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BUSTER

NEVADA PROVING GROUNDS
OCTOBER-NOVEMBER 1951

Project 2.4-2

THE EFFECT OF THERMAL RADIATION ON MATERIALS

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(6) THE EFFECT OF THERMAL RADIATION ON MATERIALS,

~~by~~

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~~and~~

~~STAFF~~

~~OF~~

~~NAVAL MATERIAL LABORATORY~~

(11) 1952,

Naval Material Laboratory
New York Naval Shipyard
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ABSTRACT[1]

Various material indicators were exposed to the thermal radiation of the atomic explosions at BUSTER to determine the effects of this exposure on these materials, the degree of correlation between these effects and those produced by laboratory sources of thermal radiation, and some of the characteristics of the radiation. These studies are a continuation of those made during GREENHOUSE, with emphasis on the effective time of the radiation with regard to initiating and sustaining the process of damage to materials, the effects of target geometry, the evaluation of protective measures and the irradiance-time and spectral characteristics of the radiation.

Analysis of the field results indicates that the thermal energy partitions of the 3.47 KT and 20.9 KT weapons (Baker and Dog shots) employed in the BUSTER tests were approximately 33 and 23 percent, respectively; these values are considerably greater than those measured during the RANGER and GREENHOUSE operations. The emitted radiation may be considered black-body, the temperatures for the Baker and Dog shots being approximately 7700°K. and 8850°K., respectively. At the distances of interest in studying the effects of thermal radiation on materials, approximately 16 percent of the radiation is in the ultraviolet and 23 percent is in the infrared. Because of the large thermal yield of these nuclear detonations, considerable damage was noted on the materials exposed. In general, this damage was in agreement with the results from exposures to the high-intensity, small-area laboratory source of thermal radiation, although the correlation studies suffered from the large number of field samples which were either unaffected or completely damaged. The damage to woods exposed at angles other than normal to the incident radiation indicated that the damage is proportional to the cosine of the angle of incidence and that the effect of inter-reflections from the sides of V-shaped wood grooves is not pronounced. The study of thermal damage as a function of time of exposure indicates that for the 3.47 KT detonation no additional damage was sustained after 200 milliseconds. For the 20.9 KT detonation most of the damage occurred between 130 and 160 milliseconds. Due to the short duration of the radiation pulse, no conclusions can be drawn from this experiment as to the contribution of the decreasing portion of the intensity-time

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[1] A glossary of radiation nomenclature employed in this report is included in Appendix B

characteristics to the total material damage. The distribution of thermal radiation within a 2x6x4 foot deep foxhole indicates that, for the orientation employed (6-foot side on the radius vector from ground zero), no significant radiation (1 cal/cm^2) is received within the forward section of the foxhole, even though as much as 18 cal/cm^2 may be incident on the exposed backwall. Of the three flameproofing cloth treatments tested, Erifon appears to be superior to either Rezgard or Pyroset, but the amount of protection from thermal radiation afforded to personnel by any of these treatments is questionable. Of the several treatments applied to the wood surfaces, Albi Temp Kote and Vita Var appear more promising than the other paints tested.

The results of the project are summarized and the future field test plans of the Naval Material Laboratory are outlined.

CHAPTER 1

INTRODUCTION

1.1 OBJECTIVES

In the Naval Material Laboratory's (NML) experiments conducted in conjunction with Operation BUSTER, various material indicators were exposed to the thermal radiation of the atomic explosion in order to extend the studies of the correlation of laboratory and field data made at GREENHOUSE, obtaining in this test such additional data as the GREENHOUSE studies indicated were required. Included in this category were the spectral and intensity-time characteristics of the thermal radiation, effects of target geometry on the degree and extent of thermal damage, and the degree of protection of flameproofing, fire-retarding and reflecting coatings on fabrics and construction materials.

1.2 HISTORICAL

The Armed Forces Special Weapons Project (AFSWP) is sponsoring a program at several government and university laboratories on the effects of thermal radiation of atomic explosions. In this program, NML is responsible for the development of laboratory sources of thermal radiation and improved methods of exposure, study of the characteristic behavior of materials under irradiation, including the measurement of critical radiant exposures, analysis of the influence of source and target parameters on thermal damage, and development of protective measures. NML participated in Operation GREENHOUSE, exposing various material indicators to determine the degree of correlation between the effects on materials of the thermal energy of an atomic explosion and the effects of the high-intensity carbon-arc source presently being used in laboratory studies. In the BUSTER tests these studies were extended with special emphasis on these problems which were not considered at GREENHOUSE or which did not yield significant results.

1.3 BASIC CONSIDERATIONS

The characteristics of the thermal radiation from an atomic explosion as derived from theoretical considerations are discussed in some detail in the *Effects of Atomic Weapons*[1]. According to theory approximately one-third of the total energy released is emitted as thermal radiation. At about 0.1 millisecond after the detonation, the ball of fire consists of an isothermal sphere of about 50-foot radius, having a temperature of about 300,000°K. The surface temperature of the ball of fire falls rapidly to a minimum, around 2,000°K., in little more than one one-hundredth of a second after the detonation of the atomic bomb. This is followed by an increase to somewhat over 7,000°K. at the second maximum, after which the surface temperature falls steadily. Since the energy emitted in the first millisecond represents only one percent of the total radiant energy, it is not considered effective in producing damage, although the photochemical and other effects of the intense ultraviolet irradiation may precondition specimens exposed to an atomic explosion. The intensity-time characteristic for the second phase of a nominal bomb detonation is given in Fig. 1.1. From theoretical considerations, it may be assumed that the fireball emits essentially black-body radiation. For radiation received at operationally important distances from a black-body source whose temperature is 10,000°K., it is calculated[2] that approximately 10 percent of the energy should be in the ultraviolet (below 4,000 Angstroms), 65 percent in the visible (between 4,000 and 8,000 Angstroms), and 25 percent in the infrared (beyond 8,000 Angstroms), if the atmospheric absorption is 60 percent per sea mile, and its water content is 1.7 cm per sea mile.

At the RANGER tests, the thermal energy partition (fraction of total energy) of the explosion was measured by the Naval Research Laboratory (NRL) as 15 to 20 percent, about one-half that value indicated by theory. These measurements were supported by NML data, obtained with passive indicators in the form of textiles, plastics and other materials.[3] The calorimeters measure the total energy incident on unit area (radiant exposure), while the materials measure this same quantity with an accuracy depending on how closely the laboratory calibrating source matches the field source. As far as is known, the spectral distribution of the emitted thermal radiation was not measured at RANGER.

In the GREENHOUSE experiments, preliminary results with passive indicators indicate that for distances represented by the NML stations, 2,000 to 3,500 yards, the thermal energy partition of the Easy shot was approximately 15 percent. The total energy received at these stations,

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[1] See Bibliography.

[2] NML Report 5046-3, Part 2 (See Bibliography) discusses the spectral characteristics of an atomic explosion.

[3] NML Report 5046-7 summarizes the results of NML's participation in Operation RANGER (See Bibliography).

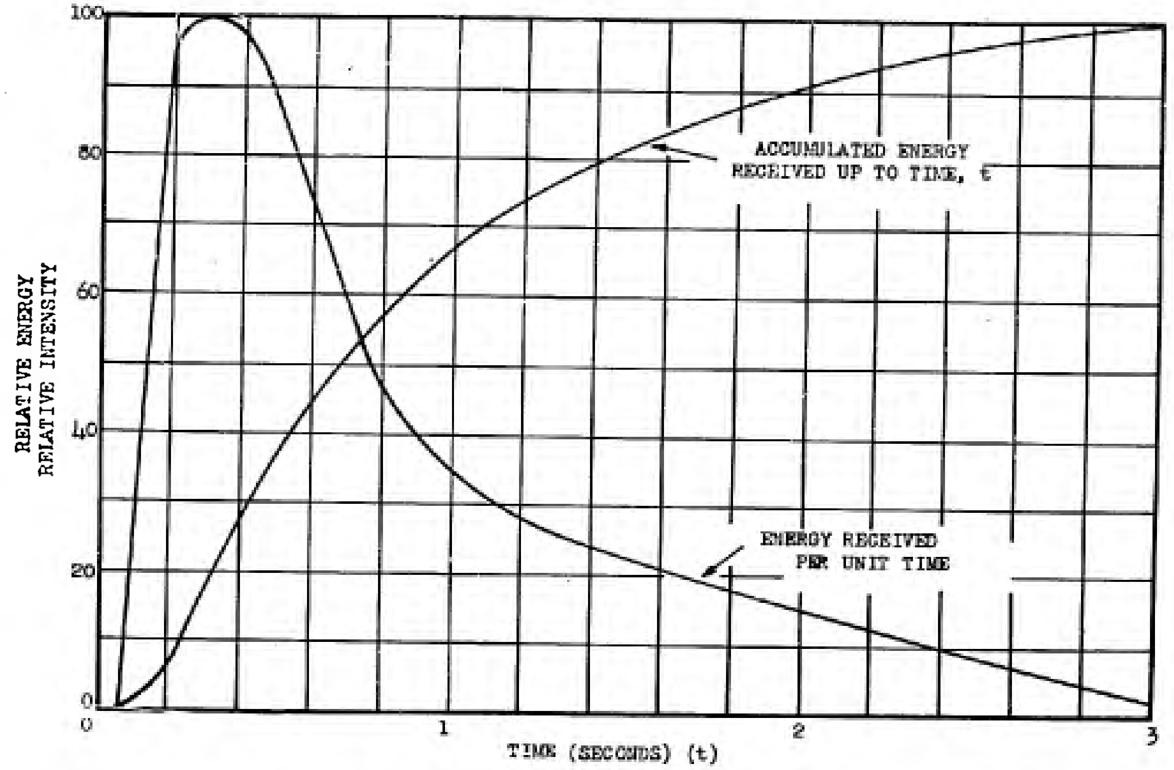

Fig. 1.1 Intensity-Time Characteristics of Second Phase of Thermal Radiation from an Atomic Explosion

measured by the NRDL calorimeters, was somewhat higher, the difference being due to the nature of the two types of measurements in that the total radiation exposure may not be effective in causing damage to some materials. The NML measurements of spectral energy distribution indicated that for the distances involved, 2,000 to 3,500 yards, there was little or no effective flux between 2,200 A (Angstroms) and 3,000 A, that approximately 8 percent of the energy received lies between 3,000 A and 4,000 A, 79 percent between 4,000 A and 8,000 A, and 13 percent beyond 8,000 A. The measured spectral distribution indicated either a spectrum which is not entirely black-body or, if the emitted radiation is black-body, a relatively high water content in the atmosphere.

The first problem of the NML BUSTER experiments concerned itself with measurement, through the use of passive metal foil receivers, of the spectral distribution of the total radiation and of the effective period of the radiation with respect to thermal damage to materials.

The second problem of the NML experiments was concerned with the effects of target geometry on the degree and extent of thermal damage. An extensive theoretical study of this problem has been initiated at various laboratories, but experimental work has lagged, due to the unavailability of a suitable large-area laboratory source of thermal radiation. Some work was done at GREENHOUSE on the study of target geometries but the relatively low radiant exposure, even at the closest station, precluded quantitative evaluation of the results.

The third problem of the NML experiments was the evaluation of fire-protective coatings for fabrics and constructional materials. The NML program on the development of protective coatings has been underway since March 1951. The laboratory evaluation of various commercial flameproofing processes has indicated several promising ones. These were applied to representative woods and fabrics and were exposed to both laboratory and field sources for the purpose of correlating the two exposures and for evaluating the relative merits of the different processes. In addition to noting the damage to the material itself, the energy transmitted and conducted through the sample was measured by means of M-6 vesicant paper, which is also temperature sensitive.

1.4 LABORATORY SOURCES OF THERMAL RADIATION

The laboratory sources employed in the NML studies of the effects of thermal radiation include the carbon-arc and graphite resistor sources.

1.4.1 Carbon-Arc Source

The carbon-arc source employed for the preparation of laboratory control samples has been described in previous NML reports.[4] The equipment consists essentially of a source of radiation and two parabolic reflectors, one to collimate the radiation, the other to focus the collimated rays upon the sample. The source is a high-intensity carbon-arc signalling searchlight with a 24-in. parabolic reflector (focal length, 9 11/16 in.). A second such reflector, placed coaxially at a distance of 12 feet from the transmitter, is used to focus the radiation. The searchlight source is operated at 65-70 volts and 78 amp. Standard Navy 24-in. searchlight, 11-mm. carbons are employed. A schematic diagram of the arrangement used for the exposure of the laboratory samples is shown in Fig. 1.2.

In order to obtain finer gradations of thermal effects than is possible by the method of single exposures to the searchlight sources, an apparatus was designed which permitted a continuous variation of the exposure time on 8-in. strips, about 1 in. wide. The variations of the exposure time are obtained by means of two methods of acceleration: one using the gravitational acceleration of falling weights and the other using a motor-driven rotating cam with pulley combinations.[5]

Since the original source of radiation in the laboratory is extended, the image at the focus of the condensing mirror also is extended. A thermoelectric cell was designed to measure the energy flux of the radiation falling upon areas of various sizes at the focus of the condensing mirror. This cell is made of copper, with 1/4 in. walls and a receiving cavity which is nearly black-body. A galvanometer connected to three thermojunctions in parallel, imbedded in the copper walls, indicates the temperature rise of the cell. Stops made of highly polished stainless steel, placed at the mouth of the cell, limit the area of cross section of the entering beam as desired. Errors due to heat reradiated from the stop are minimized by using short exposures and by substituting a reflector for the stop immediately after the exposure.[6]

The spectral energy distribution of the carbon-arc source is given in Fig. 1.3.

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[4] NML Reports 5046, Part 4; 5046, Part 5; 5046, Part 6; 5046-3, Part 1 (See Bibliography)

[5] The mathematical determination of the design of the cam has been given in NML Report 5046, Part 5; and an evaluation, using this method of calibrated strip exposures, has been discussed briefly in NML Report 5046, Part 7. (See Bibliography)

[6] Detailed description of this cell and its use, as given in NML Report 5046, Part 3, was published in the Journal of the Optical Society of America, entitled Method of Measuring High Intensities at the Focus of a Parabolic Reflector with Large Relative Aperture, G.E. Davis, JOSA, v. 39, pp. 541-543, July 1949

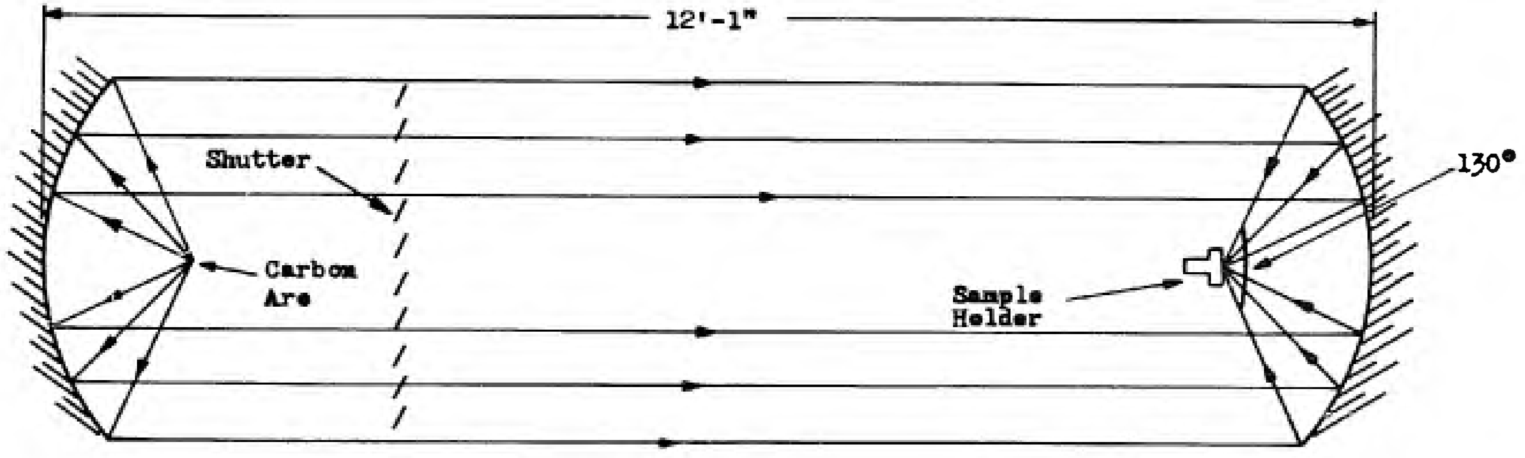

Fig. 1.2 Laboratory Arrangement for Exposure of Specimens

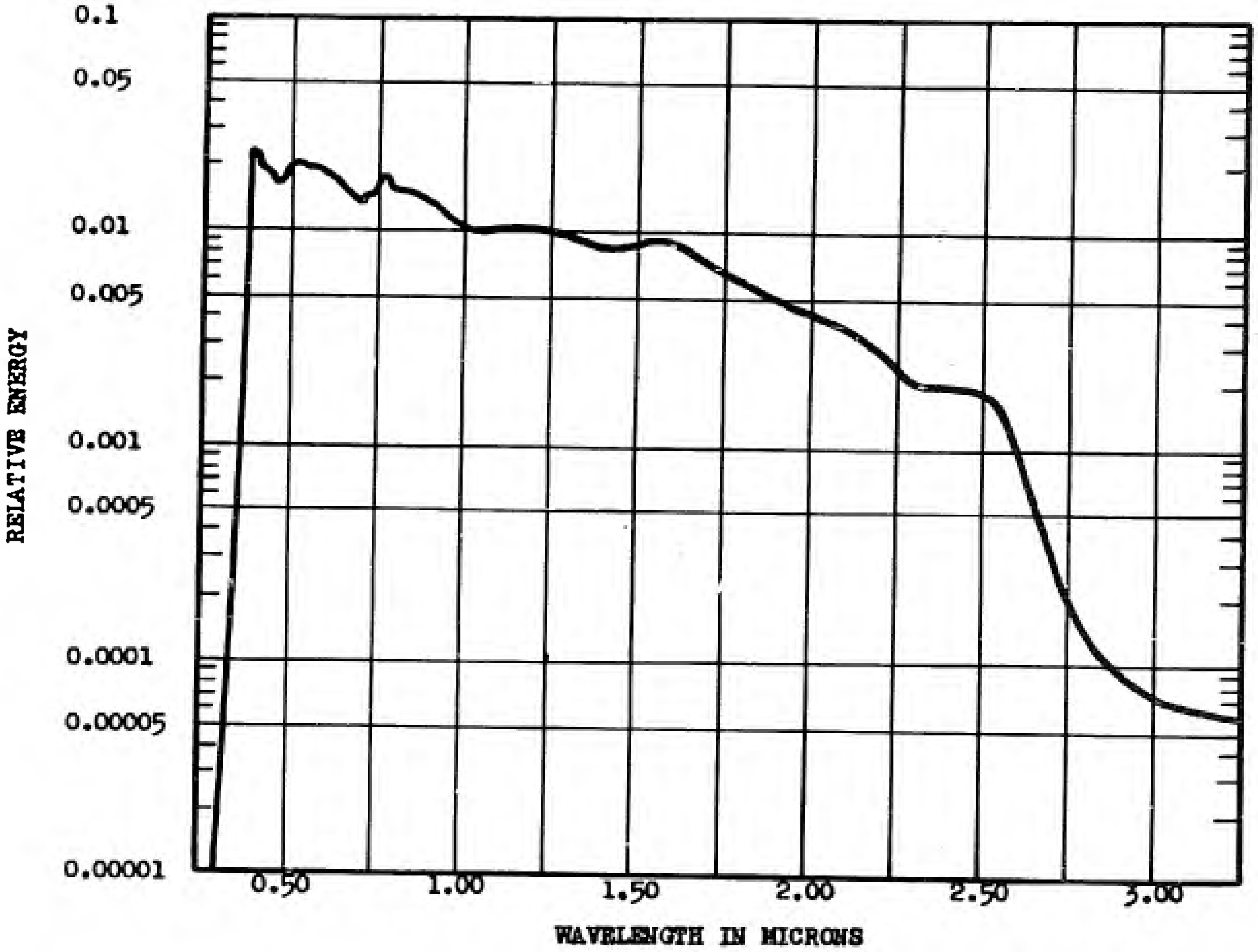

Fig. 1.3 Spectral Energy Distribution of 11-mm Carbon-Arc Source

1.4.2 Graphite Wide-Area Source

To answer the need for a laboratory source capable of irradiating a large area, a graphite resistor, graphite-lined furnace has been built. It has a foot-square aperture, and can reach a temperature of 2,400°C. without undue deterioration. The irradiance at this temperature is 70 cal/cm^{2}sec. A 10-in. aperture shutter has been built for this furnace, permitting exposure times of from 0.1 to 10 sec. This shutter has been designed to be fast-acting to eliminate unwanted heat flow transients. Difficulty was encountered in exposing materials to the radiation of this furnace because the high temperature gradients developed caused the shutter to buckle. The difficulty is only temporary and, with minor modifications to the shutter, the furnace's operation will be satisfactory. The furnace is now being calibrated in terms of the spatial and spectral distribution of the emitted energy.

