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Vision Enhancement for Fire Fighters

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The Naval Research Laboratory (NRL) has evaluated various imaging technologies for possible use by shipboard fire fighters. It has been shown that infrared technology may be used to see through the smoke typical of Navy fires, thus significantly increasing the fire fighters' effectiveness.

This report summarizes previous investigations conducted in this area as well as details of the tests and evaluations conducted by NRL.

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GLOSSARY

AVGAS	Aviation Gasoline
CNVEO	U.S. Army Center for Night Vision and Electrooptics
CPS	Collective Protection System
DCA	Damage Control Assistant
EEV	English Electric Valve
EMI	Electromagnetic Interference
FFD	Federal Fire Department
FLIR	Forward Looking Infrared
FLSC	Fire Fighting Flag Level Steering Committee
FPA	Focal Plane Arrays
FOV	Field of View
FTC Norfolk	Fleet Training Center Fire Fighting School, Norfolk, VA
FTC San Diego	Fleet Training Center Fire Fighting School, San Diego, CA
F&STD	U.S. Coast Guard Fire & Safety Test Detachment, Mobile, AL
IC	Integrated Circuit
IR	Infrared
LCT	Liquid Crystal Thermometer
LED	Light-Emitting Diodes
LFES	Localized Fire Extinguishing Systems
LTG	Lesson Topic Guides
MRT	Minimum Resolvable Temperature

NDCTC	Naval Damage Control Training Center, Philadelphia, PA
NFTI	Naval Firefighters Thermal Imager
NNBFD	Norfolk Naval Base Fire Department, Norfolk, VA
NSC	Naval Safety Center, Norfolk, VA
NSWC	Naval Surface Weapons Center, Dahlgren, VA
NWSC	Naval Weapons Support Center, Crane, IN
OBA	Oxygen Breathing Apparatus
PC	Photoconductive
PE	Photoelectric or Photoemissive
PEV	Pyroelectric Vidicon
PNSY	Philadelphia Naval Shipyard, Philadelphia, PA
PV	Photovoltaic
RF	Radio Frequency
RNEE	Royal Navy Equipment Exhibition
SAR	Search & Rescue
SCBA	Self Contained Breathing Apparatus
SRTS	Short Range Thermal Sight
TE	Thermoelectric
TGS	Trigylcine Sulfate

VISION ENHANCEMENT FOR FIRE FIGHTERS
PART I—BASIC CONCEPTS

INTRODUCTION

Fires represent a major threat to Navy assets ashore and at sea. The usual problems encountered by land-based fire fighters, such as heat, smoke, and toxic fumes, are multiplied by the special conditions faced by Naval fire fighters, such as the presence of large quantities of various fuels and the dangers posed by ordnance cookoff. Fire fighting operations at sea must be conducted in restricted spaces with limited equipment and personnel. The necessity of maintaining ship functions while simultaneously attacking the fire further constrains the available options.

Successful fire fighting operations aboard ships require fast and appropriate responses to rapidly changing situations under conditions of extreme adversity. One implication of these requirements is that fire fighters must be able to move quickly, even through smoke and fumes. A second implication is that the command authority must have an accurate, up-to-date picture of the overall situation.

These strategic requirements imply certain material requirements for the individual fire fighter. First, each fire fighter must be equipped with clothing and breathing apparatus that provides sufficient protection from the heat, smoke and toxic gases. Ideally, firefighters should also be provided with equipment that improves vision through smoke to help them find the fire more quickly and function more efficiently once the fire has been reached. Finally, there must be a communications system that allows local communication, within the fire party, and long distance communication, to higher authority. These protective, vision enhancement and communications systems should be parts of an integrated package.

Until recently, the approach to vision enhancement had been to use a face mask and flashlight and hope for the best. Usually this resulted in zero effective vision in dense smoke, and the fire fighters were forced to find their way by touch. Since the early 1970s, the Naval Research Laboratory (NRL) has conducted an on-going research effort to evaluate methods to alleviate this problem. Two different lines of investigation were undertaken. The first was to develop techniques for quickly removing dense smoke—the knockdown approach. The second was to find a method of providing thc fire fighter with usable images even in the presence of heavy smoke—the see-through approach.

In some ways, smoke knockdown appeared to be the better method. First, it could be based on an installed system that eliminated the need for fire fighters to carry additional equipment. Second, the system could also be used to permit more rapid evacuation of nonessential personnel from the scene of a fire. Finally, at the beginning of this program, the state of the art in electronics made the prospects for a compact, lightweight, rugged, and affordable imaging system rather remote.

Initially, much of the program effort was applied to the development of a system using overhead nozzles that sprayed a water-based surfactant solution to coagulate and precipitate smoke particles. Leonard [1] successfully demonstrated this knockdown system in small-scale tests. However, much more engineering development and shipboard testing would have been required to resolve the problems encountered during full-scale testing. Also, the ship alterations needed for the installation of the

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system would have been very costly and time consuming. Thus, to provide a less expensive, near-term improvement in fire fighting capability, the efforts were redirected towards the evaluation of the rapidly advancing imaging technologies. Special emphasis was given to long wavelength imaging devices because optical theory suggested that imaging systems operating at these wavelengths (beyond the visible spectrum) might provide a solution. This report describes NRL's investigation of these imaging techniques to provide true vision enhancement for fire fighters.

The remaining three chapters in Part I review some aspects of radiation theory, briefly discuss the history of the vision enhancement program at NRL, and summarize the state of the art in a few critical areas of infrared technology. Much of this information was included in this report to provide the nontechnical reader with the background for understanding the significance of the test results. Those readers who are primarily interested in recent developments may safely skip these sections. Part II reports on NRL's demonstration and validation program, including a survey of commercially available imaging systems, the results of proof-of-concept tests, and the evaluation of several candidate devices. Part III discusses the development of a doctrine for the use of thermal imaging systems in shipboard fire fighting and the deployment of these systems in the Fleet.

THEORETICAL CONSIDERATIONS

All imaging systems depend on some form of radiation to carry information from the scene to the detector. Most commonly, visible light is used for this purpose; however, other forms of electromagnetic energy (ultraviolet, infrared, radio, etc.) or acoustic energy may also be used. In all cases, detection depends on the intensity of the radiation that arrives at the sensor; this intensity, in turn, depends on two factors—the radiation intensity leaving the scene and the radiation losses while in transit (obscuration).

The radiation leaving the scene is the sum of the emission from objects in the scene and their reflection. Passive detection systems, i.e., those systems that do not include a radiation source to illuminate the scene, depend either on the reflection of stray radiation or on the natural emissions from objects in the scene. Active detectors, i.e., those detectors that incorporate illumination sources, use reflected radiation. However, it would not be prudent for shipboard fire fighting to rely on stray radiation since it may not be present at all times. Imaging systems for fire fighters should either be active devices or be dependent only on emitted radiation that can be guaranteed to be present.

Emission

All objects emit electromagnetic radiation across a wide band of wavelengths. Both the intensity of the radiation and the wavelength of maximum emission depend on the temperature of the emitting object. A theoretical perfect emitter produces an intensity spectrum as described by the Planck equation

$$R_\lambda = (2\pi c^2 h \lambda^5)\,[exp\ (hc/k\lambda T) - 1]^{-1} \tag{1}$$

where R_λ is the spectral radiancy (power per unit area per unit wavelength; $W/m^2/\mu m$), λ is the wavelength (μm) and T is the absolute temperature of the object (K). The constants c, h and k are, respectively, the velocity of light (3.00×10^8 m/s), Planck's constant (6.63×10^{-34} J-s), and Boltzmann's constant (1.38×10^{-23} J/K).

The total radiancy of such an object may be calculated by integrating over all wavelengths and is found to obey the Stefan-Boltzmann equation

$$R = \sigma T^4 \tag{2}$$

where σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8}\ W/m^2K^4$).

An object that rigorously obeys Eqs. (1, 2) would be a *blackbody*, i.e., a perfect absorber and emitter of electromagnetic radiation. In reality, of course, no objects are perfect emitters; therefore, the actual emission intensity at any temperature and wavelength is less than that predicted in Eq. (1). Nevertheless, Eq. (1) is a reasonable first approximation, at least to the shape of the spectral intensity curve.

For real objects, Eq. (2) is usually modified to

$$R = \epsilon \sigma T^4 \tag{3}$$

where ϵ (the emissivity) is a dimensionless parameter that has a value between zero and one. Emissivity is a function of the surface material, surface finish (such as rough, polished, crystalline, or amorphous), and temperature. Fortunately, for a wide range of common materials, the emissivity is relatively high and not strongly temperature dependent. Also, carbon black is one of the better emitters ($\epsilon \sim 0.95$); thus any objects exposed to black smoke soon become good emitters even if they originally had a low emissivity.

Obscuration

Particulates reduce light transmission and therefore cause obscuration by two mechanisms: scattering and absorption. In general, scattering is determined by the size and shape of the particle, while absorption depends more on the composition of the particles. Both are functions of incident wavelength. Scattering is the dominant factor in many applications, and it is the one with which we will be most concerned.

Scattering has been found to be a complex phenomenon (see, for example, Ref. 2), and the theory is beyond the scope of this discussion. Light scattering effects can be calculated from the theory, if the characteristics of the smoke are known in detail. Figure 1 presents a typical particulate size distribution for JP-5 smoke, as measured with a four-stage cascade impactor. As a practical matter, both the composition and the size distribution of smoke encountered in real fires are extremely variable and difficult to characterize. Under these circumstances, it is doubtful that rigorous theoretical calculations would be meaningful.

However, an important qualitative observation may be made. The fraction of light scattered is strongly dependent on the ratio λ/d, where λ is the wavelength of light and d is the particle diameter. When this ratio is near unity, scattering becomes very severe, while at large λ/d values, there is relatively little scattering.

Since smoke strongly scatters visible light ($\lambda \sim 10^{-7}$ to 10^{-6} m), the obvious remedy is to use longer wavelengths, thus increasing λ/d and reducing scattering losses. Possible alternatives, illustrated in Fig. 2, are infrared ($\lambda \sim 10^{-6}$ to 10^{-3} m), microwaves ($\lambda \sim 10^{-3}$ to 5×10^{-1} m), and radio waves ($\lambda > 5 \times 10^{-1}$ m). Other factors being equal, we would expect to obtain the least scattering (and therefore best smoke penetration) by using the longest possible wavelength.

Optical theory, however, predicts that the limit of angular resolution for an imaging system will be proportional to λ/a, where a is the aperture diameter of the imager. Thus, for a given aperture, shorter wavelengths provide better resolution. Conversely, a given resolution requirement can be met with smaller and lighter optics if the wavelength is reduced. Selecting the minimum wavelength consistent with reasonable smoke penetration, therefore, optimizes the image resolution, device size, and probably the weight.

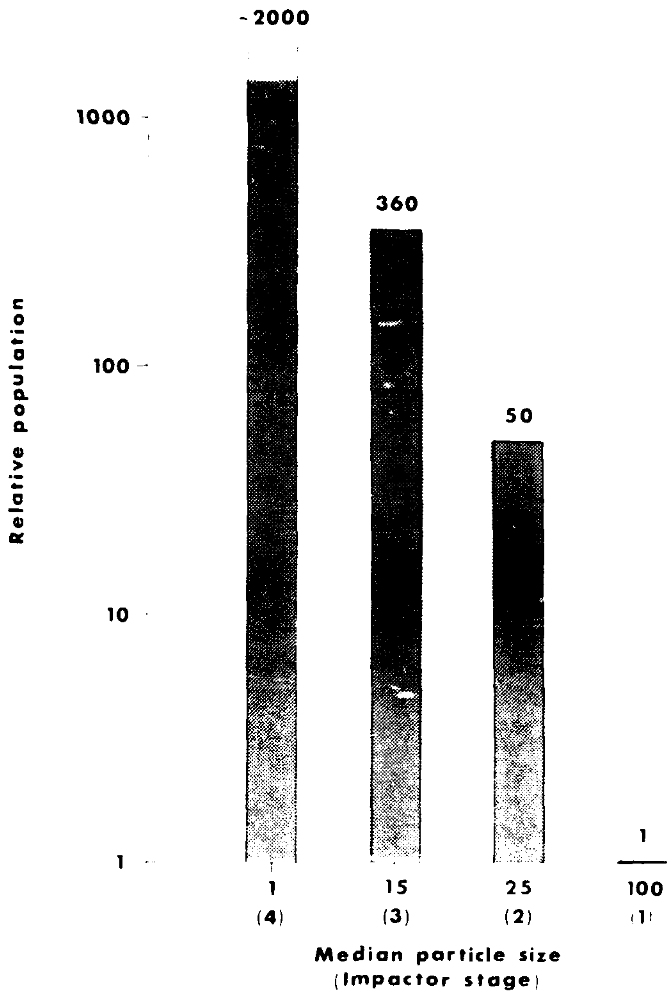


Fig. 1 – Typical particulate size distribution for JP-5 smoke. The relative particle populations of four different median particle sizes are shown. The data were obtained from a four-stage cascade impactor.

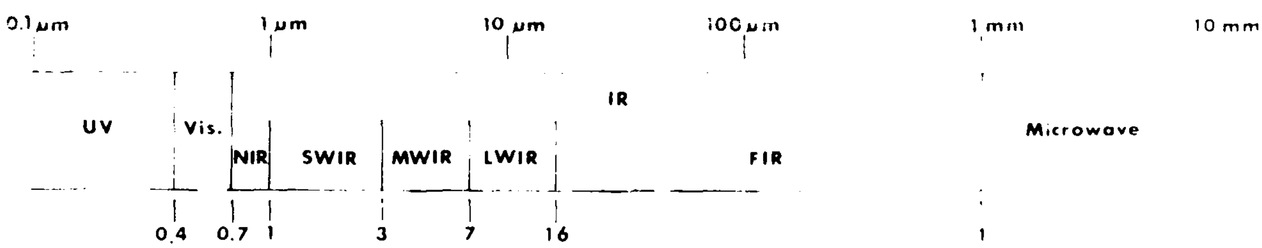


Fig. 2 — The electromagnetic spectrum. The spectral region between 0.1 μm and 10 mm includes ultraviolet (UV), visible (Vis), infrared (IR), and microwave radiation. The IR portion is subdivided into near IR (NIR), shortwave IR (SWIR), midwave IR (MWIR), longwave IR (LWIR) and far IR (FIR). The boundaries among regions are somewhat arbitrary. Those shown here were adapted from Ref. [4].

Note that the peak of the black body curve, Eq. (1), is near 10 μm for objects at temperatures near 300K (room temperature). At higher temperatures, the peak shifts to lower wavelength, but, because the total radiancy increases tremendously (Eq. (2)), the intensity in the 10 μm region remains high. Thus, considerations of emission, obscuration, and resolution all suggest that infrared might be the optimal spectral region to be used by fire fighters.

PROJECT HISTORY

Alger and Gordon [3] demonstrated these concepts fifteen years ago, using both infrared (IR) and microwave systems, Fig. 3. In 1973, they evaluated two versions of the Hughes Probeye IR imager ($\lambda = 3 - 5.4$ μm) and an experimental microwave device ($\lambda = 1$ cm) in class A and B fire scenarios. Table 1 summarizes the results of their experiments. They concluded that dense smoke attenuates 3 to 5 μm radiation rather severely but that, as expected, microwaves are relatively unaffected. Probeye devices detected strong IR sources, that is, fires; but weak emitters, such as people, room furnishings, or obstacles, were difficult or impossible to detect under these conditions. On the other hand, it was found that the microwave system could easily detect larger targets but had such low resolution that it became difficult to identify them. The smaller targets could not be detected even in the absence of smoke.

(a)

(b)

Fig. 3 — Probeye and microwave thermal detectors. (a) Two versions of the Hughes Probeye imager were tested. The commercial model (left) provided an exponential response. The device on the right was modified to give a logarithmic response and was less prone to saturation. (b) This prototype microwave device detected thermal microwave emission at a wavelength of approximately 1 cm.

Table 1(a) — Test Results from Alger and Gordon [3] (Metal Bunker)

Range (ft):	4		7.5			11		12	13	
Target[a]:	NT	NB	MT	MB	BOTTLE	BOTTLE	FIRE	FIREMAN	FT	FB
Pre-fire Test										
Probeye #1[b]	x	x	x	x	x	x	NA	x	x	x
Probeye #2[c]	x	x	x	x	x	x	NA	x	x	x
Microwave	-	-	-	-	-	-	NA	x[d]	-	-
Test #1[e,f]										
Probeye #1	x	x	x	x	-	-	NA	-	-	-
Probeye #2	x	x	x	x	-	-	NA	?	x	x
Microwave	-	-	-	-	-	-	NA	x	-	-
Test #2[e]										
Probeye #1[g]	-	x	-	-	-	-	-	NA	-	-
Probeye #2[h]	x	x	x	x	-	-	x	NA	x	x
Microwave[i]	0	0	0	0	0	0	x[j]	NA	0	0

x = target detected; — = target not detected; NA = target not used; ? = target barely detectable; 0 = no data

[a] 100 W light bulb target [N = near, M = middle, F = far, T = top (3 ft above floor), B = bottom (1 ft above floor)].

[b] Probeye #1 - Prototype signal processing system with logarithmic response (suitable for strong signals).

[c] Probeye #2 - Commercial version with exponential response (suitable for weak signals).

[d] Reflections of walls also visible.

[e] Black smoke from JP-5.

[f] Data at 9.5 min into Test #1. Fire out, but all targets invisible to the unaided eye.

[g] Data at 11 min into Test #2. All lamps invisible to the unaided eye.

[h] Data at 13 min into Test #2.

[i] Data at 8 min into Test #2. Far lamps and flames invisible to the unaided eye.

[j] Detector amplifier saturated.

Table 1(b) — Test Results from Alger and Gordon [3]
(Frame House - Visible Fires)

Range (ft):	13		19	23		25	28	32		
Target[a]:	NT	NB	DOORWAY	MT	MB	MATTRESS FIRE	WOOD FIRE	FIREMAN	FT	FB
Pre-fire Test										
Probeye #1	x	x	x	x	x	NA	NA	x	x	x
Probeye #2	0	0	0	0	0	NA	NA	x	0	0
Microwave	-	-	0	-	-	NA	NA	x[d]	-	-
Test #3[b]										
Probeye #1[c]	0	0	x[d]	-	-	-	NA	-	-	-
Probeye #2[c]	0	0	x[d]	-	-	-	NA	-	x	x
Microwave	0	0	x	0	0	*e*	NA	*e*	0	0
Test #4[f]										
Probeye #1[g]	0	0	x	0	0	-	-	NA	0	0
Probeye #2[g]	0	0	x	0	0	-	-	NA	0	0

x = target detected; - = target not detected; NA = target not used; ? = target barely detectable; 0 = no data

[a] 100 W light bulb targets [N = near, M = middle, F = far, T = top (3 ft above floor), B = bottom (1 ft above floor)].

[b] Test initiated by ignition of mattress in bedroom 1 in line-of-sight of the imager.

[c] Data at 18 min into Test #3. NT and NB barely visible to the unaided eye.

[d] Doorway appears as an area of uniform temperature.

[e] Fire and fireman not differentiated.

[f] Test #4 initiated by ignition of wood fire at 21 min into Test #3. No data reported for microwave detector.

[g] Data at 3 min into Test #4 (24 min after start of Test #3).

Table 1(c) — Test Results from Alger and Gordon [3]
(Frame House - Fire Behind Wall)

Range (ft):	13
Target:	Heated Wall
Test #5[a,b,c]	
Probeye #1	x[d]
Probeye2	x[d]
Microwave	x

[a] Test initiated by movement of the Test #4 mattress fire remains (approximately 25% of the mattress) into bedroom #2.

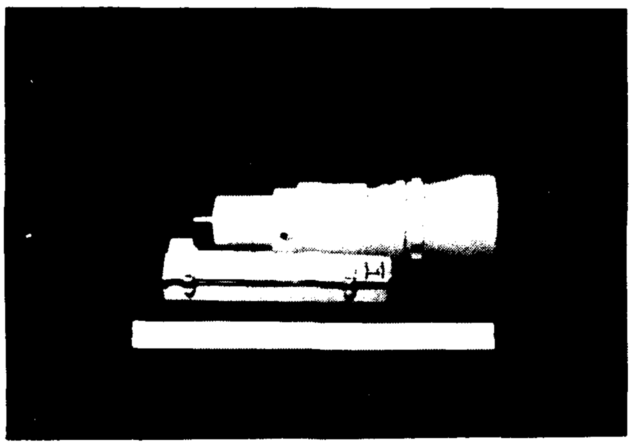
[b] Wood fire ignited at 13 min into Test #5.

[c] Data at 24 min into Test #5.

[d] Wall studs and braces also visible.

These results suggested that an intermediate wavelength might prove to be very effective. In fact, Alger and Gordon recommended the evaluation of a longer wavelength IR scanner (10 μm or greater) and a shorter wavelength microwave device, possibly in the millimeter wave region. At the time of their report, however, handheld models of such devices were not available.

Based on the negative results obtained by Alger and Gordon in 1973, the potential of using IR systems for vision enhancement in smoke appeared to be limited. However, the possibility could not be ruled out because attenuation by particulates is not the only determining factor. Detector sensitivity, transmission losses within the optical system, signal processing techniques, and other parameters are also important. Accordingly, NRL continued a low-level program to monitor the developments in IR imaging. As part of this effort, two military imagers were evaluated between 1975 and 1978—the AN/SAR-6 and the AN/TAS-2, Fig. 4. The AN/SAR-6 was a small, handheld viewer, while the AN/TAS-2 was considerably larger and significantly more sensitive. Both operated in the 3 to 5 μm region, and, although neither device was highly effective in dense, black smoke, both provided better visibility in smoke-filled atmospheres than did the unaided eye. While they were not acceptable for our intended use, these instruments demonstrated that technological advances could produce significant operational improvements and hopefully, given the right technology, a useful device could be built.



(a)

(b)

Fig. 4 — The AN/SAR-6 (a) and AN/TAS-2 (b) imagers were early military thermal imaging systems

This hope was realized in 1982, when NRL evaluated the English Electric Valve (EEV) Model P4228 thermal imaging camera, Fig. 5. The P4228 was small and light enough to be hand-held and operated in the 8 to 14 μm spectral region. Preliminary tests showed that it was capable of producing high-quality images through extremely dense, black smoke even at distances of 10 m (30 ft) or more. Based on these preliminary results, NRL initiated an extensive test and evaluation program. The work discussed in this report was performed during the period from October 1982 through October 1986.

Fig. 5 — The English Electric Valve (EEV) P4228 thermal imager was evaluated aboard the USCG test ship *A. E. Watts* during full-scale fire tests

Before discussing this program or the imagers that were evaluated, we must consider some of the technical and engineering fundamentals of thermal imaging systems. A myriad of fields, ranging from quantum mechanics to refrigerator design, have contributed to the development of modern thermal imaging systems. In the next section of this report, we present an overview of selected areas of thermal imaging technology, and we concentrate on the basic principles required to understand the specific systems discussed in the sections that follow.

SUMMARY OF SELECTED IR IMAGING TECHNOLOGIES

Table 2 shows the properties of some typical IR detectors. These detectors could be classified by size, shape, operating temperature, spectral region or numerous other parameters. Several of these factors are discussed in this section; however, we start by considering the fundamental operating principles of IR detectors.

Principles of IR Detectors

Infrared radiation may be thought of as a stream of photons, each of which carries a small quantity of energy. When absorbed by a detector, this energy is transferred to an electron in the detector and may cause a measurable change in the energy state of that electron. Alternatively, the photon's energy may be dissipated as heat, thus causing a change in the temperature in some small region of the detector. The temperature change may produce, as a secondary effect, a measurable change in some bulk property (i.e., a property not associated with any specific atom or molecule) of the detector material. Devices that operate on the first principle are called quantum detectors, and those that use the second method are thermal detectors.

Table 2 — Properties of Some Typical IR Detectors [4,5]

Detector	Practical Wavelength Range (μm)	Typical Operating Temperature (K)	Remarks
Triglycine Sulfate (TGS)	<0.2 to $>15^a$	322 (max)	Thermal Detector (Pyroelectric)
Deuterated Triglycine Sulfate (DTGS)	<0.2 to $>15^a$	334	Thermal Detector (Pyroelectric)
Lithium Tantalate ($LiTa0_3$)	<0.2 to $>15^a$	891 (max)	Thermal Detector (Pyroelectric)
Indium Antimonide (InSb)	0.6 to 5.6	77	Photovoltaic
InSb	0.5 to 6.5	195	Photoconductive
Lead Selenide (PbSe)	0.8 to 5.1	195	Photoconductive
Mercury Cadmium Telluride (HgCdTe)	6.0 - 15^b	77	Photovoltaic

[a] Thermal detectors are relatively insensitive to wavelength, therefore the practical wavelength range is determined by window materials and other system parameters.

[b] Wavelength range may be tailored to requirements by adjustment of the Hg:Cd:Te ratio during manufacture.

Thermal detectors

The classical thermal detector is the ordinary thermometer in which the absorption of photons causes a temperature increase and, as a result, the volume (a bulk property) of the working material (mercury, for example) increases. More sophisticated thermal detectors include thermocouples, in which the temperature change causes an electromotive force, and thermistors, in which the resistance is a function of temperature.

Traditional thermal detectors sometimes are satisfactory as point detectors, but experience has shown that they are not very practical in imaging applications. Systems based on the ferroelectric properties of crystals are exceptions to this rule. Some materials, notably crystals of triglycine sulfate (TGS) and related organic materials, exhibit ferroelectric behavior, which is analogous to the ferromagnetic behavior of alloys of iron and similar metals.

Ferroelectric materials are dielectric (insulating) substances composed of molecules that have inherent electric dipole moments and that are organized so that each unit cell possesses a net dipole moment. Unit cells within a small region, called a domain, have parallel dipole moments, but adjacent domains have randomly oriented moments that tend to cancel each other. Normally, the resulting crystal has no net electric dipole. However, if an external electric field is applied, the domains can be forced to realign parallel to the field in a process called *poling*. This alignment persists after the external field is removed and the resulting material is said to be polarized. The process is somewhat analogous to the induction of a permanent magnetic moment in ferromagnetic materials. For our purposes, we may consider the polarization to be due to the presence of opposite charges bound to the two crystal faces. The fact that they are bound has significant effects. Figure 6 illustrates the ferroelectric effects.

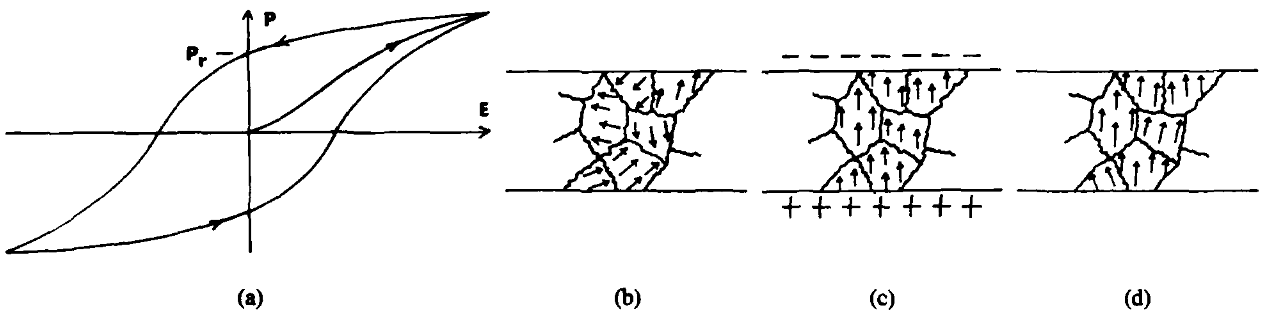


Fig. 6 — The ferroelectric effect and polarization. (a) Polarization is a function of applied electric field strength E. Ferroelectric materials exhibit hysteresis such that there is a residual polarization P_r when E is reduced to zero. (b) Prior to exposure to an E-field, the electric dipole domains are randomly oriented. The net polarization is zero. (c) During exposure to an E-field, the domains align with the field. The net polarization is dependent on the magnitude of E, as shown in (a). (d) After removal of the E-field, the domains relax somewhat but a residual net polarization P_r remains. An E-field in the opposite direction would be required to produce zero net polarization.

If the amount of polarization is dependent on the temperature, then the material is called pyroelectric. In a thermal imaging system, IR radiation incident on a pyroelectric crystal forms a pattern of hot and cold regions that produces a corresponding pattern of polarization and, therefore, of bound surface electric charge. This effect depends only on the total thermal energy deposited within a given region and not on the energies of individual photons. Pyroelectric detectors are therefore relatively insensitive to wavelength. In principle, these detectors are simple, relatively low-cost devices capable of operating quite well in the long-wavelength IR band.

Pyroelectric detectors possess several significant practical problems, however. One fundamental problem, inherent in all pyroelectric detectors, is that the net electric dipole moment is lost at temperatures above the Curie temperature T_c. This temperature corresponds to a phase transition in which the dipole domains revert to their original, random orientations. T_c varies in different materials and, in several TGS derivatives, lies in the range of 49° to 70°C (120° to 158°F). Some inorganic compounds have much higher Curie temperatures (T_c is 618°C (1144°F) for $LiTaO_3$, for example), but these compounds typically also have low sensitivity or poor handling properties.

Quantum detectors

The principles of quantum detectors are somewhat more complex. At the atomic level, absorption of a photon occurs when the energy carried by the photon is transferred to an electron, causing it to be excited to a higher energy state. Several types of quantum detectors may be distinguished, depending on what happens to the electrons. To understand these processes requires some background in the theory of crystalline materials.

A complete discussion is beyond the scope of this report; however, more information may be found in Refs. 6 and 7. In a simple approximation, we may consider that the electrons in crystals exist in one of two energy bands, each of which arises from the interaction of many atomic energy levels. The lower, or valence, band contains electrons that are bound to specific atoms and are therefore not able to move freely through the crystal. In the conduction band, which lies at higher energies, electrons are free to migrate throughout the material. The energy difference between the top of the valence band and the bottom of the conduction band is the band gap, E_g. The difference between the most energetic ground-state electron in the crystal and the least energetic free electron (i.e., an electron located in space and unaffected by the presence of the crystal) is the work function ϕ of the crystal. The band gap is large in insulators (a large amount of energy is required to excite electrons to the conduction band), and small in semiconductors (little energy is needed to promote electrons). In conductors, the conduction band is always partially filled with electrons, even in the ground state. Figure 7 illustrates these concepts.

