as orthodox semiconductors, raising the suspicion that they may conceivably be electroluminescent as well. In fact, instances have been recorded in which contaminated oils have emitted light under high voltage DC excitation, although it is not clear whether or not the process can be classified as electroluminescence. Solids which exhibit electroluminescence may be polycrystalline or single crystals, but it is not definitely known whether the phenomenon occurs in non-crystalline solids. Although electroluminors are termed "cold" light sources, they do in fact heat up somewhat during normal operation as the energy conversion (electric to light) cannot be one hundred percent efficient. However, no part of the emitting surface even approaches the temperature range of incandescence.

Electroluminescence requires the application of intense electric fields. One method used to accomplish this is to apply a moderately high voltage across a thin layer of the electroluminor. A second method is to make use of the intense electric fields which exist at pn junctions. Since the light is normally generated within the specimen, it is essential that it be transparent or at least semi-transparent. Furthermore, at least one of the electrodes must be semi-transparent to permit the radiation to be observed.
Within the present context, no distinction is made between radiation visible or non-visible to the eye. In fact, many materials emit light in the infrared region of the spectrum. For some applications, it is quite possible that this would be a desirable feature. In addition, no single physical process is implied by the term electroluminescence. On the contrary, many different mechanisms lead to phenomena legitimately classified as electroluminescence. Consequently, the survey is divided according to specimen type. Typical electroluminor parameters discussed in the following section are listed in Table V for reference.

a. Single Crystals Phosphors

The electroluminescent properties of zinc sulphide and cadmium sulphide single crystals have been studied extensively. As systematic studies cannot easily be carried out using naturally occurring crystals, most studies have been conducted using laboratory grown crystals. This in itself is a very important problem which still attracts considerable attention. Present techniques are capable of producing single crystals as large as 40 g. The crystals take the form of rods, plates, or polygonal prisms with maximum cross-sectional areas of about 1 cm². Systematic procedures have been developed for obtaining crystals of high purity or for adding various amounts of impurities such as copper, silver, arsenic, aluminum, gallium or indium.

An important problem which is not yet satisfactorily understood is that of making low resistance ohmic contacts to the crystals. Many materials such as aluminum, gold, silver, beryllium-copper, bismuth, copper, indium, platinum, tantalum and gallium have been investigated, with best results generally being obtained with the use of indium and gallium.
### TABLE V

**SUMMARY OF PROPERTIES OF TYPICAL ELECTROLUMINORS**

<table>
<thead>
<tr>
<th>HOST</th>
<th>TYPICAL IMPURITY</th>
<th>TYPE</th>
<th>OPERATING TEMP.</th>
<th>TYPICAL PEAK EMISSION WAVE LENGTH</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>CdS</td>
<td>Cu, Ag, As,</td>
<td>Injectimor</td>
<td>Room temp.</td>
<td>5800 A&lt;sup&gt;*&lt;/sup&gt;</td>
<td>Emission seems to be from spots of 10 diam.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>intrinsic</td>
<td></td>
<td></td>
<td>Spot emission</td>
</tr>
<tr>
<td>ZnS</td>
<td>Al, Ga, In</td>
<td>Injection</td>
<td>&quot;</td>
<td>5500 A&lt;sup&gt;*&lt;/sup&gt;</td>
<td>Low temp. emission curve depend upon impurity present; pn junction operated in reverse bias</td>
</tr>
<tr>
<td>Ge</td>
<td>Bo, As</td>
<td>&quot;</td>
<td>&quot;</td>
<td>17700 A&lt;sup&gt;*&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Si</td>
<td>In, Ga</td>
<td>&quot;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ge</td>
<td></td>
<td>&quot;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Si</td>
<td></td>
<td>&quot;</td>
<td></td>
<td>6200 A&lt;sup&gt;*&lt;/sup&gt;</td>
<td>10 μ spot light source</td>
</tr>
<tr>
<td>GaP</td>
<td>C, Si, Ge, Mn, S, Zn, Cu</td>
<td>Injection</td>
<td>RT</td>
<td>5900 A&lt;sup&gt;*&lt;/sup&gt;</td>
<td>Reverse currents give increased light</td>
</tr>
<tr>
<td>GaSb</td>
<td></td>
<td>Injection</td>
<td>RT</td>
<td>19700 A&lt;sup&gt;*&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>GaAs</td>
<td></td>
<td>Injection</td>
<td>RT&lt;sub&gt;&amp;77K&lt;/sub&gt;</td>
<td>10300 A&lt;sup&gt;*&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>A N</td>
<td>Cu, Mn</td>
<td>Injection</td>
<td>RT</td>
<td>5500 A&lt;sup&gt;*&lt;/sup&gt;</td>
<td></td>
</tr>
</tbody>
</table>
Of fundamental importance is the location of light emission. Unfortunately, many investigators merely report that light originated from the crystals, without any more detailed identification or description of the emission sources. Some investigators believe the emission to occur in the immediate vicinity of the contacts while still others believe the emission is more or less uniformly distributed over the bulk of the material. Experimental resolution of this problem is complicated by the high refractive index of the material. Furthermore, it is quite possible that both types of emission do occur under different circumstances. The emitting regions have been studied in some detail and it appears that emission can occur at discrete spots rather than continuously. These spots are reproducible and of extremely small size, probably less than 1 micron in diameter. The density of spots is not a function of applied voltage, and interspot distances of 2 or 3 microns have been reported. Other investigators have reported continuous emission, but clearly a problem in optical resolution is involved and further experiments are required to clarify the situation.

A significant anisotrophy in emission intensity with respect to the relative orientation of field direction and crystalline c-axis has been reported. The greatest intensities appear when the applied field is perpendicular to the c-axis. Experiments indicate that the light emission ratio for excitation parallel and normal to the c-axis can be as great as one thousand.

Electroluminescent excitation of ZnS single crystals can be achieved by constant fields. Under such
excitation, the brightness is found to increase exponentially with the applied voltage in a reversible manner until electrical breakdown occurs. Moreover, the brightness appears to be directly proportional to the current density. The brightness-voltage curves do show some dependence on the type of electrodes used and emission appears to originate in the vicinity of the electrodes. Some experiments seem to yield results contrary to those mentioned above, but it is not clear whether specimens and experimental conditions were exactly identical. Emission under constant field excitation cuts off sharply at 3.6 ev (about 3400 Å), peaks broadly at about 5500 Å, and falls off rapidly about 6000 Å in some specimens. Other specimens fail to exhibit emission in the ultra-violet region of the spectrum.

**Single crystals of ZnS electroluminesce** under the action of an applied sinusoidal voltage. The brightness observed under such excitation is periodic with twice the excitation frequency. Furthermore, several cycles of operation are required before dynamic equilibrium is achieved. There appears to be some disagreement in the literature regarding the location of emission and its dependence on electrode material. The brightness is found to increase with applied voltage and excitation frequency. Excitation frequencies as high as 1000 Mc have been used with results suggesting that inherent relaxation times are probably of the order of 1 µsec.

**Cadmium sulphide single crystals become electroluminescent in the immediate pre-breakdown region under DC excitation.** At current densities above about 1 amp/cm², the emitted light is readily observed by the unaided eye. As considerable thermal energies are developed at these current densities,
a means of crystal cooling is desirable. The emission generally occurs in the red-orange, or green part of the visible spectrum. Emission can also occur in the form of spots with spot size being of the order of 10 microns. The density and brightness of these spots tends to increase as the current is increased. Some cases of electroluminescence at lower applied voltages (two or three orders of magnitude lower) have also been reported.

