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EXPERIMENTAL PRODUCTION OF FLASH BURNS

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INTRODUCTION

The purpose of the present report is to describe the physical techniques employed in this laboratory for the experimental production of flash burns. The medical and biological results of flash burns produced by these methods will be reported separately. One of the fundamental objectives of our thermal research program has been an investigation of thermal and ionizing radiation injury resulting from exposure to the atomic bomb. For this reason it was necessary to develop laboratory methods of simulating atomic flash burns so that we could study various aspects of the problem under controlled conditions which are attained rarely in the field. The high intensity carbon arc was chosen as the source of thermal radiation most likely to approximate the conditions of exposure to the atomic fireball. The advantages of this source are that the spectral distribution and thermal intensity over limited areas are similar to those produced by an atomic bomb flash. The apparatus described below has proven valuable for such studies as the following:

(1) The clinical assessment of thermal injury at various incident doses of radiation.

(2) The effect of rate of delivery on the severity of the thermal injury.

(3) The influence of a thermal intensity varying rapidly with time as compared to a constant thermal intensity.

(4) The effects of spectral composition on thermal injury.

(5) The effect of initial skin temperature on the degree of thermal injury.

(6) The combined effects of thermal and ionizing radiation.

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(7) The protective features of clothing and military fabrics.

(8) The effects of skin pigmentation on the severity of thermal injury.

(9) The comparison of flash burns with burns produced by contact with a hot object.

Flash Burn Apparatus

A. The Searchlight

We have used a 24 inch, U.S.Army searchlight for the experimental production of flash burns. This equipment employs a parabolic mirror, 24 inches in diameter; the front surface is plated with rhodium which provides a reflectance coefficient of about 0.65 over the range of wave lengths emitted by the high intensity carbon arc. Under normal conditions the carbon arc has a traverse of 4 inches, permitting the operator to condense or diffuse the beam within narrow limits. By permanently mounting the mirror 2 inches back of its normal position, an appreciable fraction (about 25%) of the thermal energy can be focused on a small circular aperture, 54 inches in front of the mirror. Thermal intensities ranging from 2 cal/cm^2/sec over a 2 inch diameter area to 8 cal/cm^2/sec over a ½ inch diameter area can be obtained in this manner. The image is quite diffuse which is advantageous in producing a uniform burn over a moderate area.

For the thermal intensities needed in most experiments involving atomic flash burns we have replaced the parabolic mirror with a 24 inch ellipsoidal mirror purchased from Bausch and Lomb*. The mirror is of molded glass with a front surface of aluminum which gives a reflectance coefficient greater than 0.80 over the spectrum of the carbon arc. By placing the carbon arc at one focus, thermal intensities, ranging from 8 cal/cm^2/sec over a 2 inch diameter burn area to 23 cal/cm^2/sec over a ½ inch diameter burn area

* We are indebted to Dr. Herman Pearce, University of Rochester, for suggesting and helping us to obtain this mirror.

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are produced at the second focus. The mirror has wavy imperfections which, while optically undesirable, are advantageous for this application; the diffuse image at the second focus produces burns of surprising uniformity over the area limited by the burn aperture.

B. The Carbon Arc

Up to the present we have used the standard 10 millimeter, high intensity carbons which are stock equipment with the 24 inch Army searchlight. The positive carbon is cored. The arc mechanism is air cooled but we have substituted water cooling for the positive carbon, anticipating the eventual use of special high intensity carbons which are available. Water cooling has other advantages, even when used with the standard high intensity carbons. In the first place, the size of the positive carbon housing can be reduced appreciably, allowing more energy to be focused on the burn aperture. Also, the current density of the arc can be increased without damaging the housing or the mirror. Water is brought to the brass housing through polyethylene tubing to provide electrical insulation.

The carbon feed mechanism is automatic and the feed rate is adjustable. Power for the arc is furnished by a portable, gasoline driven, motor-generator set which is standard Army equipment for the 60 inch searchlight. We have used the larger motor generator set in preference to the power supply normally furnished with the 24 inch searchlight because water cooling allows us to increase the current density of the arc beyond the capacity of the smaller power plant. In future applications, the large power plant will furnish sufficient energy to operate the arc with special high intensity carbons, so that thermal intensities up to 35 cal/cm^2/sec may be obtained. At the present time we are operating the arc between 100 and 150 amperes of current with a corresponding current density ranging from 135 to 145 amp/cm^2.

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The generator has a capacity of 300 amperes at 100 volts, D.C. The actual potential drop across the arc is around 75 volts, 25 volts being the drop in the feed cables.