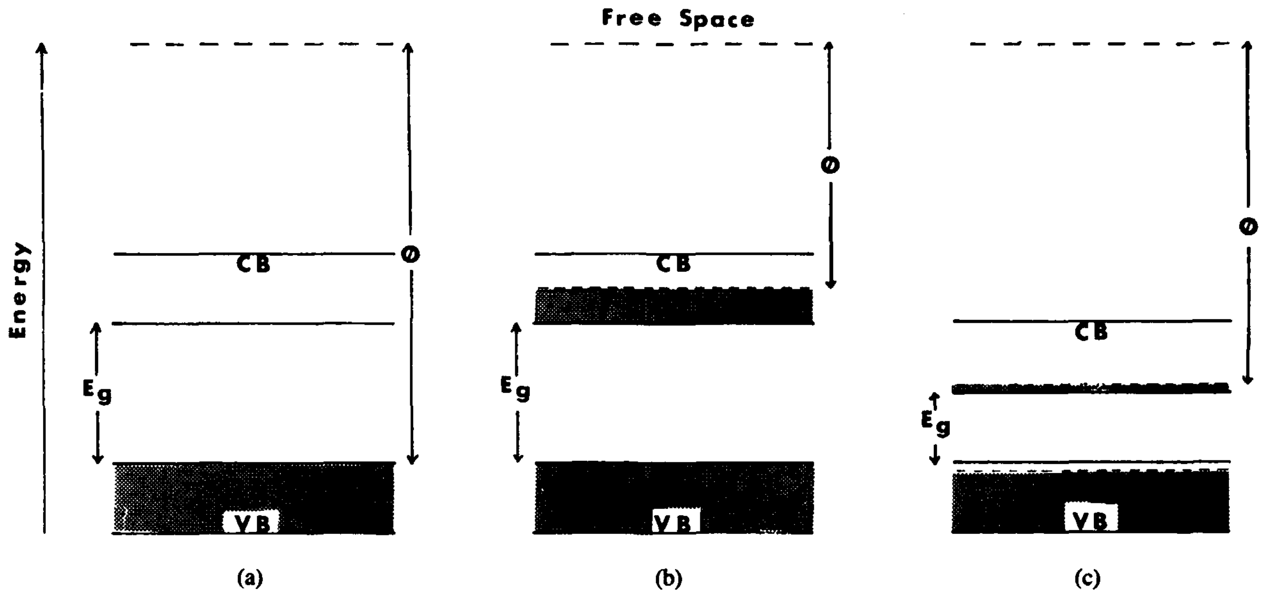


Fig. 7 — Crystal Band Structure and Free Electrons: CB = conduction band; VB = valence band. (a) Simplified band model of an insulator. E_g is the band gap energy, and the work function ϕ is the minimum energy required for an electron to escape from the surface. A perfect insulator has no electrons in the conduction band and no vacancies (holes) in the valence band. Real insulators do have some electrons in the conduction band, but the number is very small and produces a negligible conductivity. (b) Simplified band model of a conductor. The conduction band is partially filled with electrons that are free to move throughout the material. (c) Simplified band model of a semiconductor. E_g is much smaller than in an insulator. At ordinary temperatures ($\sim$300 K), the equilibrium electron energy distribution permits a significant electron density in the conduction band, which causes the conductivity to be much higher than in insulators but much lower than in conductors. At absolute zero, semiconductors would become insulators.

Conceptually, the simplest quantum detector is one in which the incident photons impart sufficient energy to cause some electrons to be emitted from the surface (Fig. 8). These free electrons, as they travel through space, constitute a current that can be measured. The magnitude of that current is proportional to the number of photons absorbed. Devices that operate on this principle are called photoelectric or photoemissive (PE) detectors. A major limitation is that the incident photons must have energies at least equal to ϕ, which, for the best currently known materials, is about one electron-volt (eV). This corresponds to a cutoff wavelength (λ_c) of approximately 1.2 μm. Consequently, PE detectors will not function in the wavelength regions of interest in our program.

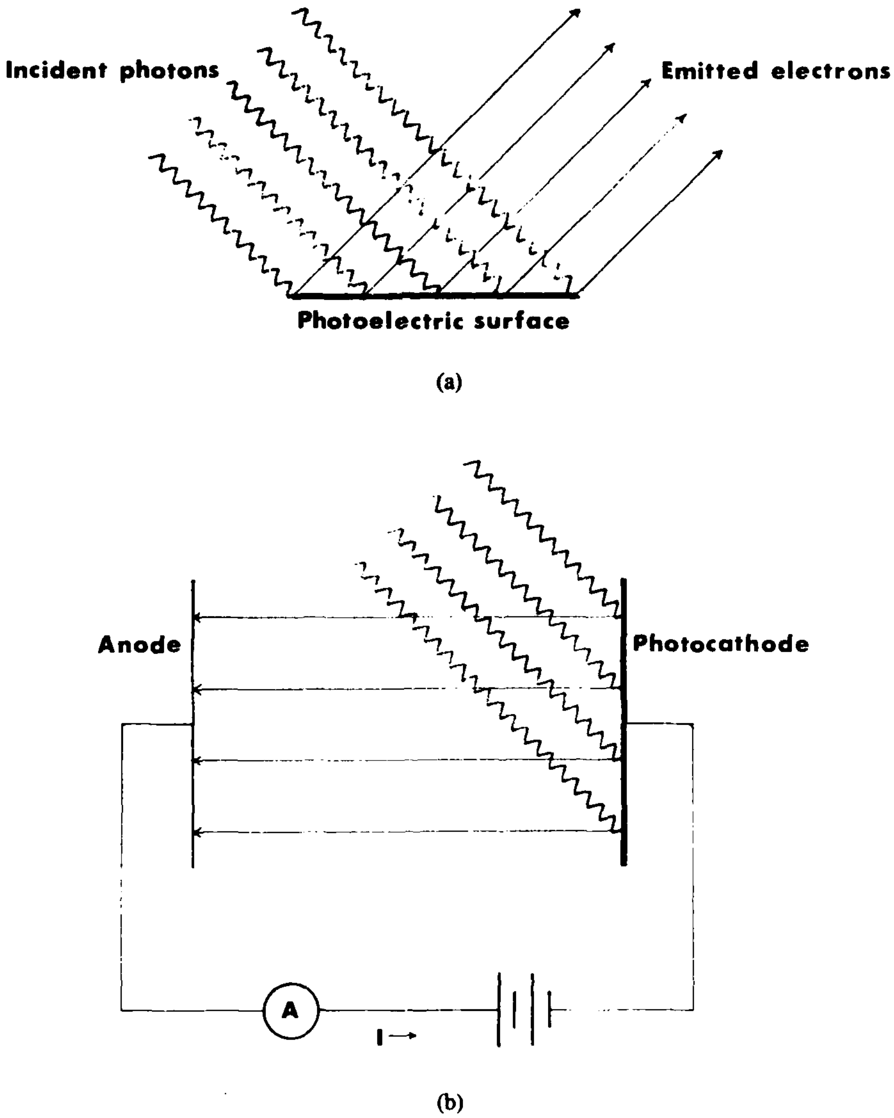


Fig. 8 — The photoelectric effect and photoemissive detectors. (a) Incident photons having energies $h\nu$ greater than the work function ϕ of the surface cause electrons to be emitted. The electron kinetic energy would be $h\nu-\phi$. (b) Photoelectrons are collected by the anode and returned to the photocathode via an external circuit. The current measured by ammeter A is proportional to the number of incident photons that have sufficient energy to liberate photoelectrons.

Intrinsic semiconductors are materials that, even in very pure crystals, have relatively small band gaps. The most common intrinsic semiconductors are germanium and silicon, but other materials, including various alloys, are also available. Because of the low E_g, little energy is required to promote electrons from the valence to the conduction band in theses materials. When this occurs, a measurable change in the conductivity of the material results. Devices that operate on this principle, as illustrated in Fig. 9, are called photoconductive (PC) detectors. Band gaps in photoconductors are significantly smaller than the work functions of photoemitters, so the threshold photon energy is also much lower. The best available intrinsic semiconductors have an E_g of ~ 0.2 eV, which corresponds to a λ_c of about 7 μm.

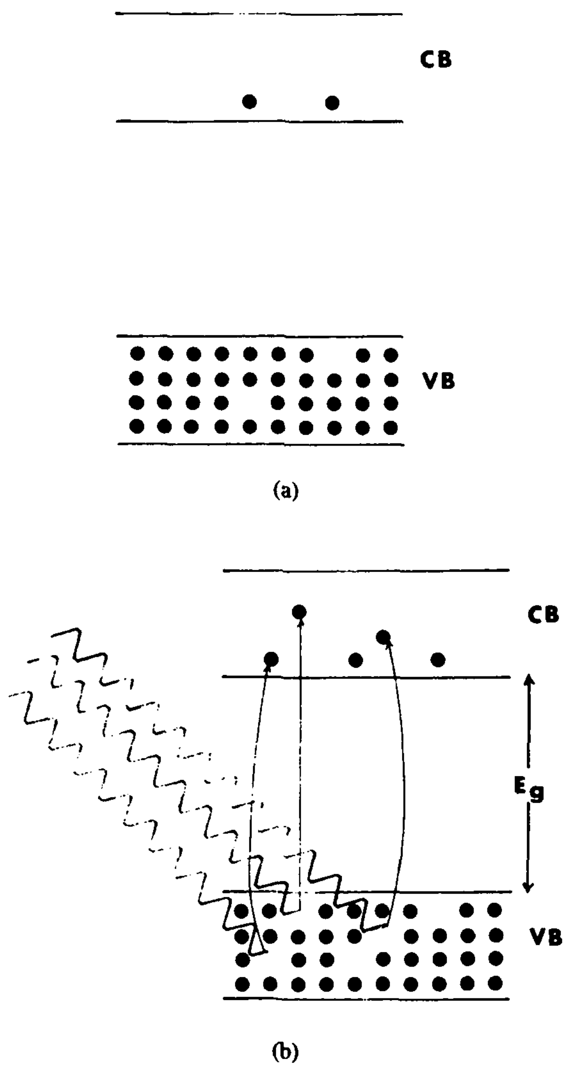


Fig. 9 — The photoconductive effect: CB = conduction band; VB = valence band. (a) In the absence of incident photons, the conductivity of an intrinsic semiconductor is small but nonzero. (b) Incident photons having energies greater than E_g excite additional electrons to the valence band, causing a measurable increase in conductivity.

When trace impurities are present in an intrinsic semiconductor, new energy levels (dopant levels) arise between the valence and conduction bands. These levels can be created and controlled by the process of doping, in which small quantities of selected impurities (dopants) are added to very pure semiconductor (host) material. The resulting doped crystal is called an extrinsic semiconductor.

Two different types of extrinsic semiconductors that have fundamentally different properties may be produced (Fig. 10). In n-type semiconductors, the dopant atoms have more valence electrons than the host atoms. The excess electrons cannot find partners with which to form bonds and end up in the dopant energy level. In this situation, the dopant level lies just below the conduction band and is referred to as the donor level because electrons are easily promoted (donated) to the conduction band. These donated electrons cause an increase in conductivity in the material.

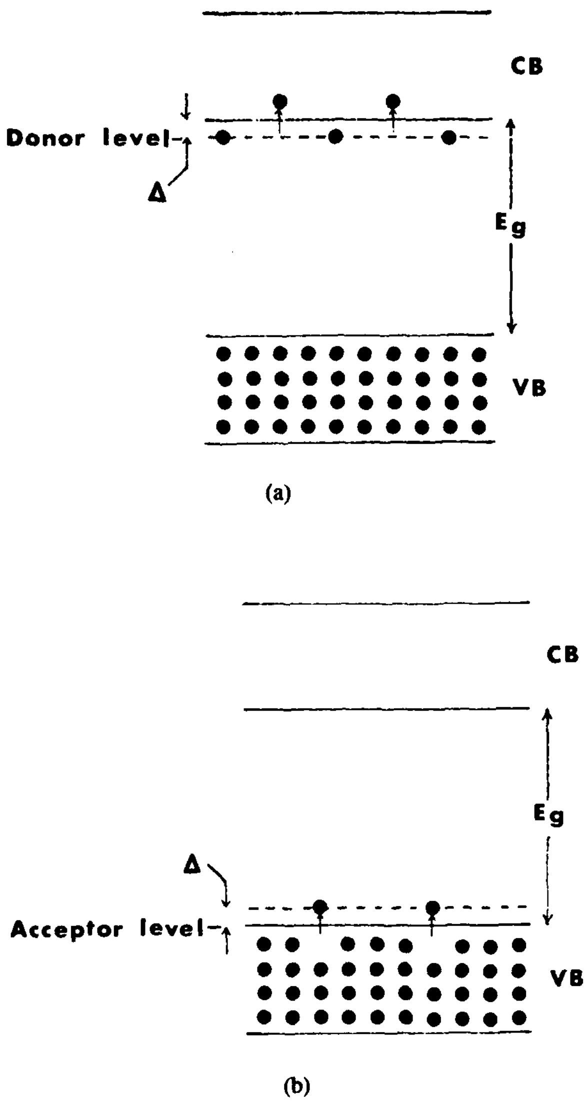


Fig. 10 — Extrinsic semiconductor band structure: CB = conduction band; VB = valence band. (a) N-type extrinsic semiconductor materials have occupied dopant levels slightly below the conduction band. Since Δ is smaller than E_g, less energy is required to excite donor level electrons than valence band electrons. Conductivity is primarily due to negative charges (electrons) in the conduction band, hence the designation n-type. (b) P-type extrinsic semiconductors have empty dopant levels, just above the valence band, which readily accept excited valence electrons. In these materials, positively charged *holes* in the valence band are the major contributors to conductivity.

P-type semiconductors result when the dopant has fewer valence electrons than the host. The dopant energy level lies just above the valence band in these materials and is initially vacant because of the deficiency of electrons. Since valence electrons are readily accepted into these vacancies, the dopant level is called the acceptor level. When the valence band electrons are excited into the acceptor level, *holes* that are left behind are free to move within the valence band. The hole conductivity within the valence band is analogous to electron conductivity within the conduction band.

P-type material is so named because its charge carriers (holes) are positive while the charge carriers (electrons) in n-type semiconductors are negative. In either type, the conductivity is greatly enhanced by photons with energies sufficient to excite electrons to or from the dopant level. Because the excitation energy (the difference between the valence band and the acceptor level or between the donor level and the conduction band) is much less than the band gap energy, it follows that the cutoff wavelengths in extrinsic PC detectors are much longer than those in intrinsic PC detectors. Also, by varying the amount and type of dopant, λ_c can be adjusted to meet special requirements. Cutoff wavelengths up to 140 μm have been obtained by using this approach.

When adjacent regions of p- and n-type material are created in a crystal, a nonequilibrium state exists due to the different concentrations of electrons and holes on opposite sides of the pn junction. Charge carriers diffuse across the junction and cause a buildup of positive charge on the n-type side and of negative charge on the p-type side. Eventually a new equilibrium is established in which the concentration gradient is counter-balanced by the electrostatic forces arising from the charge separation.

Consider what occurs when photons are absorbed within the junction region. Three possibilities occur: (1) a valence electron is excited to the acceptor level, (2) a donor electron is promoted to the conduction band, (3) a valence electron is raised to the conduction band.

The first can only occur on the p-side of the junction because there are no p-type impurities and therefore no acceptor levels on the n-side. Similarly, the second possibility can occur only on the n-side. In neither case will the mobile charge carriers cross the junction because the equilibrium electrostatic field tends to hold them in place. Consequently, neither case will produce changes in the voltage across the pn junction. However, in the third case a free hole and a free electron are produced. No matter where this pair production occurs, one of the charge carriers will be driven across the junction and cause a detectable voltage change. This detection mode is called photovoltaic (PV). Figure 11 illustrates principles of pn junctions and PV detectors.

Since PV detectors require pair production and that occurs only during transitions from the valence band to the conduction band, λ_c for these detectors is the same as for a PC detector made from the same intrinsic semiconductor material. PV detectors do have some advantages over PC detectors in sensitivity and ease of use.

The cutoff wavelengths for all of these detectors, except for extrinsic photoconductors, are in the low and middle IR regions. For this reason, it is likely that the quantum detectors that will be of most interest for fire fighter's vision enhancement will use extrinsic PC technology.

Temperature Control Requirements for IR Detectors

If we list IR detector materials according to their maximum operating temperatures (Table 2), we find that there are three broad clusters, (1) below 90 K (−297°F), (2) approximately 195 K (−108°F) and (3) near 300 K (81°F). The first question that arises is why there should be discrete temperature ranges instead of a continuum of operating temperatures. A second question is why so many of the detectors operate only at low temperatures and so few work at elevated temperatures.

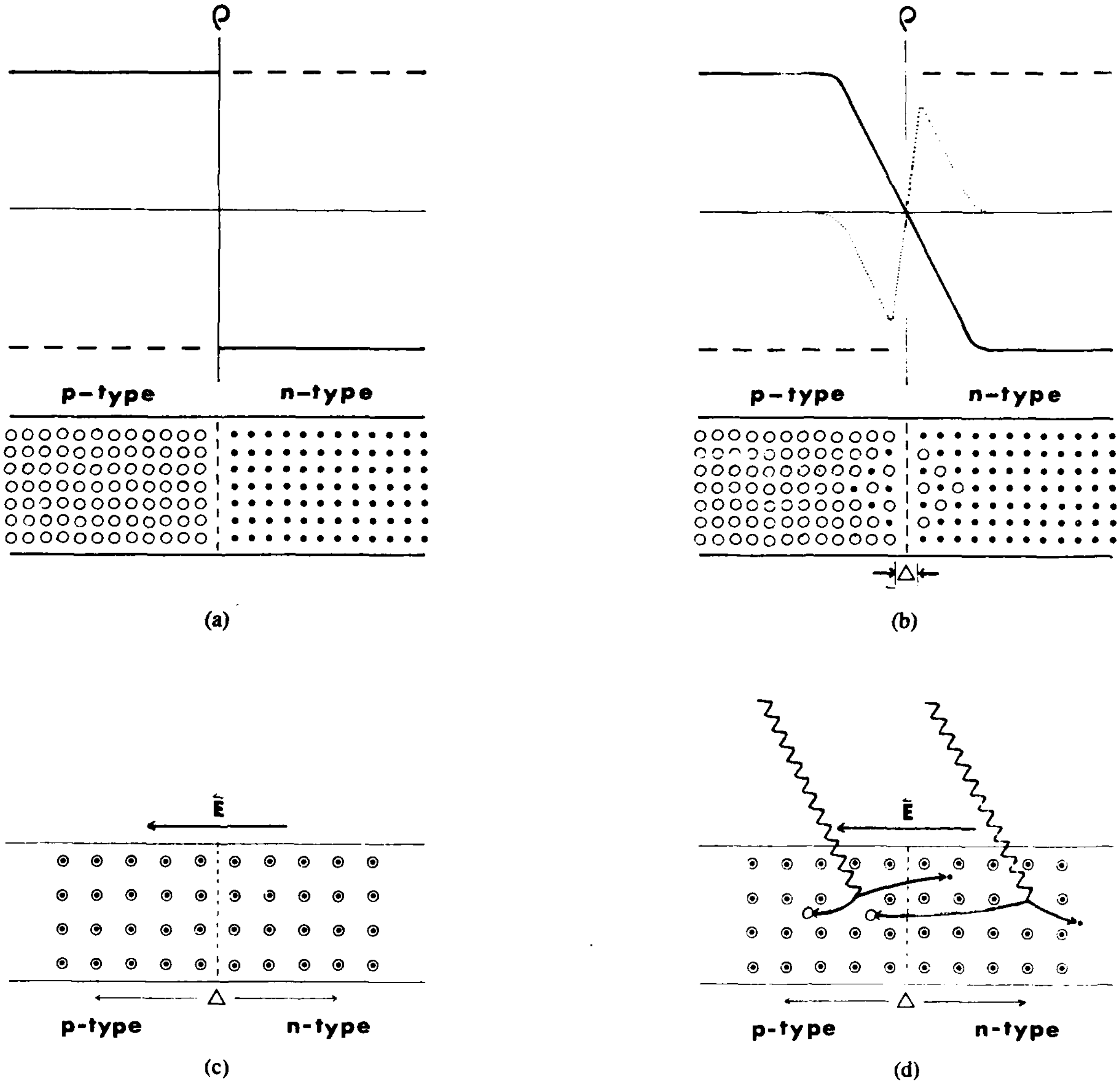


Fig. 11 — The p-n junction and the photovoltaic effect: ρ = charge density. (a) The upper graph shows that, in the absence of charge carrier diffusion, majority carrier (——) and lattice (- - -) charge densities are balanced in both p- and n-type materials. The no-diffusion case is illustrated in the lower diagram. (b) When charge carriers (o = hole, · = electron) diffuse across the junction, the carrier charge densities are perturbed but the lattice charge densities are unaffected. The resulting net charge (·······) creates an electric field in the junction region (Δ) which is equivalent to a voltage difference across the junction. (c) Because the dopant concentrations are extremely low, the junction region (Δ) contains mostly neutral atoms (represented as a hole plus an electron) of the matrix element. These atoms are influenced by the electric field arising from the nonzero net charge distribution. (d) Incident photons can create electron-hole pairs, which separate and migrate in opposite directions under the influence of the electrostatic field. This results in a reduction of the net charges on both sides of the junction, causing a change in the junction potential.

The temperature limitations of quantum detectors are largely due to thermal noise, caused by random temperature-induced electronic transitions within the detector. The Boltzmann distribution,

$$N_i / N_o = \exp(-\Delta E / kT) \tag{4}$$

gives the ratio of the number of particles in energy state i (N_i) to the number in the ground state N_0, where ΔE is the energy separation of the states, T is the absolute temperature, and k is Boltzmann's constant. This equation predicts that there always are some excited-state electrons at any temperature above absolute zero [0 K (−459°F)]. Further, it predicts that the number of excited electrons increases with an increasing temperature or with a decreasing energy difference between states. This energy difference, which corresponds to the work function (PE detectors), excitation energy (PC detectors), or band gap (PV detectors), must be small if the device is to function at long wavelengths. It follows that all IR quantum detectors have relatively large numbers of excited electrons unless the operating temperature is low. These *thermal* electrons appear as random noise which, at some temperature, mask the IR signal and render the detector ineffective. In some cases, because of the thermal noise, the electric currents can become large enough to destroy the detector.

Usually, thermal detectors do not show these temperature limitations and often can operate at much higher ambient temperatures. However, even these detector materials have some upper temperature limit, and some also have lower temperature limits. Typically, the limits are due to phase changes (the sensor melts, for example) or discontinuities in the measured property, e.g., loss of polarization in pyroelectric crystals.

As a practical matter, the required operating temperature is generally maintained by using a liquid nitrogen (LN_2) bath, a Joule-Thompson (J-T) cooler, or a thermoelectric (TE) refrigerator. The first method cools by evaporation of liquid nitrogen and the second by rapid (adiabatic) expansion of a highly compressed gas. Both methods are capable of maintaining very low temperatures so long as the supply of working fluid lasts, but both require replenishment of materials that are not readily available in the field. Typically, the LN_2 technique is used for large, vehicle-mounted FLIR (forward looking infrared) systems, while the J-T cooler is more adaptable to smaller devices (it is used in the Highes Probeye, for example).

A TE cooler requires no liquified or compressed gases since it transfers heat electrically. However, the efficiency is rather low, with power consumption approximately 100 times the energy transfer rate (i.e., a device that pumps 50 mW would require about 5 W.) This puts practical limits on the temperatures that can be maintained in low-powered portable units.

Imaging Methods

An imaging system accepts incident radiation from a two-dimensional scene and produces a corresponding two-dimensional image in the focal plane of the instrument. This optical image is then converted to an electrical equivalent, processed in some fashion, and finally reproduced on a display.

Figure 12 shows a block diagram of such a system. The size and shape of the detector and the configuration of individual detector elements are important considerations for imager design because they strongly influence the complexity of the system. Unless the imager includes an array of detector elements capable of processing the entire image at one time, a method must be provided for dissecting the scene into smaller subsets, each of which can be processed as a unit. This dissection process is called scanning.

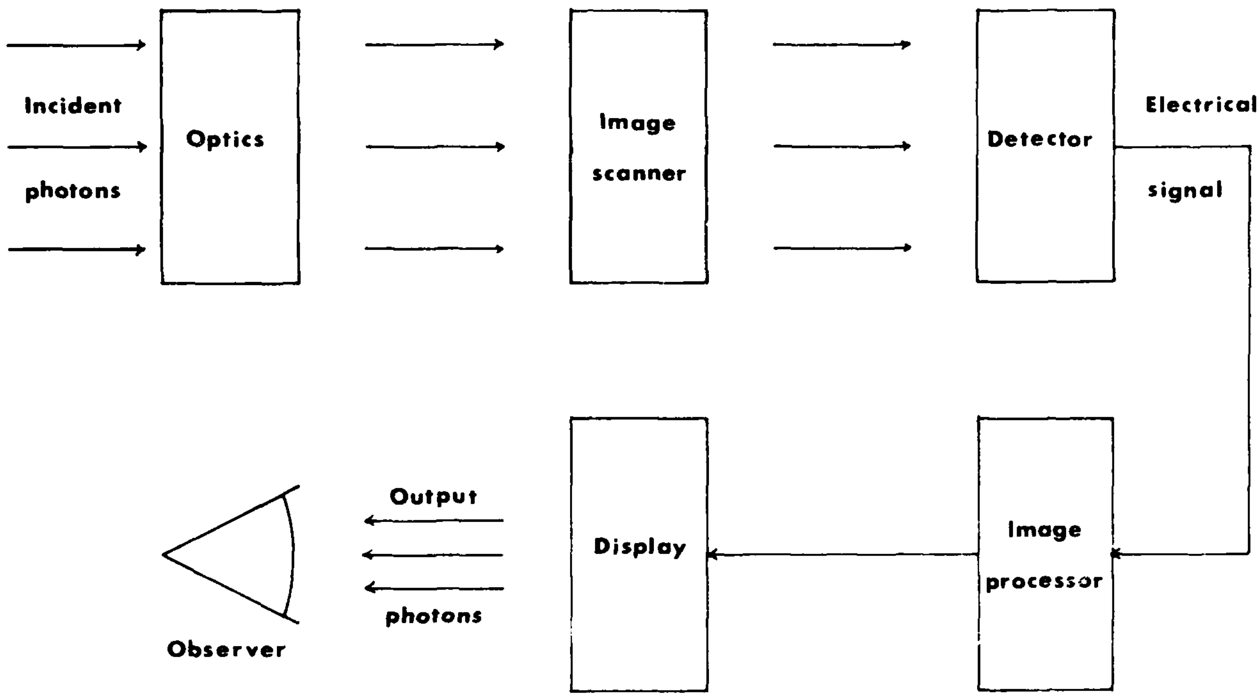


Fig. 12 — Block diagram of an imaging system. Key components of an imaging system are the optical elements (which collect, filter, and focus the incident light); the scanner (an integral part of the detector in some systems), the detector (which converts the optical image to an equivalent electrical signal); the signal processor (including amplification, noise filtering, and similar functions); and the display subsystem (typically a television-type device).

Imaging systems that incorporate multiple detector elements often use time-division multiplexing, which allows the same electronics to process and display signals from all elements. The alternative is to provide a dedicated processor and display element for each detector element. For those systems that use more than a handful of elements, the latter is prohibitively expensive and, because of the number of interconnecting wires, is not very reliable. In time-division multiplexing, the signals are processed sequentially rather than simultaneously. The multiplexer is essentially a switching network that, at any given instant, selects one signal and rejects the rest.

Scanning Imagers

Let us consider a simple point detector which we assume is located in the focal plane of the imager. This detector responds, at any instant, to radiation originating from a single, small element of the scene, which is referred to as a picture element or pixel. Conceptually, we may build up an electrical analog of the entire scene by recording the signal from one pixel, moving the detector by one detector width, recording the next pixel, and so on for the width of the image. The detector is then moved down by one detector height, and the process is repeated for a new line of pixels. Eventually, the detector will have seen all of the pixels and it will return to its starting position. The total time required to scan the scene is the frame time and the reciprocal of the frame time is the frame rate. If the frame rate is high enough, there is very little change in the scene during any single frame; therefore the image is not perceptibly blurred. A sequence of such frames gives the appearance of smooth motion within the scene, just as in a movie.

In reality, of course, the point detector is fixed and the image is scanned, usually with a system of rotating or vibrating mirrors, Two such mirrors, with properly synchronized motions about perpendicular axes, provide the required two-dimensional scanning, as shown in Fig. 13. This system is far from being ideal because of the complexity of the scanner and the relatively high probability of mechanical malfunctions.

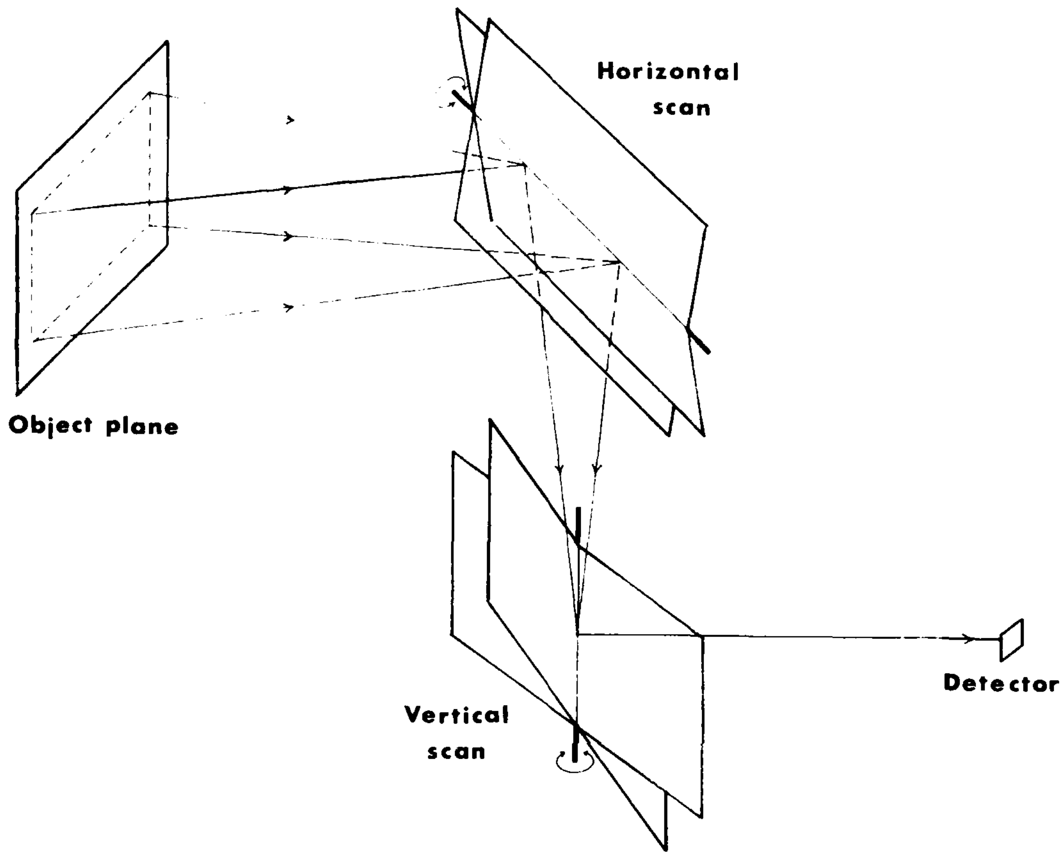


Fig. 13 — Conceptual diagram of a two-dimensional scanner. The basic two-dimensional scanner uses two mirrors, mounted on orthogonal axes, to map the image of the object plane onto a point detector.

The use of a linear array of elements permits the scanning system to be significantly simplified. Essentially, a linear array consists of many (up to several thousand) point detectors in a row. Usually they are made using integrated circuit technology on a single substrate chip. If the linear array is long enough to capture one entire row of image pixels simultaneously, then one-dimensional scanning in the direction perpendicular to the array axis is sufficient. This reduces the complexity of the mechanical scanner by more than one half because, in addition to one of the mirrors, the synchronization linkage between mirrors is eliminated. One variation, called pushbroom scanning, also eliminates the second mirror and uses the motion of the imager itself, which must be perpendicular to the axis of the array to provide the required scanning The pushbroom method is typically used on satellite or airborne reconnaissance systems.