1.5 ASSEMBLY AND MOUNTING OF MATERIALS FOR FIELD EXPOSURE

The several materials and devices, with their individual mounts, were securely fastened to panels of 3/8 or 1/2 in. duralumin, 18 in. long and 11 1/2 in. wide. Seven of these panels were mounted at each station on a frame of duralumin angle and channel. The materials exposed included metal foil energy indicators, treated and untreated cloths, fire-retardant paint samples, woods of several geometrical configurations, and an angle indicator. Glass silicone laminate backings were employed for the cloths and metal foils, and quartz windows were used in conjunction with glass filters over the metal foil energy indicators. The M-6 vesicant paper was mounted 1/8 in. behind the treated cloths in order to determine the apparent transmittance of the cloth materials; a 1/8-in. neoprene rubber grid was employed as the spacing material between the treated cloth sample and the M-6 vesicant paper. The typical panel assemblies and the structure frame are shown in Figs. 1.4 through 1.7, inclusive. Figs. 1.8, 1.9 and 1.10 are photographs of individual panels and a representative station.

The panels and frame structures were previously employed in the GREENHOUSE tests[7]; the structures were modified by hinging the vertical duralumin angle members to permit exposure of the various materials at normal incidence of the radiation for air bursts at different heights.

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[7] NML GREENHOUSE Pre-Operation Report (See Bibliography) describes the mounting of specimens in detail.

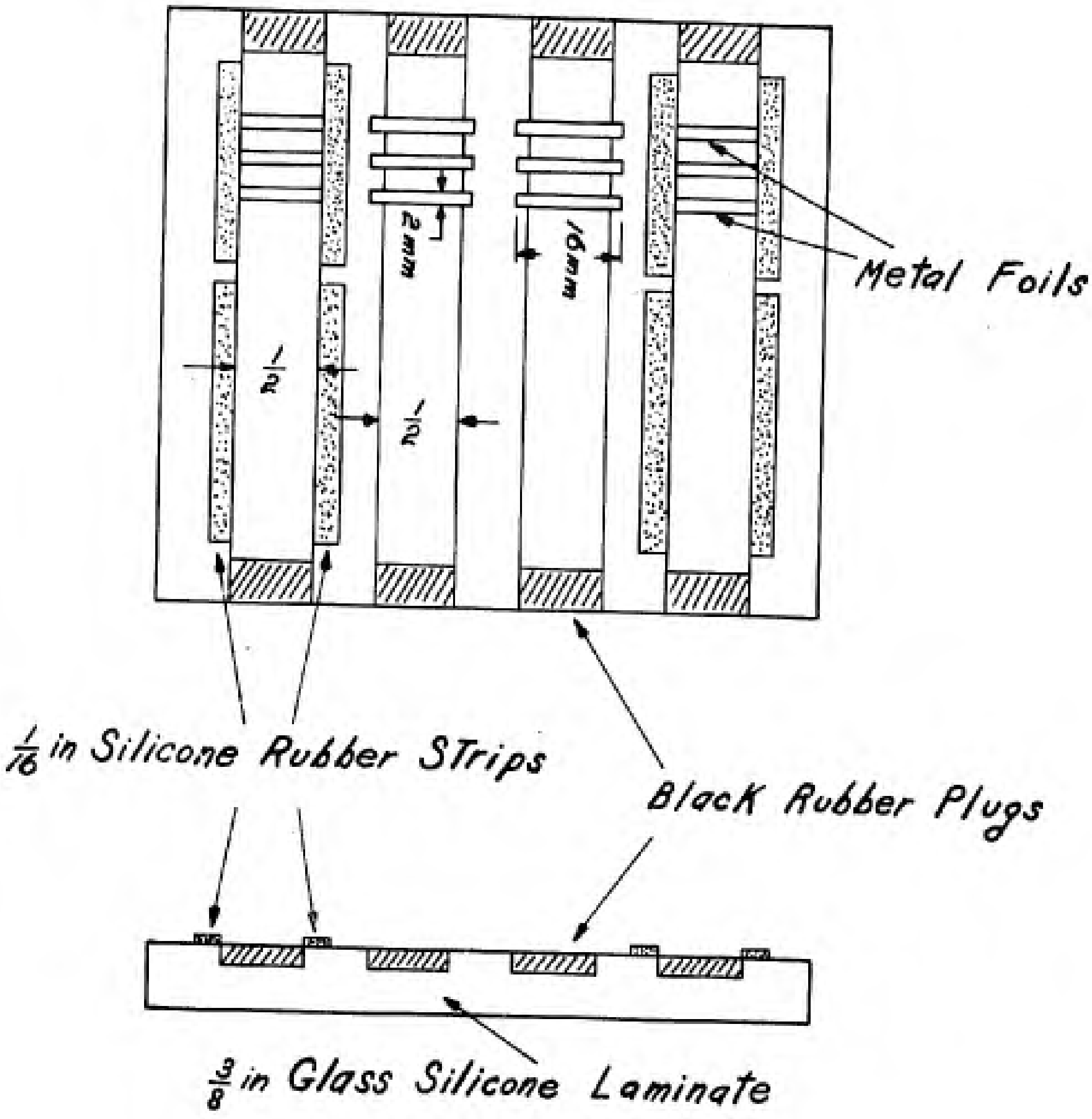
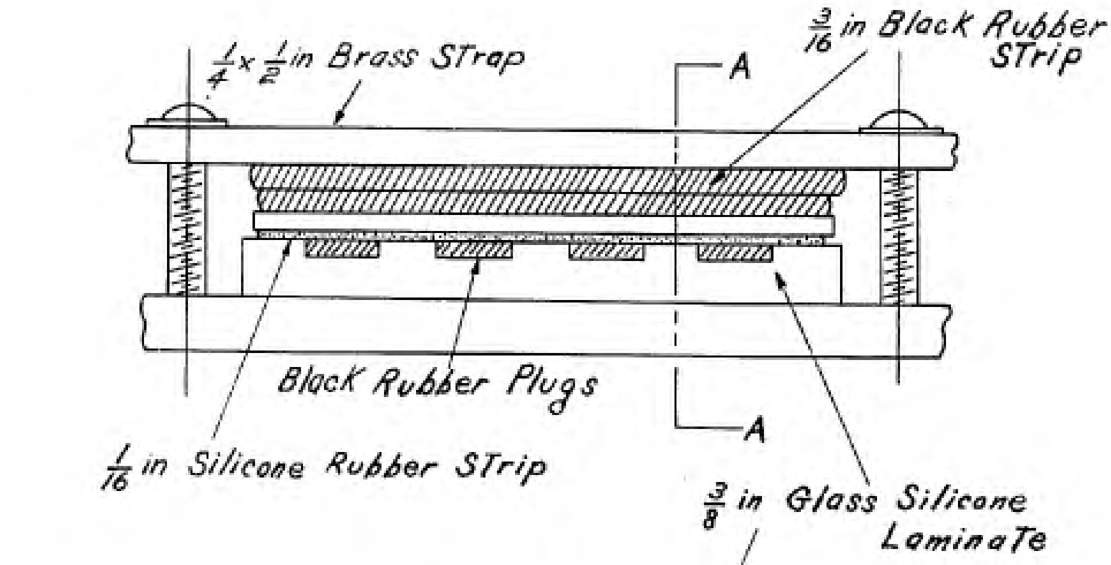


Fig. 1.4 Arrangement for Mounting Metal Foils



View A-A

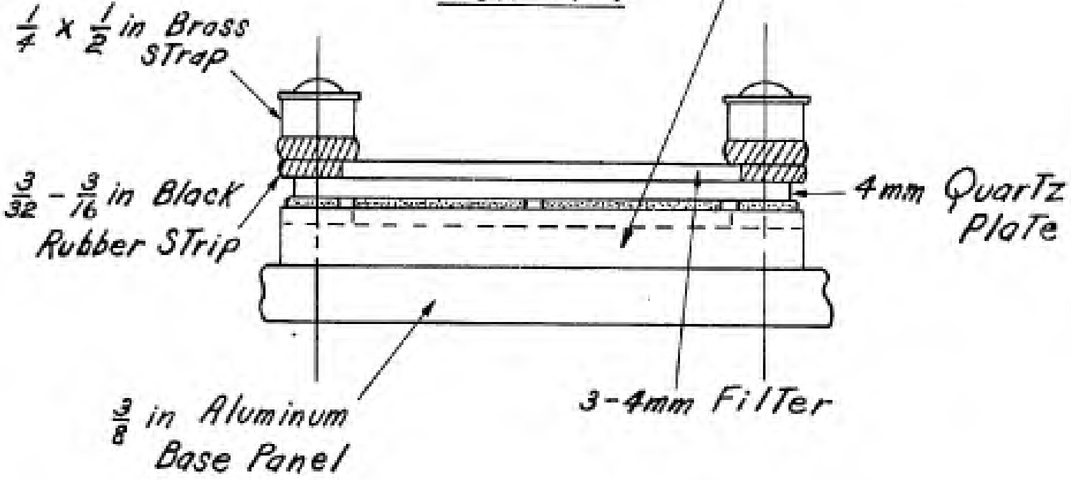


Fig. 1.5 Metal Foil Assembly

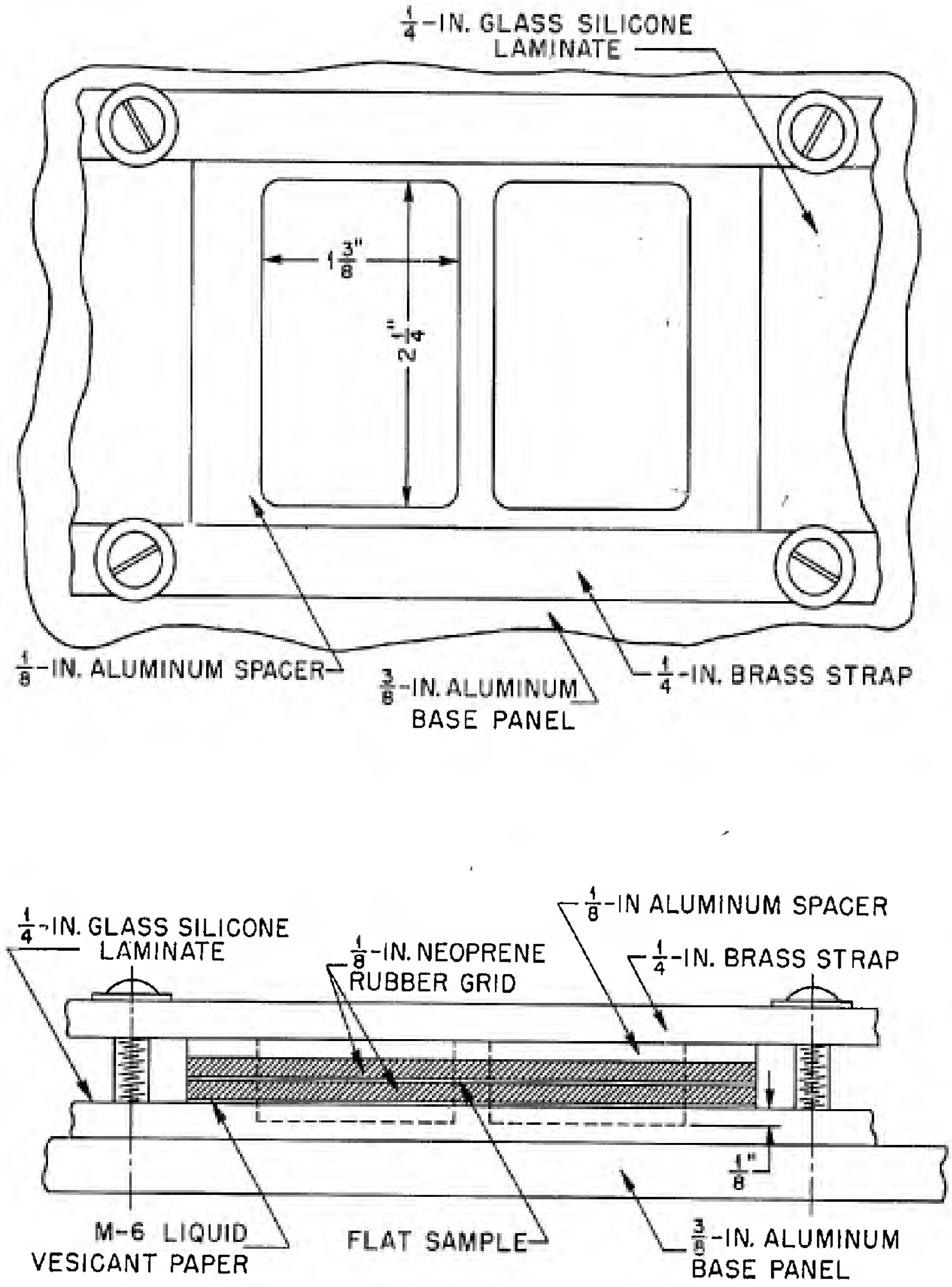


Fig. 1.6 Arrangement for Mounting Flat Samples

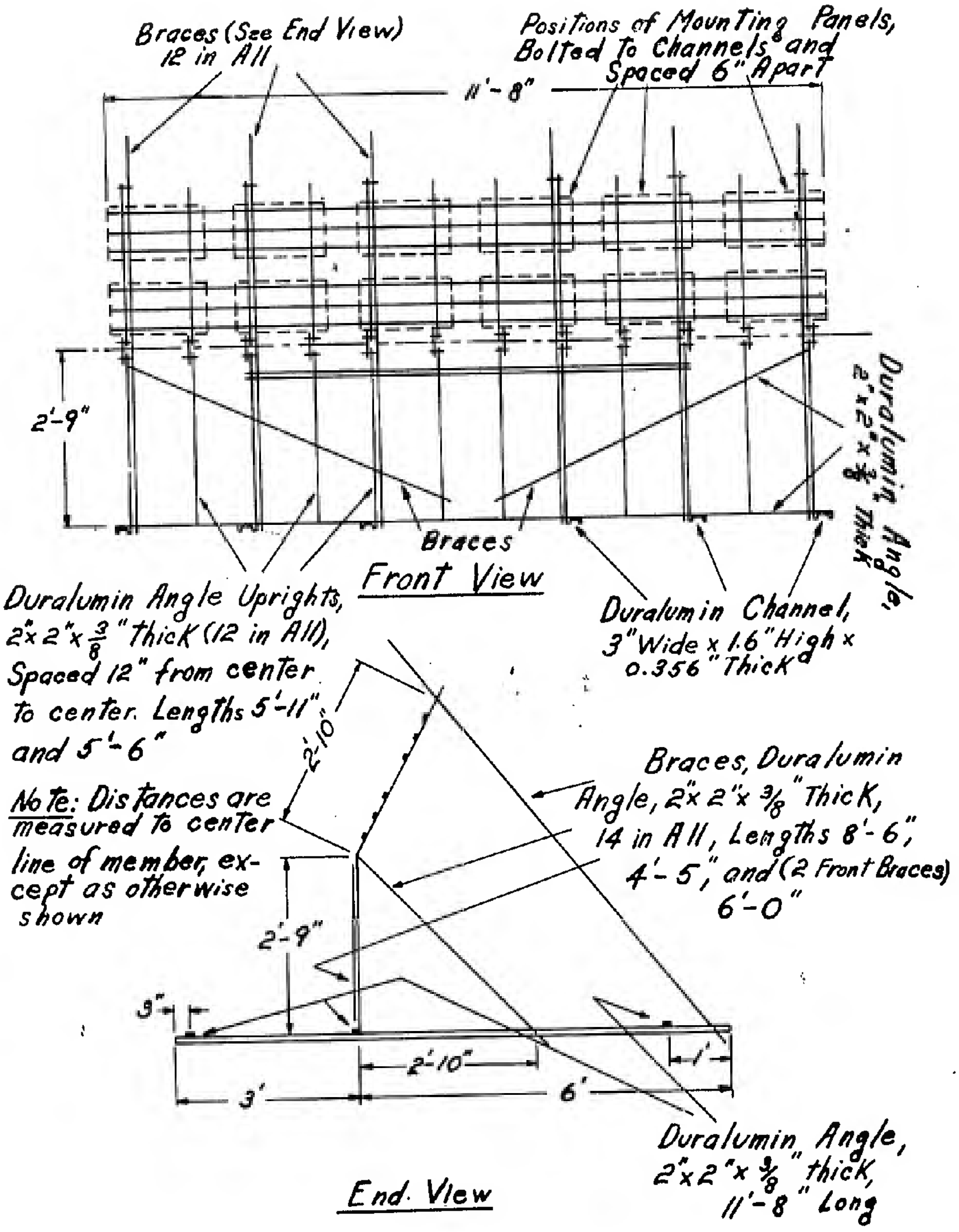


Fig. 1.7 Frame Construction

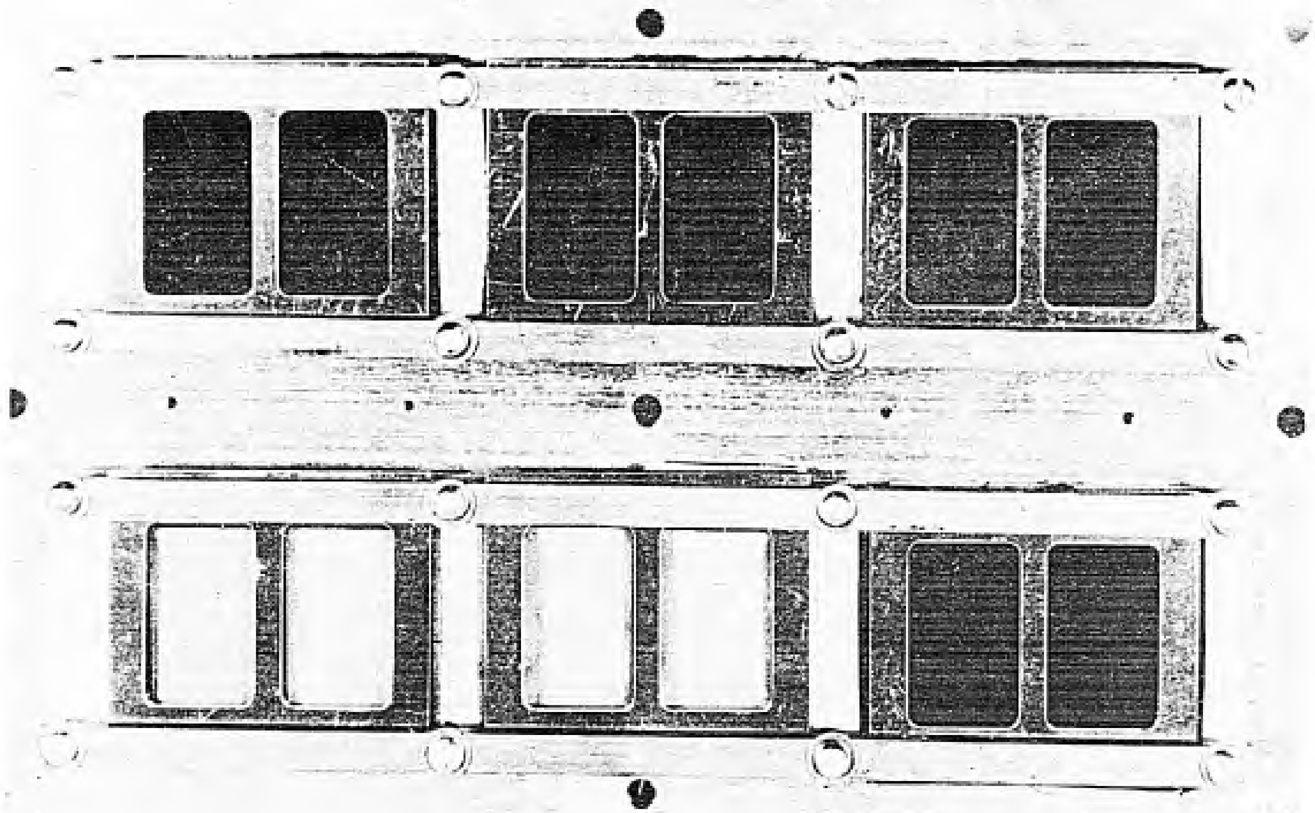


Fig. 1.8 Typical Exposure Panel Showing Textile Materials with Flameproofing Treatments

