# Thermal radiometer constructed from ordinary office supplies

*By Terry L. Lyon*

It is possible to construct a surprisingly inexpensive and simple thermal radiometer from office supplies. Although the detector was designed to evaluate thermal energy hazards to an individual located in a harsh environment, undoubtedly other applications will surface. The radiometer features a nearly flat wavelength response and a wide field-of-view, is very insensitive to both acoustic energy and radio-frequency energy, is not prone to damage, and distinguishes between radiated thermal energy and thermal energy transferred by direct contact with hot materials. It is particularly noteworthy that the detector has functioned as a direct hazard monitor for optical radiation emitted by certain flash sources.

A simple detector, constructed from readily available office supplies, can serve as a direct thermal energy hazard monitor for intense sources of optical radiation. A total hazard evaluation of such a source should also address the possibility of temporary (flashblindness) or permanent violet-induced injury to the skin and cornea. Completely different types of radiometric and photometric instrumentation and analyses are required to evaluate each of these potential hazards.

Throughout the U.S. Army's development and procurement effort for new equipment, different agencies within the Army Medical Department have studied the potential hazards from the equipment. The U.S. Army Medical Research and Development Command (USAMRDC) has conducted a wide ranging research program on biological effects of laser radiation. The Division of Ocular Hazards, Letterman Army Institute of Research (LAIR), is currently studying laser eye effects from new types of lasers.

Concurrently, the Laser Microwave Division of the U.S. Army Environmental Hygiene Agency (USAEHA) has evolved hazard analysis techniques for exposure to laser and other high intensity nonionizing radiation sources and has assisted developers, test agencies, and users in the safe operation of this equipment. To support its mission, USAEHA has developed new measurement detectors and techniques to support the development and user communities[1,2].

The thermal detector described here was designed to evaluate the potential hazards from radiated thermal energy and thermal energy transferred by direct contact with hot materials. It has been used to evaluate a few military weapon systems that emit optical radiation such as the VIPER and AT-4 shoulder fired antiarmor weapon systems, the SAWE artillery fire simulator system, and the TOW missile system.

The potential thermal hazard to the skin and cornea from optical radiation emitted by hot explosive gases usually exists relatively near the device. Ideally, the thermal radiation should be measured with an accurate radiometer. Unfortunately, most thermal detectors were developed for laser measurements and possess a relatively narrow field of view, making them un-

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suitable for measuring the total radiant exposure of someone located near a large extended source.

Also, many of these detectors respond to acoustic energy and radio-frequency energy. Fortunately, many thermally sensitive papers can record a radiant exposure at a level relatively near permissible personnel exposure limits and are insensitive to both acoustic energy and radio-frequency energy that are often present in the test environment. While such a record may not yield a precise radiometric measurement, the information may determine whether an exposure is either safe or hazardous.

The detector assembly described herein has been referred to as a "witness board." It contains a thermally sensitive paper and other window materials which can distinguish between radiated thermal energy and thermal energy transferred by direct contact with hot materials. Witness boards have been positioned at locations to simulate personnel and thus function as a direct hazard monitor for optical radiation. The detector assembly does possess some operating limitations and yet unknown characteristics.

## Description

The witness board is constructed from paper, government manifold or business forms, a manila folder, and a transparent polystyrene sheet protector—the kind used for holding papers in a three-ring binder. That is all that is required. (This is the best use for government forms that this author has found.) The completed witness board with carbon paper detector is illustrated in Fig. 1.

