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THE USE OF FAR INFRA-RED RADIATION FOR THE DETECTION OF CONCEALED METAL OBJECTS

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TECHNICAL REPORT



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16. Abstract The use of infra-red radiation for the detection of concealed metal objects has been investigated both theoretically and experimentally. The investigation was divided into two phases, one which considered passive techniques, and another which involved active sources of radiation to probe the subject. Because of the limited amount of time and equipment available, only primitive systems were studied, but the results serve as a fundamental guide to the requirements of a field operational system. The results obtained show that metals concealed by clothing can definitely be detected by observing the far infra-red radiation from the region of the hidden object. This type of system has the very attractive feature of high spatial resolution, and can easily distinguish between dangerous weapons and harmless objects.			
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I. INTRODUCTION

In recent years many sophisticated instruments have been developed to detect surface temperature. In the field of medical technology, for example, organic ailments are diagnosed by measuring variations in skin temperature¹; in other applications such as the inspection of tires², transformers³ and circuit boards⁴, defective parts are detected by means of hot spots observed on exposed surfaces. The success of infra-red techniques in these areas immediately raises the question as to whether similar I-R techniques can be used in the field of civil aviation security. A metal object close to the skin will certainly alter the radiation pattern of the body and the information contained in an infra-red photograph of a person, e.g., might prove useful in the detection of concealed weapons. This type of system has the very attractive feature of high spatial resolution, and can easily distinguish between dangerous weapons and harmless objects.

Because of the potential value of infra-red surveillance to civil aviation security, a program was established at TSC to explore the feasibility of various infra-red techniques. Two studies were instituted, one in-house, and another on contract. Both studies were limited in time and scope, and were designed to obtain as much information as possible with equipment on hand at TSC and the contractor's site. In general, the in-house program was designed to examine passive techniques, while the contractor's task was to explore active systems. The first part of this report covers the work performed at TSC. The contractor's (Barnes Engineering Co., Stamford, Conn.) final report is included as an appendix.

2. DISCUSSION OF PROBLEM

Commercially available infra-red cameras are capable of detecting temperature differences as small as 0.1°F with an angular field of view of 1 millirad. Unfortunately, however, these cameras operate at mid I-R wavelengths in the neighborhood of 10 microns, which is heavily absorbed by clothing. In the absence of clothing, as in medical diagnosis, the radiation emitted accurately represents the temperature of the skin. In the presence of clothing, however, the observed temperature may be quite different from that of the skin depending on the degree of thermal contact. This is illustrated by the infra-red photo (Fig. 1) in which the wide variations in surface temperature are due to the proximity of the clothing to the skin. Because of these large variations, a concealed metal object could easily be obscured by clothing even though the intensity of radiation from the metal and surrounding skin were quite different.

While the use of infra-red detection is seriously limited at mid I-R wavelengths, the situation is somewhat improved at far I-R wavelengths which are only moderately absorbed by clothing. The improvement results from the fact that as the absorption diminishes, fluctuations arising from thermal gradients become less important, and the ability to detect concealed metals depends primarily on the emissivity of the metal and the I-R transparency of the clothing.

In addition to the effect of thermal fluctuations, the feasibility of detection depends on the sensitivity of available detectors. This is especially true in passive far I-R systems, where the radiation emitted from the body is relatively small. In the following sections the limitations imposed by these two factors will be considered separately.



Figure 1. Infra-Red Photograph of Human Subject (L.W. Nichols in Darkness. Skin Glows Incandescent Due to Body Heat)*

*Photo Reprinted From "Applied Optics", September 1968, Vol.7, No. 9

2.1 PASSIVE SYSTEMS

2.1.1 Effect of Absorption

The threshold of absorption by clothing which would obscure the radiation from a small area of the body shielded by metal will be calculated in this section.

In the neighborhood of 300 microns and 300°K the radiation emitted from a grey body is directly proportional to ϵT where ϵ & T are the emissivity and temperature of the body respectively. At this wavelength and temperature it is assumed that the emissivity of the human body is unity and that the radiation emitted by metals is negligible.

In the absence of metal, the intensity of radiation emitted from the body depends on its thermal contact with the clothing and is proportional to:

$$\frac{T_c}{T_b} + x \left(1 - \frac{T_c}{T_b} \right)$$

x = transmissivity of the clothing ($x = 1 - \epsilon$)

T_c = absolute clothing temperature

T_b = absolute body temperature

In the presence of metal, radiation consists of energy radiated directly outward by the clothing, and energy reflected from the metal. The reflected component arises from energy radiated inward by the clothing and the ambient surroundings. The intensity of this radiation is proportional to:

$$\frac{T_c}{T_b} - x^2 \left(\frac{T_c - T_a}{T_b} \right)$$

where T_a is the ambient temperature.

In order to observe a contrast between the metallic and surrounding areas of the body, the change in radiation caused by the introduction of a metal object must be greater than or equal to the fluctuations arising from varying thermal contact with the clothing. This leads to the requirement.

$$X \geq 0.6$$

This shows that a metal object concealed by clothing which absorbs as much as 40% of the infra-red radiation can be distinguished from the surrounding area.*

2.1.2 Detector Sensitivity

If a passive system is to be used, it is necessary to detect radiation at black body intensities. At temperatures and wavelengths in the vicinity of 300°K and 300 microns, the intensity fluctuations arising from varying thermal contact are of the order of 10^{-10} W/cm², assuming an optical bandwidth of 100 microns and that 0.1% of the energy radiated over a hemisphere is collected. If the information is displayed on a television screen in the form of a picture, an electronic bandwidth of the order of 10^4 Hz is required, assuming a display of 2 frames/sec. As a consequence a useful detector must have an equivalent noise power of less than 10^{-12} W/Hz^{1/2},** and a response time of less than 100 microseconds.

*It should be pointed out that it is not necessary to have a temperature difference between the metal and the body in order to produce a contrast. In fact the minimum transmission required is independent of the temperature of the metal since its emissivity and hence the radiation emitted is negligible. This is opposed to the situation at mid I-R wavelengths which are heavily absorbed by clothing, in which case a thermal gradient is required to produce a contrast.

** 10^{-12} Watts $\sim \Delta T \approx 6 \times 10^{-4}$ °K at 300u

A survey of infra-red detectors shows that these requirements are rather stringent, but can be met by the most sensitive detectors available. These are solid state devices which operate at cryogenic temperatures. If a passive surveillance system is to be used, this type of detector is clearly necessary.

2.2 ACTIVE SYSTEMS

The limitations imposed on the absorption of clothing and the sensitivity of detection in a passive system are very much relaxed in an active system. For example, if a person were illuminated with a laser beam having an intensity as small as 10 microwatts it would be possible to reveal a piece of metal concealed by clothing which absorbs as much as 99% of the radiation. Furthermore, it would be possible to detect the radiation reflected from the metal with room temperature devices.

Of course, in an active system other considerations arise such as the added expense of the source and radiation hazards. The relative advantages of active and passive systems must be evaluated quantitatively in order to establish the optimum system. Active or passive radiation systems however, would include the spectral region between approximately 1 micron and 1 millimeter

3. OBJECTIVES, DESCRIPTION, AND RESULTS OF IN-HOUSE PROGRAM

In the second section it was determined that passive detection of a metal object concealed by clothing requires that the infra-red transmissivity of the clothing be greater than 60%. The first objective, then, was to examine the transmissivity of a variety of common fabrics, and to establish the wavelength region in which this criterion could be satisfied. The next objective was to learn if metals concealed by such fabrics could be detected by viewing the subject at these wavelengths.

Since very little, if any, data existed on the transmission of infra-red radiation through clothing, it was necessary to make these measurements in the laboratory. This was done at Professor Ali Javan's laboratory at the Massachusetts Institute of Technology, using water vapor, helium, and hydrogen cyanide lasers, generating 28, 96, and 337 micron radiation. These lasers are rather cumbersome laboratory devices which are about 10 cm in diameter and several meters long, but nevertheless they are the most convenient sources of far infra-red radiation available. They generate a collimated beam of radiation about 1-2 mm in diameter, and have a power output of about 1 milliwatt. Broad-band detectors are used to detect the far I-R energy, and consist of thermocouples, Golay cells, and point contact detectors.

In making the absorption measurements the fabric sample was placed in the path of the beam at normal incidence, and the change in output signal (amount transmitted through sample) from the detector read on an oscilloscope. The results of these measurements are shown in Table 1. An asterisk denotes that the transmission through the sample is less than 1%. This data shows that while all the common fabrics tested are strongly absorbing at short I-R wavelengths, several fabrics (nylon, rayon) are moderately transparent at long wavelengths. As a consequence, for passive metal detection it is clearly necessary to use

TABLE 1
INFRA-RED TRANSMISSION THROUGH COMMON FABRICS

<u>Sample</u>	<u>Thickness (Millimeters)</u>	<u>% Transmission</u>		
		<u>28 Microns</u>	<u>95.8 Microns</u>	<u>337 Microns</u>
Wool	0.8	*	*	21
Cotton	0.4	*	*	65
Rayon	0.1	*	22	80
Nylon	0.3	3	7	100
Vinyl	0.1	*	*	14
Leather	1.5	*	*	*
Naugahide	0.1	*	*	23
Dacrowool	0.3	3	*	43
Flannel	0.5	*	*	57
Felt	1	*	*	14

*Indicates a transmission of less than one percent

wavelengths in the far infra-red region of the spectrum.

As pointed out in Section 2. in a practical passive system a useful detector must have an equivalent noise power of less than $10^{-12} \text{ W/Hz}^{\frac{1}{2}}$. Unfortunately, this type of detector was not available at TSC, and since it would have taken too long to procure, it was not possible to test the feasibility of a passive system directly. It was therefore necessary to use the most sensitive detector on hand, and to extrapolate the results to obtain the capability of a practical system.

The most suitable detector available, which was sensitive at far infra-red wavelengths, was a Golay cell which had an equivalent noise power of approximately $10^{-8} \text{ W/Hz}^{\frac{1}{2}}$. Therefore, it was not possible to operate the system with an electronic band-width of 10^4 Hz , as mentioned in Section 2., but it was necessary to use a band-width of the order of 1 Hz. A schematic diagram of the experimental system is shown in Figure 2. Photographs of the actual equipment are shown in Figures 3 and 4.

In this arrangement a piece of metal concealed by a sample fabric is placed in front of a hot plate, which provides a uniform background of infra-red radiation and simulates the surface of the human body. Radiation from a small area in the neighborhood of the metal is then focused onto the Golay detector by means of a concave mirror. The output signal from the detector is processed by a lock-in amplifier, and the signal ultimately displayed on a strip-chart recorder. This signal is then compared with that obtained with the concealed metal removed.

In the laboratory a static system was used to probe a small, fixed area. In practice, however, a large area could be rapidly scanned by mechanically driving the concave mirror, and in a fraction of a second, a video display of the entire subject could be viewed on a television screen.

In the experiment performed here each of the sample fabrics listed in Table 1. was placed in front of the hot plate, and the radiation signal observed with and without a strip of metal behind the fabric. The fixed area probed was about one square centimeter.

The results of these measurements are shown in Figure 5. The metal used was aluminum, but the results did not differ appreciably for other metals such as copper, brass and steel.