Barium and strontium titanates, cuprous oxide, and titanium dioxide single crystals have also exhibited electroluminescence upon AC excitation. The emission for barium titanate is yellow; for strontium titanate, white; for titanium dioxide, orange white; and for cuprous oxide, infrared. Excitation frequencies up to 40 Mc have been used in the case of the titanates. The cuprous oxide also emits under excitation by DC voltages.

b. Electroluminescence at Junctions and Crystalline Boundaries

The injection of minority carriers at contacts and junctions frequently leads to electroluminescence. Observations of this type have been made on germanium and silicon single crystals with various impurities such as boron, arsenic, indium, and gallium added. At room temperature, silicon single crystals emit photons ranging from less than 1 ev. to greater than 1.25 ev. with the distribution peaking sharply at approximately 1.1 ev. At low temperatures (77°K), the distribution curves exhibit structure which is found to be dependent on the type of impurity present. The addition of indium, for example, shifts the peak of the distribution to about 0.96 ev. In all cases the emission is confined to the infrared region of the spectrum. This is to be expected as silicon has a forbidden region of only 1.1 ev. at room temperature. Similar results were obtained for germanium with a peak
for the intrinsic material appearing at 0.7 ev. corresponding to its room temperature energy gap. The addition of copper causes a subsidiary peak to appear at about 0.6 ev.

When pn junctions in silicon and germanium are operated in the reverse bias condition, light emission in the visible part of the spectrum can occur. The light emission occurs in the breakdown and pre-breakdown regions and has been observed on grown and alloyed junctions with breakdown voltages varying from 10 to 156 volts. A grown junction in a silicon crystal with a breakdown voltage of 40 volts emits a yellow light peaking at about 2 ev. and falling off rapidly above 2.5 ev. The light appears in the form of spots estimated to be 10 microns or less in size. The density of spots appears to depend on current density at low current densities and is reproducible. At high current densities (of the order of 4 amp/cm²), regions of uniform brightness appear with the brightness a sensitive function of current. Decay times associated with the emission have not been precisely determined but are less than 4 μsec.

Emission can be stimulated by forward currents in SiC crystals. The spectral range extends from about 4600 Å to about 6000 Å with two peaks, one occurring at about 4700 Å and the other at about 5300 Å. The emission can be observed at 77°K or room temperature. The brightness increases with increasing current density. At room temperature, the efficiency can be as high as 2 x 10^-6 photons/electron. At low temperatures, efficiencies as high as 2 x 10^-4 photons/electron have been observed. At room temperatures, the decay times observed are of the order of 1 μsec. The presence of iron in the SiC is very deleterious to the emission as the Fe serves as a killer center.
Electroluminescence occurs in single crystals of gallium phosphide under excitation by either AC or DC fields. An order of magnitude increase in brightness is observed when reverse currents are passed through the crystals as compared with forward currents. Several bands have been observed depending on the nature of the activators. Gallium activation results in an orange emission beginning at about 4600 Å. The addition of Zn and Cu results in a brilliant red emission with a spectral range extending from 6800 Å to beyond 8900 Å. No noticeable effect upon the orange emission results from doping with impurity elements such as C, Si, Ge, Mn or S. In addition to the red band, Zn doped crystals exhibit a yellow-green band extending from 5300 Å to 6300 Å and peaking at about 5900 Å. Decay times in these materials are less than 25 μsec.

Other III-V crystals exhibit electroluminescence. Gallium antimonide at room temperature emits light in a range from 0.7 ev. to 0.55 ev. with a peak near 0.62 ev. Current densities up to 1 amp/cm² have been passed in the forward direction by pulsing with a 50% on-off square wave generator operating at 100 cps. Similar operation on gallium arsenide crystals both at room temperatures and 77°K yields a spectrum peaked at about 1.2 ev. and extending to 1.6 and 0.8 ev. The low temperature spectral response is somewhat sharper than the room temperature response. Indium phosphide and germanium-silicon alloys have also been shown to be electroluminescent. Detailed results of the spectral response is not available in these cases; however, it is known that they peak in the energy range appropriate to the gaps in these materials. The energy gap in InP is 1.25 ev. and the gap in the Ge-Si alloy varies from 0.7 to 1.10 ev.
Electroluminescence at contacts and in the interior of crystals has been observed in aluminum phosphide and on the nitrides of boron, gallium and aluminum. AlN gives emission intensities which compare favorably with those found in zinc sulfide. An activator such as Cu, Mn, or a group II element is usually required to activate the material. The spectrum consists of a series of narrow bands between 4000 and 5000 Å and a broad continuous band from 5000 to 7000 Å. Efficiencies are of the order of $10^{-3}$ lamberts/watt.

Some II-VI compounds also behave as semiconductors and should exhibit electroluminescence under the appropriate conditions. Cadmium telluride with an energy gap of 1.45 ev. has been observed to emit light when forward current is passed through a pn junction in the crystal. The emission spectrum does in fact peak at 1.44 ev. Thus far impurities do not seem to affect the emission spectrum, although available experimental evidence is rather sketchy.

c. Microcrystalline Phosphors

One of the most thoroughly investigated electroluminophor is microcrystalline copper activated zinc sulphide. Two emission bands are observed, one peaking at 4500 Å due presumably to the presence of the copper and the second peaking at about 6500 Å. As usual, the emission characteristics depend in an important way on the method of specimen preparation. The addition of co-activators such as aluminum, indium, and gallium results in a phosphor which emits only green light providing the copper concentration is sufficiently low. Phosphors activated
in this way are relatively frequency independent for excitation frequencies from 60 to 15,000 cps. With copper and manganese both present in ZnS, a strong electroluminescence is observed with a peak at about 5850 Å.

Zinc sulphide phosphors with copper as the primary activator are strongly sensitive to the addition of chlorine. A green band in addition to the copper blue band is exhibited. The relative emission in the two bands is a sensitive function of the copper, chlorine content and the temperature of the specimen.

The effect which any particular activator has on the spectral response depends, among other things, on the band width of the parent lattice. The band width can be varied by the use of solid solutions of different composition. ZnS - ZnSe, ZnS-ZnTe, and ZnSe-ZnTe are systems of this kind and by means of them a continuous range of bandwidths can be obtained from 3.6 to 2.1 ev. The ZnS-ZnSe system with copper as activator and chlorine, iodine or bromine as a co-activator has been studied extensively. By varying the percent of ZnSe in ZnS, emission peaks are possible from 4470 Å with no ZnSe present, copper as an activator and iodine as co-activator to 6320 Å with no ZnS present, copper as an activator and chlorine as co-activator.

Electroluminescence of ZnS phosphor suspensions is possible under certain modes of operation under excitation by constant fields. Normally, the emission is very weak, but it is greatly enhanced by the addition of small amounts of manganese impurity.
The more usual method of excitation employed for microcrystalline phosphors is an applied AC voltage. ZnS:Cu, Cl and ZnS:Cu, Al phosphors when excited in this way exhibit a buildup time of about 10 msec. The brightness usually depends exponentially on applied voltage. A normal brightness voltage curve shows a relatively sharp knee at some critical voltage. Below this critical voltage, very little emission occurs, while above the critical voltage, the brightness varies nearly linearly with voltage over a limited voltage range.

Considerable interest has occurred in thin film phosphors. Several techniques have been used to obtain films of thickness of the order of one micron. These films exhibit electroluminescence at rather low applied voltages, as low as 2.2 volts at 1000 cps in fact. Under these conditions the emission spectrum is independent of applied voltage. The light output is nearly constant from 100 cps to 10,000 cps but decreases sharply with increasing temperature. In some cases, excitation by DC voltage is possible; in fact, brightness levels up to 600 ft. L. have been observed with a DC applied voltage of 85 volts.

2. Photoconductivity

A photoconductor is a material whose electrical conductivity can be increased by the absorption of light or other suitable radiation. This property of matter has been known since 1873 and since then more than one thousand papers have appeared on the subject or closely related topics. An excellent compilation of references up to 1959 appears in Photoconductivity of Solids by R. H. Bube published by John Wiley and Sons in 1960. No attempt will be made here to give a detailed description or even
a thorough survey of the mountains of information available on the subject. The course to be followed is merely to list those materials which are known photoconductors and to present some remarks on the characteristic properties of those materials.