When the length of the array is not long enough to allow simultaneous detection of an entire row of pixels, then another scanner variation may be used. In this system, flat mirrors (typically eight to ten) are mounted on the circumference of a wheel that rotates on an axis parallel to the axis of the detector array. As the wheel rotates, each mirror scans the image across the detector array. If each mirror is mounted at a slightly tilted angle with respect to the next mirror, then each projects a different field (band of pixels) onto the detector array. After one complete rotation of the wheel, all of the fields will have merged into a single frame. Figure 14 illustrates a scanning system of this type.

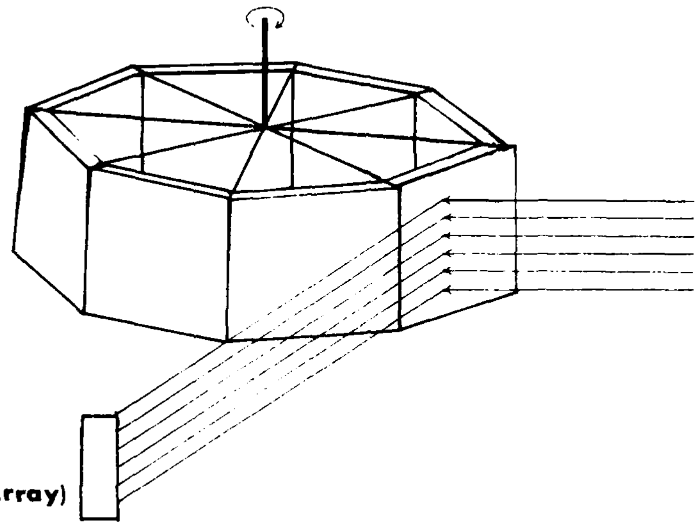


Fig. 14 — The one-dimensional mirror wheel scanner. Each mirror, mounted at a slight tilt angle with respect to the next mirror, reflects the image of a different slice of the object plane onto the linear detector array. Rotation of the wheel causes each slice to be scanned horizontally. The illustrated system, with eight mirror faces and six detectors, would dissect the image into 48 scan lines.

Staring Imagers

If the detection element is a rectangular array of point detectors, then a staring, rather than a scanning, system may be designed. The two-dimensional detector arrays used in these imagers are called staring arrays or focal-plane arrays (FPAs). From the standpoint of mechanical complexity and reliability, staring imagers are preferable to any of the previously discussed designs, except possibly for the pushbroom scanner.

Quantum detectors appear to be especially well suited for use in FPAs because microelectronic manufacturing techniques make the production of large arrays relatively easy and because the detector output signals are inherently electrical in nature. Multiplexing of the signals is usually required to reduce the number of output connections to a manageable level. Because the multiplexers generate switching noise, it is usually necessary to provide a preamplifier for each detector element to ensure that the signal is larger than the multiplexer noise.

Preamplifiers and multiplexers are easy to build in integrated circuit (IC) form. However, it is very difficult to combine the detectors with the preamplifier/multiplexer chip; therefore, a considerable effort has been devoted to trying to solve the engineering problems involved. Some detector materials can be processed with silicon IC technology, so it becomes possible to build the detector array directly onto the IC substrate. For other detector materials, a hybrid circuit approach is feasible. With this method, the detector array and the preamplifier/multiplexer IC are produced separately and mated by directly bonding the output of each detector element to the corresponding preamplifier input. Typically this is done by the indium bump method in which a small dot of indium is deposited on each input pad on the IC substitute and then the detector array is pressed onto the indium. This method is not highly reliable, mainly because of the lack of mechanical strength of the bonds and because of the different thermal expansion coefficients of the two materials. The general problem of producing rugged and reliable connections between detector arrays and IC substrates is an area of active research.

In part due to the limitations of interconnect technology, large IR detector arrays are difficult to build and expensive to produce. Many also have critical deficiencies in cutoff wavelengths, operating temperatures, or other parameters. Therefore, such detector arrays are not always feasible or affordable for a particular appplication.

Pyroelectric Vidicon Imagers

An additional problem with most imaging systems that use thermal detector arrays is that conversion of the thermal pattern into an electrical signal is required. Pyroelectric materials have an advantage in this respect because the thermal pattern is intrinsically represented as a surfae charge pattern. This is easily converted to an electrical output by charge-sensitive circuits that may be built in IC form. However, most pyroelectric materials are generally not well suited to IC processing techniques, which means that monolithic pyroelectric imagers have not proven to be very practical. It is possible to directly bond the pyroelectric elements to arrays of charge-sensitive electronic circuits by using the indium bump method. The results have not been notably successful because of the reasons already given. To circumvent these problems, most commercial pyroelectric imagers have been based on vacuum tube techniques similar to those used in vidicon television camera tubes. Because of the similarity, this type of imaging detector is known as a pyroelectric vidicon (PEV).

The PEV imager combines the signal conversion and multiplexing into a single step by using a scanning electron beam to read the charge pattern. A PEV tube contains a thin wafer of pyroelectric material, the *retina*, placed immediately behind an IR-transparent window at one end of the vacuum tube. An electron gun, located at the opposite end of the tube, produces the electron beam. Various grids, deflection plates (or coils) and electron lenses, built into (or surrounding) the tube, control the beam and cause it to raster scan the rear surface of the retina. The electron beam acts as one electrical contact to the detector element. The second contact (the signal electrode) is generally a thin, semitransparent, conductive layer deposited on the front surface of the retina.

The instantaneous electron beam current is proportional to the potential difference between the electron gun cathode and the beam terminus on the retina, almost as if there were an actual wire between these points. The gun potential is fixed, but the retina potential varies according to the sign and magnitude of the surface charge. This results in a thermally induced potential difference that modulates the beam current and produces a signal.

Previously, it was noted that pyroelectric crystals are dielectrics and that the surface charges are bound, i.e., cannot leave the surface. These properties are the cause of two effects which have important consequences in the design and operation of PEV imagers.

First, the pyroelectric retina acts like a capacitor since it consists of two oppositely charged planes (the surface charge layers) separated by a dielectric material. At steady state (i.e., constant temperature) this capacitor retains a fixed charge; no current flows through the capacitor and no signal is detected. When the temperature changes (because of a change in image intensity) the effective capacitance changes and a current pulse flows through the capacitor and is detected. The result is that pyroelectric imagers are sensitive only to intensity changes $\delta I/\delta t$ rather than to absolute intensity I. Because of this, PEVs can only see objects if they are moving with respect to the camera or if the radiation intensity is changing. In practice, many PEV-based systems allow a choice of two operating modes to overcome this problem. The first, often referred to as pan mode, requires that the camera be in continuous motion (panning). The second, chop mode, uses a rotating disk within the camera that alternately covers and exposes the PEV. This modulates the intensity, so that a changing signal is always presented to the PEV tube, and allows one to use fixed camera positions. For a typical 50% duty cycle chopper, the PEV tube is exposed only half the time, so the scene must be twice as to produce the same signal obtained in the pan mode. Consequently, the chop mode typically has only half the sensitivity of the pan mode.

Second, because the surface charges are bound to the surface, they cannot flow through an external circuit nor can external charges actually flow through the insulating retina. Instead, as the surface charge increases (becomes more positive) because of a temperature change, it is neutralized by electrons deposited on the surface from the beam. The deposited electrons are trapped on the surface. Ultimately, this would result in a negatively charged surface that would accept no further electrons from the beam. The detector would then stop functioning.

To avoid this problem, a positive charge is periodically deposited on the retina to neutralize the negative charge laid down by the electron beam. The positive current, called the pedestal current, required to do this is adjusted so that the total direct current (dc) integrated over the frame time is zero. Using this technique, the image signal appears as an ac component superimposed on an approximately dc pedestal. The pedestal is removed during signal processing. Figure 15 illustrates this process.

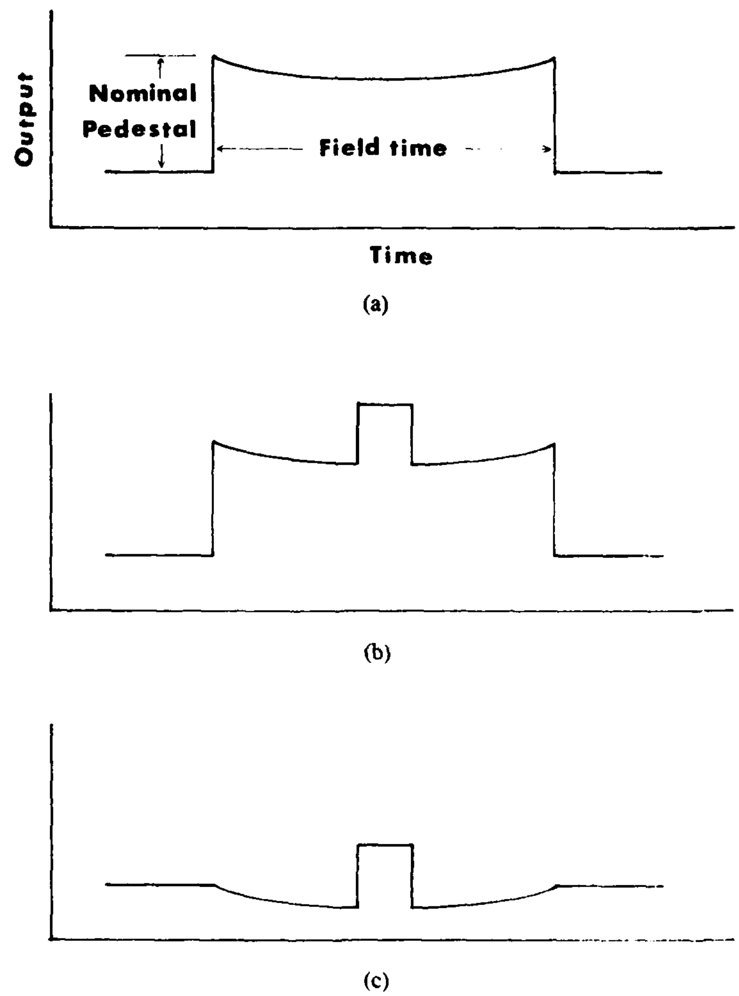


Fig. 15 — Pyroelectric vidicon pedestal and output signal. One field of the PEV output is shown for the cases of pedestal only (a) and pedestal plus signal (b). In (c), the output is shown after subtracting out the nominal pedestal current. The changing baseline is due to the variability of the actual pedestal current.

Most PEV imagers use either the ion current or the secondary emission method of generating the pedestal. The ion current technique requires a special PEV tube containing a low-pressure gas (usually an inert gas). This is often referred to as a *soft* vacuum. In operation, some of the gas is ionized by the electron beam, thus producing a positive ion current. The ion current generated in each volume element is approximately proportional to the electron beam current passing through that element and to the gas pressure. All electrons pass through the axial regions of the tube, but only a fraction of the electrons traverse the regions far off-axis. As a result, much higher ion currents are produced near the axis. To make the ion current more uniform across the retina, the grid voltages are adjusted so that only ions originating in a small volume near the retina are attracted to the surface, while ions from all other regions are deflected by the grids. In the absence of an optical signal, the surface potential on the retina reaches an equilibrium value at which the ion current and the beam current are of equal magnitudes. The presence of an optical signal then causes the electron beam current to fluctuate about this equilibrium value.

The secondary emission method does not require any gas in the tube, and PEV tubes designed to be used in this mode contain a *hard* vacuum. Secondary electrons are those ejected from a surface due to the impact of a primary electron. The ratio of secondary to primary electrons depends on the energy of the primary. At sufficiently high energies (typically 70 eV for TGS retinas), the ratio is about 1.6:1, so that bombarding the surface with electrons results in a net loss of electrons from the surface. In secondary emission tubes, low-energy electrons read the charge pattern during the left- to right-hand scan but, during flyback (the period when the beam is returned to the left end of the next scan line), high-energy, primary electrons drive secondary electrons off the retina. The secondary emission ratio is not very sensitive to small changes in beam energy, so the net positive current during flyback is nearly constant. The electron beam current, in the absence of an optical input, is again in equilibrium with the pedestal. As in the ion pedestal case, an optical input causes electron current fluctuations which are detected as an output signal.

In the chopped mode, the image heats the target during the open half cycle, and the target cools during the closed phase. This results in a 180° phase shift in the signal (reversal of positive and negative ac components) (Fig. 16(a)). By inverting the signal during one half cycle, the signal polarity is made constant for the entire chopper cycle. However, this also inverts the residual ac component of the pedestal, causing the peak amplitude of the signal to flicker at the chopper frequency (Fig. 16(b)). Figure 16(c) shows how a field subtraction technique is used to minimize this problem.

A problem that occurs in both operating modes is a *tailing* effect; this is especially noticeable when a hot (relative to the scene background) object moves across the field. The high-intensity object causes localized heating of the detector which is displayed as a bright spot.* As the object's image moves across the detector, it leaves behing a region of heated retina which slowly cools. Since the detector output signal during the cooling period is of opposite polarity to that occuring during the warming period, this region appears as a black trail behind the bright spot.

Flicker and tailing may be reduced with appropriate signal processing. Several techniques, analog and digital, have been used to accomplish this. Many of these methods use subtraction of consecutive fields or frames to cancel constant signals caused by retina defects, pedestal inhomogeneity, and similar artifacts.

Another difficulty that can occur in any planar thermal detector is blooming. This occurs because of energy transmission parallel to the plane of the retina. If a large quantity of energy is

*This assumes that a warm object is displayed as a bright image and a cool object as a dark image (the white = hot convention). Some systems provide a switch to select the inverse display (the black = hot convention).

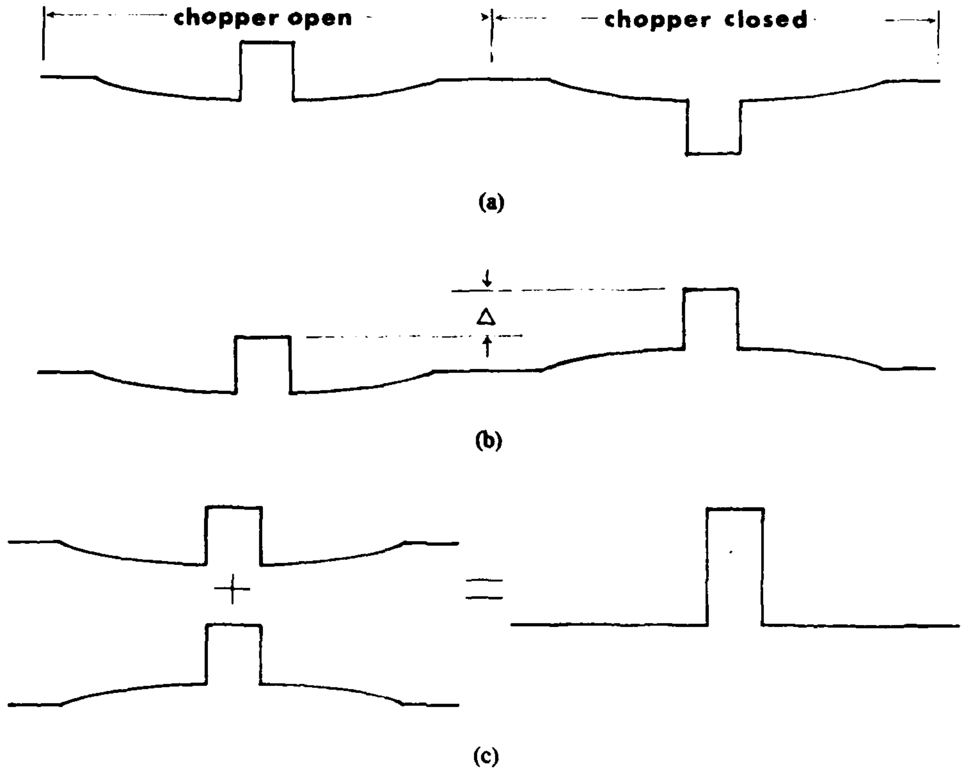


Fig. 16 — Image processing and flicker. Consecutive fields (chopper open and chopper closed) produce signals of opposite polarity (a). In the simplest form of image processing, the positive-field image is displayed without change whereas the negative-field signal is inverted prior to display (b). This results in a field-to-field amplitude variation Δ that appears as image flicker at the field frequency. A more sophisticated form of image processing subtracts the second field from the first (equivalent to addition of the inverse of the second field, shown in (c)) and displays the sum. This results in better cancellation of repetitive signals, such as the pedestal.

deposited on a small region of the detector (due to a small, intense radiation source), some of this energy spreads transversely, thus causing a region surrounding the image point to be stimulated.

Blooming may be reduced by using a reticulated target. This type of target is etched or scribed in a grid pattern to reduce transverse thermal conductance. Blooming is not eliminated, but it may be restricted to the area of the affected grid.

Imaging System Performance Measurements

A variety of parameters characterize thermal imaging system performance. Two of the more common benchmarks are minimum resolvable temperature and spatial resolution. Each of these may be accurately measured in the laboratory, but the connection between laboratory measurements and real-world performance requirements is not always evident. For example, the minimum resolvable temperature may be carefully determined by using standard, parallel bar patterns; however, this doesn't mean much to the user who needs to know whether ladder rungs will be visible during a fire.

Regardless of the laboratory tests results, the user ultimately determines the utility of a system. Accordingly, NRL's approach has been to evaluate devices in operational scenarios to the maximum practical extent. However, to better understand the systems' design trade-offs, it is important that some of the formal performance criteria be considered here. The discussion that follows is not intended to be an in-depth analysis. More details may be found in Refs. 4 and 5.

Minimum resolvable temperature (MRT) is the smallest scene temperature difference that will produce an observable pattern on the system display. Note that the MRT is a test of the entire system rather than of the detector alone, and, by definition, it is subjective since an observer must determine when the pattern becomes visible. The MRT is not a single value, since it is a function of the size of the test pattern.

The scene used for MRT tests is a standard pattern consisting of alternating hot and cold rectangular bars (each having a 7:1 aspect ratio). The temperature difference ΔT between the hot and cold bars is adjusted until the bar pattern is barely visible on the display. Multiple tests are conducted by using the same test pattern but with different observers to reduce the effects of observer subjectivity, and the average value of ΔT is reported. The process is repeated for patterns of different sizes, and the results are plotted on a graph of ΔT vs target size to produce the MRT curve.

Because the target is a repetitive pattern, it can be characterized by a spatial frequency that is analogous to the familiar concept of time frequency. The usual units of spatial frequency are cycles per milliradian (c/mrad), line pairs per millimeter (lp/mm), or, in television-like systems, TV lines per picture height (TVL/PH). Just as the inverse of frequency (period) is a unit of time, the inverse of spatial frequency is a unit of size. A cycle, which is the smallest repetitive unit of the pattern, is one pair of hot and cold bars (a line pair). A television line is the smallest displayable element of a television picture, one scan line, and is equivalent to half of a cycle.

Units of c/mrad are independent of the system under test and are determined by the geometry of the target relative to the imager. The size of the target image projected onto the focal plane of the imager determines the units of lp/mm. This calculation requires a knowledge of the focal length of the instrument as well as of the geometry of the test. To convert to TVL/PH, additional information is needed regarding the resolution of the detector and of the display.

It may be inferred, from the discussion above, that the term *spatial resolution* is somewhat ambiguous unless the nature of, and the temperature differential in, the target scene are specified. In practice, this ambiguity is avoided by using the term to mean the maximum achievable spatial resolution. For the purpose of this discussion, it is assumed that the limiting factor is the detector resolution.

For quantum detectors, the resolution limit is typically determined by the dimensions of a single detection element. Thermal detectors do not necessarily have discrete detection elements; therefore, the resolution limit may be set by the scanning system. For example, in a pyroelectric vidicon the vertical resolution depends on the spacing between successive raster scan lines, whereas the horizontal resolution may be undefined. When digital-image processing is used, the horizontal resolution can be taken to be the horizontal distance traversed by the scan beam during the sampling time of the analog to digital converter.

In any case, even when the detector resolution is well defined, the system resolution depends on the optical system. This is easy to understand if the optics are considered to perform a mapping transformation from object space (the scene) to image space (the image projected onto the focal plane). The detector characteristics determine the size of the resolution element in the image plane, as discussed above, but the size of the corresponding element in the object plane depends on the optics and on the distance to the object. The latter parameter is normally removed by specifying resolution in angular units (mrad) which may be derived from a knowledge of the detector's parameters and of the focal length of the optics. In essence, this is the inverse of the previously considered problem of converting c/mrad to lp/mm.

Note that if the optical elements are changed so as to increase field of view (FOV), then the angular resolution of the system will be reduced unless the detector system is also changed to compensate. This is a particularly important consideration for FPA-based systems because it is often extremely difficult to enlarge an FPA at an acceptable cost. Thus, it may be impractical to scaleup a narrow FOV system to provide a wide FOV.

PART II—DEMONSTRATION AND VALIDATION

SURVEY OF SELECTED THERMAL IMAGERS

In this section of the report, we discuss the design, operating characteristics, and capabilities of several commercial thermal imaging systems. This survey is not intended to be all inclusive, but rather to provide descriptive information about those imagers that have been evaluated as part of this program.

The design of any imaging system requires that trade-offs be made between conflicting goals. Choices must be made regarding such factors as ease of operation vs capability, size and weight vs power and operating time, wavelength and temperature resolution vs cost and complexity, and spatial resolution vs FOV. Which characteristics are emphasized and which are not depends, of course, on the intended market for the device. In the following discussion we point out the reasons behind some of the design decisions and how those choices might affect the use of the devices for fire fighting.

Hughes Probeye

As previously mentioned, the Probeye system, built by the Industrial Products Division of Hughes Aircraft Company, was one of the earlier thermal imagers investigated. At the time of Alger and Gordon's original work, only one version, now known as the Model 650, had been developed. During the period covered by this report, three additional models (664, 686, and 699) were produced. All four of these devices incorporate the same imaging technology. They differ in the method used for cooling the detector (some use thermoelectric while others use Joule-Thompson coolers) and in the special features offered (some models provide a readout of the temperature at the center of the field of view). Most of the following remarks about the Model 650 also pertain to the other versions.

The Model 650 was designed for industrial applications, such as temperature surveys to detect defective insulation and to locate overheated electrical equipment. The basic requirements for these tasks dictated a rugged design, narrow field of view, good temperature resolution, and operator adjustability to permit optimization of the image under a variety of conditions. Although the Hughes literature [8] mentions the location of people in smoke-filled rooms as a possible use for Probeye, the ability to penetrate smoke does not appear to have been a high priority at the time the Model 650 was designed.

The resulting imager (Fig. 3) is housed in an irregularly shaped metal case; with height, width, and length of approximately 15 × 23 × 25 cm (6 × 9 × 10 in.) and a weight of 3.5 kg (7.5 lb). These measurements include a compressed gas cylinder attached to the bottom of the housing which is required by the Joule-Thompson cooler. An internal, rechargeable battery is also included. Operating time with fully charged battery and gas cylinder is about 4h. Table 3 gives the imager's full specifications.

The optics provide an 18° horizontal × 7.5° vertical field of view that permits inspection of operating industrial facilities from safe distances. The monochrome (red on black) display is visible

Table 3 — Specifications for the Hughes Model 650 Probeye Thermal Imager

Size (H × W × L)	15 × 23 × 25 cm (6 × 9 × 10 in.)
Weight	3.4 kg (7.5 lb)
Operating Time	4 h
Power Requirements	1.5 W
Detector	6 × 1 element, InSb PV array (Joule-Thompson cooling)
Wavelength	2 to 5.6 μm
Optics	f/1.5
Field-of-View	7.5° V × 18° H
Focusing Distance	0.22 m (8 in.) to infinity (adjustable focus)
Controls	ON/OFF, brightness, contrast, focus
Display	Red LEDs (6/field × 10 fields/frame)
Sensitivity	0.1°C at 2.2 mrad
Operating Modes	Not applicable
Iris	None
Environmental	Water resistant case
Video Output	No

through a monocular eyepiece. The focus, the display brightness, and the display contrast are manually adjustable for best viewing under a wide range of conditions.

The detector is a 6 × 1 array of indium antimonide elements operating in the photovoltaic mode. As indicated in Table 2, these detectors operate at 77 K (−196°C) and have a cutoff wavelength of 5.6 μm. The required refrigeration is provided by a Joule-Thompson cooler that uses argon as the working fluid; hence the need for the high-pressure gas cylinder. Under these conditions, a temperature resolution of 0.1°C (0.2°F) is claimed.

Scanning is accomplished by using the rotating mirror wheel method shown in Fig. 14. In the Probeye there are 10 mirrors, so the scene is dissected into 10 bands and each band is subdivided by the six detector elements, thus producing a total of 60 scan lines.

The display system uses six red LEDs (light emitting diodes), each directly connected to a different detector element, so that the brightness of each LED is proportional to the instantaneous IR intensity at the corresponding element. The ingenious display uses the back faces of the ten mirrors to provide display scanning that is inherently synchronized with the detector scanning. The result is a sixty-line raster image without the need for a CRT tube or for the associated electronics. The direct connection between each detector element and the corresponding LED eliminates the need for signal multiplexing. The use of a single set of mirrors for both detector and display scanning further reduces the complexity of the system.

English Electric Valve (EEV) P4228/P4428

The British Home Office commissioned English Electric Valve (EEV), Ltd to build an IR imaging device specifically to be used by fire fighters. The early history of this program, including the initial test results and a statement of the system requirements, was summarized by Lindfield and Wells [9]. These requirements are considerably different than the requirements of most industrial applications, and the design of the EEV Model P4228 reflects these differences. For fire fighting applications, two of the more important factors are the ability to produce good imagery through heavy smoke and the ability to provide acceptable, but not necessarily optimal, images under a wide range of conditions without the necessity of manual adjustment. Other important considerations include light weight, a wide field of view, and resistance to high temperatures. Note that the latter does not imply that the temperature resolution must be exceptionally good. In fact, because of the large temperature differences expected, the minimum acceptable temperature resolution may be on the order of 1°C (2°F).

The P4228 imager (Fig. 4) is packaged in a hermetically sealed, polycarbonate cylinder approximately 24 cm in diameter × 26 cm long (9.5 × 10 in.). The total weight, including batteries, is about 4 kg (9 lb). Table 4 gives more complete specifications.

The operating lifetime of the imager at normal room temperature is 1 to 2 h, depending on whether standard or high-capacity (alkaline) batteries are used. At elevated temperatures, the operating duration may be determined by the time required for the electronics to overheat rather than by the battery life. The relatively large volume of the imager and the low thermal conductivity of the case were designed to provide good insulation. Additional thermal protection and protection against bumps is provided by an insulating blanket surrounding the plastic shell. This insulation system was intended to allow 1h of operation under normal fire fighting conditions (60°C with a 10 min excursion to 80°C).

The EEV P8092 PEV tube was selected as the detector for this application. It has a deuterated TGS retina and a germanium faceplate that was optimized to pass 8 to 14 μm radiation. This wavelength band provides better smoke penetration performance than could be obtained with shorter wavelengths. The use of deuterated TGS provides a slight increase in the Curie temperature relative to normal (protonated) TGS. The P8092 is a soft vacuum tube in which the pedestal current is provided by ion bombardment of the retina.

The P4228 imager is a staring system, so image scanning is not required. However, as is usual for PEVs, a chopper is required in order to obtain images of stationary objects. The chopper, an opaque, motor-driven disc with a spiral cutout, can be turned off when it is desirable to operate in the pan mode.

An automatic iris, controlled by a feedback signal from the PEV output, adjusts the input intensity to minimize saturation of the PEV tube without operator intervention. Similarly, the wide angle lens (FOV ~55°) has a depth of field from approximately 1 m to infinity, so focusing is not required. In fact, the only controls provided are the power and mode selector switches, neither of which need be touched during routine use.

The display is a built-in, miniature, monochrome (white on black) CRT that is electronically synchronized with the PEV tube. Alternatively, the video signal is available through a BNC connector and may be displayed or recorded on standard monitors and VCRs. In the chop mode, alternate

Table 4 — Specifications of the English Electric Valve
Models P4228 and P4428 Thermal Imagers

	P4228	P4428
Size (dia. × L)	24 × 25.9 cm (9.5 × 10.2 in.)	*Imager*: 16.5 × 26.5 cm (6.5 × 10.5 in.) *Power unit (H × W × L)*: 12.0 × 7.0 × 19.5 cm (4.75 × 2.75 × 7.75 in.)
Weight	4.0 kg (8.8 lb)	*Imager*: 3.2 kg (7.0 lb) *Power unit*: 1.0 kg (2.2 lb)
Operating Time (w/ 10 AA Duracells)	~1 hr	~1 hr
Power Requirements	0.5 A at 10-15 vdc (5 W max.)	0.3 A at 10-15 vdc (4 W)
Detector	PEV w/TGS retina (uncooled)	PEV w/TGS retina (uncooled)
Wavelength	8 to 14 μm	8 to 14 μm
Optics	18 mm, f/0.75 Ge lens	18 mm, f/0.75 Ge lens
Field-of-View	~55° (circular)	~55° (circular)
Focusing Distance	~1 m (39.3in) to infinity (fixed focus)	~1 m (39.3 in) to infinity (fixed focus)
Controls	ON/OFF, pan/chop	ON/OFF, pan/chop
Display	2.5 cm (1 in.) B & W CRT w/magnification	2.5 cm (1 in.) B & W CRT w/magnification
Sensitivity	1°C at 200 TV lines	1° C at 200 TV lines
Operating Modes	Pan/Chop	Pan/Chop
Iris	Automatic	Automatic
Environmental	Waterproof case (hermetic seal)	Waterproof case, (hermetic seal)
Video Output	Yes	Yes

fields are inverted before being displayed, so that the output polarity remains constant (hot objects are always white). Since the pedestal is not totally cancelled by this process, some residual image modulation (flicker) remains.

The Model P4428 replaced the P4228 in 1984. Figure 17 shows the new model, and Table 4 gives its specifications. From the operational standpoint, the most significant change that occurred was the packaging of the system in two modules, imager and power supply, instead of all in one unit. By removing the batteries and some of the power supply electronics, the weight of the imager module was reduced by about 1 kg (2.2 lb), even though the total weight of the system was almost unchanged. Equally important was the removal of the voltage regulator (which is a significant heat source), allowing the imager's diameter to be reduced from 24 to 16.5 cm (9.5 to 6.5 in.) without affecting the imager's thermal protection. The power supply module was attached to a harness, permitting it to be suspended from the neck rather than carried by the hand. Reducing the size and weight of the handcarried imager module made it feasible to operate the system with only one hand. A pistol grip was attached to the P4428 for this purpose. The other major change was an improvement of the image processing electronics that removed most of the chop-mode flicker through a digital subtraction process. The result was a significant improvement in image quality as compared to the Model P4228.

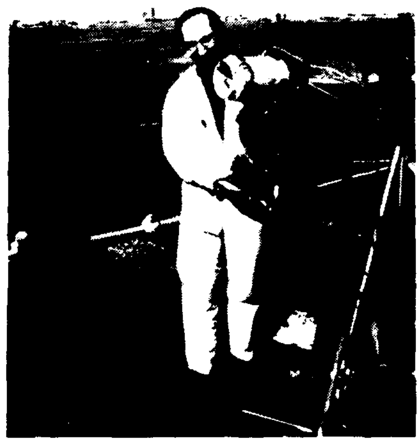


Fig. 17 — The EEV P4428 thermal imager, which replaced the Model P4228 in 1984, is shown here during testing aboard the USCG test ship *A. E. Watts*.

