THERMAL EFFECTS OF NUCLEAR WEAPONS

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The temperature accompanying the detonation of a nuclear weapon is about ten million degrees centigrade, roughly that of the sun's exterior (FIG. 1). From a thermal point of view therefore one can regard the sun as a permanently operating nuclear device. The weapon's fission products are converted into gases at extreme pressure. The sudden expansion of these very hot and highly compressed gases is responsible for much of the damage and destruction resulting from the explosion.

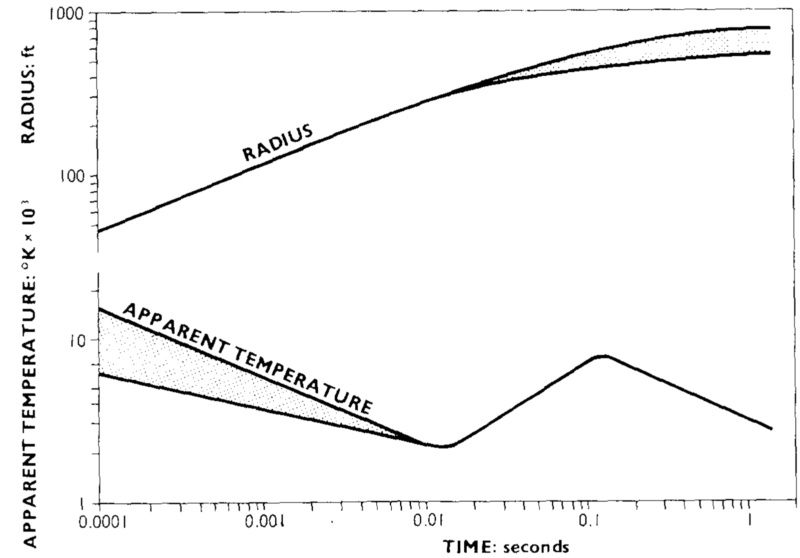

FIG. 1—RADIUS AND APPARENT TEMPERATURE OF FIREBALL VERSUS TIME FOR A 20KT AIR BURST (BELOW 50 000 FT)

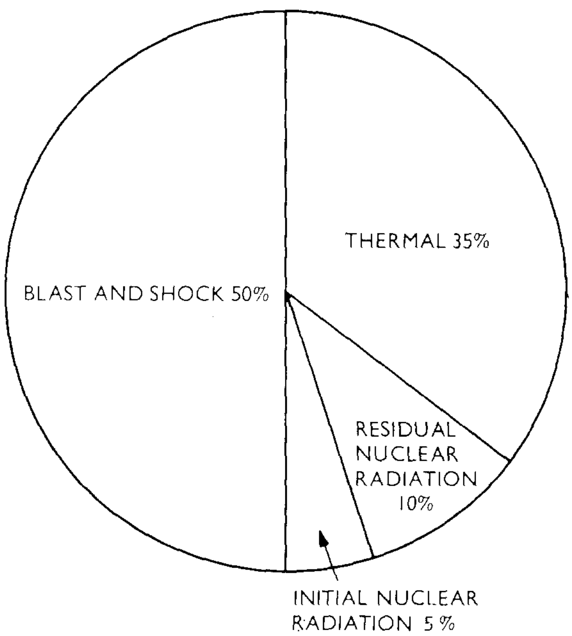

FIG. 2—DISTRIBUTION OF ENERGY IN A TYPICAL AIR BLAST BELOW 30KM ALTITUDE

The relatively large amount of thermal (light and heat) radiation from a nuclear detonation is indeed one of its most striking characteristics. This radiant energy is about one third of the total in the case of an airburst weapon (FIG. 2). As an example, the thermal radiation from an endo-atmospheric 50kt device is emitted in about two seconds (see FIG. 3), and is sufficient to cause serious burns to exposed personnel and to ignite combustible materials up to ranges of some 5000 metres. In the case of a surface burst because of the heat transfer to the surface, the hemispherical shape of the fireball, and possibly the partial shielding by surface contours, the thermal radiation seen by targets could be somewhat less.