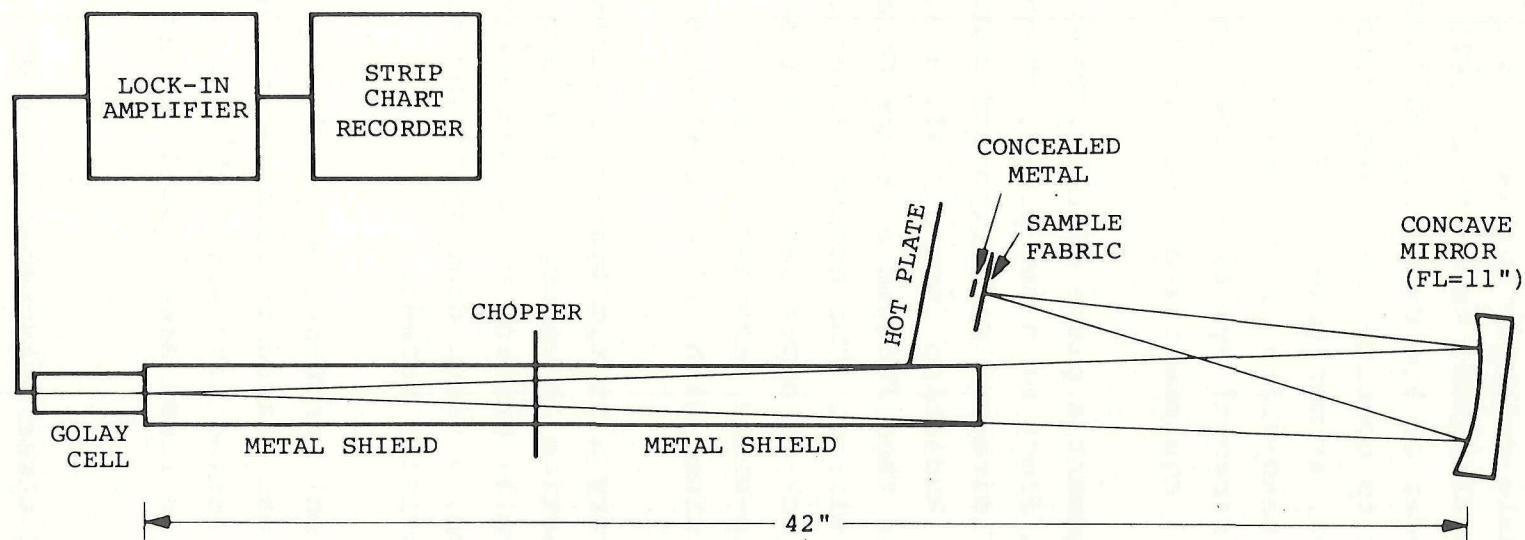


Figure 2. Experimental Arrangement for I-R Detection of Concealed Weapons

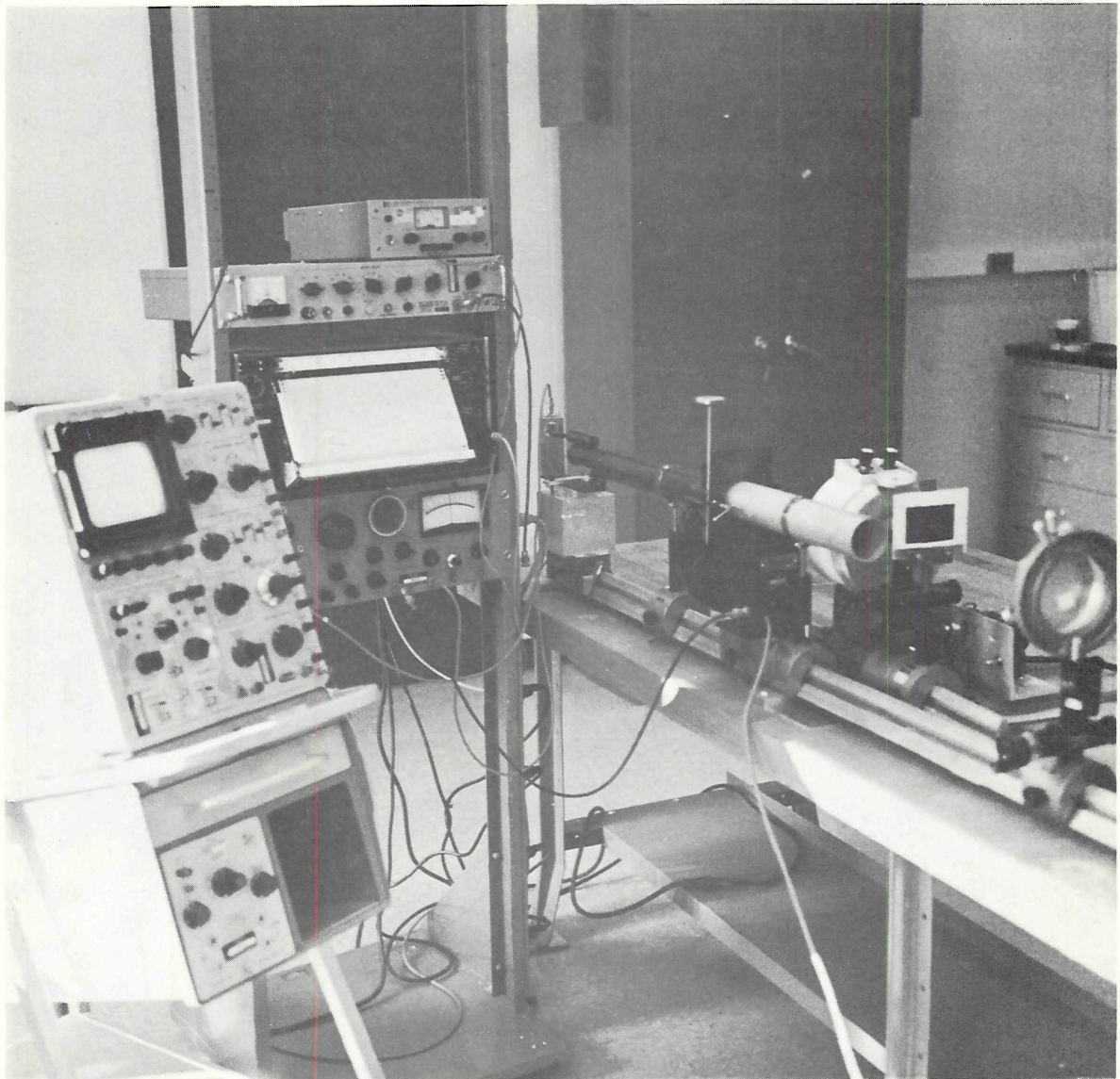


Figure 3. Laboratory System for Infra-red Surveillance of Concealed Weapons

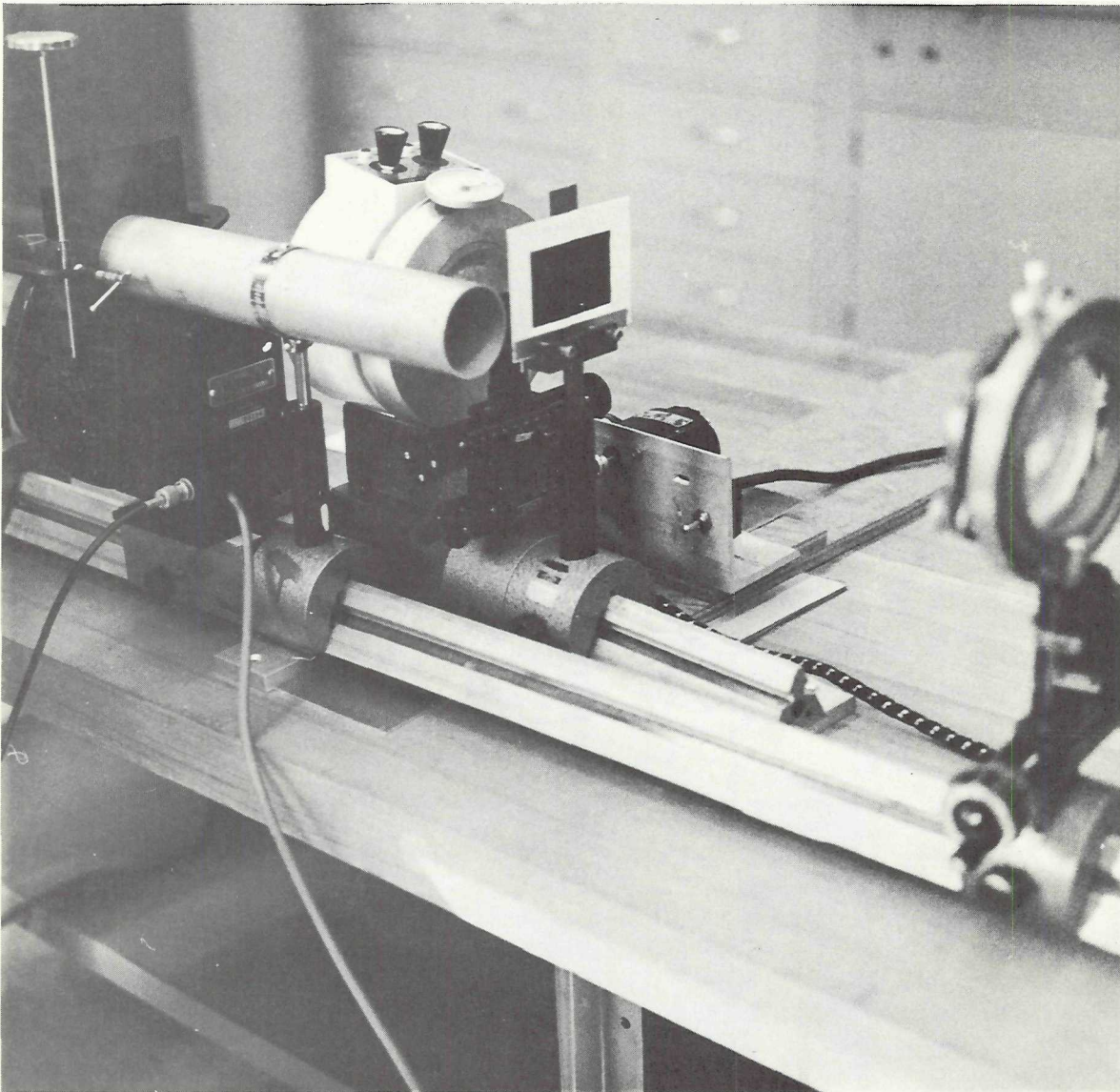


Figure 4. Enlarged View of Infra-red Detection Equipment

This data shows that metals concealed under many common fabrics substantially alter the background radiation pattern, and can easily be detected by observing the infra-red radiation emitted.

The measurements reported here were made on dry fabrics. If the fabrics were wet, I-R absorption by water could alter the results slightly. In the case of a passive system, the various contrasts shown in Figure 5 would be reduced, perhaps by a factor of two. In an active system, the effect of water would be similar if a broad-band source of radiation were used, and would be negligible if the source of radiation had a narrow band-width which corresponded to one of the transmission bands of water.

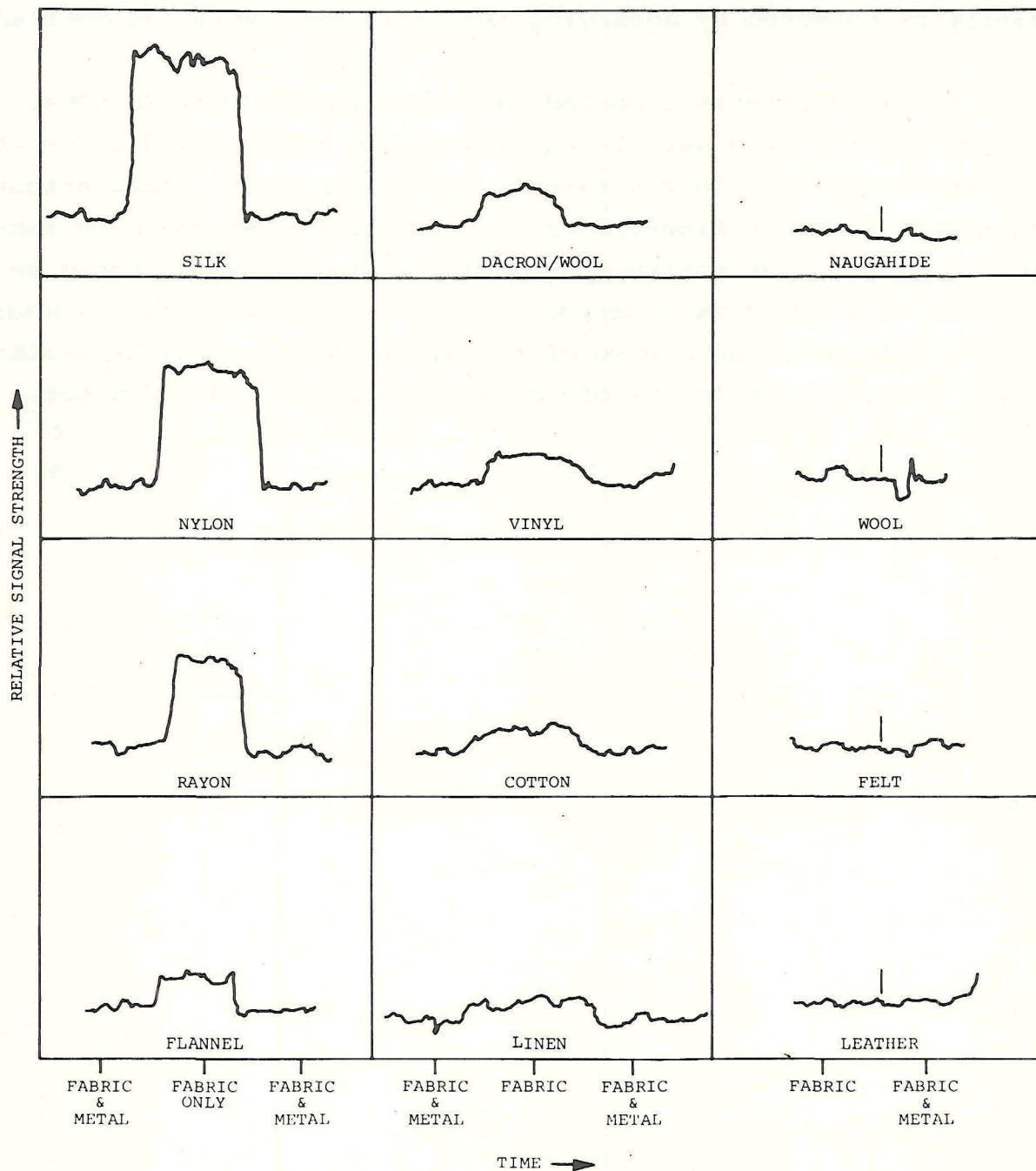


Figure 5. Radiation Observed through Fabrics With and Without Concealed Metal

4. COST OF A FIELD OPERATIONAL SYSTEM AND CONCLUSION

While the feasibility of detecting concealed metals by infra-red techniques has been demonstrated in the laboratory, a considerable amount of development must be undertaken before a field operational system can be realized. The laboratory system was a static device with a stripchart-recorder display. In practice a dynamic system would be required which would incorporate a rapid scanning camera with a video display so that the entire subject could be viewed pictorially in a fraction of a second. Analysis of the data obtained here indicates that the components required for such a system have been developed, and that an operational system could be assembled. The cost of such a system has been estimated by the Barnes Engineering Co., and is given in the Appendix.

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APPENDIX

TECHNICAL REPORT
BEC-TR-2555-1

BARNES ENGINEERING COMPANY
Defense and Space Contracts Division
44 Commerce Road
Stamford, Connecticut

FINAL TECHNICAL REPORT
FOR AN
INVESTIGATION OF LONG WAVELENGTH INFRARED
RADIOMETRIC TECHNIQUES FOR CONCEALED WEAPONS DETECTION
SUBMITTED TO
DEPARTMENT OF TRANSPORTATION
(CONTRACT NO. DOT-TSC-298)

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NOVEMBER 1971

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BRIEF

The feasibility of developing a long wavelength infrared camera for the purpose of detecting concealed weapons was investigated. Both active systems, where the target is illuminated by a laser source, and passive systems, where target self-emitted radiance is imaged, were considered. Our results showed that both techniques could be developed into workable systems.

Eliminating the laser source greatly reduces the complexity and cost of the system. The projected cost of a passive system in large quantities are under \$5,000 and may possibly run as low as \$3,000. We recommend that the passive imaging technique be pursued to the point of developing an engineering model to be evaluated in the laboratory as well as at air terminals.

FINAL TECHNICAL REPORT
FOR AN
INVESTIGATION OF LONG WAVELENGTH INFRARED
RADIOMETRIC TECHNIQUES FOR CONCEALED WEAPONS DETECTION

1. INTRODUCTION

This program had as its primary purpose the study of and experimentation with long wavelength infrared techniques to determine if it is possible to produce a long wavelength imaging system capable of detecting and displaying concealed weapons. Indications are that it is possible to use either active or passive long wavelength techniques for concealed weapons detection.

The concept is based on data obtained by DOT scientists indicating that most fabrics of which clothing is made are reasonably transparent at long wavelengths, 300-400 μ , while metal objects such as weapons would not transmit at these wavelengths. As part of the present program, equipment was assembled and measurements were made to provide quantitative data on transmission of various fabrics and reflectivity of metals. The purpose was to provide the data necessary for specifying and designing equipment that would produce an image revealing concealed weapons.

The measurements made and presented in this report show what may reasonably be expected as the energy transmitted through typical amounts of clothing and reflected from weapons.

The data presented shows that the amount of power the detector is expected to receive and process is, realistically, about two orders of magnitude lower than assumed in our preliminary

calculations (BEC Proposal P-1528). With the energy available from realizable lasers (25-50 mW for HCN lasers), an uncooled pyroelectric detector does not have sufficient sensitivity to generate a thermal image. It appears possible, however to detect and image the desired patterns if we employ cooled (liquid helium) detectors that are sensitive to the very long operating wavelengths and also have the desired fast response time.

The high sensitivity of the GaAs detector and the small amount of reflected energy received from metallic weapons prompted a reexamination of the possibility of forming a thermal image using the self-emitted radiation of the body. The signal of interest is the differential radiance, that is the difference between the radiance emitted by the human body and the amount reflected and emitted by the weapon. This signal increases rapidly as the spectral bandwidth is widened to include shorter wavelengths. Our wideband measurements indicate that if the spectral region between 100 to 400 microns is used, a thermal image can be formed with a GaAs detector.

We conclude therefore, that a thermal imaging camera equipped with a liquid helium cooled GaAs detector is feasible. This camera could be used in combination with a 25 mW HCN laser obtainable as a standard product (although rather complex and cumbersome) to operate at 337 microns. It is also possible to use only the camera with the same detector to form thermal images using self-emitted energy over a wide spectral band. Produced in quantity, the cost of the camera alone without the added requirement of an active source becomes competitive with other type systems now under consideration.

In the sections which follow we will describe the tests and instrumentation used for the measurement program, present the measured data and outline the characteristics and equipment for an ultimate instrument for detecting and imaging concealed weapons.

2. DESCRIPTION OF TEST SET-UP

2.1 Radiometer

An instrument was assembled for the planned measurement program. It consists of a Cassegrain optical system with 4 inch diameter aperture (a modified Mark IX radiometer) and a pyroelectric detector with the necessary electronics. The radiometer has provision for focusing the target from 1-1/2 ft. to infinity.

Two pyroelectric detectors were calibrated and used interchangeably in this radiometer. One has a 1 x 1 mm TGS detector mounted in a capsule with a quartz window. The second is a 5 x 5 mm detector in an identical capsule with an uncoated germanium window. Both windows are believed to have a transmission of about 50% in the wavelength region of interest. A picture of the radiometer is shown as Figure 2.1.

2.2 HCN Laser

Measurements were made at the MIT Magnet Lab on an HCN laser built under the supervision of Mr. Kenneth J. Button, leader of the Magnet-Optics Group of the Francis Bitter National Magnet Laboratory. The laser and laboratory installation are pictured in Figure 2.2.