Xedar XS-410

The Xedar Corporation produces PEV imagers that are technologically similar to the two EEV models discussed above. However, because the XS-410 was designed for the technical and industrial market, the configuration of the system is very different from that of the EEV versions. As in the case of the Hughes Probeye, to satisfy the desire for high quality imagery it is necessary to have many operator-adjustable controls.

Figure 18 shows the XS-410, and Table 5 gives its specifications. The imager is about 25 cm L × 11 cm W × 16 cm H (10 × 4 × 6 in.) and weights slightly over 3 kg (7 lb). The rechargeable battery, supplied in a pack that may be worn on a belt, normally lasts about 2.5 h.

Table 5 — Specifications for the Xedar Model XS-410 Thermal Imager

Size (H × W × L)	Imager: 15 × 10.7 × 25.4 cm (6.3 × 4.2 × 10 in.) Battery: Not specified
Weight	Imager: 3.1 kg (6.9 lb) Battery: Not specified
Operating Time	2.5 h (w/ NiCd battery pack)
Power Requirements	1.2 amp at 12 vdc (15 W max)
Detector	PEV w/TGS retina (uncooled)
Wavelength	8 to 14 μm
Optics	33 mm, f/0.7 Ge lens
Field-of-View	27° (circular)
Focusing Distance	0.15 m (6 in.) to infinity (adjustable focus)
Controls	ON/OFF, brightness, contrast, focus, iris, poling
Display	7.6 cm (3 in.) B & W CRT
Sensitivity	0.2°C at 60 TV lines
Operating Modes	Pan only
Iris	Manual (necessary for scenes > 100°C)
Environmental	Not water resistant
Video Output	Yes

Fig. 18 — The Xedar XS-410 thermal imager during an evaluation at NRL's Chesapeake Bay Detachment. Because this model was not waterproof, it was wrapped in plastic for protection during the test.

Since the imager was intended for use in a normal office or factory environment, no special provisions had been made for protection against heat, shock, water, smoke or other hazards that might be expected in the fire-fighting environment. Controls for focus, display brightness and display contrast were provided, and a manually-adjustable iris is available as an option for viewing objects hotter than 100°C. A poling switch allows the user to repolarize the PEV retina if the Curie temperature is exceeded. No mode selector (pan/chop) switch is provided because the XS-410 has no chopper. As a consequence, this device must be panned continually to obtain images of stationary objects. The standard lens provides a 27° (circular) field of view that is displayed on a built-in monochrome (white on black) CRT. A video output allows the use of external monitors and video recorders.

The detector is a PEV with TGS retina and germanium faceplate designed to operate in the 8 to 14 μm band. Unlike the EEV tubes, those used by Xedar are hard vacuum (secondary emission pedestal) tubes with electrostatic focus and deflection. The electrostatic method permits smaller, lighter designs since deflection and focus coils are eliminated.

Agema Thermovision 110 (AN/PAS-7)

The Thermovision 110, marketed by AGEMA (originally AGA), is a commercial version of the military Handheld Thermal Viewer that was originally designed and built by Magnavox for the U.S. Army. That device, designated as the AN/PAS-7, was the first passive thermal imager to be fielded by the United States military. The requirement called for a handheld, battlefield surveillance device to detect personnel and vehicles at long ranges in darkness and through fog, haze, and battlefield smoke. It was also intended to detect camouflaged people and objects.

Note that battlefield smoke, mentioned above, is quite different from the smoke produced by fires, especially fuel fires. In general, battlefield smokes are not very dense and provide significant obscuration only over very long distances. Also, the particle size distributions and other physical properties are different from those of smoke produced by fires. As a result, performance on the battlefield is not a good measure of performance in a fire situation.

The Thermovision 110 is identical to the AN/PAS-7 in most respects. The two major functional differences are that the optical window material is plastic rather than silicon and the minimum focus

Table 6 — Specifications for the AGEMA Thermovision 110 Thermal Imager

Size (H × W × L)	Imager: 14 × 24 × 8.4 cm (5.5 × 9.5 × 3.3 in.) Battery: 3.8 × 17.2 × 6.8 cm (1.5 × 6.8 × 2.7 in.)
Weight	Imager: 2.7 kg (6.0 lb) Battery: 0.9 kg (2.0 lb)
Operating Time	2 h (w/ NiCd battery)
Power Requirements	1.6 A at 6 vdc[a] (10 W)
Detector	48 × 1 element PbSe array (thermoelectric cooling)
Wavelength	3 to 5 μm
Optics	f/1[a]
Field-of-View	6° V × 12° H
Focusing Distance	~1 m (39.3 in.) to infinity (adjustable focus)
Controls	ON/OFF, brightness, contrast, focus
Display	2.5 cm (1 in.) black & green CRT
Sensitivity	0.1°C at 2.0 mrad
Operating Modes	Not applicable
Iris	None (Add-on attenuators available)
Environmental	Not specified
Video Output	No

[a] AN/PAS-7 specifications. Corresponding Thermovision 110 data were not available.

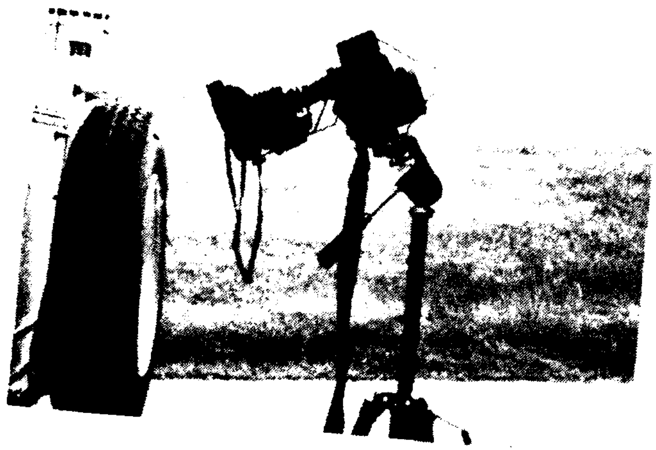


Fig. 19 — The AGEMA (originally AGA) Thermovision 110 thermal imager is a civilian version of the military AN/PAS-7 Handheld Thermal Viewer. It is shown here during a test at the NRL Chesapeake Bay Detachment smoke facility.

distance has been reduced from 8 to 1 m (25 to 3 ft). Minor changes involve the removal of the air purge port, pressure relief value, and external calibration test point. Figure 19 shows the Thermovision 110, and Table 6 gives its specifications.

The imager's height, width, and length are about 14 × 25 × 9 cm (5.5 × 9.5 × 3.3 in.) and weighs 2.7 kg (6 lb), excluding batteries. The AN/PAS-7 was originally supplied with a 2.2 kg (5 lb) belt-mounted battery good for 12 to 15 h of use. In the Thermovision 110, this was replaced by a smaller battery that weighs 0.9 kg (1.2 lb) and mounts on the imager. This battery gives about 2 h of operation. The monocular, monochrome (green on black) display has controls for contrast and brightness. A focus adjustment is also provided. For scene temperatures over 140°C, spare lens caps with holes of various sizes may be used as attenuators.

The detector is a 48-element lead selenide linear array sensitive in the 3 to 5 μm region. A four-stage thermoelectric cooler maintains the detector at an operating temperature of −70°C (−94°F). A mirror vibrating at a 30 Hz frame rate provides scanning. The ±3° angular motion of the mirror sweeps out a 6° (vertical) × 12° (horizontal) field of view. Each detector element drives a separate preamplifier and the outputs of these are multiplexed and further amplified. The processed signal is displayed on a CRT synchronized to the scan frequency.

EVALUATION OF THE ENGLISH ELECTRIC VALVE THERMAL IMAGERS FOR FIRE FIGHTING

In this section, we discuss the testing and evaluation of the commerical thermal imagers described in the previous section. For clarity, the tests are presented in a logical progression rather than in chronological order. Thus, all evaluations of the EEV imagers are discussed first, and reports of tests of the various alternative systems follow.

NRL learned of the EEV thermal imagers when an early version was demonstrated in September 1981, at the Royal Navy Equipment Exhibition (RNEE) in Portsmouth, England. Based on the performance shown at the Exhibition, NRL ordered an imager for evaluation.

Shortly after the RNEE, the British became engaged in the Falkland's Campaign during which several ships were lost to fires as a result of the Argentines' air attacks. Dense smoke was reported to be a major impediment to fire fighting in those incidents. Because of the urgency of the requirement, the Royal Navy chose to forgo a test and evaluation period and immediately placed an order for

90 Model P4228 imagers. Although these units were not delivered until after the end of the campaign, they were rapidly put to use to provide immediate improvements in shipboard fire fighting capability. Subsequent reports from The Royal Navy repeatedly stressed the importance of the thermal imaging capability, as well as their satisfaction with the Model P4228.

Since the U.S. Navy was not engaged in hostilities at that time, their requirements for improved shipboard fire fighting capability were not as urgent as those of the Royal Navy. Accordingly, NRL was able to undertake a more rigorous and extensive test and evaluation program to determine:

- whether thermal imaging capability would also be advantageous to the U.S. Navy;
- whether the EEV Model P4228 imager would be suitable to fill this role; and
- whether other devices might be equal to, or better than, the P4228.

During the course of these evaluations, only limited measurements of technical imaging parameters (such as minimum resolvable temperature and spatial resolution) were made. Although there is some relationship between these technical parameters and the perceived performance of the system, the nature of that relationship is not well understood. Therefore, operational suitability cannot readily be predicted from laboratory data. As a result, a conscious decision was made to concentrate the effort on directly answering the operational questions, rather than on determining technical specifications. The tests reported below were primarily intended to determine whether any of the available imaging systems would be good enough for shipboard applications.

Demonstration at the NRL Chesapeake Bay Detachment (CBD)

The initial tests were conducted in November 1982, at the NRL's smoke test facility located at the Chesapeake Bay Detachment (CBD). The purpose of these early experiments was twofold: (1) to verify that the P4228 imager could, in fact, see through the dense black smoke found in shipboard fires and (2) to determine whether the P4228 imager would be suitable for shipboard use.

The smoke chamber used for these demonstrations (Fig. 20) is an aircraft engine changeout shelter, with height, width, and length of 3 × 3 × 8.5 m (10 × 10 × 28 ft). Smoke was provided by combustion of three 1 ℓ (1 qt) batches of JP-5, each sweetened by the addition of about 300 ml (10 fl oz) of aviation gasoline (Avgas) to facilitate ignition of the JP-5. Each batch was placed in a separate metal burn pan having approximate dimensions of 30 × 30 × 5 cm (12 × 12 × 2 in.) In

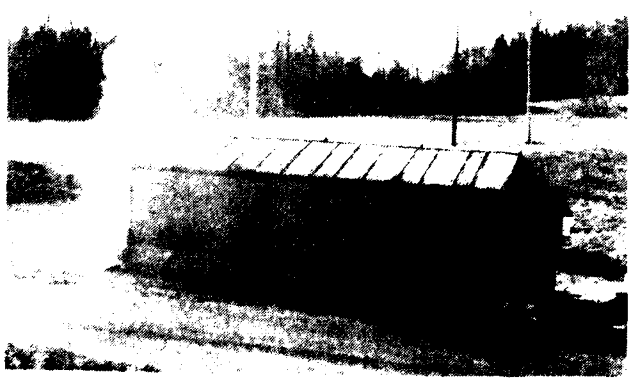


Fig. 20 — Exterior view of the CBD smoke chamber. This smoke test facility is approximately 8.5 m (28 ft) long by 3 m (10 ft) wide and about 3 m (10 ft) high at the ridge line. It has doors and observation windows at both ends. One of those windows is made of infrared-transparent plastic to permit testing of thermal imaging devices without entering the smoke environment.

earlier work, this arrangement had been shown to provide sufficient black smoke to produce zero visibility conditions within minutes.

At first, the IR imager was placed on a tripod outside the test chamber and the inside of the chamber was viewed through a thin, IR transparent, polyethylene window. During later tests, Saran Wrap (polyvinylidene chloride) was found to work equally well as a window material. The P4228 was found to function very well. It penetrated 8.5 m (28 ft) of smoke with ease and allowed clear visualization of the fire pans (both during and after combustion) and of the chamber's interior structure. When the rear doors were opened, people could easily be seen in the background through 8.5 m of black smoke. During this phase of the test, the imager had to be operated in the chop mode and the resulting image flicker was found to be somewhat objectionable.

At this stage of testing, the first camera design problem became apparent. During the smoke production phase of one test, the camera was switched off but left on the tripod pointed through the IR window at a fire pan. When switched on, the central area of the display was found to be obscured by a dark, roughly kidney-shaped blob. Upon investigation, it was determined that, in the power-off position, the camera iris was fully opened. Thus, during the pre-test fuel burn, the imager was subjected to an intense IR source that was focused onto a small region of the PEV retina. As a result, that region suffered a significant loss of sensitivity, known colloquially as a *burn*. Several hours of operation (over a period of weeks) were required before the dark blob faded to an unobjectionable level. A considerably longer time passed before the sensitivity was completely restored.

As a result of this experience, a makeshift lens cap was provided and used whenever the instrument was turned off. Note, however, that no permanent damage resulted from this event.

These demonstrations verified that the P4228 was capable of penetrating dense black smoke to distances of at least 8.5 m and that good image quality could be obtained under those circumstances. During the next phase of testing, the imager was used inside the chamber by professional fire fighters from the CBD station. Both pan and chop mode were evaluated. Because of the flicker in chop mode, the pan mode was preferred.

In one demonstration, illustrated in Fig. 21, the camera operator (fire fighter #1) stationed himself at position A, so that most of the chamber was within the field of view of the IR camera. The second person (fire fighter #2) entered through the north doorway, ignited the fuel in the fire pans (positions 1 - 3) and then went to position B. Protruding from the wall at this point were three one-half inch threaded studs. Fire fighter #2 repetitively removed nuts from these studs and screwed them on again, while fire fighter #1 observed through the IR camera. The IR view was videotaped for later analysis. The object of this test was to demonstrate the loss of hand eye coordination as smoke progressively reduced the visibility. After several minutes of zero visibility, the test was terminated and the camera operator led fire fighter #2 back to the north entrance.

On viewing the videotapes at the conclusion of the test, it was apparent that the studs became harder to find as the test progressed. Fire fighter #2 eventually was able to perform his task only by touch and with much obvious fumbling. In contrast, fire fighter #1, who was at least three times further away, could see the studs without any trouble by using the thermal imager.

The last of these preliminary tests involved the same two fire fighters. This time, several obstructions (cinder blocks) were placed at positions 4 - 6 (Fig. 21), and extra fuel was added to the fire pan at position 3 in order to ensure that it would still be burning at the end of the usual pretest burn period. The purpose of this test was to simulate an actual fire fighting operation where the fire must be located and extinguished under zero visibility conditions. The cinder block wall around fire pan 3 made it invisible from the doorway so that a certain amount of searching was required.

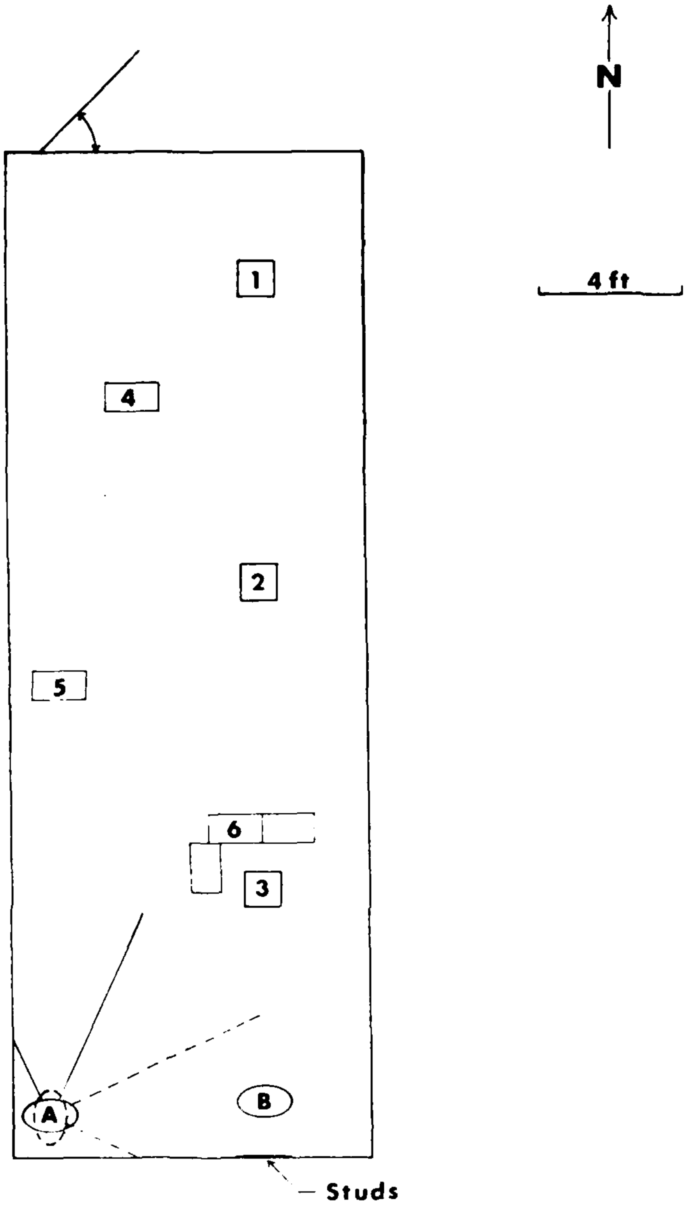


Fig. 21 — This diagram shows the approximate interior configuration of the CBD smoke chamber during one of the early proof-of-concept demonstrations. Entrance was through the door on the north end of the chamber. Fires were set in pans at positions 1 to 3. The fire fighter at position B performed tasks requiring hand-eye coordination. Using a thermal imager, the fire fighter at position A was able to observe the deterioration in the performance of those tasks as the smoke density increased. During another test, obstructions were placed at positions 4 and 5 and a low, cinder block wall was built at position B. Fire fighters were required to find and extinguish fires hidden behind the wall while avoiding the obstacles.

The fires were set as before, except that nobody stayed in the chamber during the smoke buildup period. After the pretest burn period, the camera operator led the way back into the chamber. Fire fighter #2, carrying a small, dry chemical extinguisher, followed fire fighter #1 by holding onto his self-contained breathing apparatus (SCBA) harness. Using the camera, the team leader avoided the obstacles and located the fire. The second man, instructed by the leader on how to direct the dry chemical spray, then extinguished the fire.

The results of this demonstration were very encouraging. The fireman who served as camera operator enthusiastically reported that he had no problems in seeing either the obstructions or in locating the fire. In contrast, the other fire fighter reported that he could not see the fire at all, even though he almost stepped into the pan of burning fuel. He had to be told to point the extinguisher towards his feet in order to extinguish the fire.

Just before exiting the chamber, the camera operator in these demonstrations was asked to stop and survey some pipes in the overhead space. One of these had been wrapped with a 90 W heating tape for a length of about 45 cm (18 in.). This was intended to simulate the heating effects of a short circuit in an electrical conduit. The operator located the hot region immediately despite the dense smoke and, when he viewed it from a favorable location, he could clearly see the spiral wrap pattern of the heating tape.

It became evident that operating the imager in the pan mode required more practice than using the chop mode. This was largely due to the time required to develop the smooth panning technique needed to produce high-quality images. Slow panning resulted in low-contrast, washed-out images. Panning too fast caused blurring and tailing. The fire fighters found the flicker caused by the chopper to be objectionable and preferred the pan mode in spite of the extra work involved.

The only negative reports resulting from the fire fighters' experiences were complaints about the size and weight of the device. Most people found it necessary to use both hands to support the imager while looking through it.

During a subsequent test conducted in March 1983, an estimate for the spatial resolution of the P4428 was obtained. The test conditions were similar to those used in the original evaluation, where the imager was set on a tripod outside the smoke chamber viewing through a polyvinylidene chloride window. Smoke was again produced by burning JP-5 sweetened with Avgas (approximately 3.9 ℓ (4.0 q) total volume, equally divided among three fire pans). Water-filled polyethylene bottles of various sizes served as targets. The imager spatial resolution, estimated from the size of the smallest observable bottle [5 cm (2 in.)] and the distance to the targets [3 m (10 ft)], was found to be approximately 17 mrad.

However, recall that spatial resolution is also dependent on the temperature of the target relative to the background. Thus, the estimate obtained during this test is applicable only to a limited range of circumstances. The test conditions were chosen to simulate the case of small to moderate temperature differences that result from convective heating caused by fires in remote areas. This situation might be expected to occur throughout large portions of a ship during particularly smokey fires.

Demonstration at the Norfolk Fleet Training Center Fire Fighting School

Based on the success of the CBD test program, an additional evaluation of the P4228 was scheduled at the Fleet Training Center Fire Fighting School, Norfolk, VA (FTC Norfolk) [10]. The purposes of this evaluation, which took place on December 15, 1982, were: (1) to test the device under conditions that closely resembled actual shipboard use, (2) to demonstrate the imager's capabilities to potential users, and (3) to obtain comments from experienced shipboard fire fighters regarding the utility of the concept in general and of the P4228 in particular.

Before beginning the tests, CW03 Al LaChance, Director of the Fire Fighting School, was briefed about the goals and the status of the test and evaluation program. The briefing included a demonstration and tutorial on the operation of the P4228 and a replay of video tapes of the CBD tests. In return, Mr. LaChance outlined the shipboard fire fighting problem from the perspective of the sailors. One of his main concerns was the capability for finding lost, injured, or trapped personnel. Because of this interest, the FTC Norfolk demonstration was planned to emphasize search and rescue (SAR) rather than fire fighting capability. As in the previous tests, the video outputs were recorded for later study.

Two different test facilities were used during the FTC Norfolk demonstrations. The first was a concrete blockhouse, the outside dimensions of which were about 9.5 × 12.5 m (31 × 41 ft) with a wall thickness of 0.6 m (2 ft). An internal wall, also approximately 0.6 m (2 ft) thick, divided the building into two unequal, trapezoidal rooms (Fig. 22). The larger room, known as ALPHA chamber, was filled with white smoke produced by bales of smoldering straw (class A fire). This

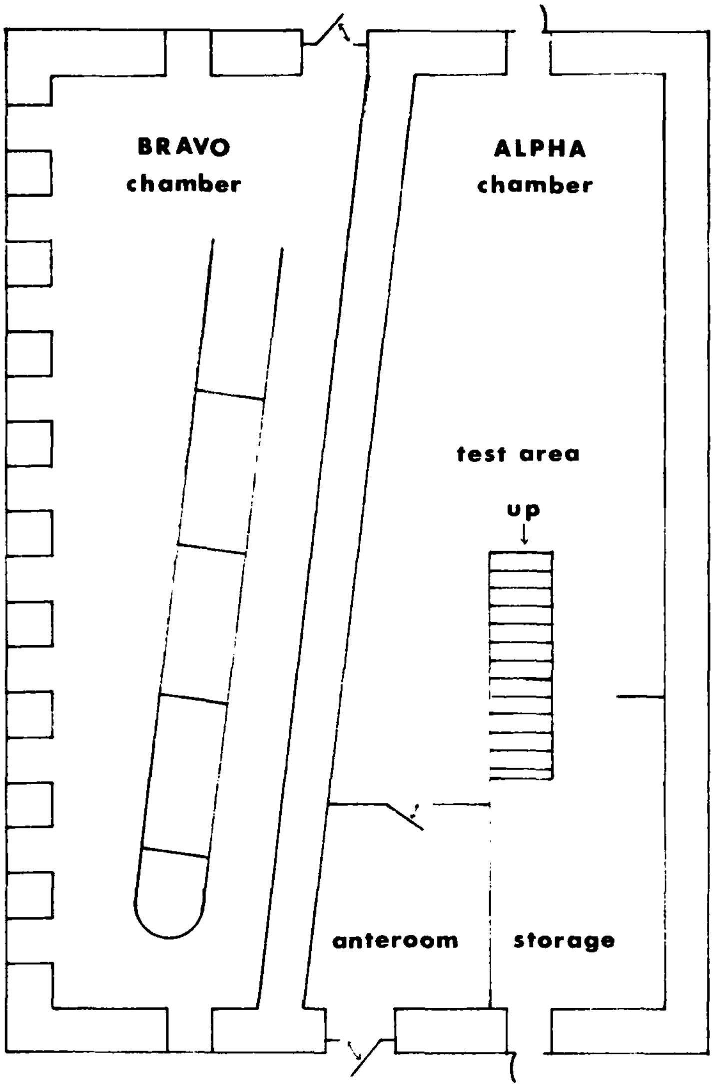


Fig. 22 — Diagram of the interior of the smoke house at FTC, Norfolk. The test area in ALPHA chamber contained a locker, various pieces of furniture, and typical debris that might be encountered in a stateroom fire. Smoke was produced by smoldering bales of straw. The portholes at the end walls could be opened for observation. BRAVO chamber was empty except for the "U"-shaped handrail and a bucket of marine diesel fuel that was burned to provide black smoke. All of the portholes in this chamber were permanently covered by steel plates.

room contained a locker, a table, chairs, and various other pieces of furniture. It was subdivided into an anteroom, a storage area, and the test area. In BRAVO chamber, burning marine diesel fuel (class B fire) was used to generate black smoke similar to that used at the CBD tests. There was no furniture in BRAVO. A "U"-shaped handrail ran the length of the compartment and recessed portholes were located in the front, rear, and one of the side walls. Zero visibility was maintained throughout the tests in both of these smoke chambers.

The second facility used during these tests was the boiler room simulator, a mock-up of part of a ship's machinery space. This facility was a tall, metal structure that contained simulated engines and auxiliary equipment on multiple levels with a bilge area below. Catwalks, located several feet above the bilge, ran between the banks of equipment. Marine diesel fuel was used to simulate bilge fires in this trainer.

The first and most impressive demonstration involved a simulated SAR mission conducted in ALPHA chamber by one of the fire school students. A staff instructor was told to hide within the chamber, playing the role of a victim. He chose to hide inside a steel locker with the open side (the locker had no door) turned towards the rear wall. The student, who had never been in the smoke chamber and had not previously seen the IR viewer, was told to find the victim. The only briefing that the student received regarding camera operation was a statement that, through the imager, warm objects would appear bright and cool objects dark.

Using a remote TV monitor outside the chamber, the NRL and FTC observers followed the progress of the search. Within the first 30 s of the search, the observers had deduced the instructor's hiding place, based on the presence of anomalous hot spots on the sides of the locker. They were caused by conduction of body heat through the locker at those points where the instructor was in contact with the metal.

The student, who had no previous experience and no expectations as to how an object should appear, missed the significance of this clue. Nevertheless, he found the victim in about 4 min. This conclusively demonstrated that the IR imager is a useful device for SAR operations, even in the hands of untrained personnel. The immediate recognition of the cause of the anomalous hot spots by more experienced personnel clearly illustrated the performance improvement that may be expected with even moderate levels of training.

To demonstrate the useful range of the viewer, one of the instructors walked to the rear of the chamber and returned. From the inner doorway of the anteroom, the instructor was clearly visible during the entire trip, a distance of approximately 10 m (32 ft). This instructor, who had many hours of experience in ALPHA Chamber, found it necessary to follow the walls in order to maintain his orientation. In contrast, the novice student had no trouble navigating freely throughout the compartment with the aid of the IR imager. Figure 23 shows the instructor, with his left hand on the wall, walking towards the rear wall of the chamber, which is clearly visible in the background.

Fig. 23 — Instructor in the ALPHA smoke chamber at FTC, Norfolk. With the EEV P4228 thermal imager, this instructor was clearly visible through nearly 10 m (32 ft) of smoke. Visibility was so bad that the instructor had to maintain contact with the wall to avoid getting lost. (NRL photo taken from videotaped image).

In BRAVO chamber, a similar demonstration was attempted using black smoke. The results were less dramatic because of the dearth of hiding places. In the first attempt, an instructor climbed over the handrail and stood on one of the support pipes near the rear of the compartment. Apparently he expected that the searcher, using the rail as a guide, would not think to check the area inside the "U." This expectation might well have been realized in a SAR mission conducted according to current practice (i.e., by touch). In this test, however, the searcher spotted the victim immediately upon entering BRAVO chamber (at a distance of approximately 11 m (35 ft). In a second attempt, the instructor hid in one of the porthole recesses in the side wall. This time the searcher had to walk most of the length of the chamber before the victim came into view.

One factor that may be of help in locating Navy personnel (as compared to civilian fire fighters) is the use, by the Navy, of an oxygen breathing apparatus (OBA). This unit generates oxygen via an exothermal chemical reaction. The generator canister, which is mounted on the chest, provides a bright IR beacon that is hard to overlook. Civilian fire fighters use a more conventional SCBA with a backmounted compressed air cylinder. In contrast to OBAs, the SCBAs appear black on the IR viewer due to the adiabatic cooling effect during use.

Questions of possible image degradation due to steam, water mist, or spray were raised several times. Since it is well known that liquid water is opaque to IR, there was some concern that the steam or mist produced during extinguishment might blind fire fighters at a critical moment.

In an attempt to address these concerns, a test was conducted in the boiler room simulator. A bilge fire was set and allowed to burn for about 5 min to heat the steel. The fire was then extinguished with water, and steam was generated by playing the hose on the bulkheads. The extinguishment process was monitored by the IR camera.

Because of the open ventilation in this compartment, it was not possible to sustain high concentrations of steam or mist. However, there was no difficulty in seeing through the steam that was produced. As expected, the hose's stream proved to be opaque and appeared as a fan of black (cold) streamers. This was not a significant impediment to vision; instead it could be very useful as an aid in directing the application of water to specific areas.

As at CBD, the weight of the P4228 and the requirement for two-hand operation were criticized and the flicker in the chop mode was considered to be very annoying. The pan mode was used almost exclusively. In addition, it was noted that the foam plastic visor had fallen off and had been lost in ALPHA chamber. The visor is not critical, but in extremely dense smoke it improves visibility by excluding smoke between the fire fighters face mask and the CRT screen in the imager. Partly in response to our criticism, EEV subsequently changed the visor to a more durable rubber material and provided bolts for a more secure attachment.

Again, the fire fighters' response was extremely enthusiastic, and it led us to our decision to push for Fleet adoption of the IR viewer concept [10].

Imager Performance in Steam

In addition to the fire fighters' questions regarding the use of thermal imagers in steamy atmospheres, the submarine damage control community expressed an interest in using an IR imaging device as an aid in locating and securing steam leaks aboard submarines. To meet these requirements, the device would have to be capable of functioning in a zero-visibility, steam/water mist environment.

The results of the machinery space test at FTC Norfolk were encouraging, but far from conclusive. A more rigorous test [11] was required to adequately address this question. A section of the NRL steam plant (Fig. 24) was chosen for this purpose, and the test was conducted in April 1983.

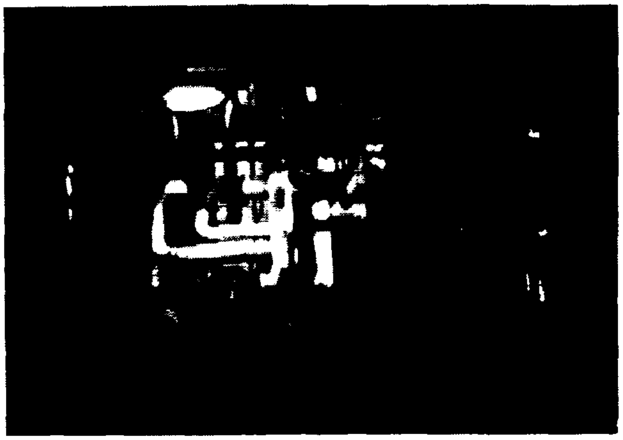


Fig. 24 — Thermal imager tests were conducted in this area of the NRL steam plant. The banks of equipment were about 3 m (10 ft) high by 5 m (16 ft) long and were separated by a narrow isle.

