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APPLICATION OF INFRARED TECHNIQUES TO MILITARY TRAINING

PHASE I

A GENERAL EXAMINATION OF THE TECHNOLOGY

U.S. NAVAL TRAINING DEVICE CENTER

PORT WASHINGTON, L.I., NEW YORK

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PHASE I

A GENERAL EXAMINATION OF THE TECHNOLOGY

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ABSTRACT

This is a report based on a study of infrared technology as it is applicable to military training problems.

It investigates particularly the specific problems of surveillance, for example, the observation of nighttime amphibious training operations, and training in identification, interpretation, location, and detection of objects.

These problems are best covered by presentation of images; therefore, techniques used in image-forming and image-scanning systems are explored. As an additional aid for the solution of other training problems, the fundamentals of infrared technology are presented. This is made up of sections on radiation theory, target and background radiation characteristics, atmospheric absorption effects, optical considerations, infrared detectors and sensors, and methods of data presentation. Comparisons of the effects of the characteristics of the various spectral modulators, such as background, atmosphere, optical components, and detectors, are presented in the corresponding sections. In addition, the techniques and components of low-light-level television are presented and compared to infrared techniques for training purposes along with a comparison of infrared and radar. The synthetic presentation of infrared information displays plus other simulation techniques are investigated as a means of training personnel in the identification and interpretation of objects. An extensive bibliography on all phases of infrared technology is included as an aid to the reader desiring more detailed information.

Affirmative conclusions as to the feasibility of the application of infrared techniques to the training considerations of surveillance, and to identification and interpretation of objects for training have been reached. It has also been concluded that television techniques are feasible for infrared image-forming in the range from 0.7 microns to 1.2 microns, as a means of infrared information distribution and display, and for image-forming at low intensity visible light levels.

Based on these conclusions, recommendations are made for further investigation toward the development of training equipment for the training applications considered.

FOREWORD

This report is intended to provide guidelines for the exploration of infrared principles as applied to training problems, and is the first of two based on an examination of the infrared technology. In recent years, infrared technology has made its appearance in both the military and the scientific fields in the form of operational equipment. From an examination of the principles involved in the operational equipments it can be presumed logically that these basic principles can be used advantageously in training applications. The published results of investigations in infrared, however, are widely scattered and are often relatively inaccessible and expressed in highly technical language, understood only by specialists in this field. Very little attempt has been made to date to collect together those leading principles which can be regarded as sufficiently established to be used as a guide to practice, particularly in the training field, and to state these simply and as straightforwardly as possible and without detailed argument. It is intended that this report will be a contribution in this direction.

The principle objective of this report is to publish the results of an investigation of the feasibility of utilizing infrared techniques in the solution of specific military training problems. In order to accomplish this, an investigation was conducted and reported on in two training areas. Firstly, the basic concepts are covered in a manner that is not only scientifically applicable, but informative reading as well, and secondly, the feasibility of utilizing the infrared technique in the solution of the two specific military training problems is reported on.

In addition to the aforementioned exposition of the basic fundamentals of the technology, the two training considerations reported on as related to the infrared technology are:

1. Surveillance, for example, the observation of nighttime training maneuvers; and
2. Training in the identification, interpretation, location and detection of objects.

In addition, an examination is made on the application of the television technique in information forming and distribution.

This Phase I Report is a general investigation report. It will be followed by a Phase II Report in which the information gathered will be reported in greater detail for the specific applications.

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TABLE OF CONTENTS

PAGE

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

PAGE

TABLE OF CONTENTS

(continued)

TABLE OF CONTENTS
(continued)

TABLE OF CONTENTS (continued)

LIST OF ILLUSTRATIONS

PAGE

LIST OF ILLUSTRATIONS
(continued)

LIST OF ILLUSTRATIONS
(continued)

LIST OF ILLUSTRATIONS
(continued)

LIST OF TABLES

1. INTRODUCTION

1.1 Historical Background

Infrared radiation was discovered by Sir William Herschel in 1800 by observing the temperature rise in thermometers placed in different positions of the sun's spectrum dispersed by a glass prism. This discovery for many years was only of academic interest. Industrial applications of IR spectrometry to chemical problems became widespread during the two decades before World War II. (For a complete history of the development in the IR field up to World War II see Reference 1 Chapter 1).

1.2 First Military Applications

Military applications of IR radiation began with World War II. The Germans carried out extensive research and development on detectors and systems for the surveillance and interception of airborne targets and IR guidance. IR applications in this country used active short-wave-length radiation in viewers such as Sniperscope and Snooperscope, in signaling and communications systems, and in amphibious landing beacons. Development work in the longer-wavelength region was done on a limited scale. After the war, the development of much more sensitive photoemissive, photovoltaic, photoconductive, and thermal detectors opened up new areas for exploitation by passive IR techniques.

Infrared has been taking its place beside well-established visual and radar techniques for the search, detection and tracking of military targets. With this greater emphasis on military applications of IR techniques, the problem of training military personnel in all phases of infrared technology is one of increasing importance.

1.3 Training Considerations - Report Concept

This report will cover those phases of infrared technology applicable to military training problems. The areas of particular interest are surveillance, for example, the observation of nighttime training maneuvers, and identification, interpretation, location and detection of objects for training. These problems are best covered by presentation of images; therefore, techniques used in image-forming and image-scanning systems will be emphasized. However, as an additional aid for the solution of specific training problems, the fundamentals of infrared technology will be presented. A brief section on radiation theory is followed by sections set up to follow radiation emitted from a source - target or background - modulated by the atmospheric transmission spectrum, through an appropriate optical system to a detector. The output of the detector is eventually displayed by some image forming display system.

Applicability to surveillance, and to the identification, interpretation, location and detection of objects for training are stressed.

Comparisons of the effects of the characteristics of the various spectral modulators, such as background, atmospheric transmission, optical components and detectors are presented in the corresponding sections.

Synthetic presentation of infrared information for training in identification and interpretation of objects is explored.

The techniques and components of low-light-level television are explored and compared to infrared techniques for training purposes. A comparison of infrared, passive and active, to radar is presented.

Recommendations and proposed IR systems for surveillance and interpretation training are developed.

It is hoped that this presentation may suggest to the reader applications of infrared techniques for training purposes other than those covered.

2. INFRARED FUNDAMENTALS AND MATERIALS

2.1 Radiation Theory

2.1.1 Electromagnetic Spectrum

Infrared radiation occupies a small portion of the electromagnetic spectrum, which extends from high-energy cosmic rays at the high frequency end to low energy radiation from commercial power lines at the low frequency end. The portion known as infrared lies between the visible part of the electromagnetic spectrum and the upper end of the microwave region. There is no sharp division between the radio and infrared spectrum; as modern microwave techniques push the limits of the radio spectrum further into the millimeter wave region, the usable infrared spectrum is being extended to close the gap between.

2.1.2 Infrared Spectrum

It is customary to divide the infrared spectrum into three regions:

(Figure 1) Near infrared - 0.75 micron to 1.5 micron (μ)
Intermediate infrared - 1.5μ to 8μ
Far infrared - 8μ to 1,000 μ

A micron is a wavelength measure equal to one millionth of a meter. Where radio and radar specifications are given in terms of frequency, infrared radiation is specified in terms of wavelength. The relationship between wavelength and frequency is given by:

$$C = \lambda \nu$$

C = free space velocity of light in meters per second
ν = frequency of radiation in cycles per second
λ = wavelength in meters

The division is arbitrary, with the limits varying somewhat according to the person defining them. These limits are widely used since they are closely related to certain effects and problems that are met within the generation and detection of infrared radiation.

The most familiar effect of infrared is the sensation of warmth produced by a heated body. Heat is a form of energy, and the physiological effect is the result of absorption of energy from infrared radiation.

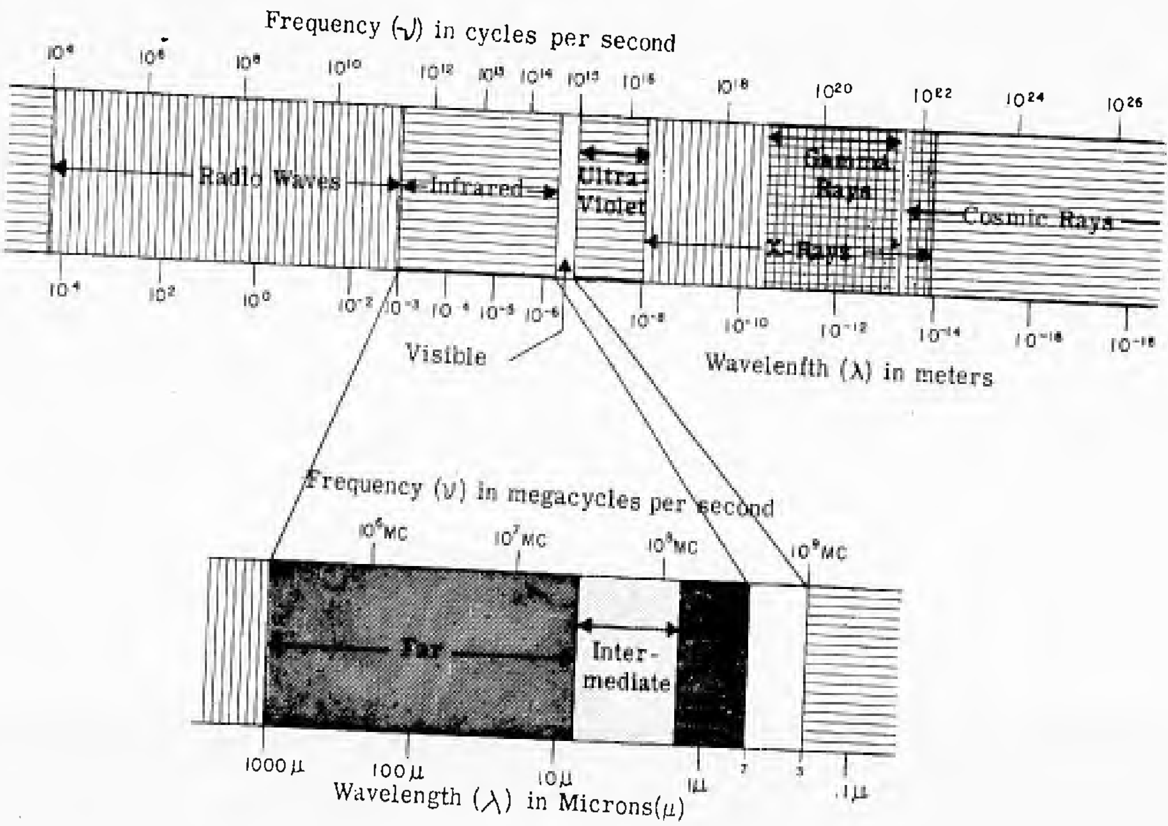


FIGURE 1 - ELECTROMAGNETIC SPECTRUM SHOWING INFRARED REGIONS

Military interest in infrared, however, is primarily due to the fact that all objects at temperatures above absolute zero (-273°C) emit electromagnetic radiations whose wavelengths are mostly in the infrared spectrum. The relationships between the temperature of a body and the amount of radiated energy, and the way in which the energy is distributed over the spectrum are of fundamental importance in the discrimination between targets and background.

2.1.3 Atomic and Molecular Vibrations

Until the middle of the 19th Century, heat was regarded as a fluid, and the heating or cooling of a body was attributed to the transfer of this fluid to or from the body. It is now known that heating a body increases the energy of the molecules or atoms of which the body is composed, and that this energy is manifested as motion. The motion is random in a gas, but in a solid the atoms or molecules are constrained by the forces that hold the solid together, so that they execute vibrations about their rest positions. Accelerated charges radiate energy as electromagnetic waves, so that the emission of radiant energy by a heated body is a characteristic of its atomic and molecular structure.

2.1.4 Blackbody Concept

If a heated body can be regarded as being made up of many electromagnetic oscillators, it should be possible to calculate the energy distribution as a function of wavelength. Since this distribution depends upon composition of the body, simplification of the calculation is carried out by introducing an ideal "blackbody", which is defined as a perfect absorber of all electromagnetic wavelengths. A blackbody is also the perfect thermal radiator at a given surface temperature; in amount and wavelength distribution, its radiation depends only on its temperature. Although actual heat sources radiate somewhat differently from a blackbody, the use of this idealization is justified by the fact that its properties are a close approximation to reality, and theoretical calculations may be carried out that would otherwise be impossible.

Almost ideal blackbody characteristics can be obtained from commercially available blackbody sources. Construction of simulated blackbody sources are described fully in the literature and will not be discussed here. (Reference 2, 3)

The characteristics of blackbody radiation are shown in Figure 2, in which the radiation flux is plotted as a function of wavelength. The important features are a shift of the wavelength corresponding to the maximum radiation flux to shorter wavelengths with increasing temperature, and a very rapid increase of total radiated energy (the area under the curve) with increasing temperature.

2.1.5 Early Theoretical Radiation Laws

Until the end of the last century all attempts to account for the blackbody radiation spectrum from theoretical considerations had been unsuccessful. The results of a calculation based on classical electrodynamics and statistical mechanics are embodied in the Rayleigh-Jeans Law, according to which

$$W = \frac{C_1}{\lambda^5} \times \frac{\lambda T}{C_2}$$

The Rayleigh-Jeans Law agrees with experiment at long wavelengths, but is greatly in error everywhere else; it leads, in fact, to the conclusion that the energy in an enclosure is infinite, which is obviously absurd.

Wien worked on the problem from the other end; trying to fit the experimentally determined distribution with a devised curve based on Maxwellian distributions. The Wien Law is:

$$W = \frac{C_1}{\lambda^5} \times \frac{1}{\exp \frac{C_2}{\lambda T}}$$

where C_1 and C_2 are constant. This fit the experimentally determined curves at the short wavelengths, but went astray at the longer ones.

2.1.6 Planck Law

The solution of the problem was achieved by Max Planck who arrived at his celebrated formula by assuming that energy is emitted and absorbed, not continuously, but in discrete packets, or "quanta", each of which has an energy $h\nu$, where h is Planck's constant and is the radiation frequency. Planck's constant and ν is the radiation frequency. Planck's equation in practical form is:

$$W_\lambda = \frac{C_1}{\lambda^5} \times \left[\frac{1}{\exp(C_2/\lambda T) - 1}\right]$$

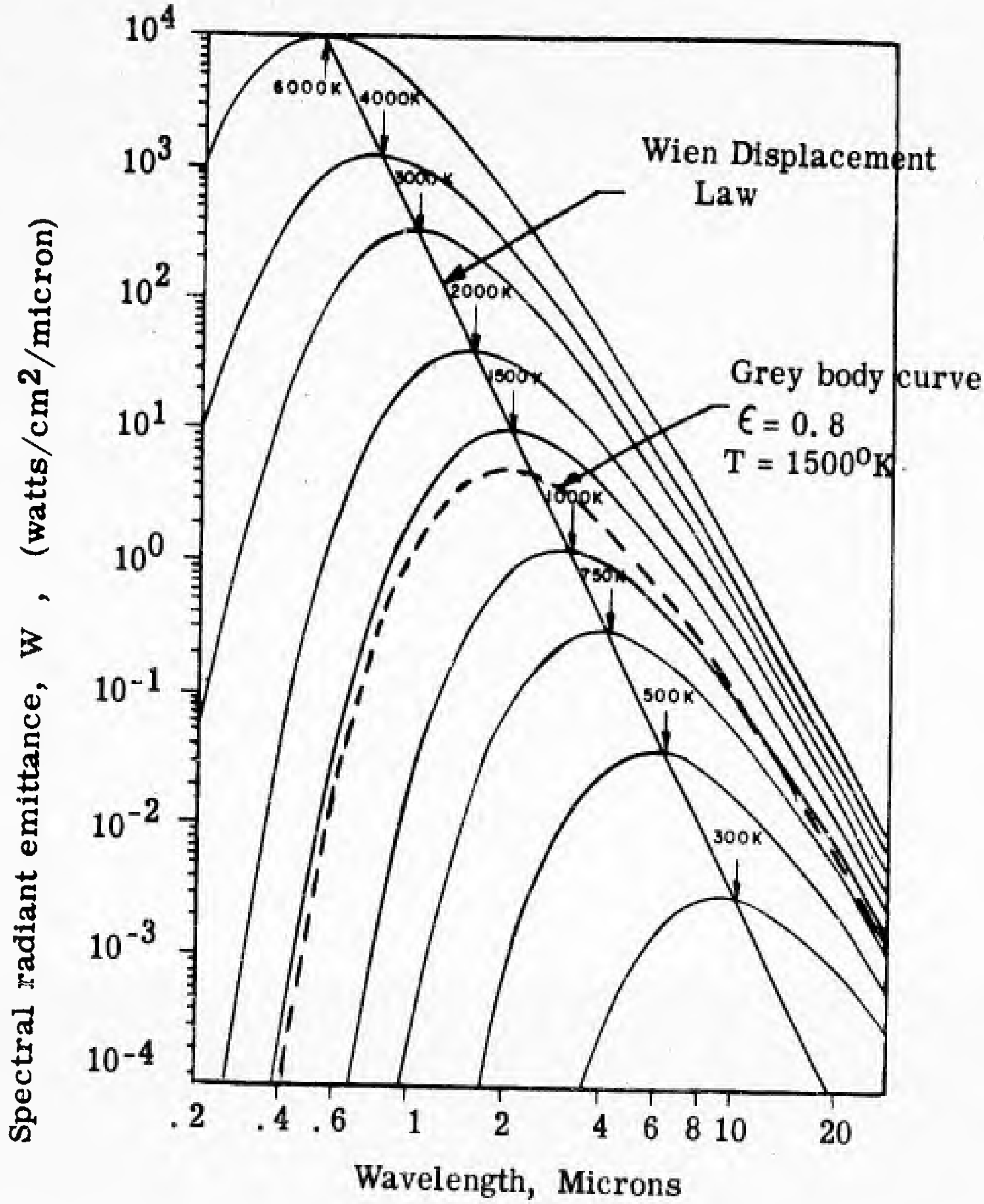


Figure 2 - Spectral Radiant Emittance Curves for Blackbodies at Several Absolute Temperatures (Showing Wien Displacement Law line and grey-body curve for $\epsilon = 0.8$ at 1500°K)

It may be seen that the Wien's and Rayleigh-Jeans' equations can be deduced from Planck's law by either neglecting the number one in relation to exp $(C_2/\lambda T)$ or expanding the exponential in a series and neglecting higher order terms.

2.1.7 Wien Displacement Law

The shift to shorter wavelengths of the peak emission with increasing temperature is known as the Wien Displacement Law. This can be obtained by differentiating Planck's formula after substituting the numerical values of the constants: (Ref. 4)

$$W_\lambda = \frac{3.740 \times 10^4}{\lambda^5} \times \frac{1}{\exp\left(\frac{1.438 \times 10^4}{\lambda T}\right) - 1}$$

and setting the derivative equal to zero. Then $\lambda_m = 2897/T$ microns (Figure 2). By substituting λ_m into Planck's formula, the peak spectral radiant emittance is:

$$W_{\lambda m} = 1.3 \times T^5 \times 10^{-15} \text{ watt/cm}^2\text{/micron}$$

The total radiant emittance from a blackbody can be obtained by integrating $W_\lambda d\lambda$ from $\lambda = 0$ to λ = infinity. The result, known as the Stefan-Boltzmann law, is

$$W = \int_0^\infty W_\lambda d\lambda = 5.67 \times T^4 \times 10^{-12} \text{ watt/cm}^2$$

Note that the total emittance is proportional to the fourth power of the absolute temperature whereas the peak spectral emittance is proportional to the fifth power of the absolute temperature.

2.1.8 Numerical Results of Radiation Laws

Table 1 gives the value of the total radiant emittance, W, for blackbody emission into a hemisphere (a solid angle of 2π steradians) for the temperatures of Figure 2.

It is interesting to note some of the numerical results of the various radiation laws. At room temperature, about 300°K, one square centimeter of an ideal blackbody emits a total power of .046 watts referenced to absolute zero. For a blackbody whose temperature exceeds that of its surroundings by one degree centigrade, assuming the surroundings to be at room temperature, the difference in emitted power is 6.2×10^{-4} watts per square centimeter. Much less power will be radiated by real bodies since the Stefan-Boltzmann law holds only for the ideal blackbody.

TABLE I

Total Blackbody Radiant Emittance
Per Sq. Cm. of Radiating Surface

Temperature, T (^{o}K)	Total Emittance, W ($watt/cm^2$)
300	0.046
500	0.35
750	1.8
1000	5.7
1500	29.
2000	91.
3000	460.
4000	1460.
6000	7380.

The wavelength at which the maximum of the energy distribution given by the Planck formula occurs is about 10 microns at room temperature. The energy from a tungsten filament lamp at average operating temperature is peaked at a wavelength slightly longer than one micron. In the case of the radiation from the sun, the energy is peaked in the middle of the visible region, at about 0.5 microns.

2.1.9 Emission and Absorption

Emission and absorption are complementary processes, and a body that absorbs a particular range of wavelengths strongly will emit the same wavelengths. This qualitiative idea was first experimentally found and expressed by Kirchoff in 1858. He defined the emissivity, $\epsilon_{\lambda T}$, as the fraction of a monochromatic beam of wavelength, λ absorbed by a real body at a temperature T. Then, if $W_{\lambda T}\, d\lambda$ is the power per unit area (radiant emittance) that would be emitted by a perfect blackbody between λ and $\lambda + d\lambda$ the real body will emit a power $\epsilon W_{\lambda T}\, d\lambda$. Since emittance and absorptance are complementary, we can define α, the absorptance by $\alpha_{\lambda T} = [W/W_{BB}]_{\lambda T}$ That is, the emissive power of a blackbody at temperature T and wavelength λ is equal to the emittance at the same wavelength of a non-blackbody source divided by the absorptance of that body if it is at the same temperature. Figure 2 also shows this relationship.

2.1.10 Reflection and Transmission - Ideal

Besides being absorbed and emitted, electromagnetic radiation can be reflected or transmitted by a medium. (See Figure 3).

Consider the case of a medium in which absorption is negligible. A beam of light is allowed to fall upon a flat plate that has been optically polished. As the beam strikes the plate a portion of the beam is reflected. The remainder of the beam travels through the plate and strikes the second surface where, again, a portion is reflected. If absorption in the plate is negligible, the beam will continue to be reflected back and forth inside the plate. Although this process will, theoretically at least, continue indefinitely, a considerable proportion of the beam is transmitted at each reflection, and the actual amount of energy left inside the plate is quickly reduced to anegligible amount. In the stead state condition there is: (Figure 3).

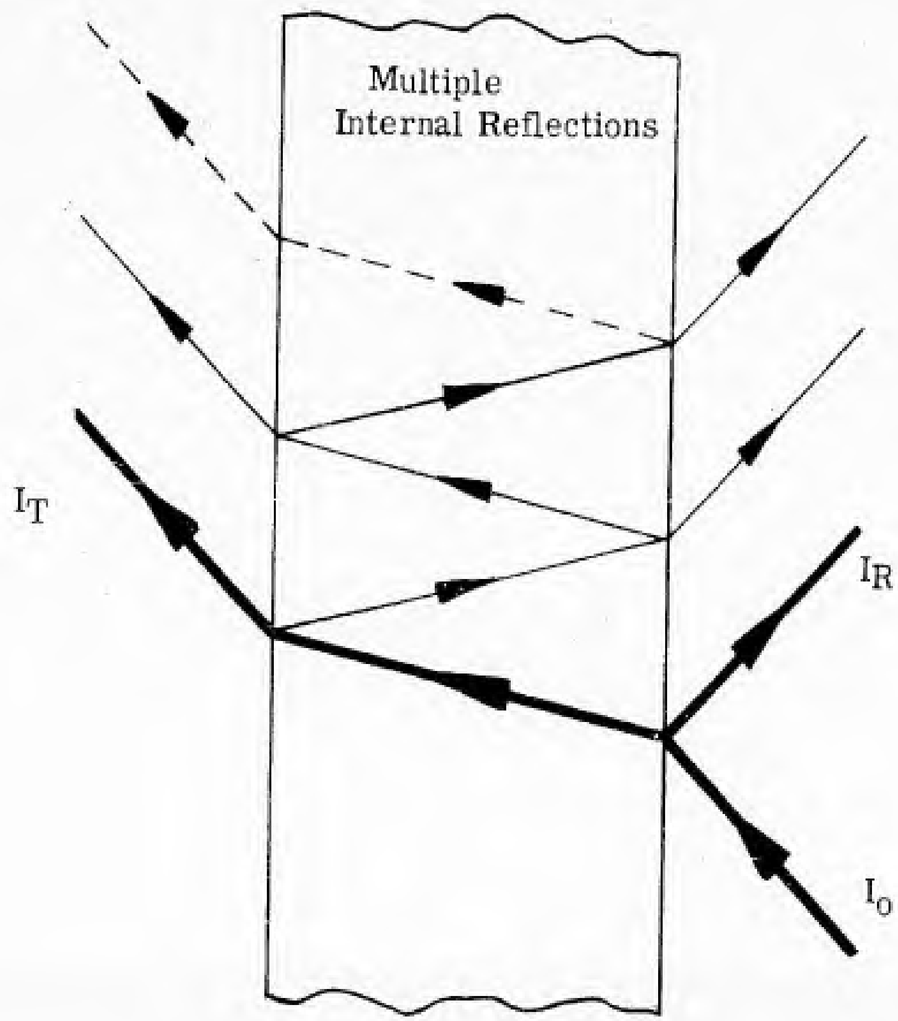


Figure 3 - Reflections and Transmissions by Non-absorbing Medium

1. The incident beam, I_0

2. The reflected beam, I_R, which is made up of the initial reflection plus a small contribution from the multiple reflections.

3. The transmitted beam, I_T, which is made up of the portion of the beam that is left after the two initial reflections, plus a small contribution from the transmissions from the multiple reflections.

A reflection coefficient, R, can be defined for such a non-absorbing plate as the fraction of the energy in a beam of radiation that is reflected when the beam strikes the plate. Similarly, a transmission coefficient can be defined as the fraction of the total incident energy that is finally transmitted.

Thus:

$$R = \frac{I_R}{I_0}$$

$$T = \frac{I_T}{I_0}$$

It is apparent that, if there is no absorption: $R + T = 1$

It is more fundamental to define a reflection coefficient, r, and a transmission coefficient, t, for a single boundary surface. These coefficients are directly related to the indices of refraction, n, of the two media that are separated by the boundary surface, and, if one of the media is air, $(n = 1)$, are given by the Fresnel formulas, assuming normal incidence:

$$r = \frac{(n - 1)^2}{(n + 1)^2}$$

$$t = \frac{4n}{(n + 1)^2}$$

In terms of r, the coefficients for a non-absorbing plate are:

$$R = \frac{1 - r}{1 + r}$$

$$T = \frac{2r}{1 + r}$$

These formulas assume that interference effects can be neglected, which they normally can be unless the plate is quite thin. The transmission and reflection coefficients are not constants, but vary with wavelength. Over restricted wavelength ranges, however, they can usually be taken as constant.

2.1.11 Absorption Effects on Reflection and Transmission

All real media absorb radiation to some extent at all wavelengths, and all exhibit strong absorption in some wavelength regions. Absorption is measured by the linear absorption coefficient, α, which is defined by:

$$I = \frac{I_0}{\exp(\alpha d)}$$

where I_0 is the initial intensity, d is the distance that the beam of radiation has traveled in the medium, and I is the intensity that remains after the beam has traveled through d. For an absorbing plate, taking reflection losses into account and neglecting interference effects, we have:

$$I = I_0 \times \frac{(1 - r)^2}{\exp(\alpha d)} \times \frac{\exp(2\alpha d)}{(1 - R^2)}$$

If the effects of multiple reflections can be neglected, as they can be except when the absorption is very small, the above relation simplifies to

$$I = I_0 \frac{(1 - r)^2}{\exp(\alpha d)}$$

Thus, optical materials should have a low value of α for the desired spectral range and a value of approaching unity everywhere else.

2.1.12 Emission and Reflection

The above equation shows, however, that bodies that reflect strongly, even if good absorbers, are poor emitters. This applies, for example, to metals, particularly if the surface is polished. Metals absorb very strongly in the visible and infrared but, when polished, have reflection coefficients not very far from unity. However, if they are deposited in the form of very small particles, they form a surface with poor reflectivity and because of their high absorption, or large absorption coefficient the emissivity from Kirchoff's Law is nearly unity. Such a surface, therefore, acts approximately as a blackbody over a range of wavelengths for which the reflection coefficient is small. This is the basis of the action of metallic "blacks". Again, if repeated reflections may be made to take place, the effective reflection coefficient may be greatly reduced and use made of the high absorption coefficient. This is the basis of some practical designs of blackbody radiators.

In order for a body to be a good emitter and approximate a blackbody, it must have both a small reflection coefficient and a large absorption coefficient.

This was expressed by Kirchoff as $r + \epsilon = 1$ (The sum of the reflection coefficient and the emissivity must be unity.)

2.1.13 Emission - A Surface Phenomenon Experiment

The concepts of emission resulting from absorption and also being a surface phenomenon can be demonstrated by a simple experiment as follows. If a cylindrical aluminum bar with a diffusely reflecting surface, about 2 ft. long and 1 in. diameter, were heated by placing each end of the bar on a separate hot plate, an infrared image device would display the bar as a gray stripe on a black background. Wrap part of the bar, say about 4 inches of it, with a piece of asbestos, and wrap another section with highly polished aluminum foil. An infrared picture of the wrapped bar would show the asbestos as a white area on a gray bar; the aluminum foil would appear almost black.

Asbestos, being a good absorber, is also a good emitter and thus gives off more radiation than even the bar. The aluminum foil, being highly reflective, has very poor emission and thus radiates very little. The fact that asbestos is considered a heat insulator and foil a good heat conductor has no bearing on this phenomenon of emission since heat conduction is a volume effect and emission is a surface effect.

Table II lists the emissivities of several well-known materials. Note the emissivity of asbestos compared to that of the various metals.

2.2 Infrared Backgrounds and Targets

Radiation in the infrared region emanates from all objects whether natural or man-made. For military-application purposes it is useful to classify an object as a target or a background.

2.2.1 Definition of Target and Background

A target is an object that is to be detected, located or identified by means of infrared techniques. A background is any distribution or pattern of radiant flux external to the observing equipment that is capable of interfering with this process. An object may thus at one time be a target and at another time be part of the background, depending on the intent of the observer. An electric power generating plant is part of the background if a tactical aircraft is intent on a ship moving on a nearby river. To a strategic bomber, the generating plant is the target; ship and river are the background. All terrain features are of interest to certain reconnaissance devices, such as mappers, and hence are targets. However, information obtained by such equipment is useful background data to others.

2.2.2 Sky Background

The sky constitutes the background for all directions of view above the horizon. It is formed by the atmosphere of the earth, including haze, fog, clouds, and precipitation, and by the moon, planets, and stars, including the sun, beyond the atmosphere. It includes special sources of radiation such as the night airglow of oxygen (O_2) and nitrogen (N_2) which is about six times as bright as starlight. It also includes the polar auroras, which are many times brighter than starlight and of unknown infrared intensity. The atmospheric emission bands of water vapor (H_2O) and carbon dioxide (CO_2) and of the ozone (O_3) layer at 50,000 to 90,000 feet also make up part of the background.

2.2.3 Daylight Sky Radiation

The daylight sky background is composed of two main parts:

(1) Sunlight scattered by air molecules, haze, clouds, and other particles makes up the major part of the radiation in the visible and near infrared wavelengths to approximately three microns. The absorption bands of water and carbon dioxide remove a part of the scattered radiation

TABLE II

Approximate Emissivities of Various Surfaces (Ref. 6)

Material	Temp. Range °C	Emissivity
Polished Metals		
Aluminum	250 to 600	0.039 to 0.057
Brass	250 to 400	0.033 to 0.037
Chromium	50 to 550	0.08 to 0.26
Copper	100	0.018
Iron	150 to 1000	0.05 to 0.37
Nickel	20 to 350	0.045 to 0.087
Zinc	250 to 350	0.045 to 0.053
Filaments		
Molybdenum	750 to 2600	0.096 to 0.29
Platinum	30 to 1200	0.036 to 0.19
Tantalum	1300 to 3000	0.19 to 0.31
Tungsten	30 to 3300	0.032 to 0.35
Other Materials		
Asbestos	40 to 350	0.93 to 0.95
Ice (wet)	0	0.97
Lampblack	20 to 350	0.95
Rubber (gray)	25	0.86

reaching the surface of the earth but contribute only weak self radiation because of the low temperature of the atmosphere. Scattered sunlight decreases in intensity on very clear days and also decreases with altitude.

(2) Self radiation by the atmosphere is dominant at the surface of the earth at wavelengths longer than three microns.

The distinction between the two parts of the daylight sky is one of relative intensity. If an infrared spectrometer is aimed at any point in the sky and intensities recorded wavelength by wavelength, positive meter deflections would result throughout the visible and near infrared region to about 3 microns because incoming scattered sunlight is predominant. Above 3 microns the meter would show a negative deflection, indicating the spectrometer is radiating more energy to space than it receives.

Three factors contribute to this effect:

a. The solar intensity decreases sharply with increasing wavelength.

b. The scattering of sunlight by the air molecules decreases sharply with increasing wavelength.

c. Beyond three microns the spectral intensity of sources at atmospheric temperatures becomes measurable; the spectrometer, being at a higher temperature, loses more energy to the atmosphere and interplanetary space than it gains. The loss is greatest, and the greatest negative deflection occurs, in regions where the atmosphere is most transparent and where the spectral intensity of the spectrometer is highest; these regions coincide with the 8 to 13 micron atmospheric window. (See section on atmospheric transmission).

2.2.4 Water Vapor (H_2O) and Carbon Dioxide (CO_2) Emission

On the short wavelength side of the 8 to 13 micron transmission band, the self emission of water vapor in the 5 to 8 micron region represents an incoming signal to detectors sensitive in that region. On the long wavelength side of the band, the fundamental band of carbon dioxide near 15 microns emits strongly. In each of these bands a very short atmospheric pathlength is sufficient to be opaque; if temperature fluctuations occur in the first few hundred feet of the atmosphere, the resulting change in emission may be enough to create a measurable noise signal in detectors sensitive in these respective wavelengths.

2.2.5 Ozone Emission

At 9.6 microns the ozone layer at 50,000 to 90,000 feet absorbs strongly, thus emitting strongly at this wavelength. Furthermore, temperatures in the ozone layer are comparable to surface temperatures. At the earth's surface the ozone layer produces an appreciable radiation flux easily measurable by detectors pointed at the sky; detectors pointed along ground level get very little background noise from the ozone layer.

2.2.6 Night Sky

In the night sky the effects of sunlight are absent. The effects of self radiation as discussed above remain essentially unaltered. One new feature appears: starlight. Stars produce measurable radiation flux densities both in the near infrared, below three microns, and in the 8 to 13 micron region.

2.2.7 Ground Backgrounds

The background for the military observer on the ground is composed ordinarily of the natural elements such as trees, shrubbery, rocks, and hills and other variations in ground level. These natural backgrounds have reflection characteristics as well as radiation emission. Since reflection and emission are both surface phenomena, the numerous variations in the surfaces of natural objects such as color, texture and movement (as in the case of leaves) make for a very noisy background. However, practically all of the radiation energy is of relatively low temperature, (around $300^{\circ}K$) especially at night. Thus detection of militarily important targets is facilitated since they are usually at some elevated temperature because of a power source. Identification by means of imaging systems is quite difficult unless a high resolution system is used.

2.2.8 Sea Backgrounds

The temperature of a sea surface remains fairly constant on the average because of its tremendous mass (Ref. 7). However, because of its motion, the reflectivity of any point is constantly changing. To an observer with infrared equipment the sea surface thus forms a very noisy background. For detection purposes, autocorrelation techniques, taking advantage of the regularity of man-created effects such as wakes of ships, can detect targets in this randomly noisy background. For imaging purposes, however, a high resolution system is necessary to permit identification of a sea target.

2.2.9 Background Measuring Programs

On 8 and 9 June 1954, an infrared conference was held at the University of Michigan. Information on infrared backgrounds was so meager it was decided to hold a conference devoted entirely to infrared backgrounds and also to form a committee dealing with background measurements.

The Background Conference was held at the Engineering and Researc' `evelopment Laboratories (ERDL) at Fort Belvoir, Va. on 22 Nove. . 1954. At this conference a group of three members, one from each of the Military Departments, was appointed to consider the selection of members and the general field of interest of a Working Group on Infrared Backgrounds. The membership of the WGIRB is composed of representatives of Defense Department research and development agencies and representatives of several of the major industrial organizations concerned with infrared. (For details of this organization and its work see Ref. 8).

In addition, an infrared atmospheric measuring program known as Infrared Measuring Program 1956 (IRMP56) was carried out under Wright Air Development Center (WADC) sponsorship to get detailed information on sky backgrounds and atmospheric transmission. (Ref. 9). The information from these reports is still in the process of being analyzed and correlated. The main result of these studies has been a demonstration of the extent of the lack of knowledge of IR background and has led to the formation of other measuring programs which are still being carried out. These are Infrared Measuring Program 1958-59 (IRMP 58-59) and Interservice Radiation Measuring Program 1959-60 (IRMP 59-60).

2.2.10 Wiener Spectrum

A comparatively recent method of graphical presentation of background noise is called the Wiener spectrum. Its great usefulness is in analysis of radiation for reticle techniques, which greatly assist in discrimination between a small target and a noisy background. However, since reticle techniques are most useful in search and track modes of air-to-air and ground-to-air systems, the reader is referred to the WGIRB report and other literature for further details (Ref. 10).

2.2.11 Target Discrimination

As mentioned above a target is any object that is to be detected, located, or identified by means of infrared techniques. For image forming systems, any or all the information could conceivably be a target. However, for surveillance or reconnaissance infrared systems, the targets are usually objects that are man-made. Thus the detection of a target becomes a matter of discriminating between the natural background and the man-made objects. In IR scanning systems target recognition is accomplished by detection of the difference between the power radiated by the target and by its background. (Ref. 9). Figure 4 shows the difference in radiant emittance (watts/cm^2) below wavelengths indicated for various target-background temperature differences at $T_o = 25^oC$.

Thus, at ordinary ambient temperature, for a 5^oC temperature difference between target and background, below 10μ, there is a maximum radiant emittance differential of about 1.5×10^{-3} watts/cm^2. Due to atmospheric and other losses, only a percentage of this energy reaches the detector.

2.2.12 Methods of Describing Targets

One of the other losses referred to above is due to the fact that the target and background radiations used to plot the curves were assumed to be blackbody radiation. Solid object radiations are basically grey body type; the blackbody curve for the temperature of the object is modified by multiplying each point on the curve by the emissivity of the object.

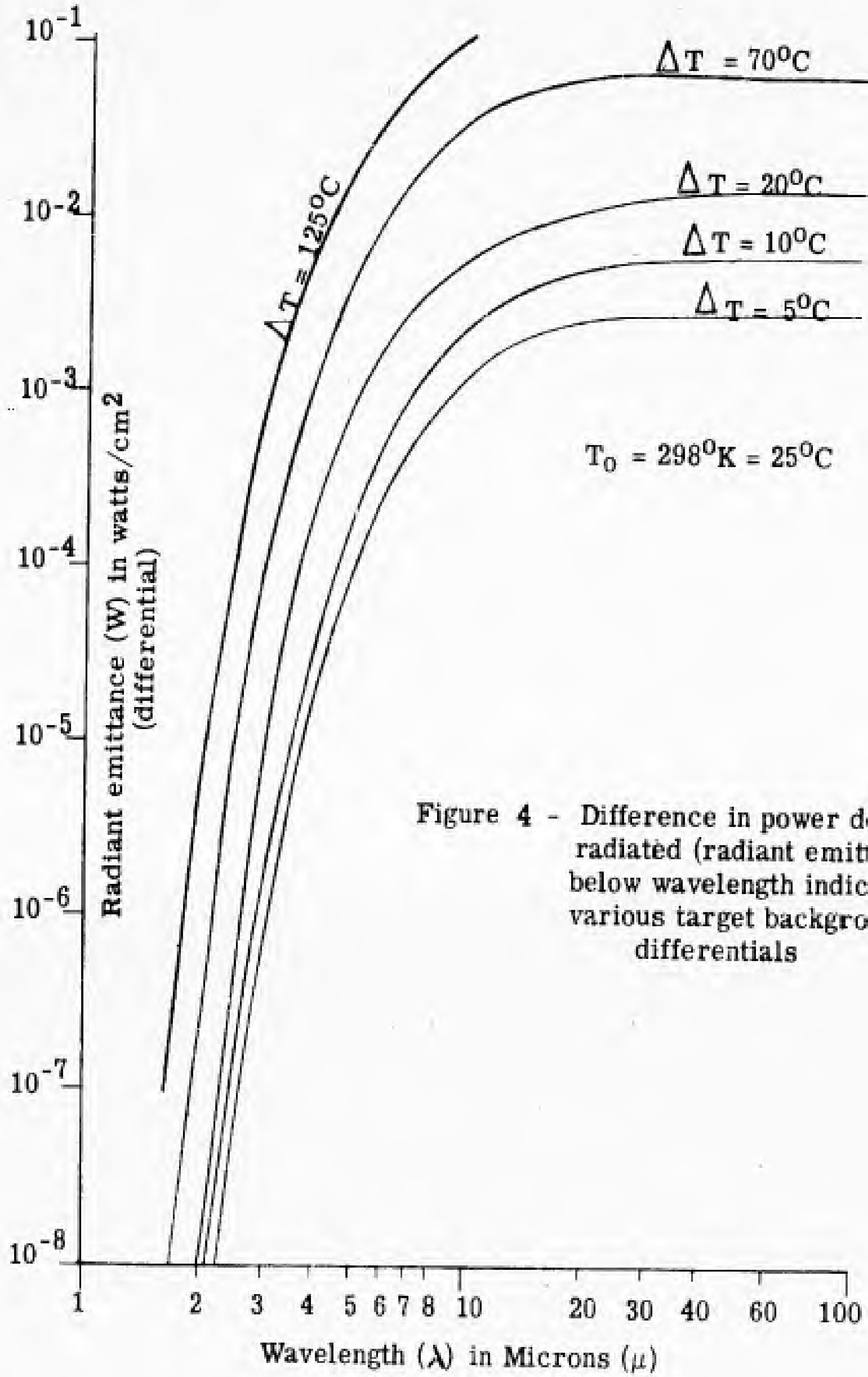


Figure 4 - Difference in power density radiated (radiant emittance, W) below wavelength indicated for various target background differentials

Radiation from a target may be specified by other means, which may be more useful in certain applications. One of these is to plot polar diagrams of radiant intensity for each of the aspects of the viewed object - top, sides, front and rear. (Figure 5). If sufficient symmetry exists one or more of these may be eliminated. A three dimensional presentation may be necessary at times.

Polar diagrams usually are based on total radiant energy measured by infrared radiometers; the output does not have spectral characteristics. Figure 6 was plotted from values obtained by a spectrometer, which measures radiation at each increment of wavelength depending on the precision of the instrument. (Note the pronounced effect of water vapor absorption at 6 microns.)

2.3 Atmospheric Phenomena

2.3.1 Considerations

The earth's atmosphere plays a very important role in the design and use of infrared sensing equipments. The radiation incident on an infrared receiver is almost always modulated by the intervening atmosphere. This atmospheric medium is an inhomogeneous and continuously changing mixture of gases, liquid droplets, and solid particles. The important gases are H_2O, CO_2, N_2 and O_3. These gases will absorb and emit radiation as a function of the number of molecules present, the wavelengths involved, and the total energy of the molecules.

The prediction of scattering effects by atmospheric particles is made difficult by the fact that Rayleigh and Mie scattering theories require knowledge of particle numbers, densities, shapes, sizes, and electrical characteristics, which in turn depend on the materials making up the particles. These parameters are not easily determined and the theories cannot take all of the factors into account, requiring many simplifying assumptions.

The transmitted radiation is also subject to refraction by the medium traversed. All these factors; absorption, emission, scattering, and refraction; vary with time and distance over the transmission path. The constant motion of the atmosphere, on macro-and microscopic scales, create these variations in as unpredictable a pattern as other meteorological factors. Only on a statistical basis are any predictions possible.

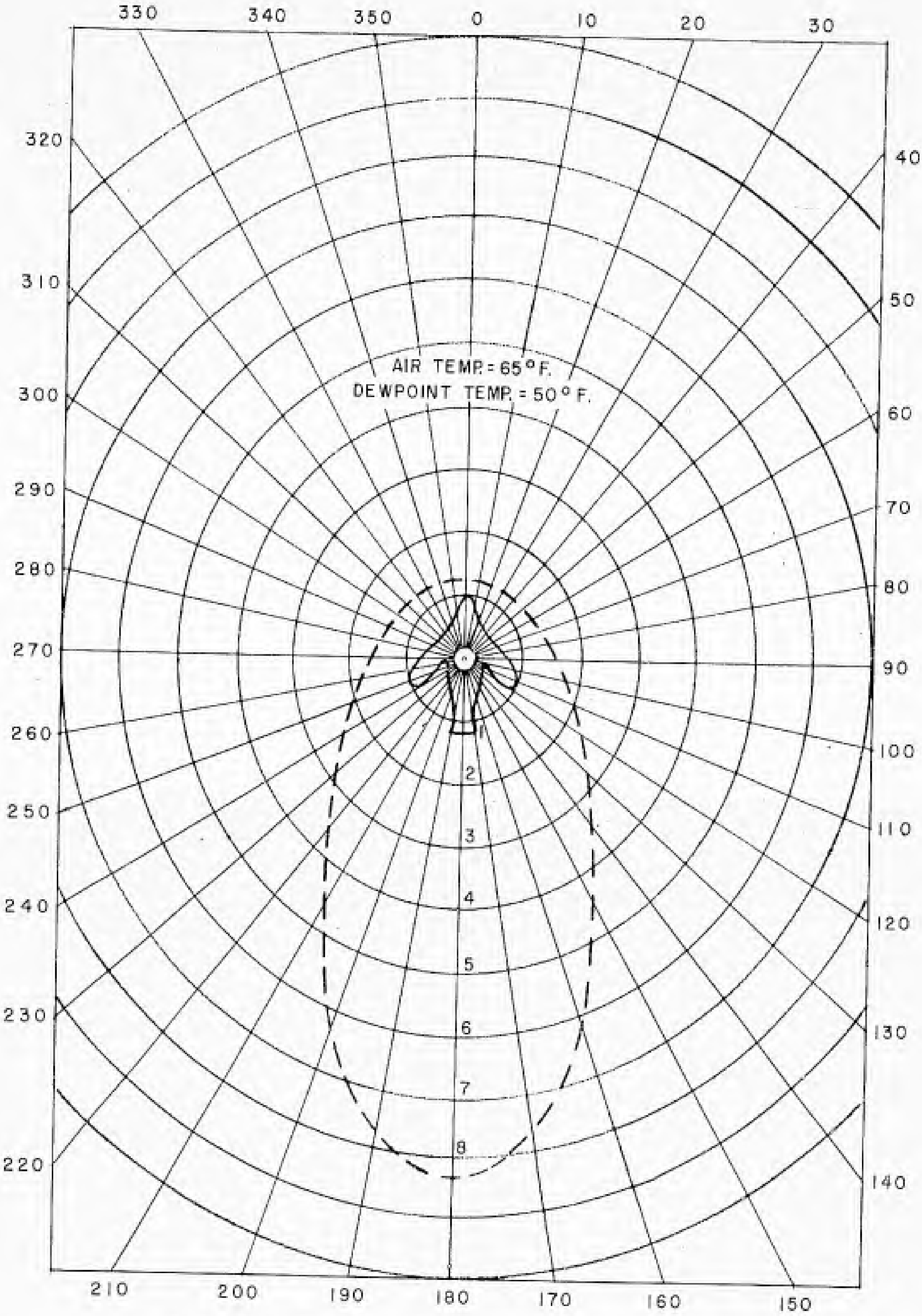


Figure 5 - Radiation Pattern of Jet Aircraft

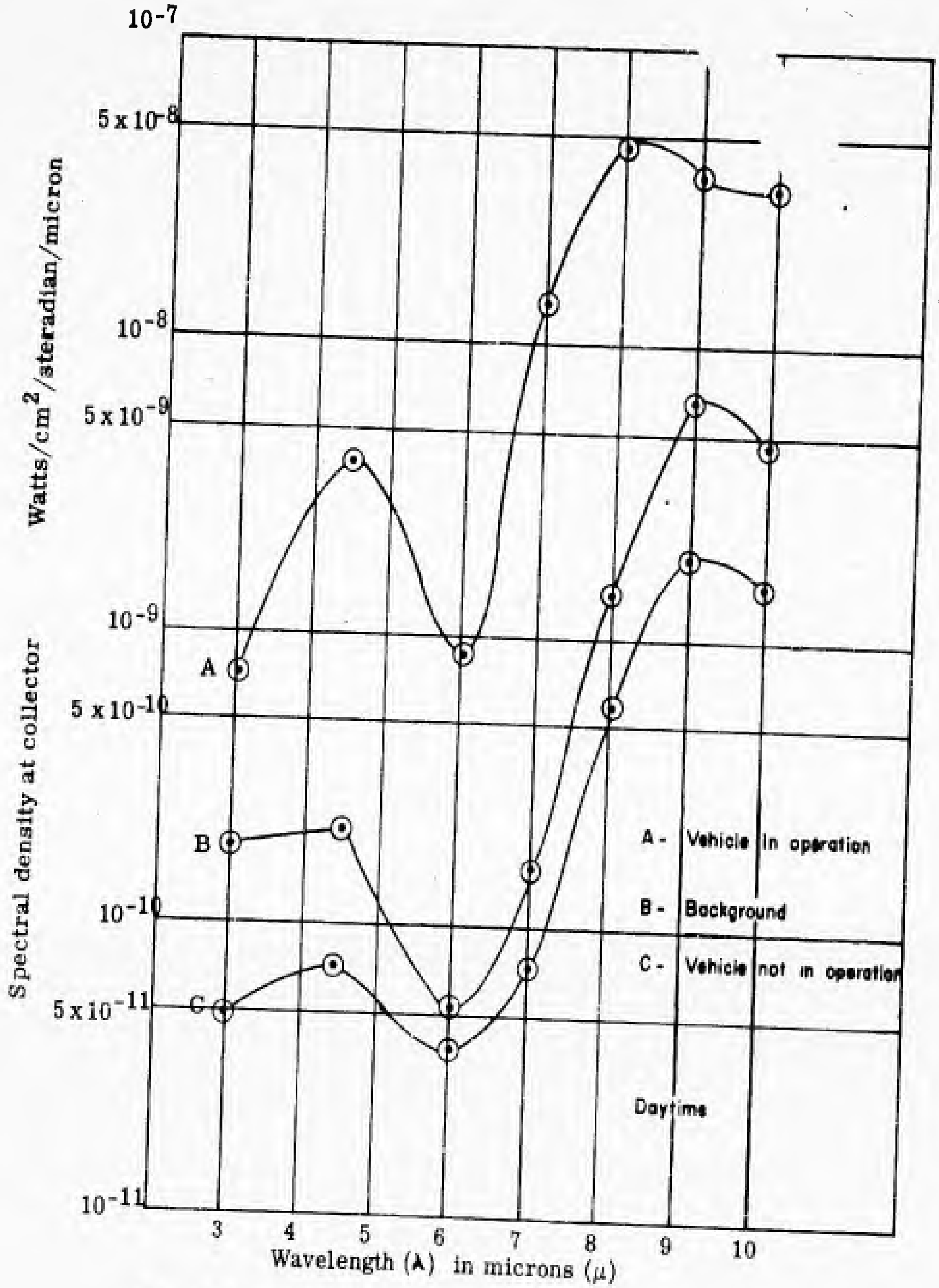


Figure 6 - Radiation from Targets and Backgrounds

In spite of the complexity of the problem, a tremendous amount of work has been done leading to an understanding of the fundamental physical processes involved. (Ref. 9, 10, 11, 12, 13, 14). The absorption and emission spectra of the more important gasses are known in the regions of interest. Meteorologists have compiled tremendous amounts of data on the composition of the atmosphere and its variations. Theories of scattering and refraction have been developed from this data and have been employed with some success. Finally, there are quite a few measurements of the transmittance at wavelengths from 0.7 microns to beyond 15 microns made through real and synthetic atmospheres.

2.3.2 Atmospheric Absorption and Transmission

Absorption of infrared radiation by the atmosphere consists primarily of the absorption spectrum of the vibration-rotation bands of H2O and CO_2. These bands are situated at certain wavelengths in the spectrum, and the regions between the bands are "windows" which transmit radiation with very little attenuation. As a first approximation, Figure 7, shows the absorption regions and windows associated with atmospheric transmission.

Under low resolution the absorption curves look smooth, but higher resolution shows each band to be made up of many small absorption lines (Figure 8) (Ref. 11).

Absorption of monochromatic radiation follows the usual exponential law; from which

$$\frac{I}{I_0} = \frac{1}{\exp(\alpha w)}$$

in which I/I_0 is the fraction of radiation transmitted through distance w and α is the absorption coefficient. The value of α at any wavelength depends on the amount of water vapor and carbon dioxide in the path length, w, and on the atmospheric pressure. Calculations based on the above equation require the spectrum to be broken up into extremely short intervals of one Angstrom (10^{-4} microns) or less, and the amount of labor required is not justified because of the variations in the water vapor content. Furthermore, the values of α are not well enough known at each wavelength to warrant this kind of computation.

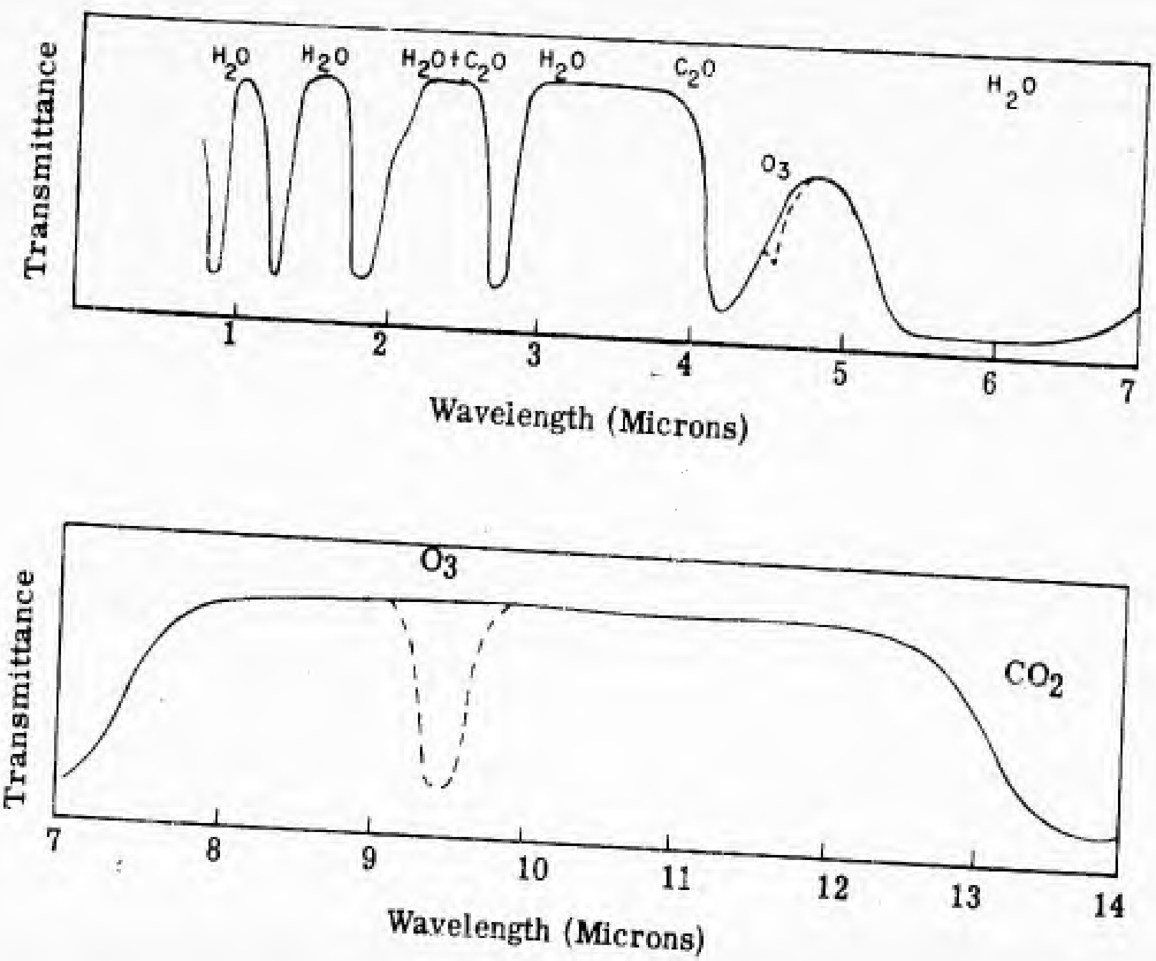


Figure 7 - The windows and absorption regions of the atmosphere

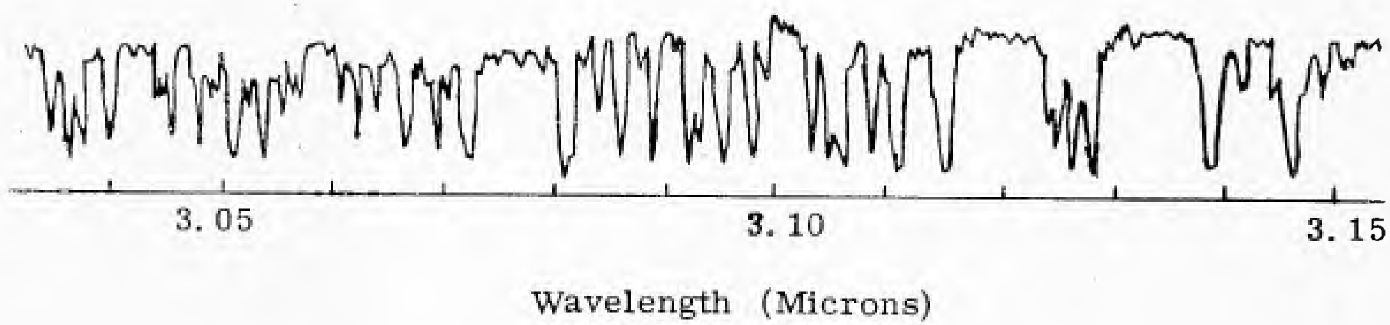


Figure 8 - Detail of Atmospheric Transmission Showing the Many Absorption Lines

Elsasser (Ref. 12) has shown that for absorption lines which are equally spaced and of equal intensity, the fractional absorption follows an error-function law defined by

$$A = \text{erf}\left[\frac{\beta}{2}\,(\pi w)^{1/4}\right]$$

where A is the absorbed fraction after traversing a path length w, and β is the error-function absorption coefficient.