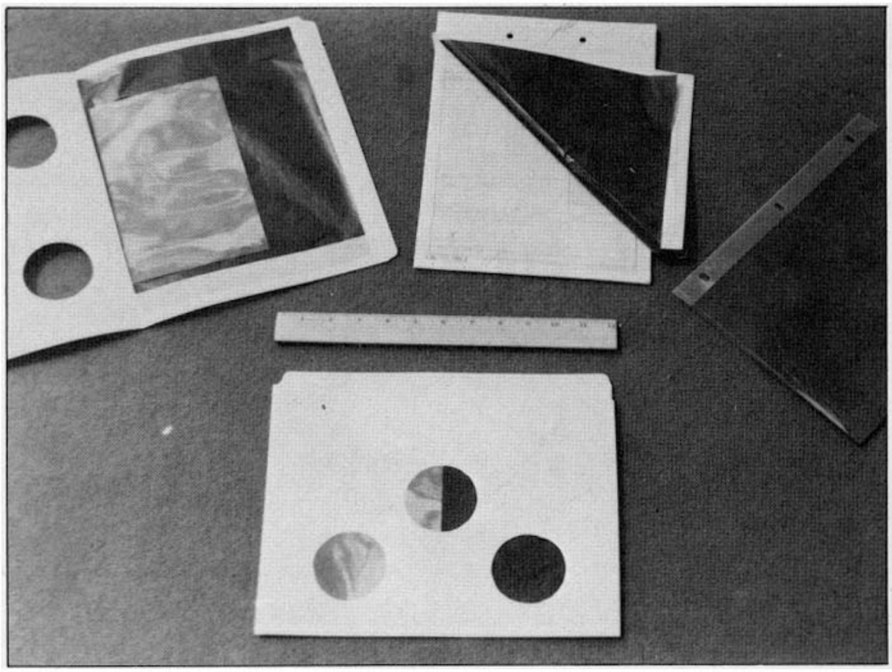

FIGURE 1. Witness board thermal radiometer with carbon paper detector and polystyrene window.

The heart of the detector is the carbon paper found inside the manifold form. As it turns out, the detector is sensitive, forgiving, and broadband. Carbon paper is black over a large wavelength region and can be "read" visually after the inked side has been exposed to a brief optical pulse exposure from either a point (laser) or large extended source. At a threshold exposure, the inked surface becomes more glossy. This can be observed in bright light at a near-specular viewing angle as illustrated in Fig. 2.

The manila folder is transformed into an insulating holder for the carbon paper. Several aperture holes are added to the exposed side of the folder to improve the contrast and readability of the carbon paper after exposure. A polystyrene sheet covers half of the holes and serve as windows which pass most of the optical radiation given off by the source while attenuating thermal energy delivered by conduction, i.e., from direct contact with hot materials such as exhaust gases. After exposure, this thermal sensor is evaluated, then retained for future reference or discarded.

## Detector characteristics

The idea of using thermally sensitive papers, such as used in reproduction copiers, to record an exposure to a small laser beam is not new.[3] However, the optical properties of ordinary carbon paper were not previously known. (The carbon paper was extracted from Travel Voucher or Subvoucher form DD 1351-2, June 1978.)

Carbon paper is a superior detector for evaluating large extended broadband sources for which few adequate detectors exist. It offers a wide absorption bandwidth with good sensitivity. An analysis of the paper suggested that it consisted of carbon granules in an organic binder. The paper was believed to be spectrally black, given that carbon is a broadband absorber which covers the radiated spectral output range of most potentially hazardous sources of optical radiation. If this could be

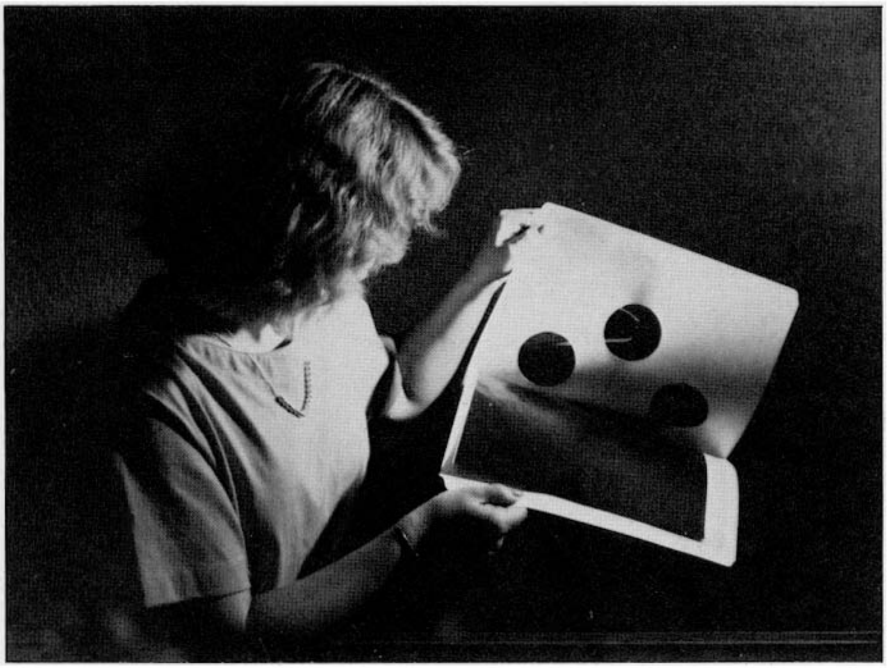

FIGURE 2. Method to observe for a superthreshold exposure to the carbon paper detector at a near-specular viewing angle with a high-intensity light.