The area selected contained two banks of steam plumbing separated by a narrow aisle and occupied a space having height, width, and length of approximately 3 × 5 × 5 m (10 × 16 × 16 ft). Two sides and the top were open to the rest of the plant. The system produced saturated steam at about 163°C (325°F) and 6.9×10^5 Pa (100 psi).

During the test, a valve was cracked to allow the steam to escape through an unconnected flange (Fig. 25). The resulting visibility in the test area varied from essentially zero to a maximum of about 1 m (3 ft). Subjects within the steam cloud were not visible to each other or to observers standing just outside the test area. Figure 26 gives an idea of the conditions existing during the initial steam release. Note that, after 1.5 min, the man standing less than 1 m (3 ft) inside the test area at the right edge of the doorway was almost totally obscured.

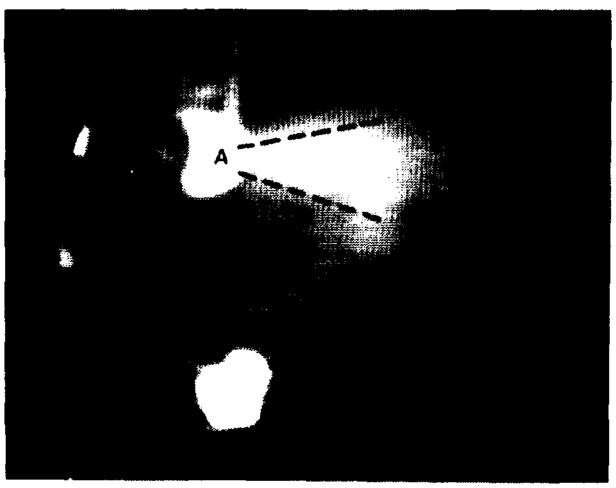


Fig. 25 — Thermal image of a steam jet. Steam escaping from the flange (A) is clearly visible (dotted outlines) in this thermal image. High-pressure steam leaks in marine propulsion plants are extremely hazardous because they are normally invisible.

(a) (b) (c)

Fig. 26 — Visible image during steam release. The reduction in visibility due to the steam release is evident in these photos. One of the steam plant operators is clearly visible prior to opening of the valve (a). In a matter of seconds, the visibility has been significantly reduced (b), and the person is almost totally obscured in less than 2 min (c).

Shortly after maximum steam density was attained, one of the NRL investigators carried the IR imager into the test area. While standing near the center of the steam cloud, he made a complete survey of the surroundings. As usual, the IR camera output was recorded during this test.

During both the original survey and the later review of the video tape, the primary area of interest was the evaluation of the visibility of people, plumbing (especially valves and joints), and steam jets. The capability of actually seeing a jet of steam is important not only for locating a leak but also for the safety of the repair party. Once the leak is located, the ability to trace pipes and to identify valves is needed to secure the leak. The detectability of people was important because of the possibility that personnel injuries would be involved in a steam line accident.

The visibility range was significantly increased, from less than 1 m (3 ft) to at least 3 m (10 ft), by using the IR imager. The maximum effective range could not be determined because of the small size of the available test space.

Pipes, valves, and fittings were easily distinguishable up to the longest available distance. Typically, the valve bodies and joints were very bright and the valve handles appeared as black silhouettes. The appearance of the pipe runs depended on how well they were insulated. Even well insulated sections, however, were clearly visible. People were not as visible as the plumbing (because of their lower temperature), but the images were comparable to those obtained in zero-visibility smoke.

Steam conditions on board submarines and surface ships are expected to be comparable to those produced in this test. Since many shipboard steam systems produce dry (rather than saturated) steam and operate at much higher temperatures (up to 480°C vs 163°C), the viewing conditions might actually be better aboard ship. The dry steam has a lower liquid concentration, so attenuation should be reduced. Also, the hotter steam jet would be a brighter IR target. Considering these factors and the results of this demonstration, it appears that IR viewers would be very useful in steam leak situations. Steam generated during extinguishment of a fire is not expected to be as dense as the steam in this test. Therefore, it is unlikely to cause significant image degradation.

The major problem encountered during this test was condensation of water on the lens, which resulted in poor resolution and contrast. The same problem was noted at CBD on occasions when the device was taken from a cold exterior environment into the warm, humid test chamber. Similar difficulties were noted in the class B fires, when carbonaceous soot deposited on the lens. In all three cases, the problem may be temporarily rectified simply by wiping the lens with a cloth or glove [11].

Imager Performance in Training Smoke

At this point in the evaluation, the utility of thermal IR imaging as a vision enhancement tool had been demonstrated in dense smoke (both white and black) and in steam. The fire fighters' response had been uniformly positive in regard to the imager's capabilities for both fire fighting and SAR. However, there were still several significant unknowns, two of which involved the use of the IR camera for training. The first unknown was the question of how to teach people to use the camera. The second was whether the IR system might be useful as a tool for teaching other techniques.

The first question, involving doctrine, tactics, and training guidelines, is discussed in Part III of this report. In answer to the second question, several FTC Norfolk instructors suggested that at least one IR monitor be installed within each smoke chamber. These would be used to videotape the students and the tapes could then be used in postexercise critiques. This application of IR imaging techniques to training was not addressed during the artificial smoke tests, but it was used during the extended evaluation period discussed in a later section.

A significant amount of the overall training program at FTC Norfolk occurs in the 19F1 simulator using an artificial (chemically generated) smoke. Also, although shipboard use of smoke generators or smoke bombs was then forbidden (these smokes were considered to have unacceptably high toxicological and explosive hazard risks), there was a strong interest in resuming such training. This raised the question of how well IR imaging systems, and the Model P4228 imager in particular, would function in various artificial smokes. Training could be a problem if devices, which operate well in smoke from real fires, proved to be unable to function in artificial smoke.

There were several reasons for concern on this point. First, the particle sizes for some artificial smoke sources can be an order of magnitude greater than those produced in most fires. This means that the artificial smoke particle size could more closely approximate the IR wavelengths used by the P4228 thermal imager. As a consequence, the scattering coefficient could sharply increase and lead to a much greater attenuation of the signal. Second, some artificial smokes are composed of small hygroscopic crystals of various salts. These crystals rapidly grow by absorbing water from the air and result in a particle that is essentially a water droplet. Since liquid water is a strong IR absorber, such a cloud of saturated aerosol particles would probably be a much stronger attenuator than the original dry aerosol. Finally, many of the smokes that are not composed of hygroscopic particles are composed of mixtures of organic compounds. Since most organics have strong absorbance bands within the infrared region, it is possible that these formulations would be even stronger attenuators than water droplet type smoke.

To investigate the P4228's capability for imaging in artificial smoke, two more tests were conducted [12]. During February 1983, the P4228 was tested in the 19F1 trainer using the standard training smoke (Chem Chex 200). The following April, NRL participated in a Naval Safety Center toxicity study of smoke simulants, including several portable smoke generators, standard military smoke grenades, and experimental smoke candles. This study was also conducted in the 19F1 trainer.

The 19F1 (Fig. 27) is a two-story building simulating the weather deck and two interior decks on a Navy vessel. Compartments are outfitted with standard Navy fittings (e.g., hatches between decks, a deep-fat fryer, and chain-link fence storage areas). A vertical divider separates port and starboard halves of the building on both interior levels. At the time of these tests, one half was outfitted with propane burners to provide a hot training environment, while the other half could only be used cold. The structure has been upgraded since then, and both halves now have hot training capability. Both halves have extensive plumbing to deliver smoke throughout. The artificial smoke compound, Chem Chex 200, is a triaryl phosphate-based liquid which is converted to smoke in a flash evaporator pipe immediately before release into the compartment.

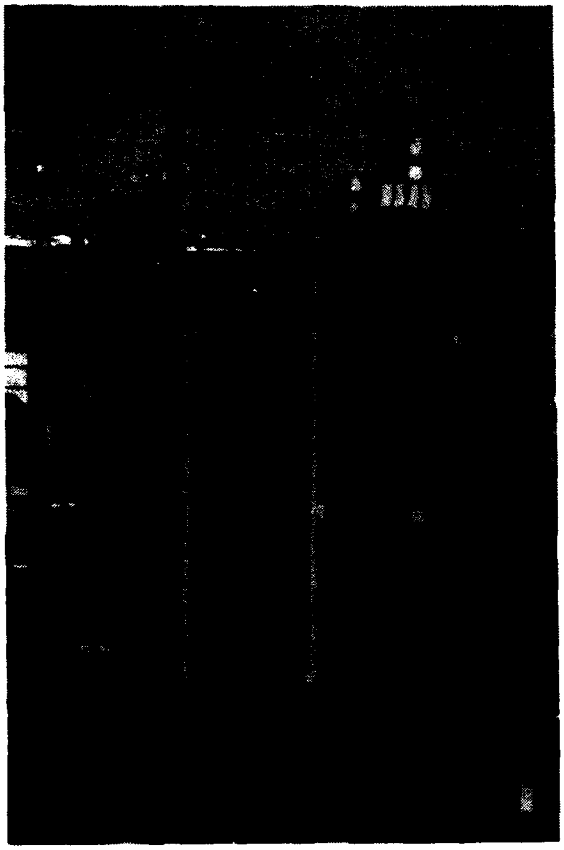


Fig. 27 — The 19F1 fire fighting trainer, located at the Fleet Training Center Fire Fighting School in Norfolk, VA, simulates the shipboard environment. The trainer is divided into two segments, each of which contains two interior decks plus the weather deck. Propane-fired burners and smoke generators provide realism during training exercises.

On February 15, 1983, taking advantage of a fortuitous opportunity, the Fire Fighting School Director, an instructor, and five NRL scientists used the thermal imager under zero-visibility conditions in the cold side of 19F1. Part of the exercise involved locating the instructor, who was hiding inside the trainer. Using the imager, most personnel involved had no trouble either in finding the victim or in avoiding obstructions (such as interior partitions, posts, or ladders). The performance of the IR imager was comparable to that obtained under relatively cold conditions with real smoke. It was noted, however, that the results in this cold compartment (no fire) were not as good as the results in hot compartments (those with fires). This relation held true even when no smoke was present in either cases. The difference is attributable to the fact that, without a localized heat source, the trainer and its contents were at almost the same temperature. The only IR signal differences were due to emissivity differences, which tended to be small. The net result was that picture contrast was poor in the isothermal situations, but it improved dramatically as soon as a fire began to heat the compartments differentially. However, even with near isothermal conditions and relatively low contrast images, it was very easy to see such details as the cement seams between cinder blocks in the walls.

During the April tests, a Fire Fighting School instructor operated the IR camera inside the cold side of 19F1. During each of the 5 to 10 min tests, a different smoke generating procedure was used, as listed in Table 7. Laser light-scattering measurements and aerosol particle sampling results from these tests have been reported in detail elsewhere [13]. Table 7 includes particle size data and visibility rankings, based partly on Ref. 13 and partly on observations by the instructors inside the 19F1.

Unaided visibility varied over a wide range, from slight degradation in Test 1 to nearly zero visibility in Tests 3, 6, and 7, depending on the smoke generation technique. In all cases, the IR system provided good imagery. The smoke generators, candles, grenades, and lasers were relatively hot

Table 7 — Artificial Smoke Test Data

Test	Smoke Generator	Particle Size[a]	Unaided Visibility Ranking[b]
1	1 Experimental Candle, NWSC[c] Type M (MKW-1)	Insufficient sample	8 (least obscured)
2	2 Experimental Candles, NWSC Type M	85% < 3.5 μm	5
3	1 Resonant Pulse Generator, Smith & Wesson "PEPPERFOG"	96% < 1.6 μm	3
4	2 Experimental Candles, NWSC Type A (ACW-1)	No Sample	7
5	1 Electric ROSCO "Smoke Generator"	Insufficient Sample	6
6	2 Electric ROSCO "Smoke Generators"	100% < 1.6 μm	1 (most obscured)
7	19F1 Trainer Smoke Chem Chex 200 (triaryl phosphate)	96% < 3.5 μm	2
	2 Smoke Pots, NAVY MK6 Mod 0	92% < 6.2 μm 77% < 1.6 μm	4

[a] From measurements of Alexander et al. [13].
[b] Derived from smoke half-life and particle-size data measured by Alexander et al. [13] and from visual sightings by FTC instructor.
[c] Naval Weapons Support Center, Crane, IN

and showed up clearly. In the case of candles, smoke and solid material could be seen as it was being ejected.

Backgrounds tended to be low contrast, similar to those previously observed in 19F1. Contrast was worst in the mornings and improved during the day as the structure was heated by the sun. This is further evidence that the contrast problem was due to the isothermal nature of the background and not to any effect of the various smokes.

It was encouraging to find that, in spite of the range of particle sizes and compositions represented by these different smoke sources, the IR viewer was able to see through all of them. Based on these results, it seems likely that the use of artificial smoke for training exercises will not adversely affect the performance of a thermal imaging system operating in the 8 to 14 μm region. However, this will have to be experimentally verified if other smoke-generating methods are adopted or if a different imaging system is used.

Shipboard Evaluation at the USCG Fire and Safety Test Detachment

Most of the previous evaluation work was carried out in FTC simulators, but no actual shipboard testing had ever been done. Although there was no reason to suspect that the IR imager would function differently aboard ship, it was decided that an on board demonstration under actual fire conditions would be valuable. In June 1983, in conjunction with previously scheduled ventilation system tests, NRL conducted such a demonstration at the U.S. Coast Guard Fire and Safety Test Detachment (F&STD) in Mobile, AL [14].

F&STD maintains two ships, shown in Fig. 28, for use as fire testbeds. This test series was conducted on the T-2 tanker, *A. E. Watts*, in conjunction with an ongoing evaluation of smoke control and removal techniques using the ship's ventilation system [15]. Figure 29 shows the deck plan of the test area and the layout of some of the test monitoring equipment.

All fires in the test series were class A, and all were set in compartment G, which simulated either a berthing space or a laundry room. The only difference between the two were the types and amounts of combustibles. Clothing and bedding, (including mattresses) were used for stateroom scenarios. Pieces of electric cable, as well as larger quantities of both clothing and bedding (but no mattresses) were used in laundry room simulations.

All fire fighting operations were conducted from the test corridor. Evaluation of the IR camera was carried out in this area and in compartment F. During some of the tests, the imager was used by USCG or NRL personnel with the images being transmitted via cable to the control room for recording and realtime observation. These tests were intended to evaluate the utility of the IR viewer during actual shipboard fire fighting operations. In other tests, the imager was suspended from the overhead in the test corridor for the entire test period. The purpose was to monitor image degradation as a function of time and temperature. A secondary purpose was to evaluate the use of installed thermal imagers for monitoring fire conditions and fire fighting operations. This capability may prove to be useful in training or even for routine observation of compartments with high fire hazards.

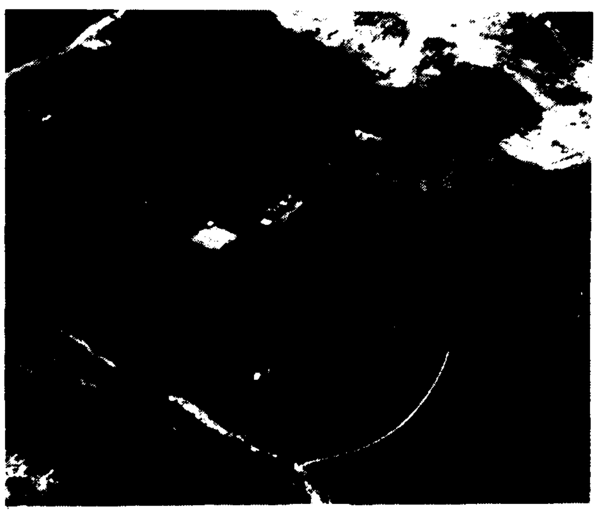


Fig. 28 — The USCG Fire and Safety Test Detachment facility at Mobile, AL, consists of two ships on which full-scale fire-fighting tests may be conducted. The lower vessel in this photo is the cargo ship MV *Mayo Lykes*, and the upper ship is a T-2 tanker, *A. E. Watts*.

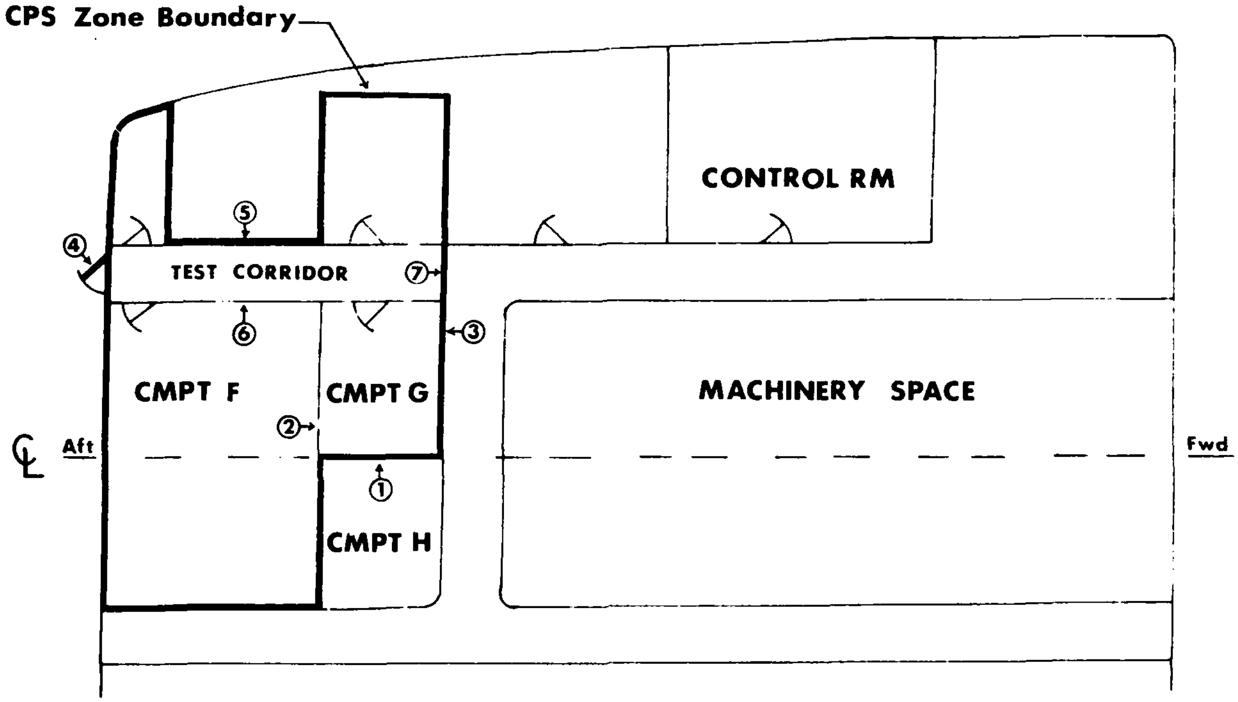


Fig. 29 — Deck plan of *A. E. Watts* during June 1983 Test. Part of the 01-level of the aft superstructure *A. E. Watts* was modified to simulate a portion of the collective protection system (CPS) proposed for USS *Arleigh Burke* (DDG 51). The bold lines indicate the CPS zone boundary. Fires were contained in compartment G, which was configured as a berthing space for half of the tests and as a laundry room for the others. Thermal imager evaluations took place in compartment F and in the test corridor. Compartment H was an observation area. ①IR window for observation of fires; ②visible light window with standard video camera; ③ visible light window for direct observation and still photography; ④ visible light windows for video and still photography of the test corridor; ⑤ backlit scale for measurement of smoke height; ⑥ video camera for continuous monitoring of smoke height scale; ⑦resolution target for IR imager evaluation.

In addition to the tests outlined above, a second IR viewer was used to monitor the conditions inside the fire compartment during some tests. This camera was located in compartment H, and the observations were carried out through an IR window installed in the G-H bulkhead. This information was useful in making real-time decisions during the experiment and was helpful in evaluating the utility of the installed imaging systems. However, the operational evaluation of these imagers was based almost entirely on the results obtained in the test corridor, especially during the tests when the imager was used by fire fighters.

In those tests in which the camera was operated manually, the device was stowed in compartment F during the preburn period, which lasted approximately 30 min. During the preburn time, various tests of the ventilation system were conducted. The amount of smoke in the corridor and in compartment F varied considerably, depending on the ventilation configuration. Visibility ranged from almost normal to essentially zero. At the end of the preburn period, fire fighters entered through the aft watertight door and used the camera to survey compartment F and the test corridor. Regardless of the unaided visibility, the images provided by the IR viewer were of high quality. In all cases, the heating ducts and lasers in compartment F were readily visible. More importantly, the door to compartment G was always considerably brighter than the surrounding bulkheads. This provided an immediate, positive indication of the fire location as the fire fighters entered the test corridor. In an actual fire incident, this information could have significantly reduced the fire fighters' response time since a compartment-by-compartment search would not have been necessary.

An attempt to estimate the spatial resolution of the imager was also made during some of these tests. For this purpose, a 23 cm (9 in.) square aluminum plate with three 2.5 × 13 cm (1 × 5 in.) black stripes was attached to the inside of the door at the forward end at the test corridor. The camera operator was asked to walk forward until the stripes could be resolved and to mark the bulkhead at that point. After the test, the distance from the mark to the target was measured, and the spatial resolution was calculated from the known geometry. It must be noted, however, that spatial resolution is also a function of the temperature and emissivity differences between the black stripes and the aluminum plate. Since the temperatures were not controlled and since the emissivities changed during the test (due to soot deposition), the spatial resolution calculated from these data is only a rough estimate.

After completing these preliminary observations, the fire fighters opened the door to compartment G, observed the conditions within, and determined the extent of involvement of the various fuel sources. The camera operators were able to distinguish between smoldering and flaming combustion. This type of information is of use in combating fires after they have been located.

Regardless of the ventilation technique used, the corridor rapidly filled with hot smoke after the fire compartment door was opened. As a consequence, the evaluation of fire conditions and the egress from the test corridor were made under low- to zero- visibility conditions. The thermal imagery under these conditions was very good. The only difficulty encountered was a tendency for the fire fighters to saturate the IR detector by dwelling on the fire. Then, when looking away from the fire, the image quality and contrast required several seconds to return to normal. As usual, the pan mode was preferred whenever the imager was manually operated.

During the tests in which the imager was suspended in the test corridor, the imager was located approximately 1.8 m (6 ft) above the deck. Since the camera was adjacent to a thermocouple (*number 16 in the USCG test plan*), the ambient temperature to which the camera was exposed was known. A liquid crystal thermometer (LCT), placed inside the camera case, provided some information about the internal temperature. During these periods of unmanned operation, the imager was placed in the chop mode since there was no provision for remote controlled panning. Because of the anticipated duration of the tests (approximately 2h each), the imager could not be run on the normal, self-contained battery pack. Instead, power was supplied by a 12V car battery located outside of the test area.

During one experiment, the corridor temperature at the imager's location reached 176°C (349°F) and was continuously above 160°C (320°F) for almost 3 min. At the conclusion of the test, the internal temperature was checked and found to exceed 55°C (131°F), the upper limit of the LCT.

As expected, the image contrast deteriorated as the temperature increased and became unusable when the ambient temperature exceeded about 120°C (248°F). Below this temperature, the image quality was good. The limiting temperature is the internal (rather than the external) temperature and is dependent on the time of exposure as well as on the ambient temperature. The 120°C limit should not be regarded as fixed for all conditions.

The image was abruptly lost as the ambient temperature approached 176°C (349°F). This failure was later found to be due to the melting of the insulation on the cable from the car battery, which caused a short circuit. After power was restored, the camera again functioned properly, although there were some jagged lines that appeared to be cracks in the retina. After further use during the following day, these lines faded away. Apparently, they were not the result of any actual damage to the retina, but it is not clear exactly what did cause the problem. The conclusion, based on these tests, was that the P4228 was considerably less sensitive to high-temperature stress than had previously been believed.

The spatial resolution of the imager was estimated from the width of the stripes on the target, 2.5 cm (1 in.), and the maximum distance at which the stripes were resolvable, about 1.8 m (6 ft). These measurements correspond to an angular resolution of about 14 mrad. As previously mentioned, the resolution tests were not definitive, but, if it is assumed that 14 mrad angular resolution is about average, then a person [about 1.8 × 0.5 m (6 × 1.5 ft)] would be expected to be detectable at distances in excess of 30 m (100 ft). In actual tests, it was found that, while people are not recognizable at distances greater than about 15 m (50 ft), they can be detected at much greater distances.

The IR imager proved to be very useful in these shipboard tests, especially in those directly related to finding and extinguishing the fire. All of the USCG personnel involved in the evaluation were favorably impressed with the concept. There was some criticism of the size and weight of the specific device, as expected. Also, there were some obvious problems with temporary blackouts caused by poor techniques employed in using the camera. One tendency was to pan too rapidly, which resulted in sudden transitions between hot and cold sources. As a consequence, since the iris did not have time to adjust properly, the image was alternately over- and underexposed. Rapid panning also produced streaking and blurring of images. At the other extreme, if panning stopped or was too slow, the image faded and contrast was lost. Some of these problems could be addressed by appropriate hardware changes, especially by reducing the iris' reaction time. However, a more productive approach might be to place greater emphasis on training to ensure that camera operators use the device most effectively.

These tests also demonstrated the value of thermal imaging with installed systems. This technique could be used during fire fighting training to provide an additional safety factor and to allow the instructors to better critique the students. Aboard ship, thermal imaging systems, installed in machinery spaces and other areas with high fire potential, might be useful for observing fire conditions and for directing fire fighting operations. These systems would have to be carefully insulated and probably provided with cooling systems to withstand the extreme temperatures that are routinely found in the overhead spaces during major fires.

Extended Evaluation at the Norfolk Fleet Training Center Fire Fighting School

In April 1983, one of the IR imagers was returned to FTC Norfolk for long-term evaluation. The major reasons were: (1) to further evaluate the utility of thermal imagers for shipboard fire fighting, (2) to give fire fighting school personnel additional experience with IR imaging, (3) to begin development of effective fire fighting and search and rescue tactics using the imager, and (4) to obtain additional operating time to better assess reliability factors. The imager was used in a variety of the fire fighting exercises between April and August.

One modification to the imager was made before delivery to FTC Norfolk. The standard, self-contained battery pack was replaced with a more powerful, belt-mounted battery. This greatly increased the operating life and slightly reduced the weight of the hand-held components of the system. Although this configuration was not practical for actual fire fighting use (because of the added bulk and the connecting power cable), it did provide a method for extended training without an inordinate battery consumption. Table 8 compares the weights and operating times of the standard package and two different modifications.

A video recorder and a logbook were also provided so that FTC could document their tests. Each time the camera was used, the operating conditions, total operating time, and operator's comments were logged. Selected tests were videotaped.

Table 8 — Weight and Endurance Characteristics of EEV P4228

	Unit From Mfg[a]	NRL SYS I[b]	NRL SYS II[c]
Weight of Hand-Held Unit (kg)	4.0	3.7	3.7
Weight of External Battery Pack (kg)	NA	4.1	2.5
Total Pkg Wt (kg)	4.0	7.8	6.2
Total Endurance (h)	1	6	8

[a] The P4228, as received from EEV, has 10 AA batteries in a cartridge contained inside the hand-held unit.
[b] SYS I = 2 × 6 vdc Nite Lite Gel Cells.
[c] SYS II = 1 × 12 vdc Globe Gel Cell.

Many of the tests repeated previous demonstrations using white, black, and artificial smoke, but provided a better evaluation of the benefits of thermal imaging for SAR and damage control investigations. For example, CW03 LaChance reported [16] that use of the IR camera resulted in a 75% reduction in fire investigation time. He noted that this was a significant improvement and, in his opinion, would be sufficient justification for deployment of IR devices on aircraft carriers and troop-carrying ships.

Aboard Naval vessels, the Damage Control Assistants (DCAs) are directly responsible for overseeing the use and maintenance of fire fighting equipment. Because the thermal imager falls within the DCA's area of responsibility, it was important to give them hands-on experience and to solicit their opinions regarding the new device. During July 1983, students in the DCA course at FTC Norfolk were given an opportunity to use the imager under realistic conditions and to comment on its performance. Operating under conditions of zero visibility and high temperature in the 19F1 trainer, the students practiced SAR and fire investigation procedures. During other exercises in 19F1, both shore-based Naval and civilian fire fighters underwent similar training.

At the conclusion of these exercises, the FTC Norfolk staff reported that better performance was obtained from the relatively inexperienced Naval personnel than from the older civilian fire fighters. This was attributed to an apparent reluctance, on the part of longtime fire fighters, to alter their usual procedures.

During many of the training exercises, the imager (operating in chop mode) was mounted overhead in 19F1 and was used to monitor and videotape students. These tapes were then used as part of the student's evaluation, and they provided a significant new capability for assessing the effectiveness of training. Also, the real-time monitoring capability added an additional safety factor to the training. Although this application of thermal imaging had been suggested on several previous occasions, this was the first time that IR videotapes were actually used as part of the training environment.

Fire fighting school personnel also experimented with various non-fire fighting uses of the imager. Attempts to detect water levels in partially flooded compartments (in the "Buttercup" damage control trainer) and liquid CO_2 levels in fire extinguishers proved unsuccessful. In the case of the "Buttercup" trainer, this was probably due to the fact that the air, water, and steel were essentially isothermal. Mr. LaChance recommended that this test be repeated under more realistic (i.e., non-isothermal) conditions. Observations during ballasting of an LSD were suggested. If successful, this could indicate that flooding is another area of damage control in which thermal imaging might prove beneficial.

In other tests, overheated electrical cables and shore-power connections were quickly found during IR surveys aboard ships and on docks. Previously, similar success in identifying defective fluorescent light ballasts in the laboratory had been reported. These results clearly demonstrate the utility of thermal imaging for locating potential trouble spots before significant fire hazards develop.

During the course of this three-month evaluation, more than 60 h of operation were logged. No imager problems or malfunctions developed. On the basis of this extended evaluation, FTC personnel made the following comments [16]:

(a) Thermal imagers would more than justify their cost in time savings during fire investigation alone.

(b) The P4228 has proven to be reliable and effective in SAR, fire fighting, and identification of potential ignition sources.

(c) IR imagers could be used to great effect in training, resulting in improvements in both efficiency and safety.

(d) Most personnel, especially the younger students, quickly learn to use IR imagers effectively.

(e) The P4228 is highly reliable and resistant to abuse by untrained users.

At the conclusion of these tests in August 1983, one of the NRL-owned imagers had been in service for 16 months while the second had been in use for 11 months. No failures had been reported for either unit.