The error function is defined by

$$\text{erf}(x) = \frac{2}{\pi}\int_0^x \frac{dt}{\exp(t^2)}$$

this value is tabulated in various mathematical handbooks (Ref. 13).

2.3.3 Effect of Water Vapor (H_2O)

For application to absorption by water vapor, the path length, w, is usually given in terms of precipitable water in the total path of radiation. In practice, w, is obtained from meteorological observations of the absolute humidity, which must frequently be computed from actual observations of the temperature and relative humidity.

The assumptions involved in the error function law are not strictly applicable to the spectral properties of the water molecule. The Ohio State University Research Foundation found that values of atmospheric absorption by water vapor lie between those predicted by the exponential law and those found by the error function. However, the actual deviations from the values predicted by the error-function are smaller than the uncertainties in the meteorological data, and the error-function law has found wide acceptance. Much work has been done on the water vapor absorption coefficient β (Ref. 14) and actual transmittance values as a function of wavelength have been calcuated for various amounts of precipitable water vapor. (Ref. 15). Absorption by selected amounts of precipitable water vapor is plotted in Figure 9 to illustrate the effect of changing water vapor content.

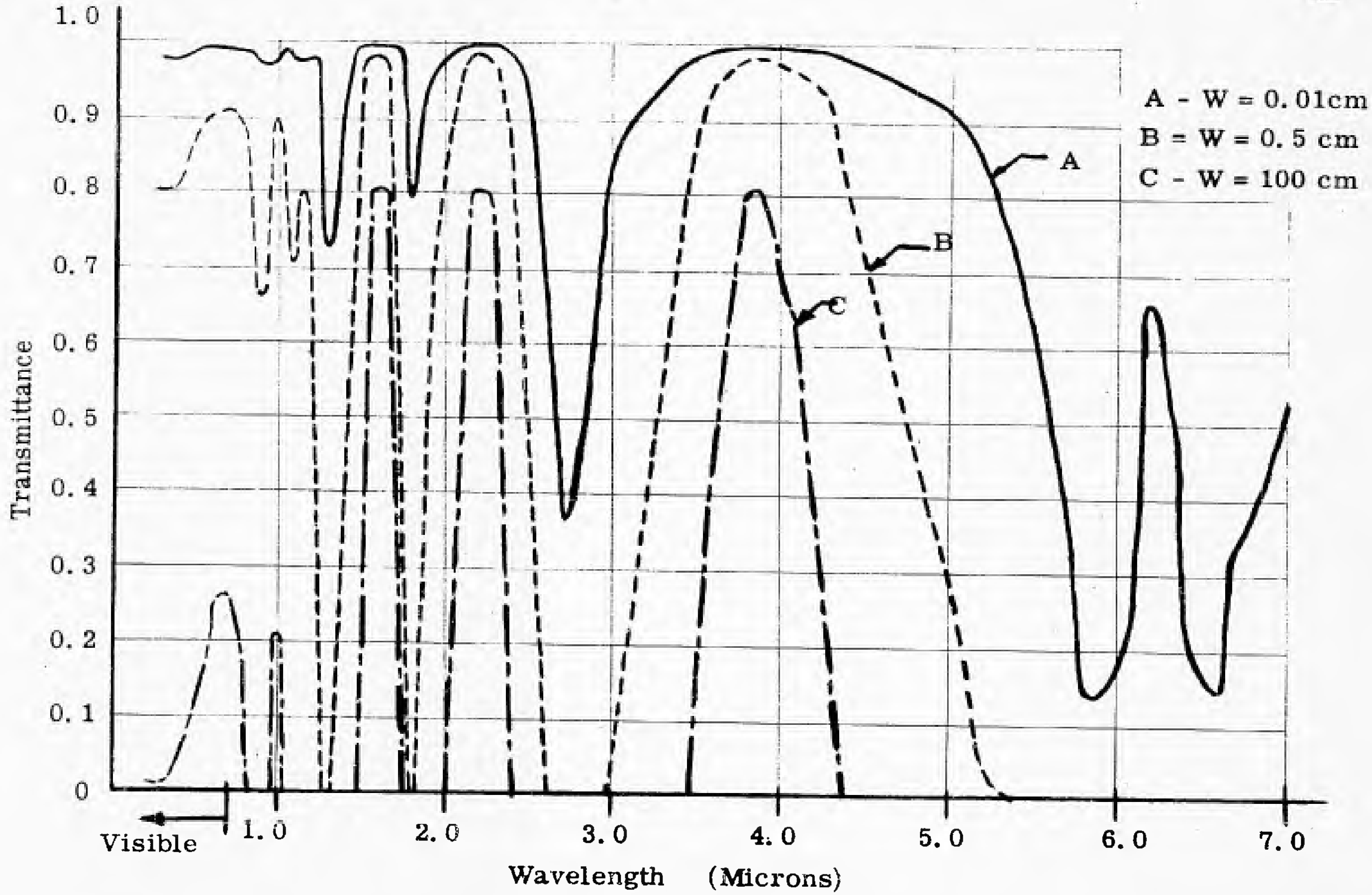


Figure 9 - Atmospheric Transmittance, H_2O Vapor, Sea Level - W = Precipitable Water Vapor

2.3.4 Effect of Carbon Dioxide (CO_2)

The principal absorption bands of carbon dioxide are at 1.4, 1.6, 2.0, 2.7, 4.3, 4.9, 5.2 and 15 microns. See Figure 10. The work of many investigators in this field has verified the predicted transmission in most regions (Ref. 16). One of the largest discrepancies was near 4.5 microns where data did not predict as much absorption as was actually found. Since this is precisely the region where hot CO_2 radiates, it is important to understand the reason for the discrepancy. The poor agreement is due to the fact that nitrous oxide (N_2O), although only a very minor constituent of the atmosphere, 0.5 parts per million (ppm) has a very strong fundamental absorption band at 4.5 microns.

2.3.5 Scattering

Scattering of infrared radiation by solid particles depends, as mentioned previously, on the number of particles, size, shape, etc. Studies of suspended particles have shown they consist of dust (with no growth in size due to water), having diameters of about 0.1 to 10 microns and condensation nuclei 10^{-3} to 1 micron diameters. Distributions of condensation nuclei have been found as shown below:

In cities	150,000 particles/cc
In small towns	50,000 particles/cc
In the country	10,000 particles/cc
In mountains and forests	1,000 particles/cc

2.3.6 Atmospheric Penetration - IR vs. Visible

In general, scattering of radiation is accomplished by particles equal to or greater than wavelength. Dust particles scatter radiation up to 10 microns in wavelength while the smaller particles only affect the near infrared. Thus infrared radiation has greater penetrating power through haze and fog than visible light, with the longer wavelengths being more effective. For infrared observations over sea surfaces, the layer of water vapor makes it necessary to use these longer wavelengths to obtain any appreciable range. Atmospheric absorption effects further reduce the useful spectral region to the 8 to 13 micron window.

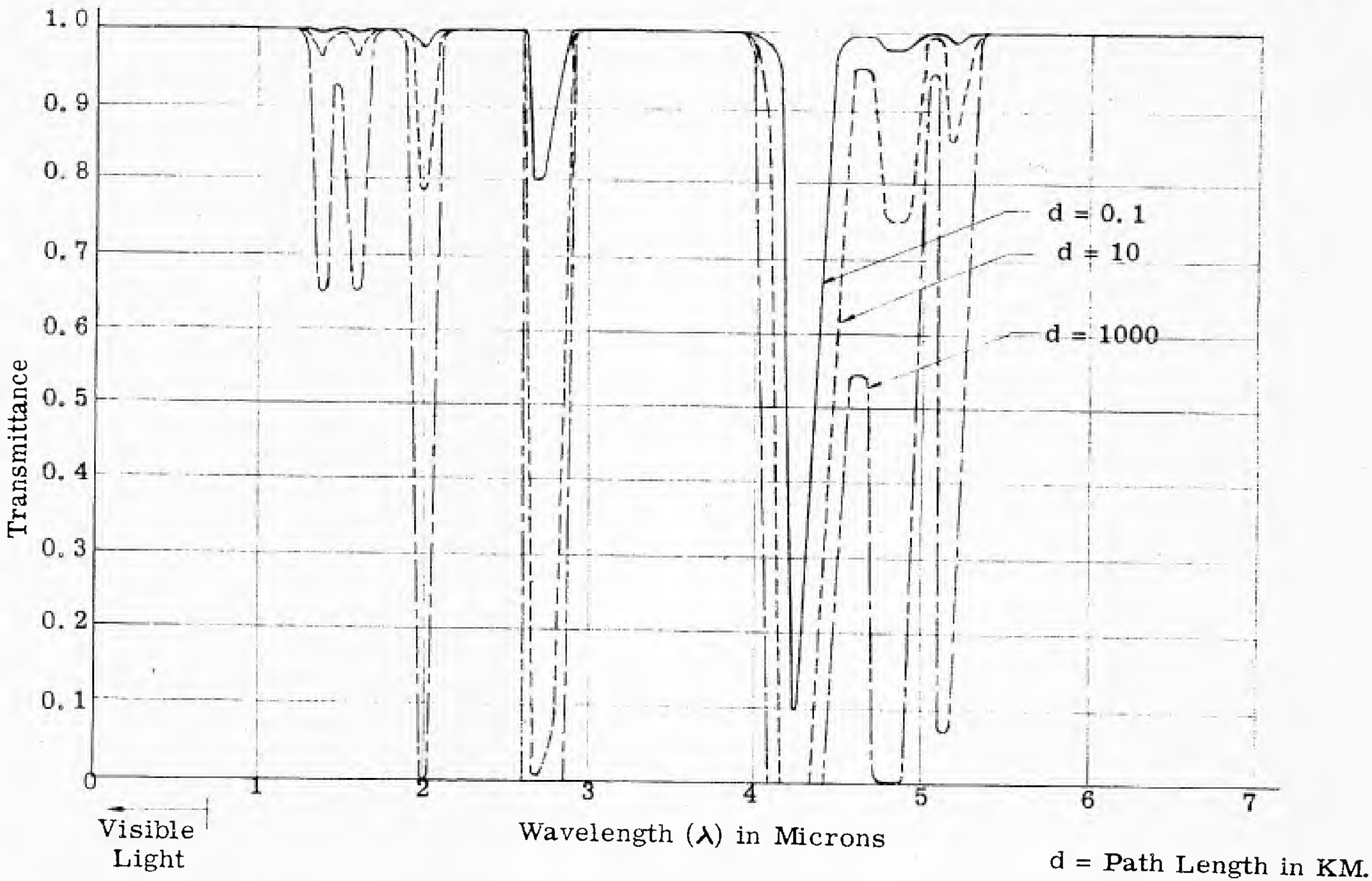


Figure 10 - Atmospheric Transmittance, CO_2, Sea Level

2.4 Optical Systems

2.4.1 General Considerations

In order to obtain sufficient infrared energy at the detector it is necessary to employ an optical system to collect the radiation and focus it on the cell. By analogy with radio systems the optical element of an infrared receiving or transmitting system corresponds to the antenna of the former. The energy pickup and directional characteristics are dependent upon the type of optical system selected.

Optical arrangements for infrared systems are usually adopted from those developed in the field of visual optics and optical engineering. Several suitable optical systems are those that are used in telescopes. While all optical arrangements are basically image-forming this property is not a requisite for infrared systems, which may be divided into image-forming and non-image forming classes. The classification depends upon whether the output of the system is to produce an image of the target or simply some response dependent upon one or more characteristics of the target. Many infrared systems fall into the non-image forming category. These include guidance systems, tracking, search, fuzing, etc. Image-forming systems either build up the image by scanning small areas, somewhat similar to television, or form the entire image at one time as an ordinary camera does.

The following discussion will be limited to those optical systems most suitable for the applications under consideration, such as the surveillance systems and systems for training in identification and interpretation which fall in the image-forming category.

2.4.2 Optical Considerations

The selection of an optimum optical configuration for an infrared system depends upon a number of factors:

1. Physical or mechanical size
2. Relative Aperture - f/number
3. Angular field of view
4. Spectral or wavelength response
5. Reflective or refractive optics
6. Aberrations

From the infrared system designer's viewpoint, the optical system may be regarded as a specialized component in much the same way that an electronic system designer would regard a special electron tube. However, in order to properly select and use an optical system, the designer must understand certain optical fundamentals. (For detailed discussion of optics, the reader is referred to any good optical text-book. Ref. 17, 18).

2.4.3 Reflective and Refractive Considerations

The elements in an optical system are either reflective, refractive or a combination of both. Because of the chromatic aberrations inherent in refractive systems, caused by the changing index of refraction with wavelengths, reflective optical systems should be most suitable for imaging purposes, especially for infrared systems. Other aberrations, such as spherical aberration, coma, astigmatism require some combination of refractive and reflective elements for best image quality.

2.4.4 Relative Aperture - f/number

One of the most important optical parameters is the relative aperture or f/number which is determined by the ratio of the focal length to the effective diameter of the optical system. An f/4.5 optical system means the focal length is 4.5 times the effective diameter. It is a measure of the radiation-gathering capability of the optical system; the smaller the f/number, the larger the effective area for a given focal length, and the greater the image brightness will be. f/number is sometimes referred to as the speed since the time needed to get the same image brightness is inversely proportional to the square of the f/number. For imaging systems, a low f/number would be desirable; however, the larger diameters associated with low f/numbers usually introduce more aberrations resulting in a decreased image quality.

2.4.5 Field of View

The field of view is a measure of the number of point sources that can be collected by the optical system in any instant. A wide angular field of view may be a desirable feature for imaging in some instances; however, the combination of wide angle and low f/number is difficult to achieve since the effects of the aberrations become more pronounced. Thus, angular field of view and f/number must be juggled in accordance with the requirements of the overall IR system. At present many systems use a small angular instantaneous field of view and low f/number; a desired resultant wide angle may be obtained by some means of scanning this small field over the wider angle.

2.4.6 Aberrations - definition

Aberrations are departures of the actual images from theoretical predictions. These are not caused by defects in the lens, but are consequences of the laws of reflection and refraction.

2.4.7 Chromatic Aberration

The focal length of a lens is a function of the index of refraction of the lens material. Since the index of refraction varies with wave length, the focal length is different for different colors. Thus, a single lens forms a series of images at varying distances from the lens and of varying sizes. Longitudinal or axial chromatic aberration is variation of image distance and lateral chromatic aberration refers to variation of image size. An exaggerated illustration is Figure 11.

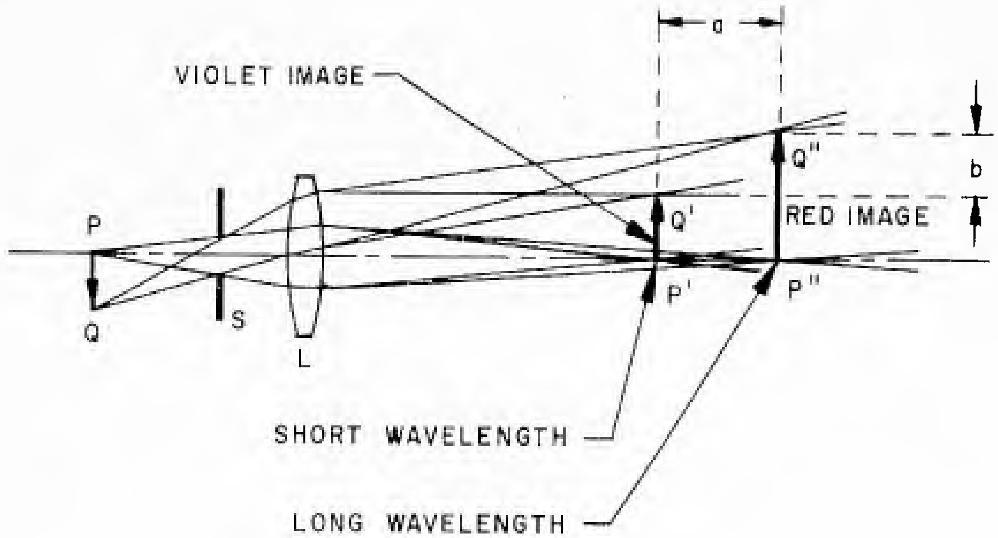
This is one of the major problems in a refractive imaging system since the spectral regions of interest are many times greater than the visible spectrum. Correction requires use of two different materials or two lenses of same material separated by an air space. A reflective system avoids this problem completely.

2.4.8 Spherical Aberration

Spherical aberration is due to the fact that parallel rays incident on a spherical surface are not reflected or refracted to the same focal point, on that radius of the surface which is parallel with the incident rays; especially if the diameter of the surface is relatively large. By proper choice of radii of curvature of the surfaces and of distances between surfaces, spherical aberration may be reduced to a minimum. In reflective systems, figuring to a paraboloid will eliminate spherical aberration, or corrector plates such as the Schmidt or Maksutov Correctors may be used. (Figure 12).

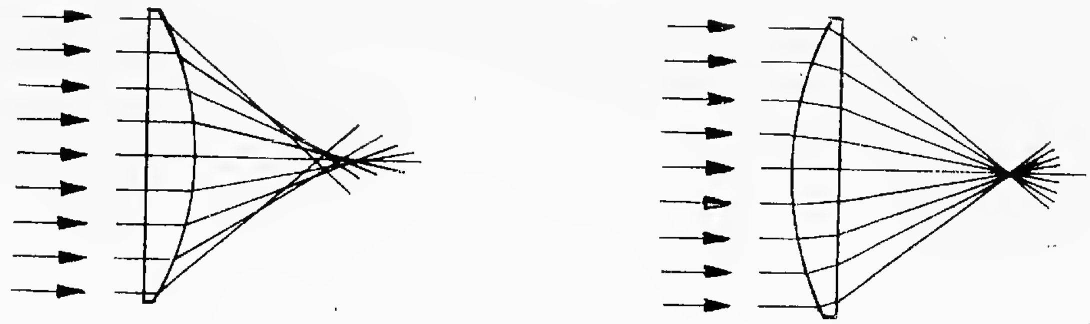
Spherical aberration results in a circular image for a point source. This is called the circle of confusion and is present to some degree in all optical systems using spherical surfaces.

Aspherical surfaces such as the paraboloid referred to above would be a means of eliminating the problem. The creation of aspherical surfaces, however, is a very costly and time-consuming procedure. Spherical surfaces, on the other hand, can be produced cheaply and quickly by machines. Thus, the cost involved must be considered in arriving at a final design.



a. Measure of axial chromatic aberration
b. Measure of lateral chromatic aberration

Figure 11 - Chromatic Aberration



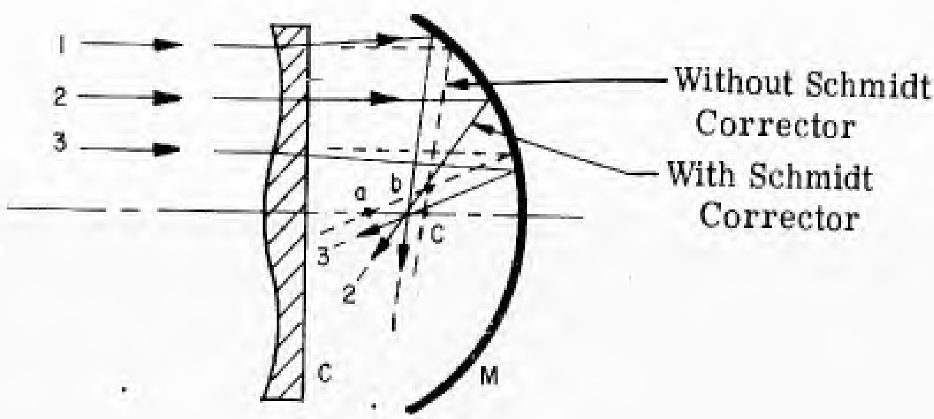
(a)

Effect of Spherical Aberration

(b)

Minimizing Spherical Aberration

Figure 12 - Spherical Aberration



(c)

Schmidt Corrector Plate for Minimizing Spherical aberration of a mirror

2.4.9 Coma

This aberration affects image points off the optical axis and is one of the factors limiting angular field of view. Figure 13 best illustrates this aberration. It will be noted that the rays through the marginal zone come to a focus at a different point in the image plane from the focus of rays passing through and near the center of the lens. This effect is true also of reflective optics, especially so of paraboloidal mirrors where an off-axis condition of more than half degree can produce an unrecognizable image.

Comatic aberrations can be minimized for a one element lens by using two different radii of curvature. A higher order of correction can be obtained by using more than one element. In some cases it is possible to minimize coma and spherical aberration at the same time by proper choice of surfaces.

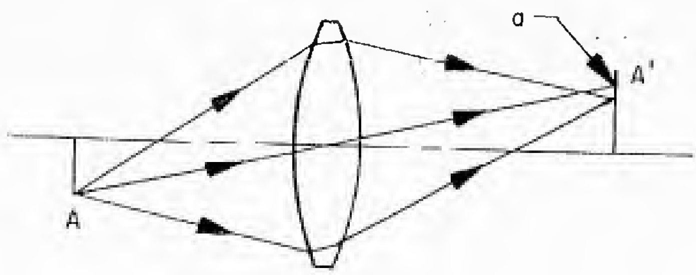
2.4.10 Astigmatism

This can be described as a special form of coma. Where coma results in spreading the image of a point over a plane perpendicular to the optical axis, astigmatism spreads the image along the axis. Figure 14 best illustrates the effects of astigmatism. The circles of the top part marked "no astigmatism present" represent the cross-section of the bundle of light rays. The astigmatism illustrated in the lower part is the distortion of these circles into elliptical patterns with the rays passing through two short lines perpendicular to each other at points B and C. Point D is the circle of least confusion. In this plane the most satisfactory image is obtained. A lens constructed with ordinary care will not show any astigmatism for a point on the optical axis of the lens, but only for points off the axis.

2.4.11 Minimizing Aberrations

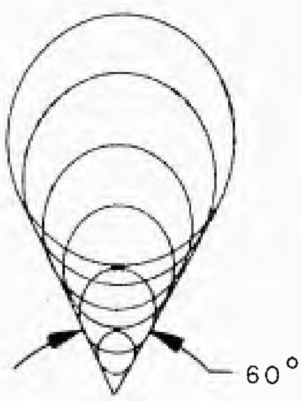
These aberrations and others (such as curvature of field and distortions) cannot all be eliminated from a single lens. Compound lenses, by balancing one aberration against another, can eliminate or reduce aberration effects. Combination reflective - refractive systems are also effective. However, the more elements an optical system has, the greater the cost; also, refractive elements cause some radiation loss through absorption and reflection. The infrared designer must juggle his optical materials and components to come up with the best system for the least cost.

Table III lists the various aberrations and their variations with image height, h, and aperture size, y. (Ref. 18).

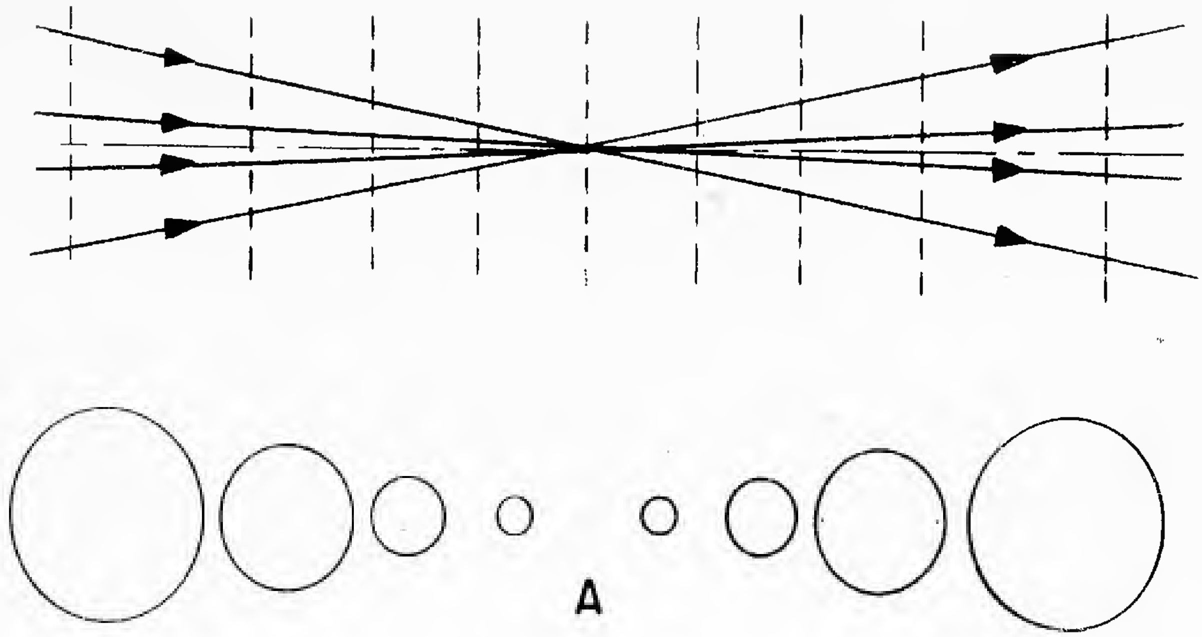


a. Focus of off-axis object

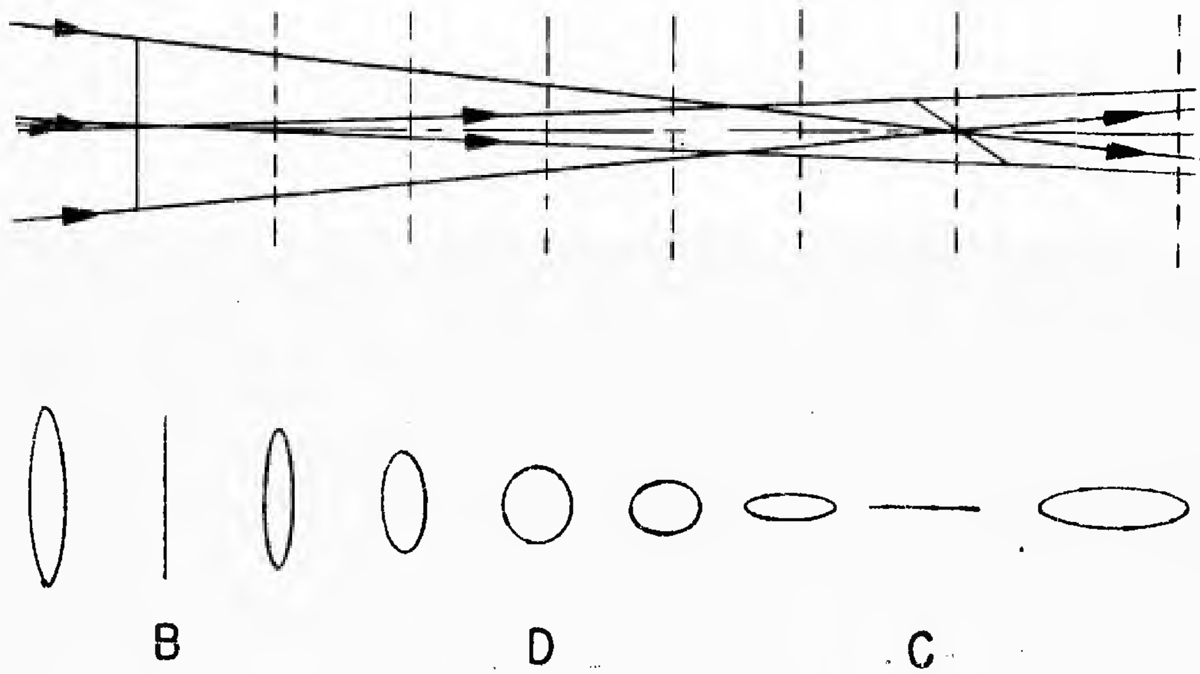
Figure 13 - Comatic Aberrations



b. Comatic image formed by cone of rays through each zone of the lens.



A - Image of a point - no astigmatism present



B - Cross-section of rays forming astigmatic image of a point.

Figure 14 - Astigmatism

TABLE III

Effect on Aberrations with Changes in Image Height and/or Aperture *

	Variation with Image Height, h	Variation with Aperture, y
Spherical Aberration	Independent	y^2
Coma	h	y^2
Astigmatism (difference in focus)	h^2	Independent
Length of Astigmatic Focal Lines)	h^2	y
Petzval Curvature	h^2	Independent
Distortion	h^3	Independent
Longitudinal Chromatic Aberration	Independent	Independent
Lateral Chromatic Aberration	h	Independent

*Ref. 18, P. 46

2.5 Optical Materials

2.5.1 Infrared Use

Optical materials are used in infrared instruments of two rather distinct types, and different specifications are imposed upon the materials by the two types of usage. The first is laboratory use of optical materials, chiefly as spectrometer prisms and as windows for spectrophotometer absorption cells. The second is the so-called "field use"; military instruments lie chiefly in this category. The specifications imposed upon optical elements for field use are obviously much more severe than for laboratory use. Only field use will be discussed since the scientific literature contains information relating to materials for laboratory use.

2.5.2 Outside Uses

From the practical point of view, one can differentiate between "inside" and "outside" uses. Outside use refers to the employment of an optical material to seal a system, such as an entrance window. Such a sealing window may be flat, as in some scanning equipments or in radiometer devices of the type made by Barnes Engineering Company and Servo Corporation of America. In missile guidance devices and the like, the window is curved, ordinarily hemispherical, and then it is often called an "irdome". Windows used in outside applications must possess suitable elastic, thermal, and chemical properties as well as adequate hardness, abrasion resistance, etc. Their melting points must be appropriately high; their thermal conductivities and thermal expansions should be optimal for the design use; they should not be water soluble to any extent, etc. Equipments used by the ground forces are more likely to encounter rain and sand erosion, whereas irdomes on guided missiles must have high melting points because of the high temperatures resulting from the supersonic speeds at which they travel. Adequate resistance to mechanical and thermal shock is also important. Other practical considerations are the maximum size, which is a real limiting factor for certain materials; cost of grinding and polishing finished components; and reproducibility. Satisfactory sealing windows, either flat or curved, can be of plastic that is supported by a wire mesh or spider backing to give adequate strength. Segmented windows can sometimes be employed, relaxing the slab-size requirement on the crystalline or glass material.

2.5.3 Re-emission

Whenever an optical element is at a temperature different from that of the detector, the problem of re-emission must be considered. This is illustrated in Figure 15, which represents an approximation to the behavior of many good optical materials. If the material is perfectly transparent (as indicated by the region marked "T") throughout the detector's wavelength range of sensitivity, then there will be no net interchange of radiant energy between the two components, for the only losses are those of reflection, marked "R". If, however, the material has an absorption region, as indicated by the area marked R + (1-T), then its emissivity in this interval is not zero and it will emit radiant energy. Some of the radiant energy may reach the detector and cause a false signal, an increase in noise, or (in extreme cases) a saturation of the detector. The pure single crystals have very nearly perfect internal transmittance, except near their cut-off wavelengths. Thus, re-emission should not be a problem as long as the window's high-transmission region extends beyond the spectral response region of the detector. Most glasses, however, exhibit absorption in the water band, 2.7 to 2.9μ, where re-emission is expected.

2.5.4 Inside Uses

Optical elements used inside an equipment are not subjected to as rigorous environmental factors as some of those just indicated. However, the location of the melting or softening point is important, as are such practical properties as thermal expansion, vibration resistance, and resistance to cold flow. One inside use of an optical element of the refractive type is as a corrector plate, necessary to reduce the spherical aberration and coma of a purely-reflecting optical system such as the popular Cassegrain type of telescope. A material of good optical quality is necessary; often it must be available in rather large pieces because the plate may determine the entrance pupil; it must be readily ground and polished to an optical surface which may not be plane or spherical but a more complicated figure. Sometimes the corrector plate serves as the outside window, then the above noted specification for atmospheric effects applies.

2.5.5 Prism Material Considerations

A prism system consisting of two or more wedges, which may be stationary or rotating, may be employed in a scanner. The purpose of these prisms is to deviate or redirect the radiation path to provide a scanning motion giving deviation without dispersion. A high index of refraction material may be selected for this application, since it keeps

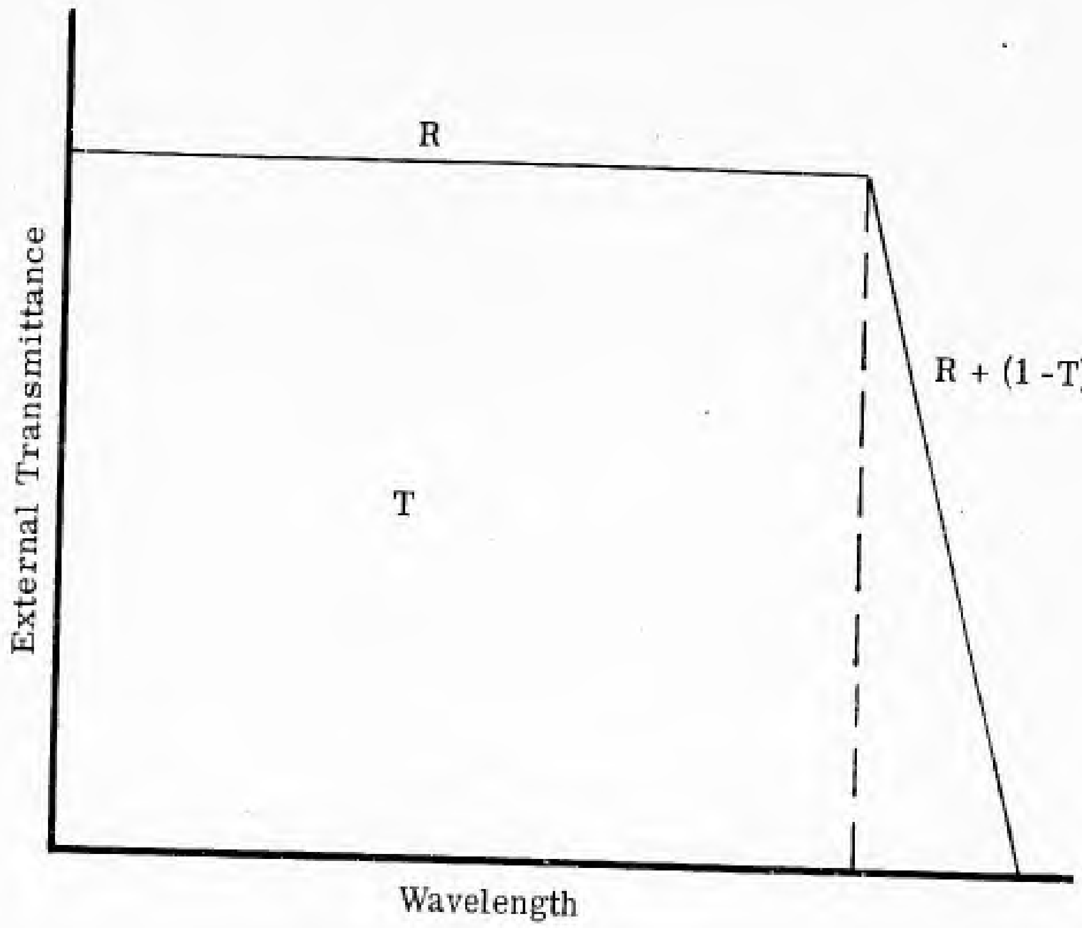


Figure 15 - Transmission and absorption of window material, illustrated schematically (Ref. 19)

the wedge angle small and hence the size and weight of the prisms at a minimum of particular importance for rotating parts; and it also keeps the absorption losses in the wedge low.

2.5.6 Lens Material Considerations

Lenses have not been used very widely in infrared instruments as radiation collectors because of the emphasis on reflecting optics; the reflecting systems have the advantage of freedom from chromatic aberration. Field lenses, though , are often used behind a reticle to image an entrance pupil on the sensitive surface of the detector. High-index materials like germanium are used in this application because a thin lens is needed and a very compact system can be made.

2.5.7 "Immersion Optics" Properties

The use of optical materials in so-called immersion optics for detectors is a particularly attractive application in the latest instrument designs. For several reasons it is often necessary to use the smallest detector possible in a system. A simple means of obtaining this goal is the use of immersion techniques that are similar to the design of immersion microscope objectives. By depositing or attaching the detector onto a flat surface which is the base of a hemisphere or hyper-hemisphere of a material having a high refractive index, the incident radiation is concentrated on a cell of very small area. Figure 16. The linear demagnification can be determined from the equations for a single refracting surface, and is proportional to the index of refraction. The area reduction is related to the square of the index. Lead sulfide detectors have been deposited directly on the flat surface of immersion lenses made of titanium dioxide or strontium titanate. Immersion optics have been recently used with bolometers using germanium as the lens material; mosaics have been made of many very small thermistors each immersed in its own immersion lens.

The properties desirable in an immersion lens are required transmission region, low electrical conductivity, high dielectric strength, and relatively high refractive index so that the optical gain is reasonably large. It is necessary that the lens material match the detector in thermal expansion so that the interface remains stable. It is also possible to use the immersion lens as a heat sink for thermal detectors; in this case high specific heat and high thermal conductivity are desirable. Since the refractive index is large, an anti-reflection coating is a critical part of the design. Particular care must be taken to insure that even off-axis oblique rays are properly handled by this coating, and that these rays are not internally reflected at the detector-lens surface.

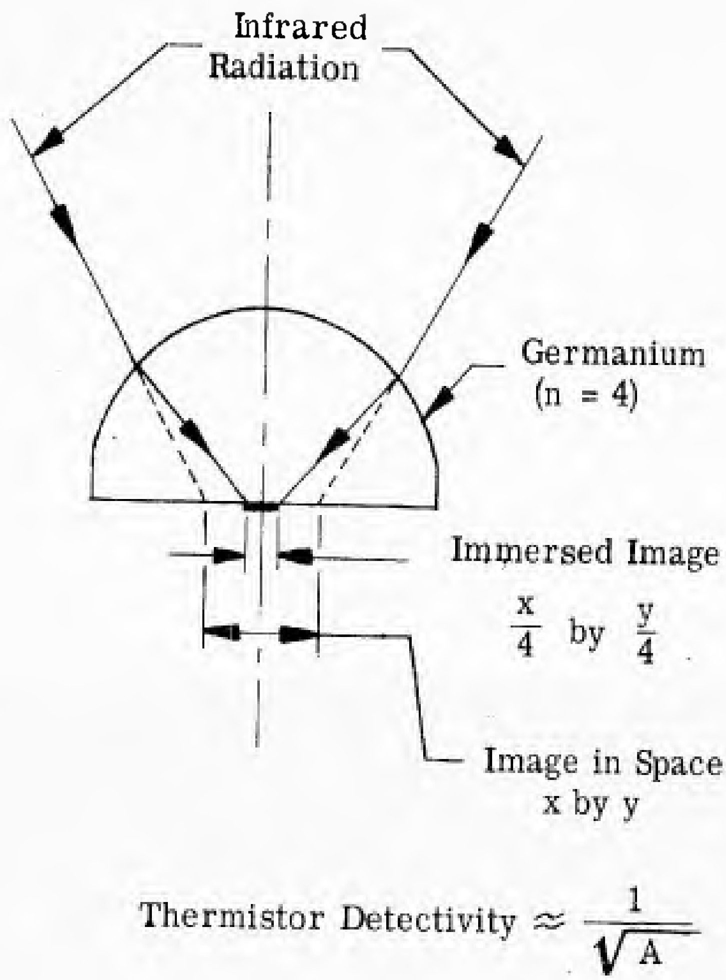


Figure 16 - Image Reduction by Immersion Optics (Ref. 25)

2.5.8 Filter Material Considerations

Optical materials are also used as filters of the cut-off or cut-on types. Because of the sharp cut-on of germanium at 1.8μ, germanium optical elements may not only serve as focussing optics but also perform the function of a cut-on filter, eliminating the shorter wavelengths where solar radiation is large. If there are ordinary glass elements in the optical system, then there is a long wavelength cut-off at about 2.8μ or less which may be useful in eliminating much of the atmospheric radiation at the longer wavelengths. Some of the single crystals have been used as cut-off filters, since they drop in transmission sharply at their long-wavelength transmission limits. However, the more common use is as cut-on filters, known as long wavelength pass filters, which are especially useful in reducing reflected and scattered sunlight effects.

2.5.9 Reflection-loss Considerations

An undesirable result of high refractive index is the large reflection loss. For ordinary glass, of refractive index 1.5, the reflection loss is about 4%. Thus the external transmittance of a glass plate is about 92% because of reflection losses at the two surfaces, neglecting any absorption loss within the glass. The reflection loss per surface for a material of refractive index 4, such as germanium, is 36%. Therefore, a simple germanium lens or filter will have a total reflection loss for the two surfaces of more than 50%, which means that over half the energy is reflected out of the beam and unavailable. A partial solution is the use of reflection-reducing coatings. But the correction is valid only for a single wavelength and the reduction is efficient over only a small wavelength band, perhaps not over the entire region of interest. Even multilayer films are not altogether satisfactory.

2.5.10 Material Development

The early workers in IR had only a few natural crystals such as quartz, fluorite, and rock salt that they could use. Developments made in growing single crystals, particularly during the World War II years, resulted in the commercial availability of a number of new materials such as silver chloride, synthetic lithium fluoride and calcium fluoride, and also some new synthetic mixed crystals of which KRS-5 is a good example. Large single crystals of synthetic sapphire, spinel, and rutile were grown. Research in solid-state physics developed highly pure and rather large pieces of germanium, silicon and other semiconductors which also have considerable use as optical materials. There has recently been a rapid growth in the availability of intermetallic single crystals of the so-called three-five and two-six types making them contenders for optical instrumentation application.

2.5.11 Glasses and Plastics

New glasses have been developed during the last few years. Arsenic trisulfide is an outstanding example. Calcium aluminate is a new glass that extends into the intermediate IR region. Plastics are not as generally used as are glasses and crystals; however, those that transmit in wavelengths of military interest are sure to be valuable.

2.5.12 Spectral Transmission Regions

Perhaps the most important single property of an optical material is its transmission range. These ranges are presented in Figure 17 in order of increasing long wavelength limit. The transmission limits are chosen on the basis of 10% external transmittance for a sample 2 mm thick. The limit cannot be defined rigorously for some materials, especially semiconductors, since, for them, the state of purity and, in some cases, crystal orientation, should also be specified. The limits indicated can be used as a general guide, however.

2.5.13 Long Wavelength or Thermal Region

The region from 8 to 13μ is the most critical as far as satisfactory optical materials are concerned. Windows can be fabricated of rock salt (NaCl), potassium bromide (KBr), and others, but these "conventional" materials are generally water soluble. Silver chloride (AgCl) can withstand moisture and even solarization if pure enough and properly coated for protection, but its homogeneity leaves something to be desired, and it is rather soft and corrosive. KRS-5 has a melting temperature of 415^{o}C, exhibits cold flow, is sometimes inhomogeneous, is toxic, is expensive and has high specific gravity so that optical elements of this material are relatively heavy. Arsenic trisulfide glass, which is often used as a window, cuts off at about 12μ and softens at 195^{o}C, a temperature that is too low for many applications. Crystalline germanium and silicon can be used, except that they are limited in size. Germanium's transmission drops rapidly with increasing temperature starting at about 125^{o}C; silicon can be used up to 300^{o}C. (Silicon irdomes up to 6 inches have been reported.)

Some of these materials are useful as corrector plates, lenses, and prisms in optical systems, but are not really as satifactory as they might be because of the limitations that have been indicated.

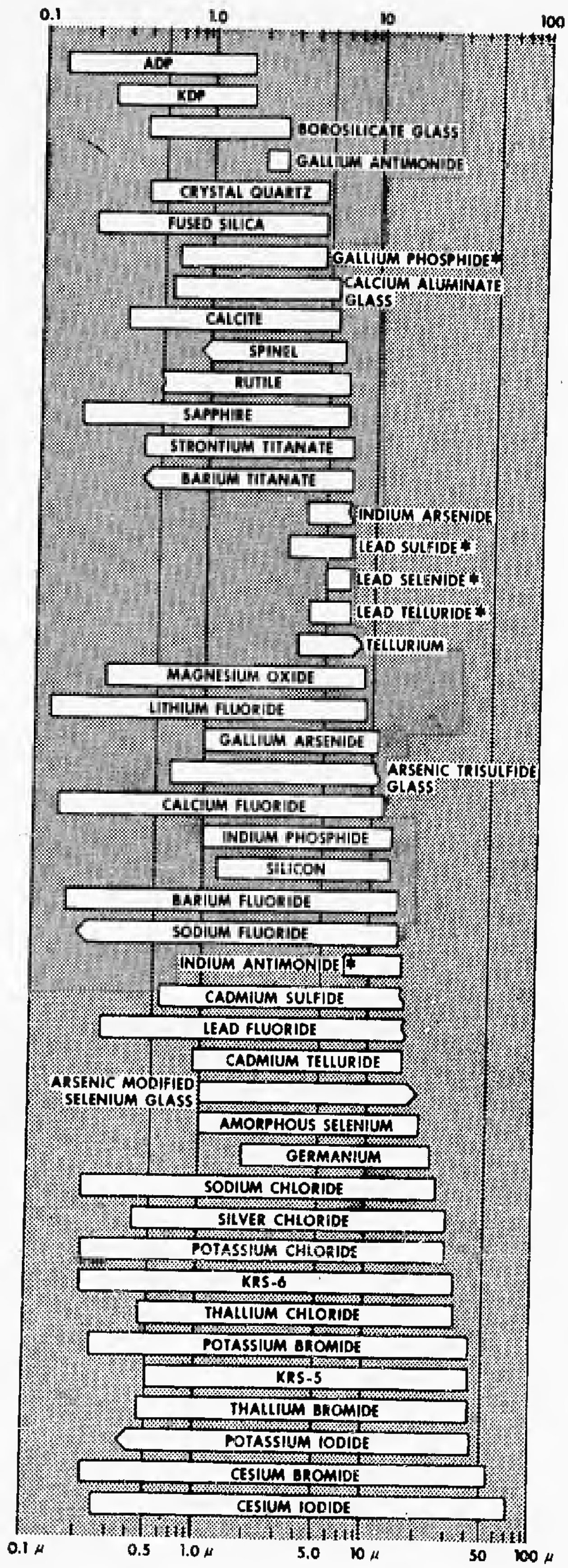


Figure 17 Transmission regions. The limiting wavelengths, for both long and short cut-off, have been chosen as those wavelengths at which a sample 2mm thick has 10% transmission. Materials marked with an asterisk (*) have a maximum external transmittance less than 10%.

Immersion lenses have been made from germanium and selenium. This is probably the least restricted of the thermal region applications because of the less strigent mechanical thermal requirements, although many problems remain.

2.5.14 The Intermediate Region

In this region, 3 to 8μ, the situation is better. In addition to the above mentioned materials, calcium-aluminate glass, sapphire, periclase, and plastics such as Kel-F can be used for irdomes. Calcium aluminate shows absorption at 2.8μ with the subsequent re-emission problem already discussed. Sapphire is available in sizes sufficiently large for most applications, but is expensive. Flat plates and segmented domes of arsenic trisulfide glass, Kel-F, etc. have also been used.

Optical elements can be constructed from germanium, silicon, rutile, sapphire, arsenic trisulfide and arsenic modified selenium glass. Silicon and germanium have not only high refractive indexes, but also low dispersions. Thus they can be used as lens and prism materials that possess high power and little chromatic aberration.

Selenium, germanium, and strontium titinate have been used for immersion lenses. Other materials are available; they should be chosen to best match the physical properties of the detector.

The use of a filter is more important in this region than in the thermal region, and there are more possibilities. Not only are there better interference filters available, but a broad range of semiconductor cut-on wavelengths lie here, and a desired cut-on can be manufactured by a proper mixture of materials.

2.5.15 Near Region

Extending from visible to 2.7μ this region is the most satisfactory from the optical materials standpoint. All the materials mentioned above are available; in addition fused silica and optical glasses can be used. Refractory type windows or domes can be made, lens systems can replace reflective or catadioptric (combination reflective-refractive) systems and virtually any desired spectral band can be isolated by an interference filter.

2.5.16 State-of-the Art Report

A detailed analysis of the performance of materials can be found in a state-of-the art report of the Infrared Information and Analysis (IRIA) group of the University of Michigan (Ref. 19). This report gives physical properties of approximately fifty different materials useful for infrared instrumentation. Table IV lists some of the materials used in infrared optical systems and a short summary of their properties.

2.6 Optical Components

2.6.1 Mirror and Lens Systems

Based on the optical considerations and the optical materials available as described in previous sections, an optical system is arrived at. This system may have mirrors, lenses, prisms, filters in many combinations. Some of these are shown in the following chart, Figure 18.

Note that mirrors have an advantage over lenses in that they can be used to create an overall shorter system at the same time acting as radiation collectors and providing some aberration corrections. Since a good imaging system requires the most aberration correction, reflective-refractive systems such as the Schmidt-Cassegrain or Maksutov-Bouwers are usually used. This choice, of course, depends upon the spectral region of interest as this affects the choice of material for the corrector plates.

2.6.2 Prisms

Prisms are used in infrared radiometers or spectrometers where the dispersive effects are necessary. Total reflection prisms, useful in visible light optical systems as a means of changing the direction of the light, are seldom used in infrared imaging systems since the absorption by the thicknesses required would offset any gain in reflection efficiency.

2.6.3 Filters

Filters are used to isolate a particular part of the spectrum. This is done in several ways. A band-pass filter transmits radiation over a narror band of wavelengths; the higher and lower wavelengths are blocked. A long-wave pass filter transmits wavelengths longer than a given wavelength, while a short-wave pass filter transmits wavelengths shorter than a given one.

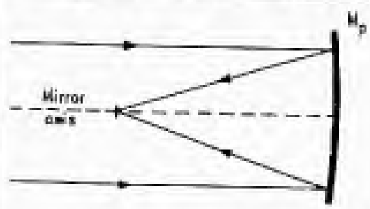
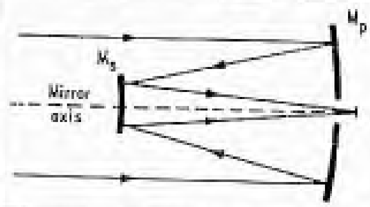
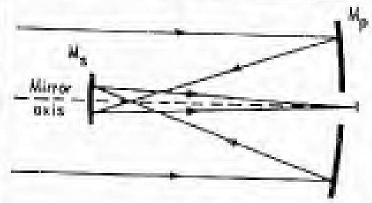
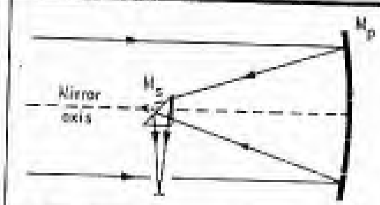
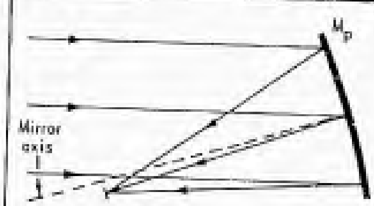
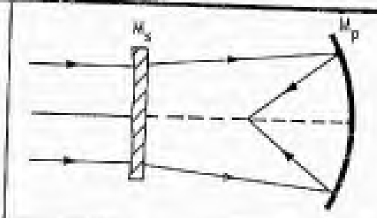
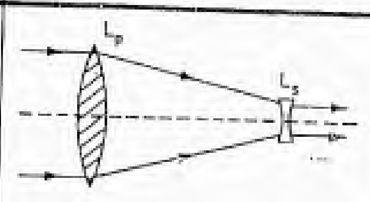
TABLE IV - Properties of Ir

Material	Spectral Range (microns)	Index of Refraction	Per Cent Trans-mission	Thickness (mm)	Maximum Size (Inches)	Cold W Solub (gms/
Glass	0.2 3.0	1.9 1.5	90	1	Unlimited	0.0
Fused Quartz SiO_2	0.2 4.0	1.48 1.41	90	1	6	0.0
Calcium Aluminate CaAl	0.4 5.0	1.63	--	--	--	Ver Slig
Sapphire Al_3O_3	0.17 5.8	1.83 1.59	88	1	6	0.0
Kel-F (Plastic)	0.3 6	1.43	80	0.15	18	0.0
Magnesium Oxide MgO	0.25 8.0	1.77 1.62	85	5.4	2	0.00
Arsenic Trisulfide As_2S_3	0.57 11.86	2.66 2.37	70	2	Over 18	0.00
Silicon Si	1.2 15.0	3.5 3.42	55 (38°C)	2.5	6	0.00
Germanium Ge	1.8 20.0	4.1 4.0	45	1.15	6	0.00
Silver Chloride AgCl	0.4 23.0	2.1 1.9	80	5	4" dia. Thin rolled sheets of large area	0.00

.E IV - Properties of Infrared Optical Materials

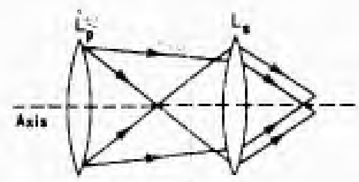
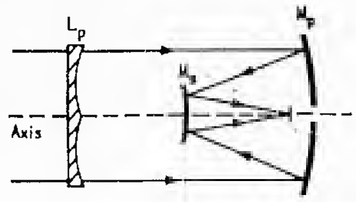
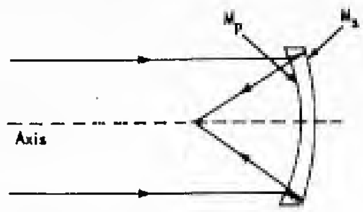
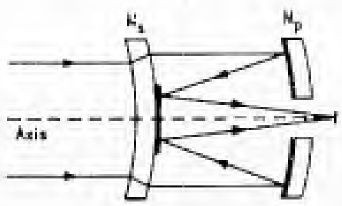
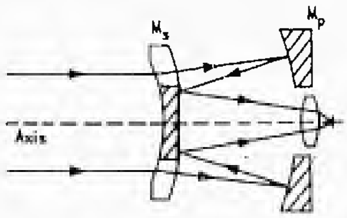
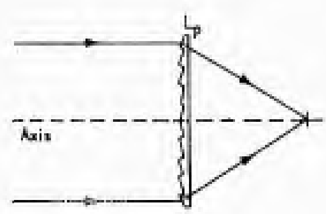
kness (m)	Maximum Size (Inches)	Cold Water Solubility (gms/100ml	Soluble In	Relative Cost	Pertinent Design Properties
1	Unlimited	0.000	HF	Low	Homogeneous. Colorless. Easily cut, ground, polished, non-toxic
	6	0.000	HF	Moderate	Good mechanical and thermal properties. Isotropic. Colorless
-	--	Very Slight	--	High	Glass. Under development. Some times crystal clear, other times brown or yellow. Water causes slight marking of polished surfaces
	6	0.000	Slightly - Acids and Alkalis	High	Hexagonal crystal. No cleavage. Does not scratch easily. Excellent mechanical and thermal properties.
15	18	0.000	---	Low	White opaque - may be transparent or translucent. Good mechanical, thermal and chemical properties. Non-toxic
4	2	0.000	Ammonia	Moderate	Colorless cubic crystal. Cleaves. Good chemical resistance. MP-2800°C.
	Over 18	0.000	Alkali	Moderate	Homogeneous red glass. Non-toxic. Non-corrosive. Thermal shock resistant. Softening temperature is 195°C. Stable
	6	0.000	Mixture HF & HNO_3	High	Steel gray, cubic crystal. MP is 1420°C. Transmission decreases over 300°C. Good mechanical and thermal properties.
5	6	0.000	Hot H_2SO_4 Aqua Regia	High	Steel gray, cubic crystal - MP is 940°C. Transmission decreases over 100°C. Hard and brittle at room temperature.
-	4" dia. Thin rolled sheets of large area	0.000	NH_4OH $Na_2S_2O_3$ KCN	High	Colorless cubic crystal. Isotropic. No cleavage. Darkens in sunlight with reduced transmission. Soft and malleable. Corrosive to metals.