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demonstrated, the paper can be calibrated directly in units of $J/cm^2$ for a broadband source.

An initial check was encouraging. The reflectivity in the near-infrared for the carbon paper was assessed by viewing the carbon paper under high-level irradiance from the sun with a near-infrared viewer and narrow band filter at 1064 nm. The surface appeared black, as was hoped for. Most other thermally sensitive papers tend to be reflective in the near-infrared portion of the optical spectrum where, unfortunately, hot exhaust gases were expected to emit the greatest amount of spectral energy.

Although thermal sensitive papers do not provide a precise value for the radiant exposure, they can provide data where other detectors might fail due to their sensitivity to electromagnetic and acoustic interference. Thus further testing was required to fully evaluate the detector's blackness.

The total spectral reflectance of carbon paper was measured using a Perkin Elmer 330 Ultraviolet, Visible, and Near Infrared Spectrophotometer (part 210-2101) with Hitachi Integrating Sphere to collect the reflected optical radiation. It was found that the carbon paper nonreflected $96 \pm 1\%$ from 400 to 1700 nm, nonreflected at least 91% out to 2375 nm, and was rarely less than 95% in this range. It was believed that the nonreflected energy was largely absorbed—not transmitted through the paper. Significant variations (line spectra) were observed out to 2600 nm—the wavelength limit of the available instrumentation. Measurements were not made at a wavelength below 400 nm. Few sources emit sufficient energy below 400 nm to create a thermal radiation hazard.

The carbon paper should also be equally sensitive to either optical radiation or thermal energy from a direct contact with a hot gas, liquid, or solid. This was assumed but not experimentally verified.

By utilizing an overlay window material such as a thin polystyrene sheet, the detector can permit easy differentiation between the thermal energy components. A polystyrene sheet (Joshua Meir Corp., PS-5, Transparent Polystyrene Sheet Protectors) was measured to pass about 89% of the optical radiation (0.3 to 30 $\mu$m) from a 3200 K blackbody radiator (1000-W tungsten lamp), while insulating the sensor from direct contact with the hot object or debris. Thus conductive thermal insults can be filtered from the radiative energy component. Measurements of spectral transmission were made with the Perkin Elmer 330 and are illustrated in Fig. 3. The transmission always exceeded 75% from 300 nm to 2440 nm.

Exposure apertures are cut into an opaque insulating mask made from the manila folder to cover the paper, to improve contrast by providing a well-defined exposure edge. This provided a marked improvement when evaluating threshold exposures to the paper.

## Calibration

The carbon paper was calibrated with a GTE Sylvania neodymium:YAG laser (model 605) operated at a wavelength of 1064 nm, which was fired through a mechanical shutter to produce a 35-msec pulse simulating a short explosive flash. The carbon paper became glossy after exposure at a threshold level of approximately 0.2 $J/cm^2$ as measured with a Scientech disk calorimeter (model 3600). A level of approximately 0.3 $J/cm^2$ was demonstrated using a Coherent Radiation $CO_2$ laser (model 40), operating at a wavelength of 10,600 nm with a 200-msec pulse duration.

A low value of thermal conductivity in carbon paper is believed responsible for the similar threshold levels. This suggests that the duration of exposure should not significantly influence the threshold sensitivity, at least for exposure durations less than 200 msec. Out of curiosity, the carbon paper was exposed to a Q-switched Nd:YAG laser (AN/GVS-5 laser rangefinder) to obseve any change in the calibration factor. A threshold level of 20 mJ/cm$^2$ was determined at 1,064 nm from a 6-ns pulse duration. This is only 10 times more sensitive than the longer pulse durations.

At a level of about 2 J/cm$^2$ from a 100-ms $CO_2$ laser, the exposed paper appearance changed drastically from glossy to very dull (diffuse). This level was slightly below the level which caused actual charring of the carbon paper. Several witness boards were exposed to approximately 80 mW/cm$^2$ sunlight for an extended period during one day. The calibration of the paper was checked after exposure, and little variation in sensitivity was noted.

The thin polystyrene sheets were also calibrated. A sample sheet was exposed to a 1000-W tungsten lamp operating at 3200 K and was found to pass about 89% of the total optical radiation from this blackbody, whereas absorption at 10,600 nm was nearly 100%. At the $CO_2$ laser wavelength, a threshold level for damage was measured with the disk calorimeter to be approximately 1 J/cm$^2$. Hence exposure to a 3200 K blackbody would have a threshold for damage of approximately 10 J/cm$^2$. Because the polystyrene sheets are more sensitive to direct contact with hot materials than to typical flash radiation from such a source, the sheets are useful to act as a detector to evaluate exposure from direct contact with hot gases and debris.