Naval Base Evaluations

A drawback in all of the preceding tests and demonstrations was that none of them involved uncontrolled fires. Even in the tests conducted at F&STD, the fires were carefully staged. That was necessary for conducting reproducible tests, and was also required for safety reasons, but it did make the tests less realistic. To maximize the probability of obtaining reports from real incidents, it was decided to place both the IR units in the field. At the suggestion of Mr. Jim Manser [17] (Naval Facilities Command, Code 10F), who was interested in obtaining data pertinent to shipyard fire fighting, one imager was deployed at the Philadelphia Naval Shipyard (PNSY) from late November 1983 through mid-March 1984. The second went to the Norfolk Naval Base Fire Department (NNBFD) from February 1984 to the middle of May 1984 [18]. In both bases, NRL personnel provided an initial briefing on the operation of the imager. Possible ways in which it might prove to be useful were also discussed, but the custodians were encouraged to experiment in order to develop the most effective tactics for various situations. As in the case of the extended testing at FTC Norfolk, logbooks were provided to document all operational time.

The results of these two evaluations provided little additional information because no significant fires occurred at either facility during the test periods. Both PNSY and NNBFD considered the tactical requirements for effective imager use, but neither had sufficient opportunity to test their ideas. Personnel at PNSY suggested that the imager be used by a fireground command officer as an aid in deploying men and equipment. NNBFD, on the other hand, preferred a concept in which the device would be assigned to an active fire fighting team. Possibly this difference can be attributed to the somewhat different perspectives of the two fire departments. PNSY seems more oriented toward structural fire fighting while the emphasis at NNBFD has been on shipboard fire fighting. Clearly, much work remains to be done to develop effective tactics. A single doctrine is unlikely to be appropriate for all the situations that may be encountered by Naval fire fighters.

At PNSY, the imager was used mostly at demonstrations for various groups, including Naval and civilian fire fighters and representatives of oil and shipping companies. On one occasion, the odor of burning electrical insulation was reported by occupants of a large office complex and the imager was used to survey the building. That particular building was a warehouse, approximately one square block in size, converted to office space by the addition of internal partitions and a drop ceiling. Electric cables and steam pipes were installed in the space above the false ceiling. The imager operator pushed aside a ceiling tile, stood on a ladder to survey the space above the ceiling in the immediate vicinity and then moved the ladder to a new location. He reported that electrical cables, steam pipes, and fluorescent lamp ballasts were easily observed, and he estimated that the IR imager reduced the investigation time by a factor of two. Also, when no source was found, the building was declared safe. Without the imager, no such certification would have been made, and a fire watch would have been required. The odor was eventually attributed to fumes from an external source that had been spread through the air conditioning system.

Based on their experiences, the PBSY operators rated the imager as highly satisfactory and indicated that it has definite advantages aboard ships for monitoring heat spread as well as in fire fighting. The major problems noted were the weight (considered heavy but not excessive), the relatively short battery life, and the fact that the device was somewhat clumsy to operate with heavy gloves.

The day after NRL delivered a P4228 camera to the NNBFD, a fire occurred in a walnut shell storage hopper at a tenant command, the Naval Air Rework Facility. On that occasion, the imager was used inside the hopper (after the fire had been extinguished) to search for potential reignition sources. The operator reported some difficulty in interpreting the scene since the imager provided no information regarding the absolute temperatures of the objects being viewed. Thus, a spot was easily identified as being hotter than its surroundings, but there was no way to know if it was hot enough to cause spontaneous ignition.

To enter the hopper, the imager operator had to climb a ladder to the top of the hopper. This turned out to be rather difficult, because of the weight and awkwardness of the P4228. When hanging from the neck strap, the camera tended to hit against the ladder. It also put additional strain on the fire fighter's neck, already burdened with a heavy helmet and a face mask.

At the time of the fire, the imager was being used with an external battery carried on a belt. The power cable often snagged because it was too long and was not well dressed. The operator suggested that the internal battery pack might have been more appropriate and would also have allowed the imager to be hoisted to the top of the ladder by rope. An alternate suggestion was to attach the battery pack to the SCBA harness. This might have alleviated the entanglement problem, but the operator would still have had to carry the imager up the ladder.

Most of the remaining imager operating time was used for training. NNBFD personnel were very impressed with the imager, but did not like its weight or the necessity of using both hands to operate it. Also, there were many misconceptions about the imager, its capabilities, and its limitations. For example, several people thought that the imager could see through objects. On the basis of this experience, NNBFD stressed the importance of training with the imager, especially regarding its limitations and the interpretation of the image.

Federal Fire Department, San Diego, CA

Shortly after having returned from PNSY, one imager was sent to the Federal Fire Department (FFD), San Diego, CA for further evaluation. That department, one of the largest federal fire departments in the country, provides protective services to the 32nd Street Naval Station and to the Naval Air Station, North Island. Because of the size of the Naval facilities, it was anticipated that the probability of a real fire occurring during the evaluation period would be relatively high. Also, FFD is one of the few departments that routinely use the Navy A-4 OBA instead of a compressed air SCBA. Thus, comments received from FFD were expected to be more directly applicable to Navy shipboard fire fighting than were those from PNSY or NNBFD.

In fact, no fires of significance did occur during the evaluation period. However, the imager was used routinely in live fire fighting exercises aboard the freighter *Constance*. Small fires were set in galley, head and storage spaces, using rubber tires to generate dense, black smoke. Trainees were told the general area in which the fire was located, but not the specific compartment. At different times, the thermal imager was used by trainee fire fighters as a tool to locate and attack the fires and by safety observers to monitor the students. The users found the imager to be extremely useful in both roles, and the comments were highly favorable.

After using the P4228, the Deputy Chief in charge of the evaluation considered thermal imaging to be vital for shipboard fire fighting. The only complaints received were, as expected, about the size and weight of the device. One user offered the unsolicited suggestion that the ideal thermal imaging system should be built into the visor of the fire fighters helmet.

Introduction of the P4428 Thermal Imager

During the evaluation of the P4228, NRL identified several improvements which would make the imager more useful to the Navy. Chief among these were size and weight reduction. Also, the following changes were thought to be desirable:

(a) The PEV tube should be protected from exposure to intense IR sources when the imager is turned off.

(b) The image flicker caused by the chopper should be greatly reduced.

(c) The visor hood should be redesigned to better conform to breathing apparatus faceplates and to prevent loss or damage during fire fighting.

(d) The battery compartment screw cap should be replaced with a twist-lock version for easier battery cartridge exchange.

(e) An internal, elapsed time indicator should be incorporated for use by service technicians.

(f) The relative iris position should be displayed in the view window as a rough measure of the temperature of objects in the scene.

Each of the suggested changes resulted from one or more specific incidents that occurred during testing.

In March 1984, EEV introduced an improved version of the P4228 thermal imager, designated as the P4428. This model incorporated most of the changes listed above. Most importantly, the hand-held portion of the system was reduced in size and weight to permit one-handed operation. This was accomplished, in part, by relocating the power supply components in a separate module intended to be suspended from a harness rather than carried by hand. All of the suggestions made by NRL, except for the last one, were also implemented. The temperature display was not added because it would have involved a major redesign of the electronics.

Due to production delays, the new power module was not available at the time that NRL purchased evaluation samples of the P4428. Accordingly, the first four units delivered were initially provided with hand-tooled prototypes of the power supply. Production versions of the power supply were retrofitted when they became available.

The first Navy demonstration of the prototype P4428 occurred in June 1984, at the FFD and at the Fleet Training Center Fire Fighting School, San Diego, CA (FTC San Diego). At that time, the new imager was used by Fire Department and Training Center personnel in a boiler room simulator and during helicopter crash training.*

Many of the people involved in this demonstration had previous experience with the P4228, and the consensus was that the new version represented a major improvement. The ability to operate the P4428 with one hand was the most important improvement; the P4228 required both hands under most circumstances. Also significant, but of lesser importance, was the superior image provided by improvements in the signal processing electronics. The objectionable flicker in the chop mode was almost eliminated, and image tailing was reduced. As a result, the chop mode was thought to provide better images than the pan mode, and it was easier to use [19].

Shipboard Evaluation of the P4428

During the fall of 1984, there were two opportunities to conduct shipboard evaluations at the F&STD facilities in Mobile, AL. The first chance occurred during the USCG Localized Fire Extinguishing Systems (LFES) test aboard MV *Mayo Lykes*. The second arose during the David Taylor Naval Ship Research and Development Center's tests of collective protection system (CPS) designs proposed for the USS *Arleigh Burke* (DDG-51) ship class. The latter tests were conducted aboard *A.E. Watts*.

LFES Tests

The primary purpose of the LFES test series was to evaluate the utility of localized (as opposed to space flooding) carbon dioxide (CO_2), fire-suppression systems for use in machinery spaces. To accomplish this, a marine diesel engine mock-up was built on the first platform deck in the number four hold of MV *Mayo Lykes*, and a CO_2 system was installed in the overhead space above the mock-up. Instruments, including thermocouples, cameras, and lasers (for optical density measurements) were placed throughout the hold. Figure 30 illustrates the test area and the instrument positions. Locations of the CO_2 nozzles have been omitted for clarity.

The requirements of the fire suppression tests dictated that the weather deck entrance to the hold remain closed during the test period. Accordingly, fire fighter access for evaluation of the thermal imagers was limited to the starboard door at the first platform level.

The NRL evaluations took place on 2-3 September 1984 during LFES tests 90 to 93 [20,21]; two model P4428 thermal imagers were used. A Model P4228 was also available and was used during one test to monitor the conditions within the hold. The P4228 and one of the P4428 imagers had

*Due to environmental restrictions on smoke release, the helicopter crash trainer at FTC San Diego is located inside a structure. As a result, a significant amount of smoke builds up during crash drills.

been modified by the installation of a type K (chromel-alumel) thermocouple inside the case near the PEV retina. A second type K thermocouple was attached to the outside of these imagers so that differential thermal measurements could be made. For easy connection to the data logging system, standard thermocouple plugs were provided on all four sensors.

To obtain thermal images comparable to ordinary video images, a thermal imager observation point (IR) was established on the second deck adjacent to one of the standard video camera installations (V), as shown in Fig. 30(b). A video cable, two thermocouple leads, and a power line were provided at this point. The latter permitted the imager to be turned on and off from a remote location and allowed longer operating times than could be obtained with standard batteries.

Test 90 was a dry run during which smoke density and temperature measurements were to be made. The first goal was to verify that the visibility on the first platform deck could be maintained near, and preferably below, 1 m (about 3 ft) for a reasonable period of time. The second goal was to determine whether the temperature at point IR would exceed the thermal imagers' limits. The latter information was required because it was not possible to move the imager after the test started. The standard video camera at point V was in no danger because it was housed in a special insulating container.

In the event that low visibility was not obtained (or could not be maintained) during Test 90, then the fuel load would be increased in later tests. If Test 90 proved that the second deck observation point was too hot, an alternate placement for the thermal imager (at a lower level) would be necessary in the following tests. However, Test 90 demonstrated that the standard fuel load (45 ℓ (12 gal)) of marine diesel fuel, sweetened with a small quantity of mineral spirits) reduced the platform deck visibility to near 1 m in less than 10 min and maintained this low visibility for approximately 20 min. This determination was based on the average of the optical density measurements from lasers L1, L2, L4 and L5. Optical density was calculated according to Eq. (5)

$$OD = \log (I_0/I) \tag{5}$$

where I and I_0 are helium-neon laser intensities with and without smoke, respectively, measured over a 1 m (3.28 ft) path length. Visibility, for the case of front illumination, is defined by Eq. (6).

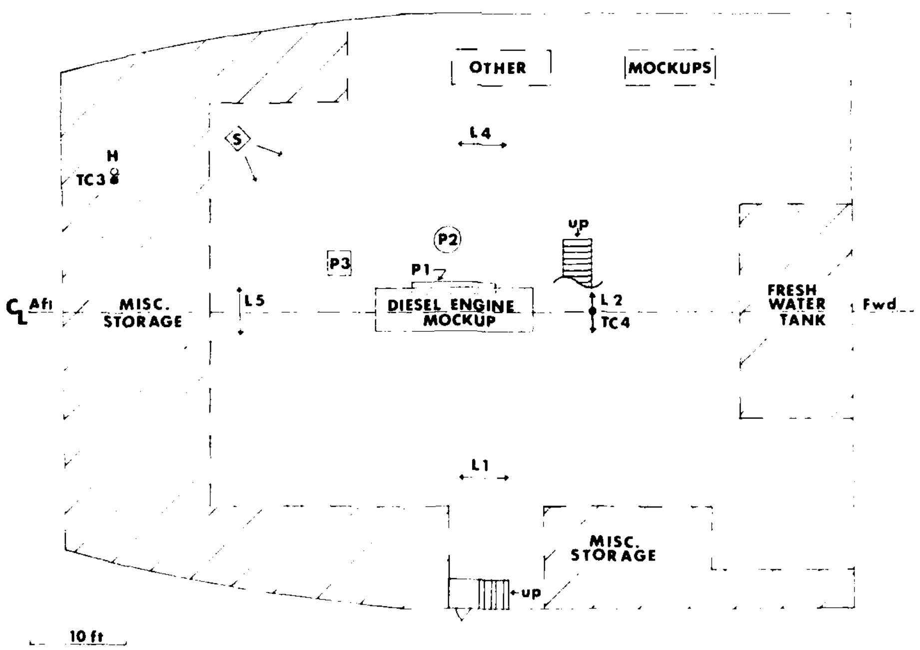
$$Vis \equiv 1/OD. \tag{6}$$

Also, the maximum temperature at the second-deck observation point was found to be about 50°C (122°F), much lower than had been anticipated. This was well below the thermal imagers' temperature limit for a 1h exposure (the planned test duration) and was not expected to pose any problems for the imagers.

Based on these results, the plans for Test 91 were finalized. The P4228 imager was installed at point IR, and both the internal and external thermocouples were connected. The imager's field of view was adjusted to cover the port side of the mock-up, approximately the same area viewed by the television camera at V. The modified P4428 was to be given to a USCG fire fighter who would use it inside the hold. A 30 m (100 ft) umbilical (coax video cable plus two thermocouple extension cables) from the point of entry was to be used for data acquisition (video and temperature) and as a safety line in the event of an emergency. The fire fighters' entry into the hold was scheduled for t = 10 min, with their exit at about t = 30 min; this would leave them with about 10 min of reserve air.

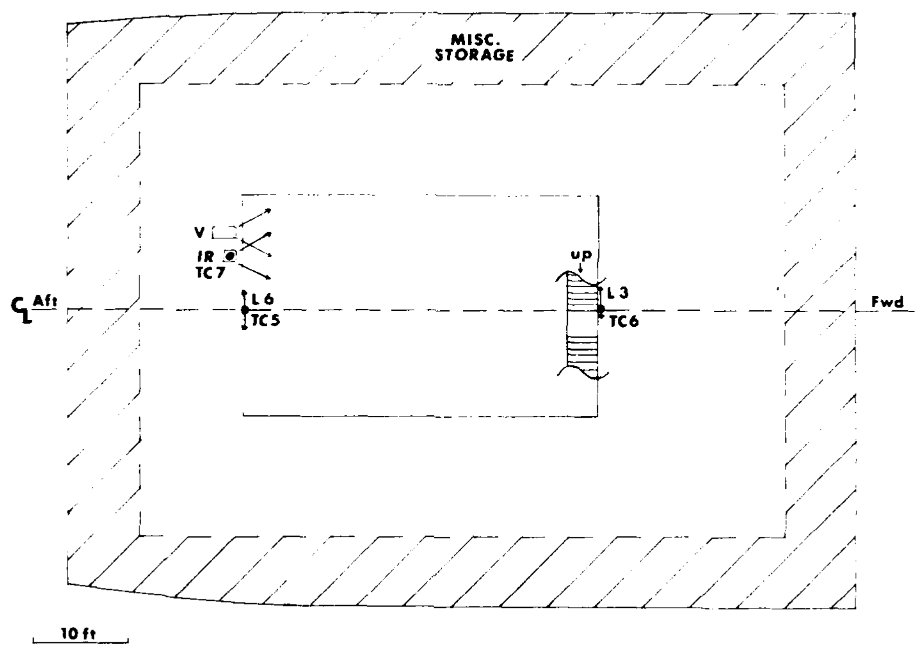
Instrument and equipment locations are indicated by the following symbols in Fig. 30:

←L→	laser (beam oriented parallel to arrow)
TC •	thermocouple
[S]<	still camera field-of-view
[V]<	video camera field-of-view
[IR]<	thermal imager field-of-view
H||	heater wands
P	fire pan

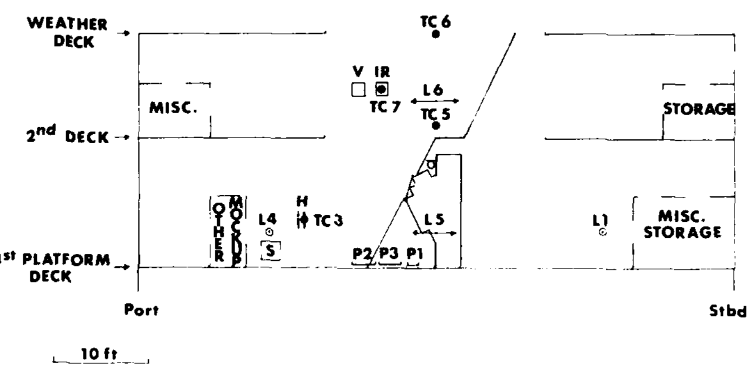


(a) Plan of view of first platform deck

Fig. 30 — Diagrams of test area aboard MV *Mayo Lykes* during September 1984 LFES tests show the configuration of the number four cargo hold



(b) Plan of view of second deck



(c) Cross-section of hold as viewed from aft

Fig. 30 (Cont'd) — Diagrams of test area aboard MV *Mayo Lykes* during September 1984 LFES tests show the configuration of the number four cargo hold

The plan called for a team of two fire fighters (wearing the standard turn-out coats and pants used by civilian fire departments), to enter the hold through the starboard door. The team leader would use the thermal imager to navigate, to avoid obstacles, and to locate the fires. The second man would follow the leader (maintaining contact through the umbilical cord) and would be responsible for managing the cable by paying it out or taking it in to avoid entanglement. In actual fire fighting, there would be no umbilical cable and the second man would probably have been responsible for a firehose. For safety reasons, a third fire fighter equipped with the second P4428, was kept on standby just outside of the entrance to the hold.

The fire fighting team was to move around the forward end of the diesel mock-up to the vicinity of the ladder going to the second deck, Fig. 30(a). At that point, the leader was to proceed aft along the port side of the test area while the second man maintained his position. The purpose of this separation was to ascertain at what distance a fire fighter could be seen.

While at the aft end of the mock-up, the team leader was to locate the fires and survey the fire damage. Two small, cylindrical 15 W heater wands [(2 cm diam × 46 cm L (0.75 × 18 in.)] were mounted vertically with a spacing of 2 cm (0.75 in.) to estimate the imager's spatial resolution under realistic conditions.

After surveying the aft area, the leader would rejoin his partner, and both would move up the ladder to the second deck to investigate the port side. Investigation of the starboard side was an option, depending on their air supply. The team would then descent the ladder, retrace their steps back to the starboard hatch and exit from the hold. The investigation of the second deck was included in order to evaluate the difficulty of climbing ladders while using the camera and also to expose the camera to higher temperatures and denser smoke.

Preparations for Test 91 proceeded according to plan until almost the last moment, when video interference suddenly appeared on both thermal imagers. This was attributed to noise pick-up from the various pumps that were turned on just before the ignition. Apparently the internal thermocouples, attached to the long, unshielded extension cables, acted as antennas.

The thermocouple inside the P4228 was especially disruptive, possibly because that cable was routed closer to power lines and other noise sources. Since it was not possible to obtain good images while simultaneously monitoring internal temperatures, the internal thermocouple was disconnected from the P4228 just before the start of the test. There were no previous data recording the temperature extremes into which fire fighters might carry a thermal imager; therefore the thermocouple installed in the P4428 was not disconnected. This resulted in degraded, but still usable, images for the fire fighter and on the video monitor located in the control room.

After ignition, the fire fighters followed the test plan to the point where they were supposed to operate on the second deck. Unfortunately, the temperature proved to be too high on the upper level, and both fire fighters were forced to retreat. The temperature at the top of the ladder during that period was later determined to have been slightly over 60°C (140°F). Apparently, this represents the upper limit for fire fighters wearing standard civilian turn-out clothing. Navy fire fighters wearing the recently developed fire fighters' ensemble are expected to have similar limitations. The temperature limit is significantly lower for sailors without this special protection.

Due to the problems encountered during Test 92, the plans were changed slightly for the following test. First, the modified P4428 would be used at the second deck observation point in an attempt to obtain useful thermal response data for the new imager. The unmodified P4428 would be given to the fire fighters to provide them with improved IR imagery. Finally, one of the fire fighters chose to wear a proximity suit, rather than the standard turn-out gear, in order to increase this thermal protection.

During Test 92, the use of the unmodified P4428 did result in improved images for the fire fighters as expected. Somewhat surprisingly, an improvement in the image from the second deck monitor camera was also noted. This may have been due to improved EMI resistance in the P4428, as opposed to the P4228, or it may have been caused by a fortuitous reduction in electromagnetic noise during Test 92 relative to that during Test 91.

Test 93 was virtually a repeat of Test 92, except that a different fire fighter operated the P4428 thermal imager. As an experiment, he chose to switch between pan and chop operating modes during the test. Flicker was noticeably worse in chop mode than in pan mode, especially when viewing very hot objects. Nevertheless, flicker in the P4428 was substantially less than that produced by the P4228. In general, the chop mode produced better images than the pan mode. This was attributed to the fact that operation in the pan mode required more technique and was therefore more difficult for inexperienced operators. The new image processing system was considered to be a significant improvement.

During the time that the fire fighters were on the port side of the engine mock-up, the visibility (estimated from L4 data) varied from approximately 0.9 m to slightly over 1.0 m (about 3 ft) on the first platform deck. The lack of visibility is graphically illustrated by thermal imager videotapes which show one of the fire fighters attempting to coil the umbilical cable. As he fumbles with the cable, it is obvious that he cannot see what he is holding in his hands. The thermal imager operator, however, has no trouble seeing his partner, the engine mock-up, and even the hatch covers at the top of the hold—a distance of about 10 m (32 ft). Laser data (L3 and L6) indicate that the visibility on the second deck was about 0.7 m (2 ft). Near the hatch covers it would have been even less.

Very poor images, characterized by noise and near whiteouts, were obtained from the monitor camera on the second deck during this test. This is partly attributed to electrical noise introduced through the thermocouple. However, inspection of the internal temperature data reveals that a temperature of about 55°C (131°F) was maintained during most of the test period. Since this approaches the Curie temperature of the PEV retina, it is reasonable to assume that the whiteout effect may have been due to the high internal temperatures.

The Model P4428 thermal imager was found to be easier to use than the older P4228 because of its reduced size. Also, the new model provided improved images. Some electromagnetic noise problems were encountered but these were attributed to the thermocouple modifications and would not be expected to occur in unmodified operational units. There was some indication that the P4428 might be slightly more EMI resistant than the older model.

As expected, the smoke penetration capability was excellent. The operators were able to clearly see objects at distances over 10 m (32 ft) when the naked-eye visibility (as estimated from laser data and confirmed by the fire fighters) was 1 m or less (less than 3 ft).

Due to the temperature limitations of the IR detector, questions had been raised regarding the operational lifetime of the thermal imager. The results of tests 92 and 93 are, therefore, of particular interest because the monitor imager was exposed to the most extreme temperatures during these tests.

Figure 31 shows the ambient temperature near the monitor imager and the imager's internal temperatures during tests 92 and 93. During test 92, the monitor imager was exposed to an average temperature of 63°C (145°F) for almost 30 min, with a peak temperature of 79°C (174°F). During this period, the internal temperature of the imager rose from 31°C (88°F) to a maximum of 43°C (109°F) and then cooled to 39°C (102°F). The imager remained in position in the hold while test 93 was being prepared. During this period (approximately 2 h), the internal temperature of the imager rose slightly, to 41°C (106°F). In test 93, the average ambient temperature was 65°C (149°F) with a maximum of 82°C (180°F). The imager's internal temperature reached a peak of 56°C (133°F).

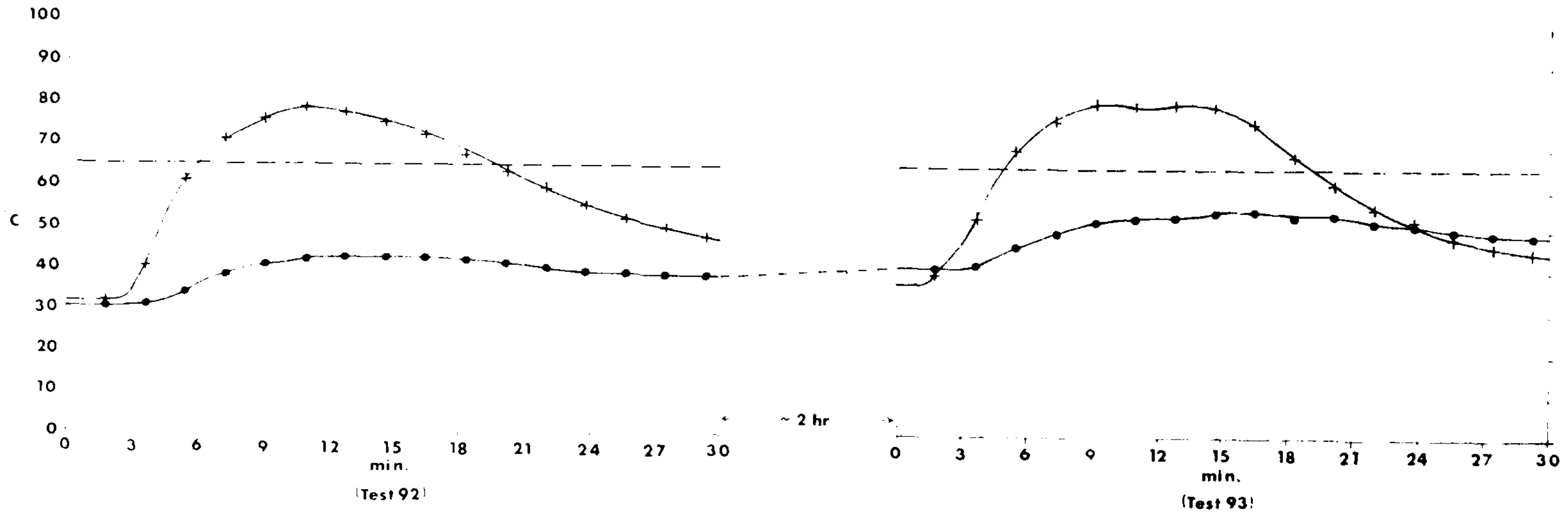


Fig. 31 — Thermal imager ambient and retina temperatures. Ambient temperature (+) and monitor camera internal temperature (•) as a function of time during tests 92 and 93. The horizontal dashed line represents the approximate upper limit for personnel wearing standard civilian turn-out clothing, as determined during test 91.

The imagers were designed with the assumption that they would be stored at approximately room temperature and would therefore initially have an internal temperature of approximately 24°C (75°F). Aboard ship, this condition will be assured by the Navy requirement that imagers be stowed in air conditioned spaces, such as Damage Control Central. The internal temperatures at the start of tests 92 and 93—31°C (88°F) and 41°C (106°F), respectively—were significantly higher than the intended stowage temperature. Thus, the conditions encountered in these tests represented a combination of elevated stowage temperature and extreme operational exposure. Even under these conditions, the P4428 continued to operate, albeit with degraded imagery. Based on this performance, it is anticipated that the temperature limits of the imager should not be a major factor under reasonable operating conditions.

The previously mentioned heat wands did provide some useful information regarding the P4428 imager's spatial resolution. When operated at a temperature differential of approximately 25°C (45°F) above ambient, the two wands were clearly resolved at distances of about 3 m (10 ft). This corresponded to a spatial resolution of about 13 mrad which may be compared to the 14 mrad estimate previously obtained for the P4228.

Considering the differences in test conditions, this is remarkably close agreement. The test target used for the P4228 estimate was an unheated plate with stripes of differing emissivity, whereas the more recent test used a heated target. The apparent ΔT in the former case (due mostly to the different heating rates of the painted vs the bare aluminum) was probably rather low. In the latter case, the ΔT was definitely large. These results are consistent with the general observation that spatial resolution improves with increasing temperature differences.

As with the earlier estimate, the spatial resolution value derived from these measurements should not be regarded as definitive. At best, it represents only a single point from the resolution vs temperature curve. However, from a practical standpoint, the measurements collectively indicate that fire fighters may reasonably expect to see features on the order of a few centimeters (several inches) in size at useful distances (i.e., within the confines of a compartment or passageway).

CPS Tests

From 1 to 7 November 1984, another thermal imager evaluation was conducted aboard *A. E. Watts* [21]. The primary purpose of this test series was to evaluate new concepts in smoke control and removal for the collective protection system (CPS) proposed for USS *Arleigh Burke* (DDG-51) class destroyers. The aft superstructure of *A. E. Watts* was reconfigured to simulate a portion of the CPS system. Three CPS zones were established, each extending vertically from the main deck through the 02-level. Zone one incorporated a fully controllable ventilation system, while zones two and three were maintained at constant positive pressure to simulate the effects of neighboring, undamaged CPS zones. Tests were conducted on the 01-level (Fig. 32) while environmental conditions were monitored on all three decks.

The 01-level test area configuration was similar to that previously used (see Fig. 29) except that the starboard and athwartship passageways were included within the boundary, and the port passageway was extended forward to include an additional compartment (01-2) and to permit the construction of an air-lock entrance to the CPS zone.

Each test was divided into three phases. In phase I, a simulated stateroom fire was set in compartment 01-5 (Fig. 32) using 154 kg (340 lb) of class A material. To simulate a small hydraulic or fuel line leak, 11.4 ℓ (3 gal) of marine diesel fuel were pumped into the fire. When the fire alarm sounded, zone one ventilation was reconfigured to test various smoke control options. In phase II,

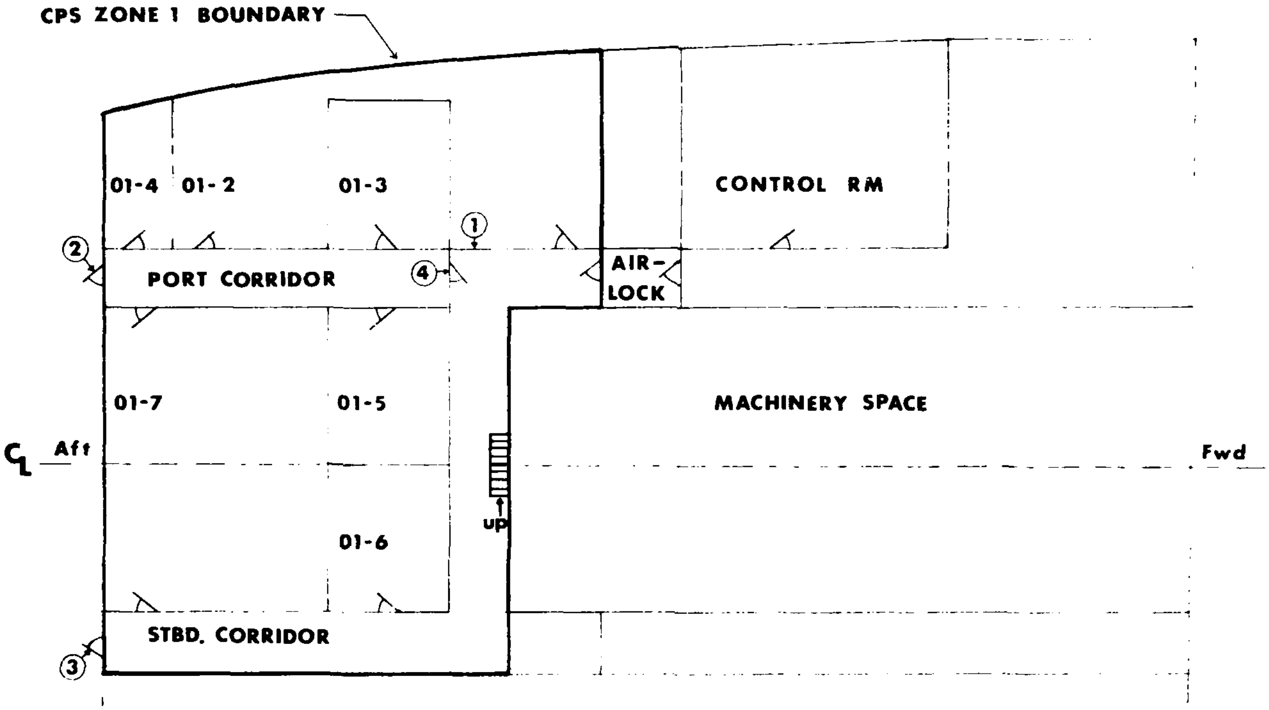


Fig. 32 — Deck plan of *A. E. Watts* 01-level during November 1984 collective protection system (CPS) tests. For all tests, the fires were located in compartment 01-5. IR windows at ① and ② permitted observation of the athwartship and port passageways during the tests. The port watertight door ② was secured for the duration of each test, and fire fighters entered and left the CPS zone via the starboard hatch ③. The interior door ④ was open during the imager tests to allow smoke to fill the zone.

smoke was allowed to build up within the zone so that thermal imagers and emergency egress route markers could be evaluated. In the final phase, the interior door ④ was closed to maximize smoke density in the port corridor and a smoke knockdown system was tested.