A solid in thermal equilibrium has its electrons (and holes) distributed among available energy states in accordance with Fermi statistics. The deeper lying states are bound states, i.e., localized in space, hence do not contribute to conductivity. The intermediate states may be free and thus capable of contributing to the conductivity, but in the case of insulators and semi-conductors they are completely filled and, therefore, do not contribute to the conductivity. The higher lying states are free and unfilled; however, a certain fraction of these levels will be thermally occupied leaving behind a like number of free holes in the intermediate levels. These carriers give rise to a temperature dependent "dark" conductivity. The absorption of light upsets the equilibrium distribution by raising more electrons from the intermediate levels to the unoccupied free states thus increasing the conductivity. Of course, these electrons remain in the excited state only until recombination processes return them to their original ground states. This temporary increase in conductivity induced by the photon-electron interaction is the phenomenon referred to as photoconductivity.

To compute the magnitude of the photoconductive current, it is only necessary to know the increase in free carrier density induced by the incident photons. However, the free carrier density will, for a given excitation rate, be dependent on the
lifetimes of the free carriers in the excited states. This leads to
the expectation that speed of response and photosensitivity should
be reciprocally related for intermittent light pulses. That this is
not the usual experimental observation suggests that recombination
can take place in a variety of ways. Indeed, it is necessary to
consider the effects of various discrete states in the forbidden
energy gap of insulators and semiconductors.

The four characteristic properties of
importance for photoconductors are their dark conductivity,
spectral response, speed of response, and photosensitivity. The
dark conductivity depends on the energy gap of the material and
on the density and type of imperfections present in the material.
In insulators the density of free carriers due to thermal excita-
tion is extremely small as the energy gaps are quite large. In
semiconductors the opposite situation can occur as some semiconductors
have very small energy gaps. This intrinsic difference between ins-
ulators and semiconductors vitally affects their respective
responses to photo-excitation and conditions of operation. For
example, insulating photoconductors can be successfully operated
at room temperatures while semiconducting photoconductors are
normally operated at low temperatures in order to reduce the dark
current. Room temperature dark conductivities in insulators are
less than about $10^{-6}$/ohm cm while those of semiconductors usually
lie between $10^{-6}$/ohm cm and $10^2$/ohm cm depending, of course, on
the energy gap in the material.

In a pure, perfect material, photons of
energy less than the energy gap are not capable of producing free
carriers and hence do not contribute to photoconductivity. This
leads to a sharp, low frequency cut-off in the photo-response curve
of the photoconductor. In practice a maximum response is usually found at a photon energy close to that of the energy gap with a subsequent fall off at higher energies. This decrease in response can be associated with absorption at the surface of the photoconductor, a region of intrinsically lower photosensitivity than the bulk region. The presence of impurities or lattice imperfections introduces discrete levels in the forbidden gap and thus leads to an additional response to light of energies less than the band gap. In general a complex level scheme is observed. Since band gaps range from 0.02 ev. in HgTe to energies greater than 5 ev. in diamond, photoconductors sensitive to photons from the ultraviolet to the infrared can be achieved.

In a pure, perfect material the speed of response would be identical with the free carrier lifetimes. In a real specimen the observed speed of response is several orders of magnitude slower than is to be expected on the basis of the free carrier lifetimes. These extended rise and decay times are caused by the trapping of free carriers at the various trapping centers which invariably exist in a real specimen. Trapping, of course, extends the rise and decay times by temporarily holding the electrons incommunicado, so to speak. That is, during excitation it removes carriers from the free state thus lengthening the rise time while during the decay process it slowly releases the trapped carriers thereby extending the decay time. The nature and density of trapping centers depends on the specimen treatment and the types of impurities contained by the host. In general, a very wide variety of trapping centers and associated photoconductor characteristics can be achieved.
The photosensitivity of a photoconductor is expressed in at least three different ways. One way is to state the minimum detectable excitation required to give a signal equal to the noise in the photoconductor. This definition of sensitivity is principally used for infrared detectors. Photoconductors of this type have sensitivities ranging down to $10^{-12}$ watt. A second way to specify photosensitivity is to give the photocurrent per unit light intensity at fixed applied field. Defined in this way the sensitivity is called the specific sensitivity and has the units of cm$^2$/ohm watt. In equation form the specific sensitivity $S$ is given by

$$S = \frac{i}{V} \frac{\lambda^2}{P}$$

where $i =$ photocurrent,
$V =$ applied voltage,
$\lambda =$ electrode spacing,
$P =$ absorbed radiation power.

The advantage of this definition is that $S$ is independent of cell geometry and light intensity provided the photocurrent is a linear function of applied field and light intensity. The most sensitive cadmium sulfide and cadmium selenide photoconductors have specific sensitivities approaching unity; however, most materials have specific sensitivities several orders of magnitude smaller. A third way to define photosensitivity is to specify the photoconductivity gain, i.e. the number of electrons flowing from one electrode to the other per photon absorbed. This is often called the quantum efficiency or quantum gain of the photoconductor. Gains as high as $10^4$ have been observed in cadmium sulfide photocells although in general the gains are orders of magnitude less. Typical photoconductor parameters discussed in the following sections are listed in Table VI for reference.
### TABLE VI

**SUMMARY OF PROPERTIES OF TYPICAL PHOTOCONDUCTORS**

<table>
<thead>
<tr>
<th>HOST</th>
<th>TYPICAL IMPURITY</th>
<th>OP. TEMP.</th>
<th>TYPICAL PEAK EMISSION WAVE LENGTH</th>
<th>SENS.</th>
<th>RESPONSE TIME</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Se</td>
<td>Group III, Acceptors</td>
<td>77°K</td>
<td>infrared</td>
<td>0.03-3 amp/lumen</td>
<td>1-10 μsec</td>
<td>Photoconductivity discovered in Se</td>
</tr>
<tr>
<td></td>
<td>Group V, Donors</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ge</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>1-10 μsec</td>
<td>Photoresponse varies from 1 x 10^-4 to 1 mho/watt</td>
</tr>
<tr>
<td>Si</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>1-10 μsec</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td></td>
</tr>
<tr>
<td>CdS</td>
<td>Group I, V, Acceptors</td>
<td>RT</td>
<td></td>
<td>50 amp/lumen</td>
<td>1 m. sec.</td>
<td>Group II-VI compound</td>
</tr>
<tr>
<td>CdSe</td>
<td>Group III, VII Donors</td>
<td>&quot;</td>
<td></td>
<td>&quot;</td>
<td>0.5 m. sec.</td>
<td>Family has many members</td>
</tr>
<tr>
<td>ZnS</td>
<td>Cl, Br, Al, Sc Ca, In (Donors)</td>
<td>&quot;</td>
<td>24800-49600A°</td>
<td>&quot;</td>
<td>&quot;</td>
<td>Addition of impurities shifts threshold from u-v to visible</td>
</tr>
<tr>
<td>ZnS</td>
<td>Cu, Ag (Acceptors)</td>
<td>&quot;</td>
<td>12390-24800A°</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>PbS</td>
<td>&quot;</td>
<td>77°K</td>
<td>25,000A°</td>
<td>10^-11 watt</td>
<td>100 /sec.</td>
<td>Low temperature</td>
</tr>
<tr>
<td>PbSe</td>
<td>&quot;</td>
<td>77°K</td>
<td>60,000A°</td>
<td>S/N=1</td>
<td>10 /sec.</td>
<td>Operation necessitated by relatively low energy gap</td>
</tr>
<tr>
<td>PbTe</td>
<td>&quot;</td>
<td>77°K</td>
<td>45,000A°</td>
<td></td>
<td>10 /sec.</td>
<td>&quot;</td>
</tr>
</tbody>
</table>
a. **Elements**