FIG. 18 (a)
INFRARED OPTICAL SYSTEMS

TYPE	RAY DIAGRAM	OPTICAL ELEMENTS	PERTINENT DESIGN CHARACTERISTICS
PARABOLOID		Reflective M_p = Paraboloidal mirror	1. Free from spherical aberration. 2. Suffers from off-axis coma. 3. Available in small and large diameters and f/numbers. 4. Low IR loss (Reflective). 5. Detector must be located in front of optics.
CASSEGRAIN		Reflective M_p = Paraboloidal mirror M_s = Hyperboloidal mirror	1. Free from spherical aberration 2. Shorter than Gregorian. 3. Permits location of detector behind optical system. 4. Quite extensively used.
GREGORIAN		Reflective M_p = Paraboloidal mirror M_s = Ellipsoidal mirror	1. Free from spherical aberration 2. Longer than cassegrain. 3. Permits location of detector behind optical system. 4. Gregorian less common than cassegrain.
NEWTONIAN		Reflective M_p = Paraboloidal mirror M_s = Reflecting prism or plane mirror	1. Suffers from off-axis coma. 2. Central obstruction by prism or mirror.
HERSCHELIAN		Reflective M_p = Paraboloidal mirror inclined axis	1. Not widely used now. 2. No central obstruction by auxilary lens. 3. Simple construction. 4. Suffers from some coma.
SCHMIDT		Reflective-refractive M_p = Spherical mirror. M_s = Refractive corrector plate	1. Produces a curved field. 2. Free of spherical aberration and coma. 3. Central obstruction by its own field surface. 4. Can obtain low f/number. 5. Sharper focus over larger area than paraboloid. 6. May be built as solid unit.
GALILEAN		Refractive L_p = Biconvex lens L_s = Biconcave lens	1. Radiation gathering power less than reflection systems. 2. Relatively short length. 3. Limited field of view. 4. Spectral response limited by lens material.

ERTINENT DESIGN CHARACTERISTICS
Free from spherical aberration. Suffers from off-axis coma. Available in small and large diameters and f/numbers. Low IR loss (Reflective). Detector must be located in front of optics.
Free from spherical aberration Shorter than Gregorian. Permits location of detector behind optical system. Quite extensively used.
Free from spherical aberration Longer than cassegrain. Permits location of detector behind optical system. Gregorian less common than cassegrain.
Suffers from off-axis coma. Central obstruction by prism or mirror.
Not widely used now. No central obstruction by auxilary lens. Simple construction. Suffers from some coma.
Produces a curved field. Free of spherical aberration and coma. Central obstruction by its own field surface. Can obtain low f/number. Sharper focus over larger area than paraboloid. May be built as solid unit.
. Radiation gathering power less than reflection systems. . Relatively short length. . Limited field of view. . Spectral response limited by lens material.

FIG. 18(b)
INFRARED OPTICAL SYSTEMS

TYPE	RAY DIAGRAM	OPTICAL ELEMENTS	PERTINENT DESIGN CHARACTERISTICS
KEPLERIAN		Refractive L_s = Biconvex lens L_p = Biconvex lens	1. Radiation gathering power less than reflection systems. 2. Spectral response limited by lens material. 3. Not widely used now.
SCHMIDT – CASSEGRAIN OR BAKER		Reflective–refractive M_p = Aspheric mirror M_s = Aspheric mirror L_p = Refractive corrector plate	1. Produces flat field. 2. Very short in length. 3. Covers large field. 4. Corrector plate has larger curvature than Schmidt.
MANGIN MIRROR		Refractive–reflective M_p = Spherical refractor M_s = Spherical reflector	1. Suitable for IR source systems. 2. Free of spherical aberration and coma. 3. Most suitable for small apertures. 4. Covers small angular field. 5. Uses spherical surfaces.
MAKSUTOV		Refractive–reflective M_p = Meniscus reflector M_s = Meniscus refractor–reflector	1. Free of spherical aberration, coma, and chromatism. 2. Very compact. 3. Large relative aperture. 4. May also use combinations of spherical and aspheric elements.
GABOR		Refractive–reflective M_p = Spherical reflector M_s = Spherical refractor–plano reflector	1. High aperture system. 2. Has mean correction of spherical aberration and coma. 3. Suitable for IR source systems.
FRESNEL LENS		Refractive L_p = Special fresnel lens	1. Free of spherical aberration. 2. Inherently lighter weight. 3. Small axial space. 4. Small thickness reduces infrared absorption. 5. Difficult to produce with present infrared transmitting materials.

Filters depend on one or more of the following phenomena: selective absorption, selective refraction, selective reflection, interference and polarization. Selective absorption depends on the spectral response of the material. Selective refraction takes advantage of the chromatic aberration effects by placing the detector at the focal point of the optics for the desired wavelength. Selective reflection is dependent on a variation of reflection coefficient with wavelength. This is particularly useful in far infrared regions.

Interference filters are of the reflection type or transmission type. These filters are usually of the narrow band-pass type and, as such, are not usually used in infrared imaging systems. For more information see Reference 20.

2.6.4 Diffraction Gratings

Diffraction gratings are used in laboratory instruments such as spectrophotometers for analysis of radiation. Effectively a diffraction grating is a large number of parallel narrow slits, as many as 5 or 10 thousand per inch. Radiation waves from these slits interfere with one another either on transmission or reflection. These interference effects cause a dispersion of the various wavelengths somewhat similar to a prism. The number of lines determines the precision whereby the various wavelengths may be separated. Thus, the diffraction grating is much more precise for radiation analysis. Further discussion is not warranted for the purposes of this report, and the reader is referred to optical texts for more detail.

3. INFRARED DETECTORS

3.1 Considerations and Characteristics

In order to detect infrared radiation, it must be absorbed and its energy converted into some measurable quantity. The output of the optical system is, thus, focussed on a material which is a good absorber of IR, and a good energy converter. These are the two basic qualitative characteristics of a good detector. To describe and compare detectors more completely they are broken down into the following quantitative characteristics:

a. Responsivity
b. Noise Equivalent Power (NEP) and Detectivity (D*)
c. Time constant
d. Spectral response

3.1.1 Responsivity

Responsivity describes the signal response. Units are usually signal volts per watt of radiation incident on the detector.

$$R(f) = \frac{V_S(f)}{W(f)}$$

$V_S(f)$ is the rms signal voltage at the modulation frequency f, and W (f) is the rms radiation power of modulation frequency f incident on the detector. R (f) will generally be a function of the time constant and other physical parameters of the detector. (Henceforth, in this report, frequency will refer to the modulation or "chopping" frequency which permits designers to use standard ac electronic circuitry.)

3.1.2 Noise Equivalent Power (NEP) and Detectivity (D*)

The NEP is a measure of the signal energy level that describes the capability of the detector. It is defined as the radiation power needed to produce a signal to noise ratio of one, or the radiation power needed to produce a signal equal to the noise level of the detector. A smaller NEP denotes a more sensitive detector. Another way to describe the detection ability of a detector is to specify its detectivity or D* (called D-star).

$$D^* = \sqrt{\frac{A}{1 cm^2}} \times \frac{1}{NEP}$$

where A = cell area in cm^2

This has the psychological asset of indicating improved performance with an increasing numerical figure. It has been recommended for use by the organizations concerned with measuring detector characteristics such as Naval Ordnance Lab. at Corona, California. The term "noise" in noise-equivalent power is made up of several types as follows:

1. Johnson noise
2. Thermal noise
3. Current noise
4. Shot noise
5. Recombination - generation noise

3.1.3 Johnson Noise (Also called Nyquist Noise)

An ohmic resistance can be pictured as a material which contains a number of free charge carriers which move about in a crystalline lattice bumping into one another and into the atoms which make up the lattice. Their motion is random with energies that depend on temperature. If a sufficiently sensitive voltmeter were placed across a resistor (or semi-conductor) it would indicate fluctuating voltages. These fluctuations represent a noise whose behavior is determined purely from thermodynamic considerations and not from the nature of the charge carriers. Johnson noise is independent of frequency for the frequency ranges normally used.

3.1.4 Thermal Noise

There is a continual interchange of radiant energy between bodies. Since they all emit radiation that is characteristic of their emissivity and temperature, this radiation can be described in terms of photons which emerge from or are incident on surfaces in a statistical manner, analogous to rain drops falling on a roof. There are statistical fluctuations in the density of photons emerging from the surroundings and falling on the detecting surface, which, on absorption, cause corresponding fluctuations in its temperature. Thermal noise is independent of frequency over the frequency ranges normally used.

3.1.5 Shot Noise

This noise is usually associated with vacuum tubes and it is described as the electrical noise that appears in the output of a tube when the grid, if any, is held at a fixed potential and the emission is temperature limited. Because of the discreteness of the electronic charge, the number of electrons emitted will fluctuate around an average value causing a fluctuating current. Semi-conductor photovoltaic detectors, also exhibit shot-type noise. In the vacuum tube case, the electrons are considered as independent and the current will consist of a series of short pulses, each pulse corresponding to the passage of an electron from cathode to anode. A similar situation prevails in the case of a semiconductor. Electrons or holes going from N type material to P type or vice versa result in current pulses appearing across the diode with the same characteristics that are observed for vacuum tubes. Shot noise also is independent of the chopping frequencies normally used.

3.1.6 Current Noise

Current noise if the voltage fluctuation that appears across the terminals of a resistor in addition to Johnson noise, when a steady current passes through the resistor. This type of noise is a low frequency phenomenon, being dependent on the reciprocal of the chopping frequency (1/f). The basic mechanisms are not well understood, but it usually appears as a noise from semiconductors and resistors made from compressed powders or deposited films; wire wound resistors do not exhibit this phenomenon.

3.1.7 Recombination - Generation Noise

This noise is associated with semiconducting photodetectors. Part of the source of this noise is the same as for thermal noise. Background radiation photons impinge on the detector in a statistical manner causing fluctuations in photo response. In the case of thermal detectors, this radiation caused a change in temperature on absorption. With photodetectors, the temperature remains unchanged, but charge carriers are liberated in fluctuating amounts causing corresponding changes in the photoeffect utilized.

In addition to this noise source, there are fluctuations induced by "phonon" interaction. In a crystal structure, all atoms in a lattice vibrate in a well organized manner to the extent that their vibrations are quantized, and can be described in particular terminology as "phonons" with energy equal to $\hbar\omega$ ($\omega = 2\pi\nu$, $\hbar = h/2\pi$, h = Planck's constant, ν = vibration frequency).

Electrons can be excited by the conduction band through "phonon" collisions. This thermal process is statistical in nature and the rate at which electrons are excited to the conduction band fluctuates.

3.1.8 Time Constant

It would be convenient to be able to give a single figure to denote the speed of response of a detector. However, the time constant cannot be rigorously described in the same manner as for an RC network, as the rise and decay times are not always simple exponentials. Experimental work, which gives evidence of the existence of two exponentials, might make it possible to describe the detectors by two time constants, a long time constant and a short one. Some detectors have more than two time constants. The Naval Ordnance Laboratory (NOL) at Corona, California has arbitrarily defined the time constant as the time required for a signal to decay from maximum amplitude to 37% of maximum. As it is the responsibility of NOL to measure and record properties of photoconductive detectors, and, since a great percentage of the section on photoconductive detectors is taken from NOL reports, this report will use the same definition.

The frequency response and time constant are roughtly related by the expression $\tau = 1/2\pi f$ where τ is the time constant in seconds and f is the modulation frequency in cps at the point where the response is 3 db down from maximum amplitude.

3.1.9 Spectral Response

This characteristic determines the spectral sensitivity of the detector. Thermal detectors, because of the means of energy conversion, do not have a characteristic response spectrum. As such they can operate far out in the long wavelength regions.

Photodetectors are limited by their characteristic spectrums. The photo-emissive detectors have limits to their spectrum determined by the work function of the medium. They are limited to detection of radiation whose quanta have an energy, $h\nu$, greater than the work function of the detector material. Since this is of the order of 1 electron-volt (ev) or higher, these detectors are limited to use in the near-infrared where photon energies are greater than 1 ev.

Photoconductors and other photo-detectors are limited by the absorption edge since a detector cannot be sensitive to energy it cannot absorb. The limit of spectral sensitivity is defined by NOL as the wavelength at which the sensitivity is one half the maximum sensitivity.

3.1.10 Detection Mechanisms - Comparisons

The mechanisms by which a material detects radiation depend upon how it reacts to the photons. Thermal detectors such as thermocouples, bolometers and gas-type detectors share the energy of a quantum of radiation amongst all the atoms and molecules making up the cell. This results in a rise in temperature which is converted into an electrical signal. A photoconductive detector uses the energy of the photon to change its resistance independently of temperature effects, and this resistance change can be converted into an electrical signal.

The means by which these energy conversions are accomplished are varied, and are brought out in the following sections.

3.2 Thermocouples

The thermocouple depends upon the discovery of Seebeck in 1826, that heating one junction of two dissimilar metals with respect to the other junction causes an electro-motive force (emf) to be generated. The direction and magnitude of the emf depends upon the properties of the junction materials and upon the temperature gradient. The emf can be expressed as $E = P12 \, \Delta T$ where P_{12} is the thermoelectric power, and is characteristic of the two materials.

If the circuit is closed a current will flow, and the above expression is no longer correct. This is a result of the Peltier effect which causes a cooling of the heated junction when current flows across it in the direction of the thermoelectric emf.

In practice, lead is used as a reference metal for determining the thermoelectric power P of a material. Then the behavior of one thermoelectric material with respect to another is determined simply by taking the difference of their constants with respect to lead. A combination is chosen so that P is as large as possible. The sensitive junction has a receiver of small mass compared to surface area attached to it. The surface is blackened to have as high an absorption coefficient as possible. The reference junction is held at constant temperature, usually in an ice-water bath.

3.2.1 Thermocouple Characteristics

A good thermocouple has a low thermal capacity, a high thermal resistance, but a low electrical resistance. As a general rule, though materials with low electrical resistance have a low thermo-electric power. Also, according to the Wiedemann-Franz law there is a relationship such that the ratio of thermal conductivity K and electrical conductivity σ at a given temperature is $K/\sigma T = L$, where L is known as the Lorentz number. It has a very nearly constant value for most materials, especially metals. This constant is

$$L_0 = 2.45 \times 10^{-8} \quad \text{volt}^2/{}^{\circ}\text{C}^2$$

A high value of L/L_0 indicates a disproportionately high electrical resistance. L/L_0 is used as a figure of merit by many people, although others prefer some ratio of P to L as a better figure since high values of P are generally associated with high values of L/L_0.

Table V, based on work done by Hornig and O'Keefe, (Ref. 21) shows the thermo-electric power, thermal and electrical conductivities, and L/L_0 for various thermoelectric materials. Table VI lists the characteristics of several thermocouples made by Hornig and O'Keefe which can be taken as representative of bi-metallic couples.

Thermocouples have been made using semi-conducting materials by E. Schwarz in England. Table VII lists the characteristics of some vacuum thermocouples and an air thermocouple.

These thermocouples are available commercially; they are at present the most effective and widely used thermal detectors for spectroscopic and other purposes where very wide spectral response is required and short time constant is not a factor.

Responsivity of modern thermocouples have an order of magnitude between 2 and 8 microvolts per microwatt. The ultimate sensitivity or NEP is determined by Johnson noise and is of the order of 3 to 5 x 10^{-11} watts for a 1 cps bandwidth. The effective time constant is a function of the dynamic resistance of the thermocouple shunted by a capacitance. These are, in turn, functions of the chopping frequency so that the time constant becomes dependent on the frequency and is, in effect, a measure of the frequency response. The measured values have orders of magnitude between 0.1 second and 0.01 second.

For image display systems - the characteristics of the thermocouple are not in a class with other detectors as far as responsivity and time constant are concerned. The cost is relatively high and the ruggedness for military field use is somewhat less than adequate.

TABLE V - Comparison of Various Thermo-Electric Materials

Material	Thermo Electric Power P ($\mu v/{}^oC$)	Thermal Conductivity K ($watt/m/{}^oC$)	Electrical Conductivity (mho/m)	$-\frac{L}{L_o}$	$\frac{P^2}{L} \times 10^{-4}$
Silver	+2.9	424	6.1×10^7	0.95	3.6
Iron	+16	67	1.0×10^7	0.92	114
Nickel	-19	59	1.3×10^7	0.63	234
Antimony	+40	20	2.4×10^6	1.1	593
Bismuth	-60	8.3	8.3×10^5	1.35	1090
Tellurium					
(a) (single crystal)	+436	1.8	2.9×10^3	85	914
(b) (poly-crystalline)	+376	1.5	3.3×10^3	62	935
(c) (poly-crystalline)	+372	1.0	5.0×10^2	270	209
(d) (Baker & Co.)	+119	2	3.2×10^4	8.4	690
Constantan	-38	21.2	2.0×10^6	1.35	437
Chromel-p	+30	20	1.2×10^6	2.3	160
95% Bi-5% Sn	+30	4.5	3.6×10^6	1.7	216
97% Bi-3% Sb	-75	7	5.8×10^5	1.65	1390
90% Bi-10% Sb	-78	5.3	6.2×10^5	1.15	2169
99.6% Te-0.4% Bi	+191	2-3	3.5×10^4	10	1490
99.1% Te-0.9% Sb	+139	2-3	4.3×10^4	7.5	1050
98.5% T4-1.5% S	+575	1.5-3	2.9×10^2	850	159
65% Sb-35% Cd	+106	1.5-4	1.7×10^5	2.0	2290
75% Sb-25% Cd	+112	1.5-4	1.4×10^5	2.0	2560

TABLE VI

Characteristics of Hornig and O'Keefe Thermocouples

Total area of receivers (mm^2) Number of Junctions	0.5 1	1.0 2	4.0 4
Electrical Resistance (ohms)	5	10	12.5
Diameter of Lead Wires ($\times 10^{-3}$ mm)			
97% Bi 3% Sb	1.6	1.6	2.1
95% Bi 5% Sn	2.0	2.0	2.6
Heat Capacity of Lead Wires ($\times 10^{-7}$ joules/^{o}C)	1.0	2.0	6.3
Total Heat Capacity ($\times 10^{-7}$ joules/^{o}C)	4.8	9.5	36.3
Response Time (seconds)	0.036	0.036	0.041
D. C. Responsivity (volts/watt)	6.5	6.5	3.8
Responsivity at 5 c/s	4.4	4.4	3.1
Minimum Detectable Power at 5 c/s ($\times 10^{-10}$ watts)	0.5	0.7	1.4
Johnson noise at 300^{o}K	2.9	4.0	4.6
Thermal noise at 300^{o}K ($\times 10^{-10}$ volts)	0.5	0.5	0.4

1

TABLE VII - Properties of Schw

Couple Number (V, vacuum, A, Air-filled)	1V	2V	3V
Receiver Area (mm^2)	4 x 0. 4	2 x 0. 2	2 x 0.
Electric Resistance (ohms)	47. 9	39. 8	42. 9
Dynamic Resistance (ohms)	6. 6	5. 8	4. 8
Responsivity (volts/watt)	22. 1	17. 0	38. 5
Time Constant (sec.)	0. 043	0. 023	0. 055
Minimum Detectable Power (watts) (for a 1c/s BW.);			
Calculated D. C.	4. 1 x 10^{-11}	4. 7 x 10^{-11}	2. 2 x 10
Calculated 5 c/s	7. 0 x 10^{-11}	5. 9 x 10^{-11}	4. 4 x 10
Measured 5 c/s	1. 5 x 10^{-10}	8. 5 x 10^{-11}	4. 6 x 1
Combined Thermo-Electric Power ($\mu v/^{o}C$)	500	.570	210
Thermal Conductance (watts/^{o}C)	4. 5 x 10^{-5}	6. 7 x 10^{-5}	1. 07 x 1
Thermal Conductance Due to Conduction (watts/^{o}C)	3. 5 x 10^{-5}	6. 3 x 10^{-5}	8. 0 x 10
Noise Factor (obs. 5 c/s)	22	25	14

2

TABLE VII - Properties of Schwarz Thermocouples

V	2V	3V	4V	5V	6A
.4	2 x 0.2	2 x 0.2	7.5	3.2	1.5
9	39.8	42.9	106	115	70
6	5.8	4.8	4.6	8.6	---
[illegible]	17.0	38.5	9	24	0.6
3	0.023	0.055	---	---	0.008
10^{-11}	4.7×10^{-11}	2.2×10^{-11}	1.5×10^{-10}	5.6×10^{-11}	1.8×10^{-9}
10^{-11}	5.9×10^{-11}	4.4×10^{-11}	----	----	1.8×10^{-9}
10^{-10}	8.5×10^{-11}	4.6×10^{-11}	----	----	2.0×10^{-9}
	.570	210	212	150	----
10^{-5}	6.7×10^{-5}	$1..07 \times 10^{-5}$	1.9×10^{-4}	5.0×10^{-5}	----
10^{-5}	6.3×10^{-5}	8.0×10^{-5}	1.4×10^{-4}	2.9×10^{-5}	----
	25	14	----	----	300

3.3 Bolometers

The operation of the bolometer depends on the change in electrical resistance of a material on heating it. This change is determined by a quantity α, the temperature coefficient of resistance:

$$\alpha = \frac{1}{R}\frac{dR}{dT} \text{ ohm/ohm - }^{o}K$$

where R is the resistance of the material at temperature T. Since the resistance of most metals over a wide temperature range is approximately proportional to the temperature,

$$\alpha = \frac{1}{T}$$

at room temperature, α = 0.0033 ohm/ohm - ^{o}K. Values vary a little from this, but not greatly. (Ref. 22). For semiconductors, R is generally given by an equation of the form $R = R_o \exp(A/T)$ with A being a positive coefficient. Then

$$\alpha = \frac{-A}{T^2}$$

Note that α is negative in this case which means the resistance goes down as the temperature goes up. Values numerically much greater than for metals may be obtained. A typical value is A = 3,000^{o}K, giving α = -.0.033 ohm/ohm - ^{o}K for room temperature. As a general rule, one finds the temperature coefficient for semiconductors is about 10 times greater than that for metals.

3.3.1 Bolometer Bridge Circuit

The usual arrangement of the bolometer detector is shown in Figure 19. R_L is a load resistance. In practice, especially when using semiconducting materials for thermistor bolometers, R_L is a bolometer as nearly identical to the active cell as possible. It is shielded from the radiation, but otherwise arranged so that any fluctuations in ambient conditions affects the detector and compensator in the same manner, and the bridge remains balanced.

The power source is arranged so that the bias current through the circuit is effectively constant (constant current generator theory). The signal observed is the change in voltage across the element due to the change in resistance.

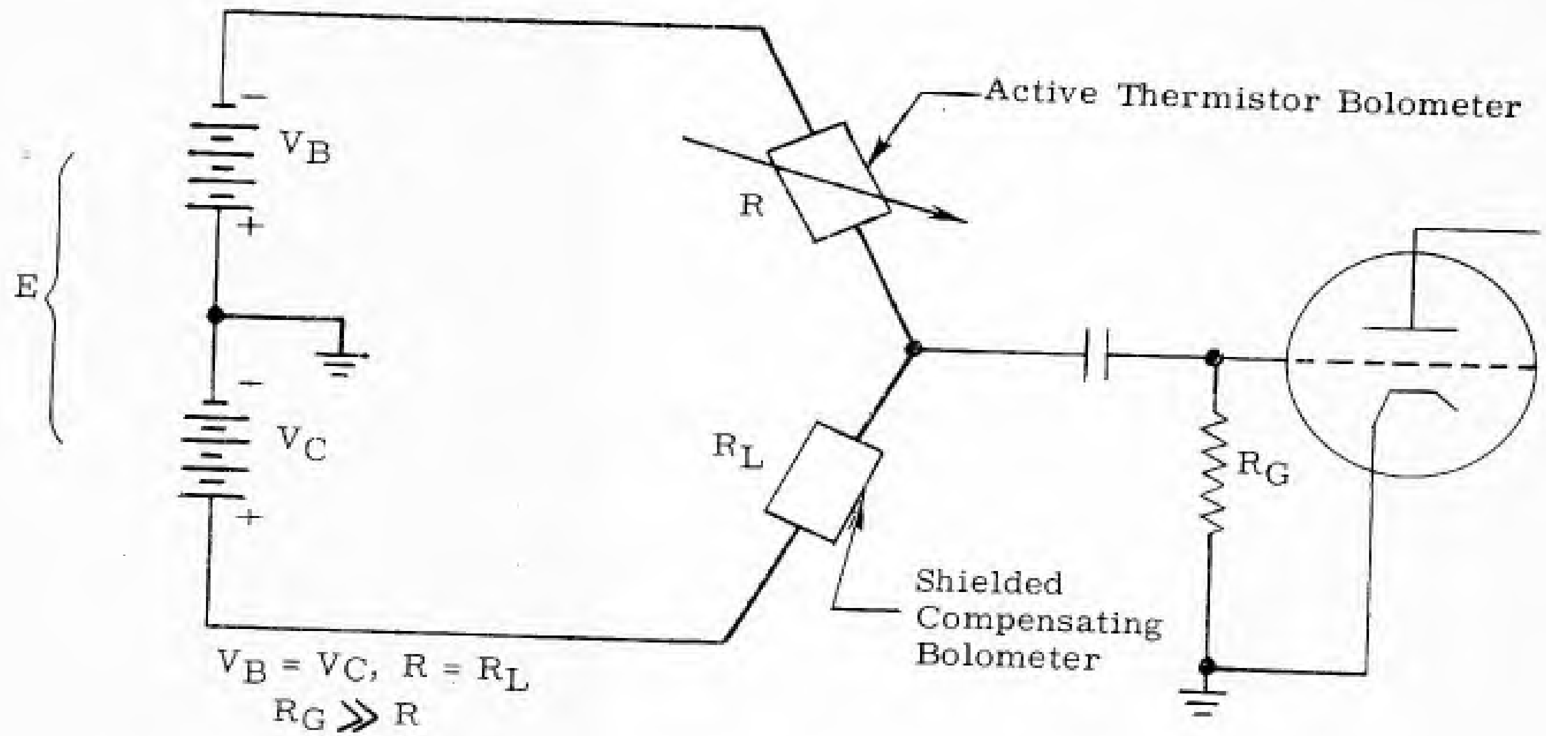


Figure 19. Typical Arrangement of Bolometer Circuit

$$\Delta V = \frac{R_e}{(R + R_e)} \times E \times \Delta R$$

$$\text{or } \frac{dV}{dR} = \frac{R_e E}{(R + R_e)^2} = \frac{E}{R + R_e} \times \frac{R_e}{R + R_e}$$

$R_e/R + R_e$ is known as the bridge factor and, for the situation described above, is equal to 1/2.

$$\left(R_e = \frac{R_L R_G}{R_L + R_G}\right)$$

The bolometer, like the thermocouple, is a very simple device, yet the design of a sensitive bolometer for radiation measurements is complicated by a number of factors. Some of these are similar to those encountered in the thermocouple. A small thermal capacity and minimum thermal losses are desirable to obtain a large responsivity, while small thermal losses tend to increase the time constant.

3.3.2 Heat Capacity, Thermal Losses, Joulean Heat

The effects of heat capacity, thermal losses and Joulean heat due to bias current can be described by the differential equation

$$\left[C_e \times \frac{d\,\Delta T}{dt}\right] + K_0\ \Delta T = \Delta W + \left[\frac{dW_h}{dt} \times \Delta T\right]$$

where

C_e = dynamic heat capacity

K_0 = static thermal conductivity

W_h = Joulean heating power

W = power absorbed due to radiation

ΔT = change in temperature due to absorbed radiation

The first term of the equation on the left is the rate of heat storage in the cell. The rate of heat flow out is given by the second term and is associated with radiation out from the cell and conduction through the heat sink. The last term on the right hand side is the variation in Joulean heat flow caused by the variation in the resistance due to the absorption of energy ΔW.

3.3.3 Bolometer Characteristics

The bolometer has problems peculiar to itself. To obtain a large responsivity the bias current and the load resistance should be as large as possible. (A load resistance may be used in place of the shielded compensating cell.) However, the thermistor bolometer is subject to self heating due to the bias current, as explained above, and actual instability can occur in a cell due to this self heating effect. This criterion for instability places a limitation on the value of the voltage and on the operating temperature; also, there is an optimum bias current beyond which little improvement can be obtained.

Semi-conductors are especially attractive for bolometer cells. As shown previously, they have a much larger temperature coefficient of resistance than is possible for metals, and a much higher resistivity. Thus semi-conductor bolometers tend to be high impedance devices of the order of megohms, permitting the arrangement of Figure 19 for driving ac electronic amplifiers.

The ultimate sensitivity or NEP is the ratio of the limiting noise voltage and the responsivity. The limiting noise is Johnson noise voltage if frequency considerations are ignored. Johnson noise is a function of the impedance so that a semiconductor would have, inherently, a larger Johnson noise than a metal bolometer. If the effect of frequency is considered, a current noise source is present at low frequencies partly caused by the method of making contact to the cell. In practice, this current noise, proportional to 1/f, can be made small enough so that a good bolometer has a total noise level when biased that is less than twice Johnson noise.

The responsivity is a measure of the temperature change due to a change in resistance in terms of volts out per watt of incident energy. The higher temperature coefficient of resistance and the higher resistivities result in a much greater change in resistance for a given temperature change in the case of semiconductor bolometers compared to metal units. The responsivity of a semiconductor bolometer is very much greater than that of a metal bolometer, thus offsetting the increased noise and resulting in a NEP for the semiconductor unit comparable to or better than the metal one.

The time constant or frequency response depends to some extent on the responsivity. It is a measure of how fast the temperature change can be made. A fast speed of response is achievable at the expense of responsivity, Figure 20. A few bolometers using thermistors, semiconductors composed of combinations of sintered or powdered metallic

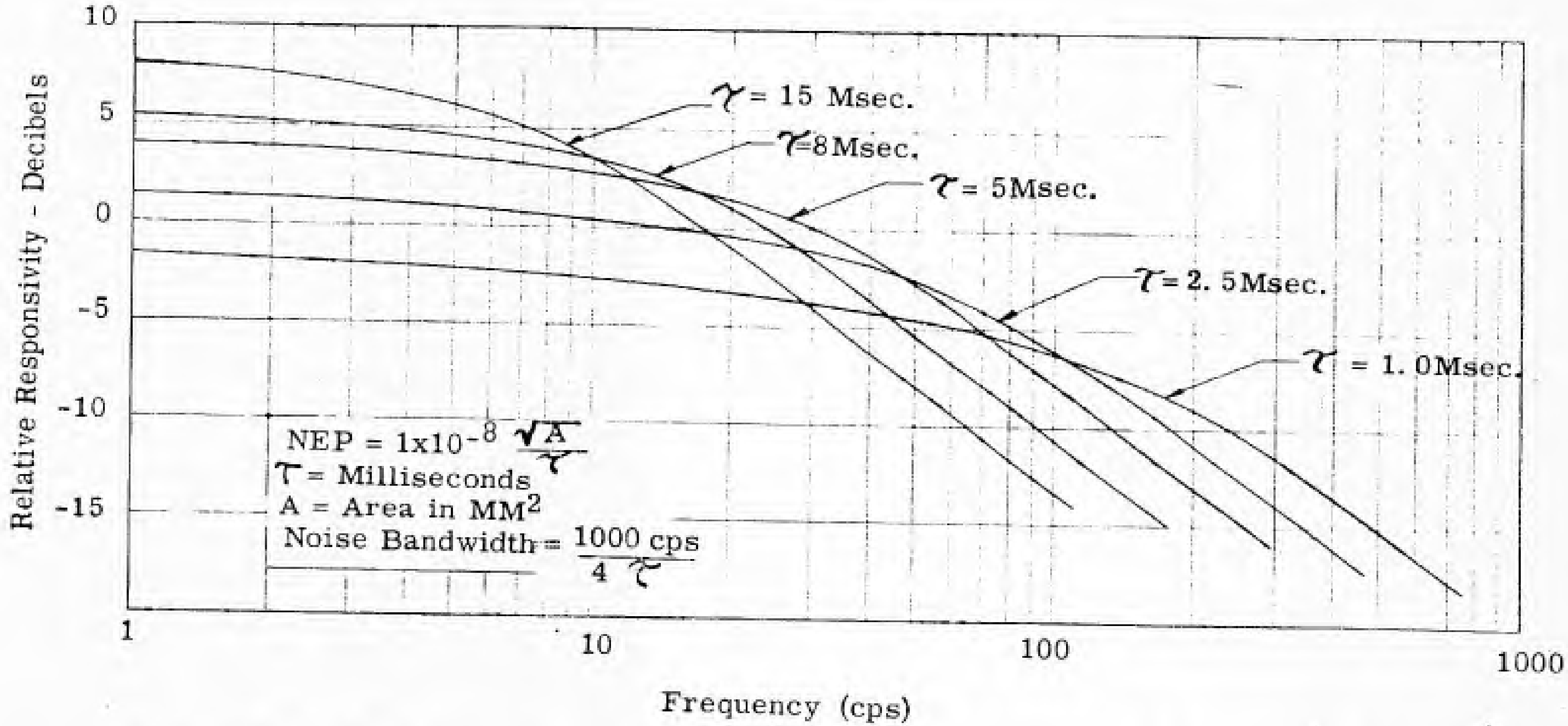


Figure 20 - Variation of Speed of Response and Responsivity as a Function of Frequency

oxides and featuring very large temperature coefficients, have been made with time constants of the order of hundreds of microseconds with responsivities around 500 - 800 microvolts per microwatt. The usual range for semiconductor bolometers are, however: (Ref. 23, 24).

Time constant	-	0.001 to 0.005 sec.
Responsivity	-	800 to 1200 microvolts/microwatt
NEP	-	10^{-9} to 10^{-10} watts
Resistance	-	1 to 5 megohms
Spectral response	-	Uniform to all wavelengths

For metal bolometers, characteristic data are:

Time constant	-	0.001 to 0.005 sec.
Responsivity	-	0.5 to 5.0 microvolts/microwatt
NEP	-	10^{-8} to 10^{-9} watts
Resistance	-	20 to 50 ohms
Spectral response	-	uniform to all wavelengths

3.3.4 Immersion Bolometers (Ref. 25)

There are limits to the optical gain that can be achieved practically with conventional optical systems in the infrared regions. In the longer wavelength regions it is necessary to use reflecting optics exclusively and these become expensive and bulky. It is possible by means of optical immersion (referred to in Section 2.5.7) of the detector cell to achieve substantial optical gain directly at the detector.

Thermistors have been attached to concentric germanium hemispheres for large gains in detectivity. The image at the plane face of the germanium lens is reduced by a factor of 4 from that of the image in space. This amounts to a reduction of 16 times in the area of the receiver and, since thermistor detectivity varies inversely with the square root of its area, a gain of four times in detectivity results.

The thermistor is mounted centrally on the plane surface of the hemisphere separated by a thin film which is transparent to infrared and electrically insulating. Detector time constant is determined by controlling the thickness of this layer. The germanium-immersed bolometer is suitable for use in optical systems having effective relative apertures down to less than f/1.0.

3.3.5 Bolometer Mosaics

A matrix or mosaic of thermistor elements can be "printed" in desired patterns on ceramic substrates. Electrical junctions are likewise printed to provide signal and bias contacts. Arrays containing 100 cells have been made by laying down a 10 x 10 matrix. Linear arrays have also been produced by this technique. The individual bolometer elements have properties comparable to the single element thermistor cells described previously. Because of its method of manufacture, printed thermistor bolometers are useful under high ambient temperature conditions.

3.3.6 Low Resistance Thermistor Bolometers for Transistors

Due to space and weight requirements work has been started on developing thermistor bolometers for use with transistor amplifiers. The high impedance, 1 to 5 megohms, of standard thermistor bolometers is not suitable for transistor amplifier matching. Optimum resistance for thermistors for coupling to transistor circuits has been determined to be of the order of 50 K ohms and work is progressing on the development of these relatively low impedance cells.

3.3.7 Superconducting Bolometer

The temperature coefficient of resistance, α, for metals in their normal state tends to zero for very low temperatures. Many metals, however, become superconducting at small values of T, their resistance dropping to zero at a particular temperature. For pure metals this transition is extremely rapid and would be difficult to use, but for some alloys the transition is relatively gradual and corresponds to a large positive value of α over a small, but finite temperature range. This is one of the major requirements of a sensitive bolometer. Columbium nitride cooled to a temperature of 14.34°K has temperature coefficient of 50 ohm/ohm - °K over the range from 14.34°K to 14.37°K. Ordinary metal has an α of 0.07 at this temperature. In addition there is a large reduction in heat capacity due to the low temperature. Since at low temperatures the specific heat becomes proportional to T^3, quite short time constants may be obtained; values of the order of 0.3 milliseconds have been reported. (Ref. 26).

The narrowness of the transition region, 0.03°C, requires a very high degree of temperature stability, thus posing quite a practical problem. The work of Milton and Andrews shows the possibility of achieving great sensitivity at tremendous expense in effort and time. In its present state, the superconducting bolometer must be regarded as a special research instrument and not as a tool for ordinary use.

3.3.8 Increased Use of Semiconductor Bolometers

Semiconductor bolometers of the thermistor type are being used in greater quantities as new materials and techniques increase the responsivity, increase detectivity and lower the time constant. Increased interest in the 8 to 13 micron atmospheric window has also played a part in focussing attention on the thermistor bolometer since the spectral response of the photoconductor detectors has not yet been extended very far into this region.

A training device incorporating a thermistor bolometer would seem quite attractive, as filters could be used to display images from targets as they would be seen by the more spectrally selective equipments designed for specific uses. This will be explored further in later sections, as there are several other factors to be considered such as optical considerations, optical materials, scanning methods, economic factors.

3.4 Pneumatic and Other Types

In its simplest form the pneumatic type of detector is made up of a small gas-filled chamber, equipped with an infrared transmitting window, some means for absorbing radiation admitted to the chamber, and finally a method for transposing pressure change in the chamber into measurable signal output, usually electrical or optical.

One device made by Hayes (Ref. 27) used a carbonized "fluff" material in a small chamber to absorb radiation. One end of the chamber was closed with a thin metal diaphragm which formed one plate of a condenser. Capacitance changes provided a direct means of measuring the radiation input.

3.4.1 Golay Cell

Zahl and Golay are responsible for the more commonly known version of the pneumatic detector, the Golay cell. (Ref 28) (Figure 21). An air or gas-filled cell contains a very thin radiation receiving membrane in the form of a layer of aluminum (0.03μ) deposited on a 0.05μ thick collodion base. The heating of this membrane causes expansion of the gas distorting the detecting membrane which is a flexible mirror. Visible light is reflected from this mirror and focussed on a photocell through a high sensitive optical amplifier. The light passes through one half of a line grid and is then reflected by the cell membrane back on to the other half of the line grid and thence to the photo-cell. Initially the images of the line grids are focussed in such a way that no light gets through. A slight distortion of the membrane will, however, defocus the image sufficiently to allow a considerable amount of light to energize the photo-cell. Helium filled detectors with $600\,\mu$sec time constant have been made; the more usual values range from 2 to 30 milliseconds with NEP of the order of 6×10^{-11} watt. The absorbing disk has a diameter as small as 0.1 inch although other sizes and shapes may be used.

Another form of the pneumatic detector utilizes the gas itself as a radiation absorber. By filling the cavity with gases having selective absorption bands, detection in certain preselected wavelength intervals may be achieved. Since mixtures of absorbing gases may be used a variety of specific wavelength response combinations can be obtained.

A sharpness and multi-region response characteristic that is difficult to obtain with optical filter methods can be achieved by this cell. Energy conversion is accomplished by using the flexible diaphragm as one plate of a capacitor and using the electrical signal to drive a standard high impedance cathode follower circuit.

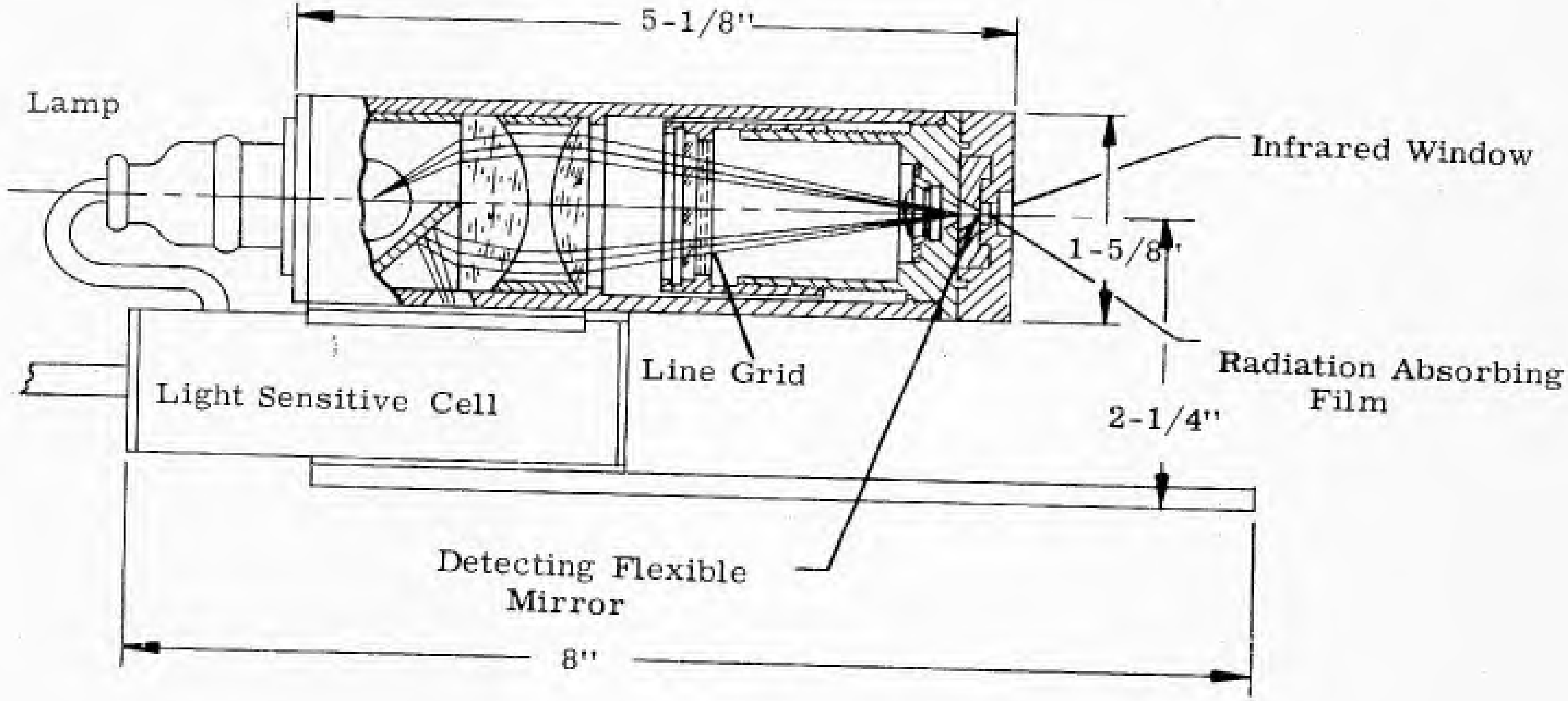


Figure 21. Golay Pneumatic Heat Detector

Response is 3000 volts/watt at 50 cps. Because of its method of operation there is no self noise, the NEP of 6×10^{-10} watt being due to radiation background noise and preamplifier noise. The effective sensing area can range from 0. 5 mm^2 to 20 cm^2. Overall size of a detector with effective area of 18. 5 mm^2 is 0. 925 in. long and 0. 437 in. diameter. Immersion optics techniques can be readily adapted. (Ref. 29).

3. 4. 2 Thermal Image Tube

Another variation of the pneumatic type makes use of the change in refractive index of the gas due to local temperature changes. (Ref. 30).

A thermal image is focused on a thin layer of infrared absorbing gas or upon an infrared absorbing membrane (that is partially transparent to visible light) immersed in a nonabsorbing gas. The local variations in the density of the gas caused by the energy variation throughout the thermal image are made visible if the corresponding refractivity variations are examined by means of a sensitive optical system of the type used to observe wind tunnel air density patterns.

Thus a directly displayed thermal image may be observed.

3. 4. 3 Thin Films

The change in rate of evaporation or condensation of thin liquid films, usually oil, on exposure to an infrared image is another type of thermal detector worthy of mention. The Evaporograph is, perhaps the best known device using this technique, and will be discussed more fully under Section 4. 7. The main disadvantages of this technique are its slow response, of the order of seconds, and the fact that the image must be wiped off before a new image can be built up.

3.5 Photodetector Transducers

Detectors that convert light energy into electrical energy based on the freeing of bound electrons by the absorption of quanta of radiation are known as photodetectors. Photodetectors count the number of effective quanta of radiation absorbed. The energy of a quantum of frequency ν is $h\nu$, h being Planck's constant. In such detectors only quanta having energies greater than E_0, the threshold energy level, are effective, the detector ignoring the presence of quanta of lower energy. The value of E_0 is frequency dependent and is usually fairly sharply defined, establishing a long-wave limit of detection. The energy of a photon (unit of a quantum), therefore, depends only on the frequency of the radiation and not the intensity. In a monochromatic field, all photons have the same energy. An increase in the intensity of the monochromatic radiation increases the number of photons emitted per unit time, but not their individual energy, and hence would increase the photocurrent. Since the time constant of photodetectors does not depend on the thermal capacity but on the photo-electric properties of the material, their time-constants are much shorter. The higher frequency response due to the short time constants allow the system designer more latitude.

3.5.1 Photodetector Types

The photodetector types classified by their modes of operation are:

1 - Photoconductive detectors
2 - Photovoltaic detectors
3 - Photoelectromagnetic detectors
4 - Photo emissive detectors
5 - Photographic Film
6 - Luminescent phosphors

The first four modes depend upon fluctuating current. Photographic film is a photodetector that depends on a photo-chemical process for its operation. The infrared quenching of luminescant phosphors is a photon absorption process that has found limited practical use to date

3.5.2 Photoconductor Theory

The photoconducting phenomenon is the increase in conductivity of a semiconductor due to an increase in the number of current carriers available for the conduction process when light energy is absorbed. Light energy, in this case, is the energy of photons from the ultraviolet, visible, and infrared regions of the spectrum. When light of the proper wavelength falls on the surface of a semi-conductor, the energy of the incident photons is expended in the transfer of electrons from the valence band across the forbidden energy gap into the conduction band.

3.5.3 Electron Energy Levels and Bands

The electronic properties of solids may be described by electron energy band theory. The Bohr model of the atom consists of a centrally located nucleus surrounded by electrons in orbit analagous to the planetary orbits of the solar system. Figure 22 shows an orbital model of the atom and the energy level diagram of the same atom. The vertical position of the horizontal lines represents the levels of energy corresponding to the various electronic orbits. The lengths of the lines correspond to the diameter of the orbits. The curves bounding the system of horizontal lines therefore represent a plot of the total energy of the atom as a function of the radius of the electronic orbit. Orbital electrons are allowed discrete values of energy which may be determined by quantum mechanics. The particular allcwed values are illustrated in the energy level diagrams by the position of the horizontal lines. Associated with every atom are a number of orbital electrons sufficient to cancel the positive charge of the nucleus.

If a number of identical atoms are brought together, a coupling process takes place and the discrete energy levels normally occupied by the electrons in the individual atoms split up into energy bands as shown in Figure 23. Electrons that bind atoms together are called valence electrons, and the energy levels that they fill are called valence levels. In each band there is a number of energy levels approximately equal to the number of atoms. The next higher band of levels arising from the lowest excitation level of the individual atom is shown to be separated from the valence band by an interval of energy in which there are no allowed energy levels. The electrons populating these bands move under quantum mechanical constraints which make the electrons in the energy levels near the top of a band act as if their masses were negative. Removal of one of these electrons leaves a vacancy which behaves like a particle having positive charge and positive mass. Such a vacancy is a positive hole.

The degree of filling of electron levels in single bands, assemblages of bands, forbidden gaps, and impurity levels may be ascertained by the use of Fermi statistics. The energy of a reference level at which the probability of filling a level is 1/2 is called the Fermi level.

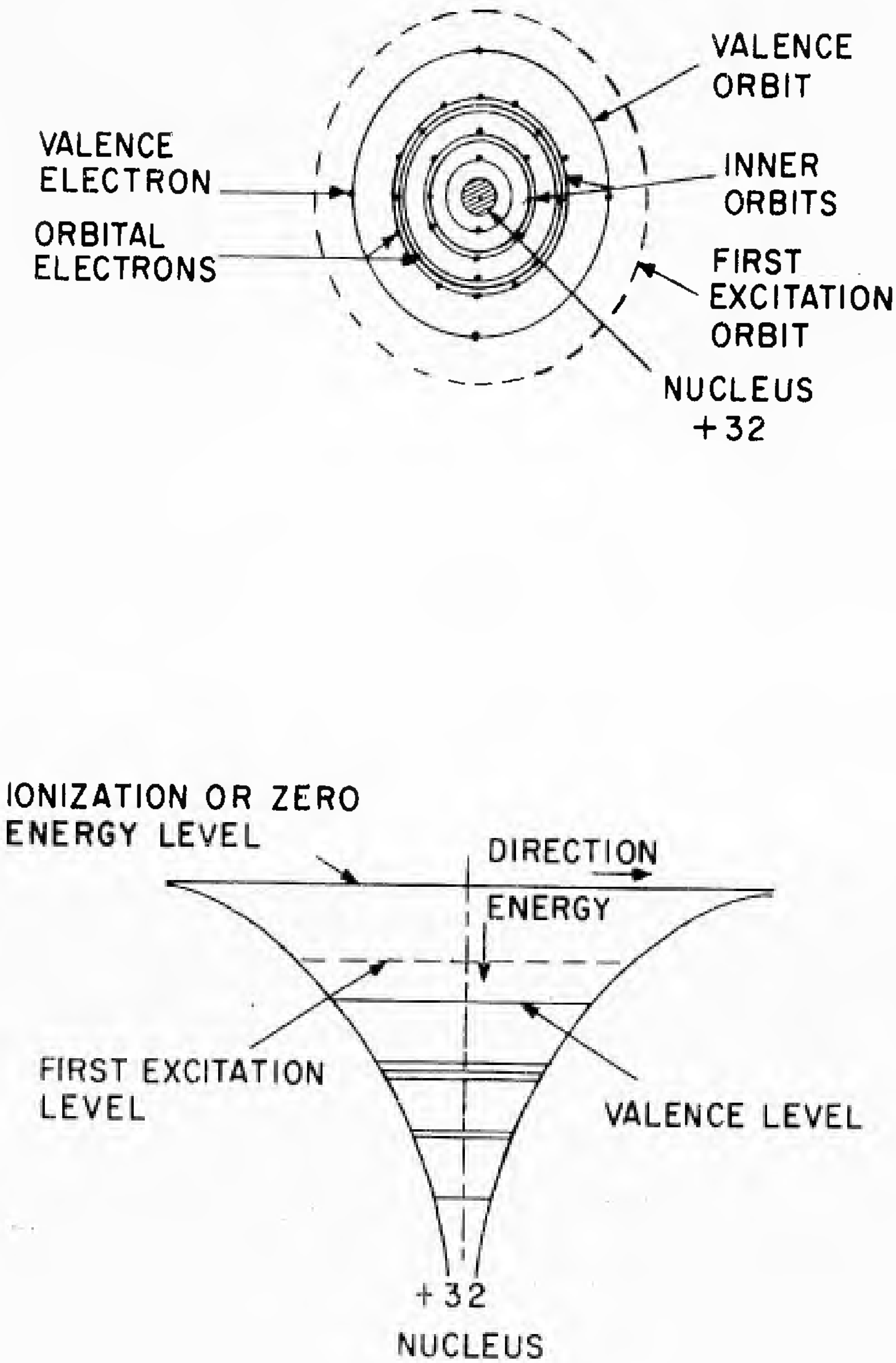
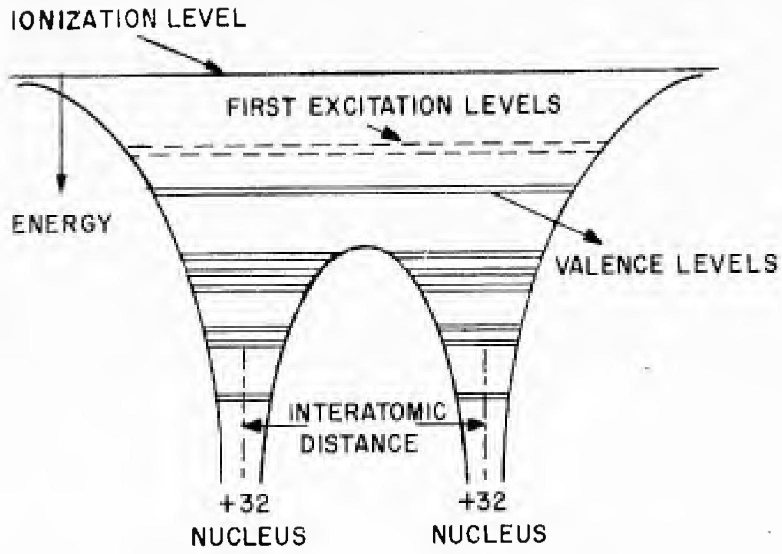
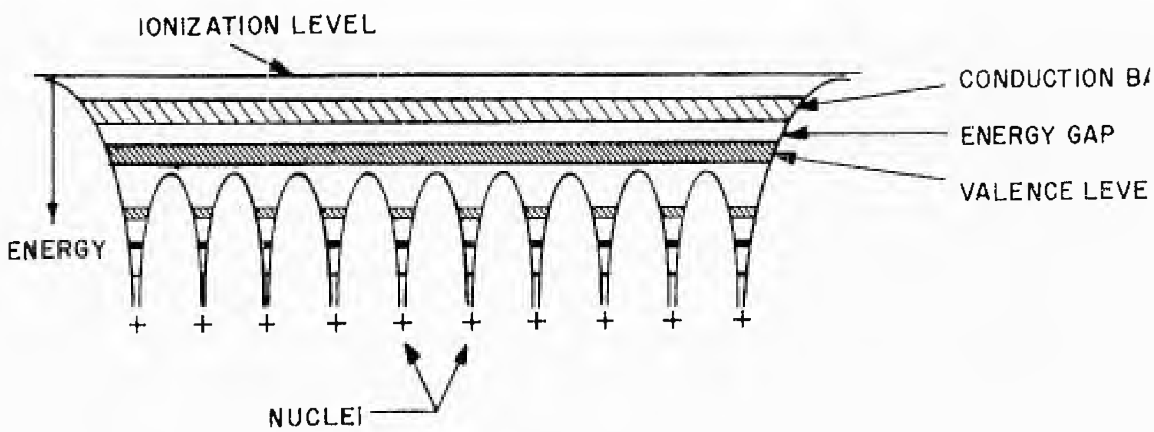


Figure 22 - Simplified Orbital Model and Energy Level Diagram of an Atom.



a. Energy Level Diagram of a Diatomic Molecule



b. Crystal Energy Level Diagram

Figure 23 - Energy Level Diagram

3.5.4 Increase in Electrical Conductivity

If the energy gap is small, a few electrons will be thermally excited to the conduction band, leaving a few vacancies in the valence band so that there are a limited number of electrons capable of cooperating with an external field, and the crystal (a large number of identical atoms) can conduct current. Such a crystal shows a resistivity several orders of magnitude higher than the resistivity of most metallic conductors and is called a semiconductor.