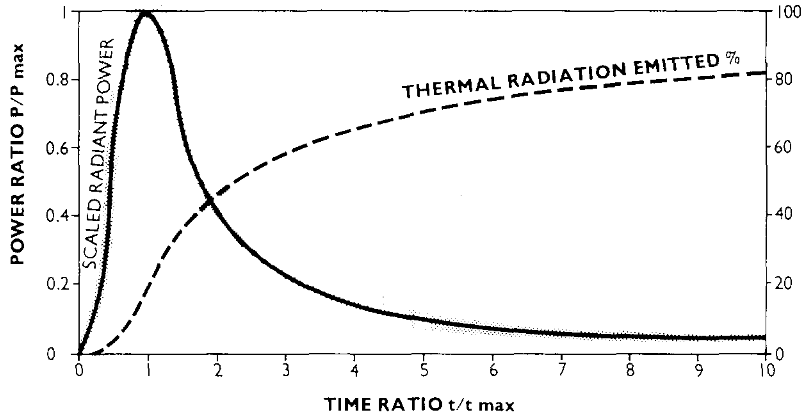

FIG. 3—GENERALIZED THERMAL PULSE

Between airbursts and surface bursts there is a transition zone in which the apparent thermal yield, viewed from the ground, decreases with increasing distortion of the fireball due to the reflected blast wave, until the thermal yield and the fireball shape resemble those of a surface burst. The other type of burst of interest to the Navy is that occurring underwater. However, the thermal effects can largely be ignored, except perhaps in very shallow water, where the effect will approximate to a ground/surface burst.

Thermal Radiation Phenomena

In a surface burst having the same yield as an air burst, there is a reduced thermal radiation emission and an apparently cooler fireball. This is due to heat transfer to the earth's land surface or water surface, the distortion of the fireball (as already mentioned), and the partial obscuring of the fireball by dust or water. With an underground burst, the fireball is further obscured by the earth column and nearly all the thermal radiation is increasingly absorbed in vaporizing as the depth of burst is increased.

In all endo-atmospheric bursts (air, surface, and ground), the thermal effect is modified by the prevailing climate conditions, e.g. the presence of clouds, fog, smoke, wind, etc. FIG. 4 relates radiant exposure and slant range under clear sky conditions.

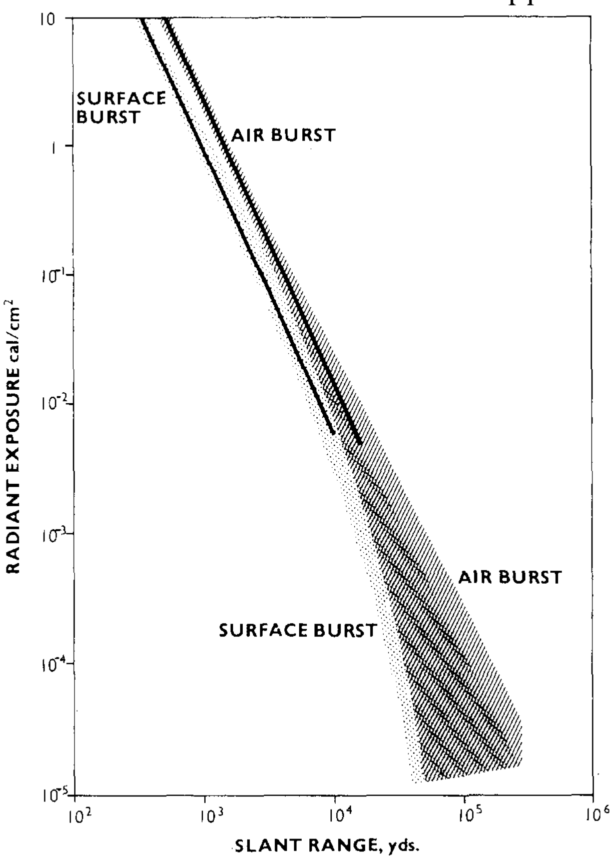

FIG. 4—RADIANT EXPOSURE VERSUS SLANT RANGE FOR AIR AND SURFACE BURSTS ON AVERAGE CLEAR DAY: 1-KT BURST

Damage Criteria

Thermal radiation produces two main effects, namely:

(*a*) Ignition of combustible materials.

(*b*) Burns to personnel.

(These may, of course, be subordinate to other predominant effects, e.g. blast and shock, depending upon such factors as weapon yield and distance from ground zero (GZ). Predictions of thermal damage to targets are limited by the accuracy with which thermal energy may be scaled in relation to yield, height of burst, slant range and prevailing weather conditions.)

Basically the damage depends upon the energy per unit area incident upon the target, and the rate at which the energy is delivered. The duration of the thermal pulse is dependent upon weapon yield and the air density at the altitude at which the weapon is detonated. Below about 7km altitude, air density changes can be ignored and the thermal pulse can be related solely to weapon yield. Above 7km, the thermal pulse gradually shortens in duration, until at about 70km a duration of, say, 1/200 second is emitted even for megaton weapons.

Damage to Materials

The damage mechanism of the thermal effect varies. Except for thin materials such as fabrics, newspapers, etc., thermal damage is confined largely to shallow depths in the exposed target surface. Damage to materials is occasioned by raising the temperature of the surface which, in the case of organic materials, brings about chemical changes or induces ignition. Highly reflective or transparent materials are relatively resistant to thermal damage. Light-coloured objects are more resistant than dark-coloured objects of the same material and thickness, because they reflect more of the incident energy.