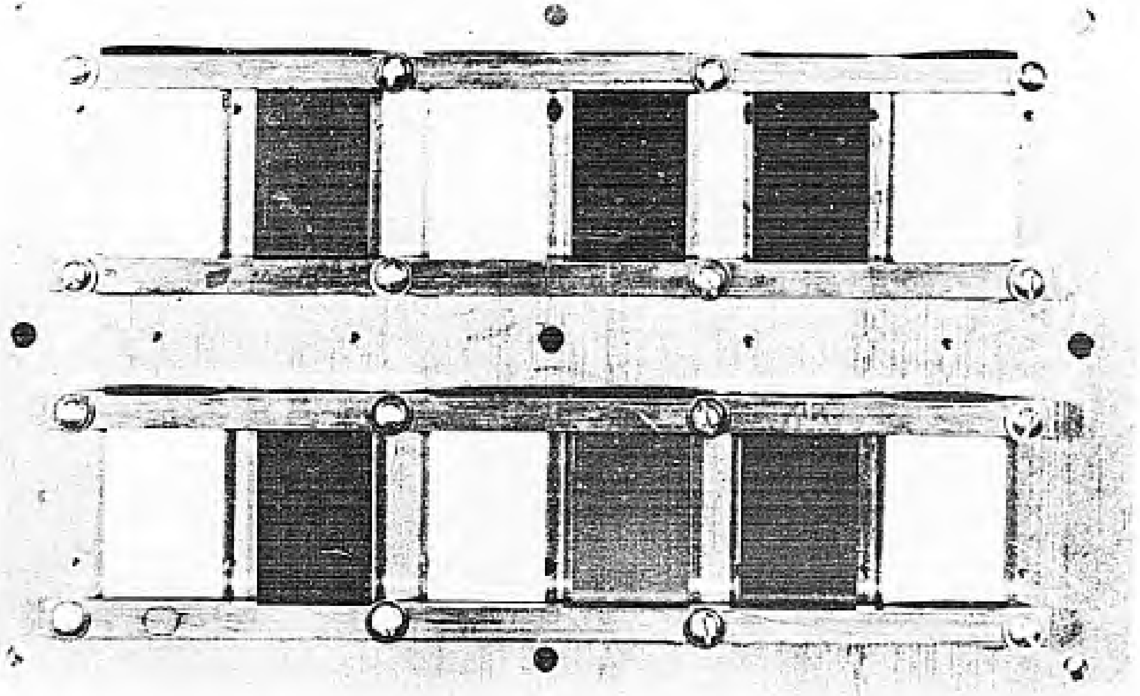


Fig. 1.9 Typical Exposure Panel Showing Woods with Fire-retarding Coatings

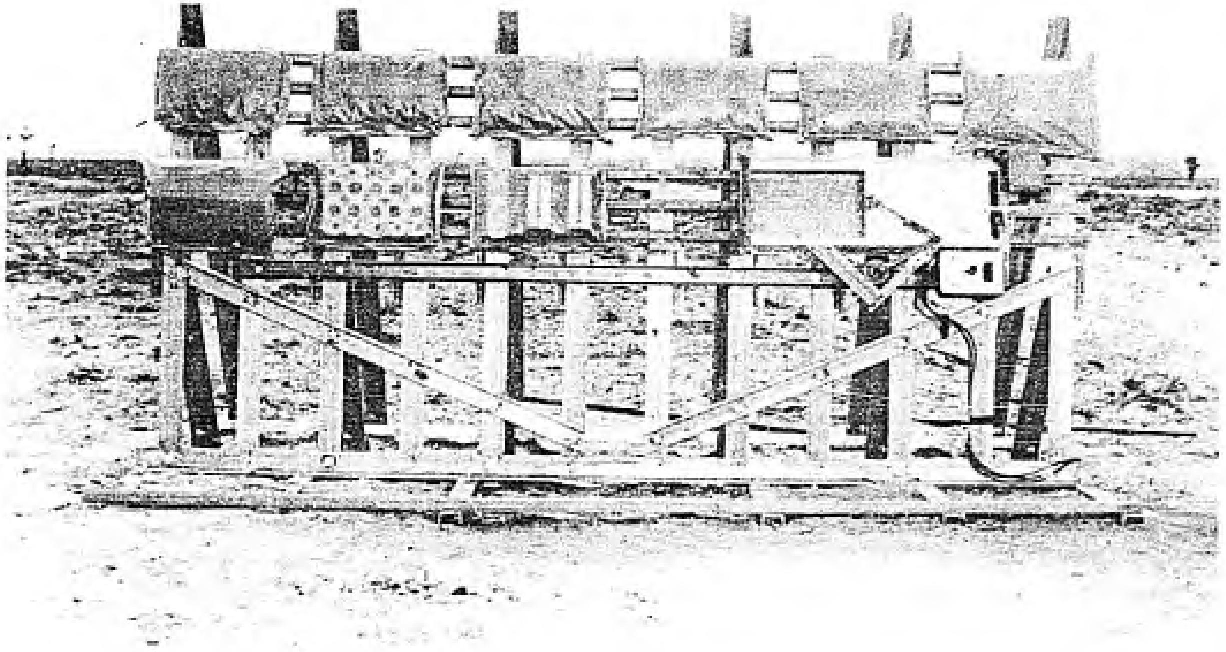


Fig. 1.10 NML Station Showing Weather-Protective Covers over Samples

1.6 PERFORMANCE OF PANELS AND FRAME STRUCTURES

Three stations, at 2,000, 4,000 and 5,000 feet from ground zero, were employed for the Baker shot; the structure at each station was anchored by means of sandbags placed on the forward end of the ground members. The sandbags were covered with a layer of sand to prevent ignition of the sandbags during the detonation. A visual check of the stations after the shot showed that the blast had no effect on either the panels or the frame structures. Study of motion pictures taken during the shot showed that the sandbags acted as "chutes", allowing sand to be blown up and on to the samples.

For Dog shot, four stations were mounted, at 4,000, 5,000, 6,000 and 7,000 feet from ground zero. Every station, except the one at 6,000 feet, was sandbagged. The sandbags were placed below and behind the panels in order to minimize the "chute" effect observed during Baker shot. Upon examination of the stations after the detonation, the 6,000-foot station was found to be displaced on one side by approximately four feet; the positions of the three sandbagged stations remained unchanged, and the "chute" effect had been greatly reduced.

During an examination of the indicator panels in the laboratory, it was noted that the edges of the neoprene rubber grids had burned during exposure and that tar-like combustion products were deposited on the samples. A few of the uncovered metal foil strips came off the mounting blocks during exposure, due to the melting of the mounting adhesive. In future field tests, NML intends to employ silicone sponge rubber grids which have a higher thermal resistance and do not liberate the tar-like combustion products.

In view of the excellent performance of the duralumin frame structures, it is apparent that the structures could be lightened, without sacrificing necessary strength, by eliminating six vertical angle members and two horizontal panel-supporting channels. It is also indicated that 4-ft. channel iron stakes could be employed for anchoring the frame structures, thereby eliminating the sandbagging and reducing the "chute" effect.

CHAPTER 2

PHYSICAL CHARACTERISTICS OF THERMAL RADIATION

2.1 TOTAL AND SPECTRAL RADIANT EXPOSURE

2.1.1 Experimental Plan

The effective radiant exposure at each station and the spectral breakdown of this energy among three broad, representative wave length regions were measured with passive receivers in the form of metal foils mounted behind quartz windows and behind each of two selected glass filters. The metal foils, 2-mm wide, 16.5-mm long, were made of lead, zinc, tin, nickel, gold, platinum and palladium in thicknesses from 1 to 5 mils. The purpose of the quartz window was to eliminate effects of weathering and other local disturbances and, at the same time, pass all radiation of significance in studying the effects of thermal radiation, from 2,200 to 30,000 A. The two filters employed, Corning 3060 and 2550, pass all radiation in that region beyond 4,000 and 8,500 A, respectively. The spectral transmittance of the quartz window and of the filters is given in Fig. 2.1. The foils were mounted on a grooved glass melamine block, providing for a suitable air gap in front of and behind the foils, as shown in Fig. 2.2.

2.1.2 Laboratory Measurements

The metal foils were calibrated in the laboratory, employing the NML 24-in. searchlight source of thermal radiation. This equipment is described in Section 1.4. Characteristic, reproducible effects, such as contraction, buckling and separation, were noted for each foil. The critical thermal energies for the various foils are listed in Appendix C, Table C.1; the values given therein are for the 11-mm carbon-arc source and a rate of application of energy of 85 cal/cm^{2}sec. On the basis of reciprocity studies it may be generalized that for the thicknesses employed the critical energies of these particular foils are not dependent on time of exposure within certain limits.

2.1.3 Analysis of Field Data

The radiant exposures at the three stations employed in Baker shot, as determined from the thermal damage to the metal foils mounted behind the quartz and filter windows, are given in Table 2.1.

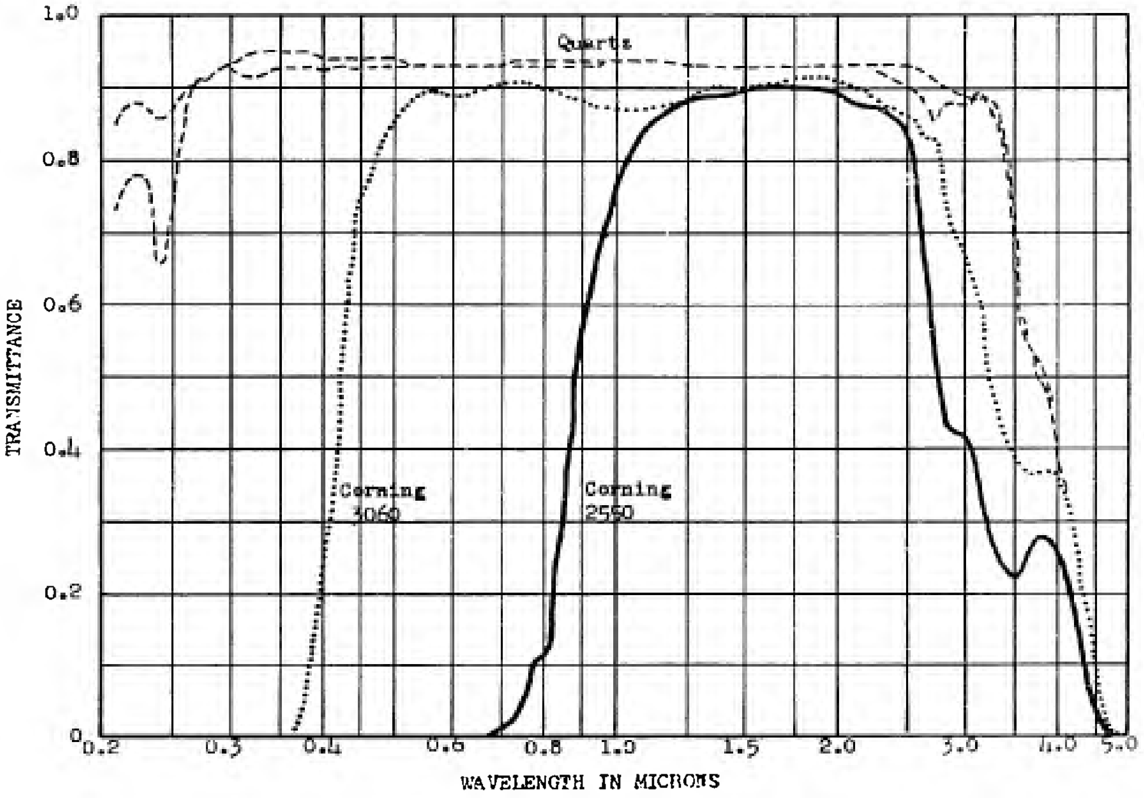


Fig. 2.1 Transmittance of Quartz Windows and of Filters for Measurement of Source Spectral Characteristics

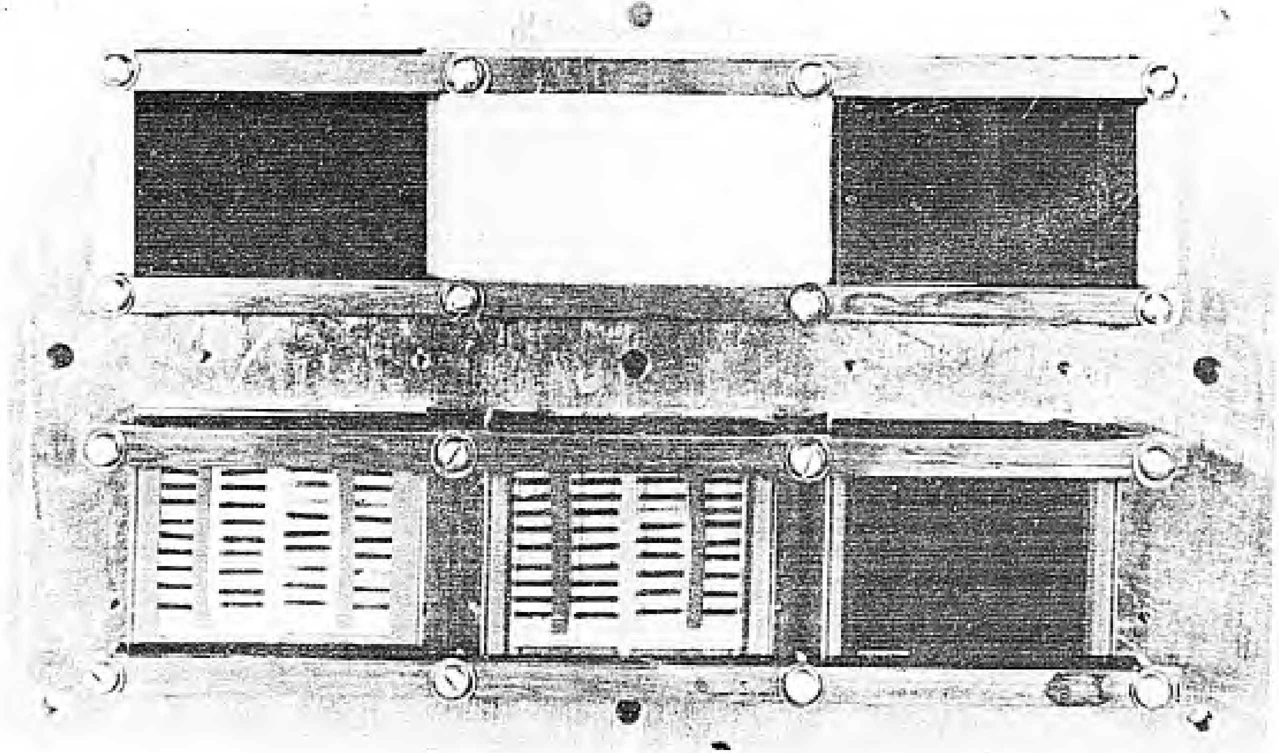


Fig. 2.2 Typical Exposure Panel Showing (Upper Row) Black Bakelite and Acetate Rayon (with and without IR Filter), (Lower Row) Plane Metal Foils with Quartz Window without Filter, with Corning 3060 and with Corning 2550 Filters

TABLE 2.1

Effective Radiant Exposure, Baker and Dog Shots

Distance from Ground Zero	Slant Distance	Effective Radiant Exposure (cal/cm^2)		
		2,200-30,000A	4,000-30,000A[1]	8,000-30,000A[1]
Baker Shot				
2,000 ft	2,280 ft	16.9	14.1	4.9
4,000	4,150	4.7	4.1	1.0
5,000	5,120	2.9	2.6	0.7
Dog Shot				
4,000 ft	4,240 ft	21.2	17.5	4.7
5,000	5,200	14.2	11.0	3.3
6,000	6,160	9.2	7.4	2.1
7,000	7,140	7.8	6.6	1.4

The values of radiant exposure over the spectral region defined by the transmittance of the quartz window are in good agreement, at the more distant stations, with the values calculated from the NRL measurements with gas calorimeters and bolometers. At the closer stations the NRL values are approximately 25 percent higher, indicating that the foils do not measure all the flux received during the cooling phase of the fireball, whereas the gas calorimeters were designed to measure all the incident radiation.

The distribution of the radiant exposure among the three broad spectral regions is readily computed and is given in Table 2.2.

---

[1] The data have been corrected for the transmittance of the filters in the manner described in Appendix A.

TABLE 2.2

Spectral Irradiance, Baker and Dog Shots

Distance from Ground Zero	Percentage of Radiant Exposure		
	UV(2,200-4,000A)	VIS(4,000-8,000A)	IR(8,000-30,000A)
Baker Shot			
2,000 ft	16.6	54.4	29.0
4,000	12.8	65.9	21.3
5,000	10.3	65.5	24.2
Dog Shot			
4,000 ft	17.4	60.4	22.2
5,000	22.6	54.2	23.2
6,000	19.6	52.6	22.8
7,000	15.4	66.7	17.9

The spectrum of the carbon arc employed in the laboratory gives approximately 4 percent below 4,000A, approximately 36 percent between 4,000 and 8,000A, and 60 percent above 8,000A. The effective field source, therefore, is considerably "whiter" than the laboratory source.

The distribution of the emittance of black-body radiation among the three selected wave length regions was computed for several temperatures. All energy below 3,000A was neglected, inasmuch as previous NRL data had indicated that the bomb spectrum has negligible energy in that region. The water content of the atmosphere at BUSTER was computed from the measured temperature and relative humidity. NRL has published a report on the transmission of infrared radiation for several visual transmittances and water contents. Making use of these data and published NRL data on the attenuation of ultraviolet radiation by the atmosphere, the curves shown in Fig. 2.3 were obtained. Application of these curves to the BUSTER data would indicate that the radiation is essentially black-body, the temperature being approximately 7,700°K. for the Baker shot and approximately 8,850°K. for the Dog shot.

2.1.4 Conclusions

The thermal partition of the bomb energy, computed from the radiant exposure data, is 33 percent for the Baker shot and 23 per-

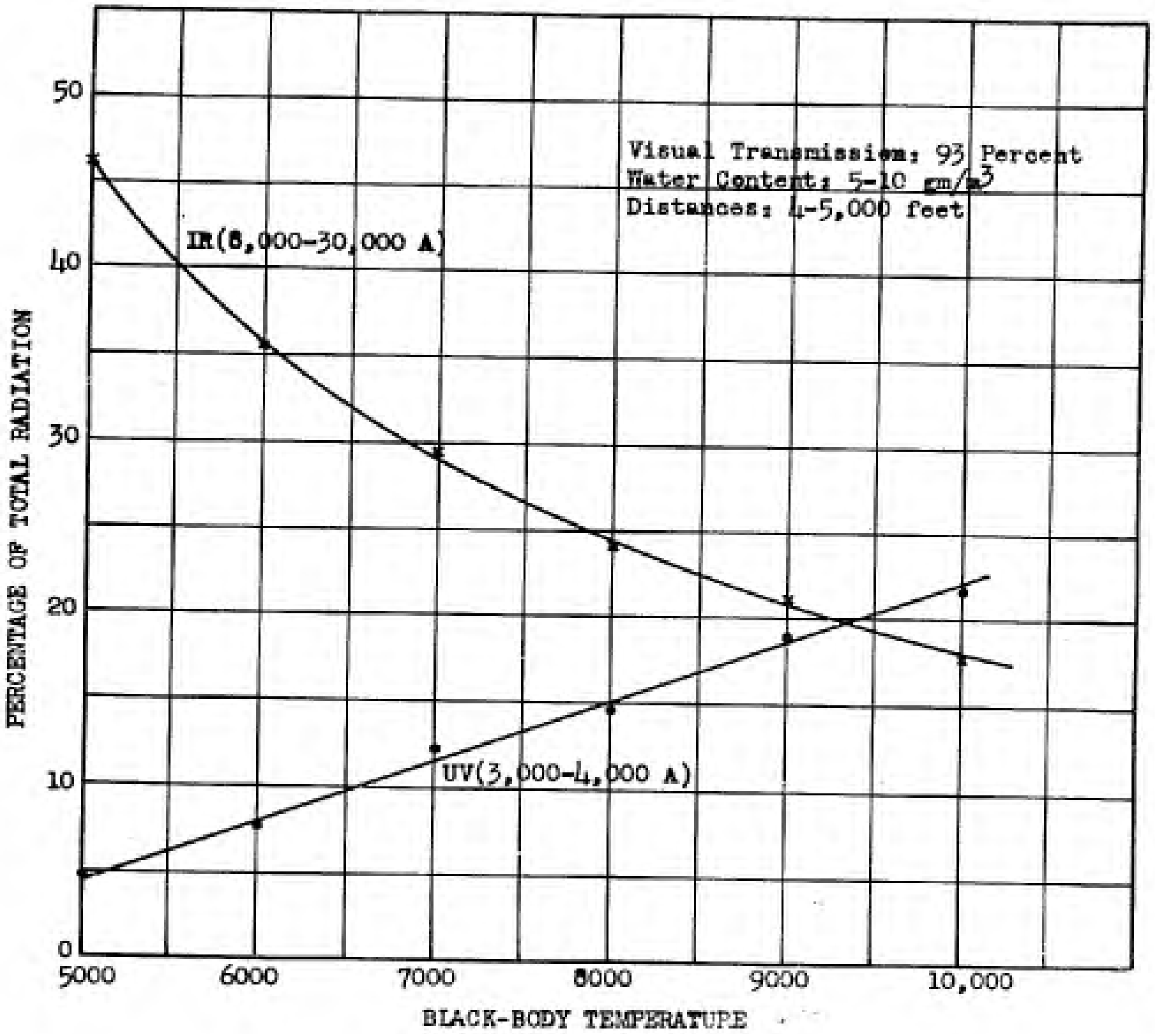


Fig. 2.3 Percentage of Black-Body Radiation in Ultraviolet and Infrared Regions for Certain Conditions

cent for the Dog shot, both of which are considerably higher than the 17 percent thermal partition determined for the RANGER detonations.[2] A considerable portion of the energy is in the ultraviolet, substantially more than in the radiation of the laboratory carbon arc. The carbon arc has considerably more infrared content than the effective field source. NML is currently investigating the effects of source spectral characteristics on the degree and extent of thermal damage. The results of this study should indicate the extent, if any, to which laboratory exposures must be modified in order to obtain a more representative spectrum. It must be remembered, however, that the spectrum of the field source, as it affects materials, depends significantly upon the transmission of the atmosphere.