3.5.5 Impurity Addition or Doping

The conductivity of a semiconductor may be altered by the controlled addition of impurities (doping). Impurities may have either greater or fewer valence electrons than the semiconductor. When the valence electrons of the impurity exceed that of the semiconductor, an N-type semiconductor results and the impurity is referred to as a donor impurity. Fewer impurity valence electrons make up a P-type semiconductor, and the impurity is referred to as an acceptor impurity.

3.5.6 N-Type Impurity

The effect of an N-type impurity is shown in Figure 24. Germanium (Ge) with four valence electrons, is doped with arsenic (As) having five valence electrons. When an arsenic atom replaces a germanium atom in the germanium crystal lattice four of its five valence electrons are used in bonding the arsenic to its neighboring germanium atoms. The extra valence electron is very lightly held and is easily given up to the conduction band. Without its fifth valence electron the arsenic ion represents a localized positive charge in the interior of the crystal, and warps the edges of the valence and conduction bands, giving rise to a few rather extensive energy levels just below the edge of the conduction band. The bending of the conduction band edges results in the reflection or scattering of electrons if they approach the impurity atom. Filled energy levels adjacent to the bottom of the conduction band are called donor levels. Since the energy gap between the donor levels and the conduction band is much less than the energy gap between the valence band and the conduction band, the donor levels will yield their electrons to the conduction band by thermal excitation at much lower temperature than are required to excite electrons from the valence to the conduction band.

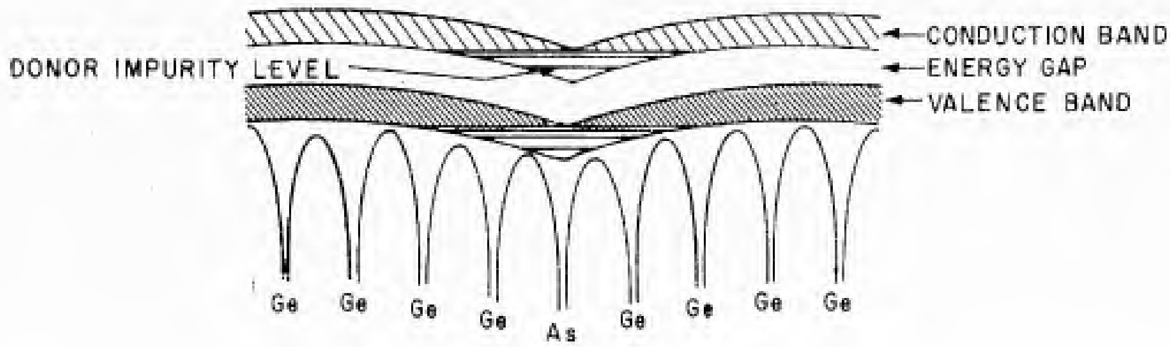


Figure 24 - Donor (N-Type) Impurity Effect on Energy Bands

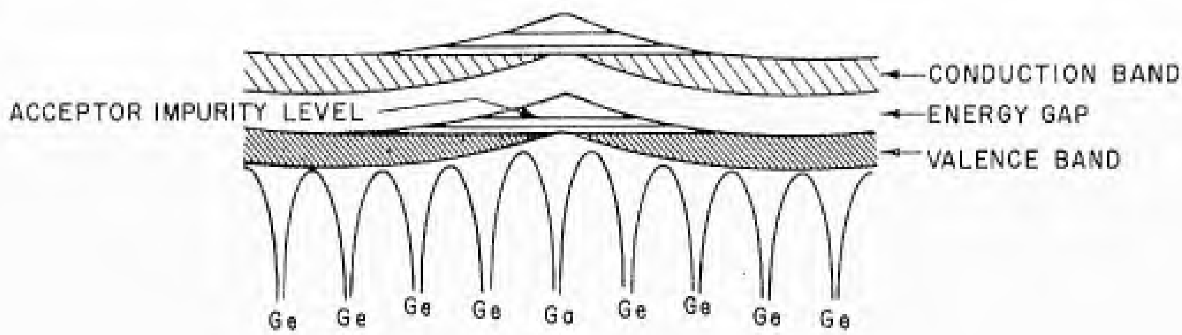


Figure 25. Acceptor (P-Type) Impurity Effect on Energy Bands

3.5.7 P-Type Impurity

The effect of a P-type impurity is shown in Figure 25. Gallium (Ga) having three valence electrons is added, and replaces a germanium atom in the germanium crystal lattice. It is able to saturate its bands in only three of its four germanium neighbors. It is, therefore, ready to accept an electron from any available source in order to saturate the band with the fourth neighbor. At ordinary temperatures the gallium atom would capture an extra electron from the valence band in order to saturate its bands with its germanium neighbors. The negative ion warps the band edges as shown. An extensive impurity energy level is found just above the top of the valence band and contains the extra electron captured by the gallium impurity. At very low temperatures this level loses its electron to the band. The empty level thus produced represents the unsaturated band of the gallium's fourth nearest neighbor. Such an energy level close to the top of the valence band is called an acceptor level, and it is relatively easy to excite an electron thermally from the valence band into this vacant energy level and thereby satisfy the bonding requirements of the gallium impurity. This process leaves a vacant energy level in the valence band.

3.5.8 Radiation Energy Required for Conduction

The minimum radiation energy required to raise an electron from the valence to the conduction band is the energy of the gap ΔE. The energy of a light quantum is the frequency of the light ν multiplied by Planck's constant h. The wavelength λ_0 of the photoconducting threshold is, therefore:

$$\lambda_0 = \frac{c}{\nu_0} = \frac{hc}{\Delta E}$$

where c is the velocity of light. The maximum energy that can raise an electron to the conduction band from the valence band is the energy difference between the bottom of the valence band to the top of the conduction band. All light energies between $h\nu_0$ and $h\nu_{max.}$ are capable of exciting some electrons across the energy gap, increasing the number of current carriers in both the valence and conduction bands, thereby contributing to the photoconducting process.

3.5.9 N and P Carrier Pairs

When a semiconductor crystal is excited by photons, and the absorbed energy is greater than the energy of the forbidden energy gap, electrons from the valence band are excited into the conduction band creating N and P type carrier pairs that would normally not be there in thermal equilibrium. As long as the extra pairs exist, the conductivity of the crystal increases. The rate at which pairs are created will be proportional to the number of suitable quanta incident on the crystal. Usually, the extra electrons and holes do not stay separated for long. They recombine by the aid of at least two methods. A conduction-band electron finds a hole in the valence band and loses energy to return to the original lower energy level. The rate at which extra N and P type carriers recombine will determine the average time these carriers can spend in the conducting state.

3.5.10 Life Times of Charge Carriers

On a pure crystal the average time spent by the charge carriers in the conducting condition and the average time for recombination are the same. However, if localized energy levels exist in an impure crystal then a portion of the time of the charge carriers may be spent in these levels (called traps) and only intermittently are the carriers free to conduct. The "life time" of the carriers is defined as the average time which the charge carrier spends in the conducting conditions, while the recombination time is defined as the average time the carrier stays in the excited states of motion which includes the time spent in temporary localized positions at traps. Thus, the recombination time is always greater than or equal to the life time.

Since the lifetime of a carrier is measured only by the average time extra carriers remain in the conducting condition, the trapping of a carrier by a recombination center ends the life of the carrier even though that carrier may have to wait for a carrier of opposite type to complete the recombination reaction; so it is not unexpected to find the lifetimes of the two carrier types differing by significant amounts. One type of carrier usually waits for the other in a recombination center.

The spectral sensitivity of a photoconductor is seen to extend between the long wavelength threshold (the wavelength corresponding to the energy gap), and the wavelength where $h\nu$ extends from the bottom of the valence band to the top of the conductor band. When $h\nu$ extends between the center of the valence band and the center of the conduction band, the excitation probability is largest.

3.6 Photoconductive Cells

Photoconductive cells may be made with semiconductors of either conductivity type and in a number of configurations as shown in Figure 26. These include the high resistivity bar, the point contact, and several junction configurations. Not illustrated, but shown later, are film types having either evaporated or chemically deposited layers. Photoconductors use external power supplies (bias), and the fundamental process involved is the modulation of the conductivity of a PN junction or bar of semiconductor material.

The spectral response, D*, and frequency response characteristics of many materials have been investigated and are the subject of continuing investigation. In the development of infrared detectors several approaches have been employed. They are based on the selection of materials whose electrical properties are such that they will have a long wavelength threshold beyond three microns, and on increasing the wavelength cutoff of a material having an intrinsic cutoff in the visible or near infrared.

3.6.1 Spectral Response

Photoconductive cells may be separated into three broad categories according to the temperature at which they are operated. Detectors sensitive at room temperature include Lead Sulfide (PbS), Lead Selenide (PbSe), Lead Telluride (PbTe), and Indium Antimonide (InSb). Figure 27 shows the typical absolute spectral response of the detectors. It should be noted that the detectivity, D*, at the peak of the spectral curve is at least 100 times greater for PbS than for the other room temperature detectors. As an order of magnitude figure, D* (-, 90, 1)* at the peak for PbS is 10^{11} cm/watt; for room temperature PbSe it is 10^{9} cm/watt.

The second group contains those detectors which show optimum sensitivity in the liquid nitrogen region. Those available include PbTe; PbSe; Germanium (Ge) doped with gold (Au) and Antimony (Sb); Ge doped with Au (referred to as Ge:Au); InSb. All but Ge:Au have a long wavelength threshold in the 5 to 7 micron region. Ge:Au has a response extending to 9.5 micron. Its sensitivity when operated at liquid-nitrogen temperature is comparable with the other detectors in this group; when cooled 10° to 15° further, its sensitivity surpasses the other detectors

D (-, 90, 1) - means measurements made at 90 cps with a 1 cps bandwidth with monochromatic radiation.

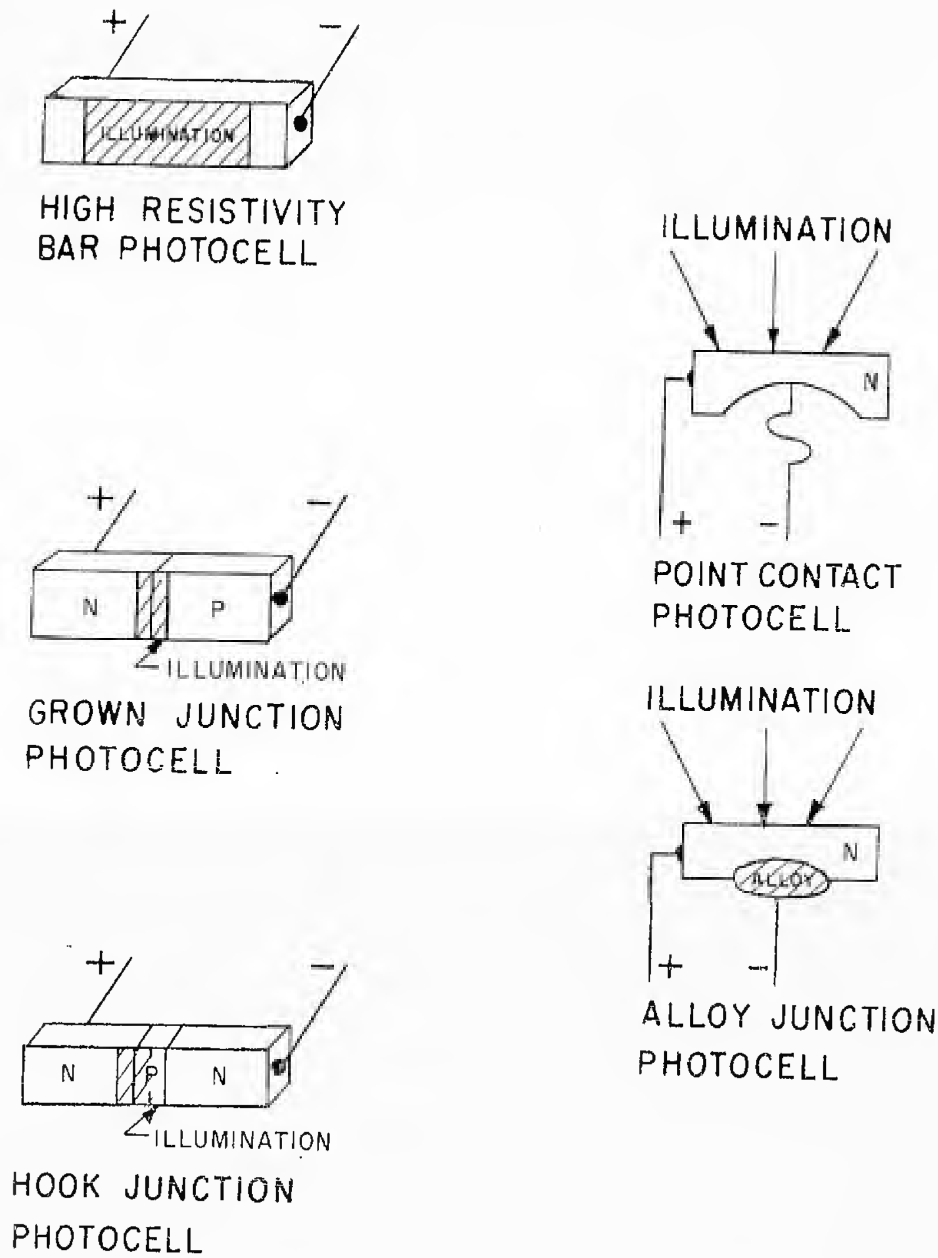


Figure 26 - Photoconductive Cell Types

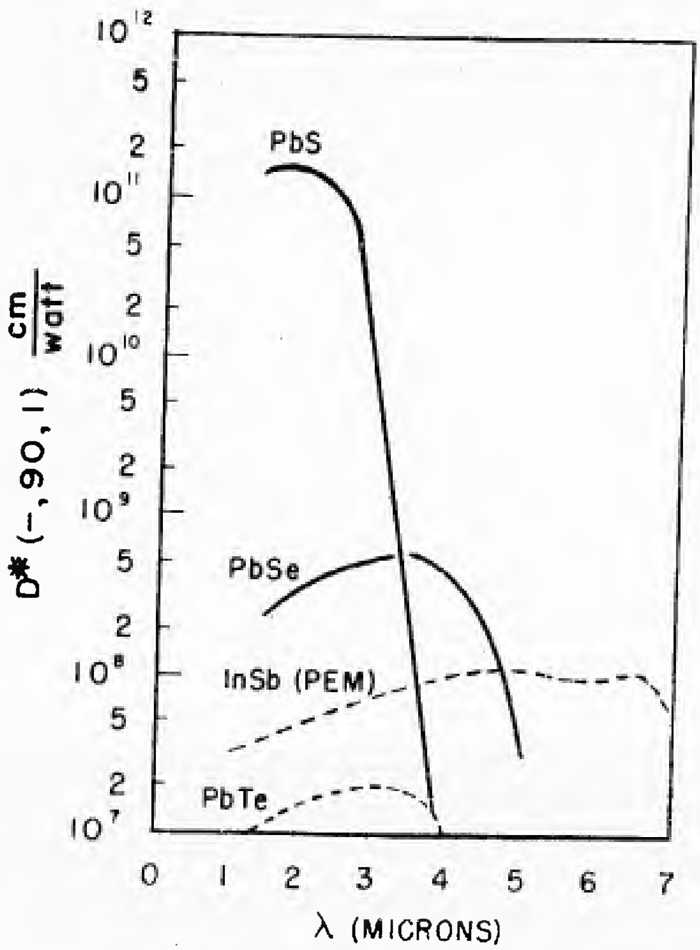


Figure 27 - Absolute Response of Room-Temperature Detectors. (Ref. 32)

in this group. Figure 28 shows the absolute response of several of these detectors. It should be noted that D* (-, 90, 1) at the peak is of the order of 10^{10} cm/watt for these detectors. There are, of course, variations among the detectors produced by one company as well as among those produced by different companies. These variations are less than an order of magnitude.

The third group contains those detectors which should be operated below liquid nitrogen temperature. They are sensitive in the 9 to 13μ window and beyond. Included in this group are Ge and Germanium-silicon (Ge - Si) alloys with various impurities. Figure 29 shows the spectral curves of Ge detectors with different impurities. Au and Sb impurities, when added in proper proportions, produce 6μ detectors. Au impurities alone lead to the 9.5μ response, Sb and Zinc (Zn) impurities combined extend the cutoff to 15μ, Zn alone to 40μ, and Sb alone to 120μ. As the spectral response extends to longer wavelengths, lower and lower temperatures are required. Thus, the 6μ detector does not improve on further cooling below liquid nitrogen temperature, the 9.5μ detector improves by a factor of 4 when the temperature is lowered an additional 10° to 15°, the 15μ detectors require a temperature of about 50°K, and the 40μ and 120μ detectors should be operated at liquid helium temperatures.

3.6.2 Signal and Noise Characteristics

In addition to the criteria of detectivity (D*) and long wavelength cutoff, the magnitude of the signal and noise of a detector must be considered. To make full use of detector characteristics, operating conditions must be such that detector noise and not equipment noise limits the performance. This is accomplished in a photoconductive detector by increasing the bias current to the point at which the S/N ratio starts to decrease with further increase in current. This is the optimum bias current. In film detectors, the S/N ratio decreases slowly when the optimum current is exceeded. An increase in the current by a factor of 5 may lead to a drop in the S/N ratio of only 30%. The bulk Ge detectors show a much more rapid drop in the S/N ratio when the optimum current is exceeded. In well-constructed Ge detectors, however, bias currents of 100 microamps are common, in contrast with currents of about 1 to 10 microamps for film detectors of the same area. In order to make possible a rapid calculation of both detector signal, S, and detector noise, N, under normal operating conditions, it is suggested that the signal factor, J_s, and the noise factor, J_n, be specified.

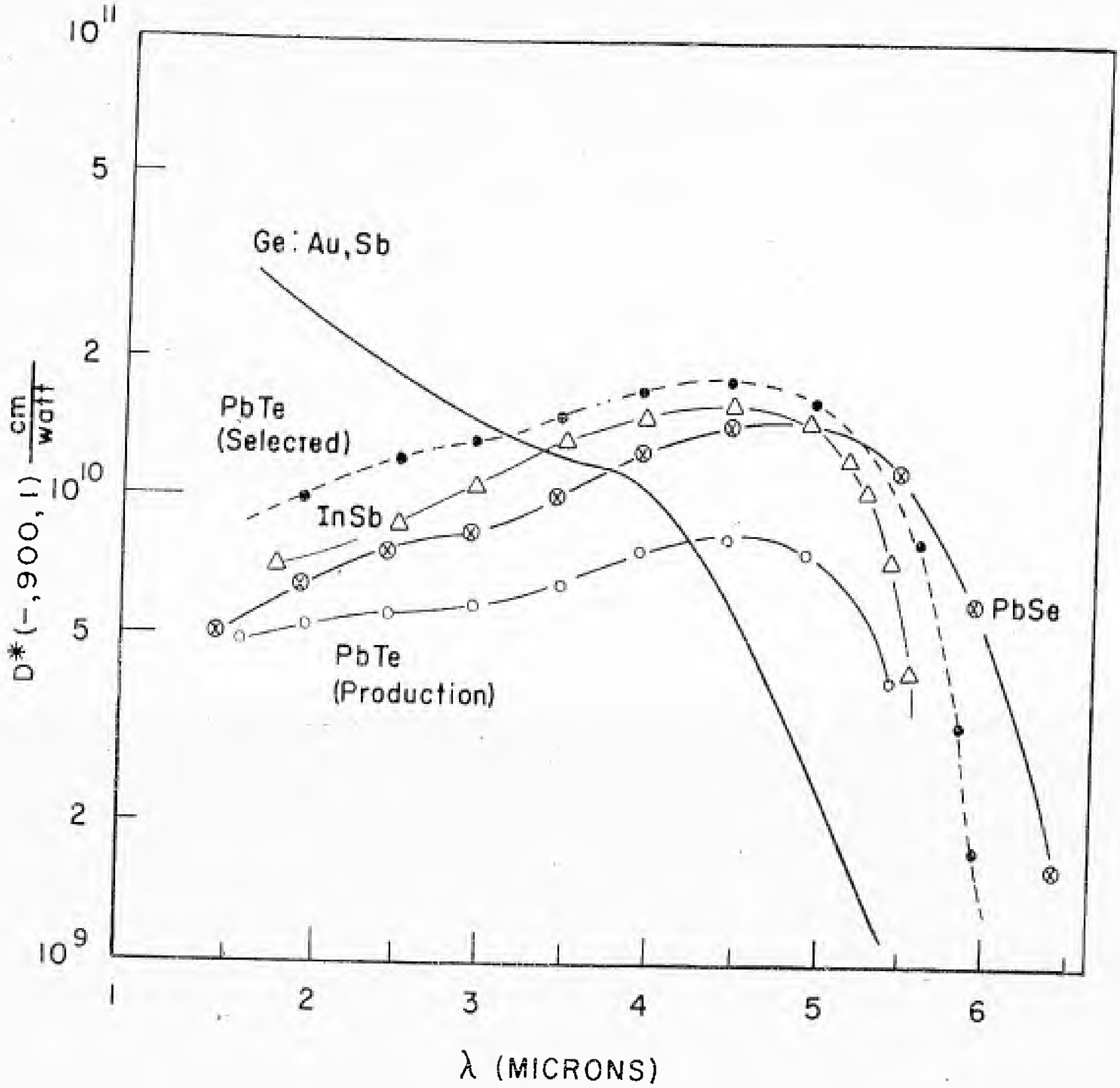


Figure 28 - Absolute Spectral Response of Cooled Detectors (Liquid-Nitrogen Temperature) (Ref. 32)

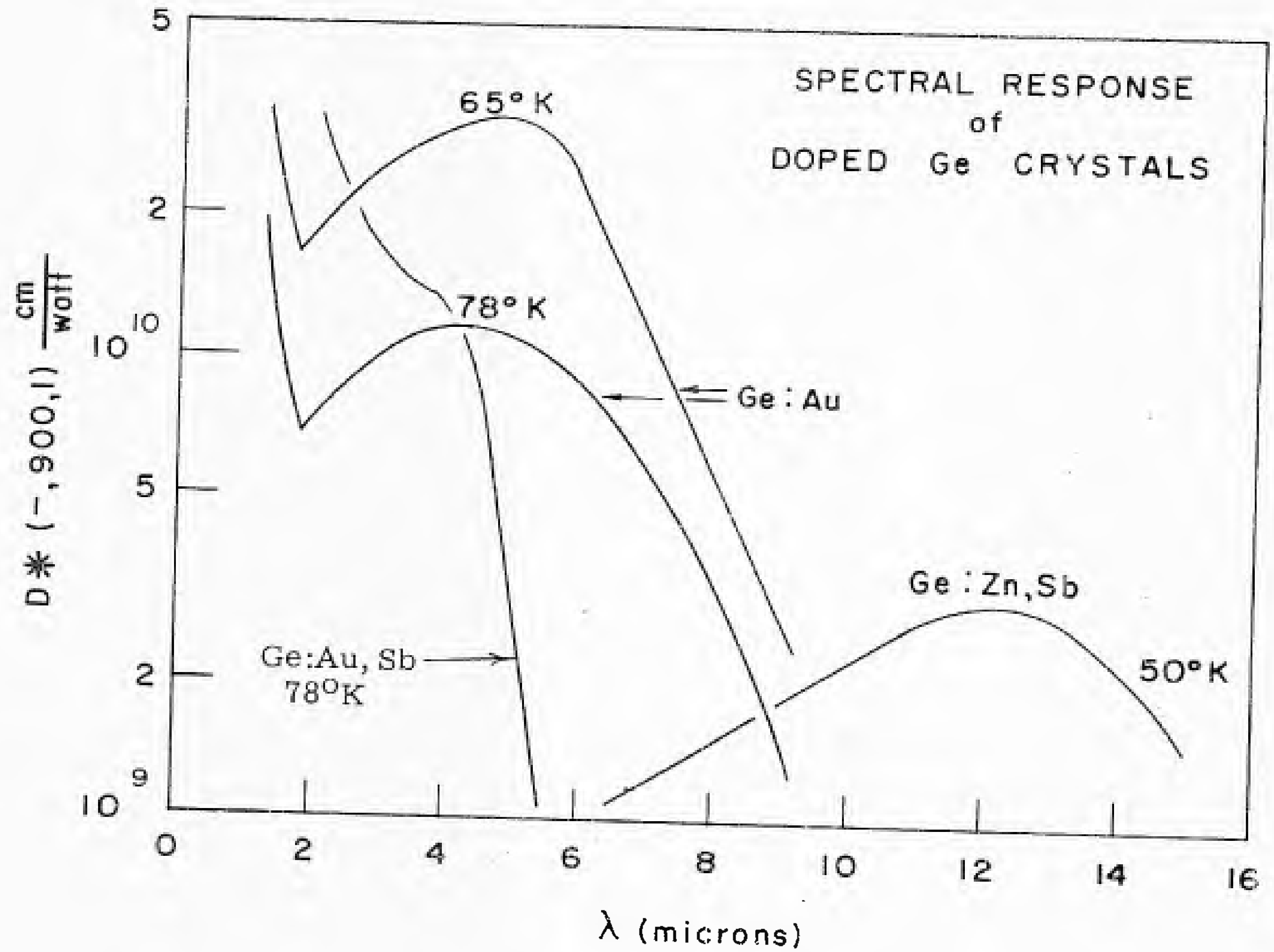


Figure 29 - Absolute Spectral Response of Doped-Germanium Crystals. (Ref. 32)

Both S and N for the optimum operating current may be determined by the relation

$$S = J_s \cdot R_{11} \cdot E \qquad J_s = \frac{s\text{ (optimum current)}}{R_{11}\ E}$$

$$N = J_n \cdot R_{11} \qquad J_n = \frac{n\text{ (optimum current)}}{R_{11}}$$

$$NEP = \frac{J_n}{J_s}$$

where R_{11} is the parallel detector-load resistance combination and E is the energy falling on the detector. In order to indicate by what factor both signal and noise may be increased to allow for a 30% drop in S/N ratio, the factor may be placed in parentheses following J_s. Thus, J_s (4) would indicate that if one allows a decrease in S/N by 30%, the signal level may be increased by a factor of 4. Well constructed 9.5 Ge detectors have so far given the largest values of J_s (0.05 amp/watt and larger); for film detectors, the values of J_s are of the order of 0.01 amp/watt.

3.6.3 Time Constant & Frequency Response

Signal and noise dependence on frequency is more involved than are the preceding parameters. Two methods are currently used to determine the speed of response of a detector. The first consists of flashing radiation pulses on the detector and observing the rise and decay of the photosignal. The second consists of varying the chopping frequency and observing the resulting changes in detector signal. When the decay in signal is exponential after the radiation source is removed, as indicated in Figure 30 a time constant may be defined and both methods yield the same result for the time constant. The exponential decay is frequently not the case. PbSe and PbTe detectors exhibit a combination of a rapid decay of the order of 10 to 20 microseconds, and a slow decay of the order of several hundred microseconds, as indicated in Figure 31. In the most desirable PbTe or PbSe detectors, the slow component should be completely absent or should contribute no more than 10% to the signal. In addition to multiple time constants, many detectors have a wavelength dependent decay behavior. This makes it vital that frequency response measurements be made with radiation in the spectral region in which the detector is to be used. PbTe frequently has a slow decay characteristic in the 1.5μ region. The 9.5μ Ge detector has a slow component extending up to 1.5μ, and the 6μ Ge detector has several slow components extending up to 2.5μ. The use of properly selected filters will, of course, reduce these effects. Beyond 1.5μ, the 9.5μ Ge detector has a time constant less than 1 microsecond.

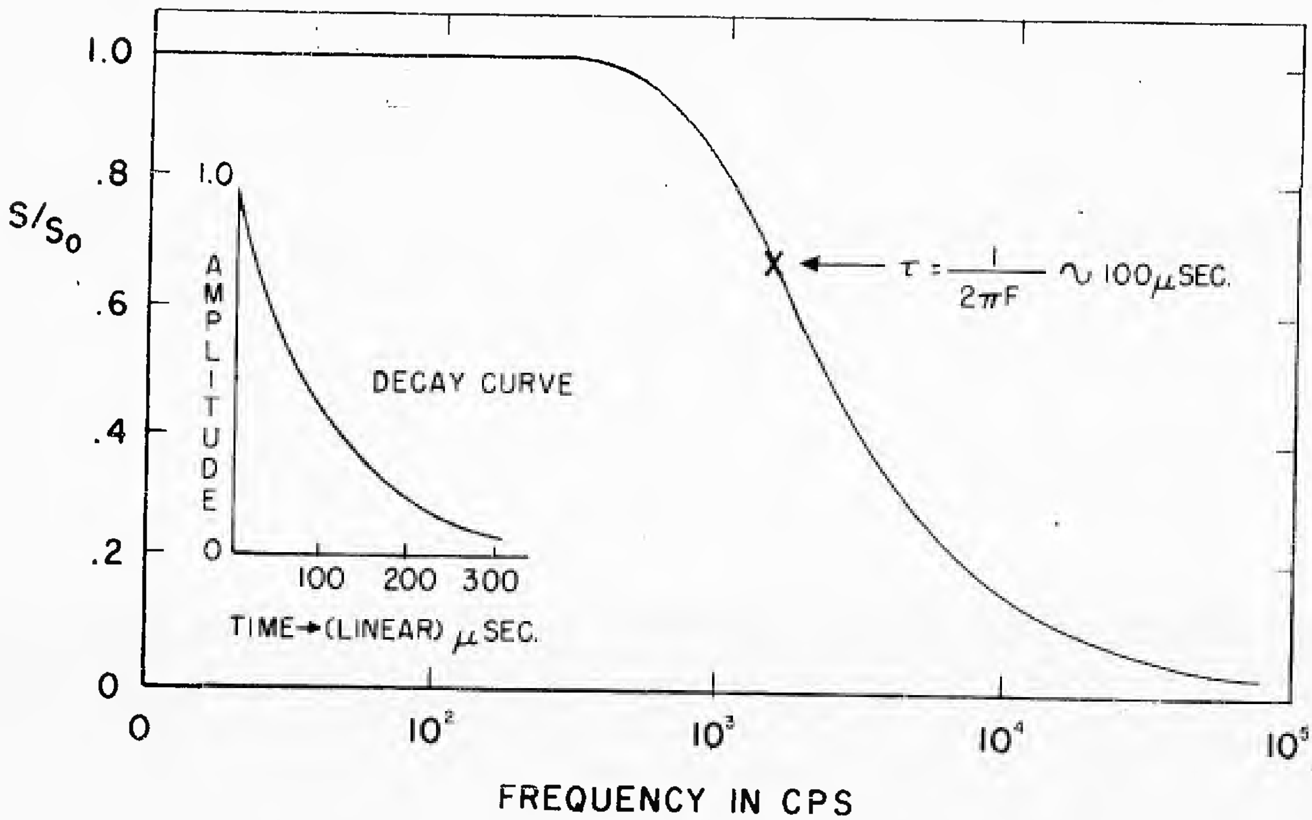


Figure 30 - Determination of Time Constant for Exponential Decay. (Ref. 32)

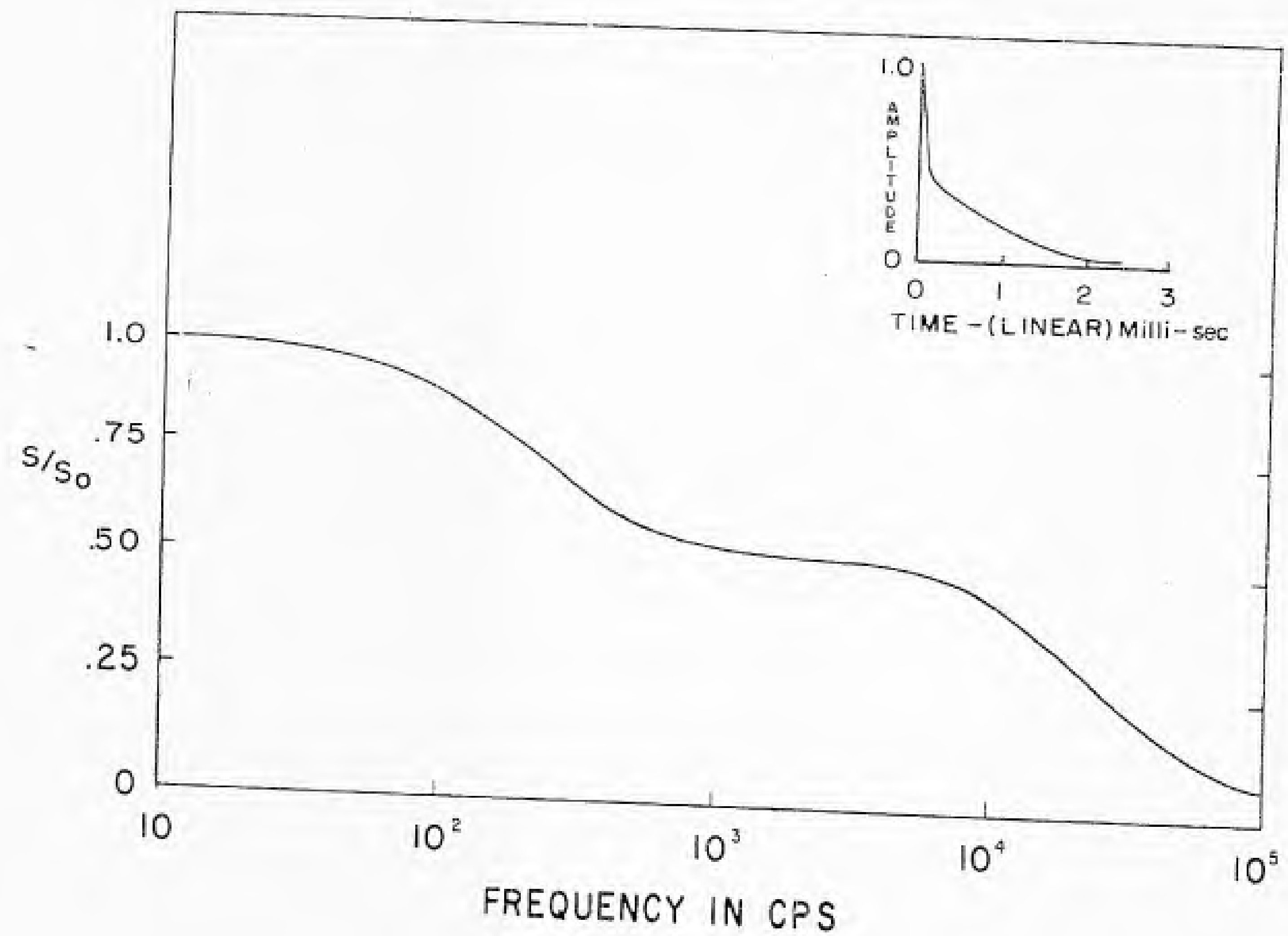


Figure 31 - Combination of Rapid and Slow Decays (Ref. 32)

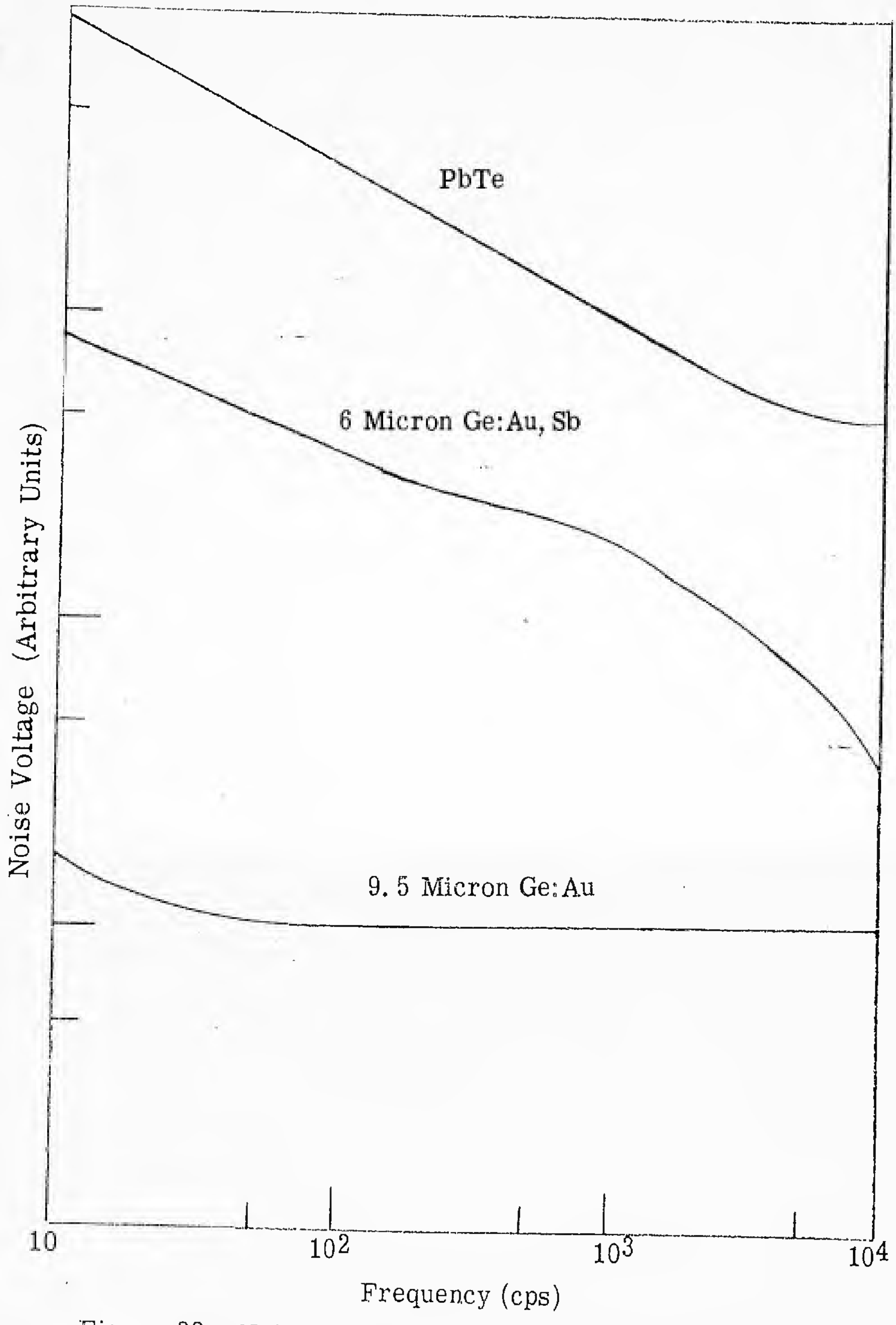


Figure 32. Noise Spectra for Several Detectors (Ref. 32)

3.6.4 Noise Spectrum

The noise spectrum of a detector, in addition to its frequency response determines its range of applicability. Figure 32 shows noise spectra for several detectors. PbTe detectors have a 1/f noise-power spectrum. Noise power in PbSe also decreases with frequency increase, but not as rapidly as 1/f. This makes PbSe useful if employed in conjunction with a circuit with a response which extends to low frequencies. The improvement of D* with frequency is not as pronounced for PbSe as for PbTe. Bulk type detectors exhibit generation-recombination noise, with a frequency dependence exactly the same as the signal. In addition, they exhibit 1/f noise at the lower frequencies. It is now possible to construct 9.5 Ge detectors in which no 1/f noise appears down to frequencies lower than 10 cps. The value of D* for this detector is thus independent of frequency over the frequency region normally used. However, 1/f noise has not been eliminated to the same degree in the other types of Ge detectors. Because of the low noise level of InSb detectors, there is incomplete data on its frequency dependence.

3.6.5 Construction of Cooled Detectors

The wide use of cooled detectors makes it desirable to describe their construction and to analyze the effect of coolant temperature on sensitivity. All have a Dewar type of construction. The various types and cell blanks available is shown in Figure 33. In film type detectors (PbTe and PbSe), where the sensitive element is either an evaporated or chemically deposited layer, the material may be deposited directly on the inner Dewar, or on glass plates which are later cemented onto the inner Dewar war. Well defined areas are possible when the sensitive layer is exposed to the atmosphere after deposition. When this is not done, the well defined area obtainable in many possible configurations is sacrificed for somewhat better sensitivity. Single crystal detectors consist of a slice of Ge or indium antimonide (InSb). In the case of Ge, desired impurities are added during crystal growth. The Ge sample is soldered to a Kovar cap or cemented directly to a glass or sapphire substrate.

Detectors such as PbSe, PbTe, InSb and 6μ Ge have their charge carrier density determined by background radiation at the operating temperature and are not sensitive to small temperature fluctuations. Liquid nitrogen or oxygen may be used as satisfactory coolants. As the long wavelength threshold is extended to 9μ, as for the 9.5μ Ge detector, the charge density at liquid nitrogen temperature is no longer determined only by the background radiation but also by the coolant temperature. Fluctuations in coolant temperature may lead to noise, unless the thermal

A, B, C, D show Dewar vacuum bottle method of cooling.

E, F, G are details of cell mountings to the substrates.

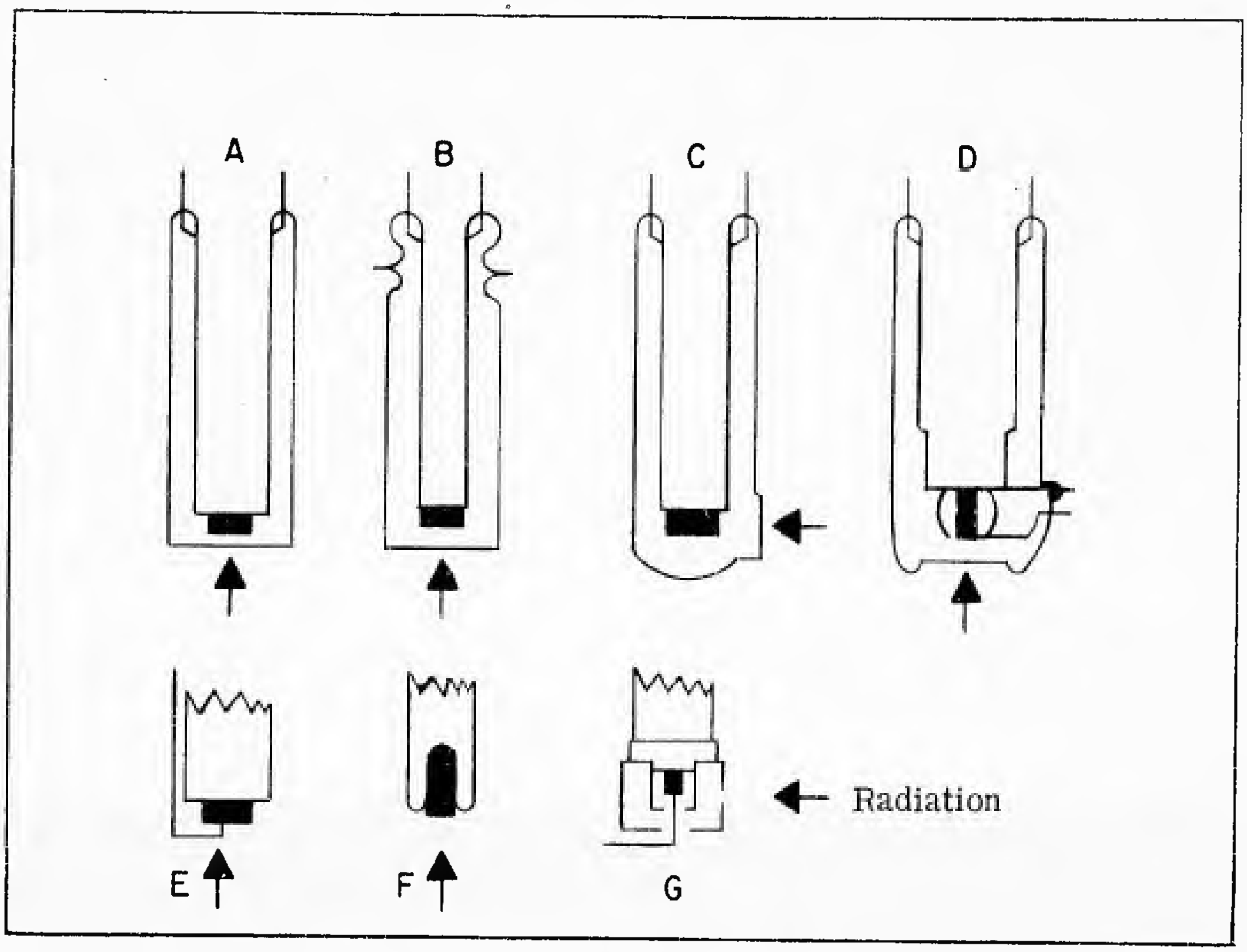


Figure 33 - Types and Shapes of Cooled Cells (Ref. 32)

capacity of the sensitive element is kept sufficiently high. Any variation above liquid nitrogen temperature leads to a decrease in sensitivity, so that contamination with oxygen would be harmful.

Engineering improvements on presently available detectors, and the search for new materials which lead to detectors with different characteristics in the various spectral regions are subjects of continuing work.

3.7 Photovoltaic Detectors

Another photoelectric property of semiconductors is the photovoltaic effect, wherein an electromotive force (emf) is generated when light (ultraviolet, visible, and IR) falls on a PN junction or a metal-semiconductor contact. The generated voltage may be used as a sensitive element to drive a photographic exposure meter, as a solar battery, or as a radiation detector for military applications.

3.7.1 Generation of EMF

In a photovoltaic cell, an emf is generated when light is absorbed in a rectifying contact or PN junction. Figure 34 illustrates the physics behind the photovoltaic process in the case of a PN junction. The junction is considered to be initially in equilibrium with no external bias applied. The absorption of a photon in the barrier with production of an electron-hole pair initiates the process. The resulting particles are separated by the built-in field of the barrier, with the electron drifting into the N-type end of the structure and the hole drifitng into the P-type end. The two regions thus become oppositely charged, and an emf appears at the terminal contacts of the PN structure. Current can thus be generated to flow in an external circuit as long as the irradiation of the junction continues.

The separation of charge in the photovoltaic process is such as to charge the N-type region minus and the P-type region plus. This charging polarity is such as to bias the PN junction forward. If no current is drawn in the external circuit, the open circuit terminal voltage builds up until the junction is sufficiently forward biased to pass forward current corresponding to the rate at which new carriers are liberated by photon absorption, and separated by the barrier field. If the external load is made finite, the generated photocurrent divides between the external circuit and the internal barrier shunt.

3.7.2 Spectral Response

The spectral response of a photovoltaic cell is the same as that of a photoconductive cell of the same material. This is true since the quantities involved in the photoliberation of electron-hole pairs are the same in both cases. One material used is 6μ diffused InSb.

The same physical process occurring in PN junction voltaic cells take place also in metal-to-semiconductor contact photovoltaic cells.

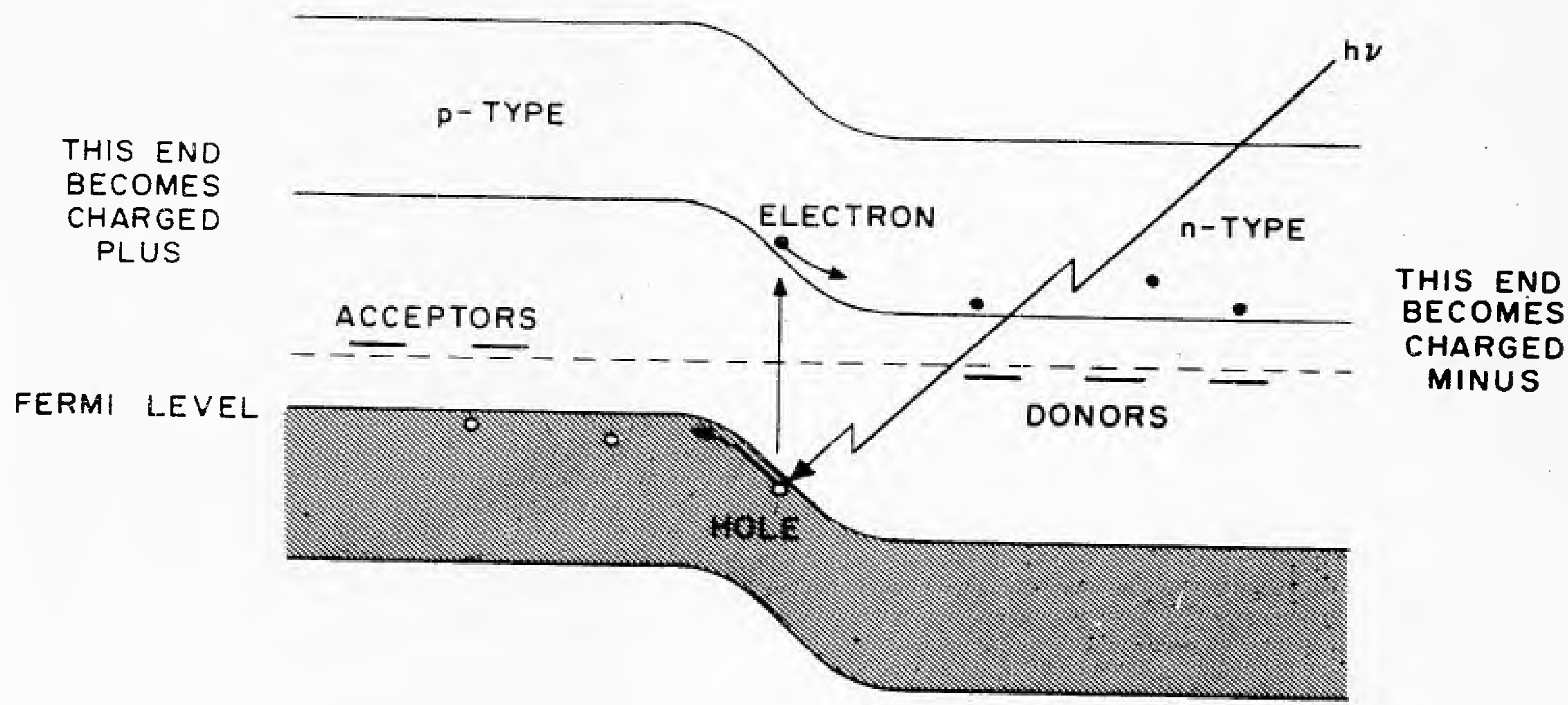


Figure 34 - Energy Level Diagram - Photovoltaic Effect

3.8 Photoelectromagnetic Detectors (PEM)

Photoelectromagnetic detectors operate in the following manner. A thin conducting strip is placed in a uniform magnetic field. Four contacts are applied to the strip as shown in Figure 35. If a beam of light normal to the magnetic field illuminates the surface of the strip, a voltage appears across the strip along the axis that is perpendicular to both the magnetic field and the beam of light. When radiation falls on the strip, extra P and N type carriers are generated at the point of absorption of the radiation. If it is assumed that the radiation is practically all absorbed near the first contact, the existence of carriers at one end and the absence of extra carriers at the other will lead to a diffusion of carriers to equalize the inhomogeneous distribution. The diffusion current tends to be deflected by the magnetic field with P-type carriers deflected one way and N-type carriers the other so that a voltage is generated across the other two contacts. The voltage generated at right angles to the diffusion current forms the signal voltage of the photomagnetoelectric effect.

The signal voltage persists as long as diffusion current flows, and disappears as soon as the flow ceases.

3.8.1 Signal Decay Dependence on Carrier Life Times

The decay of the signal is governed by a different process than the photoconductive and photovoltaic modes. The decay of the signal in the other two modes depended upon the recombination of the extra free charge carriers while the decay of the signal in the PEM mode depends upon the extinction of the diffusion of carriers even though the carriers may still exist in the separated state. If a material has a short life time carrier of P-type and a long life time carrier N-type, then the decay of the PEM signal would be governed by the short life time of the P-type carriers. The reason is that the diffusion depends upon both carrier types moving along together. If the center of charge of the P-type carrier cloud becomes separated from the center of charge of the N-type carrier cloud by more rapid diffusion, an electric field will be generated which would tend to prevent further separation. Therefore, if the P-type carriers become stuck in deep traps, the N-type carrier cloud is stuck also by virtue of the growth of a retarding field in the direction of diffusion.

3.8 Indium Antimonide as PEM Detector

Currently, the only material which has been shown to be competitive as an infrared detector operating in the PEM mode is crystalline indium antimonide. Typical detectivity D* (-, 90 cps, 1 cps) of 1.9×10^8 cm/watt has been attained, and the time constant is less than 1 microsecond.

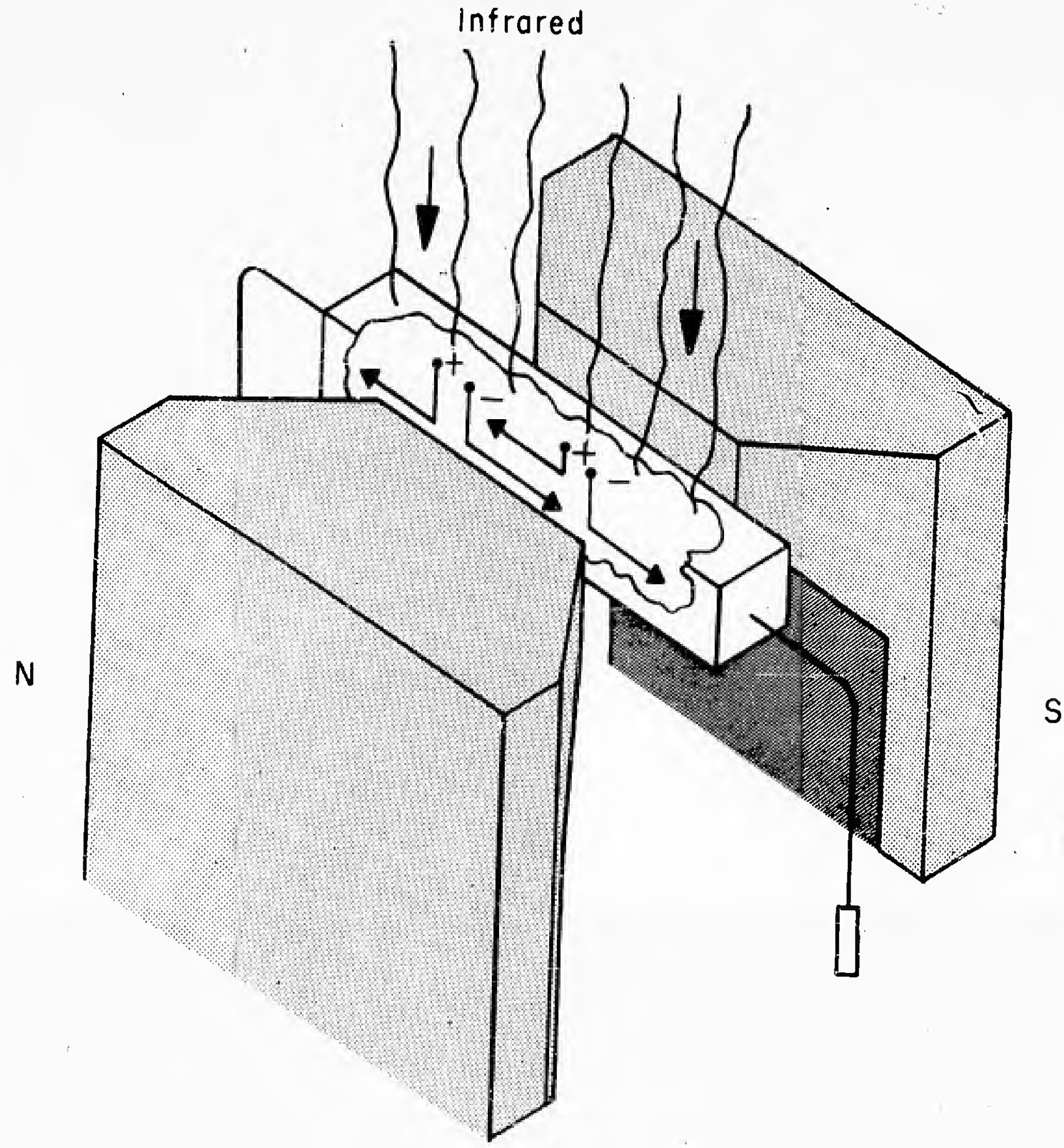


Figure 35 - Schematic Representation of the Photoelectromagnetic Effect.