The laser uses a 4 inch tube with a length of twelve feet, pumped down with a roughing pump and cooled by means of circulating water. The laser is excited by a DC power supply normally operating at 2 KV and two amperes. Details of the construction of this laser are available. However, in view of the fact that a final type weapons detection system would probably use a commercial laser that is already fully packaged rather than a laboratory type device such as the one used in tests for the

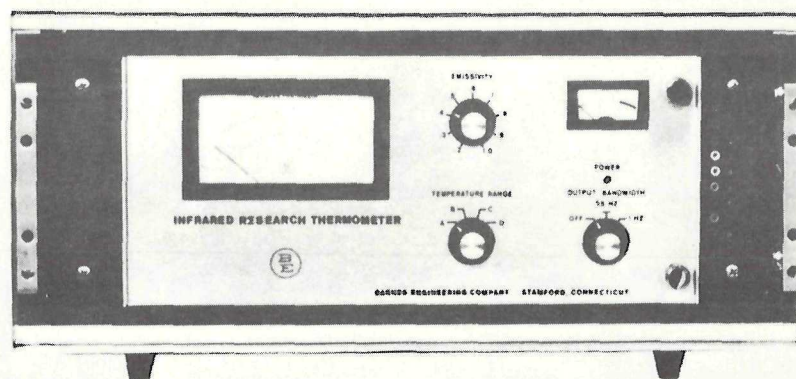
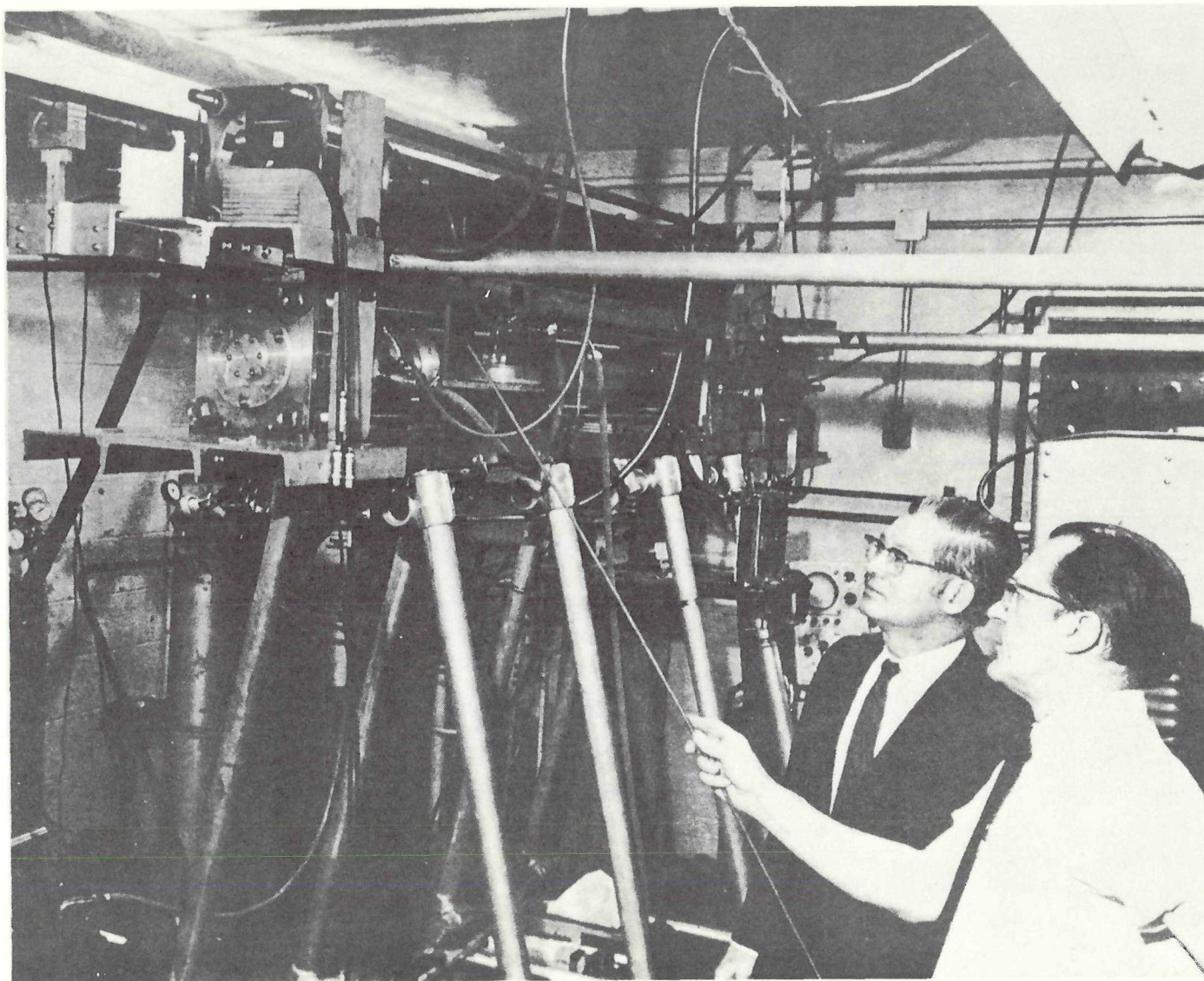


FIGURE 2.1 MODEL 12-521 INFRARED RESEARCH RADIOMETER



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Figure 2.2 HCN LASER INSTALLATION AT MIT MAGNET LABORATORY

present program, we feel that the significant characteristics of the laser are its wavelength and power output. MIT's measurements indicate that the laser has a CW output of 50 μ Watts. This number is confirmed in measurements we have made, as reported in the section following.

2.3 Detector and Amplifier

2.3.1 TGS Detector

As stated earlier, while both a 1 x 1 mm and a 5 x 5 mm TGS pyroelectric detector was fabricated, the relatively large spot size of the beam in our measurements made the larger detector more useful. It provided the larger signal and was thus used in most of the measurements.

The detector's performance was measured independently prior to its installation in the radiometer with the results as shown in Figure 2.3 which is a plot of responsivity, noise and detectivity as functions of chop frequency.

Since our interest in this measurement program is in the response to the long wavelength infrared rather than the shorter wavelengths at which the foregoing data was obtained, we wish to ascertain how much long wavelength energy is transmitted through the optics and absorbed by the detector. Unfortunately our measurement equipment does not include long wavelength spectrometers. Therefore we are presently relying on analogous measurements made with similar components at another facility. Long wavelength response measurements on TGS detectors have been made and show good absorption to beyond 500 microns. An example of the absorption and response to long wavelength radiation is shown in Figure 2.4.

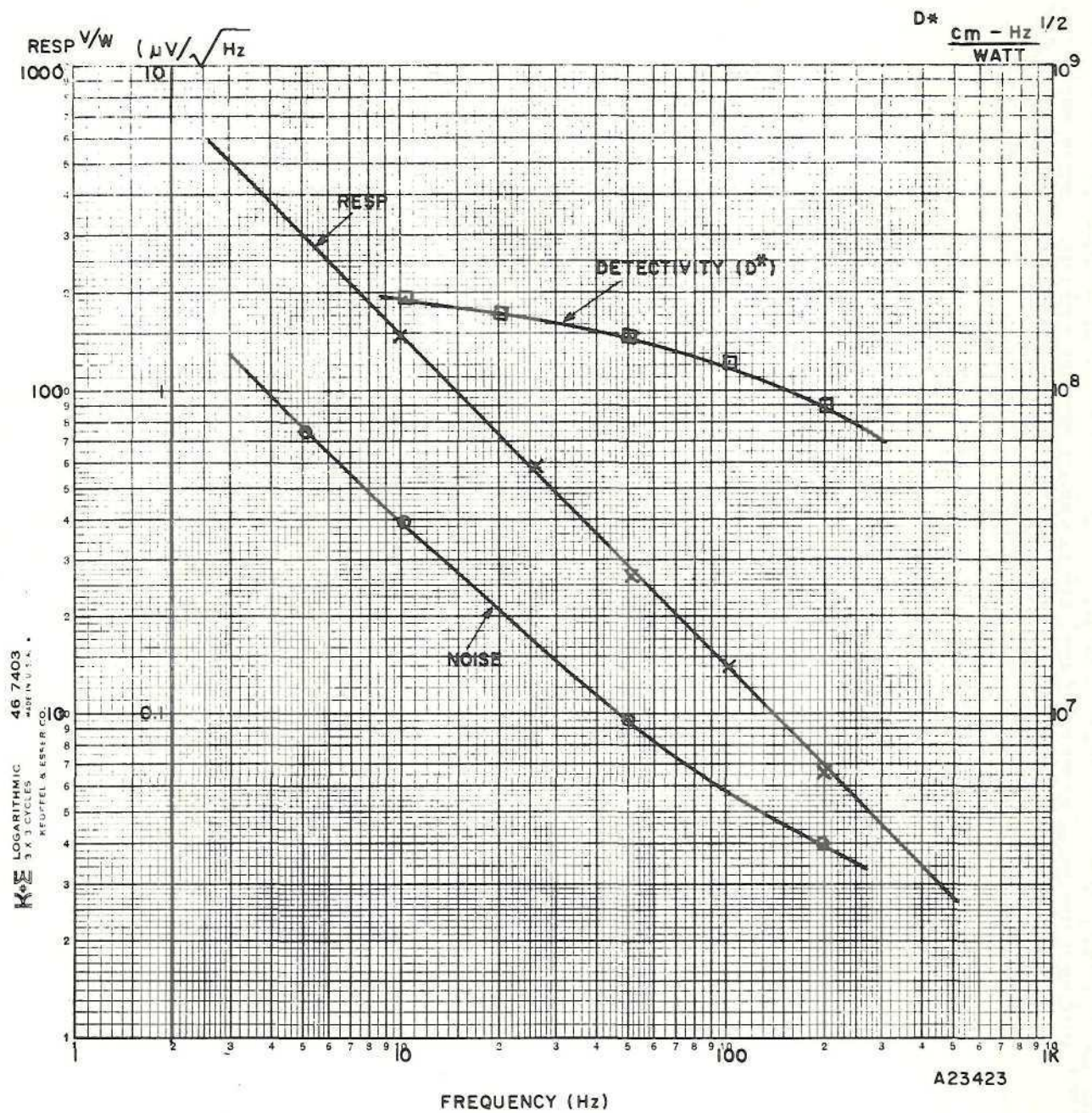
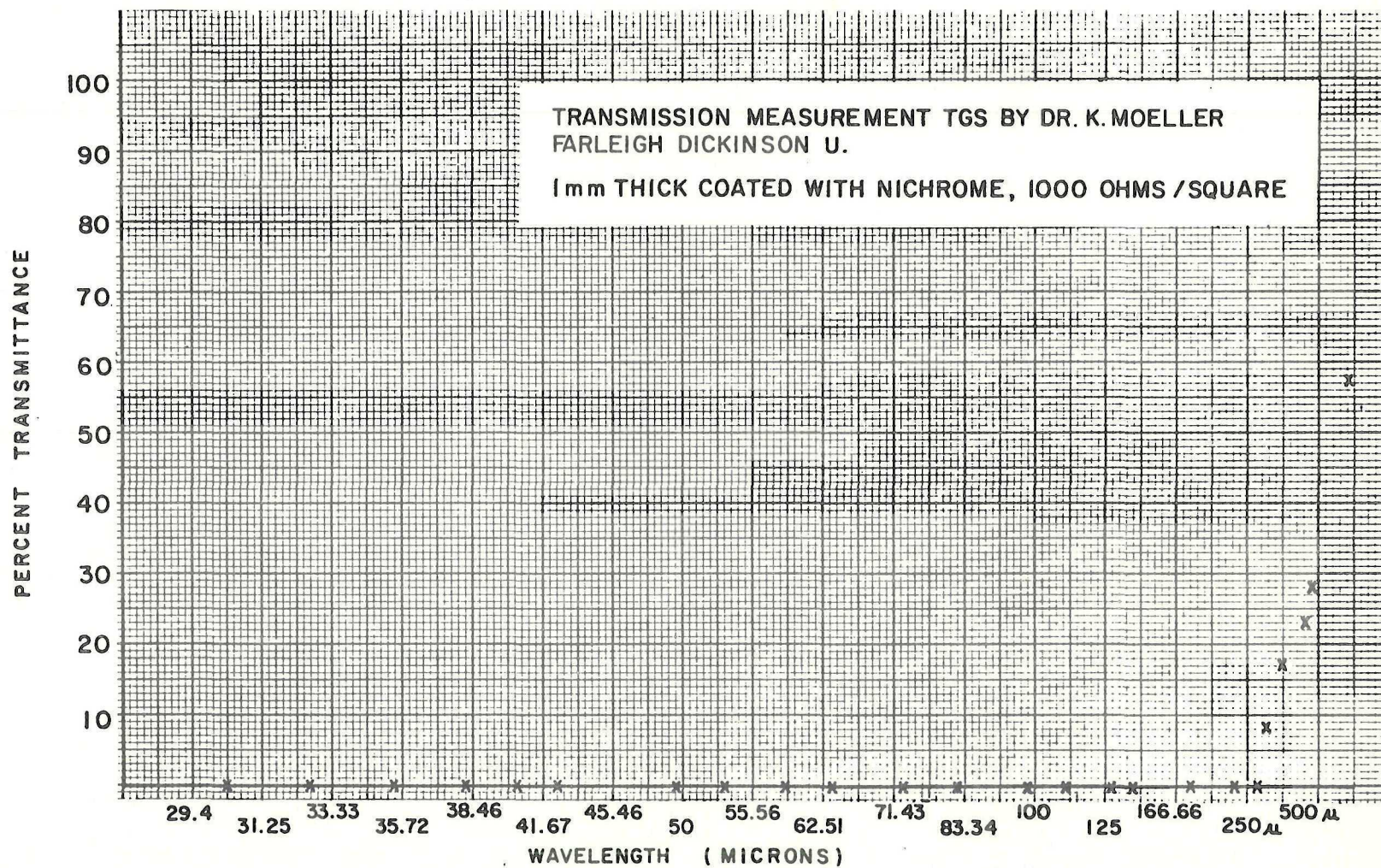
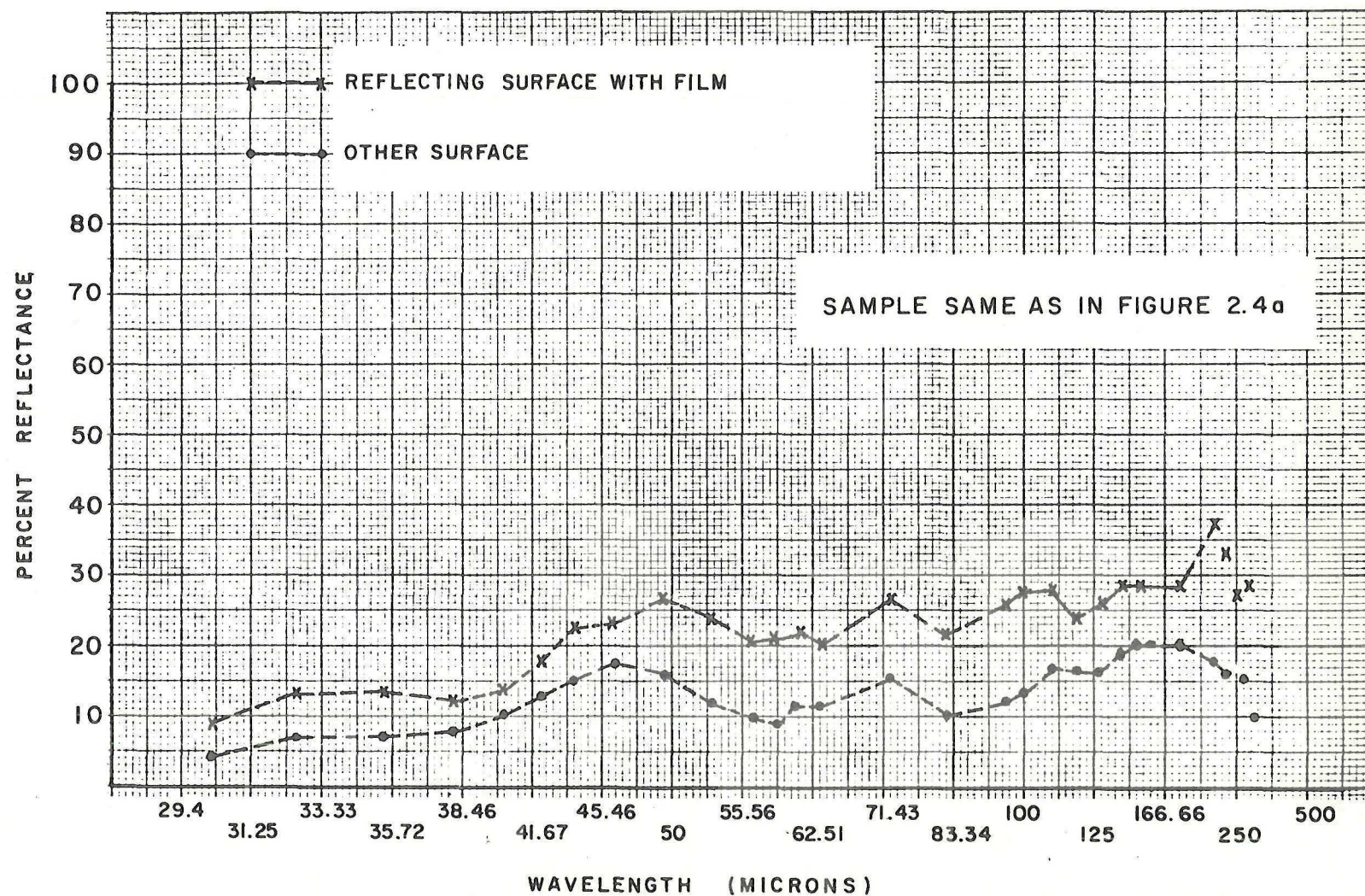


Figure 2-3. CHARACTERISTICS OF 5X5 mm. TGS DETECTOR



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Figure 2.4a TRANSMISSION OF TGS AS A FUNCTION OF WAVELENGTH



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Figure 2.4b REFLECTION OF TGS AS A FUNCTION OF WAVELENGTH

Since the 5 x 5 mm pyroelectric detector has a germanium window, the transmission of an uncoated germanium at the long wavelengths is of interest. Figure 2.5 shows such a transmission characteristic.