C. Spectral Distribution of High Intensity Arc

The current density of the carbon arc is the primary factor governing the spectral distribution of the emitted radiation. At 130 amp/cm^2, the spectral distribution approximates that of a black body at 5600°K(1). A study of the radiation transmitted through standard Corning filters while operating our arc at a density of 140 amp/cm^2 shows that approximately 40 percent of the incident radiation is composed of wave lengths between 300 and 650 millimicrons; the remaining 60 percent is beyond 650 millimicrons. According to "The Effects of Atomic Weapons"(2), the spectral distribution emanating from the fire ball of a nominal 20 KT bomb during its secondary phase of radiation corresponds to a black body temperature of about 6500°K. For a black body at this temperature, about 50 percent of the radiation is to be found at wave lengths below 650 millimicrons, while the remaining 50 percent is beyond this wave length. Since our arc, operating at 140 amp/cm^2, is roughly equivalent to a black body temperature of 5800°K, it can be seen that the high density carbon arc provides a reasonable simulation to the atomic ball of fire.

D. Flash Burn Exposures at Constant Thermal Intensity

We have designed and operated two types of shutter mechanisms for controlling thermal exposures. In the first type, the thermal intensity incident on the burn area remains constant during the exposure and only the duration can be varied. We refer to this as a square wave exposure.

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The method is illustrated diagrammatically in Figure 1 and Figure 2 is a photograph of the apparatus. The searchlight beam is intercepted by a revolving steel disc, 24 inches in diameter. A slot, 2½ inches wide and subtending an angle of 1 radian at the rim, is cut out of the wheel near the periphery. An auxiliary shutter or semaphore operated by a Ledex rotary solenoid is situated beyond the slot in the wheel, so that it intercepts the radiation beam passing through the slot. Synchronization of the revolving wheel and the semaphore shutter is accomplished by means of an electronic switching circuit containing three Thyratron tubes with a relay in the plate circuit of each. They are so arranged that when tubes 1 and 2 are in the conducting state direct current flows through the solenoid and deflects the semaphore from the burn aperture. When all 3 Thyratrons are in the conducting state, the solenoid current is interrupted and the spring driven semaphore snaps back into its normal position across the burn aperture. The Thyratrons are so connected that number 2 cannot fire until 1 has been triggered; likewise, number 3 cannot fire until 2 is conducting. A master switch must be closed by the burn operator before any of the tubes can be fired. Triggering of the Thyratrons is accomplished by means of a microswitch which closes momentarily each time the eccentric cam on the shaft reaches a position such that the slot in the wheel is beyond the burn aperture.

The cycle of operations during a burn exposure is as follows: the operator closes the master switch so that the first Thyratron will be triggered when the microswitch is closed momentarily by the cam. Number 1 Thyratron is now conducting. Upon the next revolution, Thyratron number 2 is triggered, just after the slot has revolved past the burn aperture, and the semaphore shutter is deflected rapidly from the burn aperture. During the third revolution the

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exposure takes place but when the slot is just beyond the burn aperture, Thyratron number 3 is triggered and the semaphore shutter snaps back across the aperture. It will be noted that although it requires 3 revolutions of the wheel for one burn exposure, the semaphore shutter has almost a complete revolution of the wheel in which to operate. Since the minimum time required to operate the semaphore is limited by its mass to about 0.1 seconds, this method allows the exposure time to be controlled by the angular velocity of the wheel. A ¼ hp, DC motor drives the wheel and the speed is adjustable by means of a Variac. Exposure times ranging from 16 milliseconds up to several seconds can be provided by this shutter system.

The square wave exposure apparatus has been especially valuable for studies involving a wide range of exposure times (25 milliseconds to several seconds) where the duration must be known accurately. The duration is measured with a photocell and light source mounted close to the burn aperture in such a manner that the revolving disc interrupts the light beam except when the slot passes by. The photocell is coupled to a gating circuit which controls the operation of a decade scaler. A 1000 cps oscillator feeds pulses into the scaler when the slot allows light to fall on the photocell. For example, if the exposure time is one second, the scaler records a total count of 1000. Thus, the scaler indicates directly exposure time in milliseconds.

The venetian blind type of shutter described in the next section (E) allows the thermal intensity incident on the burn aperture to be varied

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continuously from 0 to 21 cal/cm^2/sec. The square wave exposure apparatus in conjunction with the venetian blind shutter affords an extremely flexible system for controlled studies on thermal injury where the exposure time, thermal intensity and thermal dose can be varied at will.

Provisions for the insertion of Corning filters of accurately known characteristics between the semaphore shutter and the burn aperture have made it possible to investigate the spectral distribution of the carbon arc and to study the influence of spectral quality on thermal injury. The transmission characteristics of some of these filters are such that they absorb a large fraction of the incident energy. It is, therefore, important to limit the exposure time in order to prevent deterioration or actual destruction of the filter. The semaphore shutter protects the filter at all times except during actual exposure.