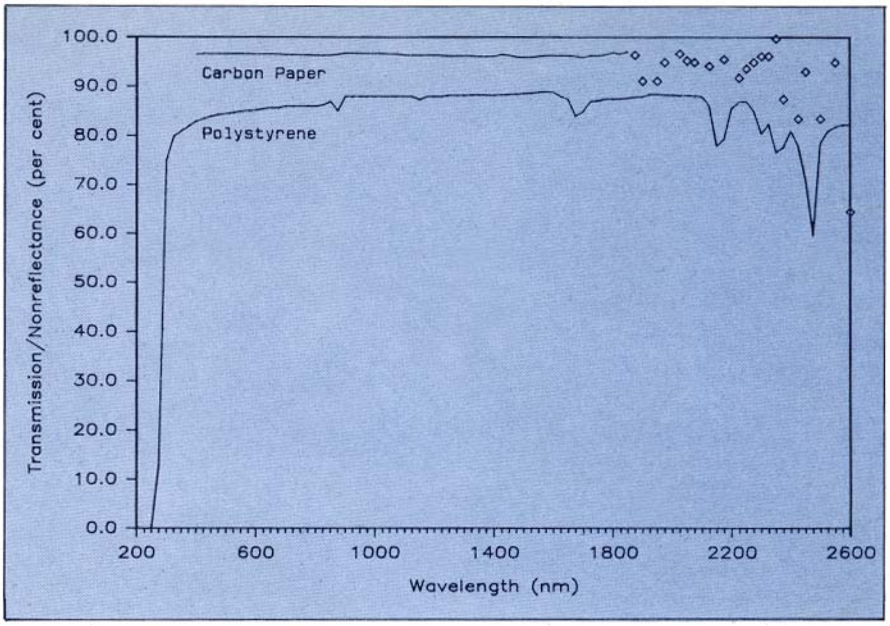


**FIGURE 3.** Spectral transmission of the polystyrene sheet protector and spectral nonreflectance of the carbon paper.

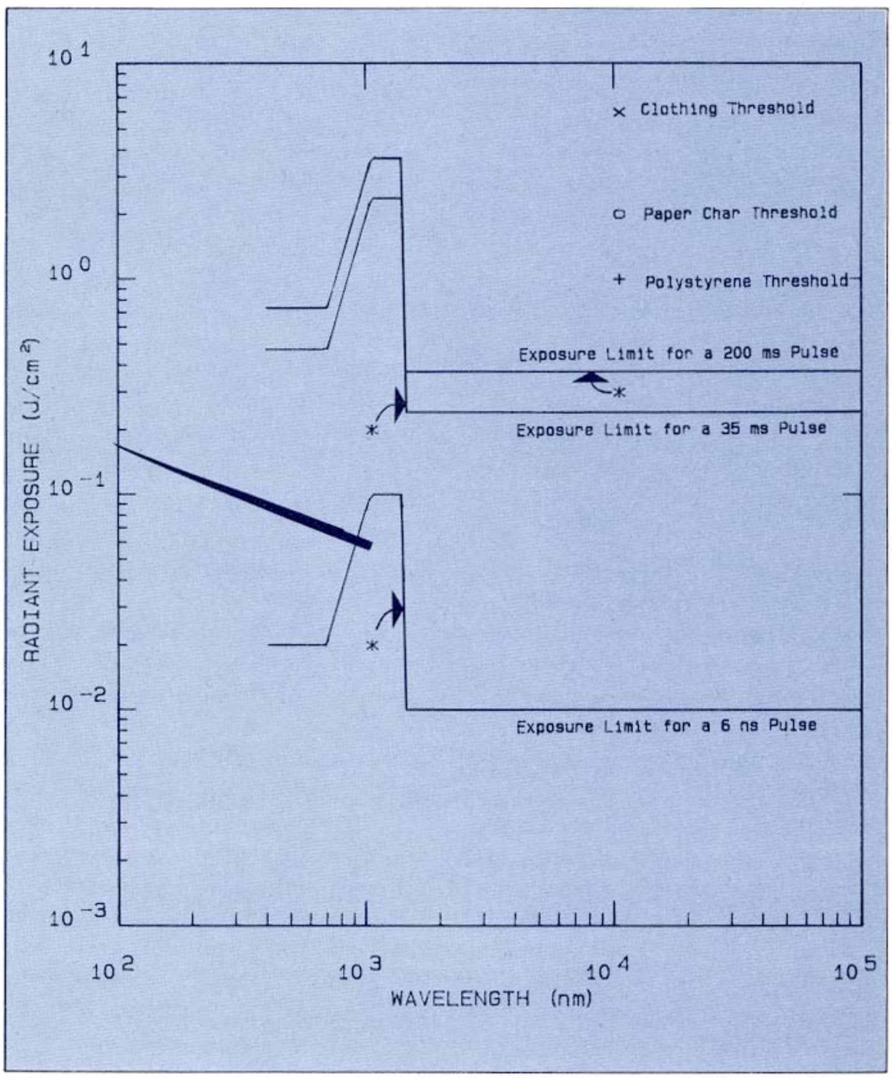


**FIGURE 4.** Personnel skin exposure limits applied to single-pulse thermal broadband radiators.

## Occupational exposure limits

The detector has been used to evaluate the potential thermal hazards from the hot exhaust gases emitted by various weapon systems. Witness boards containing the carbon paper detector with polystyrene sheets and military fabric samples were placed at locations simulating various personnel positions, such as backside of the operator of shoulder-fired anti-armor weapon systems.

Optical radiation in the region of 400 to $10^6$ nm is absorbed by the skin, and radiation in the region of 1400 to $10^6$ nm is absorbed in the cornea of the eye. If the radiant exposure supplied by the source is sufficient, these tissues can be elevated in temperature and protein denaturing can occur. For a single, short exposure, the injury will be limited to a shallow depth within the skin or cornea, since the thermal conductivity of tissue is relatively low, and the large percentage of water in underlying tissue defies an increase in temperature.

Unfortunately, official personnel exposure limits do not exist for whole-body exposures. However, standards do exist for exposure to small laser beams. The Army occupational laser exposure limits are contained in TB MED 524.[4] These limits are the same as the ANSI and ACGIH laser exposure limits.[5,6] These standards have been applied to broadband exposure from an explosive device. The exposure being relatively short in duration diminishes the importance of the area of exposure. However, the margin for safety may also be reduced.

Figure 4 illustrates the calibration data points for the carbon paper and polystyrene sheet and laser exposure limits. A 20-msec infrared exposure gives an exposure limit of 0.21 J/cm$^2$, the nominal threshold sensitivity of the carbon paper. The author could not feel this exposure level when placing his hand into the beam of a 20-msec $CO_2$ laser. Many sources may marginally exceed the conservative occupational level of Eq. (1) at close exposure distances. Few exposures would be expected to result in charred carbon paper unless it was placed next to the chemical reactants. Thus the net thermal exposure level in such an example would be less than 2 J/cm$^2$.