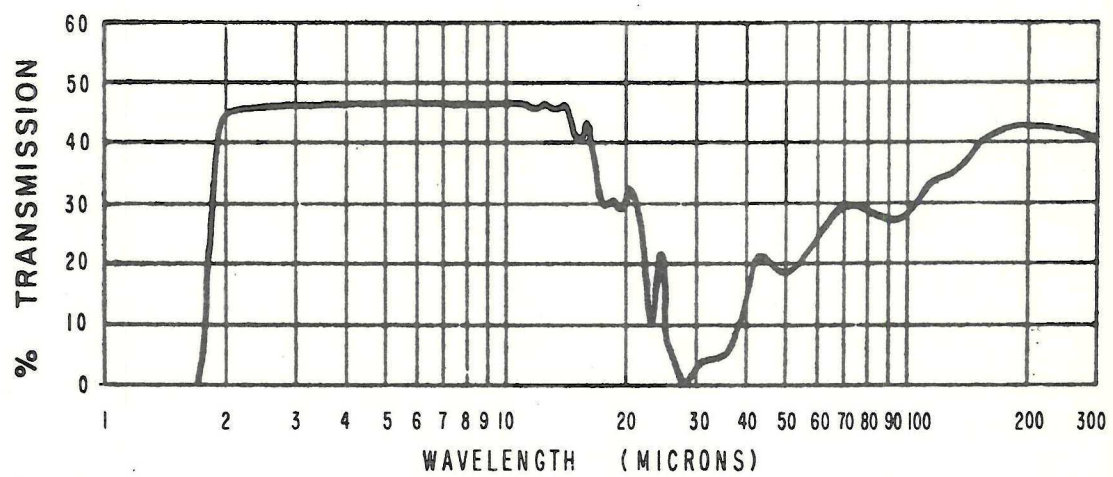
While most of the data in this report deals with relative measurements of long wavelength transmission and reflection for which the absolute values of absorption of the crystal and window transmission are not critical, the measurement of the laser power is dependent on a knowledge of these parameters. It appears, however, that our numbers are sufficiently similar to laser power measurements made with a Golay cell to provide some confidence in the correctness of these parameters. Also, separate measurements with both 1000° C and 500° K blackbody sources using a 50 micron cut-on filter further corroborates the rest of the data.

2.4 Calibration of Radiometer

The radiometer system was calibrated in several steps to obtain dependable data in the measurement program. The pyroelectric detectors were first tested independently to allow proper interpretation of later data. Responsivity and noise were measured as a function of frequency for both the 1 x 1 mm detector with its quartz window and the 5 x 5 mm detector with its germanium window.

Since the larger detector yielded better results and was used in the final measurements presented in this report, calibration data for this detector is presented in Figure 2.3. The significant parameter required for deriving radiometric data from later measurements is the responsivity at 10 Hz ($R = 150 \text{ V/W}$), the chop frequency used in most of the measurements made.

Upon installing the pyroelectric detector and a black polyethylene long wavelength cut-on filter in the radiometer, the receiver system was calibrated using two Barnes reference standard blackbody sources: a 1000°C (1273° K) source and another operated at 500° K.



A 23428

Figure 2.5. TRANSMISSION OF UNCOATED, POLISHED, 2 mm THICK GERMANIUM FLAT

2.5 Radiometer Calibration With 500° K Source

The calculations below are based on the calibration measurements made with the RS 1A blackbody source at 500° K:

With a source aperture of $A_T = 2 \text{ cm}^2$ at a distance of $d = 60 \text{ cm}$ from the radiometer optimally focused we obtained an output voltage, $V_o = 10 \text{ V}$. (Amplifier gain was $G = 1000$). Chop frequency = 10 Hz. The power on the detector is given by

$$P_D = \frac{N A_T A_o \eta}{d^2}$$

where:

N = radiance of 500° K source = $0.1 \text{ W/cm}^2 \text{-ster}$

A_o = collecting area of optics

= $50 \text{ cm}^2 \times 0.6$ (40% obscuration for the Cassegrain optics)

$\eta = 0.4$, assumed efficiency of optics including 50% transmission of uncoated detector germanium window

$$P_D = \frac{0.1 \times 2 \times 50 \times 0.6 \times 0.4}{(60)^2} \approx 6 \times 10^{-4} \text{ watts}$$

Since the signal output was 10 volts the responsivity is found to be:

$$R = \frac{V_{out}}{GP_D} = \frac{10 \text{ V}}{1000 \times 6 \times 10^{-4}} = 150 \text{ V/W}$$

This checks well with the detector responsivity measurements indicating that the efficiency factors assumed are reasonable.

2.6 Calibration of the HCN Laser

The MIT HCN laser, according to the claims of its owners and operators was said to have an output of $50 \mu\text{W}$. This claim was checked by comparison with Golay cell data provided

by MIT Magnet Lab. as well as by our own measurements using our 4 inch Cassegrain optics radiometer and 5 x 5 mm TGS detector. The data is as shown below: With the radiometer installed to directly face the laser orifice an output of 3 volts was measured with the chopper operating at 10 Hz. The laser power in a narrow 1 cm collimated beam is given by

$$P_L = \frac{V_{out}}{G R \eta}$$

assuming an efficiency of 0.4 and with the known responsivity

$$R = 150 \text{ V/W}$$

$$P_L = \frac{3}{1000 \times 150 \times 0.4} = 50 \text{ } \mu\text{W}$$

2.7 Test Set-up for Measurements at 337 Microns

The equipment described above was set up first in an in-line configuration (the radiometer facing the laser orifice) for measurements of transmission of materials.

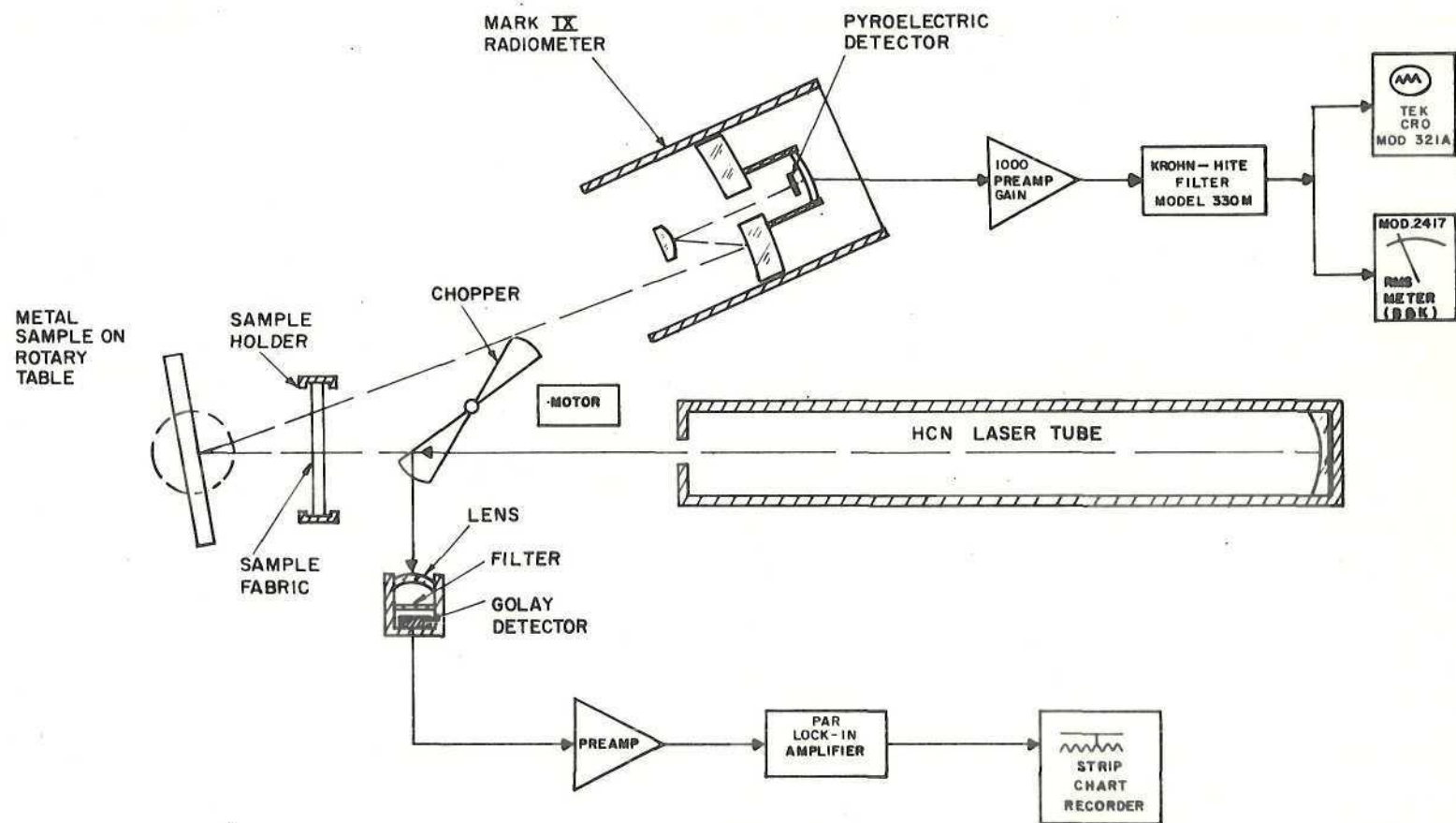
Upon completion of two sets of measurements at different laser energy levels, the radiometer was moved to a position essentially parallel to the laser tube and oriented so as to view and optimally sense reflected energy from various metal surfaces placed in front of the laser as well as metal reflectors behind various of the fabrics whose transmission was measured earlier. The radiometer was mounted on an adjustable tripod that facilitated its alignment for optimum positioning. The metal pieces were held on an adjustable ringstand that likewise permitted rotation and alignment so as to permit measurement of the maximum reflection

that could be obtained. Also a fork-like holder was made up to permit the various samples of fabrics to be clipped on and held between the laser and the reflector. A butterfly type chopper was installed between the laser and the samples (chopping radiation at about 10 Hz). A mask was placed in front of the chopper its aperture being just slightly larger than the laser orifice. This was to make sure that only laser energy at $337\ \mu$ would be modulated and produce signals. In the absence of the mask modulated radiation from the warm chopper motor or warm laser tube, etc. would produce signals that should not be confused with the $337\ \mu$ radiation of interest. The test equipment and arrangement of components are shown in Figure 2.6 . A Golay cell and processing electronics were used to continuously monitor the output of the laser and permit trimming to keep the output constant to insure that the data obtained was consistent and meaningful. The laser output was also checked separately at the beginning and end of the test program by a measurement with the Barnes radiometer and a comparison with the 500°C reference black-body source.

2.8 Test Set-up for Wideband Measurements

The same modified Mark 1X radiometer was used to make wideband spectral measurements. Useful measurements can only be made when the signal generated is substantially greater than the system noise. In order to achieve a good signal to noise ratio the following steps were taken.

- 1) A large area blackbody operating at 287°C or 260°C above ambient chopped at 2 Hz provided a large differential radiance source.



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Figure 2-6 TEST SET-UP FOR 337U LASER REFLECTION TRANSMISSION MEASUREMENT

- 2) A synchronous demodulator and very low pass filter ($\tau = 17$ sec) limited the noise bandwidth.

As a result, large signal to ratios were realized. In fact without any filters or samples in the optical path between source and radiometer, the signals generated saturated the synchronous demodulator.

Basically two filters were used to limit the spectral extent of the radiant energy reaching the detector. The first was a sheet of black polyethelene .12 mm thick. Relative spectral response of this material as given by Kimmitt, "Far Infrared Techniques" page 30, is shown in Figure 2.7. Multiple layer filters made from black polyethelene exhibited a relatively steep slope and rather poor overall transmission. Figure 2.8 shows the response of a 5 layer sample.

The second filter is a specially designed long wavelength filter made for another project by Descriptive Design and Development Corporation in Garfield, New Jersey. The spectral response for this filter is shown in Figure 2.9. Unfortunately data for wavelengths shorter than 100 microns is not reliable since the spectrometers would not show up leaks of fractions of one percent that may be significant. In view of the large signals achieved with this filter, we suspect that substantial radiation was transmitted at wavelengths shorter than 100 microns.