Crystals of certain of the elements exhibit photoconductivity; indeed, photoconductivity was discovered in selenium. In addition to selenium, germanium, silicon, and diamond are photoconductors. Point contact, pn junction and npn junction phototransistors have been made using germanium and silicon. The response times of these devices are of the order of one to ten microseconds with sensitivities ranging from 0.03 to 3 amp/lumen. As the energy gaps are small, the spectral response is in the infrared. The effects of impurities added to germanium and silicon have been extensively studied. As both these elements are group four, it is clear that group three impurities should act as acceptors and group five impurities should act as donors. Elements further removed from Group IV have in general more than a single level and may act either as donor or acceptor or in some cases as both. The Group III and V impurities usually have small ionization energies and thus have correspondingly long wavelength thresholds. Impurities such as B, Al, Ga, In and Tl from Group III and P, As, Sb, and Bi from Group V when added to germanium or silicon yield threshold wavelengths ranging from about 10 to over 100 microns. Most of the levels associated with impurities having more than one level have larger ionization energies than those of Groups III and V. Accordingly threshold wavelengths are shorter, usually of the order of a few microns. Impurities such as Cu, Au, Zn, Mn, Fe, Co, Ni, and platinum when added to germanium yield thresholds ranging from about four microns to nine microns. Copper is an exception, yielding a threshold of 29 microns. When added to silicon, impurities such as Cu, Au, Zn, Mn and Fe yield thresholds ranging from two to five microns. The small energy gaps in silicon and germanium require that these photoconductors
be operated at low temperatures, preferably at or below liquid air temperatures. The photoresponse in these materials varies from 10^{-4} to 1 mho/watt.

b. II-VI Compounds

A large number of photoconducting materials belong to the Group II-VI compound family. Two of the most common materials used as commercial photocells, cadmium sulfide and cadmium selenide, are members of this family. Many of the oxides and sulfides are known photoconductors including those of cadmium, zinc, mercury, and barium. The sulfides of calcium and strontium are photoconductors as well as the oxide of magnesium. Some of the selenides and tellurides are photoconductors including those of cadmium. Undoubtedly many more II-VI compounds are photoconductors and information concerning their properties will appear in the literature as time goes on. The impurity ionization energies in the II-VI compounds are considerably larger than those in germanium and silicon. Of course, the energy gaps of all II-VI compounds mentioned above are considerably greater than those in silicon and germanium, hence deeper lying trap states are possible. As a result, higher threshold frequencies are found in these materials compared to those observed in the germanium and silicon crystals. In general, Group I and Group V impurities act as acceptors while Group III and Group VII impurities act as donors.

Donor impurities such as Cl, Br, Al, Sc, Ga, and In when added to zinc sulfide yield ionization energies ranging between 0.25 and 0.50 ev. Acceptors such as Cu and Ag have ionization energies between 0.5 and 1.0 ev., energies comparable with the band gaps in silicon and germanium. Bromine,
acting as a donor in zinc selenide, has an ionization energy of 0.21 ev. while Cu, Ag, Sb and As, acting as acceptors, have ionization energies from 0.6 to 1.3 ev. The donor levels introduced by Cl, Br, I, Al, Ga, and In in cadmium sulfide all have small ionization energies of about 0.03 ev. However, the acceptor levels introduced by copper and silver have ionization energies which are at least an order of magnitude greater. These impurities behave very nearly the same in cadmium selenide. As these energies are all quite large, the dark currents associated with these materials are all very small. Consequently, photocells employing these materials can be operated at room temperatures.

The threshold frequency in zinc sulfide is in the near ultraviolet; however, the addition of impurities such as Mn, Ag, and Cu move the threshold into the visible part of the spectrum. On the other hand, the threshold frequency in CdSe is in the near infrared while that of CdS is in the middle of the visible spectrum. Additions of impurities such as copper and silver shift the threshold to lower frequencies, hence cadmium sulfide containing copper as an impurity has a peak response at about 6400 Å. The exact location of the peak in the photoresponse curve depends on whether the specimen is single crystal or polycrystalline and on the method of specimen preparation. Zinc selenide exhibits a double peak when copper is added as an impurity. The major peak is at about 4700 Å with the subsidiary peak at about 5100 Å. On the other hand, when antimony is the impurity the subsidiary peak appears more as a shoulder in the response curve extending out to 10 or 11 thousand angstroms. At low temperatures the shoulder is suppressed considerably and the main peak is increased and sharpened somewhat.
Cadmium sulfide and cadmium selenide are two of the most sensitive photoconductors known. Both have sensitivities ranging up to 50 amp/lumen, several orders of magnitude more sensitive than photoconductors. Associated with these high sensitivities, however, is a long response time. The response time at high light intensities is of the order of 1 msec in CdS and 1/2 msec at best in CdSe. At low light intensities the response times are considerably longer being of the order of fractions of a second to several seconds.

c. Other Inorganic Compounds

A great variety of other inorganic compounds are known photoconductors. The most important of these are perhaps the sulfide, selenide, and telluride of lead. The peak in the photoresponse curves for these compounds fall approximately at 25,000; 60,000; and 45,000 Å, respectively. As these materials have energy gaps less than 0.5 ev., the dark conductivity is very high at room temperatures. Successful operation requires low temperatures, preferably in the liquid air region. The sensitivity of these materials is very good being of the order of $10^{-11}$ to $10^{-12}$ watts for a signal to noise ratio of unity. The response times are very good considering the high sensitivity of the materials. Lead selenide and telluride both have response times of the order of ten microseconds while lead sulfide has a response time of about 100 μsec.

Photoconductivity has been observed in a large number of the halides. Most of these crystals are quite good insulators, i.e. they have rather large energy gaps. Magnesium and barium oxides also have large energy gaps and behave a great deal like the alkali halides. The thresholds associated with these
materials in the pure state are all very high, being well into the ultraviolet part of the spectrum. However, by proper treatment with X-radiation or addition of suitable impurities additional bands can be introduced in the energy gap. In this way it is possible to sensitize the photoconductors to radiation in the visible part of the spectrum.

The III-V semi-conductors are likely candidates for photoconductivity. Both indium antimonide and gallium arsenide are known photoconductors with peak response at 5 and 1 micron respectively. As the energy gap in InSb is only 0.18 ev., it is essential to operate at very low temperatures, in the liquid helium range, in order to observe its photoconductivity. However, the gap in GaAs is 1.4 ev., thus operation at much higher temperatures is feasible for gallium arsenide photoconductors. The addition of Cu, Ag and Au to indium antimonide increases the threshold to as much as 20 or 25 microns; however, the increase is primarily in the form of a shoulder at least two orders of magnitude below the peak in the photoresponse curve.

d. **Organic Photoconductors**

Many organic compounds exhibit semiconductor characteristics and thus are possible photoconductors. Energy gaps in some organic materials fall in the range from 0.2 to 1.6 ev. Many of them have gaps close to those of silicon and germanium and hence the photoconducting properties might reasonably be assumed to be similar. Anthracene with a gap of 1.6 ev. has been studied extensively and the spectral response is consistent with the energy gap. Several organic compounds containing condensed aromatic rings, some dyes and proteins have been studied. The most sensitive of
the aromatic hydrocarbons appears to be anthracene with photocurrents in the $10^{-9}$ to $10^{-10}$ amp range. Sensitivity of other aromatic hydrocarbons can be as much as five orders of magnitude less than that for anthracene. The enormous number of organic compounds available for investigation makes this a very fruitful field for research, but for developmental purposes it would seem that inorganic compounds hold more near term promise.

3. Double Activated Phosphorescence

Phosphors are substances which are capable of emitting light after having been exposed to some kind of radiation. The spontaneous emission occurring after excitation is called afterglow or background and is strongly temperature dependent. In some cases the emission can be enhanced by radiation different from the primary excitation. This phenomenon is called stimulation or double activated phosphorescence. In many cases the emission can be diminished by radiation different from the primary excitation. This phenomenon is called quenching.