2.1.5 Recommendations for Future Bomb Tests

In future field tests a considerable amount of attention should be given to determining the spectral distribution of the bomb's radiation among representative wave length regions. In view of the possible failure of the electric circuits of "active" receivers, such as bolometers and calorimeters, passive receivers in the form of metal foils, sensitive materials or paints should also be employed for this purpose.

2.2 IRRADIANCE-TIME RELATIONSHIP

2.2.1 Experimental Plan

To determine the variation with time of the damage occurring to various materials during exposure to atomic bomb thermal radiation, a special shutter and sample holder were designed for use in the BUSTER operation. By means of this device, a series of similar samples of each material were exposed, each sample being exposed for a slightly longer time than the preceding sample. (Actually, two series of each material were exposed, as will be described below.) Each of the samples was then compared with a set of samples of the same material which had been exposed in the laboratory to known radiant exposures, so that a radiant exposure, in cal/cm^2, could be assigned to each of the field samples. In this way an effective irradiance-time curve was constructed, the closeness of the curve for each material to the true irradiance-time curve depending on the reciprocity and other characteristics of the material.

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[2] NML Report 5046-7 summarizes the thermal radiation measurements made during Operation RANGER, using passive indicators in the form of papers, plastics, woods and cloths.

2.2.2 Description of Shutter and Sample Holder

The shutter had to meet three requirements: it had to be sturdy, to withstand the shock wave; it had to expose the test samples for predetermined time intervals covering the entire period of interest; and it had to measure accurately the time of exposure of each sample. The shutter (Fig. 2.4) consisted of a framework, measuring three feet by one foot, of 3 x 1 1/2 in. duralumin channel in which a 1/16-in. thick aluminum plate was mounted in a track and caused to move across the frame by means of the spring action of an ordinary door check. The door check was adjusted to give a total travel time of the plate of approximately 2 1/2 sec. The material samples were mounted directly behind the plate and arranged so that, as the shutter was driven across the frame, it uncovered one set of samples while it covered another set. In this way two sets of records were obtained. One set gave a record of material damage up to any time (t) of the entire exposure. The other gave a record of material damage after any time (t) of the entire exposure.

A phototube circuit was employed (Fig. 2.5) to activate a relay when a flash of light was incident upon it. This relay, in turn, energized a solenoid which tripped a lever initiating the shutter plate movement across the samples. This permitted the mechanism to activate itself and to be entirely self-contained. The initial time, that is, the time from the initial flash until the shutter starts moving, was determined in the laboratory using a flash lamp and motion picture studies, and was found to be 130 milliseconds.

The timing of the shutter movement was obtained by means of brass pins spaced 1 1/2 in. apart on the shutter plate. As the plate moved across the samples, the pins made contact with a smoked drum rotated by a six-volt d-c motor. From the frequency of the motor and the markings on the smoked record, the elapsed time could be obtained for any position of the shutter. For example, in the Baker shot the movement to cover one half of the first sample took 10 milliseconds; to cover all of the first sample, 20 milliseconds; the third sample was covered by 160 milliseconds; the fourth by 250 milliseconds, etc.

The materials used as test samples were chosen for a wide range of sensitivities. The materials included black acetate rayon, gray rayon, black bakelite, carbon paper, maple wood, nylon-faced wool, blue nylon, green sensitive paper, green wool, blue blotting paper, mahogany, and blue cotton. Each sample measured 1/2 in. square and was isolated from adjacent samples by aluminum strips which served as flame and conduction barriers. The samples were mounted on silicate laminate strips which were secured to a heavy iron plate bolted to the back of the angle iron frame.

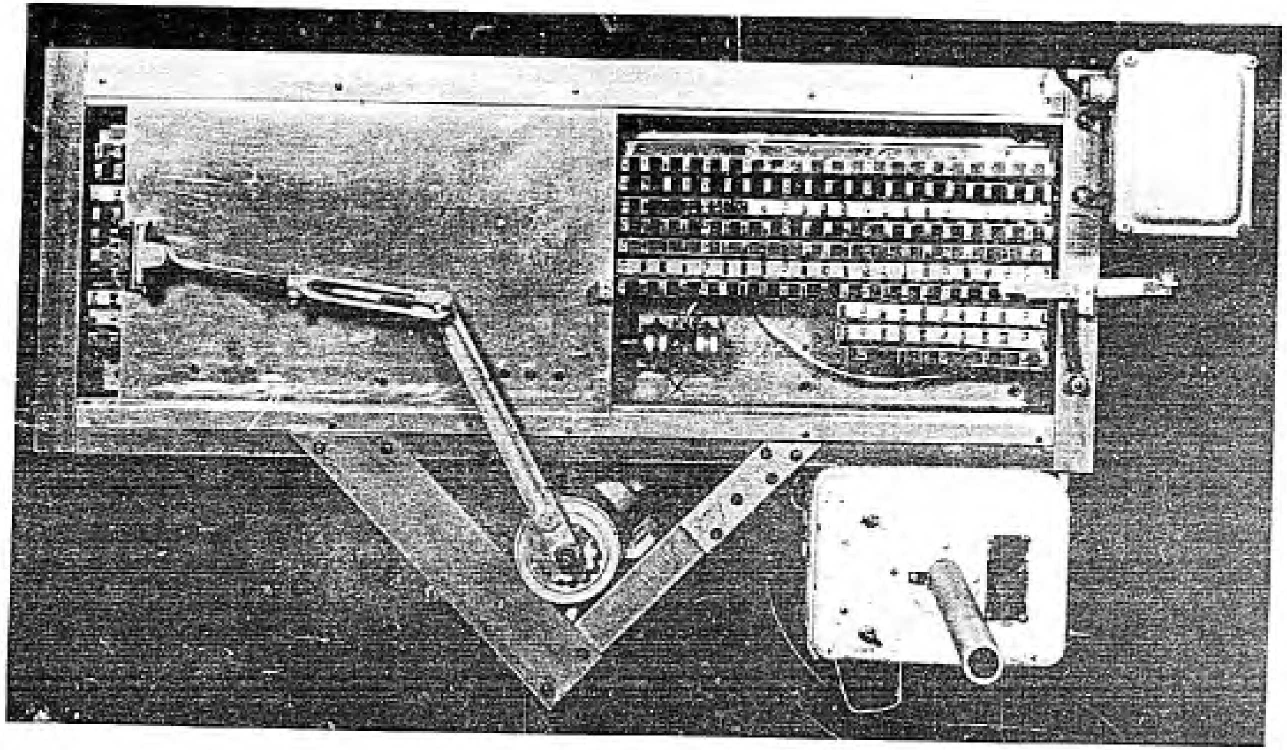

Fig. 2.4 Shutter Mechanism for Determination of Effective Exposure Time

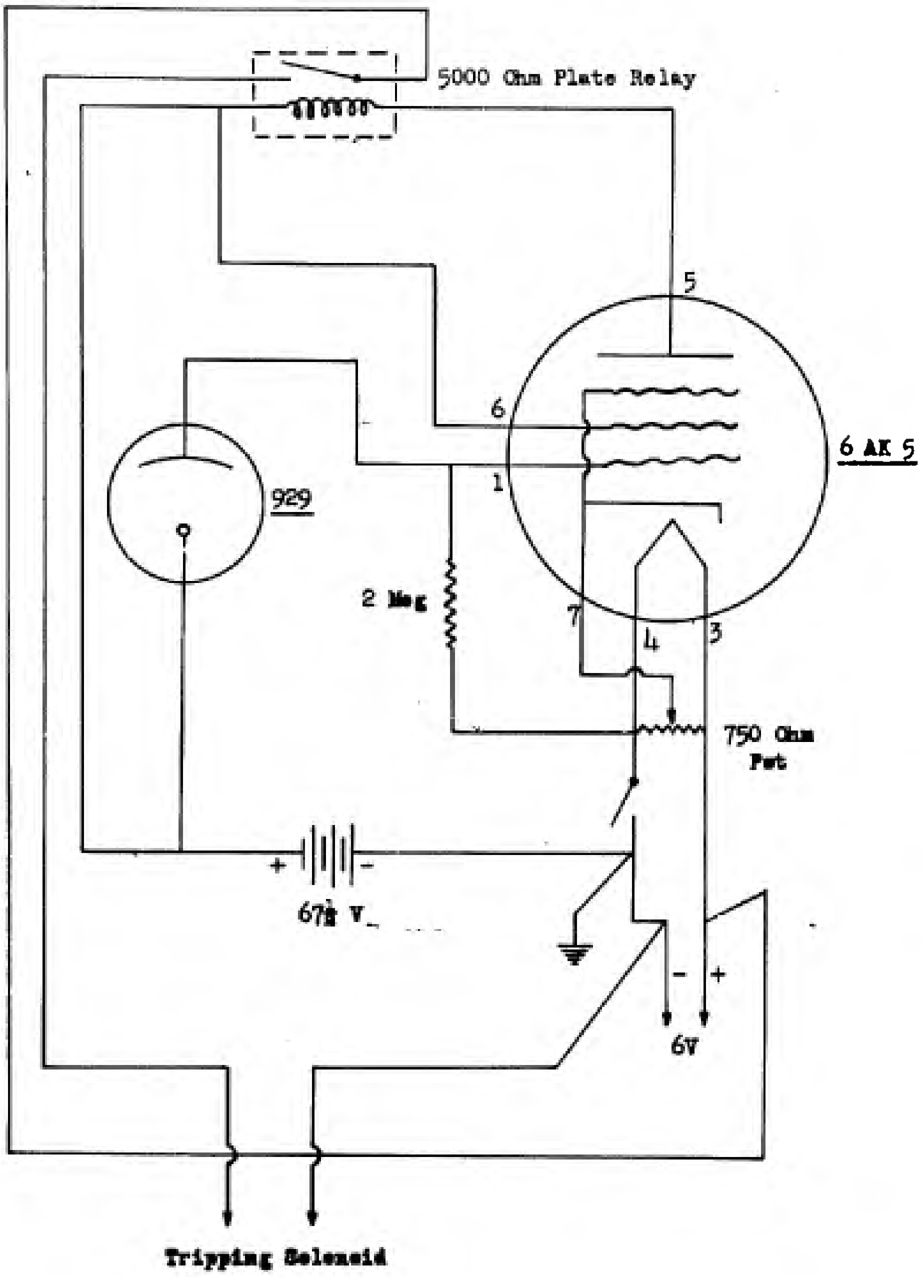

Fig. 2.5 Phototube Circuit for Activating Shutter Mechanism

2.2.3 Laboratory Measurements

The materials were calibrated in the laboratory using the carbon-arc source described in Section 1.4. The calibrations of the several materials are included in Appendix C, Table C.2.

2.2.4 Analysis of Field Data

Using the energy values for damage from the laboratory calibration of materials, the energy absorbed by the test samples in the field was evaluated by obtaining characteristic damage points. For example, for the samples covered (as against those uncovered) in the Dog shot, the green sensitive paper behaved in the manner indicated in Table 2.3.

TABLE 2.3

Typical Damage Characteristic of Green Heat-Sensitive Paper

Sample No.	Description of Effect	Assigned Radiant Exposure
First half of 1	Paper blood red with shiny deposit	5.5 cal/cm^2
Second half of 1	Paint distilled off paper	6.0 cal/cm^2
2	Paper dark brown, paint completely distilled off paper	9.0 cal/cm^2
3	Start of bleach (half dark, half light)	10.0 cal/cm^2
4	Paper bleached (light brown)	15 cal/cm^2
5	Start of charring	17 cal/cm^2
6	Char	17.5 cal/cm^2
7	Heavy char	18 cal/cm^2
8	Complete destruction	21 cal/cm^2

All the materials used in the field test followed the same pattern of damage which has been catalogued in the laboratory, with the exception of nylon-faced wool. In the field, the nylon facing of this material was coalesced and formed a crust which protected the underlayer of wool.

In the matching of field and laboratory damage no corrections were attampted for reciprocity failures.

The materials employed in this study were exposed at 5,000 feet from ground zero for the Baker shot and at 4,000 feet for the Dog shot. These stations were designed for radiant exposures of 6 cal/cm^2 and 20 cal/cm^2, respectively. Because of the unexpectedly low yield of the Baker detonation and the high thermal partitions of the two detonations, 3 cal/cm^2 and 27 cal/cm^2 were received. Consequently, the information obtained referred to the extreme limits of thermal damage; at one distance there was little significant damage, at the other, most materials suffered severe damage. However, the more sensitive materials permitted some conclusions to be drawn.

The sensitive materials showed no significant effects after approximately 180 milliseconds after the initial flash. The green vesicant paper, acetate rayon and carbon paper, which were not significantly affected before 140 milliseconds, indicated that 0.5 cal/cm^2 or less arrived before this time. It is concluded that the major portion of the effective energy arrived between 130 and 180 milliseconds. A low radiant exposure was indicated by the response of the green tropical weight wool, evidently a reciprocity breakdown caused by the reduced energy delivery rate after 200 milliseconds.

The data obtained during Baker shot showed the desirability of faster shutter action to delineate the effects occurring during the first half second, and hence the shutter was set to close in 1.5 sec. for Dog shot.

Sufficient data were obtained for the materials exposed to Dog shot to allow some conclusions as to the damage-time characteristic and as to the magnitude of the peak irradiance. In Fig. 2.6 the radiant exposure arriving up to a time (t) is plotted as a function of the time. Very little damage occurred even to the more sensitive materials before the shutter began to move. If the laboratory calibration of the trip time delay can be taken to be valid, this time was 130 milliseconds. Except for unknown electromagnetic effects in the field, this time is probably accurate to 10 milliseconds.

Most of the damage to materials occurred before 800 milliseconds, very little, if any, further damage occurring to any except the most sensitive materials. Samples of carbon paper and acetate rayon indicated some energy still arriving after 2 sec. This energy may come from the heated gases and sand as well as from the fireball.

The slope of the radiant exposure curve as a function of time indicates a much greater irradiance than has been measured by calorimeters. A peak irradiance of more than 100 cal/cm^{2}sec is indicated by the material-response curve.

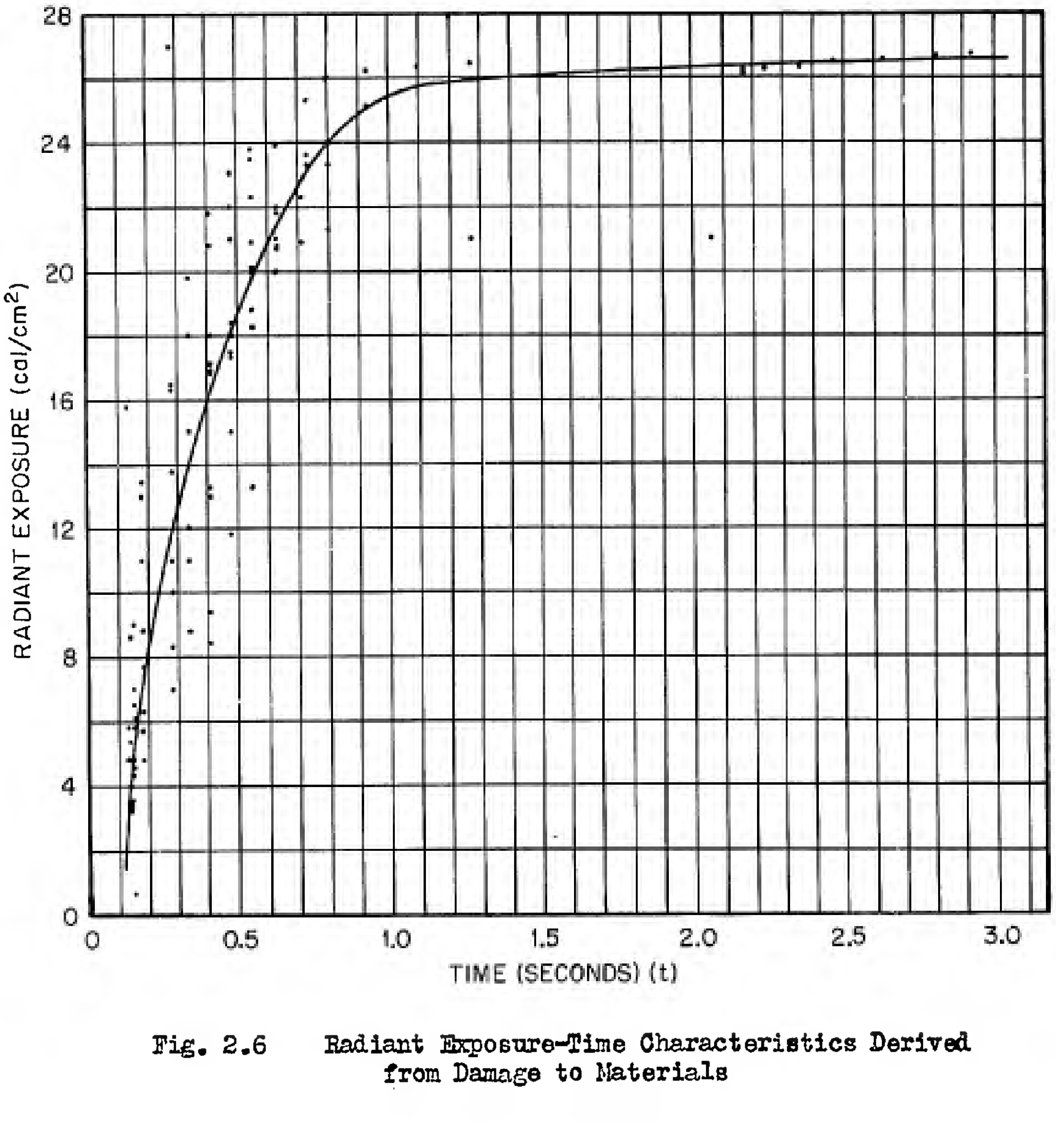

Fig. 2.6 Radiant Exposure-Time Characteristics Derived from Damage to Materials

2.2.5 Conclusions

The results of the study of material damage as a function of time indicate that for a 21 KT detonation little or no effective energy arrives before approximately 130 milliseconds. Most of the im-damage occurs between 130 and 600 milliseconds. The energy arriving after 600 milliseconds was of little importance in causing material damage. The high temperature caused by the energy arriving before this time is lowered by reradiation and conduction, the subsequent lower irradiance being insufficient to maintain or increase the high temperatures associated with further damage.

The data from the Baker shot indicate that the effective time for causing material damage was shorter there than in Dog shot, as one may expect because of the difference in bomb yields.

2.2.6 Recommendations for Future Field Tests

The method of measuring the dependence of thermal damage on time has been established. Operationally, the experiment was successful. It is proposed to make these measurements at the next weapons effects tests, studying the dependence of radiant exposure on time, distance and bomb yield, employing distances which will give damage ranging from negligible effects to complete destruction.