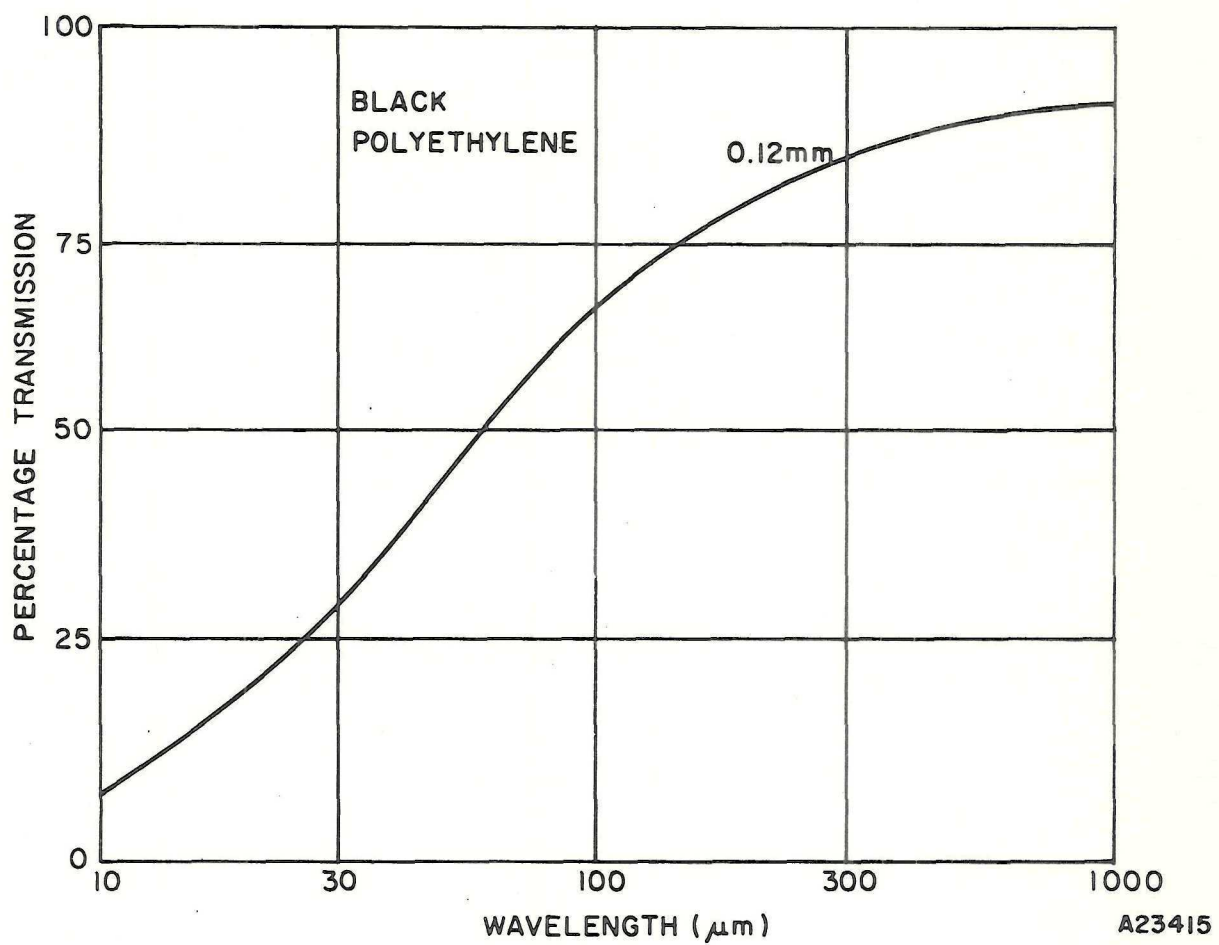


Figure 2.7 TRANSMISSION OF BLACK POLYETHYLENE

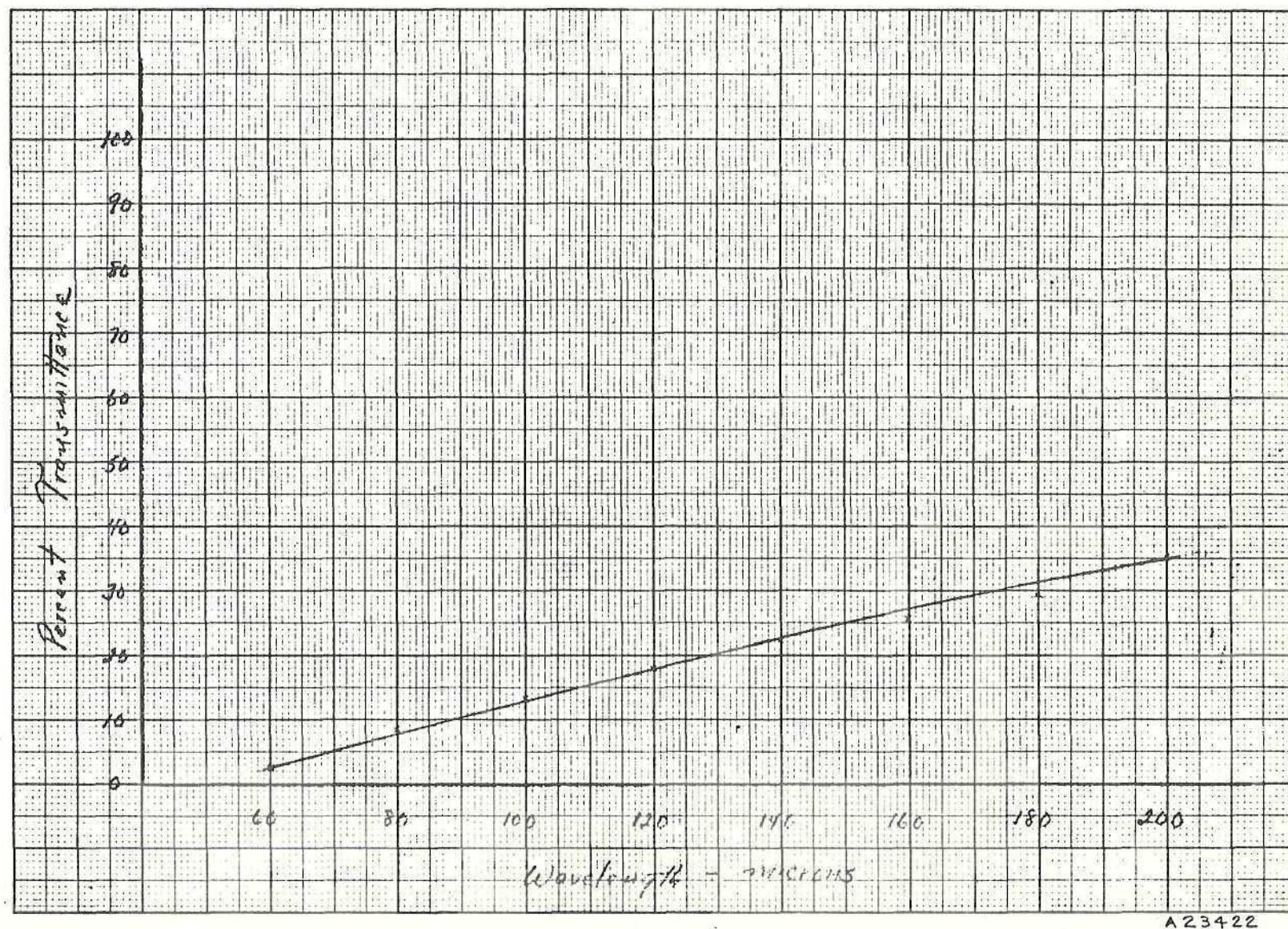


Figure 2.8. TRANSMISSION OF A 5 LAYER BLACK POLYETHYLENE FILTER

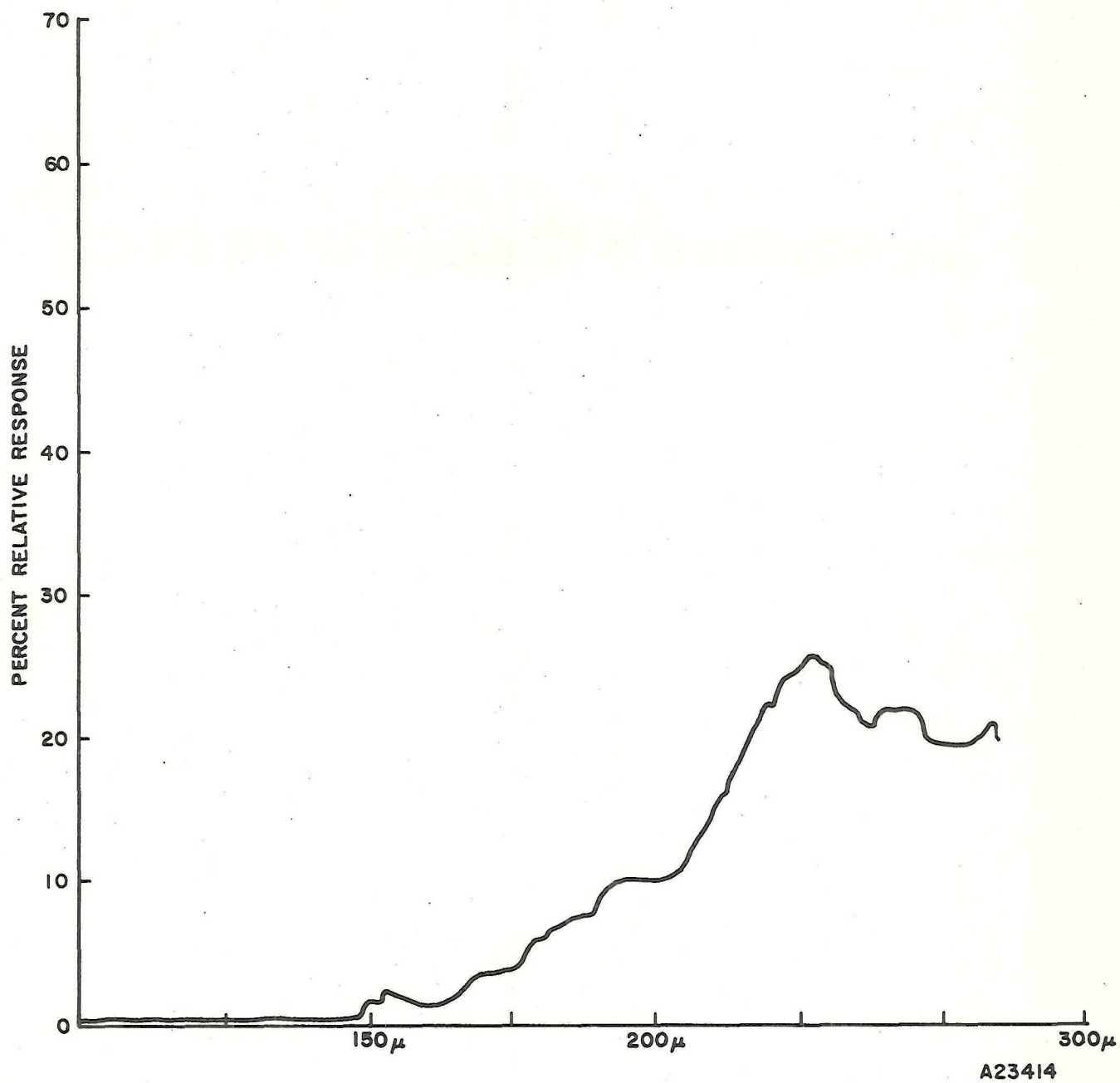


Figure 2.9 RELATIVE RESPONSE OF A SPECIALLY DESIGNED LONG WAVELENGTH INFRARED SPECTRAL FILTER

3. RESULTS OF MEASUREMENTS

With the equipment as described in the previous section measurements were made of transmission through various materials and fabrics as well as reflection from several types of metal and a variety of geometrics that are expected to produce diffuse reflection depending on the radii of curvature of these surfaces.

3.1 Measurement of Transmission

3.1.1 Measurements Made at 337 Microns

The transmission measurements made at 337 microns through various fabrics appear to confirm closely the measurements reported by DOT scientific personnel. Two sets of measurements were made at different laser power outputs to obtain some confirmation of the data and also to show if the characteristics are in some way dependent on the power level used. Table 3.1 shows the percentage transmission of 24 samples.

In addition to the two sets of measurements shown in Table 3.1, we tested transmission of combinations of materials and multiple thicknesses. This was to determine if the result of a double-pass of the laser beam after reflection from an object can be calculated mathematically in a straightforward way. It turns out that this is indeed the case. Thus, if the beam passes through a suit made of wool (sample 21) with a nylon lining (sample 5) the total transmission would be the product $T = .05 \times .85 \times .05 \times .85 \approx 2 \times 10^{-3}$. This particular combination - not the most favorable of the many samples, but also perhaps not the worst that could be found - was chosen by way of example in later calculation for a typical imaging system that may be designed for detection of concealed weapons with a far infrared thermographic system.

Table 3-1

TR2555-1

Transmission of 337 μ Radiation Through Various Materials

	<u>Material</u>	<u>#1</u>	<u>% Transmission</u>	<u>#2</u>	<u>% Transmission</u>	<u>Thickness (inches)</u>
0	Air		100%		100%	---
1	Wool		.5%		2.1%	.075
2	Paper		75%		70%	.003
3	Vinyl		75%		95%	.001
4	Cotton		35%		30%	.014
5	Nylon		85%		70%	.005
6	Thin Cotton		75%		61%	.006
7	Felt		22%		17%	.050
8	Nylon		82%		65%	.004
9	Silk		75%		59%	.005
10	Rayon		70%		59%	.013
11	Silk		80%		63%	.003
12	Jersey		25%		21.7%	.015
13	Corduroy		37%		28%	.050
14	Silk		58%		35%	.009
15	Nylon stocking (double layer)		67.5%		57%	.008
16	Nylon (double layer)		50%		17.4%	.017
17	Gauze		.55%		48%	.007
18	Wool		3.8%		5.1%	.070
19	Cotton		3.8%		5.1%	.030
20	Wool		1.2%		2.1%	.050
21	Wool		5%		5.7%	.032
22	Wool		2.5%		4.3%	.033
23	Leather (synthetic)		3%		5.2%	.033
24	Leather (tanned)		0.25%		5.2%	.090
25	Blocked (noise)		0.063%		1.3%	.050

3.1.2 Wide Spectral Bandwidth Measurements

Transmission measurements of the same sample list of materials were made using a 278°C blackbody source and the modified Mark IX radiometer described in section 2. The peak to peak radiance seen by the radiometer is the difference between that emitted by the hot source and the room temperature chopper blade. If the cut-on wavelength of the filter is 100 microns, then about 80% of the differential radiance which generates the radiometer output falls between 100 and 150 microns.

The first set of measurements tabulated in Table 3.2 were made using one black polyethelene sheet whose spectral response is shown in Fugure 2.7 and the special long wavelength filter illustrated in Figure 2.9. Virtually all the transmissions are less than the values measured at 337 microns. Since the amount of energy transmitted through the filter combination in the spectral region below 100 microns is unknown, the poor transmission could be due to relatively large amounts of short wavelength energy passed through the filter combination (50 to 100 microns) and not passed when the samples were inserted in the path.

The special long wavelength filter was removed and replaced by a filter made up of 4 sheets of black polyethylene while the single sheet in front of the radiometer was retained. Spectral transmission characteristic of a 5 sheet black polyethylene filter is shown in Figure 2.8. Table 3.3 shows the transmission of the same set of materials tested with this filter.

Comparing Tables 3.2 and 3.3 we note that the transmissions using the multilayer black polyethylene is consistently better than that achieved with the special filter illustrated in Figure 2.9.

Wideband Spectral Measurements Using One Sheet of
Black Polyethylene and Special Long Wavelength
Filter. (Blackbody Source Temperature 560°K)

	<u>MATERIAL</u>	<u>% TRANSMISSION</u>
0	Air	100 %
1	Wool	1 %
2	Paper	45 %
3	Vinyl	86 %
4	Cotton	6 %
5	Nylon	30 %
6	Thin Cotton	17 %
7	Felt	2.4 %
8	Nylon	38 %
9	Silk	40 %
10	Rayon	20 %
11	Silk	58 %
12	Jersey	4 %
13	Corduroy	10 %
14	Silk	22 %
15	Nylon Stocking (Double Layer)	22.5 %
16	Nylon (Double Layer)	59 %
17	Gauze	35 %
18	Wool	5.5 %
19	Cotton	4 %
20	Wool	4 %
21	Wool	3.5 %
22	Wool	2
23	Leather (Synthetic)	0.2 to 0.4 %
24	Leather (Tanned)	—
25	Blocked (Noise)	0.04% (RMS)

Table 3-3

TR 2555-1

Wideband Spectral Measurements Using 5 Layers of Black
Polyethylene (Blackbody Source Temperature 560°K)

	<u>Material</u>	<u>% Transmission</u>
0	Air	100%
1	Wool	4%
2	Paper	57.2%
3	Vinyl	90%
4	Cotton	15.7%
5	Nylon	47.2%
6	Thin Cotton	32.8%
7	Felt	9.2%
8	Nylon	54.3%
9	Silk	52.6%
10	Rayon	31.4%
11	Silk	62.1%
12	Jersey	10%
13	Corduroy	22.2%
14	Silk	30%
15	Nylon stocking (double layer)	35.8%
16	Nylon (double layer)	25.7%
17	Gauze	45%
18	Wool	9.7%
19	Cotton	8.9%
20	Wool	8%
21	Wool	7.7%
22	Wool	5.4%
23	Leather (synthetic)	.3%
24	Leather (tanned)	---
25	Blocked (noise)	.06% (RMS)

This evidence confirms our suspicion that this filter transmits at shorter wavelengths.

Another significant fact is that wool transmits even better in the region between 100 and 150 microns than it does at 337 microns. Since wool is one of the poorest transmitting materials, there is an advantage in operating at the shorter wavelengths.

3.1.2.1 Laboratory Measurement Data Analysis

The wideband spectral transmission measurements of the various materials are given as a percentage of the air path readings-- that is when there is no sample in the path. Actual radiometer readings will also be verified as a check on the data. For example, when 5 layers of black polyethylene were inserted in the path, the radiometer output signal was 700 millivolts. The calculation below shows that this is about the signal level we should expect.

Part of the calculation is presented in tabular form. The first column in Table 3.4 gives the radiance of a 550°K blackbody source while the second column is the radiance of a 300°K chopper. The difference is the third column ΔN which is then multiplied by the filter transmission shown in the fourth column taken from Figure 2.8. The effective differential radiance is the last column. Adding the differential radiances and multiplying by the 20 micron spectral width we have

$$\sum \Delta N T \Delta \lambda = 17 \times 10^{-7} \frac{\text{watts}}{\text{cm}^2\text{-ster-}\mu} \times 20\mu = 3.4 \times 10^{-5} \frac{\text{watts}}{\text{cm}^2\text{-ster.}}$$

We may now calculate the signal voltage out of the radiometer as follows:

Table 3.4
Effective Differential Radiance

Wavelength microns	N_{550} $10^{-7} \frac{\text{watts}}{\text{cm}^2 \cdot \text{ster} \cdot \mu}$	N_{300} $10^{-7} \frac{\text{watts}}{\text{cm}^2 \cdot \text{ster} \cdot \mu}$	ΔN $10^{-7} \frac{\text{watts}}{\text{cm}^2 \cdot \text{ster} \cdot \mu}$	T	ΔNT $10^{-7} \frac{\text{watts}}{\text{cm}^2 \cdot \text{ster} \cdot \mu}$
60	280	125	155	.029	4.3
80	94	44	50	.084	4.2
100	39.8	19.4	20.4	.13	2.7
120	19.7	9.7	10	.18	1.8
140	10.8	5.4	5.4	.22	1.2
160	6.4	3.25	3.15	.25	.79
180	4	2	2	.29	.58
200	2.66	1.37	1.3	.35	.46
220	1.83	.95	.88	.36	.32
240	1.30	.68	.62	.36	.22
260	.95	.49	.46	.36	.17
280	.71	.37	.34	.36	.12
300	.54	.28	.26	.36	.09

$$V_s = \sum \Delta N T \Delta \lambda (A_o \omega \eta_1 R G)$$

where

A_o = aperture - 50 cm^2

ω = field of view - 6.25×10^{-4} steradians

η_1 = detector window and absorption efficiency - .5

R = detector responsivity at 2 Hz - 700 volts/watt

G = amplifier gain setting - 2000

thus

$$\begin{aligned} V_s &= 3.4 \times 10^{-5} (50) (6.25 \times 10^{-4}) (.5) (700) (2000) \\ &= 800 \text{ millivolts} \end{aligned}$$

The actual reading of 700 millivolts is well within the range of approximations made for this calculation and verifies, therefore, the signal levels measured in our tests.