These phenomena can be understood qualitatively on the basis of the energy band theory of solids. At zero excitation an insulator (or semiconductor) consists of a series of filled electronic energy bands (Ref. Fig. 27a). The highest of these filled bands is called the valence band. Above this band and separated by a region called the forbidden region or energy gap lies an empty band called the conduction band. Within the forbidden region several types of energy levels can exist. These may be due to impurities added to the host crystal or any of several types of lattice imperfections. Assume two levels A and B are present in the forbidden energy gap; further, suppose that B is a metastable state, that is, the transition from B to the valence band is a forbidden transition. An electron in the valence band can absorb
an incident photon and be excited (1) to the level A. Subsequently, the electron might make a transition (2) to the metastable state B where it remains trapped. Upon further excitation (3) to level A, the electron makes the allowed transition (4) to the valence band. This would be a case of stimulated emission.

An alternate way to understand these phenomena is indicated by Figure 27b. Here the free energy of the system is plotted against some appropriate configurational coordinate. Curve A represents the ground state of the system while Curves B and C represent two possible excited states of the system. Excitation can take place either by 1) raising an electron from A to B or 1') raising an electron from A to C. After excitation (1) the system readjusts itself by phonon generation until the minimum in Curve B is achieved. This is followed by a transition to the state A with the emission of a photon of the appropriate frequency. This would normally occur almost immediately upon excitation and this constitutes a fluorescence. On the other hand, after excitation (1) the system, after phonon generation, arrives at the minimum of Curve C. Now no further transition is possible unless the system is stimulated in some way. Upon absorption of a photon (3) of appropriate frequency, the system is excited to state B whence the emission (2) is then possible. This illustrates qualitatively the way in which stimulation or double activated phosphorescence occurs. If a photon is absorbed resulting in transition (3), then no photon emission can take place, but rather the energy will be dissipated in lattice vibrations. This would be an example of quenching.

The basic requirements for double activated phosphorescence, as seen from the above discussion, are a material with a filled valence band, an energy gap and at least two different
types of levels lying within the forbidden region. The number of materials satisfying these conditions is infinitely large; however, the number of satisfactory materials from a practical standpoint is much smaller. The reasons for this are many, not the least of which is the problem of producing any given material in a completely reproducible manner. There are many instances reported in the literature where two specimens prepared by apparently identical techniques have produced rather divergent results. To make matters worse, the proprietary nature of the subject has resulted in a noticeable lack of a satisfactory compilation of phosphors and phosphor properties. The net result is that a phosphor expert with broad experience in the field of phosphor research and development is essential in any program which envisions the use of phosphors in any way.

In order to obtain the two types of energy levels in the energy gap required for stimulated emission it is necessary to add two activators to the host crystal. In this way a number of infrared sensitive phosphors have been developed. One of the activators, called the dominant activator, determines the emission spectrum for a given host lattice. The second activator, called the auxiliary or co-activator, determines the spectral distribution of sensitivity to stimulation, by radiation, often called the stimulation spectrum. As an example, strontium sulfide phosphors with samarium as co-activator exhibit a stimulation spectrum which peaks at about 1 micron. The emission spectrum, however, is found to depend on the dominant activator. The peak in the emission spectrum is 9.48, 9.49, 9.57 and 0.63 microns for dominant activators of cerium, copper, manganese and europium, respectively. In a similar manner the peak in the stimulation spectrum can be varied by using different co-activators. The use of tin as co-activator results in a peak at 0.63 microns while bismuth yields a peak at 0.88 microns.
The co-activator in many cases produces a second important effect. It is found that the addition of the co-activator considerably reduces the afterglow of the dominant activator. This reduction in afterglow can be by as much as several orders of magnitude. The reduction in afterglow is accompanied by an increase in storage time.

Appreciable photostimulable emission is not observed in phosphors which have only temperature independent exponential emission decays. This is understandable as the type of decay is characteristic of an unimolecular process and, as we have seen, for stimulated emission two centers are required. Such a phosphor, however, can be made stimulable by altering its composition. Thus rhombohedral (rbhld.) Zn₂GeO₄: Mn can be rendered photostimulable by the incorporation of SnO₂. The phosphor ZnO. 2GeO₂. 0.06SnO₂. 0.02MnO emits a green light upon stimulation by infrared light of the order of one micron. The emission decay in this case varies as an inverse power of time, characteristic of a bimolecular process.

The photostimulation and photoconduction of phosphors is very closely related. In fact, the spectral distribution of photostimulated phosphorescence is almost identical to the spectral distribution of photostimulated photoconduction in many cases. This is evidence of the fact that the same electrons are contributing to both processes. In general, however, the stimulated phosphorescence decays much more rapidly than the stimulated photocurrent.

Several of the more common stimulable phosphors are listed in Table VII. It is to be noted that these phosphors are mainly stimulable by infrared radiation. This results mainly
**TABLE VII**

**SUMMARY OF PROPERTIES OF TYPICAL DOUBLE ACTUATED PHOSPHORS**

<table>
<thead>
<tr>
<th>Phosphor</th>
<th>Peak Wave Length of</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Excitation A</td>
</tr>
<tr>
<td>1. Cub. Sr (S:Se): flux: Sm:Eu</td>
<td>4,600</td>
</tr>
<tr>
<td>2. Cub. SrS: flux: Sm:Eu</td>
<td>4,800</td>
</tr>
<tr>
<td>3. Cub. Ca(SiSe): flux: Sm:Eu</td>
<td>4,800</td>
</tr>
<tr>
<td>5. Cub. SrS: flux: Sm:Ce</td>
<td>2,900</td>
</tr>
<tr>
<td>6. Hex. ZnS:Cu:PbSO4:NaCl (2)</td>
<td>3,700</td>
</tr>
<tr>
<td>7. 2SiO2:CaO:Pb:Mn</td>
<td>*2,537</td>
</tr>
<tr>
<td>8. 3SiO2:CaO:Pb1Mn</td>
<td>*2,537</td>
</tr>
<tr>
<td>9. ZnS:0dS:Cu:Mn</td>
<td>3,700</td>
</tr>
<tr>
<td>10. ZnS:Pb:Mn</td>
<td>3,700</td>
</tr>
<tr>
<td>11. 3ZnO:2GeO2:10'06SnO2 0'02MnO</td>
<td>3,700</td>
</tr>
</tbody>
</table>

*Peak excitation used: not necessarily characteristic of the material but probably reasonably close to the maximum for the material.*
from the fact that a great deal of emphasis was placed on developing infrared sensitive phosphors dating back to the 1930's. This does not mean that phosphors stimulable by radiations other than infrared radiation have not been or could not be developed. In fact, by careful selection of host crystal, dominant activator and auxiliary activator just about any combination of excitation, emission and stimulation spectrum is possible. Of course, in addition to these variables decay times and efficiencies are also of interest. In the phosphor listed as Number 1 in Table VII the efficiency is found to be strongly dependent on the relative amounts of SrS and SrSe present in the specimen. The addition of CaS also affects the efficiency of this particular phosphor. These effects are not thoroughly understood, hence we have no way of predicting the results for a particular phosphor. This emphasizes the fact that phosphor development is a very delicate art requiring the resources of a phosphor expert of extremely broad experience.

Storage times in the phosphors vary considerably from one phosphor to another, but can easily be of the order of days. In addition, the storage times depend in an important way on the temperature of the specimen. Many of the double activated phosphors can be thermostimulated to an appreciable extent at room temperatures. Others do not show appreciable thermal stimulation until rather high temperatures are achieved. While there is some relationship between the thermal stimulation and photostimulation energies, they are not necessarily equal. In fact, the energies required for thermal stimulation are normally less than those required for photostimulation. This can be understood in a very simple way. In photostimulation the momentum of the electron being excited is conserved. Thus a vertical transition in
energy momentum space takes place (Reference: Figure 27a, transition 1). On the other hand, for thermal stimulation the electron makes a transition from an energy band minimum to an energy band maximum (as in Transition 2, Figure 27b. Clearly these will only be equal if the minimum of Band B lies directly above the maximum of Band A, while in general 2 will be less than 1.