3.9 Photoemissive Detector

Photoemissive tube operation is somewhat similar to the photodetectors previously described. A photocathode (emitter) and an anode are placed in an evacuated tube. A potential difference between anode and photocathode causes emitted electrons to flow to the anode.

The electrons of the photocathode are excited by the absorption of photons. When a photon is absorbed, it gives up an amount of energy equal to $h\nu$ to an electron. The excited electron is transported to the surface of the photocathode, and if the absorbed energy $h\nu$ is greater than E_W the energy difference between the top of the electron distribution and the potential barrier, (also called work function), the electron will be emitted into the evacuated space.

If the excitation occurs at some distance within the emitter, a further condition must be satisfied, namely, that the loss of energy during transport between the point of excitation and the surface must be small enough so that when the electron reaches the surface it still has an energy greater than E_W and can be emitted. This condition must be satisfied, and unless it is, the quantum efficiency of the emitter will be low inasmuch as only those electrons excited near the surface can escape. This, together with optical reflection loss, is the reason why metals in general are poor emitters.

3.9.1 Semiconductor Photoemitters

All efficient photoemitters are semiconductors. A characteristic of a semiconductor is that the valence electrons completely fill the valence band as shown in Figure 36. Between the valence band and the conduction band, there is a forbidden energy region (in the absence of impurities) where electrons cannot exist. In the diagram this gap is designated as Eg. The potential of the space surrounding the photoemitter is above that of the bottom of the conduction band by an amount E_a. This energy difference is known as the electron affinity.

3.9.2 Minimum Energy for Photoemission

For photoemission to occur, the excited electrons must receive from the absorbed photons an energy equal to or greater than E_g plus E_a. If the energy E_g of the forbidden band is greater than the electron affinity, an electron excited within the material to an energy only slightly greater than Eg plus E_a can move through the material to its surface with only a small loss of energy. This is because electrons cannot exist

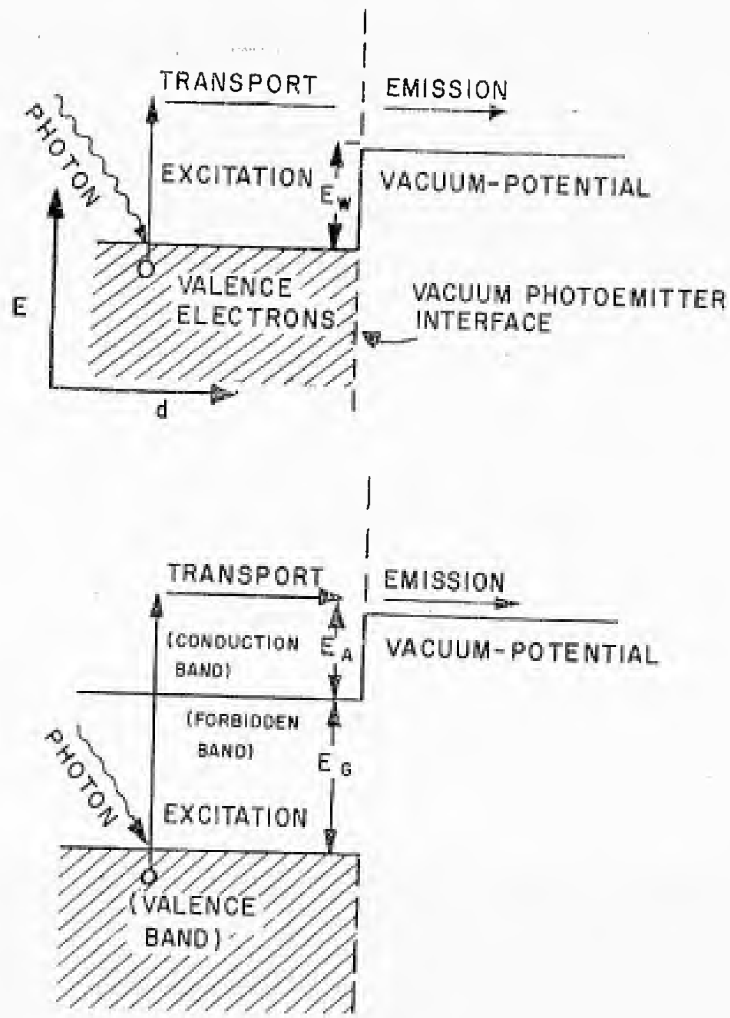


Figure 36 - Photoemitter Energy Diagram

in the forbidden band, and therefore the smallest amount of energy which can be accepted by a valence electron is E_g. An electron having the energy $E_g + E_a$ does not have energy enough to give up an amount of energy E_g to another valence electron. During the transport there will be some loss of energy by the electrons because of scattering. However, this loss is relatively low sothat semiconductors with small electron affinities may be very efficient photoemitters.

The lowest work functions which have been achieved are close to 1 electron volt (ev). Hence, the wavelengths that can be detected by photoemissive tubes are restricted to the near infrared.

3.9.3 Image Tubes

Photoemission detectors such as the image tube, made up of a semitransparent photocathde whose emission is electrostatically focused onto a phosphor viewing screen have been used as near infrared imaging devices in the Sniperscope and Snooperscope. The photocathode of the image tube is made up of a sensitized semitransparent film of silver-oxygen-cesium on the end window. Similar cathodes are frequently used in phototubes, certain types of photomultipliers and similar devices.

3.10 Infrared Sensitive Films

The infrared effects on photographic film have been used in near infrared detection, and have found applications in aerial reconnaissance and photogrammetry. Comparison of infrared and panchromatic film photographs yields information concerning camouflage and types of material because of the variation of spectral reflectance between the visible and infrared. Also infrared penetrates the atmosphere better.

The photographic process involves a photo-chemical reaction, with spectral sensitization by dyes. The photographic emulsion is formed by the mixing of silver halide crystals with a gelatin and a dye that can absorb infrared radiation. The silver halide crystal is a fairly good insulator, and photons in the blue region are required to excite electrons across the comparatively large energy gap, so that the photographic process must start with blue light, in the absence of the infrared dye. The addition of the dye allows the silver halide crystal to absorb photons in the infrared and deposit metallic silver to form the latent image. The spectral absorptivity of the dye, therefore, specifies the spectral sensitivity of infrared film. Film sensitized further into the infrared, would fog at room temperatures before it could be used. The problem in infrared film is therefore one of production and storage.

3.11 Infrared Quenching of Phosphors (Ref. 31)

When a phosphor is illuminated by ultraviolet light, it will glow with a particular color. After the ultraviolet illumination is removed, the phosphor will glow with reducing intensity. If now, the glowing phosphor is illuminated by infrared energy of proper wavelength, the glow would brighten suddenly and then disappear more rapidly than if it were not exposed to infrared radiation.

A phosphor in the form of a sheet can then be used as an image plate very much like the photographic plate itself. If the phosphor plate is placed in close contact with the photographic plate after exposure to infrared radiation, the quenching effect would then provide a darkened photographic plate in the visible region in accordance with the infrared image it has seen.

3.12 Tabulation of Infrared Transducers

Table VIII gives a tabulation of infrared transducers in terms of their modes of operation. Table IX indicates the operating parameters of a number of infrared detectors. Improvement of the various types presently available and the search for new materials is the subject of continuing effort. (Ref. 32, 33).

TABLE VIII - INFRARED TRANSDUCERS

Name or Class of Detector	Transducing Material	Transducing Property	Amplification Method
Golay cell	Absorbing solid in contact with enclosed gas	Thermal expansion in the enclosure displaces a diaphragm	Optical and Photo-Multiplier
Rotating Radio-meter	Low pressure gas and adjacent absorbing and reflecting solid surfaces	Thermal expansion against absorbing surface provides pressure to move the surfaces	No amplification used usually
Liquid Thermometer	Liquid such as mercury or alcohol constrained from a bulb container to move or expand into a capillary	Thermal expansion of liquid observed by eye	Optical
Evaporograph	Thin film of liquid on absorbing solid substrate	Differential evaporation of the liquid film	Interferometric methods
Photographic film (Herschel effect)	Silver halide exposed by visible light to form latent image	Bleaching of latent image by near infrared radiation	Densitometer
Photographic film (Dye-sensitized)	Silver halide mixed with infrared absorbing dye	Production of latent image by near infrared radiation	Densitometer
Quenched phosphor	Zinc sulfide phosphor (for example) excited by ultra-violet light	Quenching of luminescence by near infrared radiation	Photometer or photographic plate with gamma control

TABLE VIII - (continued)

Name or Class of Detector	Transducing Material	Transducing Property	Amplification Method
Photoelectric emission tubes	Photosensitive cold cathode surface	Emission of free electrons which are accelerated by electric field to the anode	Amplification by standard electronic means or directly by electric field acceleration
Thermocouple	Junction of 2 dissimilar metals or semiconductors.	Voltage generated across junction due to rise in temperature	Standard electronic means
Thermopile	Collection of thermocouples wired together usually in series	Voltage generated across junctions due to rise in temperature	Standard electronic means
Bolometer	Conducting metallic or semiconducting ribbon or wire	Change in resistance with temperature	Standard electronic means usually using a bridge circuit
Photoconductive Detectors	Semiconducting material	Change in resistance due to excitation of a free carrier interior to the material	Standard electronic means using potentiometer circuits
Photovoltaic Detectors	p-n junction of semiconductor	Generation of voltage across junction by free carrier generation interior to the material	Standard electronic means
Photomagneto-electric Detector	Semiconducting ribbon in magnetic field	Generation of Hall effect voltage due to excitation of charge carrier gradient	Standard electronic means

TABLE IX - Infrare

1

Type	Spectral Response (Microns)	Time Constant (Seconds)	Electr
Uncooled Lead Sulphide 300 deg. K (+27 deg. C)	0.25 to 2.5	1×10^{-4} to 1×10^{-5}	
Cooled Lead Sulphide 233 deg. K (-40 deg. C)	0.25 to 3.6	1×10^{-3}	
Cooled Lead Sulphide 90 deg. K (-183 deg. C)	0.25 to 4.5	2×10^{-3} to 7×10^{-3}	
Uncooled Lead Selenide 300 deg. K (+27 deg. C)	0.7 to 4.5	5×10^{-6}	
Cooled Lead Selenide 90 deg. K (-183 deg. C)	0.5 to 6.5	18×10^{-6}	
Uncooled Lead Telluride 300 deg. K (+27 deg. C)	0.5 to 3.5	20×10^{-6}	
Cooled Lead Telluride 90 deg. K (-183 deg. C)	0.5 to 5.5	1×10^{-4} to 5×10^{-4}	
Uncooled Indium Antimonide (PEM) 293 deg. K (+20 deg. C)	0.5 to 5.5	1×10^{-6}	
Cooled Indium Antimonide 90 deg. K (-183 deg. C)	0.5 to 5.5	2×10^{-6}	
Cooled Gold-Doped Germanium 90 deg. K (-183 deg. C)	0.5 to 8.5	20×10^{-6}	
Thermistor Bolometer 300 deg. K (+27 deg. C)	1 to 1000	4×10^{-3}	
Pneumatic (Golay) Detector 300 deg. K (+27 deg. C)	0.25 to 1000	1.5×10^{-2}	
Evaporograph	0.7 to 1000	0.5 to 15	
Ferroelectric Bolometer 300 deg. K (+27 deg. C)	0.5 to 1000	1×10^{-1} to 1×10^{-3}	

TABLE IX - Infrared Detector Characteristics

onstant ds)	Electrical Bandwidth (CPS)	Detectivity ($Watts^{-1}$)	Noise Equivalent Power NEP (Watts)	Area (mm^2)	Limiting Noise
4 to 5	5	2×10^{11}	5×10^{-12}	0.25 to 200	Current
3	5	5×10^{11}	2×10^{-12}	2.5	Current
to	5	1.2×10^{11}	7.7×10^{-12}	1	Current
-6	5	3.8×10^{9}	2.6×10^{-10}	6	Current
6	5	4.8×10^{9}	2.1×10^{-10}	8	Current
6					Current
to	5	2.3×10^{10}	4.4×10^{-11}	4	Current
6	5	2×10^{8}	5×10^{-9}	0.5 to 2	Current
6	5	3×10^{10}	3×10^{-11}	3.5	Current
-6	5	6.3×10^{9}	1.6×10^{-10}	3.5	Current
3	62	2×10^{8}	5×10^{-9}	0.2 to 25	Johnson
-2	10	1.6×10^{10}	6×10^{-11}		Temperature
5		$\Delta T \approx 0.1 C$ to $\Delta T \approx 2000 C$			Radiation
to	1	5.5×10^{10}	1.8×10^{-11}	0.25 and up	Johnson

4. CHARACTERISTICS OF IMAGE FORMING AND DISPLAY PRESENTATIONS

4.1 Methods of Display

The means of infrared displays are as varied as the equipment with which they operate. Logical groupings of equipment may be made based on display methods which, in turn, are determined by how rapidly the data must be processed and how much information about the target is needed. In a training application where a warning that an object is approaching from a particular sector may be all that is necessary; on the other hand, a photograph of the sector may be wanted with all possible detail. A sample grouping may be as follows: (Ref. 34).

Date Type	Target Variables	Display	Representative Equipment
Transient	one	Neon flash lamp pips	Gun-sight. Proximity Warning Indicator.
Transient	many	Cathode-ray Tubes	Air-to-air-Search. Battlefield Surveillance.
Permanent	one	Oscillograph	Railroad "hot box" Detector. Rapid Scan Spectrometer.
Permanent	many	Film	Air-to-ground Mapper. Commercial Camera.

In practice more than one display method may be used in an equipment: one for visual monitoring and another for permanent records for future study. For the purposes of this report, emphasis will be on data presentation in the form of images as opposed to meter indications, audio signals and lamps used as indicators.

4.2 Cathode Ray Tubes (CRT)

For high resolution image display the cathode ray tube excels in the infrared field as it does in other applications such as radar and visible light TV. The variety of display techniques in infrared is about as great as those associated with radar, but none are as complex as radar since the active elements are not needed.

4.2.1 Display Variations

Sophisticated infrared CRT displays have a complexity of their own. In early warning systems, other information may be displayed such as past history, data from supporting radar, television, or a second IR set responding to other wavelengths. Memory or variable persistence tubes are useful for target enhancement by integration of the signals, and by cancellation of the noise. Systems subject to variations in platform attitude, as aboard ship, can have display corrections for pitch and roll made by electrically shifting the raster up and down, and right and left. In those systems where the IR scanner moves through a circular total field of view the plan-position-indicator (PPI) type of display has been used. An interesting variation splits the scope into four concentric rings, each ring belonging to a different scan. The history of the three previous scans is then always available for comparison with the most recent trace.

4.2.2 Line or Raster Scan

The CRT display by intensity modulated line scan or raster scan is, however, the most common for those applications with which this report is concerned. For visual display, the raster scan is unexcelled, and unique scanning systems have been devised to take advantage of this type of display. Resolutions of the order of 3000 elements per line are available as well as the dynamic capability of presenting rapid motion intelligibly. Utilizing the eye's integrating effects, moving images may be displayed with stationary background removed. Special electronic switching circuits reversing the polarity of each frame displayed have been developed to achieve this result. The intensity modulated line scan used with a moving film strip is the basis for the familiar aerial mapper or reconnaissance device. The raster scan is also used with a synchronized camera to obtain a permanent record of the images.

The distortions due to use of a curve-faced CRT with a flat film surface has been the subject of much research. Another problem in transposing the image from the tube face to the photographic film is the loss of light. Using the best photographic equipment it has been shown that only one per cent or less of the light emitted from a point on the phosphor finds its way to the film (Ref. 35). About 45% of the light emitted is not received by the photographic system and is consequently wasted while the remainder appears as a halo to the emitting point due to total internal reflections at the glass-air interface of the cathode tube face.

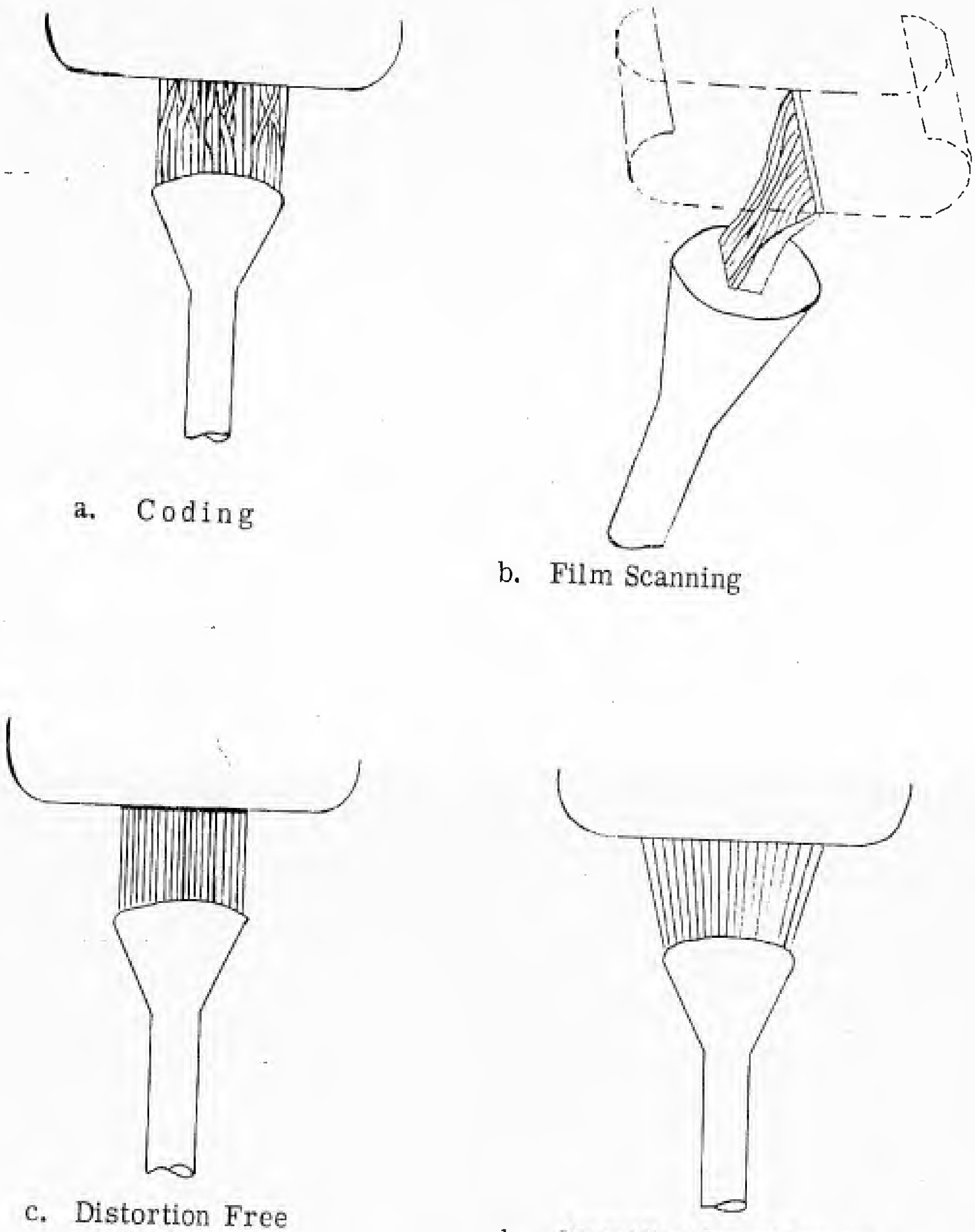
4.2.3 Fiber Optics (Ref. 36)

These difficulties could be overcome by the use of a bundle of glass fibers as the face plate of a cathode ray tube. The emitting phosphor would be deposited at one end of the fibers while a photographic film in intimate contact with the exit end of the fiber bundle would receive from 70 to 90 per cent of the emitted light without distortion. This technique called "fiber optics" is based on the fact that light entering the end of a glass rod is unable to escape out through the sides because of total internal reflections. There is no substantial change until the diameter of the rod or fiber becomes comparable to the wavelength of light, say five or ten microns. If these glass fibers are gathered into an orderly array they will transmit an image by breaking it up into separate components. These components are transmitted independently from one end of the array to the other. However, where two glass fibers come within a half wavelength of light of each other, some light will leak from one fiber to the next. By insulating each fiber from another by a thin jacket of transparent material whose index of refraction is lower than that of the fiber this problem is minimized. Further jacketing of the fiber with a thin highly reflecting metallic film has also been found valuable.

Tubes with fiber optic faceplates capable of the 70 - 90% light transmission mentioned previously are still in developmental stages, but flexible fiber bundles can be used with presently available cathode ray tubes to achieve almost comparable results to fiber optic faceplate tubes. Fibers 50 microns in diameter are most convenient for flexible bundles, but larger size fibers can also be made. In small fused assemblies, bundles can be made whose individual fibers are substantially less than 50 microns, but these are not flexible. By means of tapered fibers, tapered bundles can be made to produce magnification or demagnification of an image. By "scrambling" the fibers a different pattern from the image can be displayed. With the proper "decoding" pattern the original image may be reproduced.

In multi-element detector arrays time sharing or multiplexing is sometimes used in channelling the signals through the electronic circuitry. If the images as received were displayed as a single line scan on a CRT, fiber optics could be used in place of electronic multiplexing to unscramble the image at the photographic film surface. The end of the bundle at the film would have to be scanned in synchronism with the original scanning. One way this might be done is by scanning the bundle across the film as the film moved at right angles to the bundle scanning motion.

Figure 37 illustrates some of the methods discussed above.



a. Coding

b. Film Scanning

c. Distortion Free Transfer

d. Magnification of Image

Figure 37 - Examples of Uses of Fiber Optics

4.3 Glow Tubes

4.3.1 Direct Viewing

With their flat frequency response from dc to 150,000 cps, neon glow tubes have become one of the more widely used methods of recording image detail. One method, used in conjunction with a scanned mosaic or multiple element array, has a bank of neon glow tubes which can be viewed directly. There is a lamp for each detector element. The raster type scan produces an image similar to a TV presentation since the lamp's intensity is modulated by the detector it represents in proportion to the radiation received by the detector. One multiple detector unit built for the Navy has an oscillating presentation mirror phased with the radiometer's line of sight. To the observer, the lamps appear to flash at angular positions corresponding to the actual target coordinates. Where circumstances prevent direct viewing, the lamps can be watched with a television camera or a scanning phototube.

Infrared gun sights use neon glow tubes in configurations to take advantage of the persistence-of-vision effect of the eye.

4.3.2 Film Methods

The more common use of neon glow tubes is in conjunction with photographic film. Single glow lamps scanned by some mechanical mirror system can produce a raster-type image pattern on a photographic plate. The Thermograph is an infrared camera wherein the radiometer makes a raster scan over the field of view. Coupled to the back of the large panning mirror is a small mirror that causes the image of the modulated neon lamp to sweep across a Polaroid film in direct correspondence with the radiometer's position.

One airborne mapper has a line of fixed detectors oriented at right angles to the aircraft heading. During flight, a strip of ground parallel to the aircraft path is viewed by the system which is known as a "pushbroom" scanner. The display uses multiple neon lamps (one for each detector) placed at right angles to photographic film that is moving at a velocity proportional to the aircraft ground speed. The need for individual neon tubes arises because it is not always possible or desirable to combine multiple sources into a single channel. The use of switching devices needed for single channel operation requires each output to be sampled once per dwell time with no signal distortion. The sequential timing stability required may create complexities which overcome the savings due to single channel operation.

4.4. Infrared Film

The theory and chemical reaction of infrared film are covered under Photodetector section. Some discussion of its use would be worthwhile. Visual aerial mapping suffers from the effects of atmosphere as do ordinary cameras. Under hazy or light-cloud conditions visual aerial reconnaissance could be more successfully accomplished by use of near infrared photographic film without the light loss associated with optical filters. For ground reconnaissance or surveillance, the same consideration would apply. For study of battlefield maneuvers of troops undergoing training, an active system combined with a near IR motion picture camera might prove useful. The security-violation associated with active systems usually is not a consideration in training maneuvers.

4.4.1 Infrared Photograph Limitation

Infrared photographic films are limited to the near infrared although dyes to make longer wavelength films are available. The limitation is practical. If the film is to be reasonably sensitive, then only a slight exposure to infrared radiation of the proper wavelength should be required to form an image. It has been shown, for film sensitive out to three microns, that storage or even preparation of this film at room temperature would be sufficient to fog it before it could be used. The problem is not one of devising the longer wavelength film, but of manufacturing longer wavelength unexposed film. Since current photographic techniques are carried out at room temperature, there seems little chance of a simple approach to the extension of IR photography to longer wavelengths. A new sensitizing means is called for, one that can be triggered at selected times by some means such as an external magnetic, electric or acoustic fields. As yet this is a wide open area of research.

4.5 Image Tubes

An image tube is defined for purposes of this report as an infrared sensing device that has simultaneous read-in (compared to sequential or other methods of read-in) and simultaneous read-out. Thus the transducer obviously has to be of a size which covers the total field of view. The infrared image is converted at all points simultaneously by means to be discussed into a visible image for visual observation or photographic film preservation.

4.5.1 Photoemissive Image Tubes. (Ref. 37)

The most familiar image tubes are those that operate on the photoemissive principle discussed in previous sections. Thus these tubes are limited to the near infrared region. The 1P25A is probably the most familiar of this class as it is the transducer for the Sniperscope and Snooperscope equipments of World War II.

Basically, an infrared tube is an evacuated cylindrical glass tube, one end of which is coated with a silver-oxygen-cesium photoemissive surface known as S-1 while the other is coated with a phosphor screen. See Figure 38. Radiation incident on the photoemissive surface causes the photoelectrons to be emitted in a density pattern equivalent to the incident radiation image. These photoelectrons are accelerated toward the phosphor screen and given added energy by applying a high dc voltage, 6 to 20 KV. In addition, the electrons are focused by either an electrostatic or a magnetic field to form an electron image on the phosphor screen. The phosphor converts the electron image to a visual image whose brightness distribution is equivalent to the radiance distribution in the original infrared image. Since the photoemissive surface responds to quanta and not to thermal effects, the resultant infrared and visual images are similar to other images formed by reflected light.

4.5.2 Focusing Method

As indicated, the electron optics used to form the electron image within the image tube can be either electrostatic or magnetic. At the present time, most image tubes are electrostatically focused as the power and size requirements for this mode are very much less than for magnetic focus. Originally, intermediate focusing electrodes were required; latests designs are unipotential.

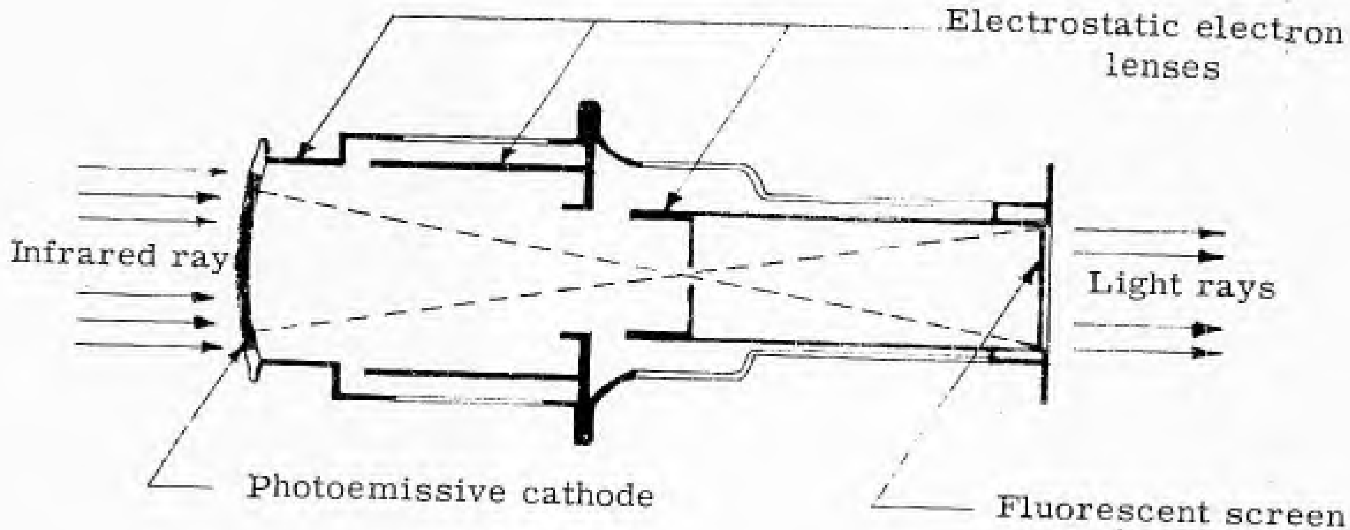


Figure 38 - Image Tube Schematic.

The tighter electron beam with resultant improved resolution of the magnetic focusing mode is the goal of several military development programs. The major bottleneck has been the unavailability of small, lightweight permanent magnets, sufficiently strong to create the necesary field strengths to control the accelerated electrons.

4.5.3 Read-out Phosphor

The read-out phosphor used in military image tubes is the P-20, zinc-cadmium-sulfide, which, although producing a yellow-green picture, is the most efficient phosphor in converting the electron energy into visible light. This phosphor has short persistence, so that moving objects may be seen clearly without smearing. If desired, long persistent phosphors or phosphors of other compositions may be used to obtain different output characteristics.

4.5.4 Overall Sensitivity

The overall sensitivity or gain of an infrared image tube is measured in terms of its "conversion index". The conversion index is determined by projecting one-tenth (0.1) lumen of 2870°K color temperature radiation from a tungsten lamp onto the photoemissive surface. A long-pass infrared filter with cutoff at 0.8 microns eliminates all visible radiation. The lumen output of the phosphor is then measured; the ratio of the output to input flux is the conversion index of the tube. The 1P25A had a conversion index of less than 0.5, but improvements in photoemissive surface sensitivity, increased operating voltages, and increased phosphor sensitivity have resulted in tubes with conversion indices as high as 40.

Examples of the newer tubes are the 6914 and 6929. These are compared in Table V with the 1P25.

Quite a few variations of the basic image converter have been proposed and experimentally developed. (Ref. 38). Most are concerned with image intensification of low level visible radiation, although one has been developed for ultraviolet radiation and another for X-ray use. The modes of operation would be applicable to infrared radiation since the basic principle is photoemission.

4.5.5 Image Intensification Methods

Methods of intensification include demagnification of images, cascading of image tubes, either by using two tubes or one tube using elements of two tubes, electron multiplication by secondary emission schemes, and image intensification by an optical feedback technique.

TABLE X

COMPARISON OF 1P25 WITH 6914 AND 6929

	1P25	6914	6929
Length	4.6 inches	2.75 inches	2.335
Diameter	1.7 inches	1.75 inches	1.375
Operating Voltage	4000 volts	16,000 volts	12KV
Intermediate Focusing Electrodes	3	None	None
Magnification, Cathode to Phosphor	0.5	0.8	0.75
Resolution	8 line pairs/ mm	28 line pairs/ mm	30
Conversion Index	0.4	30	20
S-1 Photo Surface	20-30 ua/lm	30-40 ua/lm	30-40 ua/lm

All these devices are experimental, and have not reached the stage where they can compete with the 6914 as many technical problems have yet to be solved.

The standard television camera tube, the image orthicon has been tried as a near infrared device with a near IR photoemitting surface. Manufacturing techniques have not arrived at the point where this surface can be applied consistently since processing methods have a tendency to damage the IR photo surface. However, several image orthicons have been developed with image intensifiers built into the front end. These tubes, known as the intensifier image orthicon, were developed for low-light-level TV and are under study by Engineer Research and Development Laboratories at Fort Belvoir. Success of these tubes would surely lead to attempt to make near - IR - intensifier image orthicon tubes which would solve quite a few problems in night-time viewing for battlefield surveillance.

4.6 Absorption Edge Effect

That part of the spectral response curve of a semiconductor where the detectivity falls off or "cuts off" is known as the "absorption edge" since it represents the edge of the region beyond which the semiconductor does not absorb energy. In many semiconducting materials, the position of this edge with respect to cut-off wavelengths is a function of the temperature of the material. This was borne out in previous discussions as a means of extending the spectral response region by cooling the semiconducting material. In an optical sense the absorption edge may be regarded as a transmission edge. Thus the wavelength at which the detectivity of a semiconductor falls off is that wavelength at which it starts to transmit. If radiation of a particular wavelength were incident on a semiconductor whose absorption edge included this wavelength, part of the radiation would be absorbed and the rest transmitted. Cooling the semiconductor shifts the absorption edge so that a greater percentage of the incident radiation is absorbed and less transmitted. This characteristic was used by the British to develop a thermal imaging tube.

4.6.1 Absorption Edge Image Tube (AEIT)

The absorption edge image tube was developed by the British Services Electronic Research Laboratories (SERL) by using a unique property of amorphous selenium. Where other semiconducting materials have an absorption edge that shifts into the longer wavelengths with cooling, amorphous selenium has an absorption edge that shifts to longer wavelengths on heating. Also, its absorption edge is very steep, occurring in the visible region. The sodium D lines are just inside the absorbing region with some small percentage of transmission due to the slope and curvature of the edge (Figure 39) depending on the thickness of the selenium. If a thermal image were incident on a thin selenium layer, the warmer parts of the image would cause localized heating of the selenium. These warmed areas would become more opaque to sodium light also incident on the selenium and a dark thermal image could be made visible to the eye by proper optics.

Figure 40 shows the arrangement of the absorption edge image tube. Sodium light is viewed by transmission through a metallized selenium layer. The selenium layer is made very thin. A thermal image is impressed on theselenium layer by a reflecting mirror through a sodium chloride window. Since the soldium light is transmitted better by the cool parts of the selenium, the visible thermal image is dark. The thin metal film on the sodium light side of the selenium layer causes much of the incident infrared radiation to be absorbed by the combination layer of proper thicknesses in which the radiation meets the selenium first. (Ref. 39).

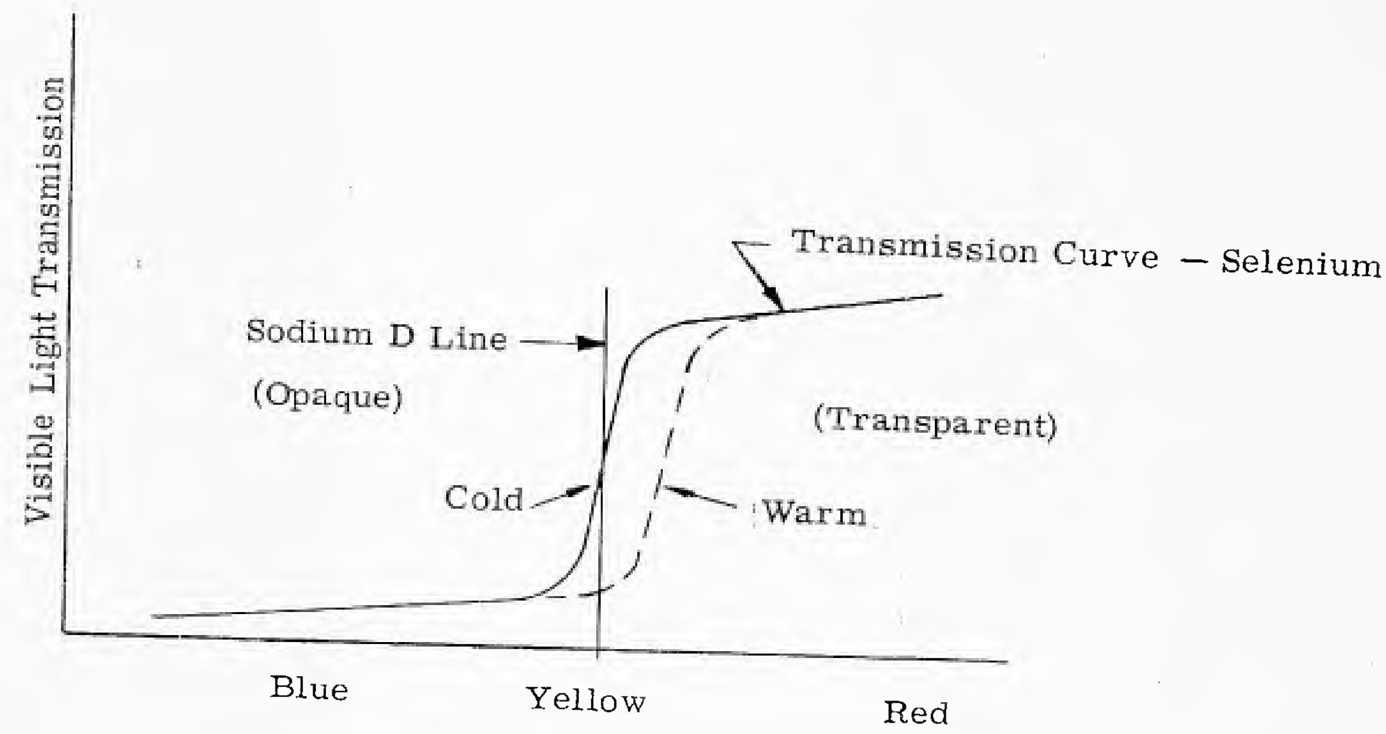


Figure 39 - Absorption Edge Effect

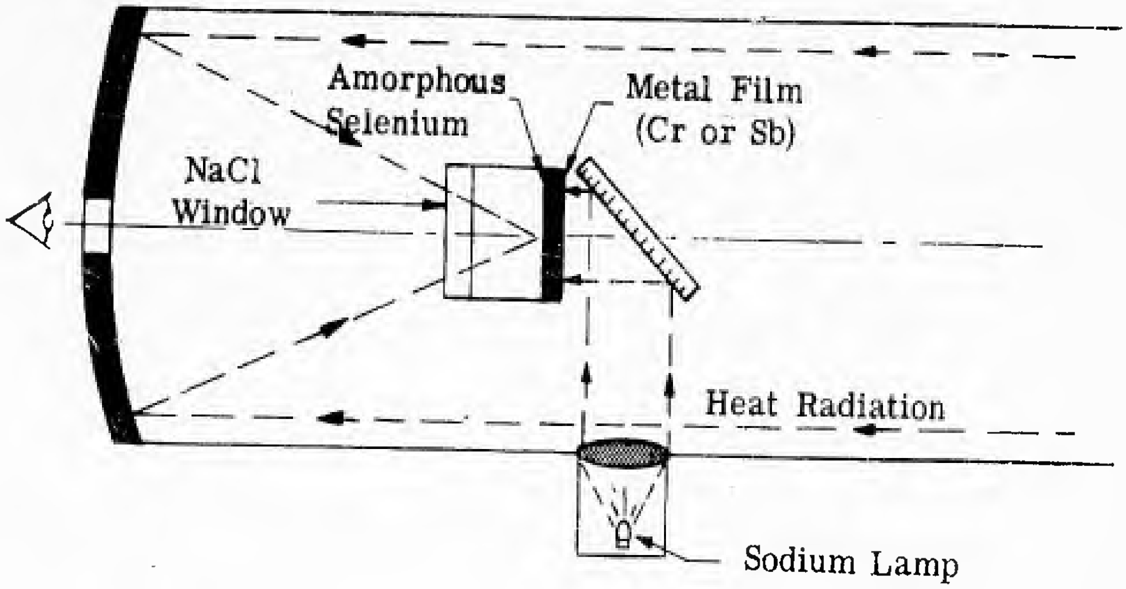


Figure 40- Absorption - edge Image Tube

4.6.2 Edgegraph Image Tube

The edgegraph was developed under Project Michigan as a variation of the AEIT to get better performance and a more psychologically satisfying image of brighter image areas representing warmer target areas. (Ref. 41).

Figure 41 shows the difference between the edgegraph and AEIT. The selenium is coated with a gold film to increase the amplitude of the back reflected ray to the point where, at ambient temperature, nearly complete cancellation, due to selected selenium thickness, occurs between the rays reflected from the front and rear surfaces. Thus the unexposed selenium film appears dark. If exposed to infrared radiation, the temperature of the selenium layer varies locally causing the shift in absorption edge. The areas of increased absorption (warmer areas) decrease the amplitude of the back reflected ray and the front reflected ray appears as a bright spot coinciding with the warmer areas of the thermal image. There is an added advantage in this mode of operation compared to the AEIT as studies have shown that the eye can detect smaller brightness differences (lower contrast ratios) where the background is dark.

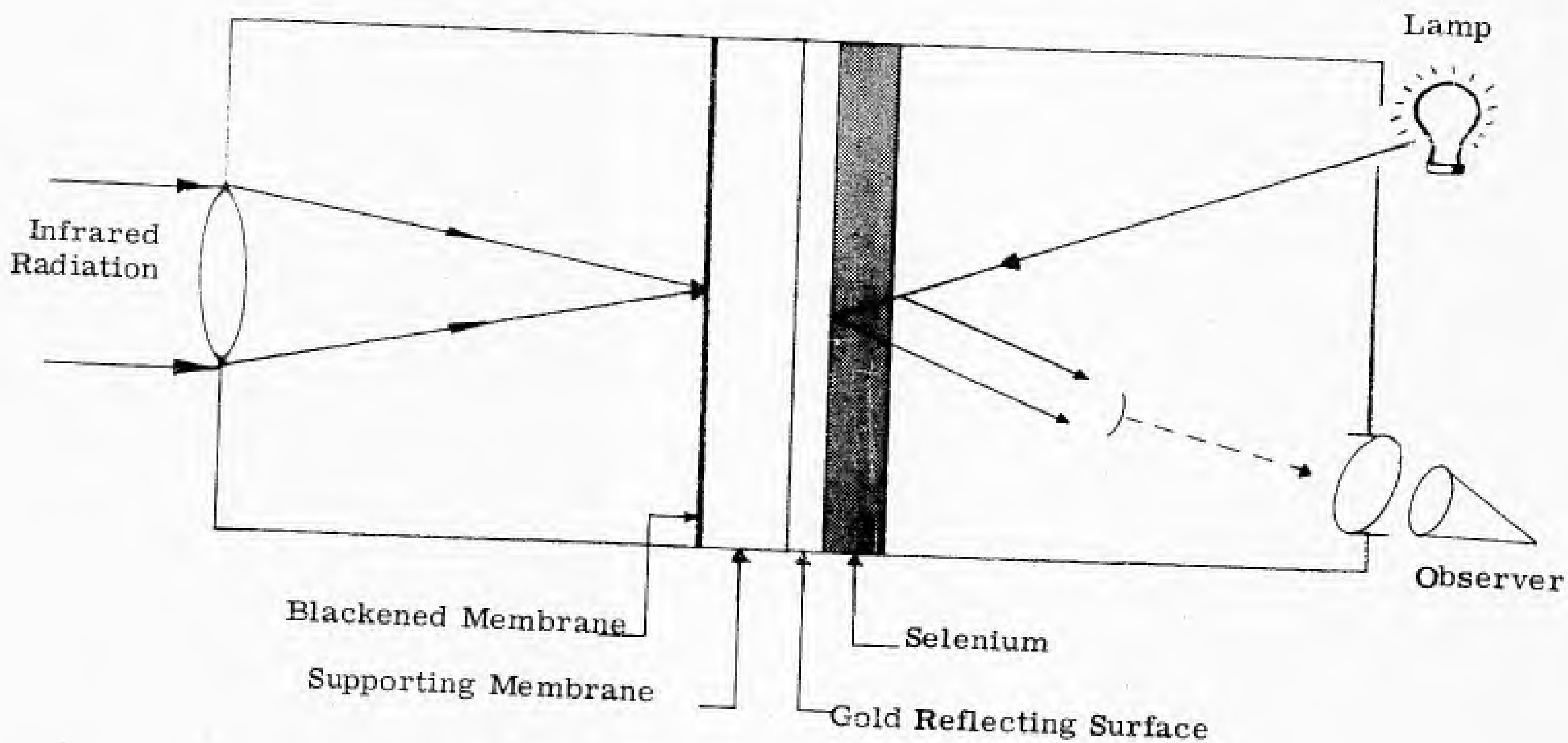


Figure 41 - Schematic of Reflection Edgegraph

4.7 Other Displays

4.7.1 Evaporograph (Ref. 42) (Figure 42)

The Evaporograph is a direct thermal imaging device using the change in rate of evaporation or condensation due to localized heating of an oil film by infrared radiation. Figure 42 shows the details of the cell. The sequence of operation is as follows.

The optical system gathers infrared radiation from the field of view and forms an image of the field on the membrane. A special coating on the front surface of the membrane absorbs this radiation and changes the temperature from point to point in accordance with the amount of radiation received by each portion of the membrane. A heat "picture" is thus impressed on the membrane. These point to point temperature variations alter the thickness of an oil film being condensed on the rear side of the membrane. Thus temperature differences are resolved into differences in oil thickness. A white light shining on the membrane is caused to be reflected as different colors giving a visible, colored thermal image of the entire field of view. The colors have no relation to the visible colors of the objects, but are "interference" colors and refer only to temperatures.

The radiant power from an object will remove oil at a certain rate from the membrane, as follows: $H_a t = KX_a$

where H_a = radiant power of the image (irradiance), watts/m^2

t = time, seconds

K = constant

X_a = oil thickness removed (arbitrary units)

The irradiance from the background or surroundings will remove oil at some other rate:

$$H_b t = KX_b$$

The difference in radiant power will then create an oil film thickness difference

$$\Delta Ht = K\Delta X$$

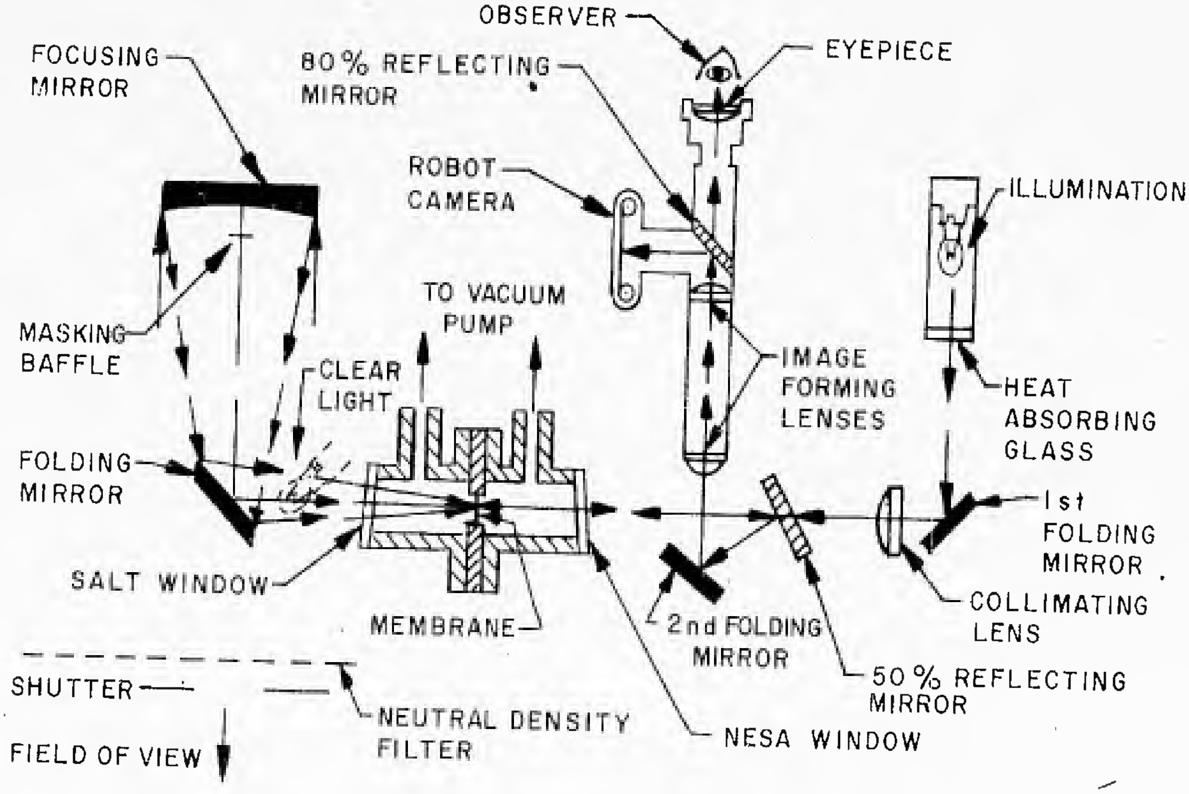


Figure 42a Evaporograph

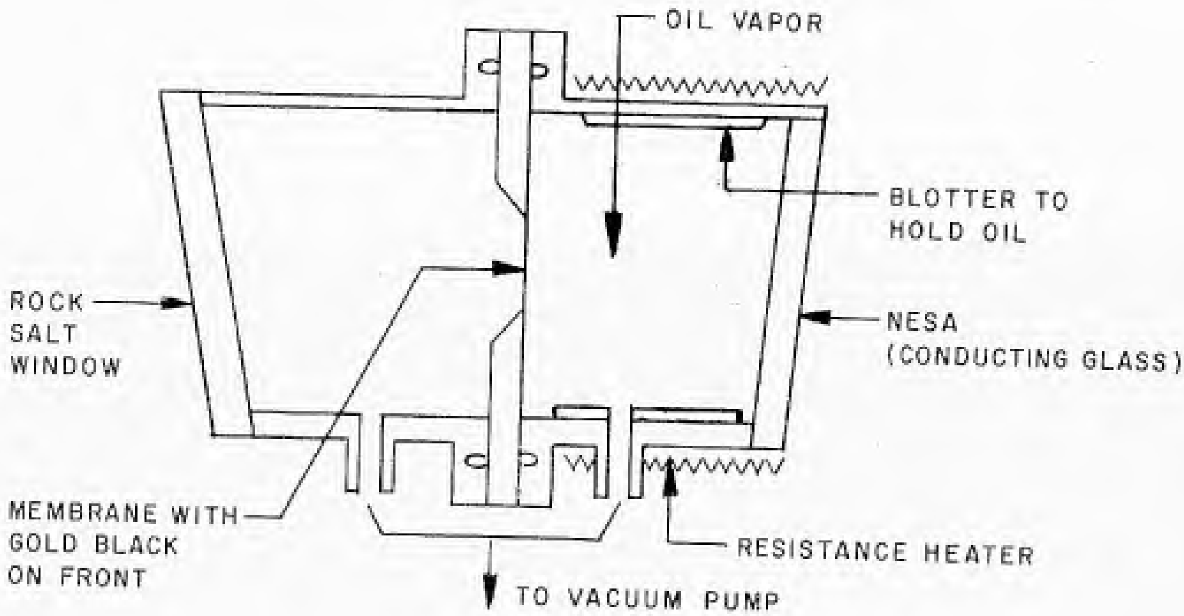


Figure 42b

Details of Evaporograph Cell from Baird Associates, Inc.

where H = net irradiance, watt/m^2

X = oil film thickness difference

The range of temperatures being observed determines the method of operation employed. Radiation from objects above 80°C will be sufficient to cause evaporation of the oil film at a rate greater than the rate of condensation; whereas, below 80°C the rate of condensation is merely retarded. In the evaporograph method for temperatures above 80°C the shutter is kept closed for several seconds to allow an initial oil film to deposit. Then radiation from the field of view causes evaporation as a function of the image.

In the condensograph method for temperatures below 80°C, the shutter is left open during the entire cycle as the radiation is not great enough to evaporate away the oil film; merely great enough to alter the rate of condensation.

In both methods, a clearing light is used to evaporate all the oil from the membrane as a means of wiping off an old image before viewing a new one.

Time required to form an image is dependent upon temperature differences. The formation of the image of a man at room temperature ($\Delta T = 30^{\circ}F$) requires about 15 seconds; a hot soldering iron ($\Delta T = 600^{\circ}F$) requires a fraction of a second.

A commercial instrument known as "Eva" is produced by Baird Associates, Inc. Its principal uses are the measurement of temperature differences for inspection purposes, insulation studies, and detection of hazardous area "hotspots" by remote monitoring.

4.7.2 Expandograph (Ref. 41)

Another thermal image tube under development by Project Michigan utilizes the change in physical dimensions of matter with temperature. The local expansion of a single or multiple-layer membrane in the neighborhood of an infrared image is used to produce a distortion, which appears as a dimple in the surface of the membrane. Since extremely small surface distortions can be detected optically, very small temperature differences (less than 1°C) can be detected in this way. The speed of response is comparable with that of the edgegraph, but the resolution achieved thus far is inadequate for practical use. It is interesting to note that resolution can be traded for sensitivity by the simple expedient of changing the tension in the membrane. This is conveniently accomplished by applying a dc heat bias to the membrane.

4.8 Color Translation

An interesting technique uses different colors in a display to indicate ranges of temperature differential. Thus yellow might indicate near IR, red for intermediate IR and green for far infrared or lowest temperature difference. This approach has been investigated by several organizations, the most familiar probably being that of the U.S. Army Signal Research and Development Laboratory (SRDL) at Fort Monmouth.

The patterns seen in color translation are quite unusual and their interpretation requires a thorough understanding of the underlying physical phenomena and processes. These processes become particularly complicated in daylight, where both reflection and emission are involved. (Ref. 43).

4.9 Comparison of Resolution and Contrast of IR Imaging Devices

A comparison of characteristics of infrared sensitive detecting and imaging devices, such as spectral response and detectivity, presumes that the terms have been defined. In the characteristics under consideration, resolution and contrast, the definitions are quite varied. Part of the difficulty lies in the different applications, and methods of information collection and display; another difficulty is that the evaluation of resolution and contrast of the display is subjective.

4.9.1 Definitions of Resolution

Resolution can be described for a detector cell in terms of its time constant or frequency response. A detector with a time constant of 1 millisecond will have a frequency response of:

$$f = \frac{1}{2\pi\tau} = \frac{1}{2\pi \times 10^{-3}} = 159 \text{ cps}$$

and will be able to resolve 318 bits of information per second.

Resolution can also be described in terms of a solid angle projected through an optical system. A cell combined with an optical system may be described as having a resolution of 1/4 degree by 1/4 degree, for example; this resolution is dependent upon the size of the cell and the optical system characteristics.

If some means of scanning to provide a raster display is employed, resolution may be given as lines per millimeter (mm), lines per inch, or, as in television practice, lines per frame or picture. Actually, if the scan rates are taken into consideration, this is just another way of expressing the frequency response of the system.

As a function of range resolution can be defined as the maximum distance at which two points are resolvable as two separate points. In this case, the optical system may be the controlling factor as the circle of confusion due to aberrations may limit the resolution.

Systems using individual cells or arrays of cells, such as photoconductors, bolometers, thermocouples, etc., have resolutions determined by cell size and frequency response. This is really resolution in terms of bits of information per second. The cell size, in conjunction with the optical system, determines the angular size of the bit, and the frequency response determines the number of these bits the system can detect in a second.

4.9.2 Resolution in Terms of a Common Reference

Comparison of system resolutions are difficult because of these several methods of defining resolution. Conversion to some common reference, such as bits per second, is necessary. This conversion requires that much more information be given than is usually supplied. For instance, an airborne reconnaissance system whose resolution is specified as 1/4 degree would have to provide lowest usable altitude, maximum aircraft velocity, and total field of view to permit conversion to bits per second.