E. The Thermal Pulse Shutter

The thermal intensity incident at a given distance from the detonation of an atomic bomb varies rapidly with time. Thermal injury results from a short pulse of radiant energy which rapidly reaches a peak intensity and then falls off with time. In order to investigate the effects of such a pulse of thermal radiation, we have constructed a special type of exposure shutter to simulate the atomic flash.

The pulse shutter operates on the principle of a venetian blind as illustrated diagrammatically in Figure 3 and shown in Figure 4. Sheet aluminum vanes are supported at each end by ball bearing shafts which pass through a cast aluminum frame. The pulleys rotate in synchronism by means of light aircraft control cable. A linkage arm, 3 inches in length, is fastened to the bottom pulley on one side of the frame and has its free end

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resting on an eccentric cam. The cam is rotated by an adjustable speed, D.C. motor through a gear box and a clutch mechanism. The clutch is constructed so that it can be engaged by pushing a lever; after one revolution of the cam which opens and closes the aluminum shutters, the clutch disengages automatically. The cam shaft is equipped with a vernier setting so that the aluminum vanes can be set manually at any desired degree of opening when the clutch is not engaged. This allows us to vary continuously the thermal intensity incident on the burn aperture. We use this method of controlling the thermal intensity when operating the square wave shutter for burn studies at constant intensity.

Pulsed exposures are controlled by the speed of the motor and the shape of the cam. Obviously, any desired pulse shape of thermal intensity vs. time can be obtained by using the desired cam shape. For flash burn studies intended to simulate the bomb we use a cam which opens the venetian shutters rather rapidly and closes them relatively slowly to imitate the "tailing off" of the thermal flash. Thermal pulses having a duration ranging from 200 milliseconds up to many seconds may be produced by varying the speed of the D.C. motor. For example, a thermal dose of 5.0 cal/cm^2 delivered is 500 milliseconds has been inflicted on human volunteers and on experimental animals. This has been compared with the thermal injury resulting from the same incident dose delivered in the same time at a constant intensity of 10 cal/cm^2/sec by means of the square wave apparatus.

The integral thermal dose can be calculated by measuring the thermal intensity as a function of angular displacement of the cam; knowing angular displacement as a function of time, it is possible to plot a graph of thermal intensity vs. time. The area under this curve represents the

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integral thermal dose in cal/cm^2. The duration of the pulse is measured directly by means of a synchronous electric clock. A microswitch actuated by the cam controls the starting and stopping of the clock which can be read accurately to 10 milliseconds.

Ideally, a shutter of this type should be placed as close as possible to the mirror. It is found experimentally that mounting the venetian blind immediately in front of the searchlight housing (18 inches from the mirror) does not cast horizontal shadows on the focal point where the burn aperture is located. Discrete values of maximum thermal intensity (shutter fully open) can be obtained by interposing metal meshes having various percentages of open space between the pulse shutter and the focal plane defining the burn area. The maximum thermal dose which can be delivered in 500 milliseconds to the burn area with the cam in current use to simulate the bomb flash is 5.5 cal/cm^2/sec. During such a burn exposure, the intensity rises to a peak of 22 cal/cm^2/sec. By interposing a series of 14 x 18 aluminum meshes (ordinary window screening), thermal doses of 0.8, 1.2, 2.0, and 3.2 cal/cm^2 can be delivered.

Control and Measurement of Thermal Intensity

We have used two methods in this laboratory of measuring the thermal intensity of the searchlight beam. The first method utilizes a constant flow, calorimetric technique developed originally for high intensity X-ray dosimetry (3). Essentially, the differential temperature rise in a column of water flowing at a known rate is measured by a thermocouple assembly consisting of 8 copper-constantan junctions connected in series.

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Four of these junctions are immersed in the flowing water before it enters the thermal radiation field while the remaining 4 junctions are immersed in the water outlet beyond the radiation field. The calorimeter is depicted diagrammatically in Figure 5. Between the two sets of junctions, the water impinges normally on a brass disc, 0.002 inches thick and 0.375 inches in diameter. The outside surface of the disc is blackened with camphor soot to simulate a black body. The surface of the disc is normal to the radiation beam. Thermoelectric emfs are recorded continuously on a Leeds and Northrup recorder. Knowing the constants of the system, flow rate, area of the disc, temperature rise in the water, the recorder can be set to read intensities directly in cal/cm^2/sec.