The phosphor listed as Number 5 in Table VII and commercially referred to as Standard VII has been widely used in devices called snooperscopes and sniperscopes. In addition to being one of the most sensitive infrared phosphors, the peak of its excitation spectrum lies in the invisible ultraviolet. Since it is essential that the devices mentioned operate with invisible radiation, this property of Standard VII has made it particularly useful. For use in an image transducer however, this property may in fact be undesirable. A phosphor such as Standard VI (listed as 2 in Table VII) probably would be more desirable since the peak of its excitation spectrum lies at 4800 Å in the visible part of the spectrum.

From Table VII it is clear that the excitation peak wavelength is less than the emission peak wavelength, which, in turn, is less than the stimulation peak wavelength. With reference to Figure 27, it is clear that the excitation peak wavelength will normally be less than the emission peak wavelength. Furthermore, it is reasonable to expect the emission peak wavelength to be less than the stimulation peak wavelength. These facts have an important bearing on any potential application of these materials. As an example, suppose a device were desired to be capable of excitation by light in the near infrared. If the device were to operate in the normal excitation, stimulation,
CONDUCTION BAND

A

B

VALENCE BAND

EXCITATION-STIMULATION SCHEME ON THE BAND
PICTURE FOR DOUBLE ACTIVATED PHOSPHORESCENCE

(A)

FREE ENERGY

CONFIGURATION COORDINATE
PHOTOSTIMULATION AND PHOTOQUENCHING ON THE FREE
ENERGY-CONFIGURATION COORDINATE PICTURE

(B)

ENERGY

MOMENTUM

PHOTOSTIMULATION (1) AND THERMAL STIMULATION (2) PROCESSES (C)

R-14,562

FIGURE 27
emission mode, the stimulation and emission wavelengths would probably be in the far infrared. In all likelihood this would be a difficult device to construct even if the material problem could be solved, as the device would have to operate at extremely low temperatures. A possible solution to a problem such as this would be to consider a slightly different mode of operation, for example, excitation, partial stimulation (accompanying emission not used), complete stimulation, and emission. This mode of operation would yield a negative image.

4. **Phototropism**

The chemical part of the literature survey was concerned with finding compounds whose properties have been described by terms such as photochromic, phototropic, tenebrescent, and evanescent. These adjectives have been used by various investigators at various times to describe materials which change color when exposed to radiation in a particular spectral region and which revert to the original color when placed in darkness or when exposed to radiation in a different spectral region. In accordance with current usage the term "phototropism" will be used in this report to designate such phenomena. The phototropic mechanism may be of a chemical or of a physical nature but generally it embraces both fields of science. This part of the literature survey report deals with materials whose phototropism is primarily of a chemical nature.

For the current image transducer concept the photosensitive material should display the following characteristics:

1. The material should change color (the term "color" in this report includes the near ultraviolet, 300–400 μm, and the near infrared, 700–800 μm) when exposed
to radiation of a given spectral characteristic, preferably in the visible portion of the spectrum. (activation or read-in).

2. The material should retain this induced color until exposed to radiation of a different spectral characteristic at which time it should revert to its original colored (or colorless) state. (erasure).

3. The material should be insensitive to a third portion of the spectrum so that the extent of the color change may be determined by measuring the transmittance (or reflectance) of the material in this spectral range. (read-out).

4. In the spectral region utilized for measurement (read-out) there should be a large difference between the molar extinction coefficients of the activated and the unactivated forms of the material. The absolute value of one form should be as high as possible so as to generate an intense color for a given input energy.

5. The speed of the activation color change should be very fast, preferably in the microsecond range or lower. The speed of the erasure change may be several orders of magnitude slower.

6. The quantum efficiency of the activation reaction should be high so as to achieve a high sensitivity.

Since scientific literature seldom deals with photosensitive materials from these points of view, it was necessary to attempt the evaluation of the properties of a material from whatever type of data was presented. Properties such as: The complexity of the reactions; the number of intermediate products; the existence
of side reactions, decomposition, etc.; the order of the reaction (unimolecular, bimolecular); velocity and equilibrium constants; temperature coefficients; physical state (crystalline, amorphous solid, solution, rigid media, etc.); were useful but not conclusive criteria in considering the utilization of the material in the image transducer application.

Basically the photochemical primary processes that may take place following the absorption of a photon by a molecule are:

1. Fluorescence emission of the absorbed radiation.
2. Deactivation by collision with other molecules.
3. Direct dissociation into simpler molecules, atoms or free radicals.
4. Dissociation caused by collision with other molecules.
5. Internal rearrangement (isomerization).
6. One or more different reactions with normal molecules.
7. Transfer of energy to normal molecules by means of inductive resonance transfer.

These primary processes are limited to a maximum quantum yield of 1, but they may be followed by secondary reactions giving a very high overall quantum yield. For the proposed image transducer applications the literature search for chemical materials was directed towards substances exhibiting photochemical processes such as #3, 4, 5, 6, and 7.

Phototropic materials may be divided into two categories, organic and inorganic. In both classes the phototropic phenomena may occur in the solid state as reported in most of the earlier literature, or in solution as described in more recent
investigations. In general, solid materials require from a few seconds to many minutes to develop a pronounced change in color, and require from a minute to several weeks for the reverse change. Solutions on the other hand generally develop a color change in from microseconds to seconds and undergo the reverse change in from seconds to several days.

Four previous surveys of the literature dealing with phototropism have been made: 1. Stobbe \(^2\) reviewed the field through 1921; 2. Chalkley \(^3\) through 1928; 3. Bhatnagar, Kapur, and Hashmi \(^4\) through 1938; and 4. Brown & Shaw \(^5\) through 1959. Brown and Shaw's survey reviewed the literature covered by Chemical Abstracts through 1959 for materials showing reversible color changes. The current survey reviews that of Brown and Shaw, covers Chemical Abstracts from 1959 through 1962, and includes additional information derived from patent files.

Among the classes of organic compounds which show phototropy are: anilis, disulfides, fulgides, hydrazones, osazones, semicarbazones, stilbene derivatives, hydrazides, spiro-pyrans, azo dyes, nitro stilbenes, dinitrobenzyl derivatives, and triphenyl methane derivatives. Considering application to the image transducing system, most of these materials for which pertinent data were given were judged to be of little promise for one or more of the following reasons:

1. The color forming reaction was attended by non-reversible side reactions. This leads to rapid fatigue (loss of phototropic properties) as an increasingly large amount of the active material is converted into non-active side products.
2. The color forming reaction involved a number of intermediate steps (or products) before yielding the final desired product. Depending upon the velocity constants and the equilibrium constants of the intermediate reactions, the time of formation and the yield of the desired colored product were limited by the least efficient reaction.

3. The reverse color change proceeded spontaneously rather than being affected by exposure to the erasure radiation. If the spontaneous reversion to the unactivated state were slow enough, the material might be useful for limited time storage, but most substances underwent the reverse color change very rapidly, with some in terms of microseconds.

4. The forward or reverse reaction was temperature dependent in an adverse manner.

5. Only a very weak color change was produced. This could be caused by
   a) low extinction coefficients in the visible part of the spectrum
   b) a low quantum yield
   c) unfavorable equilibrium conditions between the forward and reverse reactions

6. The activation (color forming) reaction was very slow. This could indicate a very low quantum yield.

7. The erasure (color bleaching) reaction was very slow.

8. The phototropic phenomenon took place only in solution, thus making impractical an image forming surface with good planimetric resolution.