This is also true of raster-type systems where resolution is given in terms of elements per picture or elements per mm. Scan rate information is needed to convert to bits per second. A TV picture with a resolution of 500 elements per line can be said to have a resolution of 500 x 500 or 250,000 elements in one frame time or 1/30 second. This is equivalent to 7,500,000 bits of information per second. It is much greater than anything achievable to date by optical-mechanical systems using thermal or photoconductive detector cells. At present, these systems have resolutions less than 100,000 bits per second. (This comparison may explain why there is such great interest in developing thermal image tubes which can be electronically scanned to provide higher resolutions over wider spectral regions.)

4.9.3 Resolution of Direct View Image Tubes

Resolutions of direct view image tubes seem to be as good as that of electronically scanned image devices. A comparison in terms of bits per second is difficult, as there are no scan rates involved. Comparison is best carried out by means of one of the standard resolution charts in terms of resolvable lines per mm. The 6929 image tube (see Section 4.5) has a resolution of 30 lines per mm or better than 750 lines per inch. The multiplier vidicon (see Section 5.3.1) has a resolution of 400 lines per inch.

The frequency response of the direct view tube such as the 6929 is considered in relation to moving targets. It determines the limiting orthogonal velocity an object can have relative to the optical axis of the image tube and still be seen. This is also true of electronically scanned image devices. The range of velocities usually encountered are well within the imaging capabilities of these devices.

4.9.4 Effect of S/N on Resolution

In the above discussion, an important factor affecting resolution has been ignored. This factor is the signal-to-noise ratio (S/N). Any comparisons made without taking S/N into consideration is almost meaningless. As a rule, low signal-to-noise ratios cause a degradation of resolution. Comparisons of systems should be made under equivalent signal-to-noise conditions. A TV system operating at low signal levels could conceivably have a poorer resolution than an optical-mechanical system operating at optimum.

This last factor makes any comparisons of systems on the basis of relative resolution and contrast very difficult since information relating resolution to signal strength is not usually given.

4.9.5 Image Quality

Actually, resolution and contrast are only two of several factors involved in any consideration of an image. The term "image quality" is used often to describe a picture; this has been based on seven factors: (Ref. 45).

1. Brightness or overall illumination level.
2. Size and shape of the images.
3. Visual noise.
4. Contrast (Brightness range between small adjacent areas).
5. Contour formation (Brightness must change sharply for contour to appear.)
6. Sharpness (Depends on both image and eye. Resolution functions as a limiting factor for sharpness - it is resolved lines which are not sharp. However, resolustion does not determine sharpness. Barely resolvable lines may or may not be sharp. This is important since it implies that resolution cannot be the sole determinant of the value of a system in terms of being able to produce images of good quality.)
7. Background Complexity.

Schade (Ref. 46) made one of the first attempts to bring some order out of this confusion by a detailed analysis of the factors determining image quality. His work and that of others (Ref. 47) are only beginnings in a field still requiring a great deal of further study.

5. PASSIVE SYSTEM SCANNING TECHNIQUES

5.1 Airborne Optical Mechanical Scanning Techniques (Ref. 48)

Since no direct imaging detector has yet been developed for operation in the intermediate or far infrared regions, high resolution detector elements have been used in conjunction with some kind of mechanical scanning process to continuously sample the field of view. The field of view is then synthesized on a CRT face or on film by intensity modulating an electron beam or a light beam with the sampling signal and deflecting the beam synchronously with the motion of the scanner.

By far the greatest number of infrared imaging systems has been developed for aerial reconnaissance activities. The common scan motion is transverse to the aircraft's flight, with the aircraft's forward motion then supplying an orthogonal scan motion. Permanent film recording is generally in the form of a strip map of the terrain below the aircraft as illustrated in Figure 43.

5.1.1 Scanning with a Plane Reflector

One popular and successful scanning technique is to rotate a 45° plane folding reflector which directs radiant energy to a fixed collector. The collector then focusses the energy upon a detector. An optical configuration is shown in Figure 44. A multi-faced pyramidal scanning mirror provides several transverse scans, per revolution. The incoming bundle of radiation, after being folded 90° by the scanning mirror is focussed upon the detector by a paraboloidal collection mirror.

5.1.2 Drum Scanner

Drum scanners can have either reflective optics or refractive optics. They may also produce several scans per revolution through the use of multiple optical elements. Figure 45 illustrates a refractive optical system.

An example of the reflective type of drum scanner is the scanner configuration shown in Figure 46. Here, three mirrors produce three 60° transverse scans per drum revolution. A unique characteristic of the reflective drum optical system is that it is constrained to an odd number of optical elements. This is so that the active mirror can "look" between the two mirrors on the opposite side of the drum.

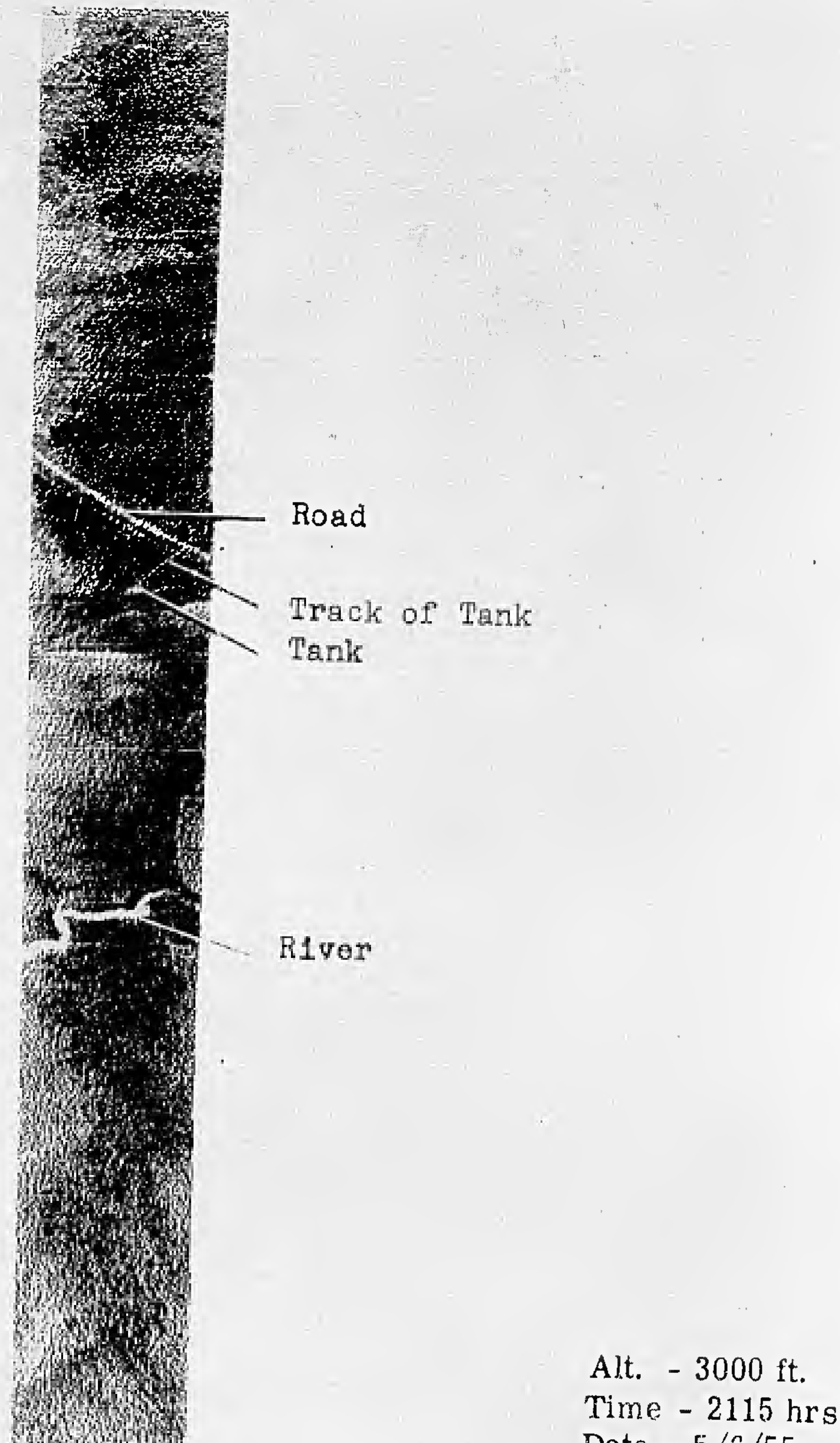


Figure 43 - Thermal Recording During Project Applejack

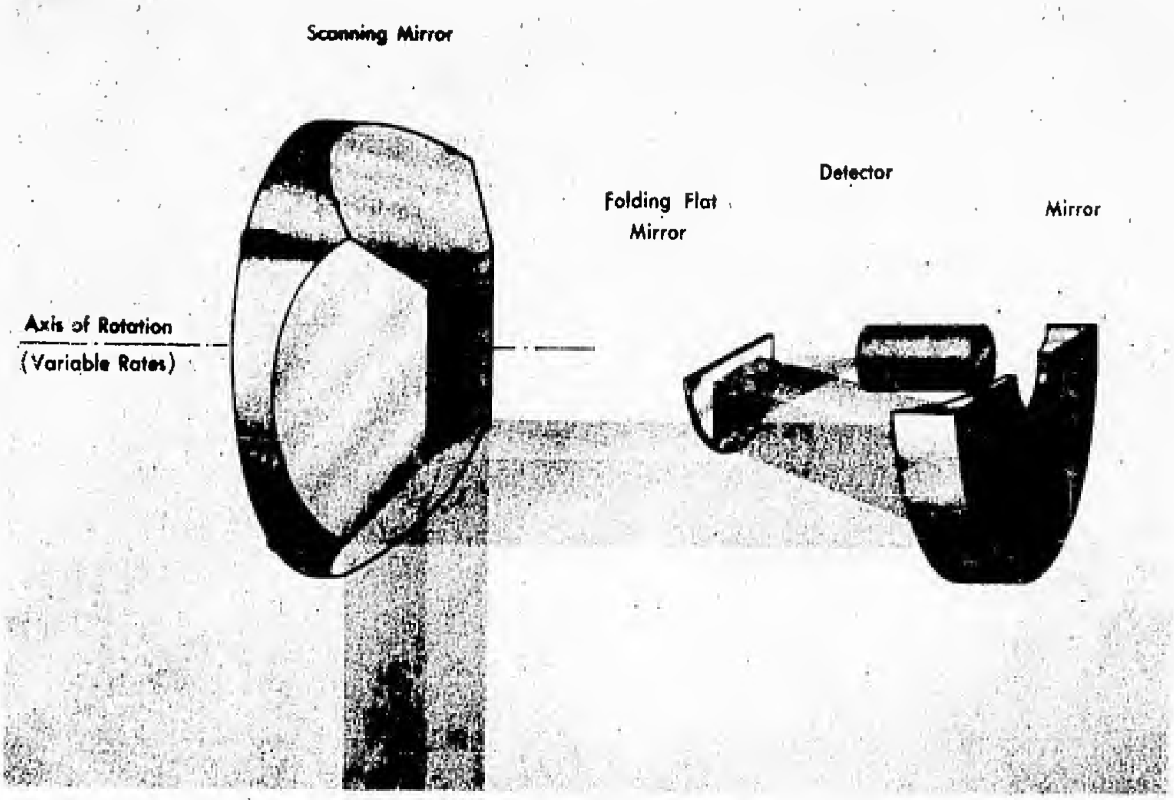


FIG. 44(a) REPRESENTATION OF OPTICAL SYSTEM

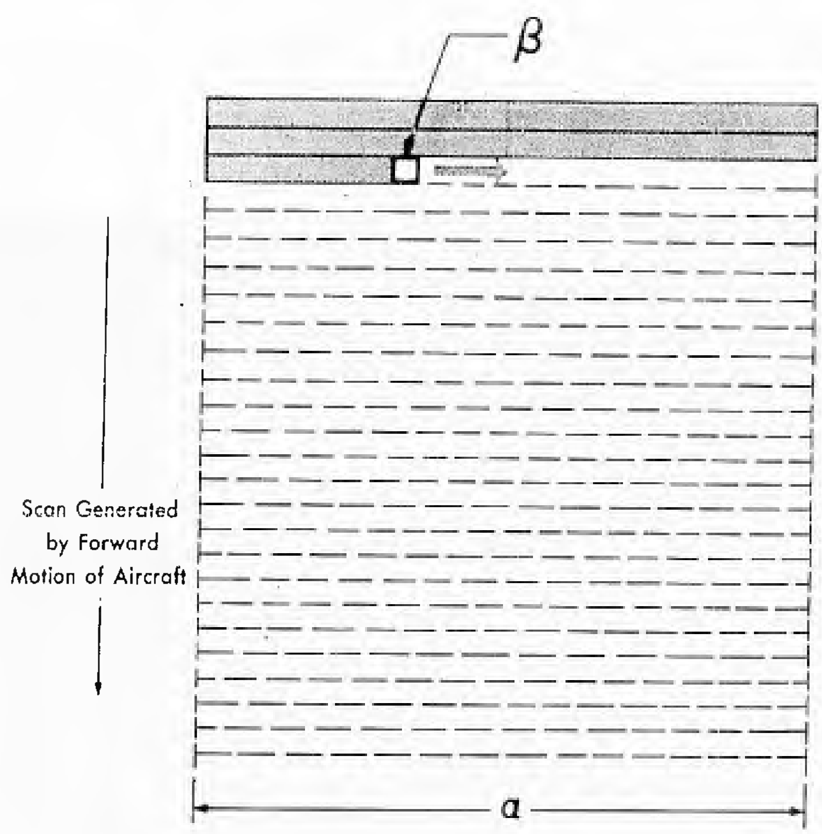


FIG. 44(b) REPRESENTATION OF SCAN PATTERN

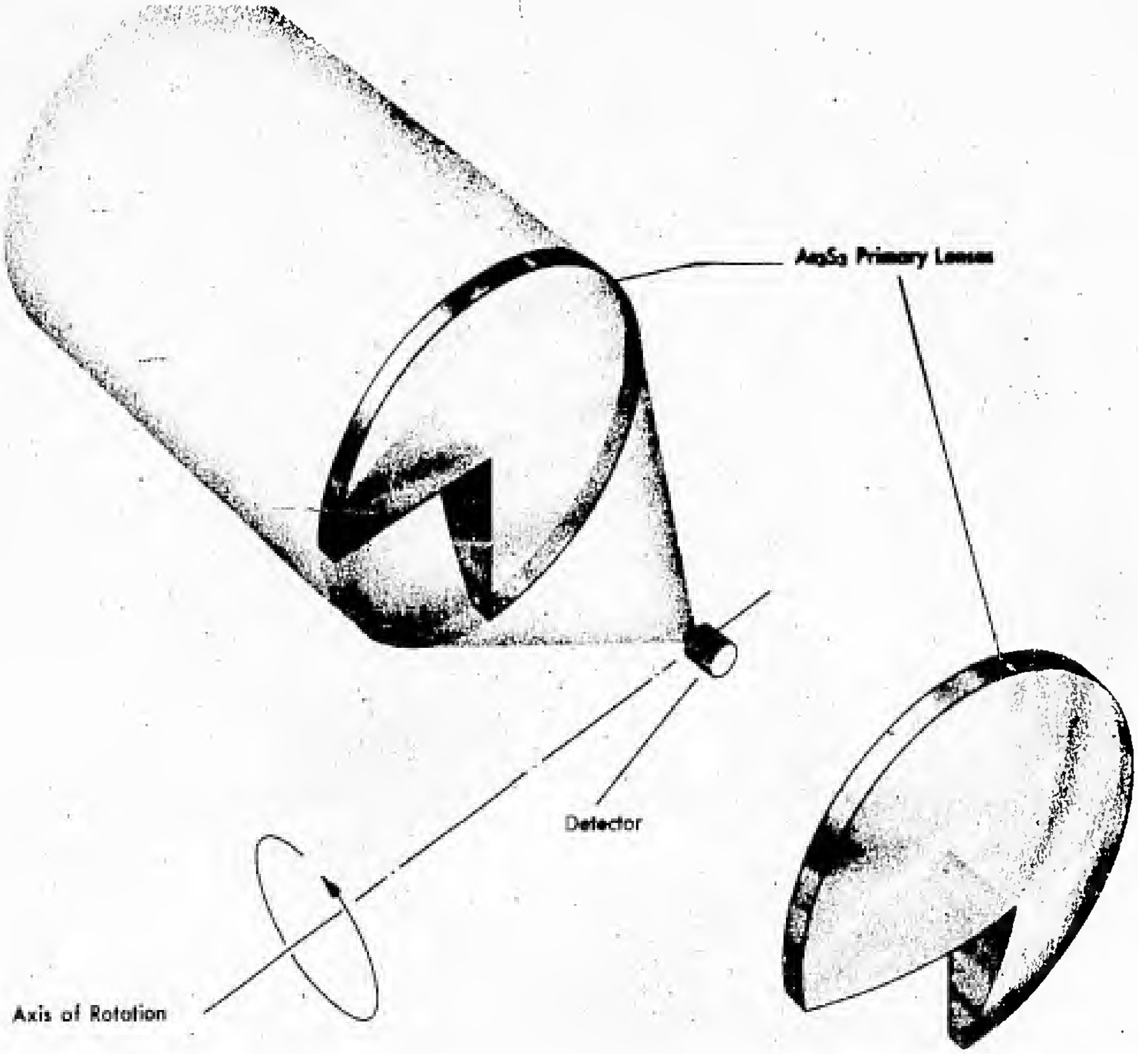


FIG. 45 (a) REPRESENTATION OF OPTICAL SYSTEM

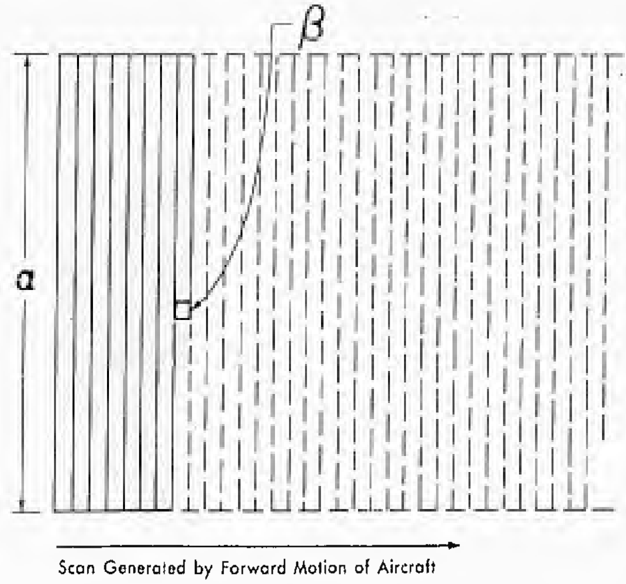


FIG. 45 (b) REPRESENTATION OF SCAN PATTERN

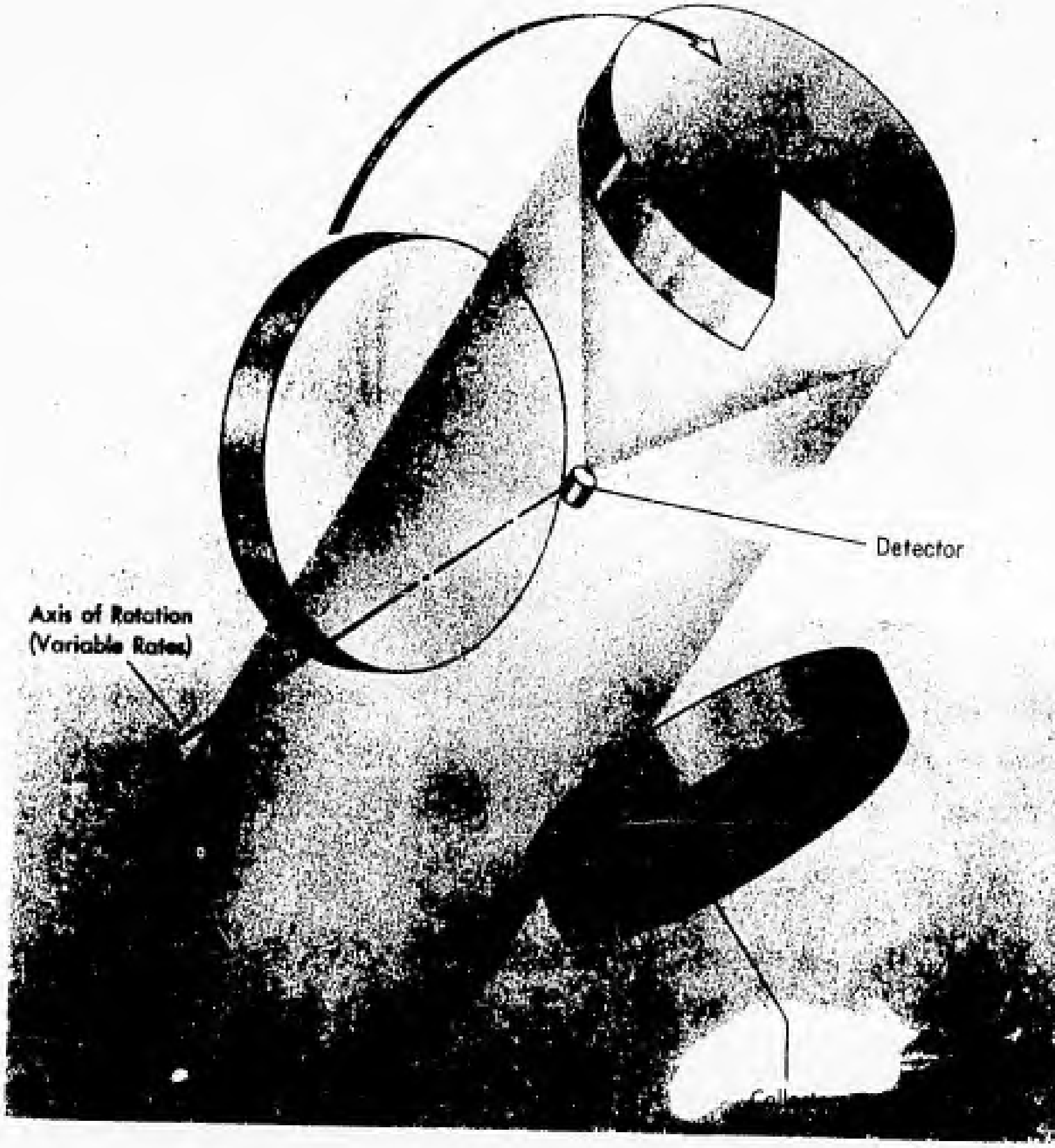
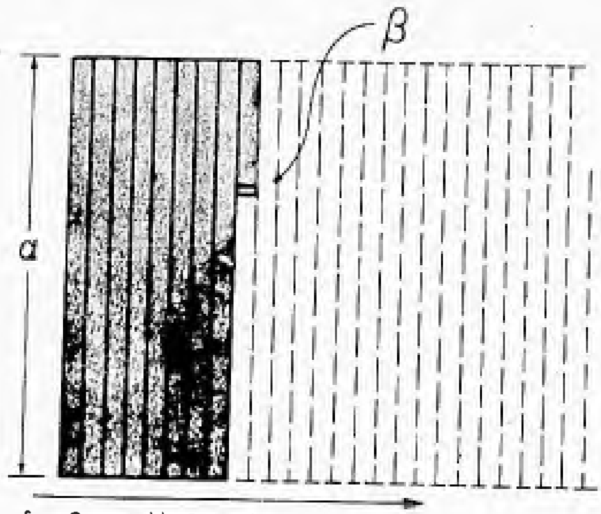


FIG. 46 REPRESENTATION OF OPTICAL SYSTEM



5.1.3 Effect of Increase in Drum Speed

Requirements for new equipment are greater angular resolution, greater total field of view, and faster coverage of the field (for aerial surveillance, this is to permit higher aircraft speeds, for battlefield surveillance, it is to permit following faster action). In order to meet these requirements, an obvious solution is to increase drum speed. However, there is a limit to increasing drum speed. It is interesting to note that the limit is established by considerations of optical quality rather than of mechanical failure or driving power. Long before the drum is stressed to failure, the forces of radial acceleration have changed the drum dimensions to such a degree that the detector no longer lies at the focal point of the optics, resulting in a degradation of angular resolution.

5.1.4 Multielement Arrays

One solution to this problem is to employ a multielement linear array of detectors. It is then possible to scan a number of lines for every sweep of the optics across the field of view. Then, for a given application, the drum speed may be divided by the number of detectors in the array.

The disadvantages of multielement detectors are twofold:

1. Electronic complexity - Each detector element needs its own preamplifier channel. Then a commutator must be employed to time-multiplex the detector signals for display on a single gun CRT. Finally, the CRT sweeps and blanking signals become more complex and critical.

2. Partial degradation of image quality - when there is an unbalance among the channels, the display appears striated. This disadvantage is eliminated if the interchannel balance can be precisely established and maintained.

An alternative approach to the problem of deflection in the optical system at high scan rates is to reduce the radius of rotation of the critical element. It will be recalled that the radial acceleration imposed upon a rotating body is proportional to its distance from the center of rotation. In line with this, a drum scanner may have a folding mirror included to redirect the converging radiation almost parallel to the scanner's axis of rotation. Figure 47 shows cross sections of a drum scanner having the same optical characteristics with and without folding. It can be seen that a marked reduction in drum diameter can be achieved. The exact amount of reduction is dependent upon the relative aperture of the optics.

5.1.5 "Inside-out" Scanner

A reflective type of drum scanner may have three techniques applied to it in order to effect a tremendous reduction in its size. Figure 48 shows the results of applying all three techniques. First, an "inside-out" configuration is employed; that is the primary optical element, instead of being on the outside drum directing the convergent radiation toward the center; is placed at near the center of rotation so that it directs the convergent radiation outward. In this fashion, the heaviest element in the scanner has been placed closest to the center or rotation. Of course, it is necessary to employ a folding mirror to redirect the convergent radiation to the detector at the center of the scanner. Advantage is taken of this necessity by making the folding mirror a convex hyperboloid, creating what is called the Cassegrainian optical system. The distance between primary and secondary reflectors in a properly designed Cassegrainian system can be made a small fraction of that required of a conventional paraboloidal primary and plane secondary having the same effective aperture. Employment of a folding mirror immediately means that a small, central position of the primary is obscured. Once more, advantage is taken of this fact to introduce, as shown, two more plano-folding mirrors. The total result is that the multiply-folded, Cassegrainian, "inside-out" scanner compresses a very long optical path into a relatively small space with the greatest mass closest to the center of rotation.

5.1.6 Image Scanner

The two scanning techniques described so far are similar in that the object plane itself is scanned. Another approach is to image the full field of view and then scan the image with a system of relay lenses. An example of this technique is shown in Figure 49. The primary optical element is the spherical reflector. It is necessary to use spherical optics in this technique since aspherics would not produce a uniform image quality over the entire image plane. This has the unfortunate result of limiting angular resolution because of spherical aberrations. The image plane for a spherical reflector, termed the Petzval surface, is itself spherical and concentric with the mirror. Therefore, image scanning can be accomplished with relay lenses located behind the image plane and rotating about the common center.

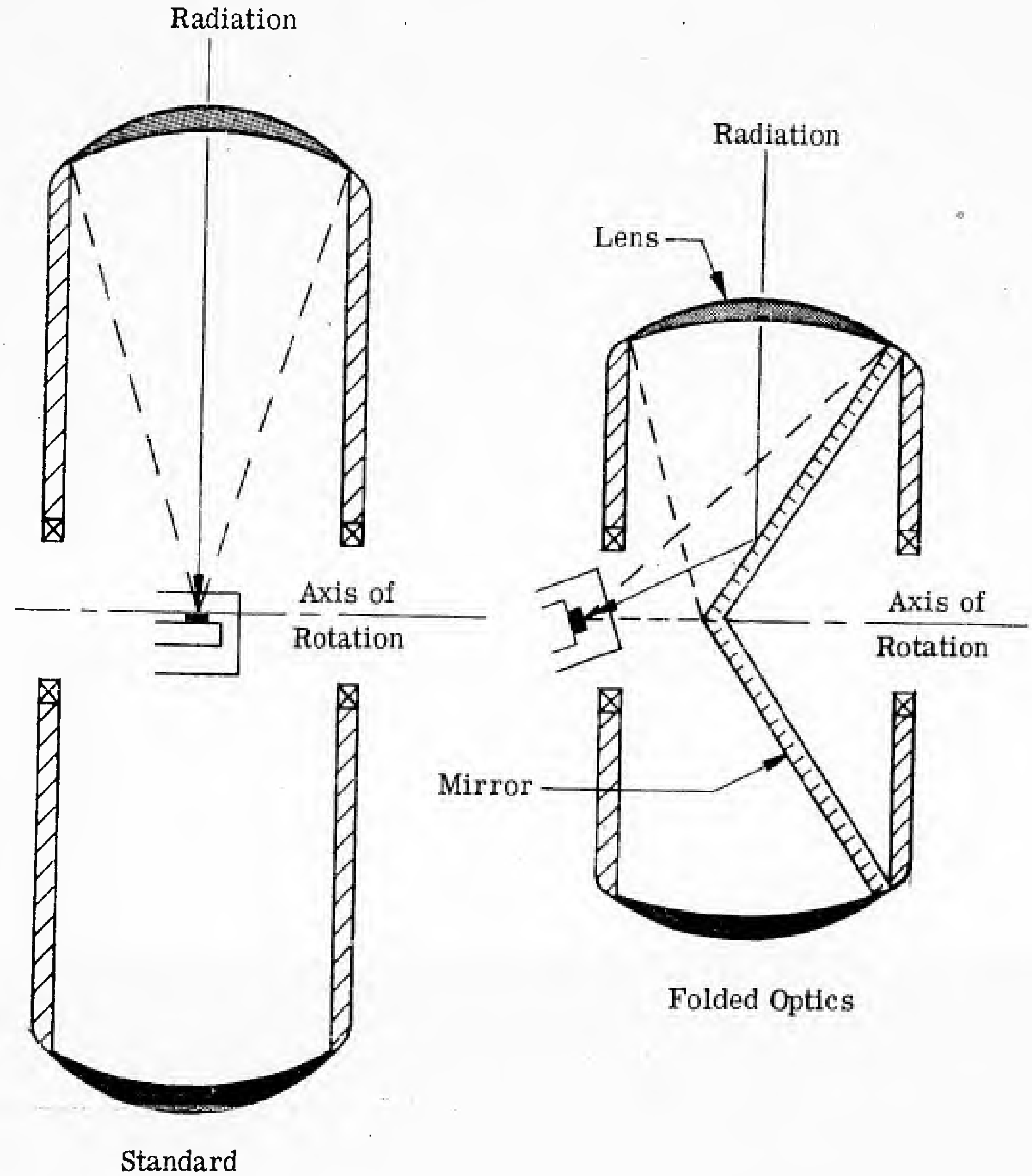
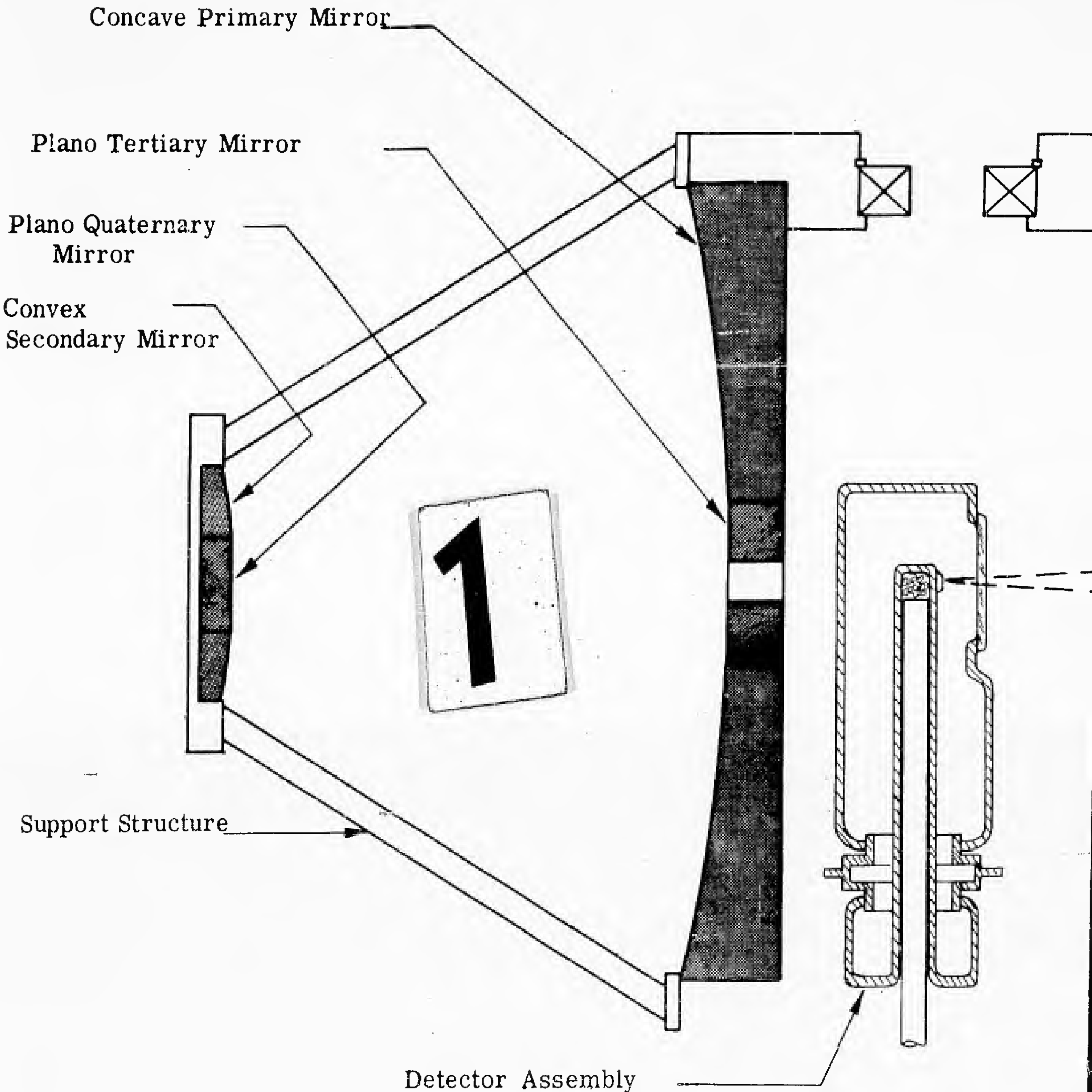


Figure 47 - Folded Drum Scanner Optics


Concave Primary Mirror
Plano Tertiary Mirror
Plano Quaternary Mirror
Convex Secondary Mirror
1
Support Structure
Detector Assembly

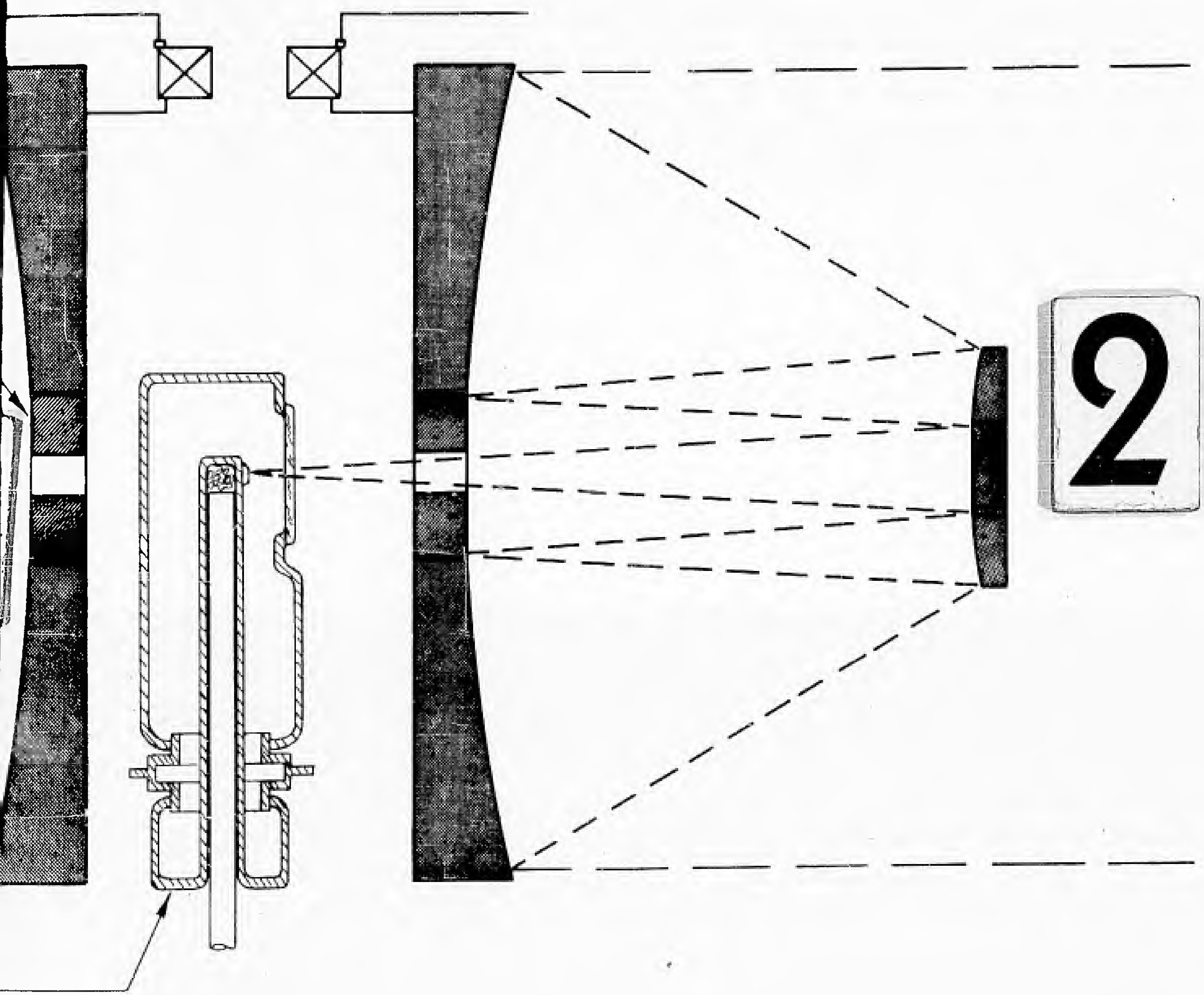


Figure 48 - Inside-Out Scanner

An added feature is an oscillating folding mirror. This mirror has a nodding motion to produce an additional slow back and forth scan. The nodding feature provides a frame-by-frame type of scan.

An image scanner of the type illustrated appears attractive when extremely high scan rates are encountered. The bulky primary optical elements are held fixed, and the scan motion is given to the far smaller relay lenses. The major drawback of this scanner is the poor optical quality of its spherical reflector. This deficiency can be overcome through the use of a spherical concentric correcting lens in what is called a Maksutov-Bouwers optical system as shown in Figure 50. As an example of the improvement achievable, the spherical aberration of 1 milliradian inherent in a spherical reflector with a relative aperture of f/2.0 can be reduced to as low as 0.02 milliradian through the addition of a concentric corrector.

5.1.7 Other Scan Configurations

Other scans have been employed on IR equipments. Prominent ones are the cloverleaf, spiral, and conical scans. Although they have qualities that make them desirable for certain applications, they do not produce a uniform distortion-free display as readily as the linear transverse scan produced by the equipment described.

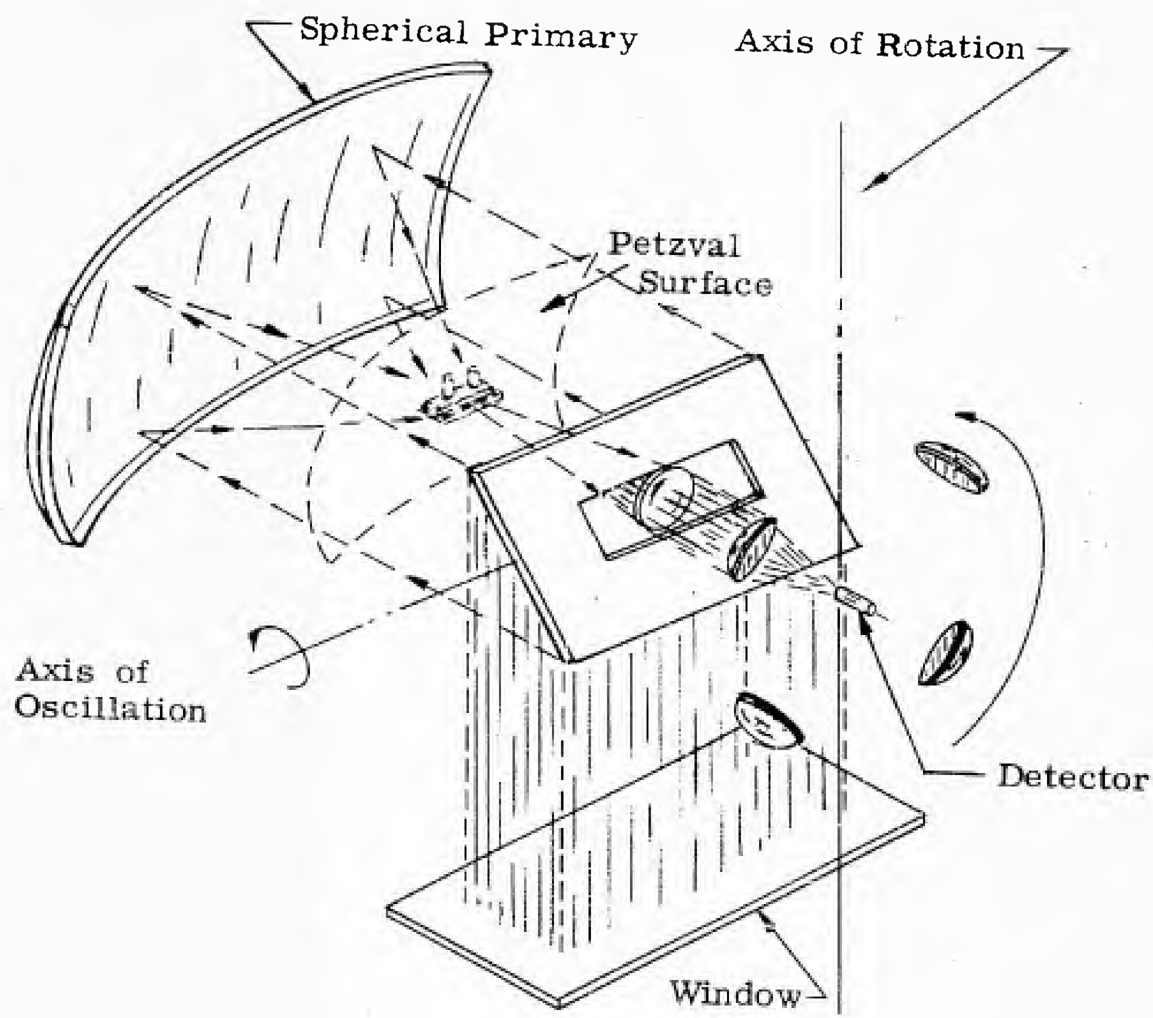


Figure 49 - Image Scanner

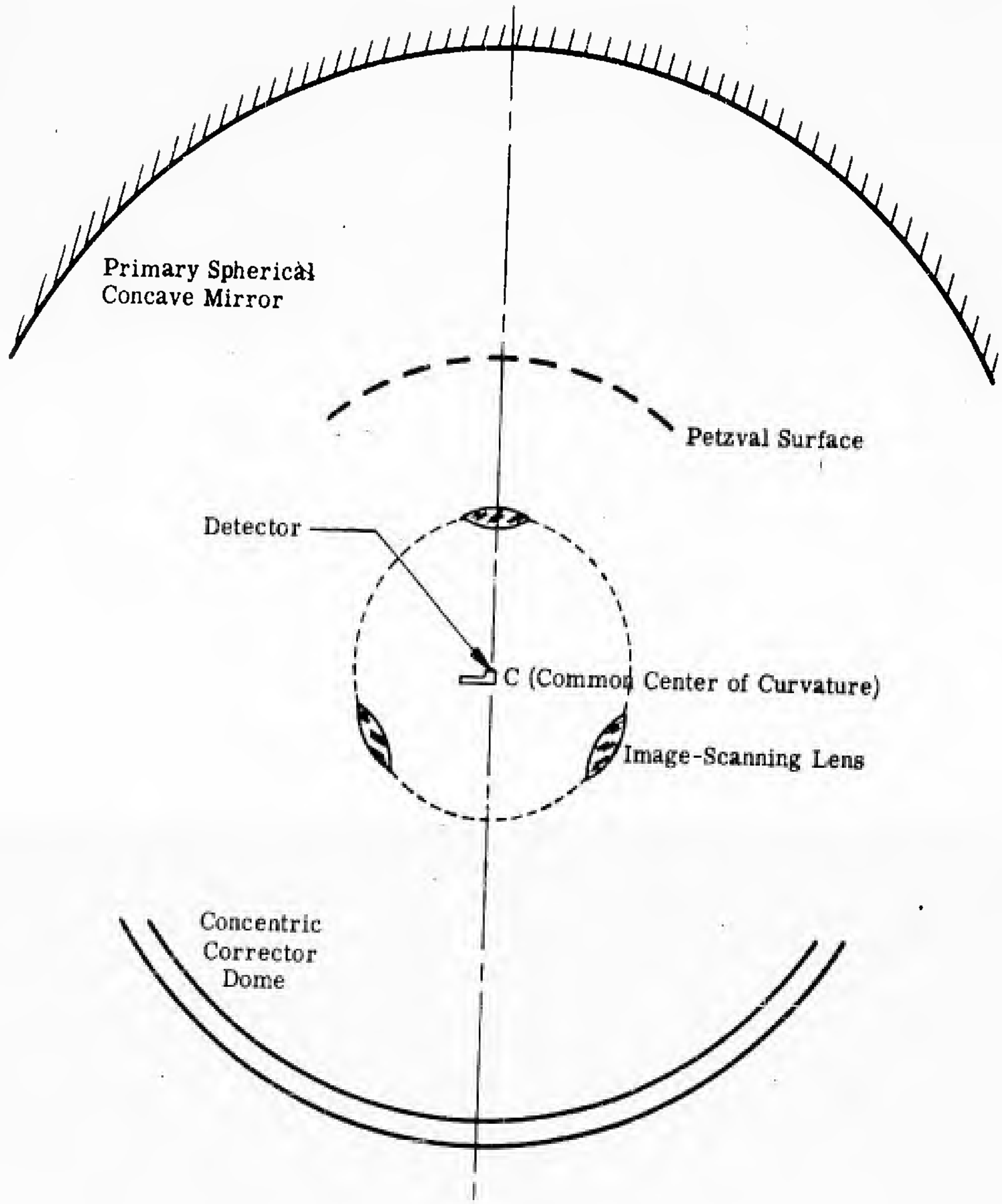


Figure 50 - Maksutov-Bouwers, Concentric, Wide Angle System with Three Image-Scanning Lenses - Schematic

5.2 Ground Based Equipment

5.2.1 Ground Version of Drum Scanner

A version of the Drum Scanner has been modified for ground use. A tripod mount with a servo-driven pitch gimbal adds a nodding vertical motion to the scanner. The unit is still adaptable to airborne operation when demounted from the tripod. Figure 51 shows the full complement of equipment.

A representative sample of infrared recordings made with the drum scanner is presented in Figure 52.

5.2.2 Far Infrared Telescope

An equipment designed specifically for battlefield viewing is the far infrared telescope, pictured with its associated components in Figure 53.

The far infrared telescope is a Newtonian telescope having a small field of view. Scanning is accomplished by rocking the mirror horizontally at a slow frame rate. A vertical array of detector elements scans a complete frame for each cycle of oscillation.

Figure 54 presents recording of personnel, showing the ability to identify distant objects by their silhouette.

5.2.3 Scanrod T-2

A simpler type of battlefield surveillance device, the Scanrod T-2 is a portable, self-contained, battery-operated equipment. It detects the presence and motion of military targets such as personnel and vehicles at various ranges. The complete unit is pictured in Figure 55.

An oscillating folding mirror generates a scan in a rotating plane reflector optical system. Instead of an intensity-modulated display, the data display is in the form of a "pip" on the oscilloscope shown in Figure 56. The height of the "pip" measures signal intensity while its position on the base line indicates the direction of the target. Figure 56 illustrates a typical display.