2.3 DISTRIBUTION OF ENERGY IN FOXHOLE

2.3.1 Experimental Plan

As part of its BUSTER studies, the NML was requested to evaluate the degree of protection from the thermal radiation of an atomic explosion afforded by a foxhole. Because of the limited time available for preparation, the spatial distribution of thermal energy within a foxhole was determined by means of sensitive passive indicators in the form of black carbon paper, green vesicant paper and green flannel shirting, materials whose sensitivities are such that radiant exposures from 0.5 to 30 cal/cm^2 can be measured conveniently. The foxhole 6x2 ft. by 4 ft. deep, was located at a distance of 3,000 feet from ground zero and was instrumented for Dog shot. The long dimension of the foxhole was parallel to the thermal line and, therefore, was on a radial line from the source. The foxhole is shown in Figs. 2.7 and 2.8.

In order to obtain a surface of known reflectance characteristics, the plywood walls of the foxhole were covered with a galvanized lining. The material indicators were mounted on 3/8-in. thick glass silicone laminate strips. Each material indicator was 1/2-in. wide and

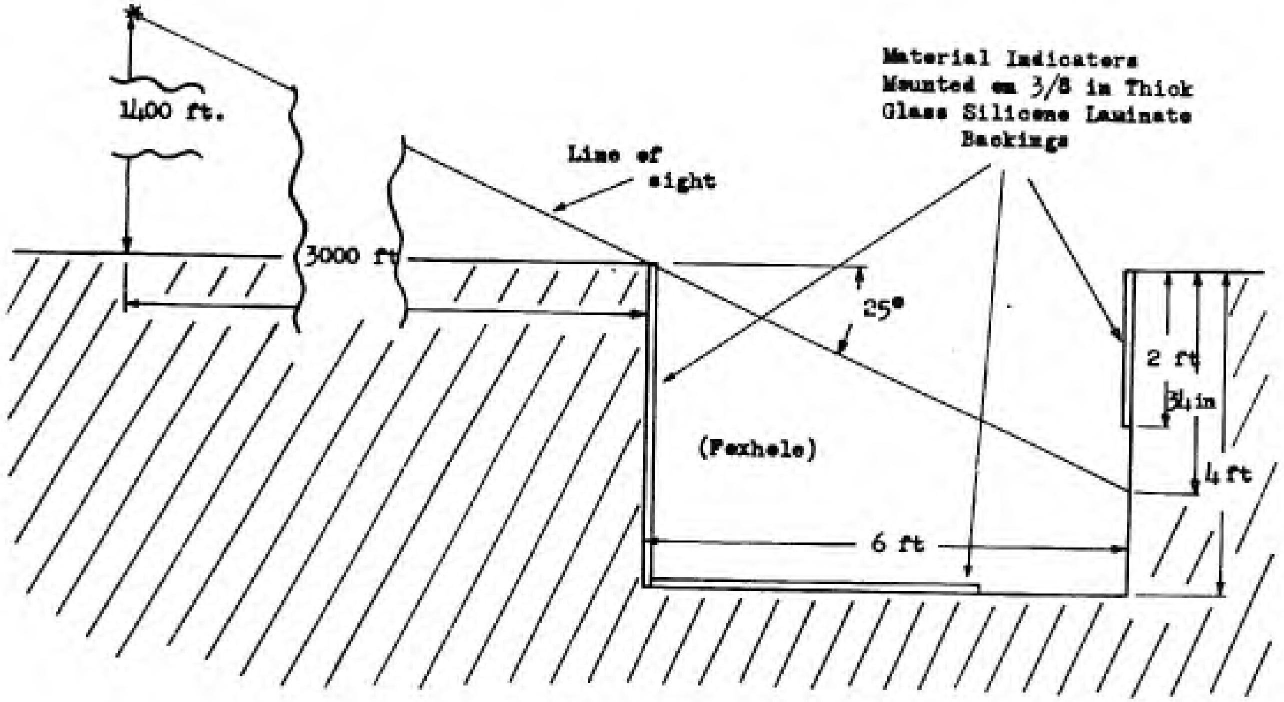

Fig. 2.7 Schematic Layout of Foxhole and Instrumentation

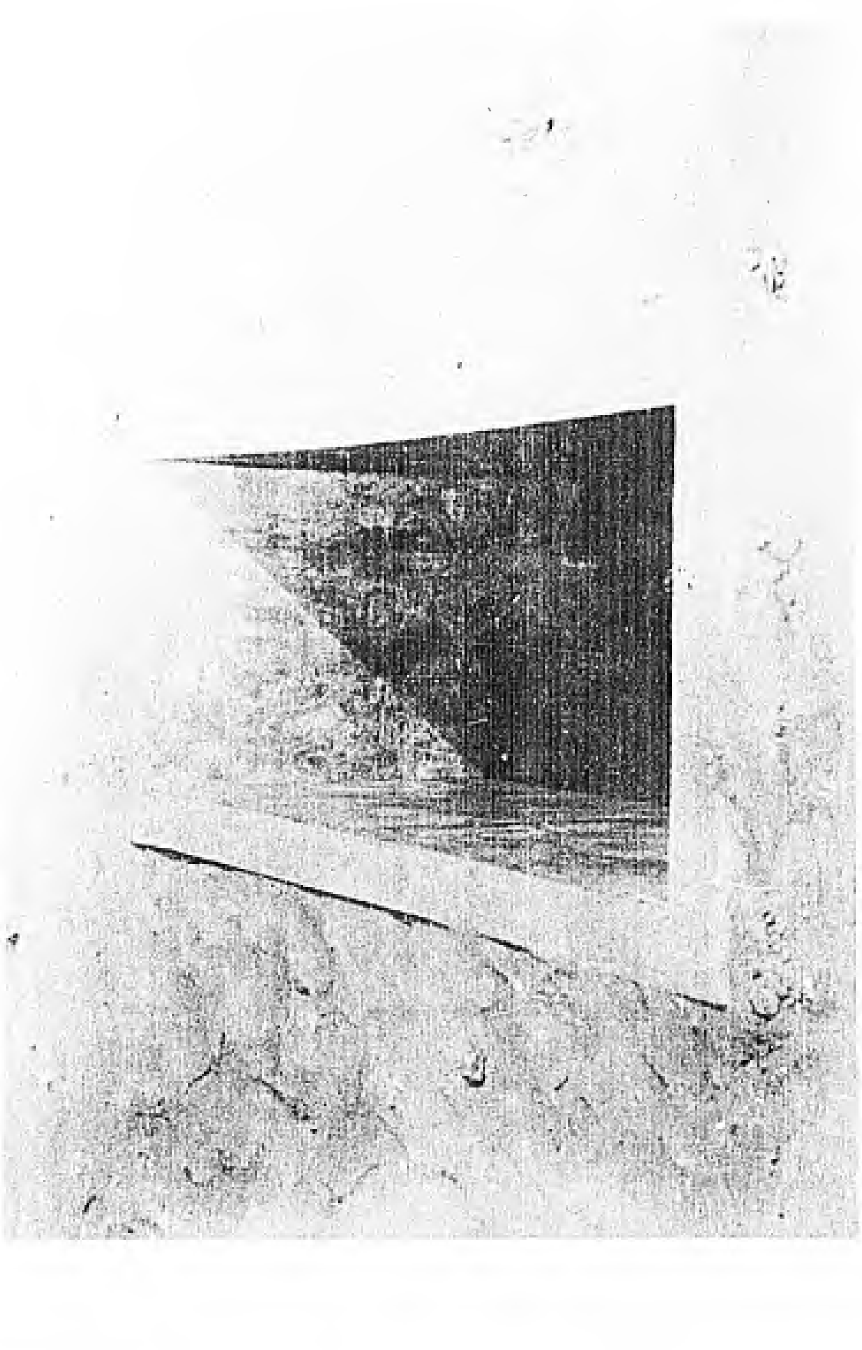

Fig. 2.8 Photograph of Foxhole Looking North

approximately 20 in. long. These strips were subdivided into samples 1 in. long, by flame checks, consisting of silicone sponge rubber strips and sheet metal clamps.

2.3.2 Laboratory Measurements

The calibration data for the three material indicators are included in Table 3.1.

2.3.3 Analysis of Field Data

The damage to the several materials was evaluated in terms of the damage noted in the laboratory calibrations. Approximately 18 cal/cm^2 was measured on the upper half of the rear wall. The energy distribution was fairly uniform. On the front wall, on which the mounted materials were directly away from ground zero, a maximum 1.3 cal/cm^2 was measured at a point 2 in. below the ground surface, and approximately 0.5 cal/cm^2 was measured 6 in. below the ground surface. There was no significant damage to the indicators mounted on the side wall. One may conclude that for a foxhole having the configuration and orientation employed in the BUSTER experiments, personnel would be adequately shielded, if they were not exposed directly to the flash. The radiation noted on the front wall may be due to the heated air and hot sand blown past the foxhole by the shock wave. It is to be noted that only 18 cal/cm^2 was measured at this distance, although extrapolation of the NML metal foil data would indicate that approximately 35 cal/cm^2 would be measured on foils or materials mounted in a manner similar to that employed at the other stations. The indicated attenuation of 50 percent is probably due to obscuration by the heated sand[3] rising from the ground immediately in front of the foxhole.

2.3.4 Conclusions

It may be concluded that personnel, were they to shield themselves from the direct radiation of the bomb, would be adequately protected by a trench having the configuration of the standard two-man foxhole. The reflectance of most earths would be less than that of the Nevada sand; the reflection would be more diffuse than that of the galvanized metal employed during the BUSTER tests.

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[3] A recent study (NML Report 5046-3, Part 19) indicates that the sand found at the Nevada Test Site explodes upon thermal irradiation and that convection currents carry the sand skyward. (See Bibliography)

2.3.5 Recommendations for Future Tests

It is believed that a somewhat more comprehensive study at a future weapons effects test would be desirable. Although the BUSTER data appear to be reliable, an investigation of the shielding effects of foxholes as a function of distance, bomb yield and foxhole geometry would provide more conclusive data.

CHAPTER 3

EFFECTS OF TARGET GEOMETRIES

3.1 EXPERIMENTAL PLAN

In the NML study of target geometries, special emphasis has been placed on the study of large flat specimens, woods exposed at angles of incidence other than normal, and on the effects of interreflections and other interaction of the sides of V-shaped wedges. The purpose of this study is to correlate field exposures with those obtained with a large-area laboratory source of thermal radiation.

The exposures employed to date in laboratory studies of the effects of thermal radiation have been limited, in the absence of a more suitable source of radiation, to small irradiated areas defined by the optical system of a carbon arc of a standard army or navy searchlight, a reflector for collimating the emitted energy and a second reflector for condensing the energy onto the target which is normally placed at the focus of this reflector. In the NML studies an irradiated area approximately 3 by 3 mm has been employed in the case of stationary exposures and a strip 2 mm wide in the case of moving exposures. The irradiated spot, which is essentially the centermost area of the diffuse image of the positive carbon, has a sharp temperature gradient in the radial direction. With this source, the effects of size of flat specimens and of more complicated geometries could not be studied. Because of the size of the irradiated spot and the converging nature of the incident radiation, the effect of the angle of incidence could not be studied. For these reasons, samples with relatively small areas have been employed in previous field tests. A laboratory source of thermal radiation which irradiates a target, 10 in. in diameter, has been developed at the NML. The characteristics of the source, a graphite resistor unit which operates at approximately 2200°C., are now being determined.

Some difficulty was encountered in the development of a shutter for timing exposures to the graphite resistor furnace because of the deformation of the blades and other metal parts under the highest irradiances available from the source. For this reason, the field damage has not been compared with that on the material exposed to the wide-area laboratory source; the correlation of thermal damage by the wide-area source with that produced in the field and by the carbon-arc source will be investigated as part of the laboratory program on the effects of thermal radiation on materials.

The two laboratory sources differ not only in geometry but in spectral characteristics. Since the spectrum of the carbon arc more closely approximates that of the field source, the field damage has been evaluated in terms of the damage caused by the carbon-arc source.

In the BUSTER study, large flat samples, 2 1/4 by 3 in., of cloths, plastics and papers were exposed to the thermal radiation of the explosions. Included in these categories are cotton, wool, rayon, nylon, bond paper, carbon paper and black bakelite. The purpose of this particular problem was to evaluate the so-called "edge" effects of the searchlight type of exposure and to correlate the field exposures with those obtained in the laboratory, using the large-area source. A second phase of the BUSTER correlation study of target geometries was the determination of the effect of the angle of incidence, through the exposure of Douglas fir woods with their surfaces normal to the incident radiation, and at angles of 54°, 66°, and 78° to the normal. In addition, Douglas fir blocks containing V-grooves having included angles of 24°, 48° and 72° were employed to determine the effect of interreflection from the sides of the groove. The geometry panels are shown in Figs. 3.1 and 3.2.

3.2 LABORATORY MEASUREMENTS

The calibrations of the materials under exposure to the laboratory carbon-arc source are included in Appendix C, Table C.2.

3.3 ANALYSIS OF FIELD DATA

3.3.1 Damage to Flat Specimens

In analyzing the thermal damage to the flat material specimens exposed in the field, radiant exposure values have been assigned to each specimen on the basis of comparison with the effects upon samples exposed to the laboratory source. The materials employed were cotton, wool, rayon, nylon, bond paper, carbon paper and Douglas fir plywood. The field specimens were rectangular, 2 1/4 by 3 in. in size. They had been mounted on glass silicone plates in a manner which provided 1/8-in. air backgrounds for the specimens.

The extent of correlation between the value of radiant exposure indicated by damage to a particular specimen and the value indicated by damage to the metal foil assemblies at the same field station was ascertained by computing the "Index of Relationship" (the ratio of the radiant exposure required in the laboratory to produce the same damage as in the field to the radiant exposure in the field); the

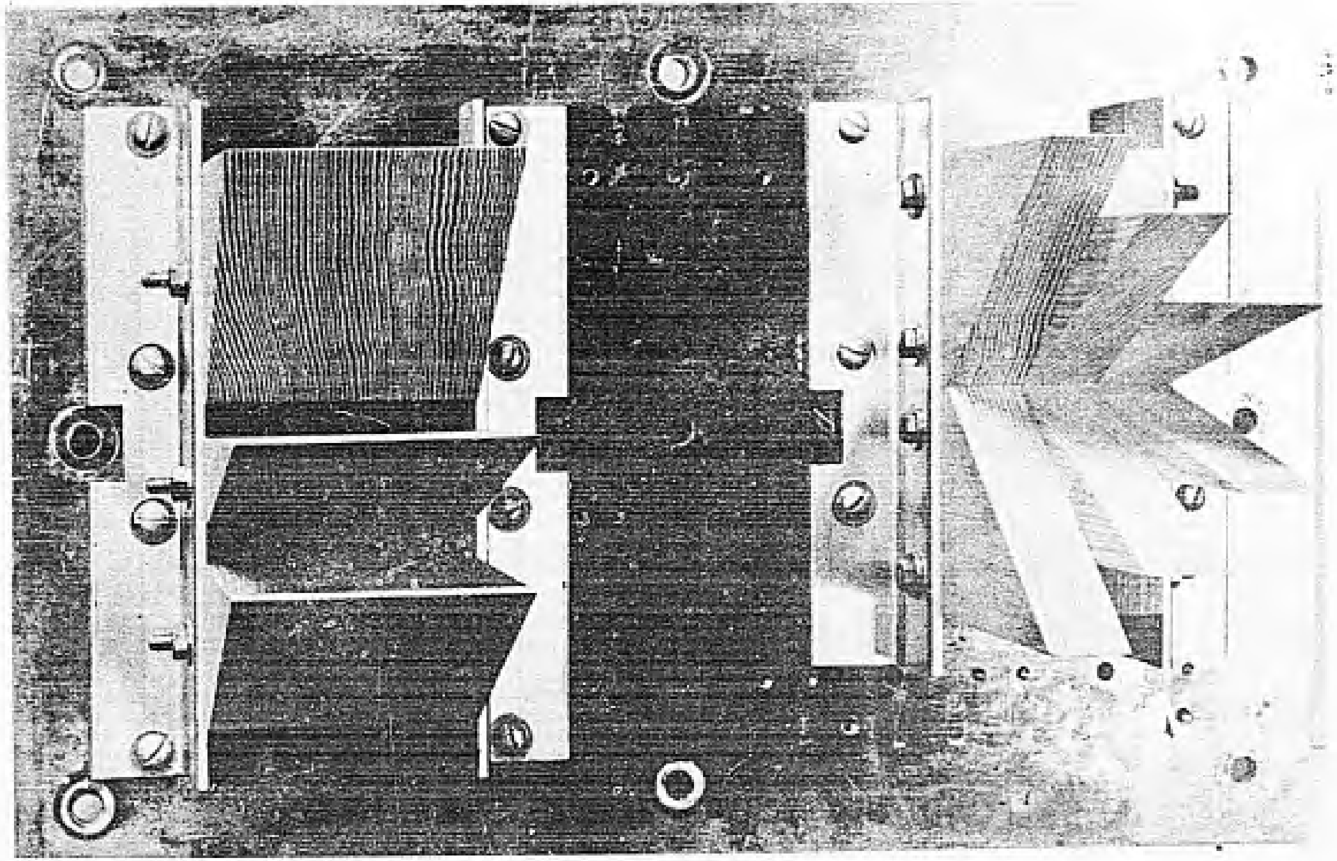

Fig. 3.1 Wood Exposure Panels Designed to Show Effect of Angle of Incidence and of V-Shaped Grooves, Before Exposure

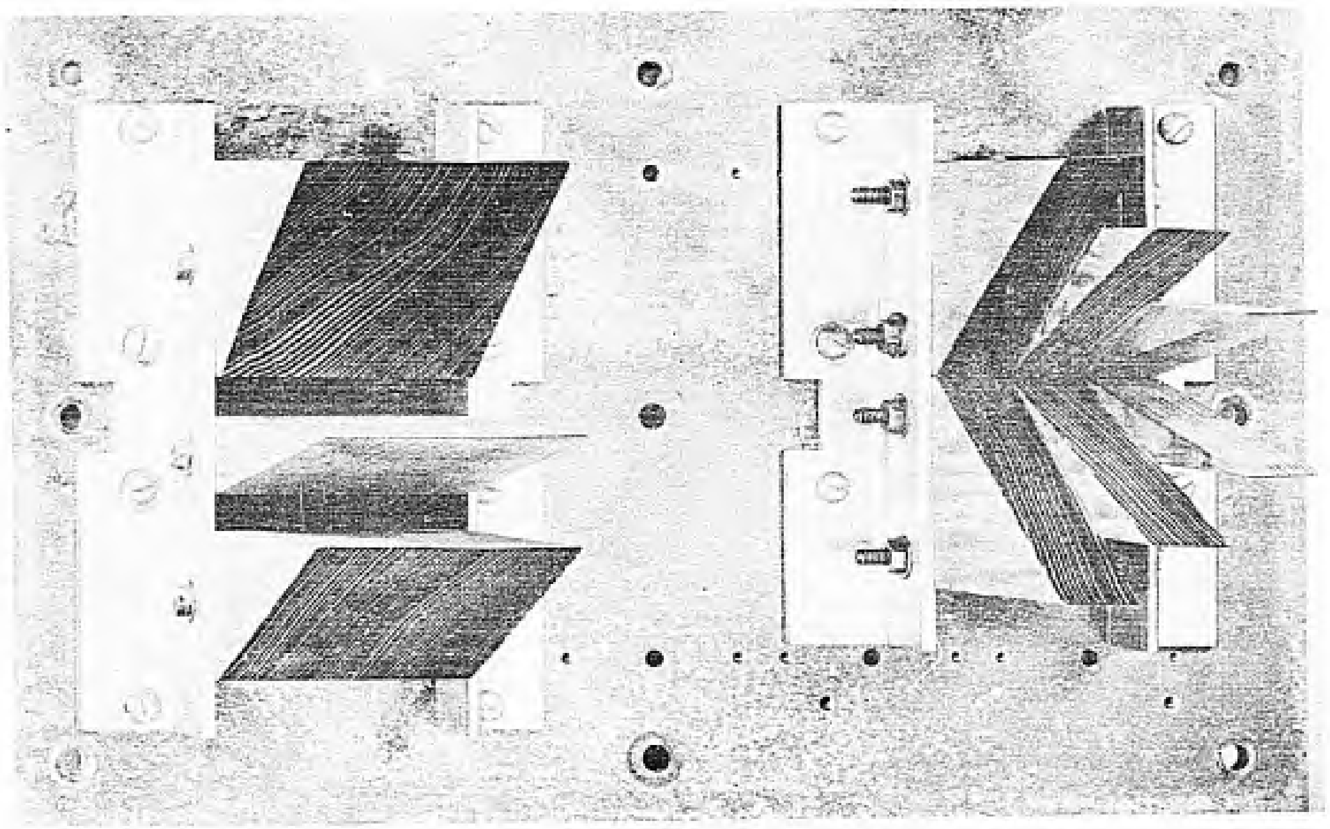

Fig. 3.2 Wood Exposure Panels Designed to Show Effect of Angle of Incidence and of V-Shaped Grooves, After Exposure

radiant exposure in the field has been defined by the damage to the foils. This comparison of laboratory and field damage is given in Appendix C, Table C.3.