3.2 Measurements of Reflection Characteristics

A group of metallic objects was assembled to permit measurement of reflectivity and diffusivity of these objects when they are illuminated by a long wavelength source. The materials used included steel, aluminum, brass, iron and a small pistol. Samples of these materials included test pieces as well as shaped objects such as cylinders, spheres, etc. of various radii of curvature.

We also checked the reflectivity of various surface finishes of the metals used. Therefore we compared several samples of aluminum and steel (flats) with polished and rough surfaces.

As was expected there was no measurable difference between these when dealing with long wavelengths. Compared with the wavelength of the source (0.337 mm), most of the roughened surfaces appear smooth and reflect specularly. The dispersion referred to elsewhere in this report is caused by the curvature of the surface.

The results of some of these measurements are shown in Table 3.5. Note that the measurements refer to an incident beam of 1 cm diameter reflected essentially on-axis into our radiometer.

3.3 Other Measurements

A considerable body of measurement data representing transmission characteristics of the test samples filters or combinations of filters. These have not been included in our report because the filters used in the measurements appear to us to have substantial leaks at the shorter wavelengths so that the data becomes suspect. These suspected leaks do not show up on spectrometer traces because of the fact that the instruments used do not have adequate amplitude resolution or dynamic range. Possible short wavelength leaks of 0.1%, that wouldn't show up on spectral transmittance measurements, could result in large measurement errors because of the enormously greater energy emitted by the blackbody source at the shorter wavelengths than it emits at very long wavelengths.

We have also made measurements with filters made up of black polyethylene in a variety of thicknesses or layers, e.g. 6, 7, 8, 9 layers, etc. The results shown for the five layer combination (Table 3.3) are considered representative.

Table 3.5
Reflectivity of Various Materials

<u>Material</u>	<u>Shape</u>	<u>Radius of Curvature</u>	<u>Reflectivity %</u>
Steel	Flat		99
Steel	Rod	1/2"	14
Steel (Ball-bearing)	Sphere	7/16"	5
Iron	Flat		98
Iron	Cyl.	1-1/4"	40
Iron	Allen wrench	3/16" hexagon	5
Brass	Flat		99
Brass	Rod	3/16"	7
Aluminum	Flat		99
Aluminum	Rod	.75"	30
Gun barrel	Rod	1/4"	10

One other measurement that was thought to be of interest involved water vapor absorption. Obviously if such absorption at long wavelengths were severe over path lengths of 5-10 feet, that may be considered in an application at an air terminal, the system may be impractical. The radiometer, equipped with a pyroelectric detector and the special long wavelength filters used for the data presented in Table 3.2, was set up to view the blackbody source with an intervening layer of water vapor developed by injecting steam into the path. With a water vapor density we estimate to be equivalent to .06 mm precipitable water at 300 cm distance, we obtained an output signal reduced by about 10% from the normal dry atmosphere readings, both for the blackbody target and the measurements that included various fabrics such as wool.

4. DETECTORS

The advantages of an uncooled thermal detector are obvious. Our initial calculation (P-1528) suggested that a tri-glycine sulfate pyroelectric detector in combination with an active HCN laser source would provide sufficient sensitivity to produce real time thermographs similar in quality to that obtained with our Model T-101 camera in the near infrared. However, the results of the tests performed at MIT showed that our assumption concerning the amount of energy reflected into the aperture of the collector was too high. Instead of 1% it turned out that we would only get about .01% through wool (one of the poorer transmitting common materials, but not the worst).

Two orders of magnitude in sensitivity must, therefore, be bridged if a feasible system is to be proposed. As described in the following section, generators with output power greater than 40 mw (the value previously assumed) are not available commercially at this time. A continuous source perhaps ten time more powerful will probably be available in the future, but it is clear that higher sensitivity than can be afforded by room temperature thermal detectors is required. Also from a medical point of view higher energy sources should be avoided.

Table 4.1 lists the parameters of the most likely detector candidates. The pyroelectric detector and the MOM (metal-metal oxide-metal) tunnel diode room temperature detectors are included as a basis of comparison.

Several of the cooled detectors are available commercially. Mullard makes an indium antimonide element which operates in a magnetic field supplied by a superconducting solenoid (Putley

Table 4.1
Characteristics of Far Infrared Detectors

<u>Detector</u>	<u>Size (mm²)</u>	<u>Operating Temperature (°K)</u>	<u>Detectivity⁺ (Hz^{1/2}) (Watts)</u>	<u>Approximate Time Constant (sec)</u>	<u>Remarks</u>
Pyroelectric	4	300	2×10^9	10^{-3}	
MOM Diode	----	300	5×10^9	10^{-10}	Laboratory device whose detectivity has been calculated
Ga As	4	4.2	7×10^{11}	10^{-8}	
In Sb	----	4.2	5.6×10^9	10^{-6}	Raytheon QKN 1548
	2	1.2	8×10^{12}	10^{-4}	Laboratory model using liquid helium cooled transformer
In Sb (magnetic field)	25	1.6°K	5×10^{11}	10^{-7}	Mullard RPY 23
Germanium bolometer	1	2	10^{13}	10^{-1}	Often referred to as the Low detector
Carbon bolometer	20	1.8	10^{11}	10^{-3}	
Ge:Ga	6	4.2	8×10^{11}	10^{-8}	Limit of detection $\approx 150 \mu\text{m}$

⁺For Modulation frequency and spectral response within range of interest

detector). Since this detector operates at 1.6°K, it requires a vacuum pump to lower pressure. The same is true of the other detectors operating below 4.2°K. Raytheon makes an indium antimonide detector operating at 4.2°K, but at that temperature its detectivity is not very much better than the pyroelectric detector. The germanium bolometer, which is the most sensitive of all the tabulated detectors, has the disadvantage of long time constant as well as requiring helium to be pumped down to 2°K. Data sheets and spectral response curves are presented in Figures 4.1, 4.2 and 4.3 following.

It would appear that among all the cooled detectors suitable for the 300 μm region, the GaAs photo-conductive detector offers the superior combination of operative parameters. This detector, as described by Stillman et al (4), has a detectivity that is more than two orders of magnitude better than the pyroelectric detector. The inherent response time is less than 10^{-8} seconds but in any case will probably be limited by the loading circuit. While the published data on the GaAs long wavelength detector represents data obtained with experimental detectors prepared and used by laboratories such as the MIT Lincoln Labs., the manufacture of this type detector is well within our own company's capability. Barnes has both the facilities and experience for designing and constructing cooled IR detectors. The GaAs detector is also available on a similar special order basis from Molelectron Corp., the manufacturer of the HCN lasers.

For passive systems we would select a Ge:Ga detector that peaks at about 100 μm as shown in Figure 4.3. As mentioned in section 2.8, the large differential radiances occur at the shorter wave-

Mullard

INDIUM ANTIMONIDE SUBMILLIMETRE WAVELENGTH INFRARED DETECTOR TYPE RPY23

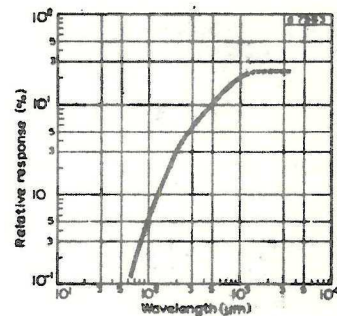
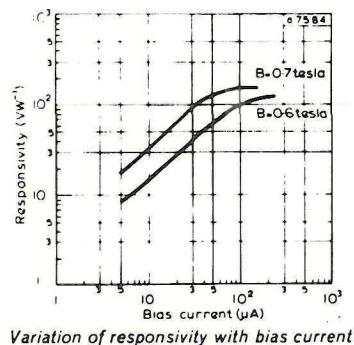
The Mullard indium antimonide sub-millimetre detector type RPY23 operates by means of a magnetic field applied to an element of high-purity indium antimonide. The magnetic field is supplied by a superconducting solenoid. The element is cooled to 1.6 K by pumped liquid helium. Two glass dewars are used, one for the liquid helium, and one for liquid nitrogen.

Spectral response range	0.15 to 10mm
Peak spectral response	approx. 1mm
Dimensions of sensitive area	5 5mm
Operating temperature	1.6 K
Resistance	0.5 to 5k Ω
Variation from detector to detector	
Time-constant	1 μ s
Detectivity	
D* (bb, 800,1)	$\geq 5 \cdot 10^{10}$ cm $\cdot$ Hz $^{1/2}$ /W $^{-1}$
D* (1mm, 800,1)	$\geq 1 \cdot 10^{12}$ cm $\cdot$ Hz $^{1/2}$ /W $^{-1}$

Responsivity
(bb,800,1) $1 \cdot 10^3$ VW $^{-1}$
(1mm, 800,1) $2 \cdot 10^3$ VW $^{-1}$
Reference values, bb,800,1, denote a grey body of emissivity 0.8 at 373 K as source, with radiation at wavelengths less than 150 μ m cut out by filter.

Encapsulation
Two glass dewars and light pipe assembly incorporating polythene detector window 2cm in diameter.
Length of light pipe from element to detector, 61cm

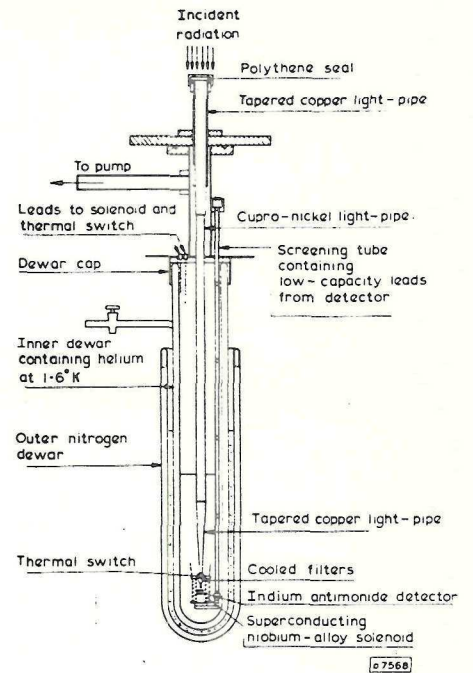
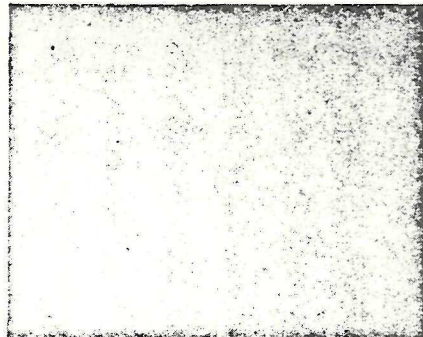
Field of view 8



CHARACTERISTICS

Figure 4.1a MULLARD InSb LONG WAVELENGTH DETECTOR SPECIFICATIONS

INDIUM ANTIMONIDE SUBMILLIMETRE WAVELENGTH INFRARED DETECTOR

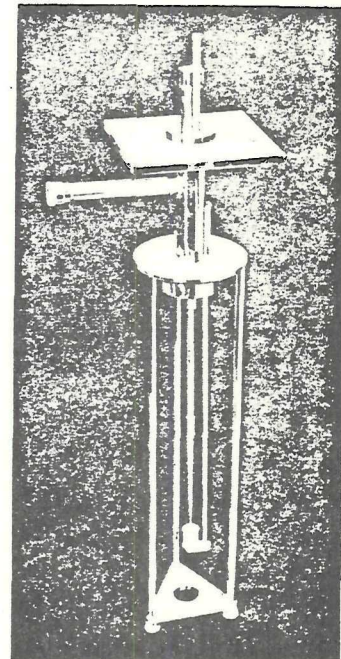
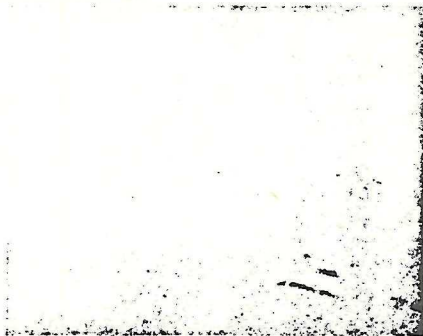


RPY23

CHARACTERISTICS



MECHANICAL DETAILS



RPY23 assembly with dewar

Figure 4.1b MULLARD InSb LONG WAVELENGTH DETECTOR SPECIFICATIONS



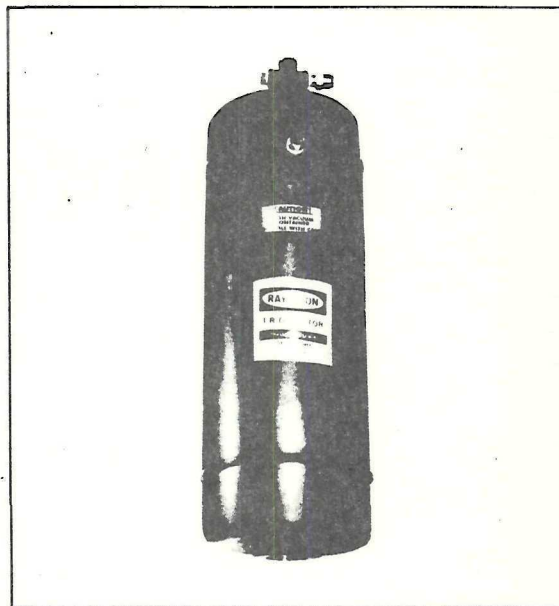
TYPES QKN1545, QKN1546, QKN1547, QKN1548 LONG WAVELENGTH INFRARED DETECTORS

- Long wavelength detection at a modest cost
- High sensitivity, fast response
- Versatile, lightweight, all-metal package
- 8 hours unattended operation
- Suitable for use as a laser detector

These infrared detectors utilize a lightweight, liquid-helium dewar, designed for operation with photoconductive copper-activated germanium (2-15 microns or 2-30 microns), photoconductive indium-activated germanium (2-100 microns), and photo-electric indium antimonide (300 microns to 8 mm).

The detectors have a response time of less than 100 nanoseconds, permitting fast scan rates and high resolution. Each of the detectors is suitable for airborne and laboratory applications.

By combining high sensitivity, long wavelength response, short time constant and eight-hours unattended operation, these detectors make possible versatile, high performance systems.



TYPICAL DETECTOR CHARACTERISTICS

	QKN1545	QKN1546	QKN1547	QKN1548
Wavelength Range in microns	2-15	2-30	2-100	300 μ to 8mm
Sensitive Element	<— P-type Ge:Cu —>		P-type Ge:In	N-type InSb
Window Material	BaF ₂	KRS-5	Polyethylene	Crystalline quartz and cooled black polyethylene
Cooled ($\sim 5^{\circ}\text{K}$) Filter	BaF ₂			
Detectivity, D* (500, 900, 1) Min. in cm cps ^{1/2} /watt	7.0×10^9	7.0×10^9	1.0×10^9	$2.0 \times 10^{10\dagger}$
Noise Equivalent Power, NEP (500, 900, 1) in watt/cps ^{1/2}	5.8×10^{-12}	5.8×10^{-12}	1.7×10^{-10}	$1.77 \times 10^{-11\dagger}$
Responsivity, R (500, 900, 1) in volts/watt	10^5	10^5	10^2	10^3
Aperture Area in cm ²	1.64×10^{-3}	1.64×10^{-3}	3.14×10^{-2}	1.26×10^{-1}
Acceptance Angle	40°	40°	90°	
Operating Temp. in °K	~ 5	~ 5	~ 5	~ 5
Impedance				
Without Bias Current in megohms	1.5	1.5	100	100 ohms
At Optimum Bias Current in K ohms	350	350	50	150 ohms
Optimum Bias Current in μ amps	10	10	50	500
Time Constant in μ sec	<0.1	<0.1	<1.0	250 nanosec.
Liquid Helium Hold Time in hours	~ 8.0	~ 8.0	~ 8.0	~ 8.0
Shield (unattended operation = 8 hours)	<— Liquid N ₂ Cooled —>			
Spectral Response	See Curve	See Curve	See Curve	See Curve
Responsivity	See Curve	See Curve	See Curve	See Curve
Noise Spectrum	See Curve	See Curve	—	—

[†]D* (4mm, 1000, 1) Min.