Additional tests conducted at the U.S. Army Environmental Hygiene Agency showed that various military clothing samples would afford sufficient protection when covering skin to an exposure level of about 6 J/cm$^2$. This was demonstrated by placing carbon paper in close contact to the backside of various military fabric samples, where the paper was again used to simulate an exposure to skin. The front of the fabric was exposed to various levels of brief $CO_2$ laser exposure. It is interesting to note that this 6 J/cm$^2$ level also corresponded to a minimum threshold damage level for the various fabrics.

Besides optical radiation-induced thermal injury, direct contact to a hot gas plasma or flame could cause thermal injury. This energy should not be confused with the radiant energy of a flash. As a byproduct of optical radiation measurements, it is possible to assess the energy flux resulting from direct contact with the flame or other hot gases. If a physical change occurs to the polystyrene sheet but not the covered carbon paper, then the exposure would be due to direct contact with a hot object and the exposure would have exceeded approximately 1 J/cm$^2$.

## Other considerations

The witness boards are fairly rugged and can easily be transported in a briefcase. Prior to making measurements, the carbon paper surfaces should be inspected: rough handling can change the surface appearance, which might be interpreted as a superthreshold exposure. When the surface has small defects, circle the damaged area with a pen or pencil prior to exposing the paper to the flash source for easy recognition.

Additional work is necessary to fully assess the traits of the carbon paper detector with the polystyrene window. Some areas that require further clarification are: variations among different brands and batches of carbon paper and polystyrene, aging characteristics (perhaps due to previous temperature and humidity exposure history), synergistic effects from ambient temperature and humidity, and the threshold level variation for exposure duration and pulse shape.

### Acknowledgements

The author wishes to thank Robert Mckenzie for conducting the spectral reflectance and transmission measurements and Philip Conner for preparation of the graphs.

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