The organic materials which exhibit phototropy are much more numerous than the inorganic substances. Among the
latter can be listed: alkaline earth sulfides and titanates, alkali halides, complex mercury salts, zinc sulfide, copper halides, bismuth oxalate, cadmium iodide, titanium oxide, rare earth chelates, molybdenum oxides, coordination complexes of chromium, and minerals of the sodalite family, especially pink hackmanite. These inorganic compounds all exhibited undesirable characteristics for application in an image transducing system. In addition to the objectionable characteristics listed for the organic compounds, many of the inorganic were phototropic by virtue of an oxidation-reduction type system. In such cases the phototropic reactions are dependent upon a continuing supply of oxidizing agent (such as atmospheric oxygen) or reducing agent. As soon as the oxidizing agent or reducing agent is exhausted the phototropy ceases.

Since none of the materials reviewed were particularly promising in all respects for use as the photosensitive surface of the image transducer, it was decided to determine what materials might be useful with a minimum of compromise between the desired properties and the existing ones:

(1) Pink hackmanite, as previously reported, gives a fairly good coloration when exposed to ultraviolet radiation. The color is stable indefinitely and can be erased with radiation in the visible portion of the spectrum. It shows no apparent fatigue in over 350,000 cycles between the activated and erased states. Its major disadvantages are very low sensitivity (low quantum yield) for both the activation and the erase reactions, and the inability to fabricate it in a suitable form (thin transparent layer with uniform
sensitivity). If the latter objection can be overcome, hackmanite could be used for an image transducer of low sensitivity, with a possible improvement in sensitivity if the "F-center" site formation can be increased.

(2) Cinnamaldehyde semicarbazone\textsuperscript{6,7} and derivatives are phototropic in the following manner: The colored form generates slowly (overnight) and spontaneously in the dark, and is erased more rapidly (minutes) in strong white light. It is reported that the phototropic cycle can be repeated indefinitely. If the erasure time can be decreased, this material would be suitable for a low sensitivity "single shot" image transducer giving a positive image by visible light. The application of heat may speed up the color generation reaction thereby making possible more rapid image-erasure cycles.

(3) Some spiropyrans\textsuperscript{8,9} at low temperatures (-60°C) upon irradiation with ultraviolet light form an intense coloration which is stable until erased by irradiation with visible light. The process can be repeated indefinitely. These materials could be used in a low sensitivity image transducer with the proper implementation for keeping the photosensitive surface cold. Alternatively, further synthesis of new spiropyrans may produce one whose spontaneous erase reaction proceeds at a negligible rate at room temperatures thus making possible operation without refrigeration.
Other materials with similar potentialities exist in the literature but require additional experimental evidence in order to evaluate their capabilities. The phototropic mechanism by which most of these materials work falls more in the field of solid state physics than in true chemical phenomena. Since true chemical mechanisms that are reversible in the sense necessary for the image transducer applications are limited to a maximum quantum yield of one, it is felt that the material required for a highly sensitive image transducer will have to depend upon physical energy state transitions with its attendant possibilities for energy amplification, rather than upon chemical reactions.

5. Discussion

The material study has been based on a need for materials (a) capable of converting an optical signal to an electrical signal, (b) capable of image retention, and (c) capable of converting an electrical signal to an optical signal. Photoconductors are capable of accomplishing function (a), i.e., conversion from a photon signal to an electrical signal. This can be accomplished in several ways depending on the mode of operation. The most useful way is to take advantage of the change in conductivity produced in the photoconductor by incident radiation. There are several types of materials and processes capable of accomplishing function (b); however, for the purposes of this study many are not applicable as the image transducer requires erasable image retention. This requirement, for example, eliminates the usual photographic process as erasure requires regeneration of the emulsion.
Many of the photochemical processes are similarly eliminated, leaving as the most useful materials those exhibiting double activated phosphorescence or phototropism. Of course, it is possible to accomplish image retention by combining a photoconductor (for optical to electrical conversion) with some other material to provide a memory cell. The optron is an example of such a device. Again, there are several ways to accomplish function (c), but the requirements of the image transducer under study eliminates many of them. Electroluminescent materials appear to hold promise for purposes of this application.

a. Conversion of an Optical Signal to an Electrical Signal

The first step in the image transducer will be to receive an incoming optical image (signal). The method used to receive the signal will depend upon the image transducer's ability to accomplish its several assignments. Ideally the transducer should immediately convert the optical image into an electrical image for transmission. Such a device does not appear to be possible in view of the system requirements for exposure time. To compensate for this, certain devices assigned other functions can be added to the system to accomplish the desired task. In all conceivable systems, however, it is necessary at some point to convert the optical signal to an electrical signal. This can be accomplished by one or another of the various photoeffects associated with photoconducting materials. The most important of these effects is that of photoconductivity itself; however, other photoeffects such as the photovoltaic, photoelectric, Dember, and photomagneto-electric effects might be employed. Both the Dember and
photomagnetoelectric effects can be considered as photovoltaic effects. The photovoltaic effects are primarily of concern in conversion of solar energy into electrical energy. The maximum efficiency of conversion achieved is of the order of 6%, obtained using Si and GaAs cells. Although energy conversion is important for application in the image transducer, other criteria must be met. The image transducer will not operate under steady state conditions (as does a solar cell), but rather under pulse conditions. Consequently, an important parameter for any potential material is the response time. The photovoltaic effects all have relatively long response times as the processes all require the buildup of voltages by minority carrier diffusion. In this respect photomultipliers (employing the photoelectric effect) and devices employing photoconductors are more nearly satisfactory. With reference to Table VI it is noted that microsecond response times have been achieved in photoconducting materials such as silicon, germanium and diamond. Response times of less than a microsecond have been observed in InSb. Such speeds are also easily achieved with photomultiplying tubes. In view of these facts the materials study* has been primarily directed towards photoconducting materials to accomplish the function of conversion of an optical signal to an electrical signal.

b. **Image Retention**

For reasons covered in the First Quarterly Report it is necessary to retain the received image in the transducer. Ideally this would be done optically, although if necessary it could be done after optical to electrical conversion. Optical storage does, in fact, appear possible by means

*) Photomultiplier tubes which are adequate are readily available; therefore no materials study is required on this aspect.
of double activated phosphors or phototropic materials. Other means, such as photographic, are possible methods of optical image storage; however, there are other system requirements to be met. In particular, the process should be erasable and have at least a moderately short response time, or more likely, a very short response time. In both respects the double activated phosphors and phototropic materials appear to be satisfactory. Erasure is easily accomplished and both have at worst moderately short response times. In addition to the response times and erasure feature the materials should be rather sensitive to incoming radiation (both visible and infrared, presumably). Some fairly sensitive infrared stimulable phosphors have been achieved.

Certain other image retention techniques can be used. Most would require conversion of the optical signal into an electrical signal first with subsequent storage of the electrical image. Further conversion of the electrical signal into a magnetic signal could also be employed with subsequent storage of the magnetic image. Such multiple conversion techniques probably unnecessarily complicate and expand the device. This expansion and complication would undoubtedly exhibit itself in increased size, weight and cost of the device. Thus electrical to magnetic conversion has been ruled out. Storage of the electrical image, on the other hand, may be feasible. A prototype of a device employing a thin layer of ferroelectric in conjunction with photoconductive materials has been shown to be capable of readin, storage and readout. The ferroelectric material performs the function of image retention in the device. Resolution and speed of the
device is less than that of the usual vidicon technique. Further investigation concerning the capabilities of materials of this type are needed to understand whether or not the limitation is one of fabrication technique or a fundamental material limitation.