[‡]NEP (4mm, 1000, 1)

Figure 4.2a RAYTHEON InSb LONG WAVELENGTH DETECTOR SPECIFICATIONS

Type QKN1548

DETAILED CHARACTERISTICSWavelength Range

The detector element is sensitive in the 300 micron to 8 mm region.

Sensitive Element

N-type indium antimonide is a photoelectric element which operates at 4.2°K.

The output signal results when incident radiation excites electrons in the detector element to higher energy levels in the conduction band. These

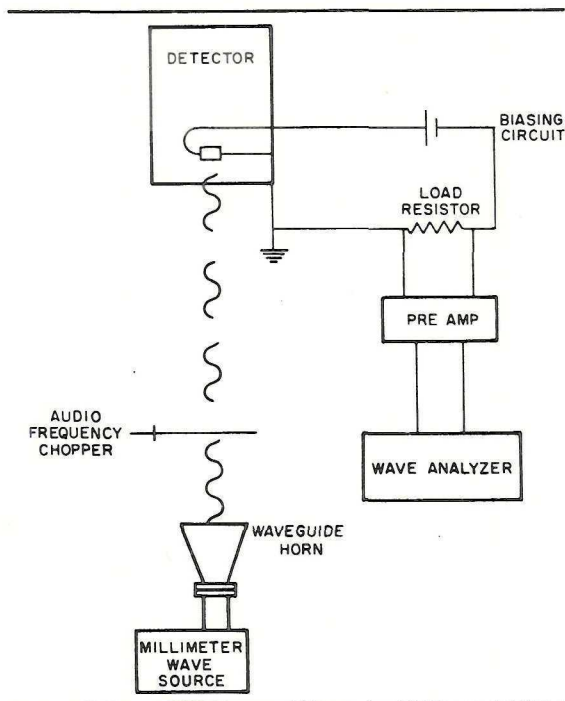
"free electrons" then cause an increase in current through the element when a suitable potential difference is applied.

Window Material

Crystalline quartz transmits in the visible and near infrared region from 0.4 to 4.5 microns. The transmission in the far infrared begins at about 45 microns and extends to the radio frequency region.

The cooled black polyethylene serves to filter out most of the short wavelength background radiation below 45 microns.

BIASING CIRCUIT SCHEMATIC AND OTHER ASSOCIATED TEST EQUIPMENT FOR MILLIMETER WAVE DETECTOR



TYPICAL SPECTRAL DETECTIVITY OF INSB MILLIMETER WAVE DETECTOR

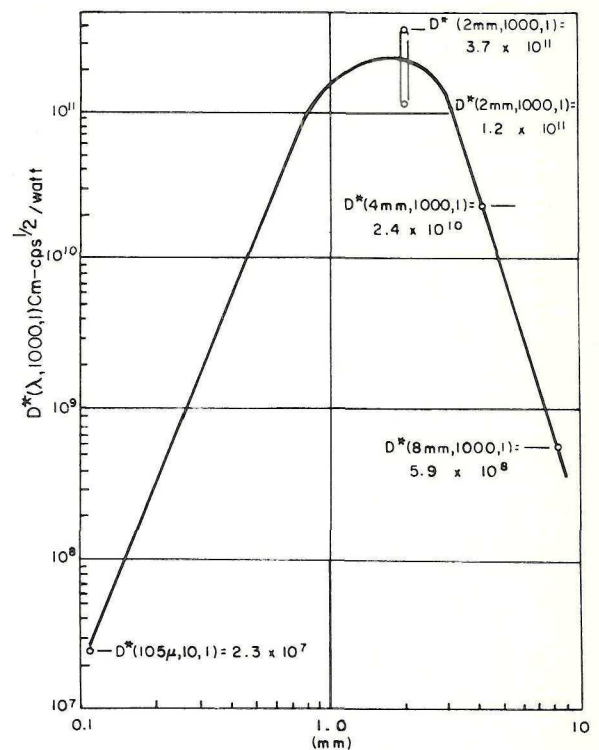


Figure 4.2b RAYTHEON InSb LONG WAVELENGTH DETECTOR SPECIFICATIONS

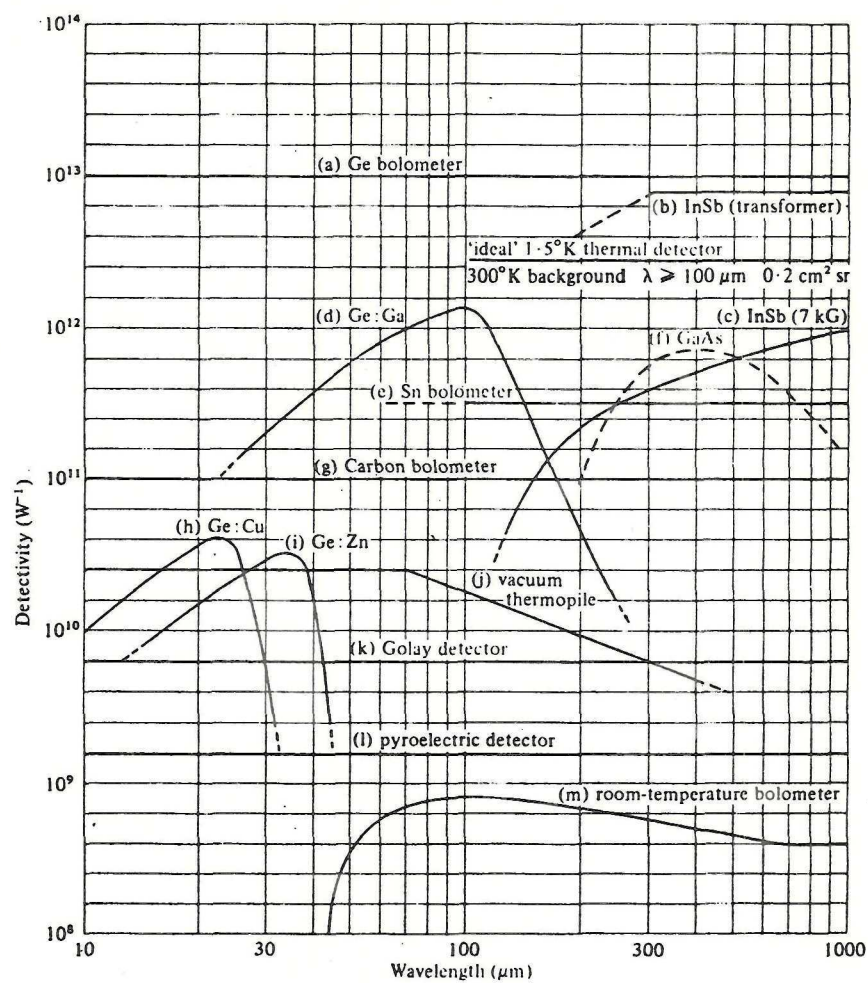


Figure 4.3 DETECTIVITY OF FAR-INFRARED DETECTORS

lengths. On an integrated basis about eighty percent of the signal generating radiance through a 5 polyethylene layer filter above 60 microns, lies between 60 and 150 microns. The Ge:Ga detector would experience some degradation since its effective cut-off is about 150 microns, but it would be most sensitive in the 60 to 120 micron region where the energy available is high. For the purposes of calculating the sensitivity of a passive system in section 7, we will use $D^* = 5 \times 10^{11}$ which is a conservative value.

5. SOURCES

In seeking an active source for the 300 μm region, we have investigated the properties of molecular gas lasers, backward wave oscillators (Carcinotion), solid state devices such as point-contact and junction diodes and harmonic generators. In addition, two rather unusual approaches which promise relatively high output power were reviewed. The following subparagraphs describe these sources.

5.1 Gas Lasers

Although their development is recent, molecular gas lasers are now available in the wavelengths from 40 to 400 μm . Table 5.1 is a list of continuous laser emissions after Kimmitt (1) and reproduced here.

The highest power output listed is 600 mW at the HCN 337 μm line. This is the wavelength which was used to make our transmission and reflection tests (section 3) and is therefore the line of greatest interest in the table. Other gas emissions lines are of very low power and much shorter wavelength. To produce the very high power output at 337 μm a tube 6.5 m in length and 10 cm in diameter was used (2). HCN lasers are now also available commercially but with more modest power rating. Molelectron, Inc. quotes a maximum of 25 mW for a continuous wave output in a 1 cm diameter beam. The data sheets shown as Figure 5.1 do not completely reflect the latest data quoted over the telephone (i.e. 25 mW), but adequately picture the instrumentation and the overall characteristics. Peak powers approximately 1000 times greater can be generated but only at slow repetition rates from 10 to 100 pulses per second.

Table 5.1

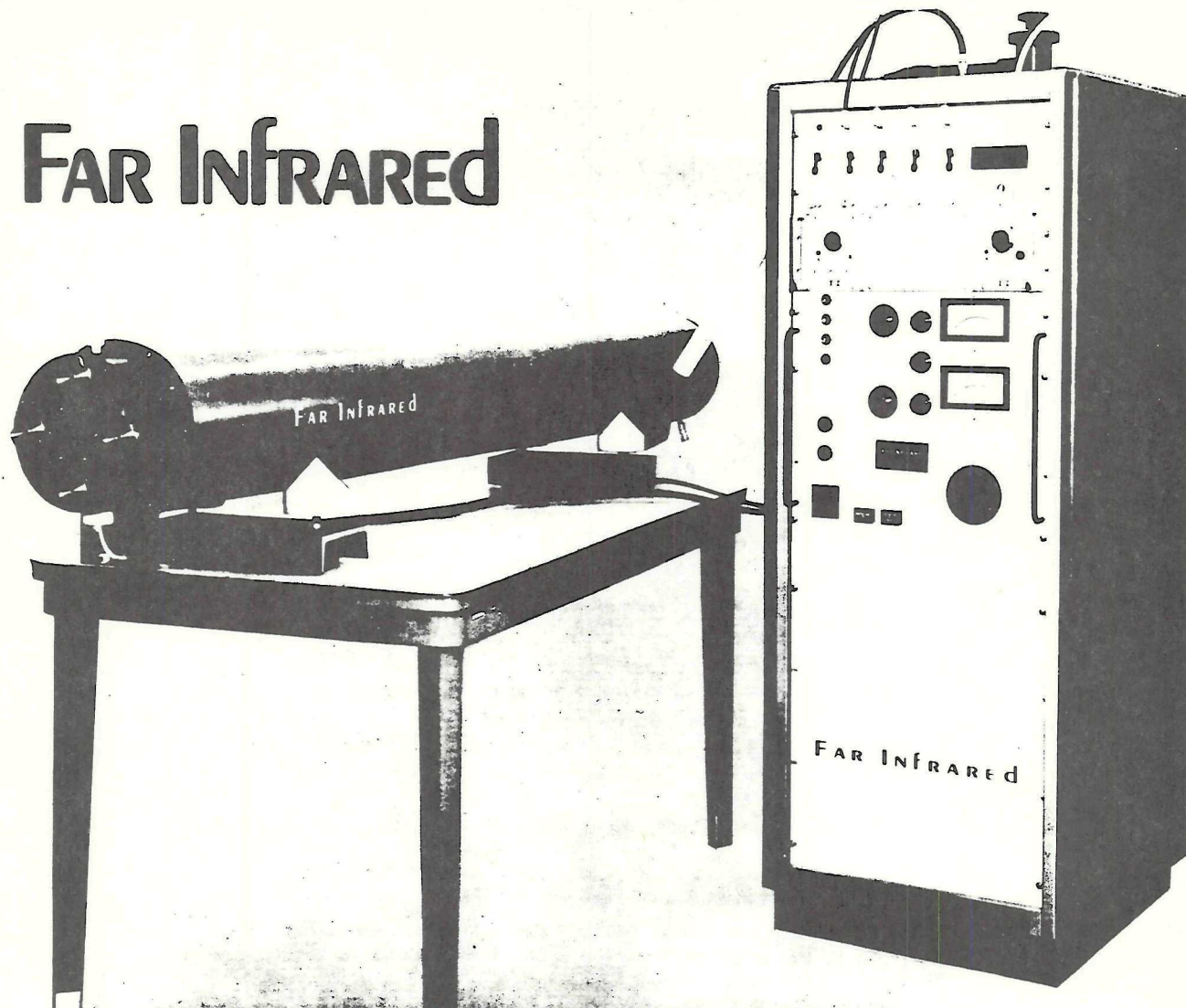
TR 2555-1

Reported Power of Various Gas Lasers

<u>Wavelength (μm)</u>	<u>Gas</u>	<u>Power</u>
47.3 ^h	H ₂ O	4 μW^h
47.7 ^h	H ₂ O	95 μW^h
55.1 ^h	H ₂ O	1.5 μW^h
78.5 ^j	H ₂ O	20. μW^h
79.1 ^f	H ₂ O	10 μW^h
84.3 ^f	D ₂ O	
95.8 ^e	He	1.5 mW ^e
107.7 ^f	D ₂ O	
115.4 ^h	H ₂ O	0.5 μW^h
118.6 ^j	H ₂ O	7 μW^h
120.1 ⁱ	H ₂ O	
128.7 ^g	HCN	
140.9 ^a	SO ₂	1.5 mW ^a
171.6 ^f	D ₂ O	
190.0 ^g	DCN	
192.5 ^a	SO ₂	300 μW^a
194.8 ^g	DCN	
204.4 ^c	DCN	
211.1 ^g	HCN	
216.3 ^e	He	100 μW^e
220.3 ^f	H ₂ O	2 μW^h
284.0 ^b	HCN	
309.7 ^b	HCN	
310.9 ^f	HCN	60 mW ^d
335.2 ^b	HCN	
336.6 ^f	HCN	600 mW ^d
372.5 ^b	HCN	

Note: See end of section 5 for footnotes.

FAR INFRARED



MOLECULAR GAS LASER

The Far Infrared Model 215 is a pulsed molecular gas laser optimized for high output power, mode purity, and pulse stability. The Model 215C operates pulsed or continuous wave.

Cavity length	2.1 m
Tube diameter	15 cm
Output coupling hole (for high gain transitions)	9.5 mm
Electrical pulse energy	15 to 50 joules
Pulse rate	0.5 to 5 Hz
Gas flow rate	500 l/min

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(408) 738-2661
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 CORPORATION

FAR INFRARED

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Figure 5.1a MOLECTRON CORP. LASER

Figure 5.1 b

TR 2555-1

Specifications of Molelectron Corp. Model 375 Laser

Laser Model #	375
Output Power	25 mW
Laser Medium	HCN
Wavelength	337 μ m
Output Coupling Hole	1 cm diam
Beam Divergence	$1.22 \frac{\lambda}{d}$
Polarization	Vertical
Cavity Length	4 m
Cavity Stability	<10 μ m/hr after 1 hr warm-up
Amplitude Stability	<10%/hr after 1 hr warm-up
Excitation	Stabilized DC
Vacuum System	500 l/m flowing
Inlet Manifold	Five toggle valve switched needle valves
Cooling System	Flow-through water cooling; 0.5 GPM min flow; 70° F max inlet temperature
Input Power	208 3 ϕ , 20A/line, 60 Hz
Laser Head Dimensions	96" x 18" x 7"
Warranty	One year

5.2 Backward-Wave Oscillator

Backward-wave generators, the most famous of which is the "carcinotron" manufactured by CSF/Thomson in France, are sources of continuous power at millimeter and submillimeter wavelengths. Unfortunately the power falls off sharply as the device approaches its short wavelength limit. Whereas 1 W is available at 1 mm, only 1 mW can be attained at 380 μm .