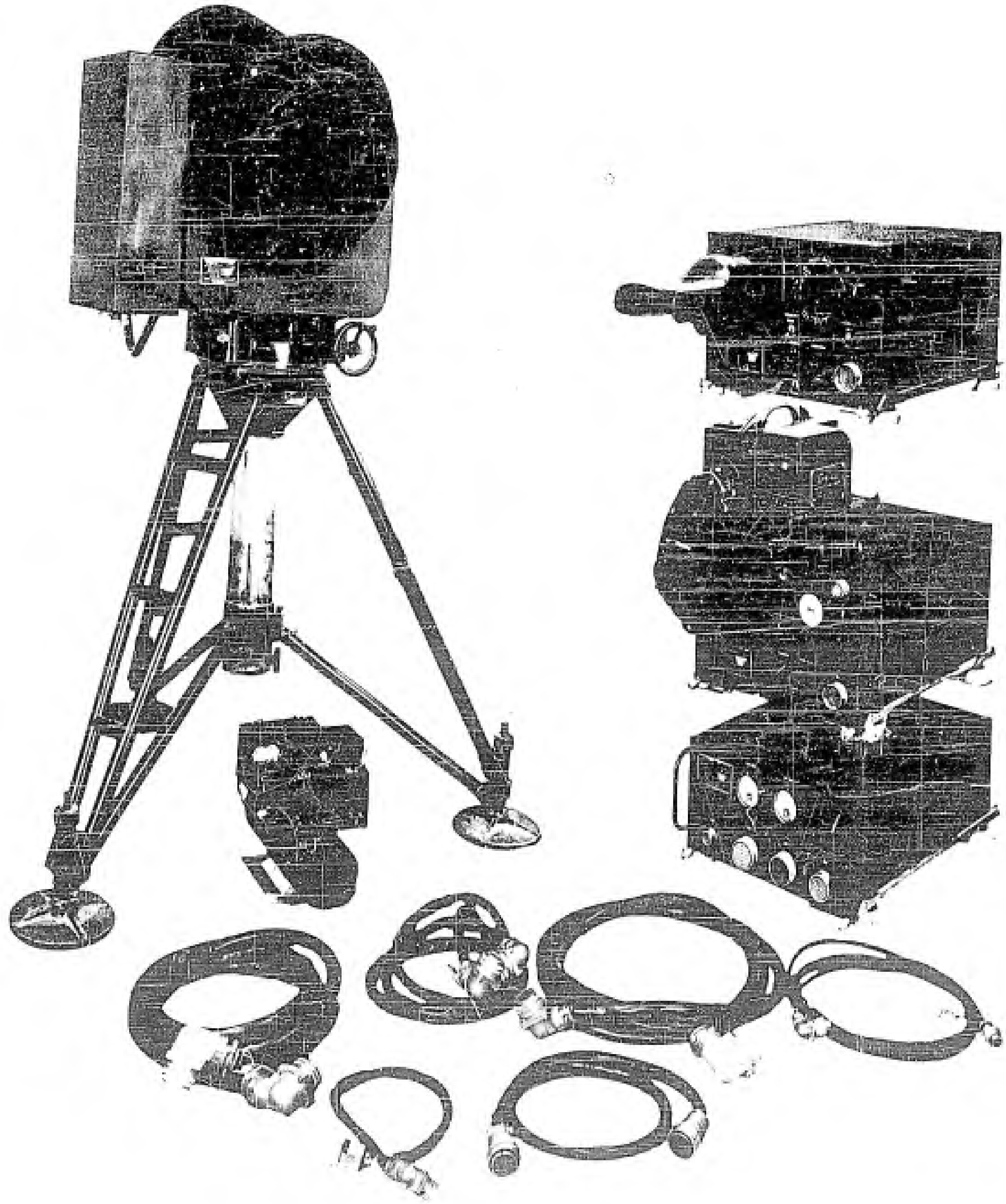
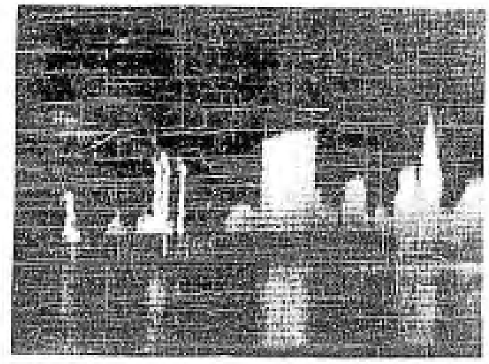
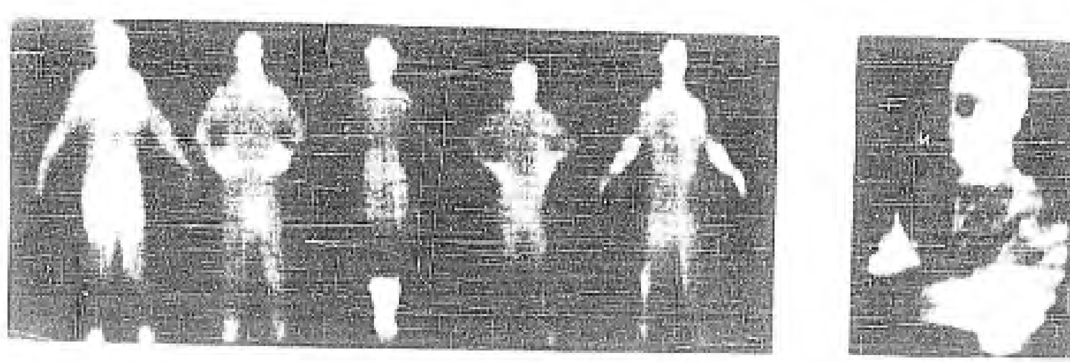


Figure 51 - Ground Based Drum Scanner



MANHATTAN SKYLINE



PERSONNEL

Figure 52 - Recording Taken by Modified Thermar

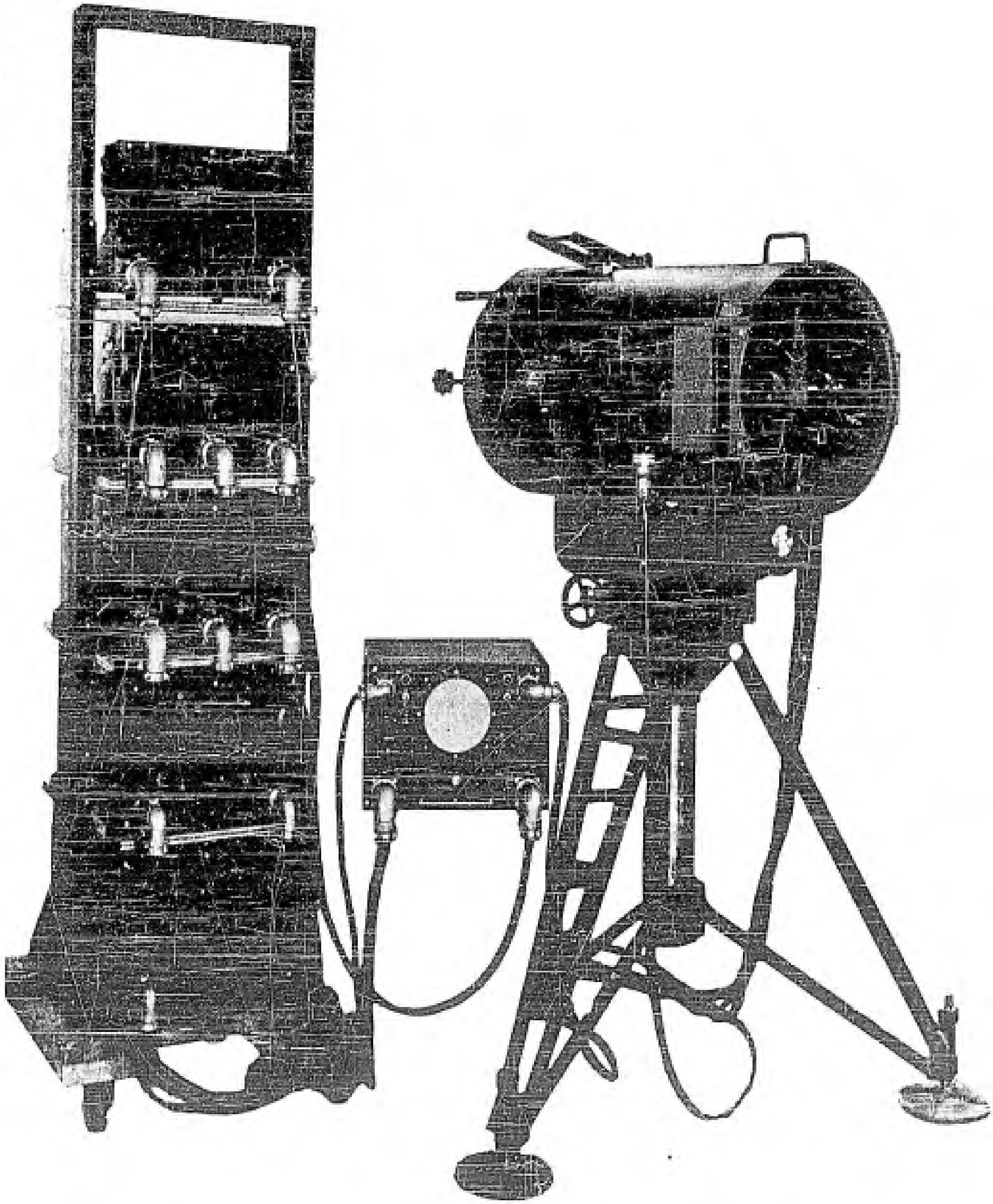


Figure 53 - Far Infrared Telescope

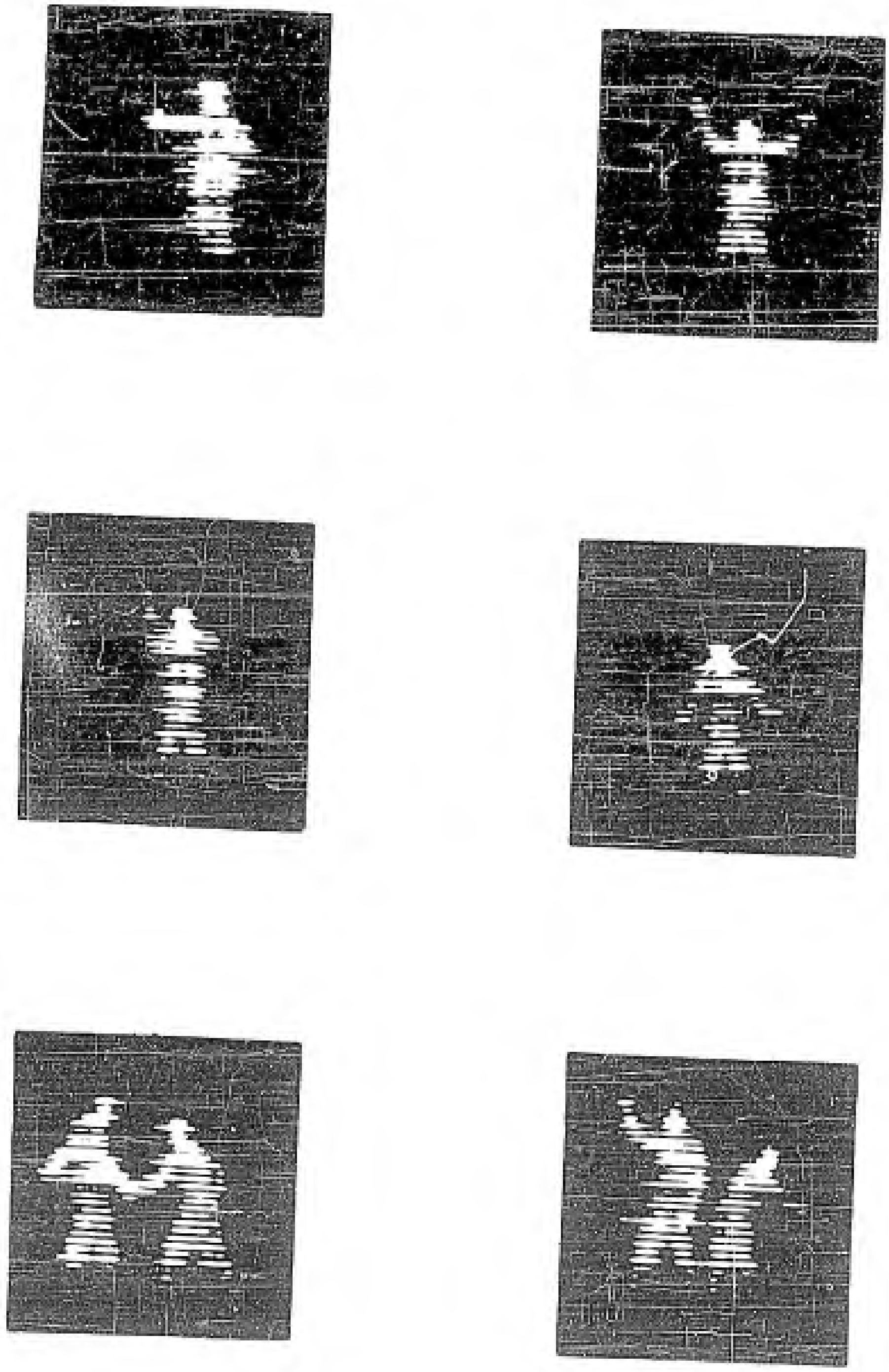


Figure 54 - Recording of Moving Personnel

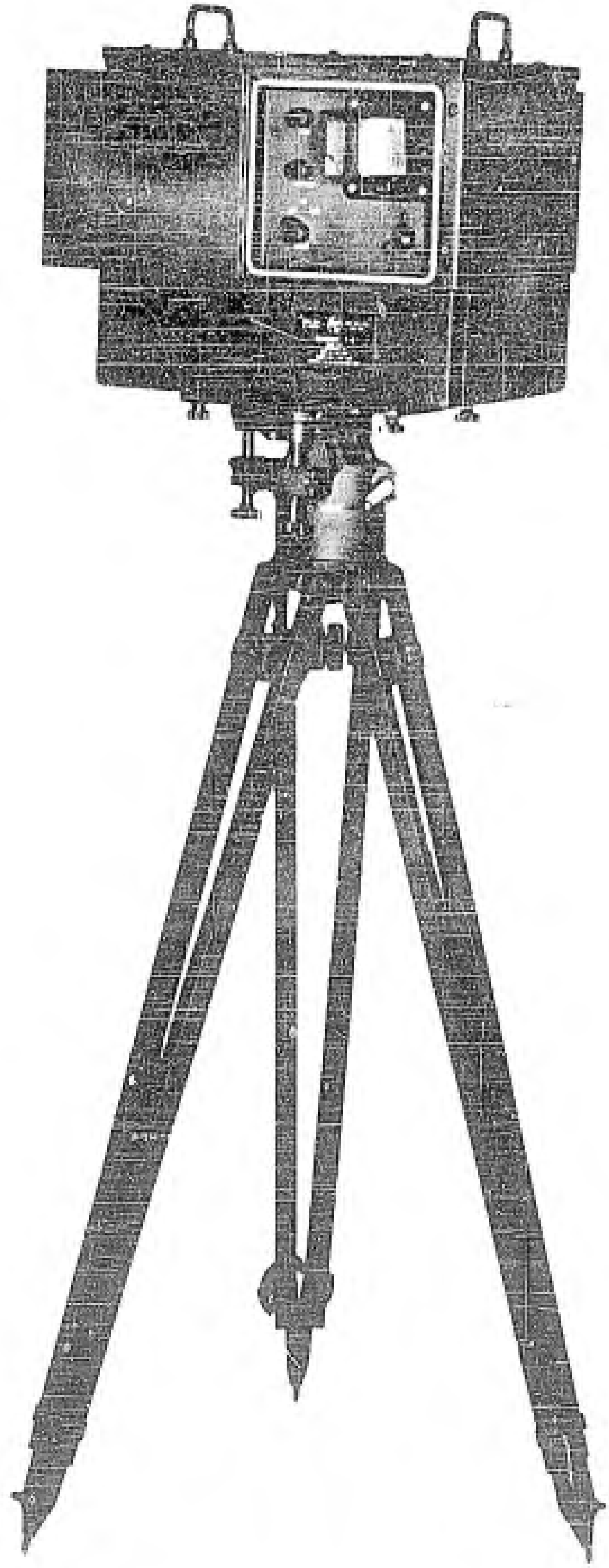


Figure 55 - SCANROD T-2

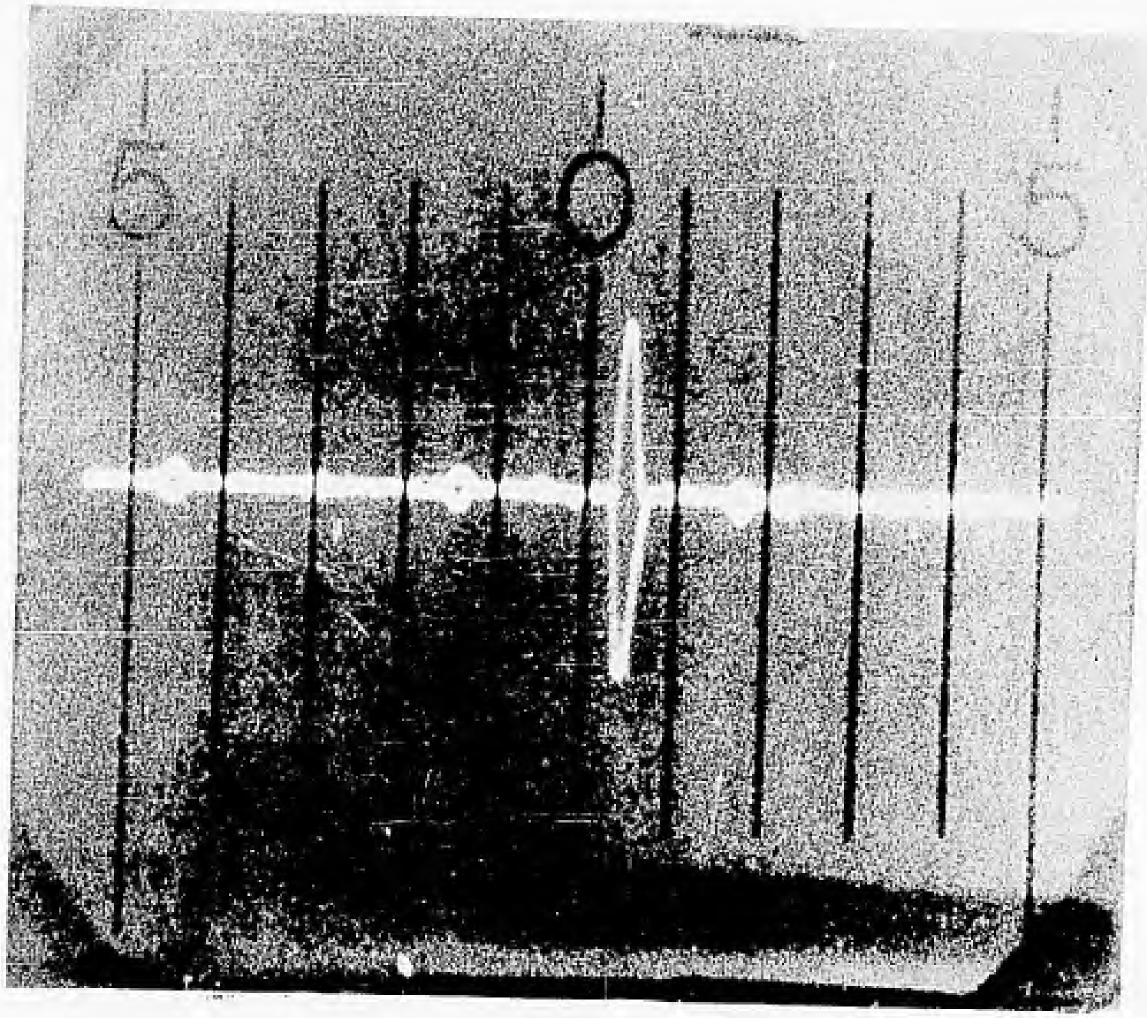


Figure 56 - Scanrod T-2 Display

5.3 Electronic Scanning

These systems are built around transducers which can be scanned by some electroni, means in such a manner as to permit a raster display on a CRT. The appeal of this technique is the fact that modified or even standard television techniques and circuitry may be applied. Satisfactory design of such a tube would effectively make for a practical infrared television system.

Scanning by an electron beam can produce images from large area detector material and from mosaics of small area detector cells. For the visible and near-infrared regions photoemissive types of detectors are most suitable, and are the basis for the image orthicon and image-intensifier orthicon. Their sensitivities are usually expressed in microamperes (μa) per lumen of illumination on the photosensitive surface. For a near IR sensitive surface this is usually μa per watt.

Electronically scanned imaging tubes are being developed for the intermediate and far infrared.

5.3.1 Infrared Image Pickup Tube

In a sense, infrared television is presently available in the vidicon type of infrared pickup tube. But the spectral response in only out to 2 microns and thus depends mostly on reflected radiation from the targets. For night viewing, because of the atmosphere, reflectivity of targets, and general low level of ambient radiation, target-reflected radiation incident on the IR vidicon is so low that effective ranges are limited to the order of one hundred feet or less. Objects at 150°C or higher can be imaged by their own radiation and the effective range is thus more than doubled.

Infrared vidicon tubes mentioned above use room temperature lead sulfide (PbS) as the detecting element at one end of the tube. Scanning is done by a low velocity electron beam focussed by a longitudinal magnetic field and deflected by a system of orthogonial deflecting coils producing fields at right angles to the motion of the beam. Figure 57 shows the basic arrangement of the infrared vidicon and schematic target operation.

5.3.2 Operation of the Multiplier IR Image Pick-Up Tube

The operation of this pick-up tube may be described as follows. (Ref. 49). "First, assuming the tube is in complete darkness, any small element of area of the photoconductor under the beam receives electrons and becomes increasingly negative until it reaches approximately the potential of the gun cathode. Thereafter, the beam electrons can no longer reach this element, but are turned back by the negative

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"An important point to notice in connection with this type of operation is that every picture element of the target which is illuminated conducts a photocurrent during the entire time and stores the accumulated information as a positive surface charge for the frame period while the beam is elsewhere on the target. This storage operation leads to a gain in signal-to-noise ratio proportional to the square root of the number of picture elements in the image area, as compared to the same photoconductor used in a system where point-by-point scanning is employed. For a high definition picture, such as the tube under discussion is capable of producing (400 line picture), the gain in signal-to-noise ratio is of the order of 500 times."

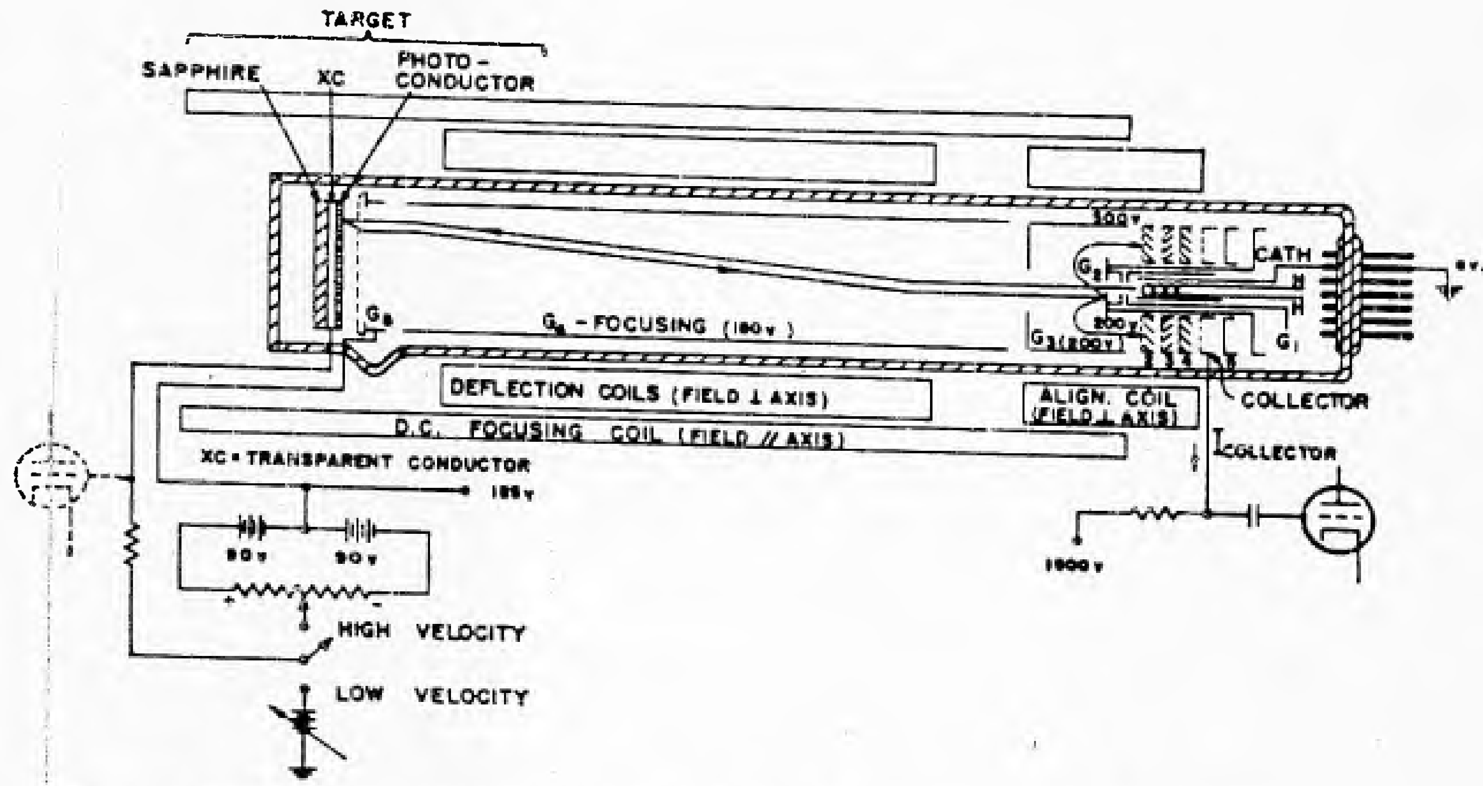

Figure 57 - Basic Arrangement of Infrared Photoconductive Beam Scanning Pickup Tube.

5.3.3 Photoconductive Target Material

The photoconductive material of the target must satisfy two conflicting requirements, relatively long wavelength IR sensitivity, and high resistivity for storage operation. Photoconductive semiconductor theory shows the relationship between radiation wavelength, λ, in microns, and photon energy, E, in electron-volts (ev) is:

$$E = \frac{1.234}{\lambda}$$

If a photoconductor is to be senitive to 2 micron radiation, the binding energy of the charge carriers must be 0.617 ev or less A normal semiconductor, with a binding energy as small as this, will have very low resistivity at room temperature. Resistivity of normal lead sulfide at room temperature is only a few ohm-centimeters. This is about 10 orders of magnitude lower than required for storage operation; therefore the lead sulfide must be greatly modified. This is done by evaporating lead oxide on a suitable substrate, activating with sulfur and a heating treatment, followed by a final layer of lead oxide. The resulting extremely complex structure has the necessary high resistance.

A two-inch diameter tube is similar to the image orthicon without an image section and can be operated with image orthicon focusing and deflection components. A one inch diameter tube without a multiplier can be used directly in vidicon TV cameras in place of the visible light vidicon.

5.3.4 Spectral Response

The spectral response of this tube is shown in Figure 58. This response reflects the contributions of a form of lead oxide response, having its maximum in the middle of the visible spectrum, and the lead sulfide response, which peaks in the near infrared and extends out to about 2.1 microns.

5.3.5 New Developments in Infrared Pick-up Tubes

New developments in semiconductive materials have led to the construction of infrared pickup tubes using lead telluride or doped single crystal silicon targets in place of lead sulfide. These have a response out to 6 microns or better. Frame speeds of better than 25 milliseconds are reported, and a minimum temperature difference of $2^{o}C$ is reported detectable. Resolutions of 0.75 minutes of arc (about 25 lines per mm) are claimed. However, the operating temperature for the characteristics is $90^{o}K$ (liquid oxygen) (Ref. 40).

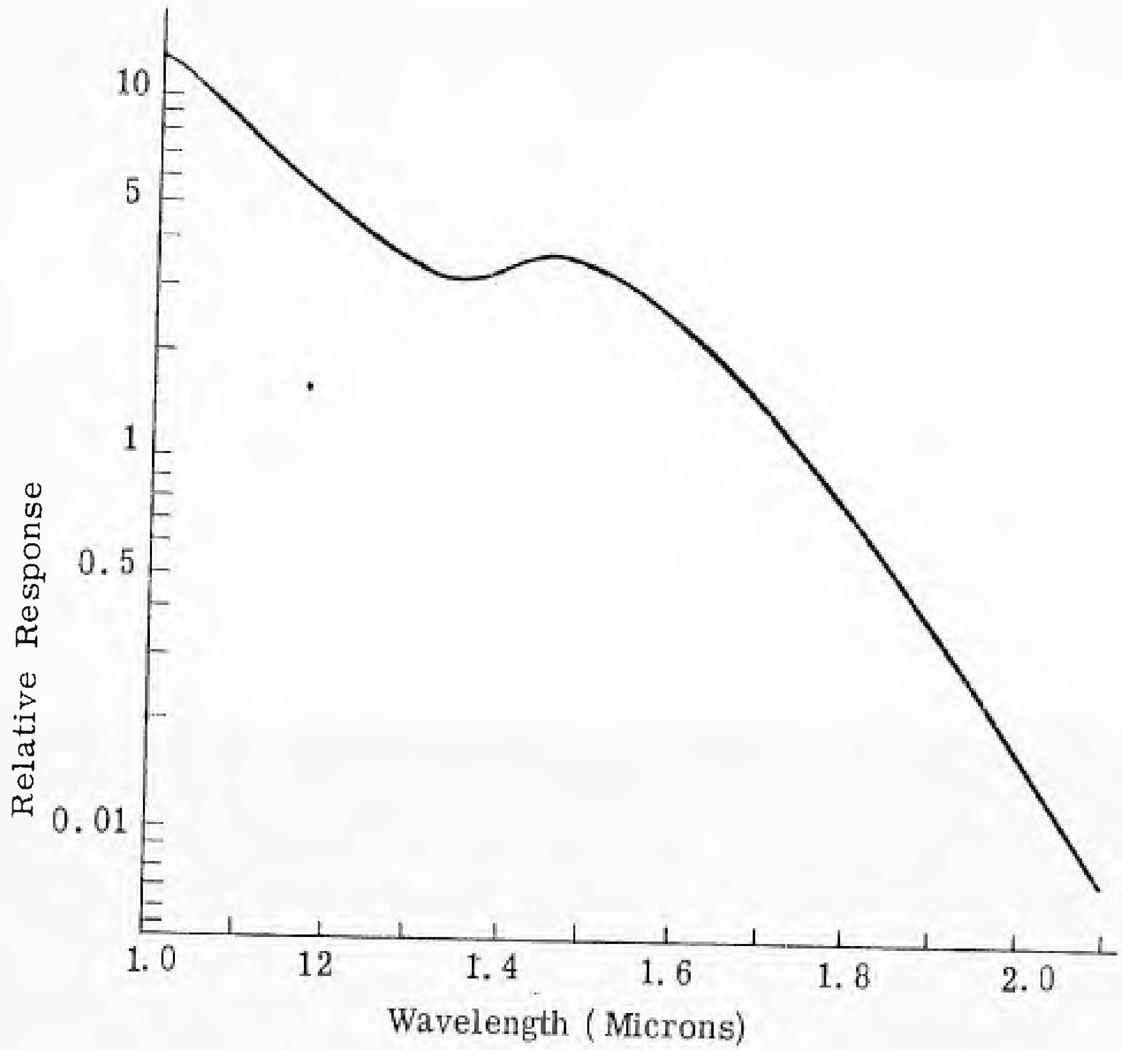

Figure 58 - Spectral response of infrared pickup tube.

Figure 59 illustrates the operation of this device. Thermal radiation is imaged on the retina which is the bismuth-cesium layer evaporated onto an aluminum oxide film. The thermal image causes variations in the photoemission characteristics of the bismuth-cesium. The light beam from the flying-spot scanning system causes the emission of photoelectrons to the multiplier section. The thermally induced variation of photoemission characteristics results in a modulated current corresponding to the thermal image. The resulting video signal, acted on and amplified by conventional electronics, is eventually displayed on a CRT in synchronism with the flying spot tube raster-type scan.

The major problem in manufacture of this device has been one of successfully reproducing the bismuth-cesium retina. Another disadvantage, of course, is the need for operating at liquid air temperature.

5.3.7 Infrared Image Converter (Ref. 51)

Investigations at another company have been along the line of adapting the simplicity of the visible light vidicon to infrared by use of thermistor bolometer material in place of the photoconductor material ordinarily employed. (Figure 60).

The bolometer layer becomes more conductive at those points where the thermal image causes a temperature rise. The scanning electron beam deposits more electrons at these points. The chromium backing electrode conducts the time-sequential changes in current produced by the thermally-created changes in conductivity of the bolometer layer and the scanning electron beam to the output lead.

A very low value of NEP per picture element is theoretically achievable. However, experimental values of NEP were higher by two orders of magnitude since useful sensitivity was limited by spurious, fixed pattern background signals and stray pickup rather than random noise.

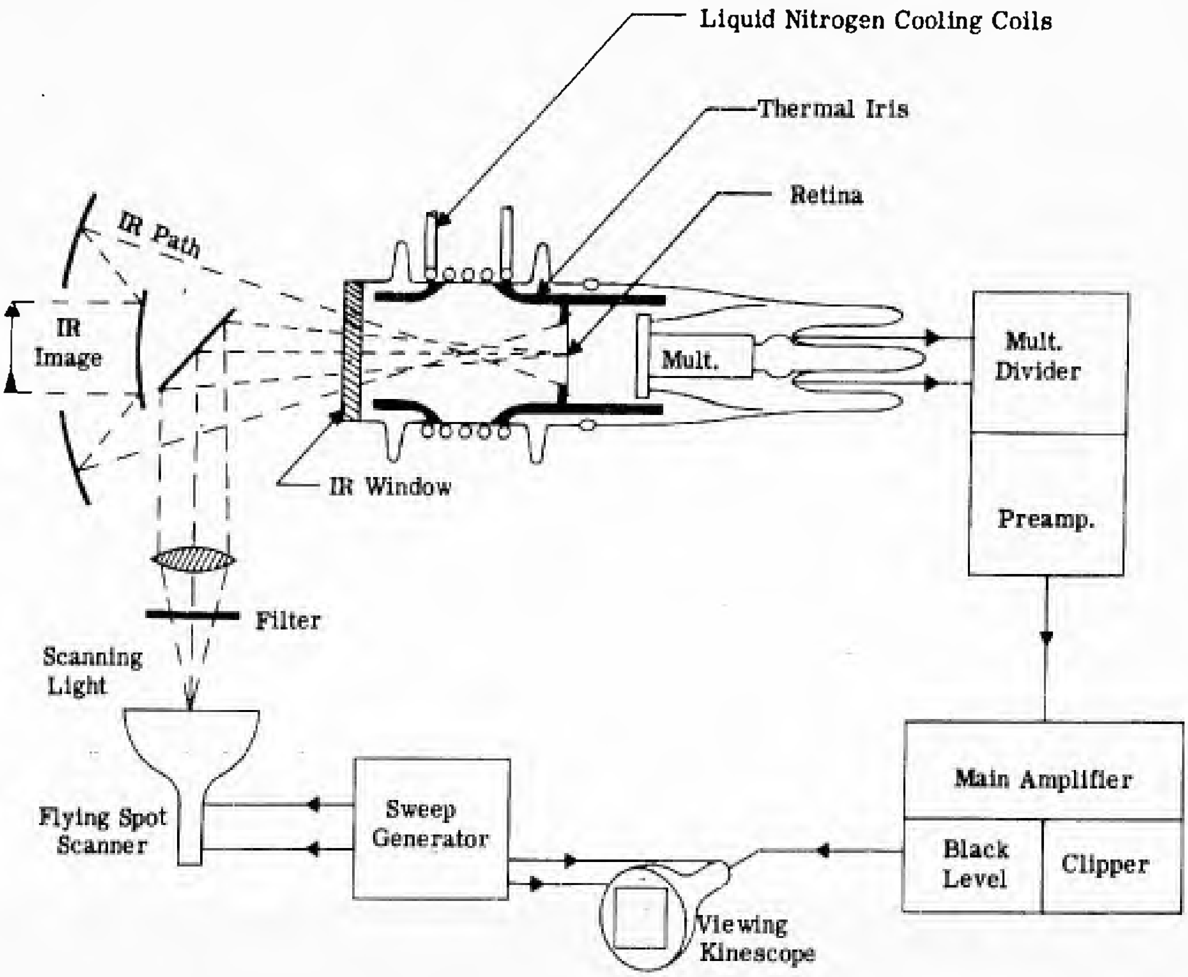

Figure 59 - Far Infrared System

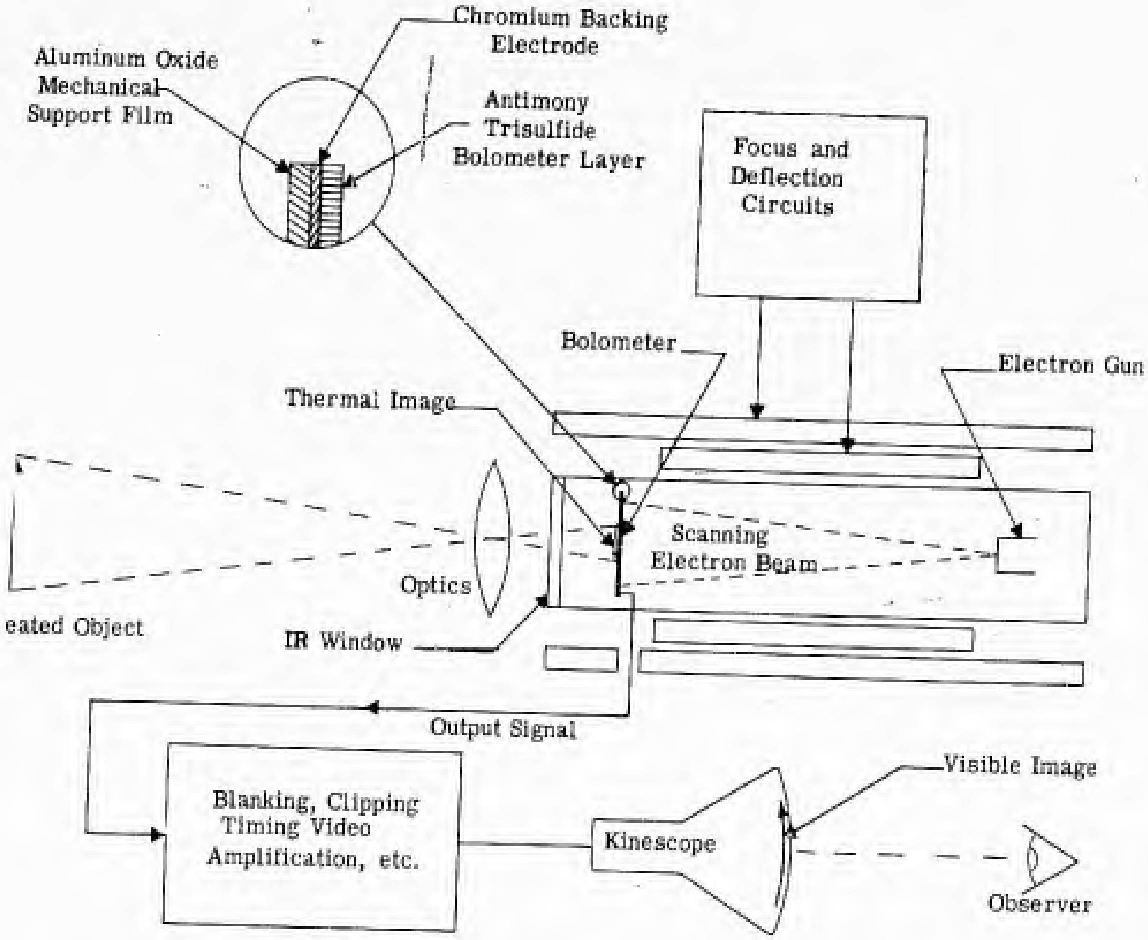

Figure 60 - Schematic of **Electrically Scanned Thermal Image System**

The bolometer layer used was antimony trisulfide (Sb_2S_3) deposited on a chromium backing electrode; this was all supported on aluminum oxide (Al_2O_3) film. Work is progressing on the use of teflon films as a supporting membrane. The referenced report presents a list of advantages, disadvantages and future possibilities which are reproduced below.

5.3.8 Advantageous Properties of the Thermicon

1. Rapid Response - Continuous viewing of moving objects.
2. Passive Systems - Undetectable and unjammable by known techniques.
3. Non-Selective Sensitivity - Utilizes all infrared radiation, particularly the vital 10 micron region.
4. Stable detector - Based on a stable, easily reproduced bolometer effect. (At present uses Antimony Trisulfide)
5. Thermal Information Storage - Wastes none of the input energy from the viewed scene, will detect short radiation pulses.
6. Electrical Storage - Utilizes electrical charge storage type scan for increased output current.
7. Daylight Operation - Not overly sensitive to, or saturated by sunlight and other short wavelength energy sources.
8. Standard television circuitry - Uses well-known techniques, can be remotely and multiplely viewed, and the scan rates are easily varied.
9. Ambient Temperature Operations - Operates satisfactorily at or even above room temperature, but can be cooled for added sensitivity.
10. Long Life - Should have operating lifetimes comparable with ordinary vacuum tubes.
11. Dual Detectability - Can also be operated as a photoconductive camera system of the vidicon type in the visible spectral region.
12. Possibility of Improvement - Not yet pushing any basic limits.

5.3.9 Disadvantages of the Thermicon

1. Unfinished systems - Not yet ready for field testing or incorporation into complete systems.

2. Low present sensitivity - Not yet capable of detecting objects less than about 10 to 20°C above or below ambient.

3. Technically difficult - Has relatively long history of development.

4. Indirect Viewing - Is not a direct image-forming converter tube.

5. Semi-Portability - Would be at least as large as closed circuit TV equipment.

6. Spurious background signals - At present the observer can be easily misled by the fixed pattern background signals.

7. Fragile - The thin films may be too delicate to meet some specifications.

8. Hard to Cool - Would require major design changes for efficient cooling.

9. Background Cancellations - Will require some type of storage system to cancel the fixed pattern backbround signals.

5.3.10 Future Possibilities of the Thermicon

1. Cancellation System - For storage of the fixed background signal and subsequent cancellation. Could use magnetic drum delay line, radechon tube, or other similar device. Maximum expected gain in sensitivity: 100 times.

2. Cooling - Cool the pickup tube to improve sensitivity. Maximum expected gain in sensitivity - 30 times.

3. Thinner Films - Find new mounting techniques or use a mesh support, or new film material. Maximum expected gain in the total number of resolved picutre elements: 10 times. Maximum expected decrease in the response time: 3 times.

4. Uniform Films and Improved Electron Optics - Development of better film and tube construction techniques to reduce the fixed background signal. Maximum expected improvement in the signal-to-noise ratio - 10 times.

5.3.11 Mosaic Image Tube (Ref. 52)

A variation of the image pick-up tube is the mosaic image tube developed by another company. The principle operation is that of the visible light vidicon where the signal is obtained directly from the photoconductive detector. The vidicon uses a solid plate of photoconductive material as the detector; the mosaic image tube uses a mosaic of many small photoconductive cells mounted on a supporting film. The vidicon, like the image pick-up tube, uses a specially developed complex mixture to obtain the high resistivities necessary for operation. The mosaic image tube accomplishes a similar result by using many small-area detector cells, connecting each to a common collector ring and obtaining information from each cell by scanning an electron beam over the cells.

Two basic configurations are used. One is a strip mosaic; a series of parallel strips of photoconductive material, across which a constant voltage is applied, forms the face of the tube. On the back of this face is a thin dielectric, over which the electron beam scans a parallel line pattern, which is perpendicular to the direction of the strips. As a result, a two-dimensional raster is obtained from the strip-and-scan combination. (Ref. 53).

When a thermal image is focused on this face, the resistance of the warmer photoelements change proportional to the thermal image, producing corresponding changes in the potential of the dielectric. When the scanning beam reaches such a point, the equilibrium potential of the dielectric is reestablished, causing a small current to flow through the dielectric. As a result, a signal appears at the collector ring output of the mosaic. By scanning a CRT in synchronism with the tube scan, a television raster-type display is created. Of course the resolution is limited to the number of parallel strips.

The other configuration is a mosaic of many very small-area cells deposited on a dielectric to form a square or rectangular pattern. The scanning and operation are the same as described above.

Also under development is an image tube consisting of a single-line array of bolometer detector cells for use in aerial reconnaissance. This would require a single electronic scan line whose output into an intensity modulated CRT would generate a strip map of film moving perpendicularly to the line scan.

5.3.12 Commutator "Scan"

A form of electronic scan is the commutation scheme used to "pick off" the signals from a linear array of detector cells such as used in aerial "pushbroom" scanning. Commutation is usually done by means of electronic switching techniques at the outputs of the amplifier channels used for each detector cell. The complexity of this "scanning" means, requiring an amplifier channel for each cell as the signal level is too small to be switched at the detector, would be greatly reduced if the scanned-array image tube development is successful.

6. ACTIVE SYSTEMS

6.1 Steady or Fixed Radiation Systems

The active IR system uses an infrared source to provide illumination of the objects or area of interest. The infrared sensor detects the reflected energy from targets and background less the atmospheric attenuation. Thus the active system provides no real indication as to the emissivity of the objects. Because of the power required to provide the necessary illumination over usable distances, these devices are usually limited to the near infrared.

Recourse to blackbody theory will show this more clearly. The higher temperature curves exceed the lower temperature ones over the entire spectral range. Radiation curves that peak at the longer wavelengths provide much less energy at these longer wavelengths than the curves that peak at shorter wavelengths. Visible light sources provide even more energy at longer wavelengths than would an infrared source.

The path length for the radiant energy detected by an active system is twice as long as radiation emitted by an object and detected. The atmospheric attenuation plus the inverse square law require a source radiation energy for an active system detector at least four times greater than the radiation energy emitted from an object at the same wavelength. Thus, to get the greatest range, a high-temperature source must be used. Usually, this consists of a high intensity tungsten filament lamp with a filter over it so as to cut off the visible region. Development of gas discharge lamps for this purpose is being carried out as well as the use of carbon-arc searchlights. The hotter the source the greater the infrared energy at all wavelengths; the problem then becomes one of finding a filter to withstand the high temperatures.

Since most of the non-visible energy is in the near-infrared practically all active systems operate in this region. Also, atmospheric absorptions are not as detrimental here as they are in the intermediate infrared region so that much longer ranges are possible. Thus, it is usual to combine the active source with an image tube of some kind for detection and identification of targets.

6.1.1 Direct View Image Systems

The best example of an active infrared imaging system is the well-known Snooperscope. This was merely the combination mentioned above, an infrared source and an image tube. Variations of this combination are the Sniperscope (searchlight and viewer mounted on a rifle) and infrared binoculars which could be either hand held or mounted on a helmet.

Another active system, the T-5 Metascope uses the principle of infrared quenching of phosphors as described in previous sections. This device is a small, compact viewer useful for reading maps in the field, looking at road signs, or just following a trail. Where the Snooperscope uses a telescope for looking at distant objects, the Metascope has an optical system for comparatively short range viewing. Thus its source radiation energy can be much less and detection by enemy IR detectors is minimized.

6.1.2 Infrared Television - 7500 to 12,000 Angstroms Spectral Region

As previously discussed under the infrared image pick-up tube section, infrared television is really dependent upon a satisfactory camera tube. Camera tubes capable of covering the spectral region from 7500 to 12,000 Angstrom units (0.75 to 1.2 microns) have been developed by several organizations. But the era of IR-TV comparable to visible light TV is still in the future. The major bottleneck has been the lack of ability to make a reproducible detecting surface. Sensitivity, spectral response, and resolution capabilities are characteristics which have yet to be stabilized from tube to tube. Deterioration of the sensitive surface with time is another obstacle to be overcome before true IR-TV is a reality. Night-time IR-TV as used at present is an active device because of its limited spectral response. Passive IR-TV has some limited use in daytime operations for its capability to pierce light fog and haze further than visible light TV.

In either case it is subject to the limitations of the optical system; the low f/number and wide-angular field of view considerations pointed out in the section on optical considerations. An active system has some advantage in this case, since it can provide its own invisible illumination at night. By radiating its energy in a very narrow beam, it can "see" further with appropriate optics than the passive system can. "Panning" or moving this narrow beam over the area under surveillance in synchronism with the camera permits a much larger area to be covered.

Active IR-TV suffers from the same problem that afflicts all active surveillance systems, namely, breach of security. An enemy with a detector can pick up the radiation at a much greater range than that at which he can be detected. The use of the very narrow beam of radiation does minimize this breach of security as the enemy has to be practically in line with the beam to spot it. Use of flares by either side does enhance the detection ability of the system and reduces the risk of detection by permitting extinction of the system's active source.

6.1.3 Infrared Photographic Film Systems

Although active systems have usually been associated with ground surveillance, airborne active systems are no rarity. Usually this has been a visible light system with the data presentation being on photographic film. However, there has been a good deal of work done towards the development of a active IR aerial reconnaissance using IR film. One major advantage of active IR over active visible reconnaissance systems is the detection of camouflage cover. Another advantage is the ability of the IR to pierce light fog and ground haze which tend to blind an active visible system. The active sources have been searchlights, scanned or fixed, and flares. The spectral region is limited to the near infrared due to the limitations of infrared film discussed previously.

6.2 Modulated Radiation Techniques

Modulation, in some manner, of the comparatively continuous illumination source supplies another dimension to an active infrared system. By appropriate optical and electronic means this added feature may be used to provide very accurate ranging information. Another variation permits voice communication between selected groups without breaking radio silence.

6.2.1 IR Ranging Techniques

All electromagnetic radiation has the same velocity in a vacuum as the well known velocity of light, 2.9978×10^8m/sec. or 9.835×10^8 feet/sec. Using this finite velocity for infrared radiation, a ranging device using active IR techniques is possible by employing techniques similar to those used in radar. Such a ranging device has been developed using visible light (ref. 54).

If a very short pulse of high intensity light were transmitted by an optical system which collimated the light pulse, it would travel away from the transmitter at the rate of 983.5 feet per microsecond. Any objects in its path would cause reflection of this light pulse. Some of this reflected energy would be sent back along the path of the light pulse, collected by the same optical system acting as receiver and, by means of mirrors, imaged at a photomultiplier tube. If the photomultiplier tube were turned on (gated on) a short time, say 3 microseconds, after the pulse was transmitted, reflections from objects 1475.4 feet away would cause an electrical signal to be generated by the photomultiplier tube. The number 491.8 feet (983.5/2) per microsecond is known as the range conversion factor, and is constant for air (since velocity of light in air is practically the same as it is in a vacuum). It is also expressed as 163.9 yards per microsecond.

The length of time the photomultiplier tube is turned on determines the accuracy of the ranging. If this time is one tenth (0.1) microsecond, the best range accuracy is 49 ft. or 16 yards. Of course, the length of "on" time might be made only 0.01 microseconds for accuracy of 1.6 yards, but this is quite difficult electronically due to "jitter" and switching transients as the "gate" goes on and off. One of the more practical methods is to use a wider gate, say 0.5 microseconds or even 1 microsecond and display the signal received on an oscilloscope of appropriate sweep speed. A one microsecond sweep speed would display a depth of 163.9 yards and could be so calibrated. Any targets in this depth and in the very narrow beam of the light pulse would appear on the sweep trace as a "pip" the correct number of feet beyond the start of the trace which has been determined by the first or "turn-on gate". Thus the total range to any desired target can be obtained readily.

The transmitted light beams are not perfectly collimated, having some slight spread (0.1 to 0.5 degrees) depending on the optics and the amount the lamp is displaced from the focal point. This displacement is necessary as a mirror has to be placed near the same point upon which to image the return beam. Field lenses are used to reimage the light onto the photomultiplier tube.

Visible light lamps have been developed whose major radiation energy is emitted in less than a microsecond. The peak intensity is much brighter than the sun's surface. The high intensity and very short duration of the light pulse is accomplished by discharging the stored energy of a large capacitor through the lamp. Effectively, the lamp acts to short circuit the capacitor.

6.2.2 Application of Visible Techniques to IR

The visible light ranging techniques discussed above are basically applicable to infrared. The major problem is one of radiation source. The requirements for such a source are very high radiant intensity, small size, capability of being triggered on and off very rapidly, and richness in infrared radiation. For blackbody type of emitters the first and last requirements are contradictory unless a filter were used to cut off the visible radiation. The ability to trigger a black body radiator on and off very rapidly is determined by its thermal capacity and thermal conductivity. It is exactly analogous to an electrical circuit consisting of a capacitor and resistor in parallel. The time constant is the ratio of capacitance to conductivity. Time to reach peak intensity on starting and the time to decay to zero after being turned off are determined by this time constant. A blackbody source with intensities suitable for a ranging system would have a very large thermal capacitance and a low thermal conductivity with correspondingly long time constant.

Gaseous radiation sources do not have the limitations of black body or surface radiators. Spectra of gaseous discharges reveal the radiation to be in very narrow lines. The position of these lines in the electromagnetic spectrum is different for each element, somewhat like fingerprints. The time constant of gas discharge or arc lamps is quite short. Therefore, a gas whose spectral "fingerprint" lines are in the infrared would possibly meet the requirements stated previously.

6.2.3 IR Sources for Active Systems (Ref. 55)

A great deal of work along this line has been done in connection with infrared communications systems. The results achieved to date have been limited to the near infrared region. Cesium-vapor arc lamps are one useful source due to the resonance spectral lines of cesium vapor at 0.8521 microns (8521 Angstroms) and at 0.8944 microns (8944 Angstroms) at atmospheric pressure. Mercury-xeonon high pressure arc lamps are another source of near infrared radiation, having several spectral lines between 0.85 and 1.0 micron. Information from Hanovia Chemical and Mfg. Company shows the radiant sources in the lamp are the xenon continuum emitted by highly heated xenon molecules; xenon ionization-line spectral emission, mostly in the infrared; tungsten electrode continuum from incandescent electrodes, and the heated quartz body. (Figure 61).

The air lamp used in the visible light ranging systems could conceivably be used in the near infrared with a suitable filter as its radiation contains the spectral lines of all the elements making up the atmosphere. The filter material would have to be capable of withstanding the tremendous amount of heat generated, however.

Infrared ranging is still in the development stage for applications to convoy control, minesweeping formation control, and surveying under security conditions. These applications use a cooperative target such as a triple mirror to get the maximum range from the relatively lower radiant intensity of the infrared source.

6.2.4 Images from Pulsed-Active Systems

The infrared detection devices are either infrared photoemissive multiplier tubes or lead sulfide cells. A storage image-converter tube under development (Ref. 56) was designed for use with a pulsed infrared source to minimize breach of security. For test and comparisons to a non-pulsed viewer, source pulse lengths of 200 microseconds were used

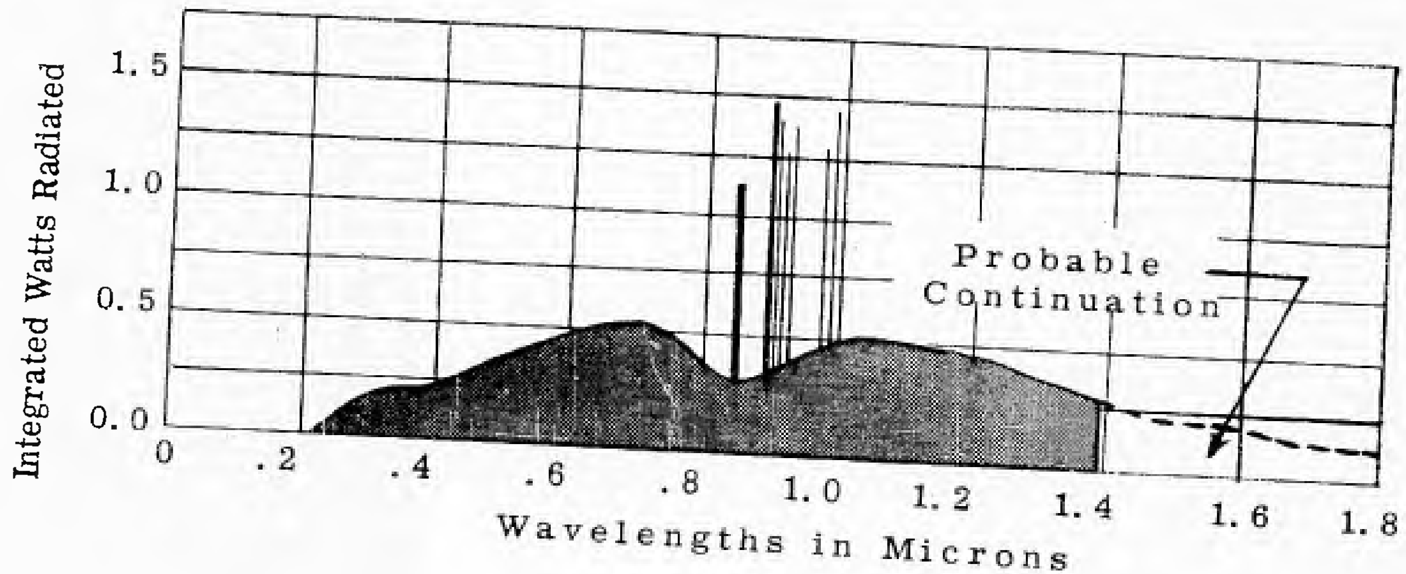

Figure 61 - Spectral distribution of a xenon high-pressure arc

It is conceivable that such a viewer could be combined with an infrared ranging device of poor accuracy to provide an image of a selected cross-section. Backscatter present in continuous viewing situations tends to deteriorate the quality of the image as it raises the background noise level. A pulsed-ranging viewing system would eliminate backscatter from all ranges up to the selected one. The requirement of poor accuracy is to provide some depth to the image. Thus an accuracy of 50 feet, considered poor for precise ranging, would provide an image covering the 50 feet succeeding the range selected; anything beyond or before this 50 foot depth would not be imaged.

Passive methods to determine range are also under investigation. (Ref. 57). The most successful technique so far, has been use of optical focussing methods with conversion into video or audio displays.

6.2.5 Infrared Communication Techniques

Signalling by turning a light source on and off in accordance with some pattern such as the Morse code is probably the most familiar optical communication method. This "blinker" system is relatively slow, of the order of 6 to 10 words per minute. A method of modulating a beam of light much as a carrier wave is modulated by audio frequencies in radio was first suggested by Alexander Graham Bell in 1880. Systems developed over the years have increased in complexity and sophistication. Modern infrared systems under development will be capable of code, voice, teletype and facsimile transmission. (Ref. 58.)

Transmitters range from 300 watt to 2500 watt mercury-xenon lamps. Receivers are lead sulfide cells. Directional characteristics of the transmitting systems vary from narrow beam directional to 360° omnidirectional depending on the application. For Navy use, stable platform for stabilizing against roll and pitch motion of the ship is a necessity, as is some means of automatic tracking.

For Army use a simple system has been developed using current modulated tungsten filament lamp with a lead sulfide detector in a small housing. The entire unit weighs 10.5 pounds. (Ref. 59.)

Optical communications provide a means of delivering messages secure from jamming and interception while permitting full utilization of the element of surprise. Infrared optical communications provide, in addition to this, increased range and secure night-time operation.

For training applications, an IR communicator could be setup ashore as a beacon or for guidance and training control. (Figure 62.)

Image formation may be transmitted by this means from some infrared image-forming device, such as those described previously, provided the bandwidth is less than 10 kc. This is the frequency at which the xenon arc response to a modulating signal falls off to 30%.

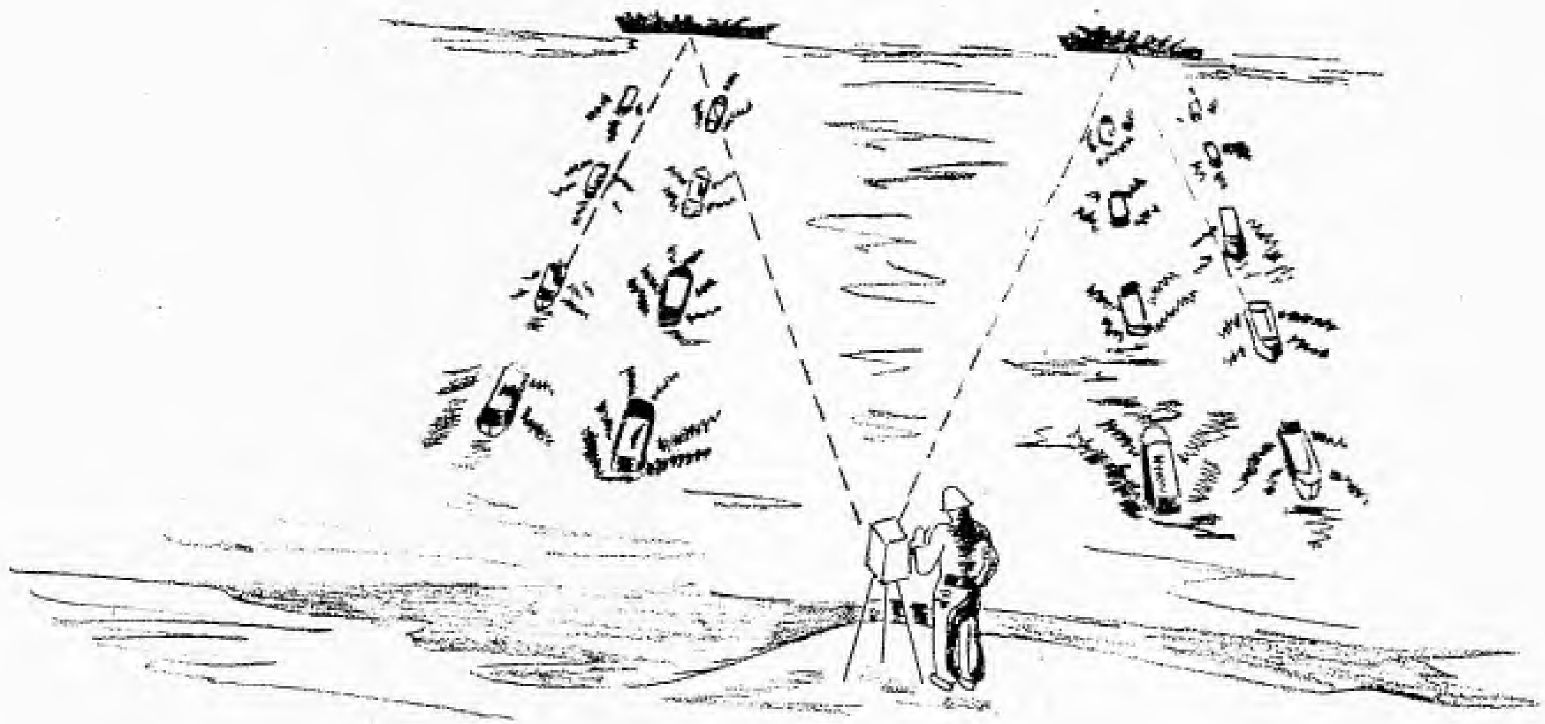

Figure 62 - A typical amphibious operation.

7. TELEVISION TECHNIQUES

Television electronic scanning techniques have direct application to infrared technology. Image conversion from infrared to visible, and infrared information distribution, either before or after conversion, are examples of this application. As a further aid to night viewing, low intensity visible light television techniques have been developed.

7.1 Infrared Image-forming

This topic has been covered in detail in Section 5.3 and Section 6.1.2, but will be presented here as review.

7.1.1 Photoemissive Methods

Photoemissive image-forming methods are basically of the direct view image tube type which by themselves do not use TV scanning techniques. A combination pickup tube known as the "intensifier image orthicon" is under development with IR capabilities out to 2 microns. The rest of the system uses conventional television circuitry. This development was undertaken when attempts to produce an image orthicon with an infrared sensitive photoemitting surface failed due to deterioration of the infrared sensitive surface caused by the required manufacturing processes.