In view of the foregoing discussion it was decided to emphasize, during the present reporting period, the investigation of double activated phosphors and phototropic materials for possible use in an image retention device. Subsequent investigations should be expanded to include a more thorough consideration of the capabilities and limitations of such materials as ferroelectrics for use in an image retention device.

c. Conversion of an Electrical Signal to an Optical Signal

There are several ways in which an electrical signal can be converted into an optical signal. Many of these, however, do not meet the requirements of the proposed image transducer. Such methods as thermal radiation from a heated element or gaseous discharge are undesirable for several reasons. Power requirements are high, resolution is poor, response times are much too long and system requirements in general are undesirable. In all these respects the electroluminescent materials (so called cold light sources) are quite adequate. Particularly those materials exhibiting injection electroluminescence appear to have desirable properties. Overall efficiencies are surprisingly good and response times are very short. Light emission in nearly any segment of the
spectrum from ultraviolet to far infrared appears feasible by suitable doping of the electroluminescent materials. Power requirements are very modest and high resolution devices are a distinct possibility.

The use of materials capable of conversion of an electrical signal into an optical signal suggests the possibility of construction of a matrix light source. Such a light source could be used as a digital readout device in conjunction with an image retention component (employing a double activated phosphor, for example). For these reasons, considerable effort has been expended in examining the capabilities and properties of electroluminescent materials.
C. EXPERIMENTAL INVESTIGATION

In order to fully evaluate hackmanite and other tenebrescent materials, and thus assure a complete investigation, Marquardt has initiated experiments to determine a means of fabricating these materials in a suitable form. This form must have optical transparency in the unexcited state and durability in the form of thin films.

The method of preparing hackmanite samples conceived at TMC will exploit the use of high pressure-high temperature and electrical techniques. It should be noted that in the materials literature survey, no such method was found.

As a first step, the preparation of available and conventional "F" center materials - such as hackmanite and the alkali metal halides has been attempted. The initial experimental phases were aimed at producing 1) clear thin wafers of potassium bromide, 2) similar wafers containing a band of transparent layer hackmanite powder, and 3) thin wafers of fused hackmanite.

After a study of the optical properties resulting from the use of high pressure, high temperature processing, the second step will be the preparation of thin films of special "F-center" materials to obtain desired properties.

As has been indicated, one objective of recent experimental work was to change the physical properties of hackmanite without changing its optical properties.

Many times, the optical properties of solid materials
can be best studied when these material are embedded in a potassium bromide wafer. Attempts have been made at TMC to prepare samples of hackmanite by this method. Also, suitably doped potassium bromide itself is a potential "F center" material. Therefore, its use herein was obvious.

The materials used for the first experimental fabricating work consisted of laboratory grade, chemically pure potassium bromide and a small quantity of natural hackmanite. The optical properties of different pieces of the latter were observed before and after reduction to the powdered form necessary for the high pressure, high temperature mold.

The observations confirmed literature information - such as orange fluorescence under ultra violet exposure, bleaching under white light, and pinkish colors under other conditions. Figure 28 presents a photograph of the UV Exposing Unit made for exposing various samples to UV light at various density levels. Repeated observations showed consistent results.

Initial work was accomplished in the 50 ton vacuum hot press shown in the photographs of Figures 29 and 30. The first exploratory preparation consisted of a two layer sample in silver dichloride. One layer contained a pea sized flake of hackmanite, another layer a mixture of powdered hackmanite and potassium bromide in a weight ratio of

\[ \frac{W_h}{W_{KBr}} = 30/70 \]

These materials were held one hour at ten thousand atmospheres and 190°F.

Post run examination showed that the flake was undamaged as expected but that the powder was not fused into a transparent media. These results indicated the necessity for a wide range of mold setups to optimize the results.
ULTRAVIOLET EXPOSING UNIT

LIGHT SOURCE

FILTERS

SAMPLE

FRONT VIEW

FIGURE 28
GRAPHITE LAYER PRESSING EQUIPMENT

OVERALL

FIGURE 29
GRAPHITE LAYER PRESSING EQUIPMENT CLOSEUP

PISTON-CYLINDER ASSEMBLY
Accordingly, several subsequent setups (at lower pressures combined with a range of outgassing and temperature treatments) led to clear 1/8" thick wafers of KBr but scarred the polished surfaces of the mold fixture before a completely satisfactory hackmanite sample was produced. A total of 14 tests were made with the last establishing pressing conditions which appear to have satisfactory results.

Figure 31 is a photograph of four 1/8" KBr wafers showing the progressive improvement. The black shadows on the samples on the right are caused by surface contamination due to molybdenum disulphide which was used to eliminate sticking.

During the next reporting period, the fixture will be repaired and more hackmanite will be obtained to explore the probability of making wafers without KBr.

Subsequently the series of experiments will be continued to determine the limiting properties of "F-center"coloration. This will include an extension of the experiments of Pohl & Hirsch (Reference 10) using KBr with and without HBr.

In these Marquardt experiments a crystal sample will be heated to about 1000°F in the high pressure fixture - but with the pressure not applied. At this temperature, a direct current will be applied. The combination of electrolytic and electronic conduction (especially with a mixture containing hydrogen bromide) will form a non-stoichiometric halide due to differential diffusion rates and reduction of the metal ions. At this point, an application of pressure should freeze the crystal in an optimal condition for "F"-center" phenomena.
POTASSIUM BROMIDE WAFERS
D. RECOMMENDATIONS

The material study work has supplied sufficient information on electroluminescers, photoconductors, double activated phosphors and phototropic materials to lend direction to the development of a system concept. During the next quarter, the following areas should be accentuated:

1. Literature survey for ferroelectric materials which show promise for image retention.

2. Experimental investigations on materials displaying \( e[n]^2 \) phenomena.

3. The experiments on the preparation of a suitable hackmanite specimen shall be continued along the lines suggested by the preliminary results recorded in this report.
E. REFERENCES

Literature Survey


3. Chalkley, L., Jr., Chem Reviews, 6, 217 (1929)
V. CONCLUSIONS

(1) It is now possible to define the performance characteristics of image transducers for various missions based on analytical studies of scene composition, and a survey of the current state-of-the-art. These results will assist in establishing design criteria for an advanced photo facsimile transmission system.

(2) The number of resolving elements for image readout can be increased by use of a technique which converts the raster scan into a single scanning line with orthogonal scanning accomplished by introducing relative motion between the image and the line.

(3) Regenerative image retention can be accomplished through the use of a combination of materials such as a photoconductor and electroluminor (the optron) or a photoconductor and ferroelectric (the ferrotron).

(4) The fabrication of an ordered fiber optic array for high resolution readout is not feasible at the present time because the development of fiber forming equipment capable of accurate positioning of very small diameter fibers in the vast numbers required is beyond the current state-of-the-art.

(5) Materials exhibiting electroluminescence, double-activated phosphorescence, photoconductivity, and ferroelectricity are promising for image transducing. Phototropic materials show too slow a response for the contemplated system.

(6) Natural hackmanite has characteristics (such as poor sensitivity and lack of clarity) which make it unsuitable for use in an image transducer. Experiments designed to overcome these shortcomings are required.
VI. PROGRAM FOR NEXT INTERVAL

A. SYSTEM ANALYSIS

The studies of image transducing parameters and their inter-relations will be continued in order: (1) to delineate parameter trade-off possibilities (2) to establish ranges for the parameters based on practical limitations and desirable performance characteristics for various missions and (3) to establish design criteria for an advanced image transducer.

B. COMPONENT RESEARCH

A matrix light source selection system for switching, programming and selecting the light source elements will be evolved and its cost and practicality evaluated. This switching system should also be applicable for the electronic matrix readout.

The analysis of concepts for image retention and readout utilizing the results obtained in the previous material literature survey and in the state-of-the-art survey of image transducers will continue. Specific solid state devices will be analyzed.

C. MATERIAL STUDY

Analytical and experimental investigations to select an image transducing material for further development will be continued. This will include an evaluation of the materials included in this quarterly report. Further experiments will be conducted with synthetic hackmanite. The study and analysis of ferroelectric materials which show promise for image retention will be continued.
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