The averages for all of the flat samples of the laboratory exposures needed to reproduce the thermal damage which the field exposures produced, indicate that taken as a group the materials behaved as if the incident exposures were those given in Table 3.1.

TABLE 3.1

Radiant Exposures Using Flat Material Samples as Passive Indicators

Shot	Distance from Ground Zero	Radiant Exposure	
		Flat Samples	Metal Foils
Baker	2,000 ft	>18 cal/cm^2	16.9 cal/cm^2
	4,000	5.3	4.7
	5,000	2.4	2.9
Dog	4,000	>18	21.2
	5,000	16	14.2
	6,000	15	9.2
	7,000	15	7.8

Since many of the material specimens were either totally destroyed or completely unaffected, the corresponding assigned radiant exposure values are in the nature of limits, i.e., for destruction or less than the critical threshold value.

For 8 of the 20 positive indications defined by point values, the index of relationship is within the range from 0.70 to 1.30. For 14 positive indications, the index of relationship is within the range from 0.50 to 1.50. Because of this fact, the 50 indicators falling in this category were eliminated from the analysis of the index of relationship.

The variations in index of relationship from one specimen to another and from one material to another are due to differences in the characteristics of the laboratory and field sources, including spectrum and intensity-time. It is believed that a larger and more diverse selection of materials would yield an average index of relationship closer to unity.

3.3.2 Angular Dependence of Thermal Damage

The results of the study of the effect of angle of incidence upon thermal damage to Douglas fir indicate a response in general agreement with the "cosine law"; there was some indication that the angular dependence of thermal damage was influenced by the upward movement of the source. This error in general would be greater for the angles of incidence closest to 90°, since the cosine varies most rapidly in that neighborhood, and would be greatest at the nearest stations.

3.3.3 Effect of Interreflections

With the exception of two specimens whose effects may be considered to be due to extraneous causes, such as plainly visible saw marks, there were no indications in the V-grooves of the existence of an energy buildup. The degree of char within the groove was in every case less than that on the flat surface exposed normal to the line of incidence of the radiation at the same station.

3.4 CONCLUSIONS

The correlation of field damage with that determined under exposure to the laboratory carbon-arc source indicates that laboratory exposures are indicative of the damage to be encountered during exposure in an atomic explosion. The correlation is such that the field damage in most cases can be predicted with satisfactory results by the damage in the laboratory. Target size in the range encountered does not appear to be a significant factor in evaluating damage. For materials oriented at angles other than normal to the incident radiation, the damage was essentially that for a specimen at normal incidence, corrected by the cosine factor. There was no significant build-up of energy in grooves as a result of interreflections from the surface of the groove.

3.5 RECOMMENDATIONS FOR FUTURE FIELD TESTS

Since flaming of wood samples has been encountered infrequently in the field, future target geometry work should concentrate on the construction of samples which will indicate the properties necessary for the starting of fires. More work might be done on the effect of grooves and holes, because of the great variation possible in the geometric parameters, groove or hole angle, groove or hole height, groove length, and in the surface characteristics.

CHAPTER 4

PROTECTIVE MEASURES

4.1 EXPERIMENTAL PLAN

Existing protective coatings are applied to fabrics and constructional materials primarily for limiting the extent of flame propagation of materials. The mechanisms by which these protective coatings or impregnations can minimize damage by thermal radiation are as follow:

(a) The fire-retardant material intumesces, forming an insulating mat over the surface of the material, thereby preventing any further damage. Typical is Albi Temp Kote 99.

(b) The coating materials may be loaded physically with non-combustible chemicals which decrease the flammability of the basic material. Typical is Vita Var Exterior 20.

(c) Highly reflecting metals may be applied to the materials to decrease the amount of incident radiation absorbed by the material. Typical is Glyptol 2527.

(d) Endothermic changes in the fire-retardant agents absorb some of the radiant energy incident on the material and thereby maintain the temperature of the material below the ignition value. Typical is Federal Paint Specification TT-E-489 paint.

(e) There is a decomposition of the fire-retardant material with the evolution of non-oxydizing gases that envelop the material and prevent the ignition of combustible products. Typical is Monsanta Chemical's Rezgard A.

(f) There is a chemical modification of the cellulose molecules of the material, causing a decrease in the combustible gases evolved as the cellulose is broken down by the incident radiation. Typical is American Cyanamid's Pyroset D.

(g) The molecules of metals such as titanium or antimony are bonded chemically to the cellulose molecules, thereby forming a more resistant compound. Typical is DuPont's Erifon.

(h) The chemical salts of the fire-retardant fuse below the ignition temperature of the material and form a non-permeable melt over the material.

In the present experiment, a fire-retardant of each of the foregoing types except the last was used. Samples of two representative woods, white pine and maple, were coated with Albi Temp Kote 99, Vita Var Exterior 20, Glyptol 2527, Federal Specification TT-E-489 and 485b paints and an olive drab low infrared reflecting paint. Three basic textile materials, 7.5 oz black cotton twill, 6 oz black cotton twill and 7.5 oz khaki cotton twill, were impregnated, using Monsanto's Rezgard A, American Cyanamid's Pyroset D and DuPont's Erifon treatments on individual cloth specimens from a single mill run.

In applying the fire-retardant paints to the woods, the wood specimen was first planed flat and given two coats of clear lacquer sealer with a light sanding operation after each application. The wood specimen was then clamped in a bracket, the bracket was leveled and an overflow of the paint sample was dripped onto the specimen with a spatula. A doctor blade with a 5-mil clearance was then drawn at a uniform speed over the wood specimen, spreading a uniform 5-mil wet thickness film of paint over the surface of the specimen.

The impregnated cloth specimens were cut and mounted with M-6 liquid vesicant heat sensitive paper backing, leaving a 1/16- and 1/8-in. air gap between the cloth and paper for the laboratory and field exposures, respectively.

These samples were exposed at BUSTER and to the carbon-arc laboratory source of thermal radiation to obtain the relative merits of the several treatments under field conditions and to obtain a correlation between laboratory and field exposures.

4.2 LABORATORY MEASUREMENTS

4.2.1 Flameproofing Treatments of Cloths

The critical thermal energies of the treated cloths were determined under exposure to the carbon-arc laboratory source at a rate of energy application of 85 cal/cm^{2}sec. The data are presented in Appendix C, Table C.4.

In evaluating the characteristics of clothing materials under exposure to thermal radiation, not only are the destructive effects on the materials themselves of interest but also the amount of heat transmitted through such layers which is incident upon the skin and which may cause serious burns. The apparent transmittances of thermal radiation by the several treated cloths were measured by exposing them to the carbon-arc source with indicators in the form of M-6 vesicant paper, which is heat sensitive, mounted behind the cloths with an air gap of 1/16 in. The energies incident on the cloth which would produce certain effects on the indicator paper and the total energies required to produce the same effects directly on the paper were measured and the "apparent transmittances" of the cloths were computed as the ratios of these two values. The "apparent transmittance" was compared with the wave length average spectral transmittance of light by the material, measured spectrophotometrically in the region 4,000 to 10,000 A. The results are summarized in Appendix C, Table C.5.

The critical thermal energies and apparent transmittances of the treated cloths measured in the laboratory indicate that commercial flameproofing treatments do not increase the resistance of these materials to possible destruction under exposure to high-intensity radiation of short duration.

4.2.2 Fire-retarding Coatings on Woods

The critical thermal energies of the coated woods, determined in the laboratory, are listed in Appendix C, Table C.6. The results of the laboratory evaluations of the paints indicate that Vita Var Exterior 20 is slightly superior to Federal Specification TT-E-485b and Glyptol 2527 paints, with Albi Temp Kote 99 and Federal Specification TT-E-489 paints following in the degree of protection afforded the wood specimen.

4.3 ANALYSIS OF FIELD DATA

4.3.1 Flameproofing Treatments of Cloths

The radiant exposures at the several stations employed in both detonations were such that the damage to the treated fabrics was either threshold or so severe that the material was destroyed. The treated cloths had been dyed black in order to increase their sensitivity, but the unexpectedly high radiant exposures at the four stations employed in Dog shot resulted in damage to most cloths and made computations of heat transmission impossible. For the few cases in which it was possible to compare laboratory and field damage (Table C.7, Appendix C), the damage in the field was similar to that which would be expected at the radiant exposure level indicated by the damage to the metal foils. The damage at the more distant stations was somewhat greater than the laboratory damage.

Of the several flameproofing treatments employed with cloths in the BUSTER tests, Erifon appears to offer more protection to personnel than Pyroset D or Rezgard A, although the degree of protection from radiation gained by these treatments was not large enough to be evident from the few field data available.

4.3.2 Fire-retarding Coatings on Woods

The comparison of field and laboratory damage to the coated woods is summarized in Appendix C, Table C.8. The field damage appears to be much more severe than the corresponding damage in the laboratory. Prior to the Baker detonation the samples were exposed to a severe rainfall, followed by forced drying for 24 hours. Since some of the paints are water-soluble, the data for the Baker shot may not be truly representative of the several paints' performance.

Of the several treatments applied to the wood surfaces, Albi Temp Kote and Vita Var appear more promising than the other paints, although depth of char and other quantitative studies have not been made. These data will be reported as part of the laboratory program on the effects of thermal radiation on materials.

4.4 CONCLUSIONS AND RECOMMENDATIONS

With reference to the treated cloths, none of the flameproofing materials investigated afforded any considerable protection to the cloths. As a matter of fact, the critical energies of the treated cloths as determined in the laboratory are at best equal to and in most cases less than the critical energies of the untreated base textiles. The meager field data, however, indicate that the flame-retardant treatments were of some use. The apparent transmittances of the treated cloths is in most cases higher than the apparent transmissions of the untreated cloths. These observations show that flameproofing, while desirable to prevent the propagation of flame, is not a simple and complete solution for increasing the resistance of textiles to thermal radiation. As an alternative, increasing the reflectance and thereby reducing the absorptance appears to be the best method of increasing the resistance to high-intensity thermal radiation.

Notwithstanding the meagerness of the field data, the relative standing of the various protective measures as determined in BUSTER is in good agreement with their relative standing as found in the laboratory. A more thorough analysis of the field samples may well improve the correlation between the laboratory and field results, where more detailed analysis of the effect of field parameters such as wetting and forced drying, as before Baker shot, has been applied. The laboratory high-intensity carbon-arc source appears to be adequate as a means for evaluating the relative protective merits of treatments. It is recommended that an investigation be conducted to determine the influence of such properties of materials as absorptance and heat conductance, in order to lead to the development of a material assembly with the desirable characteristics of low absorptance, low heat transmittance and conductance, resistance to flame propagation and high critical energy of destruction.

CHAPTER 5

SUMMARY

5.1 SIGNIFICANT FINDINGS

In evaluating damage to materials resulting from exposure to the thermal radiation of an atomic detonation and in establishing the validity of an experimental program in the laboratory, the following physical characteristics are important:

(a) Total radiant exposure as a function of bomb yield and distance from burst.

(b) Spectral distribution of energy among representative, broad wave length intervals.

(c) Variation of irradiance with time.

The thermal partition of the radiation from the Baker and Dog shots was computed from the NML radiant exposure data, assuming yields of 3.5 KT and 21 KT, respectively. Approximately 33 percent of the radiation released during the 3.5 KT detonation and 23 percent of the energy released in the 21 KT detonation were emitted as thermal radiation. These values compare with approximately 15 percent for the RANGER and GREENHOUSE (Easy) detonations.

The relatively low radiant exposure on the exposed back wall of the foxhole indicates a substantial attenuation of the energy for indicators mounted on or close to the earth's surface. According to preliminary laboratory studies of the behavior of Yucca and Frenchman Flat sand, the sand "explodes" upon irradiation, and convection currents carry the sand particles into the air. These sand particles, rising at the instant of irradiation, may obscure the view of the fireball during the latter part of the pulse. Since the RANGER samples were mounted close to the ground a similar obscuring phenomenon may have occurred, making the data unreliable. The Easy detonation at GREENHOUSE was a tower shot; the resulting ground dust cloud obscured the view of the fireball from the thermal stations, destroying the reliability of thermal partition data derived from measurements at these stations.

The apparent radiant exposures at each station derived from averageing the laboratory exposures required to produce the same damage as that noted in the field were computed for the coated woods, the flat specimens (cloths, papers, and woods), and the woods mounted at angles other than normal to the incident radiation (values were cosine-corrected). These data, and the radiant exposures obtained from the metal foils and NRL gas calorimeters, are listed below:

TABLE 5.1

Apparent Radiant Exposures Using
Materials as Passive Indicators

Shot	Distance from Ground Zero	Radiant Exposure (cal/cm^2)				
		Metal Foils	Flat Specimens	Inclined Woods	Coated Woods	NRL Gas Calorimeters
Baker	2000 ft	16.9	> 18	25	32	20
	4000	4.7	5.3	5.8	5.7	5.0
	5000	2.9	2.4	< 4.8	2.8	2.9
Dog	4000 ft	21.2	> 18	26	37	29
	5000	14.2	16	17	26	19
	6000	9.2	15	13	17	14
	7000	7.8	15	13	11	10

These data are noteworthy in two respects. The average radiant exposure at each station, computed from the passive indicators, checks well with the NRL Gas Calorimeter data. Secondly, the metal foils read low at most stations. The first observation leads to the general conclusion that a large number of passive indicators will give radiant exposure values which will agree substantially with instrument-type detectors. The second observation leads to the conclusion that metals because of their relatively high heat conductance do not respond to the cooling phase of the fireball as much as the other classes of materials.

The spectra of the two detonations studied indicated that the emission is essentially black-body, the temperature of the 3.5 KT detonation being 7700°K. and that of the 21 KT detonation, 8850°K. Since only 22-25 percent of the radiation is in the infrared regions, there need be no concern that protection against the thermal radiation of atomic detonations will be at variance with camouflage and concealment against infrared devices.

Although this difference in temperature between the two shots does influence the spectral distribution of the emitted radiation, the atmosphere reduces the ultraviolet and infrared contents sufficiently that one may say that, on the average, at the distances of interest, 16 percent of the energy is in the ultraviolet and 23 percent in the infrared. The spectrum of the Easy shot in GREENHOUSE measured in the same manner showed 8 and13 percent in the ultraviolet and infrared regions, respectively. The salt-laden atmosphere at Eniwetok and higher equivalent black-body temperature of the source may account for the difference.

The irradiance-time characteristic, measured with calorimeters by NRDL, indicates a longer pulse time and lower maximum irradiance than does the damage to the materials. Because of the definite possibility of instrumental errors it remains probable that the measurements reported herein are reasonably accurate. It is unfortunate that either the pulse time was shorter or the total radiant exposure was higher at the stations selected for the experiments than the designed values. The method of measurement, however, proved highly successful. The maximum irradiance in Dog shot was greater than 100 cal/cm^{2}sec at the station at which the total energy was 21 or 27 cal/cm^2, considering material damage or instrumental indication, respectively.

The damage to the field samples was essentially that which would be predicted from the damage resulting from exposures to the laboratory carbon-arc source of thermal radiation. For those samples for which laboratory damage does not match field damage, it is difficult to isolate the source parameters responsible for the lack of correlation. The lack of correlation may be due to differences in the source spectral and irradiance-time characteristics, as well as weather, blast and other exposure conditions. The field damage could not be compared with exposures to the laboratory wide-area source of thermal radiation, but it is intended that the field samples will be employed as reference standards in evaluating exposures to this unit. Although the area irradiated by the graphite resistor furnace is much larger than the carbon-arc spot, the temperature departs much more from the desired temperature.

The protective measures studies have shown that commercial flameproofing treatments of cloths are not effective in protecting personnel. The proper approach in a program aimed at protecting personnel against thermal radiation appears to lie in modifying the color of the outer clothing and in providing two or more layers of clothing between the outer garment and the skin. A laboratory study is underway at NML to determine the basic data on transmission of heat through clothing. Some wood coatings appear more successful than others, but the post-shot analysis of the field damage, including depth-of-char studies, has not been completed.

The results of the experiment to determine the spatial distribution of thermal energy in a conventional two-man foxhole indicate that adequate protection is afforded personnel if they avoid the direct radiation from the detonation. It would be difficult, however, to generalize these findings to a foxhole whose length radial to ground zero is less than 6 feet.

5.2 NML STUDIES AT FUTURE BOMB TESTS

The NML proposes to conduct the following investigations at the next weapons effects tests:

(a) Measurement of the spectral radiant exposure for a series of detonations, as a function of bomb yield and distance from the burst.

(b) Study of the irradiance as a function of time, for several bomb yields and distances.

(c) Study of the spatial distribution within a foxhole as a function of foxhole geometry and distance from burst.

(d) Study of the heat transmission and conduction through layers of clothing.

These studies should add to the knowledges available at present and assist in determining the validity of laboratory studies of the effects of thermal radiation.

APPENDIX A

TRANSMITTANCE OF FILTER WINDOWS

In determining the spectral breakdown of the radiant exposure through the use of active or passive indicators in conjunction with filters, it is desirable that the filters reject all energy outside the pass band and pass non-selectively energy in all wave lengths within the wave length interval of immediate interest. It is difficult to obtain such filters in practice. The underlying consideration in selecting filters whose nominal cutoff wave lengths are 4,000 and 8,000 A was to divide the energy into the three bands, ultraviolet, visible, and infrared, with which the military are concerned in the development of secure optical communications equipment and camouflage methods. As analysis of the data presented in Fig. 2.1 would indicate, the Corning filters 3060 and 2550 do not have the desired sharp cutoffs.

The radiant exposure at any distance from an atomic detonation is defined by the relationship,

$$Q = \int_{0}^{t_o} \int_{\lambda_1}^{\lambda_2} H_\lambda(\lambda,t)\, d\lambda\, dt, \tag{A.1}$$

where $H_\lambda(\lambda,t)d\lambda$ is the irradiance in the wave length interval, λ to $\lambda+d\lambda$, at the instant t, t_o is the total time of irradiation, and λ_1 and λ_2 define the spectrum of interest.

The radiant exposure behind the quartz (or filter) window is then given by

$$Q' = \int_{0}^{t_o} \int_{\lambda_1}^{\lambda_2} t_\lambda\, H_\lambda(\lambda,t)\, d\lambda\, dt, \tag{A.2}$$

where t_λ is the spectral transmittance of the quartz or filter window at wave length, λ.

Because of the high temperatures which would develop in the windows and because of the convergent nature of the incident radiation, laboratory calibrations of the foils behind the quartz and filters were not practicable. The field damage to the metal foils were analyzed with reference to the laboratory calibrations of the foils, in which a constant irradiance is employed and the times for typical damage are noted. The radiant exposure falling on the window is given by

$$Q = Q'/t_{av} \tag{A.3}$$

where Q' is the radiant exposure on the foils and t_{av} is the average transmittance of the window. The average transmittance of the window depends upon the spectral distribution of the source, which is also dependent on time,

$$t_{av} = \frac{\int_{o}^{t_o} \int_{\lambda_1}^{\lambda_2} t_\lambda \, H_\lambda \, d\lambda \, dt}{\int_{o}^{t_o} \int_{\lambda_1}^{\lambda_2} H_\lambda \, d\lambda \, dt} . \tag{A.4}$$

The spectral distribution of the flash of an atomic detonation is not accurately known, but it is black-body to at least a first approximation, the temperature ranging from 10,000°K. down to 3,000°K. The effective transmittances of the windows were determined, for black-body radiation at 3,000° and 10,000°K.[1], using the simplified relationships,

$$t_{av} = \frac{\sum_{\lambda_1}^{\lambda_2} t_\lambda \, H_\lambda \, \Delta\lambda}{\sum_{\lambda_1}^{\lambda_2} H_\lambda \, \Delta\lambda} . \tag{A.5}$$

The effective transmittances of the windows are given in Table A.1.

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[1] The black-body radiation for these temperatures attenuated through 6,000 feet of atmosphere (60% visual transmission) was employed. See NML Report No. 5046-3, Part 2.