5.3 Harmonic Generation

Large powers available from microwave generators such as klystrons and magnetrons at wavelengths of several millimeters have given rise to attempts to produce harmonics in the submillimeter range. At the other end of the spectrum, the relatively large peak powers available at wavelengths less than 30 μm suggested the possibility of obtaining long wavelength difference frequencies after mixing in a nonlinear crystal.

The success of these experiments have been rather limited. Harmonic generators have produced outputs at 250 μm , 295 μm , 430 μm and 700 μm but with powers in the μwatt range. Mixing experiments have also produced very low powers and have not yet been extended to wavelengths longer than 100 μm .

5.4 Solid State Devices

This class of generators includes Impatt diodes, Josephson diodes and bulk gallium arsenide devices. At present none of these devices have been operated at wavelengths shorter than 3 mm., however we are including them in this review because some investigators anticipate future operation at wavelengths in the submillimeter range. Average power is about 100 mW at 3 mm, but the predicted power output for submillimeter operation is in the milliwatt range.

5.5 Electron Beam Device

A new technique for generating submillimeter waves has been reported by Mizuno et al (3). This technique employs an electron beam which interacts with a grating and a Fabry-Perot cavity to produce short wavelength radiation. Experiments with a tube designed to operate at a wavelength of 2.8 mm have resulted in pulses with 1 Watt peak power output. CW operation has also been demonstrated.

It is predicted that wavelengths shorter than 400 μm and average powers up to several hundred milliwatts will be possible with this technique. When compared to 1 mW available from a backward wave tube at this wavelength and 25 mW from the 337 μm line of an HCN laser, the potential increase of an order of magnitude in source power is significant.

5.6 Raman Oscillator

Another unusual source of radiation from 50 to 250 μm has been described by Sussman et al (4). The device consists of a lithium niobate crystal placed in front of a Q-switched ruby laser. Stimulated Raman and parametric scattering from an absorbing optical mode of the crystal are obtained. Peak powers of 10 to 100 W have been demonstrated.

5.7 Mercury Arc

The mercury arc is a gas plasma that radiates as a blackbody in the far infrared. Although the literature on this type of source is not always clear, a summary presented by Kimmit (1) shows that an effective temperature of mercury arcs is no greater than 500°K at 330 μm . This evaluation, confirmed by Stanevich (5), is a reasonable upper bound of a practical lamp.

A blackbody at 500°K radiates about $.1 \text{ mW/cm}^2\text{-ster}$ for all wavelengths beyond $250 \text{ }\mu\text{m}$. Since the $A\Omega$ product arc size times angular intercept in $\text{cm}^2\text{-steradians}$ cannot practically be much greater than one even for a large lamp, the total available power is quite low, considerably less than a milliwatt.

5.8 Conclusions

There is a paucity of sources in the 300 to 400 μm region of the spectrum. As can be deduced from the foregoing discussions, the search for high power has been far ranging. The electron beam device for example holds the promise of an order of magnitude greater power than the commercially available HCN laser.

At present, however, it appears to us that our best choice is to use an HCN laser that is offered as a commercial product. The Moleclectron Corp. Model 375 HCN laser (having a 25 mW cW output) is chosen as the "source" for the concealed weapons detection and imaging system. With rapid development of other sources, both narrow and wide band, it is conceivable that in the near future other choices will present themselves. These can then be examined for consideration both from the standpoint of performance and physical aspects such as size utility, cost effectiveness, etc.

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- (5) A. E. Stanevich, I. A. Brodskiy and N. G. Yaroslavskiy, "The Spectral Luninance of Long-Wavelength IR Radiation Sources."

Footnotes

- (a) Dyubko et al., 1968.
- (b) Hocker and Javan, 1967.
- (c) Hocker and Javan, 1968.
- (d) Kotthaus, 1968.
- (e) Levine and Javan, 1969.
- (f) Muller and Flesher, 1966.
- (g) Muller and Flesher, 1967.
- (h) Pollack et al., 1967.
- (i) Pollack and Tomlinson, 1968.
- (j) Witteman and Bleekrode, 1964.

6. ACTIVE SYSTEM FEASIBILITY CALCULATION

Having selected the best possible source and detector now available, the performance of a scanning system using these components will be evaluated. The calculations are similar to those presented in our proposal P-1528.

Bandwidth is based on a working distance of 5-2/3 feet (172 cm) and a spot size for the laser beam equal to 1 cm in diameter. The instantaneous field of view is then,

$$\omega = \frac{1 \text{ cm}}{172 \text{ cm}} = 5.8 \text{ mrad} = \frac{1^\circ}{3}$$

A total field of 10° by 20° and a frame rate of 4 per second requires a bandwidth

$$BW = \frac{30 \times 60 \times 4}{2} = 3600 \text{ Hz}$$

Assuming a 4 inch collecting aperture and a processing efficiency of 70%, the effective $\eta A \Omega$ (efficiency times collecting area times target subtense) is

$$\begin{aligned} \eta A \Omega &= .7 (50) (5.8 \times 10^{-3})^2 \\ &= 1.18 \times 10^{-3} \text{ cm}^2 \text{ ster} \end{aligned}$$

and in the scanning bandwidth of 3600 Hz

$$\frac{(BW)^{1/2}}{\eta A \Omega} = \frac{(3600)^{1/2}}{1.18 \times 10^{-3}} = 5.1 \times 10^4 \frac{\text{Hz}^{1/2}}{\text{cm}^2 \text{ ster}}$$

From Table 4.1, we may now introduce the detectivity of a GaAs detector ($7 \times 10^{11} \frac{\text{Hz}^{1/2}}{\text{watts}}$) and calculate the Noise Equivalent Radiance of the instrument.

$$\begin{aligned}
 NE\Delta N &= \frac{(BW)^{1/2}}{D\eta A\Omega} \\
 &= \frac{5.1 \times 10^4}{7 \times 10^{11}} = 7.3 \times 10^{-8} \frac{\text{watts}}{\text{cm}^2 \text{-ster}}
 \end{aligned}$$

The HCN laser source we have chosen emits $P_L = 25 \text{ mW}$ in a 1 cm diameter beam. If we assume a curved metal target that fills the entire beam and is covered by a layer of woolen fabric, only .01% of the incident power is returned as borne out by our measurements.* This is a reasonably conservative set of circumstances. That is the transmission τ over the target area A_T times the angular dispersion Ω_T equals

$$\frac{\tau}{A_T \Omega} = 1 \times 10^{-4} \text{ cm}^{-2} \text{ ster}^{-1}$$

The effective radiance of our target is, therefore:

$$\begin{aligned}
 N &= \frac{P_L \tau}{A_T \Omega} \\
 &= 25 \times 10^{-3} \times 1 \times 10^{-4} \\
 &= 25 \times 10^{-7} \frac{\text{watts}}{\text{cm}^2 \text{ ster}}
 \end{aligned}$$

Our signal to noise ratio

$$\begin{aligned}
 \frac{S}{N} &= \frac{N}{NE\Delta N} = \frac{25 \times 10^{-7}}{7.3 \times 10^{-8}} \frac{\frac{\text{watts}}{\text{cm}^2 \text{ ster}}}{\frac{\text{watts}}{\text{cm}^2 \text{ ster}}} \\
 &= 34
 \end{aligned}$$

*See Tables 3.1 and 3.2

This is about the same S/N calculated in P-1528. The major difference is the much lower amount of power received from the target (2 order of magnitude) which is compensated for by a cooled detector approximately two orders of magnitude more sensitive.

7. DETECTION BY SELF-EMISSION

In the foregoing we have reviewed the problem of detecting concealed weapons through use of a laser illuminator. The conclusions we reached were that it appears to be possible to produce an image of the concealed weapon. However the system, with existing components, is rather cumbersome and expensive. The lower energy of the reflected beam than we originally expected (due to rather severe losses in diffusion from complex geometric shapes of the metals and absorption losses in going through multiple layers of fabrics) made it necessary to consider use of more sensitive detectors like the liquid helium detectors we have been analyzing (Ga As, Ge:Ga, etc.).

If we consider use of the helium cooled detectors in an optimized state-of-the-art scanning system, it should be possible to obtain sufficient signal-to-noise from self-emitted radiation to see a silhouette of a weapon. The transmission characteristic for most fabrics although not as high as measured at 337 micron radiation is sufficiently good in the broadband spectral interval from 100 to 400 microns as shown by the broadband measurements tabulated in Table 3.3. The frame rate can be made low (e.g., 1 frame/second) and other scan system parameters adjusted to make it possible to obtain a sufficient signal-to-noise ratio. A sample calculation is given below.

Consider a thermograph using a 10" optical collector with a focal length of 15 cm and with an instantaneous field of view of 6 x 6 mrad. (1 cm resolution at a distance of 5 feet). The detector will be a Ge:Ga long wavelength sensitive detector (cooled to 4.2°K) with a $D^* = 5 \times 10^{11}$. Its size will have to be

chosen to cover the 6 mrad field of view, its width will be 37.5 cm x 0.006 cm = 0.225 cm. Its area will be $A_D = (.225)^2 \text{ cm}^2$. To cover a $10^\circ \times 20^\circ$ FOV in one second will require a bandwidth of $\Delta f = 1000 \text{ Hz}$. The NEP of the detector will be

$$\text{NEP}(\lambda, 1-1000) = \frac{(A_D)^{1/2} (\Delta f)^{1/2}}{D^*} = \frac{.225 \times 32}{5 \times 10^{11}} \approx 1.4 \times 10^{-11} \text{ watts}$$

The energy on the detector is estimated on the assumption of a spectral band of 50 microns that is from 100-150 microns for a body temperature 10°C higher than the ambient background ($300^\circ\text{K}-290^\circ\text{K}$). Using the Stefan-Boltzmann Law or tables as found in references like Pivovonski and Nagel*, the radiance is found to be

$$N_{\Delta\lambda} = 3.0 \times 10^{-6} \text{ watts/cm}^2\text{-ster}$$

The power on the detector is found from

$$P_D = N_{\Delta\lambda} \omega A_o \eta_1 \eta_2 \eta_3$$

where $\omega = 36 \times 10^{-6}$ steradians, $A_o = 500 \text{ cm}^2$, $\eta_1 = .3$ for the optics and filter, $\eta_2 = .40$ for the scanning duty cycle and $\eta_3 = .05$ for typical wide band transmission of wool from Table 3.3.

$$\begin{aligned} P_D &= 3.0 \times 10^{-6} \times 3.6 \times 10^{-5} \times 500 \times .3 \times .4 \times .05 \\ &= 32.4 \times 10^{-11} \text{ watts} \end{aligned}$$

With an NEP of 1.4×10^{-11} we can expect a signal to noise ratio of 23 which should make it possible to obtain reasonable image quality.

* Pivovonsky, Mark & Nagel, Max R., TABLES OF BLACKBODY RADIATION FUNCTIONS, Macmillen & Co., N. Y. 1961

8. SAFETY

The U. S. Department of Health, Education and Welfare, Public Health Service publishes a booklet entitled "Regulations, Standards, and Guides for Microwaves, Ultraviolet Radiation, and Radiation from Lasers and Television Receivers - An Annotated Bibliography." The last printing is dated April 1969. The laws and codes listed include those of the English and Australian governments as well as the American government and agencies.

Of all the 15 rules and guidelines on lasers discussed in this publication, the most applicable is a U. S. Atomic Energy Commission regulation. This document is the draft of an addition to the AEC Standard Operating Procedure at the Nevada Test Site (NTS), NTSO-05X1, February 8, 1968. The limits specified for permitted power density directly falling on the cornea, in the wavelength region greater than $1.4\mu\text{m}$, is 1.0 w/cm^2 . As expected the eye is the most sensitive portion of the body; the limits for skin are much higher.

As discussed in the section on sources, the 25 milliwatt output from the HCN laser is in a 1 cm diameter beam. The flux density is thus much less than the limit quoted above. Actually, a source of several hundreds milliwatts or greater would still be well within acceptable limits particularly when one takes into account the dwell time of the beam which would be quite small. There is thus no danger of damage from the long wavelength thermal emission. Furthermore the aqueous film on the human eye serves as an absorber at the long wavelengths which also protects the cornea from possible damage.

Insofar as the visible emission of common HCN lasers is concerned it is our plan to employ a filter (e.g. carbon impregnated polyethylene) to eliminate emission at any wavelengths below 50 microns.

9. FUTURE POTENTIAL FOR ACTIVE LONG WAVELENGTH CONCEALED WEAPONS DETECTION SYSTEM

If one projects continued improvements, simplifications and a proliferation of uses of the long wavelength sources and receivers, that will significantly reduce their ultimate cost, then the active long wavelength concealed weapons detection system discussed in this report can become a useful commercial product competitive economically with other approaches and probably more effective. It has advantages over other presently developed systems. It will produce a recognizable shape that makes it possible to clearly identify a weapon, unlike the magnetic sensors. It will not be hazardous to people subjected to scrutiny as the X ray system is believed to be. It will produce real-time images providing a large number of "looks" so that the search can be more thorough than one with a system that produces only one picture. Yet individual frames can be "frozen" and stored for later review and investigation. The features must be related to the cost-effectiveness of a scheme for concealed weapons detection.

The components considered in sections 4 and 5 that are suitable for a concealed weapon detection system are at present rather costly, with the laser costing about 20K and the scanner detection, likewise in the range 20-25K. Undoubtedly these costs will be reduced as the components are brought to the level of development needed for quantity production if a lucrative application is found. More likely, however, with continued development work in the comparatively uncharted field of long wavelength

infrared techniques we expect to see a trend toward use of simpler components. Rather than the gas laser we expect that solid state devices emitting at long wavelengths will be more practical and inexpensive.

IMPATT diodes that are at present only laboratory devices generate long wavelength radiation with power levels of the order of a milliwatt. Undoubtedly, however, it will be possible to generate orders of magnitude greater power than has been shown to-date. These diodes bear the same relationship to the gas laser as do Light Emitting Diodes (LED) to ruby lasers. They are far simpler and smaller. Once a useful application is found they are mass-produced and their cost is sharply reduced. Such developments may be expected for the IMPATT diode. Similarly, for the scanner and receiver the cost of the components may be expected to decrease markedly if an application is found that holds forth hope for extensive production. The liquid helium cooled detector packages presently cost in the vicinity of \$5,000, but are believed to be no more complex than more conventional shorter wavelength IR detectors that sell for \$500 - \$1,000. It is possible to project a per system cost of about \$10,000 for the "active" concealed weapons detection system in production quantities of 500 - 1,000 systems based on use of solid state sources and simplified 4°K temperature operated detectors and scanners.

10. POTENTIAL FOR A PASSIVE LONG WAVELENGTH CONCEALED WEAPONS DETECTION SYSTEM

A passive long wavelength concealed weapons detection system would appear to have a number of significant advantages over other approaches presently being considered for this application. It would present a real time image of the subject that readily reveals the presence, location and shape of weapons. The scheme, depending as it does only on self-emission from the heat of the body, is less direction sensitive than the "active" system that depends on reflection of a laser beam, with attendant dispersion/diffusion losses. The person being searched is in no way irradiated. There is thus no possibility of any objection on medical or biological grounds, as with the X ray system, for example. Also, unlike the magnetic system, the passive IR system is expected to provide reasonably good resolution and quality images. The images may also be recorded for later observation and study. These advantages should be kept in mind when considering a cost comparison with other concealed weapons detection techniques.

At present a thermograph using reflecting optics (e.g., BEC-Bofors T-101) costs about 25K. Changing to a liquid helium cooled detector would increase the cost by about 5K. If one could contemplate large quantity production for a thermograph of this type after an attractive new application has been uncovered, such as the one presently considered, the picture changes radically. Once the initial engineering and development costs have been amortized one can project a cost in production quantities of

500 - 1,000 that are well under \$5,000, possibly in the 3K area. The cooled detectors are expected to cost between 500 - 1K.

The scanning system and electronics are expected to cost under 1.5K and a display system can be priced under 1K based on display monitor oscilloscopes presently marketed by companies like Tektronix and Hewlett-Packard.

On the basis of the above we believe that the long wavelength passive IR imaging system is competitive both in performance and economically with other systems presently being considered and we believe it worthwhile to pursue the technique further to the point of developing an engineering model that may be evaluated in the laboratory as well as at air terminals.

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