The thermal imager evaluations that were carried out during this period were intended to address two issues: 1) the evaluation of possible alternatives to the P4428 and 2) the development of a doctrine for the use of thermal imaging equipment by Navy fire fighters. Consequently, part of the available test time was devoted to the evaluation of the AGEMA Thermovision 110, and the results of those tests are reported in a following section of this report. During the remainder of the time, two USCG fire fighters and one civilian engineer used the P4428, as they would have in actual fire fighting, to navigate through the smoke-filled passageways, locate the fire, and investigate damage. Although little technical information was acquired, the operational experience was a valuable contribution to the development of training, tactics, and doctrine.

Several different Model P4428 thermal imagers, including the one with an installed thermocouple, were used during these tests. Infrared-transparent windows at positions ① and ② permitted observation of the athwartship and port corridors even when they were filled with dense smoke. Because instrumentation had been installed in the port watertight door ②, it was not feasible to use this entry point during a test. Accordingly, all thermal imager evaluations were conducted by personnel entering through the starboard door ③ and walking around to the forward end of the port corridor.

All three users of the P4428 reported that the imager performed very well and proved to be a useful fire-fighting tool. The primary problem encountered during the test was the repeated fogging of the lens caused by water condensation and soot deposits. Usually, this could be temporarily remedied by wiping the lens with a rag or glove. In the most severe cases, the fire fighters were able to keep the lens clean for only 5 to 10 s at a time.

The problem of condensation is an annoying one, but almost unavoidable. This problem has been observed on occasions with all thermal imagers yet tested. However, the problem seems more dependent on the fire conditions, such as temperature, humidity, and "oilyness" of the smoke, than on the imager.

A secondary problem that occurred during some of the tests was the video interference involving the thermocouple-equipped imager. As in the earlier tests aboard MV *Mayo Lykes*, this was apparently caused by pickup of radio frequency noise through the long thermocouple wires. Interference did not cause any significant problems with the unmodified unit.

Electromagnetic Interference and Environmental Testing

The evaluations reported above demonstrate that thermal imaging provides an entirely new fire fighting capability which greatly improves efficiency, decreases response time, and reduces damage. However, many questions have been raised about the suitability of the Model P4428 for shipboard use. The known temperature limitations of the PEV sensor, the susceptibility of the imager to shock or vibration damage and the potential for electromagnetic interference (EMI) were of special concern. Accordingly, the laboratory evaluation of these effects was a high priority, and, when the P4428 became available, four units were committed to these studies. The Naval Surface Weapons Center (NSWC) conducted the EMI and environmental effects tests for NRL. These tests began before the shipboard evaluations and continued into 1985. The performance reduction at elevated temperatures and the EMI problems noted during shipboard testing provided additional incentive to determine the physical limitations of the P4428.

NSWC conducted testing in accordance with MIL-STD-810 (Environmental Test Methods and Engineering Guidelines) and MIL-STD-461 (Electromagnetic Emission and Susceptibility Requirements for the Control of Electromagnetic Interference). They reported [22] that the P4428 failed to pass humidity and thermal shock tests. Although it passed the EMI test simulating the environment below decks, NSWC predicted that some interference would occur in the actual shipboard environment and that permanent damage was likely on an aircraft carrier's electronically noisy flight and hangar decks. All four test units were reported to have significant gas leak rates.

These conclusions were unexpected because they contradicted the highly favorable reports received from the Royal Navy, which already had several hundred P4228 and P4428 units deployed at that time. Consequently, NRL undertook an effort to resolve the apparent discrepancies between laboratory testing and operational experience.

The first step was to visit USS *Enterprise* (CVN 65) and evaluate the imager's EMI response during at-sea evolutions. This evaluation [23] was conducted on 3 May 1985 in conjunction with a Fire Fighting Assistance Team visit to recertify the onboard fire fighting systems for flight operations. Pending the completion of recertification, USS *Enterprise* was restricted to helicopter operations.

The P4428 was used (and the images recorded) in selected areas of the ship (Table 9) starting on the fifth deck and moving upward, toward higher levels of exposure to radio frequency (RF) fields. No performance degradation was observed on or below the main deck (hangar deck) or on any level within the island. Outside the ship's skin, some slight interference was noted during operation of the imager on the 04 level (flight deck), as shown in Fig. 33. The worst manifestation was a series of moving horizontal lines that were intermittently superimposed on the image. In addition to this obvious interference, the P4428 seemed to respond more slowly to sudden changes in scene brightness and seemed to saturate more readily when viewing hot objects. These latter effects were subtle and may have been subjective rather than real interference. However, even the horizontal lines did not significantly compromise the image quality, although they were annoying.

Table 9 — Areas in Which the P4428 Thermal Imager Was Operated Aboard USS *Enterprise* (CVN-65)

Area/Compartment	Description	Results
5-17-0A	Dry goods storage	Excellent image
3-47-2-J	#2 JP-5 filter room	Excellent image
2-106-3	Crews mess	Excellent image
2-107-1	Emergency diesel generator room	Excellent image
Main deck	Hangar	Excellent image
04 level	Flight deck	Slight, intermittent interference
09 level	Balcony	Slight, intermittent interference
09 level	Interior	Excellent image
010 level	Balcony	Severe interference
010 level	Interior	Excellent image
011 level	Balcony	Severe interference
011 level	Interior	Excellent image

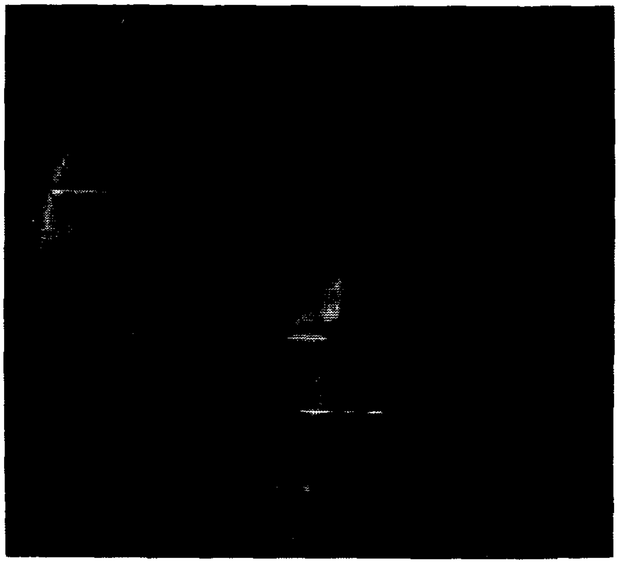


Fig. 33 — Worst-case image obtained on the flight deck of the USS *Enterprise* (CVN 65). Sailors are visible in the center and at the left. An F-4 is in the far background with its tail near the center and nose at the right. (NRL photo taken from videotaped image).

Further observations were made on each balcony through the 011 level. Access to the balconies above the 011 level was prohibited due to the RF radiation hazards during normal ship operations. The periods of intermittent horizontal-line interference increased in frequency from the 04 through the 09 level balconies but were never sufficiently serious to preclude the use of the imager.

Severe interference (Fig. 34) was noted on the 010 and 011 level balconies. At those position, jagged black and white bands totally obscured the image most of the time, but acceptable imagery was intermittently possible. Excellent images were obtained within the island, even at the 010 and 011 levels. The imager's automatic iris began to oscillate slightly at the 011 level. This effect was detected only because of the audible cycling of the iris drive motor and limit switch. No noticeable degradation of the image could be attributed to this oscillation. The use of pan mode resulted in a slight reduction of the interference, but the P4428 was effectively useless on the balconies above the 09 level.

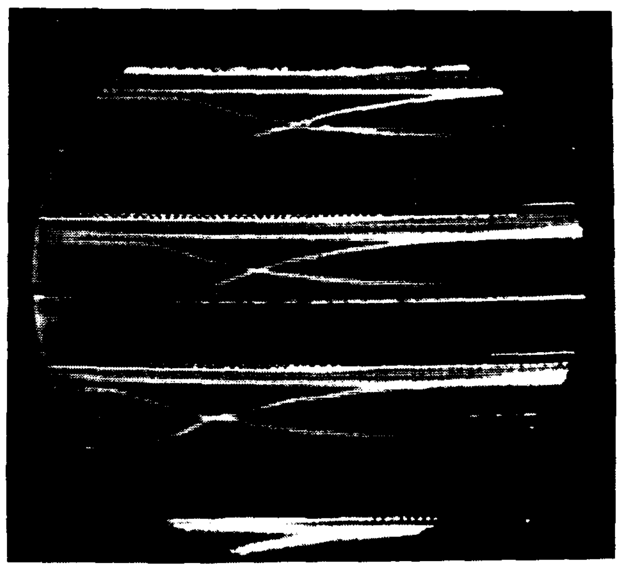


Fig. 34 — Worst-case image obtained on the 010-level balcony of USS *Enterprise* (CVN 65). (NRL photo taken from videotaped image).

These results may not be entirely applicable during full flight operations, but they are in agreement with the Royal Navy's operational experiences. Since it is unlikely that the RF field strength inside the ship's skin would increase greatly during full operations, this evaluation strongly suggested that the potential for EMI problems within the ship would not be as severe as indicated in the NSWC report [22]. Also, concerns that the P4428 might be damaged or even destroyed merely by carrying it across the flight or hangar deck appear to be groundless. Although some EMI susceptibility is possible under extreme conditions, those conditions are unlikely to arise during actual fire fighting. The imager is expected to be used inside the ship, where smoke accumulation is severe, and not on the flight deck or balconies.

In subsequent discussions with NSWC, it was determined that the RF field strength hypothesized in their report did indeed correspond to extreme levels which would not normally be encountered below decks.

The second phase of NRL's effort to resolve the discrepancies between laboratory test results and operating experience involved as assessment of the environmental test methods and the intended purposes of those tests, as stated in MIL-STD-810. The results of this analysis [24] revealed that many of the discrepancies, especially those involving humidity and thermal shock tests, can be traced to excessively severe test conditions. The humidity test, for example, uses an elevated temperature and relative humdity in order to accelerate the test. The upper temperature limit used in that test, 65°C (149°F), was above the Curie point of the PEV imaging tube. Thus, it was inevitable that the imager would fail. In other cases, the test procedure was found to be inappropriate. For example, the leak test involved pressurization of the imager case and measurement of the outward leakage. However, the case was designed to vent internal overpressure (in order to avoid a potentially catastrophic failure) while preventing inward leakage of possibly explosive or corrosive gases. The appropriate test procedure is to partially evacuate the case and measure the inward leak rate.

The results of this comparison between laboratory testing and operational usage underscored the importance of careful selection of test conditions and procedures. If the test environments do not represent realistic conditions, then the test results have little meaning in the real world.

EVALUATION OF ALTERNATIVES TO THE ENGLISH ELECTRIC VALVE THERMAL IMAGERS

Throughout the evaluation program, NRL has had frequent contacts with industrial and military development laboratories in order to stay abreast of new technologies in thermal imaging. The Army Center for Night Vision and Electrooptics (CNVEO, formerly the Army Night Vision and Electrooptics Laboratory) has been especially helpful in this regard. They have made available several prototype systems that incorporate state-of-the-art thermal imaging technology, and CNVEO personnel have participated in evaluations of those devices at the CBD facility. The most recent of these tests involved engineering development models of the Short Range Thermal Sight (SRTS). The SRTS will be the Army's next generation night rifle sight.

The SRTS devices and similar prototype systems were not configured to meet fire fighting requirements and were treated as technology testbeds, rather than as serious candidates for the Navy application. For this reason, none of those devices is discussed in this report. However, some of the imaging technology that was demonstrated, especially that of the SRTS devices, does offer the promise of significant performance improvements in second- and third-generation fire fighters' imagers.

As was previously mentioned, several companies other than EEV are now producing thermal imagers in the same size, weight, and price range as the P4228 and P4428. Unlike the military prototypes mentioned above, these devices were considered as candidates for Navy procurement. The early evaluation of the Hughes Aircraft Company Probeye imager, conducted by Alger and Gordon, has already been discussed. More recently, Xedar Corporation and AGEMA proposed various models from their respective product lines as alternatives to the EEV devices. The design and specifications of the XS-410 and the AGEMA Thermovision 110 have been described in detail in a previous section of this report.

Although the results of the evaluations are reported here independently of the EEV results, the work described in this section was actually performed in parallel with the evaluation of the EEV devices.

Demonstration of the Xedar XS-410

In March 1983, an evaluation of the XS-410 was conducted at the NRL Chesapeake Bay Detachment using the smoke chamber shown in Fig. 19. Because of the similarities of the imaging technology used in the XS-410 and the EEV P4228 (this test occurred prior to the introduction of the P4428) the performance of the two imagers was expected to be comparable. However, differences in packaging and construction justified a test.

The XS-410 was loaned to NRL for this test, and a Xedar representative was present to demonstrate the imager and to assist in some aspects of the evaluation. Because the imager was neither thermally insulated nor hermetically sealed, it was not capable of functioning in the smoke, water, and heat of the typical fire fighting environment. As a consequence, the use of completely realistic test conditions was not feasible. Nevertheless, valuable information was obtained, especially about the man-machine interface [25].

As in previous tests performed in the CBD smoke chamber, JP-5 fuel sweetened with Avgas was burned to produce dense black smoke. Approximately 3.9 ℓ (4.0 qt) of fuel were used and the fuel was divided equally among three metal pans. During the initial test phase, the XS-410 was mounted on a tripod outside the chamber. Observations of the interior were made through an IR-transparent window (polyvinylidene chloride film). At the time of the test the ambient temperature was approximately 0°C (32°F). In the second phase of the test, the imager was wrapped in plastic (for protection against smoke and condensation) and was taken into the smoke chamber by a fire fighter. The temperature in the chamber was monitored to ensure that the relatively vulnerable XS-410 was not damaged. Peak temperatures were found to be about 120°C (250°F).

The XS-410, as expected, provided excellent images and clearly showed structural features at the opposite end of the chamber, a distance of 8.5 m (28 ft). Using a series of water-filled polyethylene bottles as targets, the XS-410's spatial resolution was estimated, as previously described for the EEV P4228. At a range of 3 m (10 ft), all bottles were easily resolved. Since there were no unresolvable targets, the actual spatial resolution limit could not be determined. However, using the diameter of the smallest targets—2.5 cm (1 in.)—the resolution was estimated to be better than 8 mrads.

Because of the dependence of the spatial resolution on scene temperature differences, this resolution estimate is of limited applicability. However, since the EEV P4228 and the Xedar XS-410 were tested under essentially identical conditions, the results can be used as a measure of the relative performance of the two systems, albeit under a restricted set of conditions.

Table 10 shows the comparisons. Although the absolute spatial resolutions differ by a factor of two, the FOV-normalized resolutions are the same. The normalization process is required because the large difference in the fields of view makes direct comparison meaningless.

Table 10 — Spatial Resolution Comparison Between the EEV P4228, P4428, Xedar XS-410, and Thermovision 110

	EEV P4228	EEV P4428	Xedar XS-410	Thermovision 110
Nominal FOV (deg)	55	55	27	12 H × 6 V
Estimated Spatial Resolution (mrad)	17	17	8	8
Normalized Resolution (mrad/deg)	0.309	0.309	0.296	0.667

One goal of this demonstration was to determine how much automation is required in a fire fighting imager. Specifically, the trade-offs between ease of use and improved imagery were evaluated. The XS-410 incorporates controls for focus, iris, display contrast, and display brightness, whereas the P4228 has none of these adjustments. In theory, the XS-410 is capable of providing better images since the control settings can be optimized for the viewing conditions.

In practice, the necessity for making continual adjustments caused a significant increase in the operator's workload and distracted the fire fighter from the primary task of attacking the fire. Also, manual adjustments proved to be too slow to compensate for the rapid intensity changes encountered. Thus, the hypothetical image improvement never materialized. These results made it clear that ease of use is extremely important to the fire fighter—more important than improved imagery or reduced weight.

Demonstration of the AGEMA Thermovision 110

An initial evaluation of the AGEMA (then AGA) Thermovision 110 was conducted during May 1984 at the NRL Chesapeake Bay Detachment smoke chamber [26]. AGEMA lent an imager for use in this test, and a company representative was present to observe and to provide advice regarding the operation of the imager.

Because of the vast technological and engineering differences between the Thermovision 110 and the EEV P4428, several major questions needed to be addressed during this evaluation. The foremost of these was whether the Thermovision 110, operating in the 3 to 5 μm IR band, would be capable of penetrating dense smoke. None of the previously tested short wavelength imagers (including the Army's AN/PAS-7, which was the military predecessor of the Thermovision 110) had proven to be satisfactory. However, at the time of these tests, the Thermovision 110 was already in use aboard some Navy ships (for preventative maintenance inspections) and it would have been logistically advantageous to use the same device for fire fighting. Accordingly, it was appropriate to evaluate the potential of the Thermovision 110 for this new application.

As in previous tests at the CBD smoke chamber, 3.9 ℓ (4.0 qt) of a 3:1 mixture of JP-5 and Avgas was burned to provide zero visibility. The imager was setup on a tripod outside the chamber (using a polyvinylidene chloride window) and the previously used set of water-filled polyethylene bottles provided targets inside the chamber. The distance from the window to the targets was 3 m (10 ft). For these tests, the Thermovision 110 was equipped with a special eyepiece which permitted a Polaroid camera to be coupled to the imager.

Image quality under these conditions was surprisingly good, with all targets resolved and a significant amount of background detail visible at ranges up to 8.5 m (28 ft). As in the case of the Xedar XS-410, the absence of unresolved targets prevented a determination of the actual spatial resolution of the Thermovision 110, but an upper estimate of 8 mrad was obtained. After correcting for the different fields of view, the normalized resolution of the Thermovision 110 was estimated to be about half that of the other imagers. The results of this evaluation have been included in Table 10.

Following the test described above, the fire fighter took the Thermovision 110 into the smoke chamber for operational evaluation. Under heavy smoke conditions (again produced by a burning fuel mixture), the imager was used to navigate and to locate hot spots. The eyepiece was replaced by one of a larger diameter which provided better visibility when used with a breathing apparatus mask. As in the previous test, the image quality was much better than had been predicted.

The operating controls of the Thermovision 110 (focus, display brightness, and display contrast) resemble those of the Xedar XS-410. For this reason, it was anticipated that fire fighters would encounter a similar level of difficulty in operating the Thermovision 110. However, no such problems were reported. This difference may be attributed to a combination of several factors. In general, it appears that display brightness and contrast are not subject to wide variations under normal operating conditions; therefore, those controls require little or no attention from the operator. The sensor is subjected to large, rapid changes in intensity during a fire, so frequent adjustment of the iris may be required. Since the Thermovision 110 permitted no such adjustment (and, in fact, does not have an iris), a significant portion of the workload was eliminated. The slow advance of the fire fighter, coupled with the relatively large, uncluttered space in the test chamber, minimized the requirements for refocusing. Thus, the Thermovision 110 required much less attention from the operator than had been expected.

The most significant conclusion from these tests was that operation in the 8 to 14 μm band might not be an absolute requirement for fire fighting thermal imaging systems. This had significant implications concerning the development of a second generation imager. In particular, the possible use of the 3 to 5 μm band would permit consideration of many detector options that would otherwise be precluded. Based on the positive outcome of these tests, a Thermovision 110 was purchased for further evaluation, and additional tests were planned.

Shipboard Evaluation of the Thermovision 110

Follow-on testing was conducted at USCG Fire and Safety Test Detachment during 1 to 7 November 1984 [26]. This work, carried out in conjunction with collective protection system tests, was performed in parallel with the previously discussed shipboard evaluation of the EEV P4428.

Figure 32 illustrates the layout of the test area on the 01-level of *A. E. Watts*. All fires were set in compartment 01-5; clothing and bedding were used to simulate the fuel load that might be present in a typical stateroom. To promote ignition and to simulate class B fuels that might be present, 11.4 ℓ (3 gal) of marine diesel fuel were added.

A Kodak Irtran 2 (zinc sulfide) IR window, installed in the watertight door at the aft end of the port passageway, permitted conditions within the corridor to be observed and photographed with the

Thermovision 110. Because of the attached instrumentation, this door remained secured throughout each test. Thus, in those tests in which the imager was used inside the test area, the fire fighters entered through the starboard watertight door, crossed via the athwartship passage, and approached the fire from forward.

As an aid in estimating visibility during the tests, floodlights at the forward end of the corridor were oriented towards a viewing window adjacent to the IR window in the aft watertight door. The Thermovision 110 was adjusted so that these lights were not in the imager's field of view. The distance from the lights to the viewing window was approximately 8 m (26 ft).

The Polaroid camera adaptor eyepiece permitted photographs to be taken during all tests in which the Thermovision 110 was used to observe the test area from the outside. Also, the fire fighters tried the small eyepiece during some of their evaluations and used the larger eyepiece in the remaining trials.

Photographs taken with the Polaroid attachment are shown in Fig. 35. Figure 35(a), taken just before the start of the test, illustrates the pattern recognition problem that often occurs when imagers with narrow FOV (telephoto) optics are used in close quarters; large objects are visible but not easily identifiable because only small portions can be seen. This situation did not arise during the CBD tests due to the small size of the targets used. This is one of the reasons that a wide FOV has been recommended for the fire fighting application.

In Fig. 35(b), taken approximately 20 min after the test began, the deterioration of the image is clearly evident. The smoke was relatively light at the time that the photograph was taken (the floodlights in the passageway were still clearly visible through the viewing window) yet almost all the details have been obscured in the thermal image.

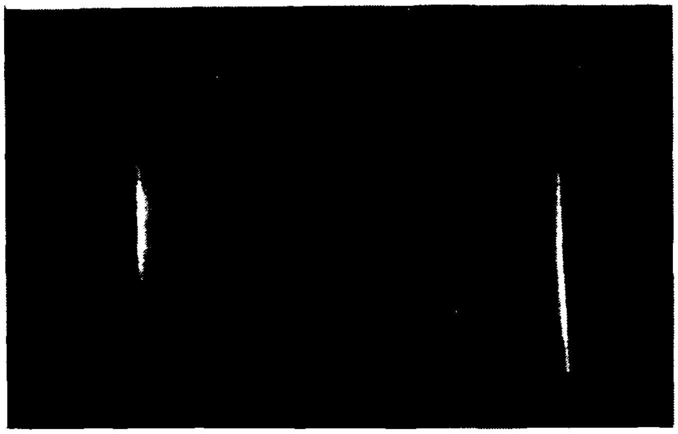
It was not feasible to photograph the image while the Thermovision 110 was being carried and used by the fire fighters. Thus, the evaluation of that phase of the test was dependent on the operators' comments. Their major criticism was that the Thermovision 110 had a very limited effective range—estimated to be approximately 2 m (6 ft).

The reason for the discrepancy in estimated operating range between the test at CBD and the shipboard test (8.5 m and 2 m, respectively) could not be definitely determined, but was presumed to be due to differences in test conditions. Since the shipboard tests were more operationally realistic, and because those results were in better agreement with previous evaluation of similar imagers, it is likely that the 2 m estimate is more accurate.

This evaluation demonstrated the importance of a relatively wide FOV for an imager used in confined spaces. The minimum acceptable viewing angle was not determined, but was clearly much greater than the 12° (horizontal) provided by the Thermovision 110.

To a lesser extent, the requirement for simplicity of operation was also reconfirmed. Consideration of these results in conjunction with those obtained for the Xedar XS-410 suggests that the manual iris is the largest contributor to operator workload. It follows that the elimination or automation of this function should receive a high priority in future designs.

(a)



(b)

Fig. 35 — Thermovision 110 images obtained during November 1984 collective protection system tests. The Thermovision 110 was set up on the fantail of *A. E. Watts* looking forward through the IR window in the water-tight door of the port corridor (Fig. 32). Photograph (a), taken prior to the start of test 19, illustrates the image obtained when no smoke was present in the corridor. Photograph (b) was taken 20 min after the test began when light smoke was present. Lights at the forward end of the port corridor were still visible through the viewport adjacent to the IR window but were outside the FOV of the Thermovision 110.

PART III—PROCUREMENT AND DEPLOYMENT

DOCTRINE FOR THE P4428

In April 1985, the Naval Sea Systems Command (NAVSEASYSCOM) formerly requested authorization to procure P4428 thermal imagers for immediate use by the Fleet. This decision was based primarily on the results of NRL evaluations and secondarily on reports of Royal Navy operational experience. NAVSEASYSCOM recognized that the P4428 had some minor technical shortcomings that would necessitate some operational restrictions, such as stowage in air-conditioned spaces. However, the new fire fighting capabilities provided by thermal imaging were considered to be sufficiently important to justify a limited deployment of the best available commercial system, pending development of better devices. For easy reference, the new system was designated the Naval Fire Fighters Thermal Imager and was given the acronym NFTI, pronounced "nifty."

The prospect of near-term deployment caused a redirection of NRL efforts towards collection of the technical information required for development of a doctrine for use of the P4428 and for development of a training curriculum to implement this doctrine. NAVSEASYSCOM authorized NRL to procure thirteen additional Model P4428 thermal imagers to be issued to Navy fire fighting and damage control schools. This permitted the instructors to become familiar with the new equipment and allowed the course curriculum managers to write lesson plans, known as lesson topic guides (LTGs), for the thermal imager. In parallel with this effort, NRL began drafting a doctrine based on the experience acquired during test and evaluation, conducted additional evaluation exercises specifically for the purpose of developing the doctrine, and worked with the training commands to validate the draft doctrine.

Shipboard Cable Fire Fighting Test

Previous evaluations of the P4428 always had some unrealistic aspects. Those that were conducted at schools involved Navy personnel, equipment, and procedures, but the fire fighting environment was somewhat artificial. Those carried out aboard ships at the USCG facility involved real fire fighting environments, but the equipment and procedures often deviated from Navy standards. Neither case provided an adequate test of the integration of the imager into the Navy fire fighting doctrine.

The Navy electric cable fire tests and the Navy electrical cable fire fighting tests provided an opportunity to fill this gap [27]. A total of 40 cable fire tests were conducted aboard the test ship *A. E. Watts* at the USCG Fire and Safety Test Detachment from April to August 1985. Eight of those were dedicated to testing fire fighting equipment and methods. With the exception of the equipment under test, standard, Navy-issue fire fighting equipment was used. The attack team, composed of Navy fire fighters and fire fighting instructors, used Navy procedures that were modified as required to evaluate new concepts and take advantage of the capabilities of the new equipment. A separate support team provided hose tenders and emergency backup, but did not participate in the actual fire fighting. Table 11 lists the test personnel and their qualifications.

The attack team, consisting of a nozzleman, NFTI operator, and two hose tenders, was smaller than that currently required by Navy doctrine. This was done to evaluate the feasibility of future

Table 11 — Test Personnel

Attack Team Members	
LT Terrence Toomey (USN, Ret.)	Past qualified fire fighting instructor and field chief.
EMC Bill Owens (USN)	Qualified field chief for live fire fighting evolutions at USN Fire School, Charleston, S.C.
PS1 Al Parker (USCG, Reserve)	Fire fighting instructor for USCG Reserve Unit and invited instructor at Louisiana State University Fire School.
HT3 Glen Landon (USN)	Assigned to ship's fire party on USS *Yosemite* (AD-19).
Support Team Members	
DCC Ned Niedringhaus	USCG
Mr. Carl Fulper	NRL

reductions in the size of the fire party. Members of the team were rotated among the assignments. The NFTI operator served as team leader since he was the only person able to clearly see the overall situation.

The NFTI was used by the attack team at least once during each of the fire fighting tests, but not during every entry attempt. The team found the NFTI to be very useful in the following specific areas:

- *Locating the fire compartment access: The compartment* access door was hard to locate when the NFTI was not used. During one entry attempt, the compartment access was passed even though the fire fighting team was quite familiar with the layout of the passageway. When the NFTI was used, the compartment access was located without difficulty.

- Monitoring the hose spray: The NFTI was extremely useful in recognizing water patterns through steam and smoke, allowing the NFTI operator to notify the nozzleman when the stream shape was inadvertently altered during nose handling. This is critical, especially in fighting large pool tires and fires in energized electrical cables, where inadvertent use of a straight stream could be highly dangerous. Figure 36 clearly shows the nozzle pattern—in this case a fan pattern.

- Confirming fire out: The NFTI was successful in confirming fire out. When the fire appeared to be out to the naked eye, pulsations were sometimes seen with the NFTI. Closer visual inspection revealed that cables were still burning within the bundle. After additional hosing, the NFTI showed the fire to be out.

Several significant problem areas were encountered during these tests. The first, obscuration caused by water condensation and soot on the NFTI lens, was familiar from previous evaluations. However, the extreme heat stress observed during these cable fires aggravated this problem in an unforeseen manner. The fire fighters rapidly became fatigued, and the team leader found it difficult, if not impossible, to continuously hold the imager up to his mask. Consequently, the preferred method of operation was to view the surroundings intermittently, allowing the NFTI to hang from its harness most of the time. As a result, the OBA face mask and the NFTI viewing screen, as well as the lens, became covered with soot and condensation. Thus, the operator had three surfaces to clean, rather than only one.