TABLE A.1

Effective Transmittance of Filter Windows

Filter	Spectral Band	Black-Body Temperature	Transmittance
Corning 3060	4,000-30,000 A	3,000°K. 10,000°K.	0.887 0.817
Corning 2550	8,000-30,000 A	3,000°K. 10,000°K.	0.775 0.626

In determining the spectral distribution of the radiant exposure, the average of the two transmittance values for each filter was employed.

APPENDIX B

GLOSSARY OF RADIATION NOMENCLATURE

A glossary is given here because of the lack of unanimity in usage among radiometrists. The system followed is that of the Optical Society of America.[1] Where a concept of use in thermal radiation effects study is not defined there, a suitable term has been invented. These new terms plus applicable O.S.A. terms are included in this glossary.

Concept	Symbol	Unit	Definition
Radiant flux	P	cal/sec	Power in the form of electromagnetic radiation.
Radiant energy	U	cal	Energy in the form of electromagnetic radiation.
Radiant emittance	W	cal/cm^2sec	Radiant flux per unit surface area emitted by a source.
Irradiance	H	cal/cm^2sec	Radiant flux per unit area falling on a surface.
Spectral irradiance	H_λ	$cal/cm^2sec\mu$	Radiant flux per unit area per wavelength interval falling on a surface.
Radiant exposure	Q	cal/cm^2	Irradiance integrated with respect to time, that is, the radiant energy which falls per unit area on a surface during a given time interval.

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[1] Journal of the Optical Society of America. A Study of Photometric Nomenclature. P. Moon and D. E. Spencer, Vol. 36, No. 11 (November 1946).

Concept	Symbol	Unit	Definition
Critical energy	Q_c		Radiant exposure required for a given effect on a material sample.
Radiant dosage	D	cal/cm^2	That portion of the radiant exposure which is absorbed by a material surface during a given time interval.
Thermal radiation resistance	R	cal/cm^2	The radiant exposure required to damage a given material. Value varies with conditions.
Spectral reflectance	r_λ		The radiant flux reflected from a material surface divided by the incident flux, at each wavelength. Flux refers to spatial total flux. For other conditions, conditions are to be specified.
Spectral transmittance	t_λ		Analogous to just above, for transmission instead of reflection.
Radiant reflectance	r		$\frac{\int r_\lambda P_\lambda d\lambda}{\int P_\lambda d\lambda}$, where P_λ is incident spectral radiant flux. Value of r depends on source used.
Radiant transmittance	t		Analogous to just above.
Radiant absorptance	A		Unity - t - r.
Spectral emissivity	e_λ		$\frac{W_\lambda}{W_{BB\lambda}}$, where W_{BB} refers to black body.
Total emissivity	e		$\frac{\int W_\lambda d\lambda}{\int W_{BB\lambda} d\lambda}$

Concept	Symbol	Unit	Definition
Apparent transmittance			The ratio of all the heat (including radiant, conducted, etc. heat) per unit area leaving the back surface of a flat sample to the radiant exposure at the front surface during the same time interval. Conditions of measurement must be specified. Used in evaluating protective ability of clothing materials.
Equivalent laboratory (radiant) exposure			The radiant exposure in the laboratory which will damage a given field-exposed sample to the same extent it was damaged in the field.
Index of relationship			The ratio of the equivalent laboratory exposure to the field radiant exposure.

APPENDIX C

LABORATORY CALIBRATION DATA

The laboratory calibrations of the several materials and indicators are included herein in tabular form. The comparisons of laboratory and field damage are also given.

TABLE C.1

Critical Thermal Energies of Metal Foils
for Energy Application Rate of 85 cal/cm^{2}sec

Foil	Effect	Critical Energy (cal/cm^2)
Lead, 1 mil thick, untreated	Buckling begins	0.57
	Melting begins	0.99
	Extreme contraction	1.4
	Separation	2.0
Lead, 2 mils thick, untreated	Contraction begins	2.5
	Extreme contraction	4.5
	Separation	5.2
Lead, 2 mils thick, treated	Melting begins	1.0
	Extreme contraction	1.3
Lead, 3 mils thick, untreated	Buckling begins	3.1
	Contraction begins	4.0
	Extreme contraction	5.2
Lead, 4 mils thick, untreated	Buckling begins	3.6
	Contraction begins	4.5
Lead, 5 mils thick, untreated	Buckling begins	5.2
	Melting begins	6.3
	Separation	9-10

TABLE C.1 (Cont.)

Critical Thermal Energies of Metal Foils for Energy Application Rate of 85 cal/cm^2sec

Foil	Effect	Critical Energy (cal/cm^2)
Tin, 1 mil thick, untreated	Buckling begins	1.4
	Dulling of surface	2.6
	Contraction begins	2.8
	Marked contraction	4.0
Tin, 1 mil thick, treated	Wrinkling begins	0.46
	Contraction begins	0.84
	Separation	1.1
Tin, 2 mils thick, untreated	Buckling begins	1.7
	Contraction begins	2.5
	Extreme contraction	5.2
Tin, 3 mils thick, untreated	Buckling begins	3.2
	Melting begins	4.8
Zinc, 2 mils thick, untreated	Melting begins	1.7
Nickel, 1 mil thick, untreated	Initial discoloration	3.4
	Buckling	3.6
	Beginning of melting	8.7
	Separation	13.0
Nickel, 2 mils thick untreated	Beginning of buckling	7.2
	Beginning of discoloration	8.8
	Separation	23
Gold, 1 mil thick, untreated	Beginning of buckling	7.6
	Separation	21
Gold, 2 mils thick, untreated	Beginning of buckling	16
	Beginning of melting	33
Platinum, 1 mil thick, untreated	Beginning of buckling	6.9
	Melting	14
	Separation	18

TABLE C.1 (Cont.)

Critical Thermal Energies of Metal Foils
for Energy Application Rate of 85 cal/cm^{2}sec

Foil	Effect	Critical Energy (cal/cm^2)
Palladium, 1 mil thick untreated	Buckling begins	7.2
	Melting	18
	Separation	21

TABLE C.2

Critical Thermal Energies of Materials Exposed to Thermal Radiation at Irradiance of 85 cal/cm^{2}sec

Material	Effect	Critical Energy (cal/cm2)
Cotton, shirting weight, low visible, low IR reflectance, untreated (gray)	Slight scorching Pronounced blackening Complete destruction	3.7 7.0 13.3
Cotton, shirting weight, low visible, high IR reflectance, untreated (blue)	Faint discoloration Color changes to gold Complete destruction	3.5 6.3 18
Cotton, duck, low visible, low IR reflectance, untreated, O.D.	Slight scorching Pronounced blackening Complete destruction	3.5 6.8 16
Wool, tropical weight, low visible, low IR reflectance, untreated (green)	Slight scorching Pronounced yellowing Shiny deposit Complete destruction	1.9 3.0 5.6 21
Wool, tropical weight, low visible, low IR reflectance, flameproofed (green)	Nap scorched Shiny deposit Complete destruction	1.8 6.5 11
Wool, tropical weight, low visible, low IR reflectance, untreated (black)	Nap scorched Shiny deposit Complete destruction	1.8 3.6 11
Wool, tropical worsted, USMC, khaki	Nap scorched Shiny crust appears Complete destruction	8.6 13.0 18

TABLE C.2 (Cont.)

Critical Thermal Energies of Materials Exposed to Thermal Radiation at Irradiance of 85 cal/cm^{2}sec

Material	Effect	Critical Energy (cal/cm^2)
Flannel, shirting, USMC, green	Nap scorched Shiny crust appears Complete destruction	2.2 5.3 18
Rayon, average weight, low visible, low IR reflectance, untreated (gray)	Slight scorching Severe scorching Complete burning	6.5 7.5 8.4
Rayon, acetate neckerchief	Scorching begins Destruction	0.46 0.56
Nylon, average weight, low visible, low IR reflectance, untreated (blue)	Melting starts Complete destruction	3.5 4.8
Nylon-faced, wool backing	Slight scorching Scorching with crease in material Outer surface begins to melt Wool exposed due to melting of nylon Wool scorched Complete destruction	3.2 3.6 6.3 7.6 9.4 13.5
Mahogany, untreated	Slight scorching Intense scorching	3.1 6.8
Maple, untreated	One grain slightly scorched Intense scorching	9.5 18
Douglas fir (specimen in field condition)	First grain starts to scorch Second grain starts to scorch	3.3 16
Douglas fir (sanded with 5/0 garnet finishing paper)	First grain starts to scorch Second grain starts to scorch	5.6-6.7 17

TABLE C.2 (Cont.)

Critical Thermal Energies of Materials Exposed to Thermal Radiation at Irradiance of 85 cal/cm²sec

Material	Effect	Critical Energy (cal/cm²)
Paper, bond, cherry	Very faint bleaching	6.5
	Faint discoloration	7.2
	Complete destruction	8.8
Paper, bond, yellow	Faint discoloration	9.5
	Complete destruction	17
Paper, blotting, blue	Faint discoloration	4.7
	Charring	10
	Intense blackening	14
	Complete destruction	27
Paper, vesicant, green (M6) (over glass silicone)	Turns orange	0.45
	Turns brick red	1.1
	Paint distills off	5.6
	Paper begins to char	17
	Paper destroyed	34
Paper, carbon, black	Faint dulling of surface	0.47
	Complete destruction	0.78
Bakelite, black, smooth	Stippling of surface begins	3.3
	Begins to gray	6.0

TABLE C.3

Comparison of Laboratory and Field Thermal Damage

Material	BUSTER Shot	Distance from Ground Zero (Feet)	Gross Description of Effect	Radiant Exposure (cal/cm^2)	Equivalent Laboratory Radiant Exposure (cal/cm^2)	Index of Relationship
Cotton, shirting weight, low visible, low IR reflectance, untreated (gray)	B	2000	Complete destruction	16.9	>16	
	B	4000	Slight brown scorching	4.7	5.8-6.9	1.2-1.5
	B	5000	No effect	2.9	<3.7	
	D	4000	Complete destruction	21.2	>16	
	D	5000	Complete destruction	14.2	>16	
	D	6000	Partial destruction	9.2	>16	
	D	7000	Black charring	7.8	16	2.1
Cotton, duck, low visible, low IR reflectance, untreated, O.D.	B	2000	Complete destruction	16.9	>16	
	B	4000	Slight brown scorching	4.7	<3.4	<0.72
	B	5000	No effect	2.9	<<1.4	<0.48
	D	4000	Complete destruction	21.2	>16	
	D	5000	Complete destruction	14.2	>16	
	D	6000	Black scorching	9.2	15	1.6
	D	7000	Slight black scorch	7.8	13-15	1.7-1.9
Wool, tropical weight, low visible, low IR reflectance, untreated (green)	B	2000	Complete destruction	16.9	>11	
	B	4000	Brown scorching	4.7	5.0	1.1
	B	5000	Slight tan scorch	2.9	2.2	0.76
	D	4000	Complete destruction	21.2	>11	
	D	5000	Complete destruction	14.2	>11	
	D	6000	Complete destruction	9.2	>11	
	D	7000	Complete destruction	7.8	>11	

TABLE C.3 (Cont.)

Comparison of Laboratory and Field Thermal Damage

Material	BUSTER Shot	Distance from Ground Zero (Feet)	Gross Description of Effect	Radiant Exposure (cal/cm^2)	Equivalent Laboratory Radiant Exposure (cal/cm^2)	Index of Relation-ship
Paper, bond, cherry	B	2000	Complete destruction	16.9	>8.8	
	B	4000	Slight bleaching, and tan scorching			
	B	5000	No effect	4.7	7.4	1.6
	D	4000	Complete destruction	2.9	<6.5	
	D	5000	Complete destruction	21.2	>8.8	
	D	6000	Complete destruction	14.2	>8.8	
	D	7000	Complete destruction	9.2	>8.8	
				7.8	>8.8	>1.1
Paper, bond, yellow	B	2000	Complete destruction	16.9	>18	
	B	4000	No effect	4.7	<8.8	
	B	5000	No effect	2.9	<8.8	
	D	4000	Complete destruction	21.2	>18	
	D	5000	Complete destruction	14.2	>18	
	D	6000	Complete destruction	9.2	>18	
	D	7000	Complete destruction	7.8	>18	
Paper, carbon, black	B	2000	Complete destruction	16.9	>0.78	
	B	4000	Complete destruction	4.7	>0.78	
	B	5000	Complete destruction	2.9	>0.78	
	D	4000	Complete destruction	21.2	>0.78	
	D	5000	Complete destruction	14.2	>0.78	
	D	6000	Complete destruction	9.2	>0.78	
	D	7000	Complete destruction	7.8	>0.78	

TABLE C.3 (Cont.)

Comparison of Laboratory and Field Thermal Damage

Material	BUSTER Shot	Distance from Ground Zero (Feet)	Gross Description of Effect	Radiant Exposure (cal/cm^2)	Equivalent Laboratory Radiant Exposure (cal/cm^2)	Index of Relationship
Douglas fir plywood (cross background)	B	2000	Black charring of both grains	16.9	>16	>0.95
	B	4000	One grain slightly scorched	4.7	3.3-4.5	0.70-0.96
	B	5000	No effect	2.9		
	D	4000	Black charring of both grains	21.2		
	D	5000	Black charring of first grain and most of second grain	14.2	16	1.1
	D	6000	Black charring of first grain, light scorch of second grain	9.2	15-16	1.7
Flannel, shirting, USMC (green)	B	2000	Complete destruction	16.9	>18	>1.1
	B	4000	Intense brown scorching	4.7	4.2-5.2	0.89-1.1
	B	5000	Tan nap scorching	2.9	2.3	0.79
	D	4000	Complete destruction	21.2	>18	
	D	5000	Complete destruction	14.2	>18	>1.3
	D	6000	Complete destruction	9.2	>18	>2.0
	D	7000	Partial destruction	7.8	18	2.3

TABLE C.3 (Cont.)

Comparison of Laboratory and Field Thermal Damage

Material	BUSTER Shot	Distance from Ground Zero (Feet)	Gross Description of Effect	Radiant Exposure (cal/cm^2)	Equivalent Laboratory Radiant Exposure (cal/cm^2)	Index of Relationship
Rayon, average weight, low visible, low IR reflectance, untreated (gray)	B	2000	Complete destruction	16.9	>8.4	
	B	4000	Slight yellowing	4.7	6.3-7.1	1.3-1.5
	B	5000	No effect	2.9	<6.6	
	D	4000	Complete destruction	21.2	>8.4	
	D	5000	Complete destruction	14.2	>8.4	
	D	6000	Complete destruction	9.2	>8.4	
	D	7000	Complete destruction	7.8	>8.4	
Nylon, average weight, low visible, low IR reflectance, untreated (blue)	B	2000	Complete destruction	16.9	>4.4	
	B	4000	Complete destruction	4.7	>4.4	
	B	5000	Beginning of melting	2.9	3.7-4.1	1.3-1.4
	D	4000	Complete destruction	21.2	>4.4	
	D	5000	Complete destruction	14.2	>4.4	
	D	6000	Complete destruction	9.2	>4.4	
	D	7000	Complete destruction	7.8	>4.4	
Wool, tropical weight, low visible, low IR reflectance, flameproofed (green)	B	2000	Complete destruction	16.9	>12	
	B	4000	Brown scorching	4.7	4.5	0.96
	B	5000	Slight tan scorching	2.9	1.9	0.66
	D	4000	Complete destruction	21.2	>12	
	D	5000	Complete destruction	14.2	>12	
	D	6000	Complete destruction	9.2	>12	> 1.3
	D	7000	Complete destruction	7.8	>12	> 1.5

TABLE C.3 (Cont.)

Comparison of Laboratory and Field Thermal Damage

Material	BUSTER Shot	Distance from Ground Zero (Feet)	Gross Description of Effect	Radiant Exposure (cal/cm^2)	Equivalent Laboratory Radiant Exposure (cal/cm^2)	Index of Relationship
Wool, tropical weight, low visible, low IR reflectance, untreated (black)	B	2000	Complete destruction	16.9	>11	
	B	4000	Intense brown scorching	4.7	3.4	0.72
	B	5000	Slight brown scorching	2.9	1.8	0.62
	D	4000	Complete destruction	21.2	>11	
	D	5000	Complete destruction	14.2	>11	
	D	6000	Complete destruction	9.2	>11	1.2
	D	7000	Complete destruction	7.8	>11	1.4
Wool, tropical worsted, USMC (khaki)	B	2000	Complete destruction	16.9	>17	>1
	B	4000	No effect	4.7	< 7.2	<1.5
	B	5000	No effect	2.9	< 7.2	< 2.5
	D	4000	Complete destruction	21.2	>17	
	D	5000	Complete destruction	14.2	>17	>1.2
	D	6000	Complete destruction	9.2	>17	>1.8
	D	7000	Intense brown scorching	7.8	11-13	1.5-1.7

TABLE C.4

Critical Radiant Exposure of Cloths Exposed to Thermal Radiation at an Irradiance of 85 cal/cm^{2}sec

Material	Description of Effect	Critical Energy (cal/cm^2)
Cotton twill, white, 6 oz, untreated	Sporadic scorching and destruction	42.7
	Complete destruction	54.6
Cotton twill, white, 6 oz, (Erifon 15-20 percent add-on)	Sporadic scorching	13.7
	Sporadic destruction	24-44
Cotton twill, black, 6 oz, untreated	Faint discoloration	1.4
	Slight scorching	6.3
	Complete destruction	12.2
Cotton twill, black, 6 oz, (Erifon 15-20 percent add-on)	Faint discoloration	1.4
	Slight scorching	4.5
	Destruction	12.2
Cotton twill, black, 6 oz, (Rezgard 12-15 percent add-on)	Faint discoloration	1.5
	Destruction (turns brittle, is not consumed)	7.2
Cotton twill, black, 6 oz, (Pyroset 15-20 percent add-on)	Faint discoloration	1.4
	Slight scorching	4.4
	Destruction (turns brittle, is not consumed)	14
Cotton twill, white, 7.5 oz,	Sporadic scorching	13-53
	Destruction	55

TABLE C.4 (Cont.)

Critical Radiant Exposure of Cloths Exposed to Thermal Radiation
at an Irradiance of 85 cal/cm^2sec

Material	Description of Effect	Critical Energy (cal/cm^2)
Cotton twill, white, 7.5 oz, (Erifon 15-20 percent add-on)	Sporadic scorching Sporadic destruction Destruction (turns brittle, is not consumed)	16 24-44 44
Cotton twill, khaki, 7.5 oz, untreated	Faint discoloration Destruction (turns brittle, is not consumed)	7.4 15
Cotton twill, khaki, 7.5 oz, (Erifon 15-20 percent add-on)	Faint discoloration Slight scorching Destruction (turns brittle, is not consumed)	5.6 6.7 15
Cotton twill, khaki, 7.5 oz, (Rezgard 12-15 percent add-on)	Faint discoloration Destruction	7.5 15
Cotton twill, khaki, 7.5 oz, (Pyroset 15-20 percent add-on)	Faint discoloration Slight scorching Destruction (turns brittle, is not consumed)	4.4 5.6 14
Cotton twill, black, 7.5 oz, untreated	Faint discoloration Slight scorching Complete destruction	1.4 6.5 12.2

TABLE C.4 (Cont.)

Critical Radiant Exposure of Cloths Exposed to Thermal Radiation at an Irradiance of 85 cal/cm^{2}sec

Material	Description of Effect	Critical Energy (cal/cm^2)
Cotton twill, black, 7.5 oz, (Erifon 15-20 percent add-on)	Faint discoloration	1.4
	Slight scorching	4.7
	Destruction	12.2
Cotton twill, black, 7.5 oz, (Rezgard 12-15 percent add-on)	Faint discoloration	1.4
	Destruction (turns brittle, is not consumed)	12.2
Cotton twill, black, 7.5 oz, (Pyroset 15-20 percent add-on)	Faint discoloration	1.4
	Slight scorching	4.5
	Destruction (turns brittle, is not consumed)	10

TABLE C.5

Effects of M-6 Liquid Vesicant Paper Underneath Treated and Untreated Cloths and Apparent Transmittance of Radiation Through the Cloths

Material	Effect on M-6 Liquid Vesicant Paper		Radiant Exposure on Cloth (cal/cm^2)	Apparent Trans-mittance (Percent)	Optical Trans-mittance (Percent)
	Description	Critical Energy (cal/cm^2)			
Cotton twill, white, 6 oz, untreated	Turns orange Turns brick red Destruction	0.44 1.1 21	5.7 12.2 62.5	7.7 9.0 34	6.7
Cotton twill, white, 6 oz, (Erifon 15-20 percent add-on)	Turns orange Turns brick red Destruction	0.44 1.1 21	12.2 17.5 73	3.6 6.3 29	5.1
Cotton twill, black, 6 oz, untreated	Turns orange[a]	0.44	6.9	6.5	5.0
Cotton twill, black, 6 oz, (Erifon 15-20 percent add-on)	Turns orange[a]	0.44	5.7	7.7	3.5
Cotton twill, black, 6 oz, (Rezgard 12-15 percent add-on)	Turns orange[a]	0.44	4.7	9.4	4.4
Cotton twill, black, 6 oz, (Pyroset 15-20 percent add-on)	Turns orange Turns brick red	0.44 1.1	6.4 17	6.9 6.5	4.8

[a] Further results on M-6 paper obscured by distillation products.