In practice the searchlight operator uses the recorder to set the carbons for the maximum intensity compatible with the experimental conditions (in nearly all of our work, 22 to 23 cal/cm^2/sec is the intensity used). It should be emphasized that the searchlight operator seeks to maintain a constant distance between the positive and negative carbons during all experimental runs, so that the current density and hence the spectral composition and thermal intensity will remain as constant as possible at all times. This is important since we do not measure the thermal intensity during the actual burn exposure but assume that the average of recordings taken before and after the exposure are representative of the intensity within experimental errors. We are confident that this procedure is justified so long as the exposure time is not too short (less than

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300 milliseconds). Inherent variations in intensity due to momentary fluctuations of the carbon arc are unimportant except for short exposures. Variations in intensity of more than 5 percent are usually traceable to such factors as uneven feed rate, eccentric rotation of the positive carbon, chipping of the positive crater, voltage fluctuations in the power supply and burning either the positive or the negative carbon too near the end. Experience has shown that the intensity can be maintained constant within 3 to 5 percent over a 15 minute period; this performance can be repeated at the same intensity after the substitution of fresh carbons.

The constant flow calorimetric technique for measuring thermal intensities has been checked by another method which involves measuring the rise in temperature of a pure silver disc of known mass and dimensions. The exposed surface of the disc is coated with camphor soot and has a diameter of 0.375 inches corresponding to the blackened receiver used in the water calorimeter. The rim and back surface of the disc are polished to reflect stray radiation and the disc is suspended in a manner to minimize conduction. A copper-constantan thermocouple junction is soldered to the back surface while the other junction is immersed in ice water. The thermoelectric emf is recorded on a Leeds and Northrup strip chart recorder. The disc is exposed to the radiation beam for an accurately known time by means of the square wave shutter apparatus. The temperature rise traced on the recorder is a straight line. Care is taken to cool the disc below room temperature before an exposure and the final temperature is limited by the exposure time to values a few degrees above room temperature. In this manner, radiation, conduction, and convection losses are minimized.

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Intensities measured with the silver disc agree with the water calorimeter to within 5 percent. Since both methods measure the intensity over an area which is smaller than the burn area, heat sensitive paper (Chemical Corps, U.S. Army, Paper Liquid Vesicant Detector M6) and photographic proof paper are employed to evaluate the uniformity of intensity over the entire area. In fact, intensities over the 2 inch diameter area are limited to those which are obtainable without evidence of non-uniformity or "hot spots". This is done by defocusing the searchlight. For the small ½ inch burn aperture, intensities of 23 cal/cm^2/sec can be produced uniformly without defocusing. The heat sensitive paper method of evaluating the uniformity of the radiation field is accurate enough for most biologic studies of thermal injury and there has been no need for elaborate probe methods in this laboratory.

The water calorimeter and the silver disc methods of measuring thermal intensity assume that the blackened receiver absorbs all of the radiation falling upon it and that there is no heat loss from radiation, conduction and convection. Camphor soot approximates a black body; while the radiation from the ellipsoidal mirror is a converging beam and not parallel light, the maximum angle between the converging light rays and a normal to the blackened receiver is only 9 degrees. All surfaces except the receiver are coated with aluminum paint to reduce radiation losses and the temperature rise is kept to a minimum consistent with accurate measurement. In the case of the water calorimeter, this is accomplished by using a high flowrate of water. We believe that the errors introduced in these methods of calibrating the thermal intensity are negligible for most biologic applications. Unavoidable heat losses and other imperfections result in minimum values since correction for these factors would increase the thermal intensity.

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The Burn Platform and Aperture

Figure 6 illustrates the burn platform and limiting aperture which has been used in producing burns on experimental animals and human volunteers. The large plywood shield protects the experimental subject from glare and serves as a mount for a water cooled brass plate having a 2 inch diameter aperture. A separately water cooled brass disc having a ½ inch diameter hole can be inserted in the 2 inch diameter aperture for small burns at high intensity. The larger burn aperture (2 inch diameter) is used primarily for dogs where it is desired to cover a large percentage of the body area with burns. For example, an average dog requires about 50 burns to cover 20 percent of its body area. This takes about 8 minutes. The anesthetized dog is supported from a movable rack (not shown in Figure 6) by thongs tied to his feet and is moved across the aperture by two or more operators. Separate, 2 inch diameter burns are produced at each exposure until one side of the animal has received about 25 burns. The animal is reversed to the other side and the procedure repeated.

Thermal injury on humans is inflicted with the ½ inch diameter aperture. Usually, the subject's arm is held against the aperture by the burn surgeon. From 9 to 12 small burns can be inflicted on the upper arm without undue discomfort to the volunteer.

SUMMARY

Experimental methods of producing flash burns with a 24 inch Army searchlight equipped with an ellipsoidal mirror are described. The spectral distribution of the carbon arc is compared with that from the atomic bomb and it is concluded that the carbon arc provides a reasonable simulation of atomic flash burns so far as spectral quality is concerned. Exposure techniques

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employing constant thermal intensity and an intensity varying rapidly with time are described and two methods of measuring thermal intensity are given. Methods of producing flash burns on experimental animals and human volunteers are described briefly.

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