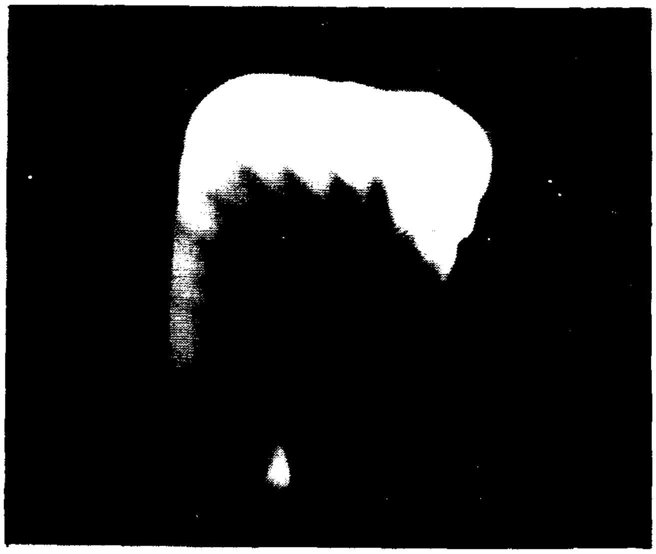


Fig. 36 — The fanlike water spray pattern produced by the nozzle is clearly visible through the NFTI (NRL photo taken from videotaped image).

A second difficulty was caused by poor communications between the team leader and the team members. Due to the very high noise levels encountered, the lack of OBA voice amplification, and the rather poor acoustic qualities of the OBA masks, verbal communication was all but impossible. This is a frequent problem, but it is especially difficult for the thermal imager operator because he has the greatest need to communicate detailed information. The members of the fire fighting team developed a set of tactile signals, involving pushing, pulling, and tapping to impart basic directions. This method, however, was far from ideal. One fundamental problem is that the team members must be in very close proximity for this technique to work, but this is not always feasible or desirable. The thermal imager, for example, was most effective when located far enough behind the nozzleman to provide the team leader with a clear view of the entire scene; that distance was sometimes too far to allow physical contact between the two team members. In the absence of effective voice amplifiers or direct radio contact between team members, the team leader was forced to make a compromise between a good viewing position and a good communication position.

The final, and potentially most serious, problem was discovered when the NFTI was first used with the A-4 OBA. Donning the NFTI harness over the head crimped the OBA hoses and restricted breathing. In later tests, the NFTI was mounted by lacing the harness through and around the central casting of the A-4 OBA. This procedure worked as a temporary expedient but was not truly satisfactory because it made it impossible to easily remove and handoff the NFTI. During these tests, no definitive solution to this problem was found, but several possibilities, including a new harness design, were proposed.

Initial P4228 Issue to Schools

Based in large part on these tests, a draft doctrine was prepared in November 1985, at approximately the same time that the first of the 13 new thermal imagers was received. Beginning in December 1985, these imagers were distributed to selected Atlantic and Pacific Fleet training schools. First priority was given to the fire fighting and damage control schools, which ha . primary responsibility for training sailors in new techniques. The Surface Warfare Officers School was provided with one imager for familiarization training of new DCAs, since they have responsibility for all aspects of shipboard damage control and must be kept aware of new developments in equipment and procedures. Third priority went to representative Fleet Training Units and Groups, which conduct at-sea refresher training on ships that are about to deploy. Copies of the draft doctrine were sent with each imager to guide its use. NRL provided technical information to support curriculum development and also supplied logbooks so that each school's operational experience would be recorded.

The Naval Damage Control Training Center, (NDCTC) Philadelphia, PA took the lead in developing course materials. As curriculum manager for the senior enlisted damage control course, NDCTC wrote the LTG specifically for that course. However, copies of their LTG were circulated among the other schools to serve as the basis for changes in other courses also. FTC, San Diego became the lead school for development of the doctrine, which was extensively rewritten as a result of their suggestions and comments. One strong suggestion that was adopted was to emphasize capabilities rather than specific procedures. They recommended that potential users be told what the imager can do, what it can not do, and how those capabilities had previously been useful. The sailors could then make the best use of the imager depending on their situation.

Interestingly, none of the schools involved in these activities reported crimping of the OBA air hoses by the imager harness. Several alternate methods for carrying the imager were tried, including a new harness design for the imager and the use of spring clips to directly attach the imager to the OBA straps. None of these techniques proved to be superior to the original method and, with due care, it was possible to avoid interference with the OBA.

Shipboard Smoke Curtain Tests

In October 1986, the crew of USS *Spruance* (DD 963) participated in a test aboard *A. E. Watts* at the USCG F&STD. Tests were conducted in the aft superstructure, primarily on the 01-level, which was configured essentially as in the CPS tests (see Fig. 32). Some additional test work was performed on the 02-level.

The primary purpose of these tests was to evaluate alternative designs for smoke curtains, which were intended to control the diffusion of smoke through the ship. A secondary purpose was to provide additional testing of new equipment scheduled to be released to the Fleet, including the P4428 thermal imager.

During the tests, USS *Spruance* sent a different duty section each day and provided their own fire fighting equipment. Smoke curtains, thermal imagers, and other specialized equipment required for the tests were provided by NRL and other laboratories.

One exercise was held each day and, prior to the test, the USS *Spruance* crew members were given a tour of the test area to become familiar with the layout. The planned location of the fire was not disclosed. Although the same location was used each day, the fire fighters were not aware of this and, consequently, had to search for the fire. After the tour, the USS *Spruance* personnel mustered at the bow while the final test preparations were made. After ignition of the fire, smoke was allowed to build-up before the alarm sounded. At the alarm, the fire fighters responded as they would have on their own ship. Test personnel and officers from USS *Spruance*, using OBAs, stayed within the test area and used thermal imagers to observe and video tape the fire fighters in action. A posttest critique session gave the sailors a chance to comment on the equipment and procedures.

The major lesson regarding the thermal imager that was learned from this exercise was the importance of prior training and practice. On several occasions, problems with the imager were reported, and in each case, the cause was operator error due to lack of training and experience. One problem frequently occurred when the operator stood up in an environment containing stratified heat layers. Hot soot particles in the upper layer, being good infrared emitters, caused a whiteout condition somewhat similar to that which occurs when bright lights are used in a fog bank. The effect is almost the same as that observed when the lens becomes coated with soot. The operator would wipe the lens clean and, observing no improvement in the image, report the imager inoperative.

Based on these experiences, and on another round of comments from the training schools, the draft doctrine was again rewritten to place more emphasis on anticipated operational problems and on methods of circumventing those problems. The resulting draft doctrine (Appendix A) has been submitted to NAVSEASYSCOM for formal approval.

FLEET INTRODUCTION

In February 1986, after reviewing the results of NRL's test and evaluation program, the CV Fire Fighting Flag Level Steering Committee approved the P4428 for procurement. NAVSEASYSCOM was directed to immediately proceed with contracting and, at the same time, to pursue a development program for an improved imaging system. The latter was envisioned as a device providing equal or better images in a much smaller and lighter package.

A contract for the purchase of 473 Model P4428 thermal imagers, plus appropriate spare parts, was awarded in July 1986. Deliveries began almost immediately, with the initial units earmarked for aircraft carriers, followed by helicopter-carrying assault ships and other high-value ships assigned to potentially high-risk missions. Eventually, all major surface combatants and selected auxiliary ships are scheduled to receive at least one imager; the largest ships will receive two imagers.

Because of the positive responses from the Fleet, and because the 473 units ordered under the initial contract will not provide even a minimum capability for the entire Fleet, an additional procurement of 406 P4428 imagers was subsequently approved, and a second contract was awarded in June 1987. This permitted an increased allocation to the surface Fleet as well as initial issues to the submarine forces and to Military Sealift Command transport ships.

However, even this number does not approach the original program goal of 2250 imagers (one per repair locker on every ship). In the aftermath of the USS *Stark* and USS *Samuel B. Roberts* incidents, the priority for improvements in fire fighting and damage control capabilities has increased. As a result, a competitive procurement of 1000 more thermal imagers has recently been approved. This contract will ultimately bring the total number of imagers in the Fleet to approximately 1800 and, it is hoped, will provide an adequate capability until the second generation NFTI is ready for deployment.

As of January 1988, 417 thermal imagers had actually been issued to Navy ships [28]. Although the number or fires in which they have been used is still rather small, those ships that have made use of the imager have reported excellent results. In several incidents, the NFTI has assisted in the rapid extinguishment of smokey fires before they got out of control. In one case—a fire in a void space that produced heavy smoke—the imager quickly located hot spots, and the fire was extinguished with minimal damage. In a second instance, it allowed fire fighters to find a fire concealed within the ship's laundry vent ducts. In that case, the actual fire was two decks away from the place where smoke appeared. In yet another example, after a major engine room fire, NFTI was successfully used to locate and quench hot spots that could have caused a reflash. In summary, the reports received from the Fleet indicate that fire fighting efficiency has increased and that material losses have been reduced as a result of the use of the NFTI.

REFERENCES

1. J.T. Leonard, A. Fryar, and R. Countess, "Wetting and Smoke Knockdown Characteristics of Surfactant Solutions," NRL Memorandum Report 3449, Feb. 1977.

2. S.K. Friedlander, *Smoke Dust and Haze* (John Wiley & Sons, New York, 1977), Ch 5.

3. R.S. Alger and A.S. Gordon, "Preliminary Evaluation of Infrared and Microwave Devices as Visual Aids to Firemen in Smoke Filled Compartments," private communication, 1972.

4. R.D. Hudson, *Infrared Systems Engineering* (John Wiley & Sons, New York, 1969).

5. W.L. Wolfe and G.J. Zissis, eds., *The Infrared Handbook*, revised ed. (Office of Naval Research, Wash., DC, 1985).

6. C. Kittel, *Introduction to Solid State Physics*, 4th ed. (John Wiley & Sons, New York, 1971).

7. J.M. Ziman, *Principles of the Theory of Solids* (Cambridge University Press, Cambridge, Great Britain, 1971).

8. Hughes Aircraft Company brochure SL 2491, "Probeye Infrared Viewers," Hughes Aircraft Company, Ind. Prod. Div., Carlsbad, CA, 1981.

9. A.G. Lindfield and A.C. Wells, "Assisting the Vision of Firemen in Smoke—The Development and Trial of a Thermal Imaging System," Joint Committee on Fire Research Report 17, London, England, 1971.

10. F.K. Lepple, J.B. Hoover, and J.T. Leonard, "Demonstration of Thermal Imaging Device for Firefighters," NRL Letter Report 6180-6, Jan. 1983.

11. J.B. Hoover, F.K. Lepple, and J.T. Leonard, "Demonstration of Thermal Infrared Imaging Through Steam," NRL Letter Report 6180-651, Jul. 1983.

12. F.K. Lepple, J.B. Hoover, and J.T. Leonard, "Performance of EEV Infrared Imager in Various Training Smokes," NRL Letter Report 6180-657, Oct. 1987.

13. F.W. Williams, J.I. Alexander, S.D. Brandow, H.G. Eaton, C.R. Kaplan, R.S. Sheinson, C.H. Williams, and J.P. Stone, "Training Smoke," NRL Memorandum Report 5290, Mar. 1984.

14. J.B. Hoover, F.K. Lepple, and J.T. Leonard, "Shipboard Evaluation of EEV P4228 Thermal Infrared Imaging Camera," NRL Letter Report 6180-701, Nov. 1983.

15. R. Carey, "Smoke Control and Toxic Gas Removal for Stateroom and Laundry Spaces Aboard Navy Ships," SME-83-82, David Taylor Naval Ship Research and Development Center, Annapolis, MD, 1983.

16. A. LaChance, Fleet Training Center Fire Fighting School, Norfolk, VA, private communication, Sept. 1983.

17. J. Manser, Naval Facilities Command Letter 10F/JMM 11320, Nov. 1983.

18. F.K. Lepple, J.B. Hoover, and J.T. Leonard, "Results of Three Month Evaluation of EEV Thermal Infrared Device at Fleet Training Center, Norfolk, VA," NRL Letter Report 6180-106, Mar. 1984.

19. J.B. Hoover. "First Navy Use of One-Handed (EEV Model P4428) Fire Fighters' Thermal Imager," NRL Memorandum 6180-697, Jul. 1984.

20. F.K. Lepple, J.B. Hoover, and J.T. Leonard, "Summary of Shipboard Fire Testing of EEV Model P4428 Thermal Imaging Device," NRL Letter Report 6180-1034, Oct. 1984.

21. J.B. Hoover, F.K. Lepple, and J.T. Leonard, "Shipboard Evaluation of EEV P4428 Thermal Infrared Imaging Camera," NRL Letter Report 6180-53, Apr. 1986.

22. H.L. Simpson, Naval Surface Weapons Center Letter 8200 H12-HLS, Apr. 1986.

23. J.B. Hoover and J.T. Leonard, "Investigation of Reported Electromagnetic Interference Deficiencies in the P4428 Thermal Imager," NRL Letter Report 6180-591, Oct. 1986.

24. J.B. Hoover, "Comments on the Environmental and Electromagnetic Interference Testing of the Model P4428 Thermal Imager Conducted by Naval Surface Weapons Center," NRL Letter Report 6180-101, May 1987.

25. J.B. Hoover, F.K. Lepple, and J.T. Leonard, "Comparison of EEV and Xedar Thermal Infrared Imaging Devices," NRL Letter Report 6180-592, Aug. 1983.

26. J.B. Hoover, F.K. Lepple, and J.T. Leonard, "Comparison of English Electric Valve (EEV) and AGA Thermal Imaging Devices," NRL Letter Report 6180-62, Jan. 1986.

27. J.B. Hoover and J.T. Leonard, "Performance of EEV Model P4428 Thermal Imager During Shipboard Cable Fire Tests," NRL Letter Report 6180-1055, Dec. 1985.

28. J. Thompson, "NFTI Status Summary," Naval Ship Systems Engineering Station, Code 045C, Philadelphia, PA, 31 Dec. 1987.

Appendix A

NRL ltr. 6180-100 of 20 Feb 1987 (w/enclosures)

3900/NRL Prob 61-0064-0-7
Ser 6180-100

20 Feb 1987

From: Commanding Officer, Naval Research Laboratory
To: Commander, Naval Sea Systems Command (SEA 55X24, Dan Spadone)

Subj: NAVAL FIREFIGHTERS THERMAL IMAGER

Ref: (a) COMTRAPAC ltr 1300 Ser N232/2490 dtd 23 Jun 1986

Encl: (1) Distribution List
(2) Draft Doctrine for the Naval Firefighters Thermal Imager (NFTI)

1. As part of the Naval Research Laboratory's (NRL) effort supporting acquisition of the interim Naval Firefighters Thermal Imager (NFTI), NRL has drafted a proposed doctrine for NFTI use. The original draft was based on NRL's extensive test and evaluation work at Navy fire fighting schools and at the U.S.Coast Guard's Fire and Safety Test Detachment.

2. During the past year, five schools and two underway training detachments have incorporated NFTI into their curricula and have had the opportunity to use and comment on the draft doctrine. In addition, it has been circulated to participants in the ongoing NRL test and evaluation program. Enclosure (1) is a list of Navy schools and vessels which have had experience with the NFTI and which have been asked to comment on the draft doctrine.

3. Extensive revisions to the draft doctrine have been made based on comments received. The resulting document, enclosure (2), is submitted for your review and promulgation.

4. Please note that the Fire Party organization has been assumed to be in accordance with the proposed NWP 62-1 revision (reference (a)) rather than with the current NWP 62-1 (Rev A) of March 1985. In particular, the revised doctrine incorporates the concept of an attack team leader who would, in most cases, be responsible for operation of the NFTI.

5. In a previous version of the doctrine, a set of hand signals was included for use when high ambient noise levels precluded voice communications. These were eliminated at the suggestion of Fleet Training Center, San Diego. However, the Naval Damage Control Training Center has indicated that such communications should be addressed. Accordingly, a set of suggested signals has been included in the Appendix.

6. NRL recommends that the enclosed draft doctrine be accepted and promulgated.

Copy to:

SEA 05R23 (C. Pohler)
SEA 55XD (CDR Hadley)
SEA 56Y5 (R. Darwin)
SEA CEL MP-212 (J. Collis)

(ENCLOSURE 1 to NRL ltr. 6180-100)

Distribution List

Naval Damage Control Training Center (LT Shields)
Fleet Training Center Fire Fighting School, Norfolk, VA (LCDR Carpenter)
Naval Technical Training Center (LT Wachter)
Fleet Training Center Fire Fighting School, San Diego, CA (LT Sharp)
Fleet Training Unit, Little Creek, VA (LCDR Klingler)
Fleet Training Group, Guantanamo Bay (LT Houston)
CNET (J. O'Kelly)
USS RANGER (CW02 Erickson)
USS JOHN F. KENNEDY (LT Feidt)
USS SPRUANCE (LTJG Brown)
USS PREBLE (ENS Looges)
USS FULTON (LT Brown)
USS SAIPAN (LT Williams)
USS W.S. SIMS (HT2 Nissenzone)

(ENCLOSURE 2 to NRL ltr. 6180-100)

DOCTRINE FOR THE NAVAL FIREFIGHTERS THERMAL IMAGER (NFTI)

1.0 INTRODUCTION

The Naval Firefighters Thermal Imager provides the fleet with an improved capability to perform shipboard fire fighting and other damage control functions in smoke-filled compartments. The ability to "see" through smoke will significantly improve fire fighters' ability to (a) investigate reported fires, (b) locate the seat of the fire, (c) locate and rescue trapped or injured personnel, (d) set and maintain fire boundaries and (e) locate reignition sources during overhaul.

The NFTI is based on infrared thermal imaging and produces television-like images showing the temperature differences between objects. The current device, designated as the English Electric Valve (EEV) Model P4428-USN, is roughly the size and shape of a one-gallon can. The black and white television display shows hot objects as white, cold objects as black and objects of intermediate temperatures as shades of gray.

This draft doctrine for fleet implementation of the NFTI is based on several years of evaluation at:

- Fleet Training Centers
- Naval Damage Control Training Center
- Naval Technical Training Center
- USCG Fire and Safety Test Detachment
- Naval Research Laboratory

Ships and training groups are encouraged to report to the type commander's damage control or training and readiness officers their actual operational experiences and ideas on how the NFTI can be better employed. This subject will be discussed at the annual OPNAV Damage Control/Fire Fighting Working Group conferences in November 1986 and 1987 to determine the final operational doctrine for the NFTI.

For the purposes of this doctrine, Fire Party organization is assumed to be in accordance with the March 1986 revision of NWP 62-1 (chapter nine) which provides for a five man attack team consisting of a team leader, two nozzlemen and two hosemen. Under this concept, the attack team leader is responsible for command and control of the team and for communication with the on-scene leader.

2.0 ALLOWANGE AND STOWAGE

Initial outfitting will provide two NFTIs each for CV/CVN, BB, LHA, LPH, and CG/CGN ships. Other battle group ships will receive one NFTI.

In order to maximize the time during which the imager may be exposed to high temperatures, it is important that the imager be stowed at moderate temperatures. An air-conditioned habitation space should be used. It is recommended that one NFTI be stowed in Damage Control Central (DCC) and that the second unit, if any, be stowed in Auxiliary DCC.

Although the Commanding Officer is responsible for all equipment aboard the ship, custody for the NFTI should be assigned to the DCA via the Engineer Officer. The DCA would be responsible for maintenance and use of the NFTI. The DCA shall ensure that at least the following personnel are qualified to operate the NFTI: attack team leaders, on-scene leaders, investigators, nozzlemen/hosemen and fire boundarymen.

3.0 DEPLOYMENT

Effective shipboard fire fighting requires maximum flexibility in responding to the specific conditions encountered. The NFTI will enhance fire fighters' flexibility by rapidly providing important information on the location of the fire and progress in extinguishing it. The guidance which follows is meant to provide insight into the effective utilization of the NFTI in fighting shipboard fires, but the man on the scene must always be prepared to make adaptions to deal with the fire at hand.

When a fire alarm is sounded while the ship is not at GQ, an assigned runner would immediately get the NFTI from DCC (or from the alternate stowage location) and report to the on-scene leader for instructions. GQ procedure will be similar, except that the NFTI may l staged at a designated repair locker rather than kept in DCC. The runner would then take the NFTI from the staging area to the appropriate on-scene leader as directed by the DCA via the repair locker leader located at the staging area. In either case, when the NFTI arrives at the scene it should be checked out, as provided below (Section 4.0), and made ready for immediate issue.

The on-scene leader will determine the best way to employ the NFTI based on the existing conditions. Normally, the NFTI would be used by the attack team leader to immediately locate and combat the fire. Under some circumstances, the NFTI might profitably be used by an investigator to locate flooding or other damage, to rescue personnel from smoke-filled spaces or to establish fire boundaries. It should be borne in mind that the primary purpose of the NFTI is to accelerate the initial attack on the fire. Use of the NFTI by the investigator could delay the start of actual fire fighting since the investigator is not supported by a hose team. In addition, the absence of a hose for self-protection increases the hazard to the investigator.

4.0 PRE-USE CHECKOUT

To ensure that fully charged batteries are available, the on-line battery cartridge and one spare cartridge should be checked prior to use. The NFTI's battery condition indicator lights, located in the camera, can be used for these checks - insert a battery cartridge, turn on the NFTI (press the red button on the power supply module), allow sufficient time for the image to stabilize and then verify that all five lights are on. Battery cartridges should not be used whenever less than a full charge is indicated.

CAUTION: ALL FIVE LIGHTS MAY ILLUMINATE BRIEFLY IF THE BATTERIES ARE WEAK BUT NOT TOTALLY DEAD. WAIT FOR THE IMAGE TO STABILIZE.

NOTE: See Section 6.0 (Maintenance) for instructions in the event that fewer than five lights illuminate.

5.0 OPERATION

The NFTI operator (attack team leader or as designated by the on-scene leader) should turn on the NFTI (red button) and double check the battery status lights (as described above) before entering a smoke-filled space. In addition, verify that the NFTI is operating in "chop" mode - if it is not (i.e., it is in "pan" mode) the image will fade away when the NFTI is held perfectly still. Mode changes are accomplished by pressing the blue button on the front of the imager.

It is recommended that the user carry at least one extra battery cartridge, since even fresh batteries (AA alkaline) last only about 1 - 1.5 hours (depending on the battery and the temperature). The voltage decays rapidly near the end of the battery life. As a matter of practice, the operator should be ready to replace the NFTI's battery cartridge when the second light emitting diode on the battery charge indicator goes out. Operators should be able to change battery cartridges in total darkness.

In a smoke-filled space, soot will build up on the NFTI lens, view window and OBA face mask, causing picture contrast to degrade. During a real fire, water condensation makes this problem even worse. The operator should wipe the optical surfaces as necessary to remove this build-up. It is highly recommended that the NFTI operator carry a rag for this purpose as they have been found to be more effective than fire fighters' gloves. This rag should be carried in a pocket or boot top to reduce its exposure to flames and smoke. This is necessary in order to minimize the fire hazard and to keep it as clean as possible.

Due to the wide field-of-view of the NFTI, it is easy to misjudge distances until sufficient experience has been gained. Most people find that slow, steady movement, accompanied by continual scanning of the scene during the approach, helps maintain their orientation. A side to side scan also provides important information on hazards in the area and the best direction in which to proceed. Do not neglect to use a vertical scan occasionally - not all hazards are at deck level.

The NFTI is designed to operate at 60°C (140°F) ambient temperature with 10 minutes at 80°C (176°F) during a one hour period. This represents a typical maximum tolerance for an operator in a fire fighting situation. If the unit's internal temperature gets too high, picture contrast degrades and the picture gets lighter. The screen would be uniformly gray or white if the unit fails due to excessive heat. This loss of contrast would not be improved by wiping the unit's lens. Should the unit get too hot it must be cooled off, e.g., by removing it from the fire to a cooler area. For this reason, it is good practice to remove the unit from the fire area if it is not really needed.

The NFTI's screen will also appear uniformly gray or white when viewing a scene that is (a) very hot, or (b) all at the same temperature. In the first case, the problem is due to the unit's sensor becoming overloaded; the picture will return if the camera is pointed toward a cooler scene. In the second case, there are no thermal gradients for the camera to sense; this condition is commonly found when there is no fire (as in a drill) but could also occur during a fire if the operator is within a stratified layer of hot smoke.

It is a good practice to avoid overloads by looking directly at the fire as little as possible - it is more useful to keep the fire at the edge of the field-of-view. When a hot gas layer is encountered the image can usually be improved by staying low, below the high temperature layer. During a drill or when moving through areas far from the fire there is little that you can do to improve the image.

During fire fighting, the spray from the nozzles may form an optical barrier impenetrable to the thermal imager. Due to the low water temperature this appears as an opaque, black curtain. It is not a problem when straight streams are used but sometimes occurs with fan patterns. The solution is to have the nozzleman temporarily redirect the nozzle to provide a clear field of view.

6.0 TACTICS

As mentioned above, the NFTI will most often be used by the attack team. In this case, an arrangement that has been found to work well, where space permits, is for the team leader to be located behind and between the nozzlemen. In very narrow areas the team should advance with the leader in front followed by the number one nozzleman (holding the leader's "D" ring). Other team members will follow in single file. When the team reaches the fire, the number one nozzleman would move around the team leader far enough to use his nozzle. The number two nozzleman should also move as far forward as possible without losing contact with the team leader. The nozzlemen should stay as low as possible to allow the team leader to see over them. Figure A1 illustrates these formations.

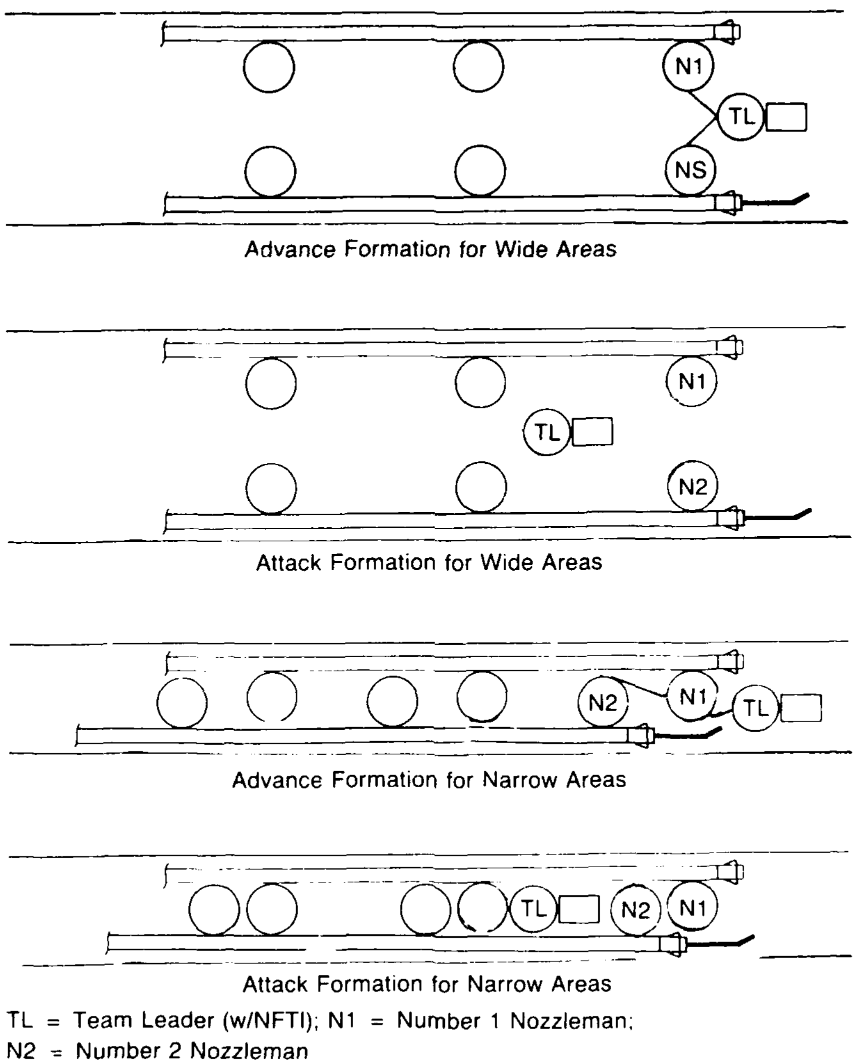


Fig. A1 — Attack formations

Due to the high noise levels associated with fire fighting, verbal communications between the team leader and the nozzlemen are likely to be difficult at best. In this situation, tactile signals have been found to be effective. Appendix B includes a representative set which may be useful to the attack team.

The number one hoseman would be the primary back-up for the team leader in the operation of the NFTI. The NFTI harness is designed for easy removal so that the unit can be passed from the user to the backup should the user be unable to carry on.

7.0 MAINTENANCE

While the NFTI will be incorporated into the ship's Planned Maintenance System (PMS), it will require very little preventive maintenance. Shipboard corrective maintenance on the interim NFTI consists of changing the unit's harness, muff, or visor should these become damaged during operation. In addition, the fuse, located in the battery cartridge, may need occasional replacement. Shipboard maintenance on the NFTI will be performed by a DC rating and will not require additional personnel. More extensive repairs on the NFTI will be performed at the depot level or by the manufacturer.

After use, the unit's exterior should be cleaned with warm, soapy fresh water. AFFF solution has been found to work very well. All battery cartridges should be checked after each use of the NFTI. The procedure given above in Section 4.0 (Pre-use Checkout) may be used. In the event that fewer than five lights illuminate, then the batteries should be replaced (see instruction manual). If no lights come on even after replacing batteries, then replace the fuse (see instruction manual).

Battery checks should be made at a minimal frequency of every month. The extra battery cartridges supplied with the unit should be checked at the same time as those in the unit itself. This part of PMS will automatically be accomplished if the NFTI is used for routine fire fighting drills.

In addition, the NFTI should be used for at least one hour per month in order to maintain proper operation of the sensor. This would also be accomplished automatically if the unit is used during fire fighting drills.

8.0 TRAINING

Training in the operation of the NFTI will be included in all Navy fire fighting and damage control schools. It should also be incorporated into the Damage Control Assistant course at the Surface Warfare Officers School. Operation, maintenance and repair procedures for the NFTI should be included in the DC "A" School. Shoreside operational training should include actual fire conditions (heat, steam, noise, darkness) to assure maximum personnel readiness when faced with a real fire.

The NFTI should be used as an integral part of most shipboard fire fighting drills. Realism during training is an important goal. To this end, shipboard training should ideally be performed in total darkness. If a blackout is not feasible, then team members (except the NFTI operator) may be blindfolded. In the latter case, it is important to ensure that the NFTI operator actually uses the imager and does not cheat. Loud background noise, simulating the crackling, hose spray and steaming of a real fire provides additional realism. Training smoke should be used if an approved smoke generator is available. To assure full integration of the NFTI into the fire fighters' operations, obstructions can be put in the fire fighters' path which will require the use of the NFTI. Specific exercises in FXP-3 which may be modified to incorporate the NFTI include:

- Locating Damage Control Fittings (Z-1-D)

- Fire Extinguishment and Smoke Clearance (Z-27-D)
- Providing Casualty Power (Z-31-D)
- Hit in Machinery Space (Z-32-D)

Appendix B

SOME USEFUL SIGNALS FOR THE ATTACK TEAM LEADER

Verbal communications between the team leader and the nozzlemen have been found to be almost impossible over the noise created by the fire, the hose spray and the steam generated. The following set of signals have been found to provide effective communications during live fire fighting evolutions. It is assumed that the team leader is behind the nozzlemen but close enough to touch them.

Command	Signal from NFTI Operator
Move Forward	Forward pressure on back
Move Back	Gentle pull on "D"-ring
Stream Down (for NFTI view)	Tap on leg
Direct Stream:	
Right	Tap outside right shoulder
Up and Right	Tap top right shoulder
Left	Tap outside left shoulder
Up and Left	Tap top left shoulder
Vertical sweep	Alternately tap helmet top & lower back
Horizontal Sweep	Alternately tap both outside shoulders
Back out	3 or more quick tugs on D-ring