TABLE C.5 (Cont.)

Effects of M-6 Liquid Vesicant Paper Underneath Treated and Untreated Cloths and Apparent Transmittance of Radiation Through the Cloths

Material	Effect on M-6 Liquid Vesicant Paper		Radiant Exposure on Cloth (cal/cm^2)	Apparent Trans-mittance (Percent)	Optical Trans-mittance (Percent)
	Description	Critical Energy (cal/cm^2)			
Cotton twill, white, 7.5 oz, untreated	Turns orange Turns brick red Destruction	0.44 1.1 21	12.2 22 68	3.6 5.0 31	5.8
Cotton twill, white, 7.5 oz, (Erifon 15-20 percent add-on)	Turns orange Distillation of paint	0.44 5.9	14 60	3.1 9.8	
Cotton twill, khaki, 7.5 oz, untreated	Turns orange	0.44	12.2	3.6	3.4
Cotton twill, khaki, 7.5 oz, (Erifon 15-20 percent add-on)	Turns orange[a]	0.44	12.2	3.6	2.7
Cotton twill, khaki, 7.5 oz, (Rezgard 12-15 percent add-on)	Turns orange[a]	0.44	10.1	4.4	3.8
Cotton twill, khaki, 7.5 oz, (Pyroset 15-20 percent add-on)	Turns orange Turns brick red	0.44 1.1	10.7 15.5	4.1 7.1	2.8
Cotton twill, black, 7.5 oz, untreated	Turns orange[a]	0.44	8.4	5.2	3.5

[a] Further results on M-6 paper obscured by distillation products.

TABLE C.5 (Cont.)

Effects of M-6 Liquid Vesicant Paper Underneath Treated and Untreated Cloths and Apparent Transmittance of Radiation Through the Cloths

Material	Effect on M-6 Liquid Vesicant Paper		Radiant Exposure on Cloth (cal/cm^2)	Apparent Transmittance (Percent)	Optical Transmittance (Percent)
	Description	Critical Energy (cal/cm^2)			
Cotton twill, black, 7.5 oz, (Erifon 15-20 percent add-on)	Turns orange[a]	0.44	7.2	6.1	2.0
Cotton twill, black, 7.5 oz, (Rezgard 12-15 percent add-on)	Turns orange	0.44	5.7	7.7	4.1
	Turns brick red	1.1	14	7.9	
Cotton twill, black, 7.5 oz, (Pyroset 15-20 percent add-on)	Turns orange	0.44	7.0	6.3	
	Turns brick red	1.1	14	7.9	4.1
	Distillation of paint	5.9	36	16.4	

[a] Further results on M-6 paper obscured by distillation products.

TABLE C.6

Critical Radiant Exposures of Materials Exposed to Thermal Radiation at an Irradiance of 85 $cal/cm^2 sec$

Material	Description of Effect	Critical Energy (cal/cm^2)
Lacquer on maple	Lacquer blisters leaving wood partially denuded	2.8
	Lacquer chars, wood browns	5.5
	Wood chars	7.4
Albi Temp Kote 99 over lacquer on maple	Faint discoloration	0.86
	Paint turns brown	3.2
	Paint chars	4.1
	Wood chars	13
Vita Var Ext. 20 over lacquer on maple	Faint discoloration	2.8
	Paint blisters	3.2
	Paint turns brown	3.4
	Paint chars, intumescence begins	5.4
	Wood chars	39
Glyptol 2527 high IR reflectance over lacquer on maple	Faint discoloration	1.7
	Sporadic blistering	2.0
	Intumescence starts, underlayer turns orange and paint turns brownish-red	2.8
	Pale green intumescence	3.1
	Paint chars	7.1
	Sporadic charring of wood	11.1-23

TABLE C.6 (Cont.)

Critical Radiant Exposures of Materials Exposed to Thermal Radiation at an Irradiance of 85 cal/cm^{2}sec

Material	Description of Effect	Critical Energy (cal/cm^2)
TT-E-485b over lacquer on maple	Faint discoloration	0.78
	Paint blisters	1.2
	Paint chars	2.2
	Wood chars	25
Lacquer on white pine	Lacquer blisters leaving wood partially denuded	2.8
	Sporadic charring of wood and lacquer	5.0-9.2
	Wood chars	9.2
Albi Temp Kote 99 over lacquer on white pine	Faint discoloration	0.85
	Browning of paint	2.8
	Paint chars, intumescence begins	5.2
	Wood chars	15
Vita Var Ext. 20 over lacquer on white pine	Paint blisters	1.7
	Faint discoloration	1.9
	Paint chars, intumescence begins	4.0
	Wood chars	26
Glyptol 2527 high IR reflectance over lacquer on white pine	Intumescence starts	1.0
	Paint turns brownish red, underlayer turns orange	2.4
	Red wedge turns pale green	3.1
	Paint chars	5.5
	Underlayer blisters	10
	Wood surface completely charred	22

TABLE C.6 (Cont.)

Critical Radiant Exposures of Materials Exposed to
Thermal Radiation at an Irradiance of 85 $cal/cm^2 sec$

Material	Description of Effect	Critical Energy (cal/cm^2)
TT-E-489 over lacquer on white pine	Paint blisters	0.78
	Paint turns brick red	0.99
	Paint chars	1.4
	Formation of red flaky mat	3.1
	Wood chars	17
Vinyl black over Albi Temp Kote 99 (5 mils wet film) on white pine	Faint discoloration	0.78
	Vinyl black chars	1.2
	Vinyl black cracks and exposes Albi Temp Kote	2.8
	Albi Temp Kote turns brown, intumescence begins	12.2
	Wood chars	15
O.D. low IR reflecting paint over lacquer on white pine	Intumescence starts	1.4
	Faint discoloration	2.2
	Paint surface turns light brown	3.3
	Paint chars	3.7
	Wood chars	15

TABLE C.7

Thermal Damage to Flameproofed Cloths Exposed to BUSTER Detonations

Material	Shot	Distance	Gross Description of Effects	Radiant Exposure (cal/cm^2)	Equivalent Laboratory Value (cal/cm^2)
Cotton twill, black, 6 oz, untreated	B	2000 ft	Destruction	16.9	12.2
	B	4000	Discoloration and slight charring	4.7	12.2
	B	5000	No effect	2.9	1.4
	D	4000	Destruction	21.2	12.2
	D	5000	Destruction	14.2	12.2
	D	6000	Destruction	9.2	12.2
	D	7000	Destruction	7.8	12.2
Cotton twill, black, 6 oz, Erifon (15-20 percent add-on) flameproofed	B	2000	Destruction	16.9	11.1
	B	4000	Slight discoloration	4.7	3.1
	B	5000	No effect	2.9	1.4
	D	4000	Destruction	21.2	11.1
	D	5000	Destruction	14.2	11.1
	D	6000	Destruction	9.2	11.1
	D	7000	Destruction	7.8	11.1
Cotton twill, black, 6 oz, Rezgard (12-15 percent add-on) flameproofed	B	2000	Destruction	16.9	7.2
	B	4000	Slight scorching	4.7	6.9
	B	5000	No effect	2.9	1.4
	D	4000	Destruction	21.2	7.2
	D	5000	Destruction	14.2	7.2
	D	6000	Destruction	9.2	7.2
	D	7000	Destruction	7.8	7.2

TABLE C.7 (Cont.)

Thermal Damage to Flameproofed Cloths
Exposed to BUSTER Detonations

Material	Shot	Distance	Gross Description of Effects	Radiant Exposure (cal/cm^2)	Equivalent Laboratory Value (cal/cm^2)
Cotton twill, black, 6 oz, Pyroset (15-20 percent add-on) flameproofed	B	2000 ft	Destruction	16.9	14
	B	4000	Slight discoloration	4.7	5.3
	B	5000	No effect	2.9	1.4
	D	4000	Destruction	21.2	14
	D	5000	Destruction	14.2	14
	D	6000	Destruction	9.2	14
	D	7000	Destruction	7.8	14
Cotton twill, black, 7.5 oz, untreated	B	2000	Destruction	16.9	12.2
	B	4000	Slight scorching	4.7	5.3
	B	5000	No effect	2.9	1.4
	D	4000	Destruction	21.2	12.2
	D	5000	Destruction	14.2	12.2
	D	6000	Destruction	9.2	12.2
	D	7000	Destruction	7.8	12.2
Cotton twill, black, 7.5 oz, Erifon (15-20 percent add-on) flameproofed	B	2000	Destruction	16.9	11.1
	B	4000	Slight discoloration	4.7	3.7
	B	5000	No effect	2.9	1.4
	D	4000	Destruction	21.2	11.1
	D	5000	Destruction	14.2	11.1
	D	6000	Destruction	9.2	11.1
	D	7000	Destruction	7.8	11.1

TABLE C.7 (Cont.)

Thermal Damage to Flameproofed Cloths Exposed to BUSTER Detonations

Material	Shot	Distance	Gross Description of Effects	Radiant Exposure (cal/cm^2)	Equivalent Laboratory Value (cal/cm^2)
Cotton twill, black, 7.5 oz, Rezgard (12-15 percent add-on) flameproofed	B	2000 ft	Destruction	16.9	12.2
	B	4000	Slight discoloration and charring	4.7	3.9
	B	5000	No effect	2.9	1.4
	D	4000	Destruction	21.2	12.2
	D	5000	Destruction	14.2	12.2
	D	6000	Destruction	9.2	12.2
	D	7000	Destruction	7.8	12.2
Cotton twill, black, 7.5 oz, Pyroset (15-20 percent add-on) flameproofed	B	2000	Destruction	16.9	10.0
	B	4000	Slight discoloration	4.7	5.3
	B	5000	No effect	2.9	1.4
	D	4000	Destruction	21.2	10.0
	D	5000	Destruction	14.2	10.0
	D	6000	Destruction	9.2	10.0
	D	7000	Destruction	7.8	10.0
Cotton twill, khaki, 7.5 oz, untreated	B	2000	Destruction	16.9	15.0
	B	4000	Slight discoloration	4.7	7.3
	B	5000	No effect	2.9	7.3
	D	4000	Destruction	21.2	15.0
	D	5000	Destruction	14.2	15.0
	D	6000	Destruction	9.2	15.0
	D	7000	Destruction	7.8	15.0

TABLE C.7 (Cont.)

Thermal Damage to Flameproofed Cloths Exposed to BUSTER Detonations

Material	Shot	Distance	Gross Description of Effects	Radiant Exposure (cal/cm^2)	Equivalent Laboratory Value (cal/cm^2)
Cotton twill, khaki, 7.5 oz, Erifon (15-20 percent add-on) flameproofed	B	2000 ft	Destruction	16.9	15.0
	B	4000	Slight discoloration	4.7	5.6
	B	5000	No effect	2.9	5.6
	D	4000	Destruction	21.2	15.0
	D	5000	Destruction	14.2	15.0
	D	6000	Destruction	9.2	15.0
	D	7000	Destruction	7.8	15.0
Cotton twill, khaki, 7.5 oz, Rezgard (12-15 percent add-on) flameproofed	B	2000	Destruction	16.9	15.0
	B	4000	Slight discoloration	4.7	7.5
	B	5000	No effect	2.9	7.5
	D	4000	Destruction	21.2	15.0
	D	5000	Destruction	14.2	15.0
	D	6000	Destruction	9.2	15.0
	D	7000	Destruction	7.8	15.0
Cotton twill, khaki, 7.5 oz, Pyroset (15-20 percent add-on) flameproofed	B	2000	Destruction	16.9	14.2
	B	4000	Slight discoloration	4.7	4.8
	B	5000	No effect	2.9	4.5
	D	4000	Destruction	21.2	14.2
	D	5000	Destruction	14.2	14.2
	D	6000	Destruction	9.2	14.2
	D	7000	Destruction	7.8	14.2

TABLE C.8

Thermal Damage to Coated Woods Exposed to BUSTER Detonations

Material	Shot	Distance	Description of Gross Effects: On Wood	Description of Gross Effects: On Paint	Radiant Exposure (cal/cm^2)	Equivalent Laboratory Value (cal/cm^2)
Lacquer on maple	B	2000 ft	Wood charred	Lacquer charred	16.9	31.5
	B	4000	No effect	Lacquer blistered	4.7	4.7
	B	5000	No effect	No effect	2.9	2.8
	D	4000	Wood charred	Lacquer charred	21.2	33.5
	D	5000	Wood charred	Lacquer charred	14.2	15.0
	D	6000	Wood charred	Lacquer charred	9.2	12.0
	D	7000	Wood charred	Lacquer charred	7.8	7.5
Albi Temp Kote over lacquer on maple	B	2000	Wood charred	Destruction	16.9	13-45
	B	4000	No effect	Slight discoloration	4.7	a
	B	5000	No effect	No effect	2.9	2.8
	D	4000	Wood charred	Intumescence	21.2	46.5
	D	5000	No effect	Intumescence and char	14.2	11.5
	D	6000	No effect	Intumescence and char	9.2	5.2
	D	7000	No effect	Paint charred	7.8	8.5
Vita Var Ext. 20 over lacquer on maple	B	2000	Slight wood char	Intumescence and char	16.9	30-53
	B	4000	No effect	Blistering and discoloration	4.7	3.6
	B	5000	No effect	No effect	2.9	2.8
	D	4000	Wood charred	Paint charred	21.2	50
	D	5000	Wood charred	Blistering and char	14.2	52
	D	6000	Wood charred	Paint charred	9.2	5.2-53
	D	7000	No effect	Paint blistered and charred	7.8	3.2-5.8

a No comparable effect from laboratory calibrations or surface of sample obscured by foreign material.

TABLE C.8 (Cont.)

Thermal Damage to Coated Woods Exposed to BUSTER Detonations

Material	Shot	Distance	Description of Gross Effects		Radiant Exposure (cal/cm^2)	Equivalent Laboratory Value (cal/cm^2)
			On Wood	On Paint		
Glyptol 2527 over lacquer on maple	B	2000 ft	Wood charred	Destruction	16.9	27
	B	4000	Bright orange deposit on wood	Intumescence of paint	4.7	5.5
	B	5000	Red deposit on wood	Intumescence and slight redenning of paint	2.9	3.2
	D	4000	Wood charred	Paint removed leaving wood denuded	21.2	27
	D	5000	Wood charred	Intumescence	14.2	a
	D	6000	Reddish deposit on wood	Intumescence	9.2	6-14
	D	7000	Reddish deposit on wood	Intumescence	7.8	6.5
TT-E-485b over lacquer on maple	B	2000	Wood charred	Destruction	16.9	29
	B	4000	Slight discoloration and sporadic charring	Reddening and flaking of paint	4.7	5-10
	B	5000	No effect	Intumescence and blistering of paint	2.9	1.6
	D	4000	Wood charred	Destruction	21.2	27-43
	D	5000	Wood charred	Destruction	14.2	14.5
	D	6000	Wood charred	Destruction	9.2	14-25
	D	7000	Wood charred	Destruction	7.8	14-26

[a] No comparable effect from laboratory calibrations or surface of sample obscured by foreign material.

TABLE C.8 (Cont.)

Thermal Damage to Coated Woods Exposed to BUSTER Detonations

Material	Shot	Distance	Description of Gross Effects		Radiant Exposure (cal/cm^2)	Equivalent Laboratory Value (cal/cm^2)
			On Wood	On Paint		
Lacquer on white pine	B	2000 ft	Wood charred	Lacquer charred	16.9	56
	B	4000	Sporadic wood char	Lacquer charred	4.7	7.6-11
	B	5000	No effect	Slight discoloration	2.9	2.8
	D	4000	Wood charred	Lacquer charred	21.2	60
	D	5000	Wood charred	Lacquer charred	14.2	48
	D	6000	Wood charred	Lacquer charred	9.2	31
	D	7000	Wood charred	Lacquer charred	7.8	25
Albi Temp Kote over lacquer on white pine	B	2000	Wood charred	Destruction	16.9	18
	B	4000	Slight wood char	Intumescence blistering and char of paint	4.7	3.3-6
	B	5000	No effect	Intumescence and blistering	2.9	1.7
	D	4000	Wood charred	Paint and lacquer charred	21.2	13.5
	D	5000	Wood charred	Paint charred	14.2	16.5
	D	6000	Wood charred	Paint charred	9.2	14.0
	D	7000	Wood charred	Intumescence and char of Paint	7.8	14.5
Vita Var Ext. 20 over lacquer on white pine	B	2000	Wood charred	Destruction	16.9	28
	B	4000	No effect	Intumescence of paint and browning of lacquer	4.7	3-5.7
	B	5000	No effect	Intumescence of paint	2.9	2.0

TABLE C.8 (Cont.)

Thermal Damage to Coated Woods Exposed to BUSTER Detonations

Material	Shot	Distance	Description of Gross Effects		Radiant Exposure (cal/cm^2)	Equivalent Laboratory Value (cal/cm^2)
			On Wood	On Paint		
	D	4000 ft	Wood charred	Paint destruction and lacquer char	21.2	28.5
	D	5000	Slight wood char	Paint destruction and lacquer char	14.2	26
	D	6000	No effect	Paint destruction and lacquer char	9.2	25
	D	7000	No effect	Intumescence and sporadic charring of paint	7.8	4-7
Glyptol 2527 over lacquer on white pine	B	2000	Red deposit and wood char	Destruction	16.9	19.5
	B	4000	Reddish orange deposit	Intumescence, dark green in color	4.7	7.4
	B	5000	Red deposit on wood	Intumescence color varies from red to green	2.9	2.4-4.0
	D	4000	Wood charred	Destruction	21.2	28
	D	5000	Wood charred	Destruction	14.2	31.5
	D	6000	Orange deposit and wood char	Destruction	9.2	9-23
	D	7000	Red deposit and wood char	Destruction	7.8	7-11

TABLE C.8 (Cont.)

Thermal Damage to Coated Woods Exposed to BUSTER Detonations

Material	Shot	Distance	Description of Gross Effects		Radiant Exposure (cal/cm^2)	Equivalent Laboratory Value (cal/cm^2)
			On Wood	On Paint		
TT-E-489 over lacquer on white pine	B	2000 ft	Wood charred	Destruction	16.9	15-27
	B	4000	No effect	Destruction	4.7	4-8.8
	B	5000	Paint discoloration	Destruction	2.9	4.9
	D	4000	Wood charred	Destruction	21.2	27
	D	5000	Wood charred	Destruction	14.2	17.5
	D	6000	Wood charred	Paint charred, lacquer blistered and charred	9.2	16.0
	D	7000	Wood charred	Destruction	7.8	14.5
Vinyl Black over Albi Temp Kote (5 mils) over lacquer on white pine	B	2000	Wood charred	Vinyl paint destroyed, Albi charred	16.9	50
	B	4000	No effect	Vinyl paint destroyed, slight discoloration of Albi	4.7	5.0
	B	5000	No effect	Vinyl paint cracked	2.9	2.7
	D	4000	Wood charred	Vinyl paint destroyed, Albi intumesces	21.2	27-54
	D	6000	Wood charred	Vinyl paint destroyed, Albi intumesces and charred	9.2	23
	D	7000	No effect	Vinyl paint destroyed, Albi intumesces and charred	7.8	20.5

TABLE C.8 (Cont.)

Thermal Damage to Coated Woods Exposed to BUSTER Detonations

Material	Shot	Distance	Description of Gross Effects		Radiant Exposure (cal/cm^2)	Equivalent Laboratory Value (cal/cm^2)
			On Wood	On Paint		
O.D. low IR reflectance over lacquer on white pine	B	2000 ft	Wood charred	Destruction	16.9	27
	B	4000	Faint discoloration	Brown crust formation	4.7	4-11
	B	5000	No effect	Intumescence and faint discoloration	2.9	1.4-3.0
	D	4000	Wood charred	Destruction	21.2	49
	D	5000	Wood charred	Destruction	14.2	25.5
	D	6000	Wood charred	Destruction	9.2	15
	D	7000	Wood charred	Destruction	7.8	14.5

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