7.1.2 Photoconductive Methods

Infrared television using photoconductive pickup tubes is also under development. Several industrial organizations have produced scanned imaging tubes using such varied methods as surface storage combined with the gain of a multiplier section, straight photoconductive effect, and flying spot scanning of a specially sensitized surface.

Near infrared television systems are furthest along in development. Photoconductive and bolometer type pickup tubes for use in intermediate and far infrared regions are under investigation. The major problem in these investigations is the development of infrared sensitive materials that will remain stable over the desired spectral range from tube to tube after processing.

7.2 Infrared Information Distribution and Display by TV Methods

Distribution of IR information refers to dissemination of the data after it has been recorded or to the display of the detected infrared radiation at some point remote from the detector. Both distribution requirements referred to above can be carried out by closed circuit television systems. Broadcast techniques (wireless) are usually limited to the second requirement involving original information display at a remote point. However, infrared closed circuit or broadcast TV are still developmental, and systems for original pickup and display are not available at present.

7.2.1 Closed Circuit Television as a Training Medium

Using infrared information after it has been recorded either on film or tape, any one of the many available closed circuit TV systems can be employed to train large groups of men. Although similar to motion picture training films, this method has several advantages over a filmed presentation. (Ref. 60).

These advantages are as follows:

1. The latest equipment can be demonstrated.
2. Film sequences are more likely to be up to date.
3. The instruction can be changed as circumstances require.
4. The student, by means of intercom, may ask questions and get prompt answers.
5. Teaching aids combined with film and live pickups, both local and remote, provide the instructor with an education medium of unparalleled flexibility, impact, clarity and speed.
6. The use of several receivers permits all the men, in small groups, to have the equivalent of front row seats where details of equipments may be more readily seen and understood.

Closed circuit television definitely has a place as a means of training military personnel in the identification and interpretation of objects as displayed by infrared systems.

7.2.2 Closed Circuit TV for Use with Simulation Techniques

Simulated infrared information can be displayed by closed circuit techniques with the inclusion of controls to permit simulated movement of the synthetic display. Other controls may be incorporated to demonstrate the difference between daylight and night time images of the same scene.

At present infrared television devices have not reached the stage of development where they can be used for original information collection and distribution. However, optical-mechanical scanning systems have been developed to present a scanned raster image, although not truly a television type raster. These can be used as closed circuit systems or as broadcast systems.

7.3 Low Intensity Visible Light Image-forming

Although the infrared pickup tubes for use in an infrared TV system are still developmental, viewing under nighttime or other conditions of low intensity visible light is possible by means of special visible light TV systems.

The following is a comparison of the low-intensity light level capabilities of several standard and developmental television camera tubes.

Tube Type	Approximate Minimum Scene Illumination Requirements (ft. -candles)
Conventional Image Orthicon 5820	1×10^{-3}
Wide-spaced I. O. 6849	1×10^{-4}
Image Intensifier Orthicon-Single Stage	2×10^{-5}
Developmental I. O. with High Resistance Target	1×10^{-5}
Developmental Wide-spaced I. O. C73469 (RCA)	5×10^{-5}

7.3.1 Image-Intensifier Methods

A visible light-near-infrared-single-stage intensifier-image orthicon has been developed and is being used in systems designed for Wright Air Development Center (WADC) and Engineer Research and Development Labs (ERDL). (Ref. 61).

The image intensifier orthicon (IIO) is a combination of the image orthicon TV camera tube and one or more image tube sections sealed into a single unit.

With an optical system of f/0.75 and signal-to-noise ratio of 5:1, the single stage II0 will operate at approximately 2×10^{-5} foot-candles of ambient light. Thus, the II0 will permit the TV system to produce images of targets having sufficient detail to allow recognition and interpretation at illumination levels lower than that at which a dark adapted eye may operate. The natural integration characteristic of the eye is useful in filtering much of the noise from the TV display so that considerable intelligence of a military nature can be extracted at low signal-to-noise ratios (S/N).

Visual acuity of the eye drops by a factor of 4 to 1 at scene brightness of 10^{-4} foot-lamberts. This means that a given size target could be imaged with equal clarity only at ranges decreased by four times, all other factors remaining equal. The II0 is not limited in this respect. Use of variable focal length optical systems such as the Zoomar, or a variable step or turret type system, permits wide-angle-low-magnification surveillance with change to narrow-view high-magnification for close-up inspection of suspect areas.

7.3.2 Near IR Capability

The image intensifier section provides the II0 with a near IR sensitivity out to 1.5 microns. The low light level capability combined with the near IR sensitivity provide the II0 television system with the following characteristics:

a. Night seeing capability.
b. Sterrable, stable, and variable optics may be used.
c. Unobstructed view from aircraft by pod or other mounting methods.
d. Integrated display.
e. Non-radiating, non-jammable.
f. May be remotely controlled.
g. Haze and camouflage penetration.

These characteristics are valuable for daytime operation also, although direct vision plus visual aids may provide more and better information under clear weather conditions. Also, statement (e) should be qualified by limiting it to low level highlights, as well as low level of ambient illumination. The relatively narrow dynamic range of the basic image orthicon operated at low ambient light levels causes it to saturate if a point of highlight illumination is more than twice the ambient level.

It is generally conceded by investigators that the TV system exceeds the aided eye only for narrow fields of view and then only at night. However, some of the other capabilities listed in previous paragraphs make up this apparently poor showing.

Figure 63 shows the ambient illumination generally found after astronomical twilight under various weather conditions. The darkest night has ambient of 2×10^{-5}-foot candles which is within the capability of the I10. Statistically, it is obvious that the ambient illumination, as a rule, will be greater than this lowest figure, making the TV system that much more effective.

Operating with near IR source, beamed to cover the field of view of the TV system , the low light level capability of the system can be very much improved. For large area coverage, sources could be suitably placed around a perimeter or carried by helicopter. Under most training conditions, the security violation by the active source is not a problem, making this kind of arrangement particularly suited to training applications of nighttime surveillance.

7.3.3 Low Light Level Image Orthicon (I. O)

The standard image-orthicon (5820) has the capability of viewing under low light levels down to less than full moonlight (of the order of 10^{-3} foot-candles of illumination) if the circuitry is carefully designed so that the tube's beam noise is the limiting factor. However, due to the construction of the tube (Figure 64), the high capacity, caused by the close spacing (.004 to .008 inches), between the thin glass target and the mesh causes "smearing" of relative object motion. If a stationary target suddenly moves, it seems to disappear from the CRT display until it stops, when it will suddenly reappear in a new position. To correct this obviously unsatisfactory condition, a modified tube was developed (6849). The target-to-mesh spacing is very much greater (0.150 inches) so that motion down to the noise limit is detectable. Other changes in tube construction lowered the usable illumination level to starlight (10^{-4} foot-candles).

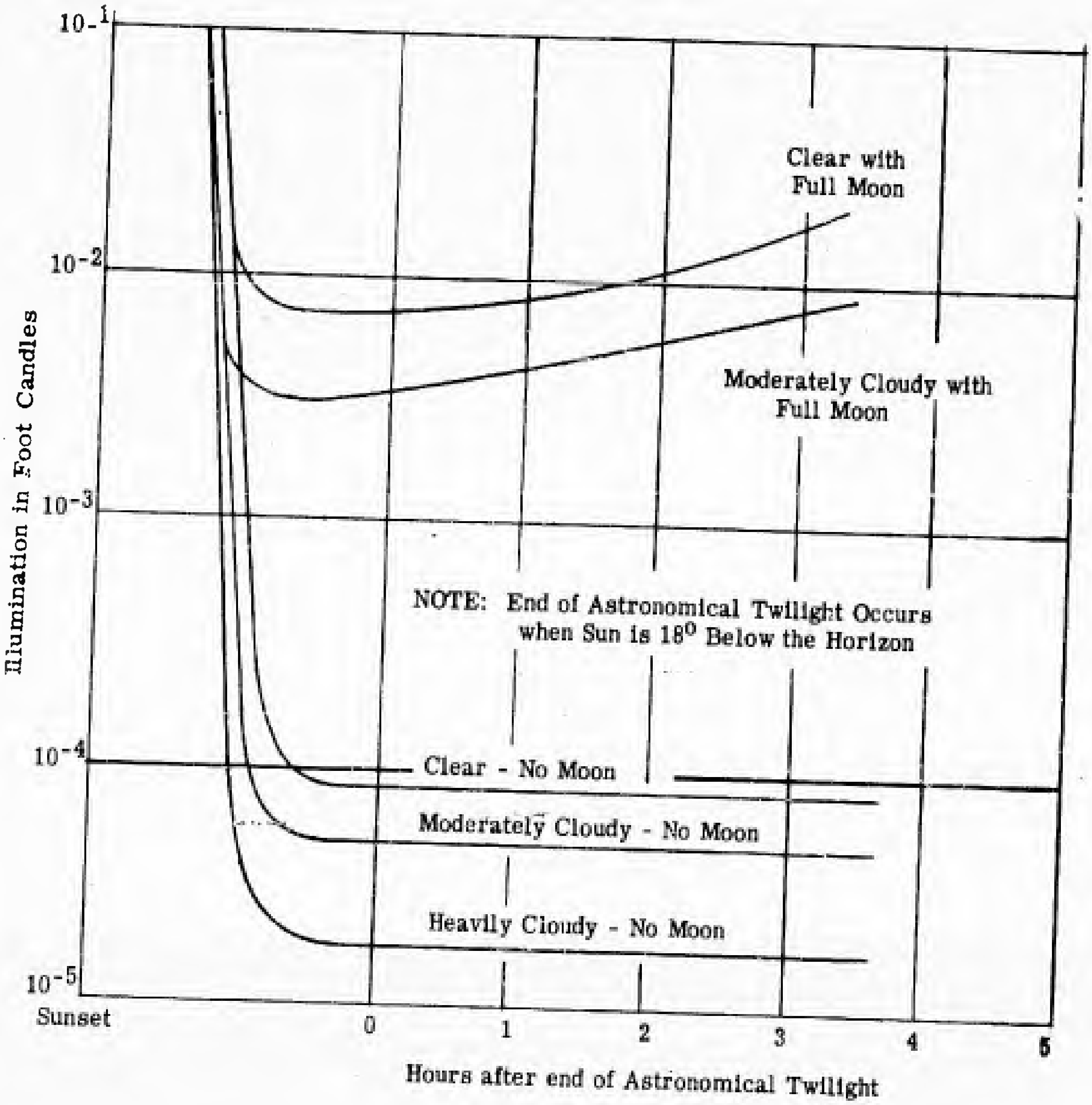

Figure 63 - Variation of Night Time Illumination with Atmospheric Conditions

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7.3.4 "Lumicon" TV System

This system, developed by Bendix, has the capability of presenting usable pictures under starlight conditions. The amplifier circuits and the auxiliary sweep and blanking circuits were designed for very low noise operation with shielding to reduce pickup to a minimum. It was designed as a light amplifier for use with under-exposed X-ray images so as to reduce the harmful effects of X-rays. Demonstrations of the system showed some near IR capability. Used as an active near IR system, excellent pictures of high resolution were presented under apparently no light conditions.

7.3.5 "Nite Owl" TV System

The beam noise limitation on lowest usable light level has been the subject of much investigation. The problem arises from the method of operation of the tube. Photons cause emission of electrons from the photo cathode to the thin glass target (Figure 64, Section 7.3.2). The electrons pass through the mesh and strike the target causing secondary emission. These secondary emission electrons are collected by the mesh, leaving a positive charge on the target. Because of the thinness of the glass target (.002 inches), a similar positive charge pattern appears on the opposite or scanned side. This side is scanned by the electron beam. At points of positive charge, the beam deposits electrons before returning to the multiplier section. The electron beam is modulated in this manner; areas of no signal returning the unmodulated beam to the multiplier.

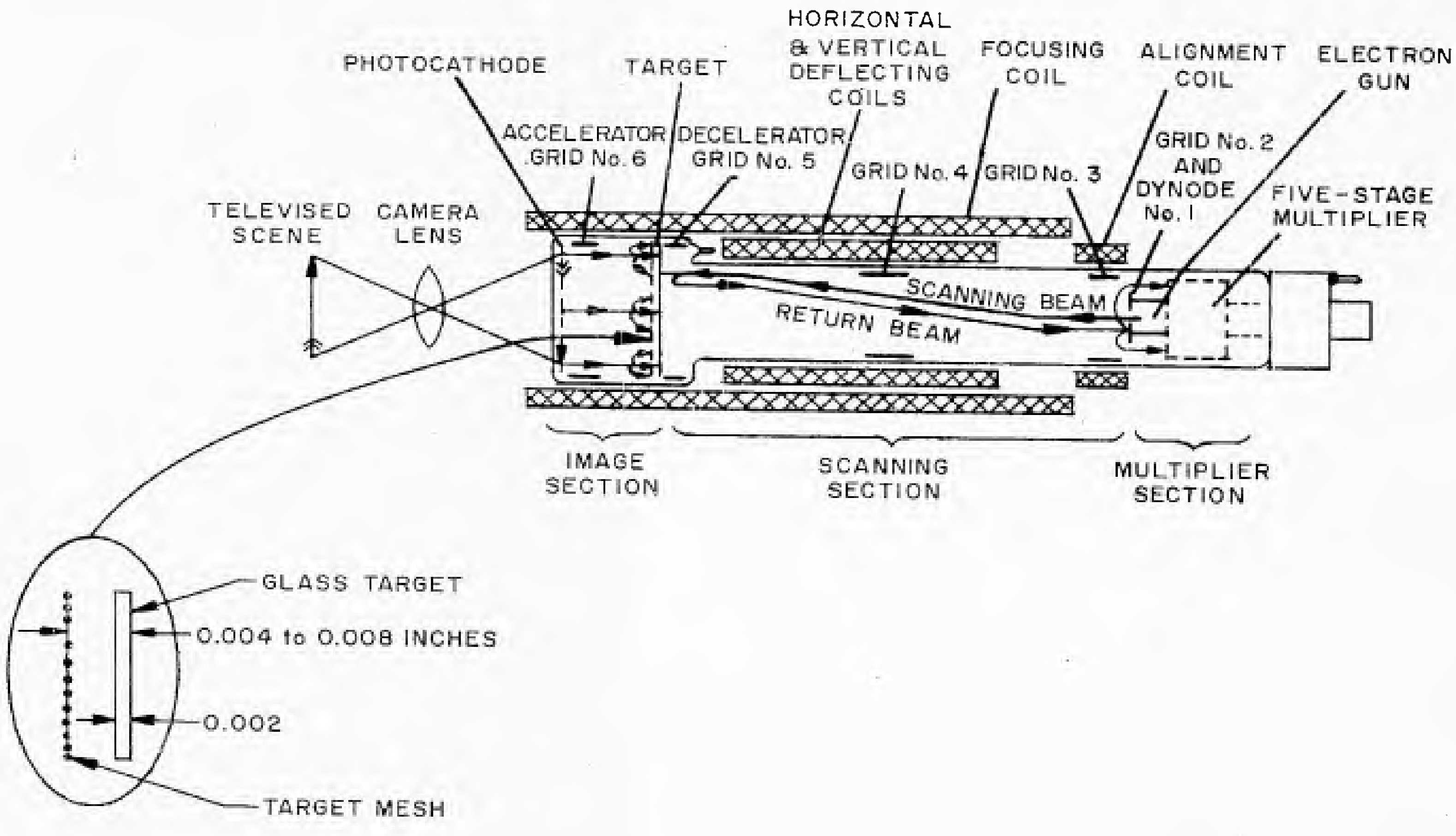

Figure 64 - Schematic Arrangement of Type 5820
Image Orthicon

Attempts to use feedback of the beam noise to cancel itself failed, as this resulted in an oscillating system.

The invention of a special circuit using a modified form of beam feedback permitted the Farrand Optical Company, Inc. to design a very low noise TV camera. The usable light level is less than 10^{-5} foot-candles. Figure 65 shows this in terms of highlight illumination. Note the dependence of resolution and contrast on signal level.

Qualitative tests showed that the image orthicon photo cathode surface had some near IR sensitivity, but quantitative results were not obtained. It is believed that part of the sensitivity of the "Nite Owl" camera is due to this near IR capability.

One disadvantage of low light level TV is its lack of dynamic range. If the ambient light level were suddenly raised, by flare or searchlight or other means, the system becomes saturated until the beam current is readjusted. The lost time may be as much as one minute, depending on the new light level and operator reaction time in resetting the controls.

In adjusting to the new highlight levels of illumination, information in the dark spots, previously visible, are lost unless they are illuminated by the new sources.

During development, the "Nite Owl" used first the 5820 and later the 6849 camera tubes. New tube developments by the several camera tube manufacturers such as more sensitive photocathode surfaces and high lateral resistance targets are being investigated. Preliminary work shows promise of reducing usable light levels significantly. With darkest night ambient levels of 2×10^{-5} foot-candles (Figure 63) the improved "Nite Owl" should be able to present detail not available at present.

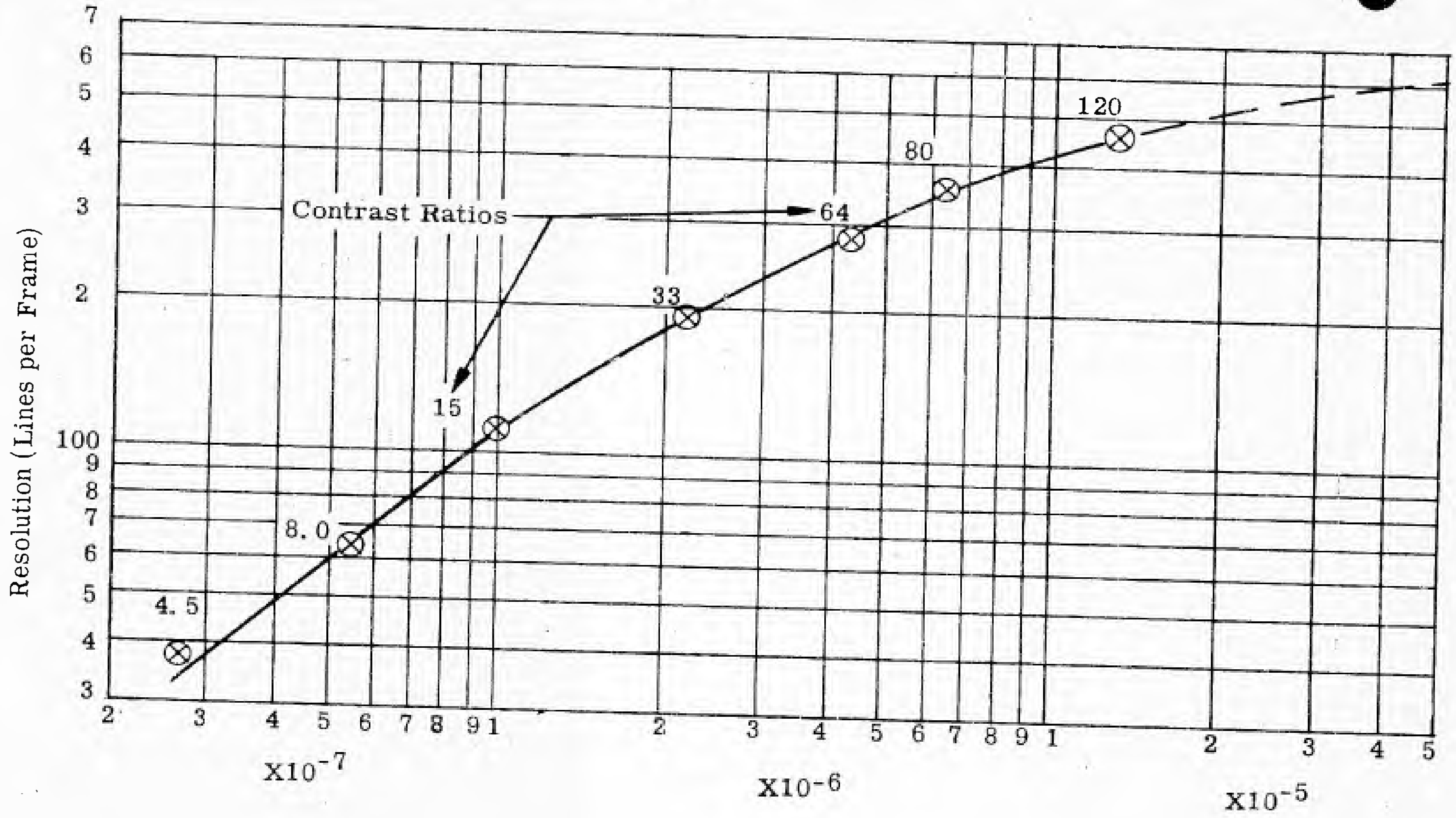

Figure 65. Sensitivity of Low-Light-Level Television

8. TRAINING CONSIDERATIONS

Infrared instruments and infrared techniques may be used in many diverse ways in the training of military personnel. In training for the application of infrared instruments (instrument herein defined as any device utilizing infrared energy in the performance of its function), the instrument may be used directly in training, owing to the comparative simplicity of infrared instruments; or simulation techniques may be employed. Infrared instruments may also be used as auxiliary training aids in the evaluation of performance, night or day, of battlefield training exercises and troop maneuvers.

8.1 Specific Infrared Applications

The applications of infrared have been broad in scope and its potential is far from exhausted. The many fields where infrared has been used will be noted in the following section. The discussion of training considerations, however, will be confined to:

a. Imaging systems for surveillance
b. the identification, interpretation, location and detection of objects.

8.1.1 Military Applications

The military applications of infrared techniques include the following fields:

1. Missile-borne homing devices
2. IR fire control
    a. Where greater angular accuracy than that provided by radar is required.
    b. Where low angle-operation near the ground or sea is required.
3. Passive search for Bomber Defense
4. Airborne Early Warning
5. Ballistic Missile Detection
6. Viewing systems in both near and far infrared. (active and passive)

    a. Sniperscope
    b. Metascope (map reading and signalling)
    c. Infrared periscopes and binoculars
    d. Image tubes
    e. Television
    f. Thermograph
    g. Evaporograph

7. Infrared Reconnaissance
    a. Ground to Ground
    b. Air to Ground
    c. Space to Ground
8. Infrared Communications
    a. Invisible Signalling
    b. IR Beacons
9. Missile Range Instruments
    a. Tracking aids
    b. Infrared tracking systems
    c. Gunnery hit-evaluator
10. Infrared Navigation Aids
    a. Celestial Tracker (star, sun or moon)
    b. Horizon Locator
    c. Infrared Map Matching
11. Infrared Countermeasures
12. Satellite Tracker
13. Satellite Weather Observation and Forecasting
14. Anti-submarine Warfare
    a. Snorkel detector
    b. Wake detector
15. Aircraft anti-collision warning
16. IR Aids to station keeping

8.1.2 Non-Military Applications

Non-military applications involve the use of infrared spectrophotometers and absorption analyzers for the identification and analysis of many substances. These instruments may also be included in the design of process controllers. Industrial radiometers and pyrometers are used to measure temperature remotely and may be used for process control, fire detection, and detection of overheated journal boxes in railroad cars. Infrared imaging devices are used in medicine for the location of pathological tissue and isolation of micro-organisms.

8.2 Simulation as Training Aid

In order to promote the proper use of infrared devices, adequate training must be provided. In addition to theoretical grounding, the student before being sent into the field, should receive some practical experience. Direct experience with the device to be used would be desirable, but owing to the cost and complexity of many devices, the use of simulation techniques is indicated.

Simulation is a valuable tool for the training and evaluation of system performance. Simulation may be a supplementary procedure to analysis and design, carried out prior to manufacture for the synthesis, optimization, or modification of an instrument or system in order to meet desired performance criteria. System performance may thereby be verified and optimum operating techniques developed.

Simulation techniques are of two classes: mathematical and physical. In the mathematical model, the entire system is represented in terms of mathematical relations that can be programmed into digital or analogue computors. The physical method uses the system, actual or physically simulated, subjecting it to the same or similar stimuli that would be met under typical operating conditions. The physical method includes techniques for developing synthetic displays of imaging systems.

8. 2. 1 Application to IR Systems

The IR systems that would be most applicable for use in training are of the image forming class. Images encountered in infrared systems a re frequently similar to photographs taken in the visible region of the spectrum, or they may be oscillographs that have similar information content as photographs. The representation of intensity modulated patterns within known spatial coordinates comprises the infrared images of interest.

The requirments for image quality in infrared instrumentation vary broadly with the intended application. A great deal depends on whether it is required merely to detect an object or to recognize fine details. The resolution, contrast, brightness and other characteristics of the simulated images will therefore vary in accordance with the use of the system and will determine the design of the training simulator.

8. 2. 2 Simulated - Display Variations

The scenes that would be simulated for IR system training would have a spatial background, including land, water and air masses, and be capable of presenting targets of military interest within the background. The ability to detect personnel, guns, missiles, aircraft, and military supply build-up areas would be provided. The read-out devices for this type of instrument include photographic film for permanent recording and detailed study, or moving image displays as seen on a cathode ray tube display (i. e. television) for timely read-out and interpretation. Permanent displays may be used directly for training in photo-interpretation and simulation equipment may be devised for training in the production of permanent displays. The simulator may be made up of the necessary components of the system for photoproduction using models as targets, or electrical signals may be simulated electronically. Electronic simulation would include both integrated scan and signal generators using conventional vacuum tubes and transistors, and magnetic tape-recorded signal and scan information. The simulated signals may be used to drive a cathode ray tube whose screen would be photographed. Transient displays may be generated in a similar manner with the cathode ray tube read directly rather than photographically.

8.3 Surveillance as a Training Consideration

The parameters of surveillance systems are determined by the system application and may be classified into three groups. The groups are ground-to-ground, air-to-ground and space-to-ground reconnaissance and mapping. The purpose of all of these equipments is to acquire the greatest amount of accurate data concerning the area and the personnel, in order that the data may be analyzed to obtain the maximum information for presentation in the most timely and useful manner. The information may be used for maneuver evaluation and would aid in the determination of personnel reaction.

8.3.1 Ground-to-Ground IR Surveillance

Ground-to-ground infrared instruments are generally required to present data not otherwise available regarding terrain, personnel, military targets and other items of military interest on a real time basis for immediate action. These instruments include the Sniperscope, Metascope, Infrared Periscope and binoculars, image tubes, and low light level television. Also in development are the AN/AAR-12, an airborne infrared scanner modified for ground use, a far infrared telescope designed for ground use, Scanrod T-2, a non-imaging scanner, and the AN/GAS-1(XE-4) Infrared Gunflash Detector.

Instruments for ground-to-ground use are generally small and simple enough to operate for direct training in their use, and would not require auxiliary training aids. The training problem, mainly, involves learning to interpret the infrared images as seen by the readout devices of the instruments. Direct photographs of the readouts may serve the purpose in some applications.

Infrared reconnaissance instruments may be used during training maneuvers to aid the officers in evaluating the troops. The AN/AAR-12, an air-to-ground surveillance system modified for ground use, and far infrared telescope have been used for battlefield surveillance and would serve the purpose well. During clear nights, a closed loop television system designed to operate at low light levels and responsive in the near infrared, may be used.

8. 3. 2 Air-to-Ground IR Surveillance

Air-to-ground infrared surveillance devices most frequently use image dissecting systems as described in the Scanning Methods section of this report. The signals are processed and used to drive a cathode ray tube that writes on a line basis in synchronism with the scanner. Photographic film is drawn along the image plane of the cathode ray tube face at a speed proportional to the velocity over altitude ratio of the aircraft and a strip map is thereby generated on film. The photographs may be processed in the air and read on the ground. Radio links transmitting video information derived from film for bandwidth compression, back to the ground from aircraft have been used. Frame-by-frame viewers as with image tubes and television are confined to slow speeds due to the image motion compensation problems.

As a training aid, air-to-ground surveillance would be useful in evaluating the performance of large groups of troops or vehicles during training maneuvers. Use of optical-mechanical scanning systems with intermediate or far IR capability and/or near IR electronic scanning systems would aid in arriving at rapid and accurate evaluation of the training problem.

8. 3. 3 Space-to-Earth Surveillance

Surveillance from space, e. g., from a satellite, has several advantages. The great altitudes involved allows coverage of large parts of the earth's surface, and, if the satellite is properly oriented in a polar orbit, the entire earth may be scanned in a relatively short time. Information regarding cloud and storm structure, radiant heat exchange, temperature distributions on earth, and many other heat and temperature parameters may be observed. Photointerpretation would be the primary training need in this field.

8.4 Identification, Interpretation, Location and Detection of Objects for Training

Training in identification, interpretation, location and detection of objects sensed by infrared instruments involves analysis of photographs and direct reading of imaging devices. Infrared photographs from high resolution systems operating during daylight may be similar to visible light photographs. Night photographs and areas of little thermal change result in photographs and images determined by various conditions. The modification of system outputs by the atmosphere, the time of day, cloud conditions and target distance affect the image quality. Experience with the particular infrared device under its operating conditions would provide the basis for training in interpretation.

8.4.1 Photographs from IR Systems

Photographs from IR systems for training purposes would demonstrate a variety of situations as seen by the infrared system observer. The effects on image quality by the atmosphere, the time of day, cloud conditions and target distance must be learned. The effects may differ in varying degrees between equipments. A library for each equipment would provide a training aid. Film may be projected for viewing by large groups. Figure 66 shows two typical photographs taken with IR viewing systems under various conditions. As determined by the thermal characteristics of the scene, and spectral response of the viewing system, the viewed scene may be of high photographic quality with a great deal of detail for information extraction regarding targets and background, or have only hot bodies visible with their backgrounds not available. Both photographs contain information of value within their application.

8.4.2 Locally Heated Models

In another method for training in interpretation of displays from systems such as image dissectors, image tubes, and television, models of typical scenes that are locally heated may be built. Objects heated to produce thermal images may be placed in the model, and the scene viewed directly by an infrared system. The model may be enclosed in a box that has openings for several types of imaging devices. The thermal characteristics of the models may be varied from a control panel, and a number of atmospheric conditions may be simulated by blowing vapors and aerosol particles of various sizes and composition over the scene. Atmospheric turbulance may also be simulated

Altitude - 3000 feet
V/H - 5°/Sec.

Ground Speed - 180 mph
Weather - Clear

Figure 66 - Republic Aviation Corporation

by the proper application of blowers. The terrain model may be made from a master plaster cast of the scene. The thermal characteristics would be simulated by local heating using resistance elements and the reflectivity of the various areas being viewed would be simulated by the application of properly selected paints. Figure 67 shows a cut-away view of a typical model and its enclosure with the various control devices that may be used either individually or simultaneously for viewing.

In order to make the simulator usable by large groups, a closed loop television display of the image read-out may be used with an adequate number of kinescope displays to accommodate the group.

8.4.3 Painted Models

Simulated infrared trainers for imaging systems may be made to operate using visible light. Models that are illuminated by visible light but painted to appear like infrared images when viewed would be used. The models would be made of pressed material in a suitable mold and painted to simulate the thermal scene. In order to simulate different conditions, the color and intensity of light could be varied by filters and atmospheric conditions could be varied by vapors and aerosols. The models would use paints that are best suited to simulate background and target characteristics. The viewing devices would be visual optical systems, image tubes, and television. The configuration used with locally heated models would also be applicable to painted models. The container for the models, the read-out devices, and the control devices, may be housed in a trailer for portability, or set up in a more permanent facility.

8.4.4 Touched-Up Photographs

Direct photographs made under visible conditions may be touched-up to appear like infrared images. The photographs would be taken under conditions conducive to good photography which is generally less costly than direct infrared image generation. Touch-up may be performed by hand and the resulting reproduced photograph would have all of the characteristics required for training. A method has been developed for producing a simulated IR photograph from a visible light photograph. Originally intended for briefing of air crews before a mission, this method provides a means of creating IR photographs for training purposes (Ref. 63).

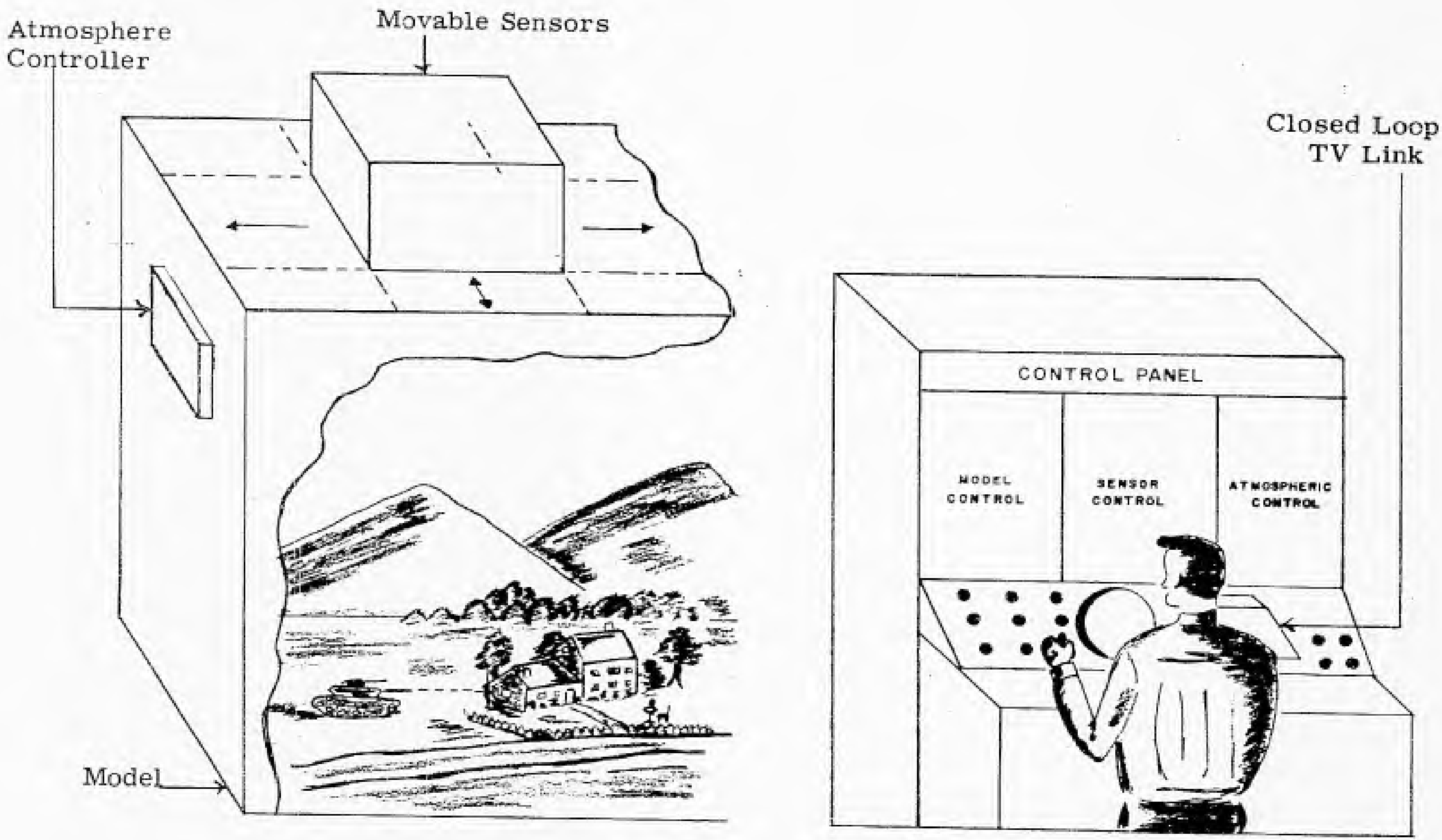

Figure 67 - Typical IR Model Type Trainer

A visible-light photograph of an area is touched-up with several different colors of specially compounded paints in accordance with the expected thermal radiation. The touched-up photograph is illuminated with colored lights. The colored lights serve to simulate various ambient conditions and can demonstrate such effects as intensity variations between target and background, and variations between the several components of the background. Photographs are made under the aforementioned conditions in black and white and appear as IR photographs that may be presented to air crews as representative of the target's IR environment.

8.4.5 Electronically Simulated Oscilloscope Displays

Electronically simulated oscilloscope displays may be used for training in infrared interpretation of objects where complex signals do not exist. The displays may be written on the face of a cathode ray tube that has a raster or circular sweep pattern. The appearance of typical trucks, missiles, aircraft, personnel, and other isolated military targets may be simulated by electronic signal generators. Background signals are too complex to be generated electronically.

8.4.6 Taped IR

Video tape with infrared image information may be used to generate television pictures of the information. The bandwidth required for infrared images is similar to the bandwidth needed for visible pictures obtained with tape and should not present any problems not presently existing in the making of video tape. In fact, some IR systems have bandwidths narrow enough to permit the use of audio frequency tape recorders.

8.5 Comparison of Simulation Methods

Table XI tabulates the advantages and disadvantages of the training aids discussed in this section. Photographs, either direct IR or touched-up visible, are simple to make, easily reproduced, and can provide many training conditions from a compiled library. The image quality of photographs is very good, and they may be handled and stored easily without deterioration. Photographs do not offer training for the operation of the equipment and their use is limited to photo-interpretation.

The use of models, either locally heated or painted, offers a versatile means of simulation of infrared instruments and the environments that they would be expected to operate in. The models may be scanned by the entire gamut of infrared viewing devices and their associated read-outs in a suitably synthesized simulation configuration. The read-outs would be readily adaptable to group viewing. Non-programmed training may be used with this method, making available to the instructor a wide assortment of training situations that are not anticipated by the student.

Electronic methods are limited in use owing to the complexity in generating the high information content of many infrared instruments. Video tape is the most promising technique for image simulation, but is comparatively costly and complex if high frequencies are used. Video tape does not allow direct experience with the scanning instrument being simulated but does allow direct experience with all read-out controls.

TABLE XI - Comparison of IR Simulation Methods

Method	Advantages	Disadvantages
Direct Photograph of IR Displays	1 - Low unit cost 2 - High image quality 3 - Readily reproducible 4 - Easy storage 5 - Portable 6 - Long storage life 7 - Ease of handling	1 - No correlation between equipment and photograph 2 - Non-programmed 3 - Is 2 dimensional 4 - Lacks realism
Locally Heated Models	1 - Direct equipment viewing 2 - Can simulate various conditions with relative simplicity. 3 - Can use a number of different viewing methods 4 - Group viewing capabilities	1 - Relatively complex 2 - Relatively large size 3 - Non-programmed
Painted Models	1 - Direct equipment viewing 2 - Can use a number of different viewing methods 3 - Group viewing capabilities 4 - Can simulate various conditions.	1 - Relatively complex 2 - Relatively large size
Touched-up Visible Photographs	Same as direct IR photographs	Same as direct IR photographs

TABLE XI - Comparison of IR Simulation Methods (continued)

Method	Advantages	Disadvantages
Electronic Simulation		1 - Presently beyond state-of-art 2 - Can only reproduce relatively simple conditions 3 - Complex
Taped IR	1 - Good quality picture 2 - Group viewing capabilities 3 - Can tape many conditions and store conveniently	1 - Complex 2 - Large 3 - Expensive 4 - No direct operation of equipment

9. COMPARISON OF IR AND OTHER TRAINING TECHNIQUES

Surveillance of tactical, strategic, and logistic areas during day and night and under all weather conditions is a capability of great military importance. A number of techniques have been used to achieve the capability with varying proficiencies. The techniques include the use of infrared systems, visible light systems (photographic, optical, television, and visible image dissectors), and radar systems. Surveillance systems are used also for reconnaissance and mapping. The information derived from these systems may be employed as an aid in making military decisions, evaluation of maneuvers, and the establishment of an information bank as an aid in decision making and in training. The data from these systems are presented in the form of images that contain large quantities of information. The extent of the information available from the images is determined by the capabilities of the user; either human, machine, or a combination of both.

9.1 Performance of Surveillance Systems

The effectiveness of surveillance systems may be based on a number of criteria pertinent to their application. In battlefield surveillance, the information requirements are, in general, determined by the weapons and typical missions of the unit. The essential information pertains to the enemy, the terrain, and the weather. The ability of the system to provide the necessary information with a minimum of equipment, ease of interpretation, and timeliness of the information are factors in the evaluation of the system. The ability of the adversary to influence the operation of the system must also be considered. Table XII is a compilation of representative surveillance systems and their performance capabilities.

The natural tools of military men for acquiring information regarding the enemy have become less and less adequate as the complexity of warfare has increased through the years. In order to be effective in this complex environment, there is an increasing need for rapid and continuous surveillance. The necessity to train military men in the use of surveillance instruments appears to have a place in military training programs.

The diverse requirements of surveillance systems may be examined more readily in groups of ground based and airborne systems. In both groups, formation of images of ground areas is of primary importance.

TABLE XII - Comparison of IR and Other

Performance Factor	Infrared			
	Image Dissector	Image Tube	Photographic	TV
Passive	Yes	Yes	Daylight Only	Daylight
Active	Limited to Near IR	Limited to Near IR	Flash and Searchlight	Searchlig and Puls
Day-Night Capability	Yes	Yes	Limited	Limited
Weather				
Haze	Yes	Yes	No	No
Fog	Limited	Limited	No	No
Rain	Limited	Limited	No	No
Snow	Limited	Limited	No	No
Geometric Accuracy	2-dimensional display	2-dimensional display	Some depth capability	2-dimens display
Resolution Limitation	Optical system Detector Combination	Phospher size and Halation	Film Grain Size	Target m Transmis Bandwidth
Moving object Detection Capability	Yes	Yes	Limited to Sequential Photos	Yes
Can it be detected by the enemy	Passive - No Active - Yes	Passive - No Active - Yes	Passive - No Active - Yes	Passive - Active -

omparison of IR and Other Training Techniques

Visible				
hotographic	TV	Image Dissector	Image Tube	Radar
aylight Only	Daylight Only	Daylight Only	Daylight Only	No
lash and earchlight	Searchlight and Pulsed Light	Searchlight	Searchlight and Pulsed Light	Yes
imited	Limited	Limited	Limited	Yes
	No No No No	No No No No	No No No No	Yes Limited at upper end of spectrum
me depth pability	2-dimensional display·	2-dimensional display	2-dimensional display	2-dimensional display
lm Grain ze	Target mesh and Transmission Bandwidth	Optical System Detector Combination	Phospher Size and Halation	CRT spot size
mited to quential otos	Yes	Yes	Yes	Yes
ssive - No tive - Yes	Passive - No Active - Yes	Passive - No Active - Yes	Passive - No Active - Yes	Yes

TABLE XII - Comparison of IR and Ot

Performance Factor	Infrared			
	Image Dissector	Image Tube	Photographic	
Can it be jammed	Very low probability	Very low probability	Very low probability	Very prob
Can it be deceived	Yes	Yes	Yes	Yes
Can it see through camouflage	Yes	Yes	No	No
Acoustic Noise	Slight	Low	Low	Sligh
Size	Moderate	Small	Small	Mode
Weight	Moderate	Low	Low	Mode
Power	Moderate	Low	Very Low	Mode
Information Capacity	High	High	High	High
Information Timeliness	Immediate	Immediate	Slight delay	Imme
Communications Capability	Yes	Require Auxiliary Equipment	Require Auxiliary Equipment	Yes

1

parison of IR and Other Training Techniques (continued)

Visible				
tographic	TV	Image Dissector	Image Tube	Radar
y low ability	Very low probability	Very low probability	Very low probability	Yes
	Yes	Yes	Yes	Yes
	No	No	No	No
y	Slight	Slight	Low	Moderate
ll	Moderate	Moderate	Small	Large
y	Moderate	Moderate	Low	High
y Low	Moderate	Moderate	Low	High
h	High	High	High	High
ht delay	Immediate	Immediate	Immediate	Immediate
uire iliary ipment	Yes	Yes	Require Auxiliary	Yes

2

All of the systems being compared are effectively confined to line of sight situations. Ground surveillance is, therefore, limited by external conditions. When targets to be observed are shadowed, it becomes necessary to carry the system within sensing range of the target. In modern warfare the operational field is extensive, and further requirements for communication of data, navigation, and position finding are imposed on the system. Distant targets are, in general, observed by airborne surveillance systems.

The selection of a system for use in a given surveillance situation for training would involve consideration of the performance factors peculiar to the system.

9.1.1 Advantages and Disadvantages of Performance

The performance of surveillance systems may be evaluated from a number of factors. The weighting values of these factors varies with the use of the system and would, therefore, be considered only for a given application. The ability to operate without radiating energy that may be detected by the enemy is very desirable. Passive operation would forestall enemy countermeasures, direct attack, or a change in his plans if he were aware that he was being observed. In the case of ground systems where the enemy is close, acoustical noise is also a factor. Infrared systems can be designed to operate day and night passively while visible systems are confined to daylight conditions for passive operation. Radar performs during day and night, but does not have the capability to operate without radiating and is susceptible to enemy detection and countermeasures. For training however, active systems do have definite value as security requirements are not as strict.

9.1.2 Weather Capability

The ability to operate all weather is effectively a measure of how far into adverse weather one may operate. The factors of adverse weather are haze, fog, rain, and snow. The variations within these factors are broad. Visible light systems cannot see through comparatively light haze, fog, rain, and snow conditions and are the first to become ineffective due to weather. Infrared systems can penetrate haze, fog, rain, and snow of greater density and particle size with the longer infrared wavelengths more effective as the particle size and density increases. Radar shows better weather capability than infrared. High resolution V-band radar, however, cannot penetrate clouds and fog of significantly greater particle size and density than far infrared. Pulsed-IR viewing systems might have value under adverse weather conditions as a surveillance training aid.

9.1.3 Image Comparisons

The images formed by infrared, visible, and radar systems are two dimensional and have good geometric accuracy provided that an accurate base or familiar objects are available. Range measurements are made in radar systems since they are active and transit time can be measured and translated into range information.

The resolution limits of photographic, image dissector, television, image tube, and radar displays are determined by different factors. The optics associated with the infrared and visible systems generally provide resolution capability exceeding that of the human eye, and, therefore, would not be considered as limiting any of these systems.

Photographic images are limited by the film grain size. The film to be used would be selected with due consideration to the light level, system light gathering capability, and the resolution required.

Image dissectors, either infrared or visible, reach their resolution limit where the incoming energy generates a signal that cannot overcome detector noise. The combination of optical light gathering and detector noise parameters must be considered.

The factors that limit television systems are the target-mesh size of the camera tube, the kinescope spot size, and the transmission bandwidth.

Image tubes are limited by the phosphor grain size and halation, which effectively increases the size of each resolution element.

Owing to the longer ranges encountered in radar systems, the cathode ray tube spot size is the limiting factor in resolution.

9.1.4 Communication Capability

As mentioned previously, the necessity for communications capability exists in surveillance systems that are carried to the scene of interest. In the systems where a filmed image is produced, or is capable of being produced, the film may be scanned by a flying spot scanner or modulated glow tube to generate video data for transmission over a radio link. Present rapid film processors are capable of developing and fixing film in several seconds so that the time delay between surveillance and viewing is not significant. The scan rates selected would be compatible with the bandwidth required for good image quality and transmission capability of the radio link. The other systems, producing images by electronic means, have an inherent capability for transmitting this information over radio link.

9.2 Economic Consideration

9.2.1 Surveillance Training Aids

A suitable surveillance system to aid in the evaluation of training maneuvers during day and night conditions would be confined to infrared or radar. Radar systems are significantly costlier than comparable infrared systems. The additional requirements of an antenna, a transmitter, and the larger transportation facilities make up the difference in cost. In general, infrared circuitry is less complex than radar and would be less costly to develop.

9.2.2 Simulation Training Aids

Training aids in the operation of radar and infrared using simulation are comparable in cost. The simulation techniques of terrain and target for both systems involve the use of models. Infrared models may either be painted or heated and would provide greater flexibility in use. Non-programmed training sessions may be employed. Direct infrared viewing may be employed with heated models, offering realism in training not available with radar simulators. Due to the different information content, IR simulators would not generally be interchangeable with radar trainers.

9.3 Physical Considerations

9.3.1 Mobility

Mobility of infrared, visible, and radar systems is a function of their size and weight. All of the systems being considered are mobile. In order of ease of mobility, they are: photographic, image tube, television, infrared and visible image dissectors, and radar. Operation of all of the systems in motion requires that they be vibration free and the effects of image motion removed. A gyroscopic reference system may be used for stabilization and a velocity over altitude correction applied to both frame and line scanning systems. Mobility of surveillance training aids is more necessary than for simulation training aids.

9.3.2 Relative Complexity

The relative complexity of radar, image dissectors, television, image tube and photographic systems may be compared with proper consideration to the system applications. Since the conditions of application are so diverse, the systems will be compared in a broad sense, rather than in a specific application. Radar is the most complex in terms of the number of components, stabilization, and maintenance. Radar is an active system and requires a source of radiant energy. The relatively high energy encountered in radar systems results in lower system reliability and a greater maintenance problem. The frequency at which radar operates requires components that are considerably larger than those needed for infrared or visible light systems used as surveillance training aids. Simulators for radar and IR would have comparable complexity.

9.3.3 Size, Weight and Power Comparison

The size and weight of the systems being discussed can be compared on the basis of equal image production capability. The large size of radar antennas for the formation of beamwidths narrow enough to produce images suitable for surveillance and the generation of radiant energy are the salient differences. Presently, 70 kilomegacycles appear to be the upper frequency of efficient power generation and imposes the limit on antenna size reduction. These factors make radar orders of magnitude larger in size, weight, and power than comparable infrared and visible systems.

9.3.4 Mechanical vs. Electronic Scanning

Mechanical scanning requires the use of high-speed moving parts and an accurately aligned integral optical system. The scanner must be statically and dynamically balanced and operated in a suitably clean environment. Electronic scanning does not involve moving parts. The scanning process may be carried out in much shorter periods of time and can be used as either line or frame scanners. Electronic scanners are compact and do not require large amounts of power. The electronic viewing devices such as the image orthicon and other image tubes, however, are relatively complex. Direct comparison between electronic and mechanical scanning should be made on the basis of a specific application only.

10. CONCLUSIONS AND RECOMMENDATIONS

10.1 Conclusions

The information presented in this report leads to the following conclusions:

10.1.1 Infrared techniques have definite value to the military services by providing information available by no other methods. Therefore, training in all phases of infrared technology appears to have a place in military training programs.

10.1.2 The state-of-the-art indicates that surveillance as a training application is feasible in the near infrared region out to 2 microns with passive and active systems using television techniques under night viewing conditions. The images displayed under these conditions are similar to visible light image system displays.

10.1.3 The state-of-the-art indicates that passive infrared image-forming techniques at wavelengths longer than 2 microns are feasible for surveillance as a training application. Under these conditions, however, the images of familiar objects are displayed with unfamiliar shadings and contours.

10.1.4 Active systems beyond 2 microns have been hampered by a lack of suitable IR sources, although the problem is under investigation.

10.1.5 The unfamiliar images of familiar objects introduces a need for training in identification, interpretation, location, and detection of objects as displayed by the longer wavelength infrared imaging systems.

10.1.6 The infrared image of an object has many variations depending on the time of day, weather conditions, and operational status (i.e. power on or off.) These variations, in addition to Sec. 10.1.5, introduce a need for an infrared simulator that can simulate images under all conditions, and from instruments operating in different infrared regions.

10.1.7 The state-of-the-art indicates that low intensity visible light television techniques are feasible and practical means of surveillance for training applications. The techniques of low light level TV appear to take advantage of the limited near infrared sensitivity inherent in the sensor for viewing under haze or light fog conditions.

10.2 Recommendations

Based on the above listed conclusions, the following recommendations are made:

10.2.1 The techniques and components of low light level and infrared television should be further explored with the view of developing passive and/or active infrared equipment for each training application; for example, the night time observation of troop maneuvers or amphibious operations.

10.2.2 The techniques and components of passive infrared image-forming systems operating in the longer wavelengths should be further explored with the view of developing an instrument for training personnel in the identification, interpretation, location, and detection of objects as well as for the uses listed under 10.2.1.

10.2.3 A study program to investigate, compile, and catalog infrared images of military targets, personnel, vehicles, ships, aircraft, and places) along with comparable visual images is highly recommended. It is considered that this information is necessary if any comprehensive simulation program for training purposes is to be effective.

11. CONCLUDING SUMMARY

Since the end of World War II, an extensive program has been undertaken under the cognizance of the various defense organizations to develop the techniques, materials, and components of infrared technology. The results to date of continuing programs to study background and target radiation patterns, and absorption and emission effects of the atmosphere have been presented in this report. A survey of optical materials used in infrared technology has been made and data as to their properties and spectral transmission and absorption regions have been included in the report. In addition to a review of thermal detectors' properties, the results of a survey of the developments in the rapidly changing photoconductor field have been presented. Other methods of detecting and converting infrared energy have also been covered, as well as the techniques and components of low light level television. Various methods of display of infrared information have been presented with emphasis placed on image displays useful for surveillance as a training application, and for training in interpretation, identification, location, and detection of objects. A summary of scanning methods, optical-mechanical and electronic, as well as a review of active system techniques and components have been made.

All the above related information has, in addition, been covered from the viewpoint of the training considerations of surveillance, and of identification and interpretation of objects. Also, from the viewpoint of training considerations, a comparison of the techniques of infrared technology has been made with other methods of information collection.

Based on the information presented in the report, affirmative conclusions as to the feasibility of the application of infrared techniques to the training considerations of surveillance, and to identification and interpretation of objects for training have been made. It was also concluded that the television electronic scanning process is feasible:

a. As a direct means of infrared image forming in the range of 7500 to 12,000 Angstrom units.

b. As a means of infrared information distribution and display.

c. As a means of low intensity visible light image forming in those applications of military training problems where low intensity levels of visible light are a factor.

As a result of these conclusions, recommendations were made for further investigation toward the development of training equipment for each of the training applications considered.

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13. APPENDIX

I

List of names, symbols, units, and brief description of the most important physical radiation quantities as recommended by WGIRB.

Symbol	Name	Unit	Description
$\underline{U}$	Radiant energy	Joule	Total Radiant Energy
u	Radiant energy density	Joule/cm^2	Radiant energy per unit volume
P	Radiant power or flux	Watt	Rate of transfer of radiant energy
W	Radiant emittance	Watt/cm^2	Radiant power per unit area emitted from a surface source
H	Irradiance	Watt/cm^2	Radiant power per unit area incident upon a surface
J	Radiant intensity	Watt/steradian	Radiant power per unit solid angle from a source
N	Radiance	Watt/ster/cm^2	Radiant power per unit solid angle per unit area from a source
P_λ	Spectral Radiant flux	Watt/micron (μ)	Radiant power per unit wavelength

Radiation Equations and Constants

$$W_\lambda = \frac{C_1}{\lambda^5} \times \frac{\lambda T}{C_2}$$ Rayleigh - Jean's Law

$$W_\lambda = \frac{C_1}{\lambda^5} \times \frac{1}{\exp(C_2/\lambda T)}$$ Wien's Law

$$W_\lambda = \frac{C_1}{\lambda^5} \times \frac{1}{\exp(C_2/\lambda T) - 1}$$ Planck's Law

$$\lambda_m = \frac{2897.9}{T}$$ microns

$$W = \sigma T^4$$ watts/cm^2

$W_\lambda = \epsilon W_\lambda$ (blackbody) Kirchoff's Law

$C_1 = 3.7403 \times 10^4$ watts/cm^2/micron

$C_2 = 1.438$ micron-degree

$\sigma = 5.668 \times 10^{-12}$ watt/cm^2/deg. K^4

ϵ = Emissivity

α = Absorptivity

COOLING TEMPERATURES

(at 14.7 psi)

Liquid Nitrogen	-195.8°C	77.38°K
Liquid Oxygen	-182.86°C	90.32°K
Liquid Helium	-268.9°C	4.28°K
Liquid Hydrogen	-252.8°C	20.38°K
Liquid Air	-192°C	81.18°K
Absolute Zero	-273.18°C	0°K
Dry Ice (Solid CO_2)	-78.50°C	194.68°K

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Minneapolis-Honeywell Reg. Company, Aeronautical Division, 2600 Ridgway Road, Minneapolis 13, Minnesota, MKD: John W. Senders

Department of Psychology, The Ohio State University, Columbus 10, Ohio

Ohio State University Research Foundation, 1314 Kinnear Road, Columbus 8, Ohio, MKD: Aviation Psychology Lab.

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John Hopkins University, 3115 St. Paul Street, Baltimore 2, Maryland, MKD: Psychological Laboratory

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