Thick organic materials such as wood, plastics, or heavy fabrics do not support combustion, but merely char when exposed to nuclear thermal radiation. During delivery of the pulse, there may be some surface flaming but combustion is not sustained when the thermal pulse decays. Bare metal is unchanged unless structurally weakened or melted by heat action. As is to be expected, the thicker the metal the more resistant it is to thermal effects.

Thermal damage to ships externally is generally limited to superficial scorching of exposed organic surfaces, e.g. paintwork, ropes, cordage, etc. Prewetting systems, if in operation, would of course greatly reduce this hazard.

Within a ship, the thermal flash may affect instrumentation—those for visual use, e.g. sights and binoculars, and those which may be termed imaging systems, e.g. night sights, low light television, image tube cameras, etc. 'Visual' instruments can transmit a hazard to the user's eyes, whereas imaging systems should, in general, insulate the user from thermal hazards; although they may themselves be damaged by the UV content of the light flash.

Damage to Personnel (Skin)

Damage to personnel is modified by a number of factors. Their position in the target area, their attitude (standing, lying down, etc.), the type and amount of clothing worn, climatic conditions, and, of course, the degree of shelter or shielding available.

Bare skin burns are classified broadly as:

(*a*) first degree—where the skin is reddened;

(*b*) second degree—where partial skin blistering or destruction takes place;

(*c*) third degree—where the full thickness of the skin is destroyed.

FIG. 5 shows critical radiant exposure for first and second degree burns on bare skin as a function of yield. The shaded areas reflect variations in individual response due to skin colour and skin temperature. Light-coloured skins are more susceptible to attack than dark skins.

Such burns are related to the total radiant exposure and its rate of delivery. The intensity of each depends on weapon yield and height of burst for a given total exposure. As the weapon yield increases, the thermal radiation is delivered over a longer period of time—and thus a lower rate—for endo-atmospheric explosions.

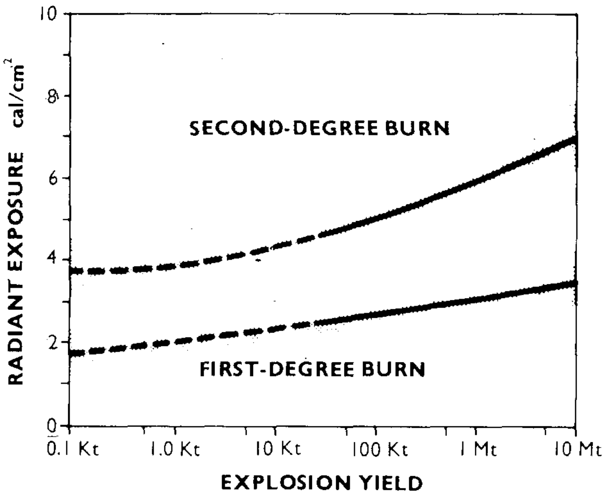

FIG. 5—MEDIAN EFFECTIVE RADIANT EXPOSURE FOR FIRST AND SECOND DEGREE BURNS ON BARE SKIN

It may be appropriate at this point to introduce the term 'Combat Ineffective'. A combat ineffective is defined as a person who, because of his injuries, is no longer capable of carrying out his assigned tasks. This differs from the more common term 'casualty' which is defined as an individual whose injuries require medical attention. Damage to certain areas of the body produces a greater number of combat ineffectives than damage to other areas. Burns of any degree in the area surrounding the eyes will cause the eyes to swell shut, and burns to the hands or legs that lead to loss of mobility are particularly apt to cause ineffectiveness. If a sufficient portion of the total body area is burned, physiological shock follows and the individual becomes a casualty. When more than 10 or 15 per cent. of the total body area has received second degree burns (or worse), shock may be expected. The importance of injuries to the hands and eyes in producing combat ineffectives, coupled with the vulnerability of these parts because of lack of protection under ordinary circumstances, indicates the desirability of providing protection for these areas when nuclear attack is likely.

Damage to Personnel (Eyes)

One particular type of thermal damage is the effect on the eyes. This may lead to temporary damage, commonly referred to as flash blindness, or to permanent damage as in chorioretinal burns. Flash blindness is another name for the after-image seen when the eye is exposed to a bright light. The persistence of the after-image depends where on the retina it was generated, and by far the most persistent and troublesome are those that cover the *macula*. A familiar example is the after-image caused by a photographic flash-bulb. If one happens to look directly at the discharge, the after-image covers the *macula* and persists for some time—a minute is not exceptional. Difficulty will be found in attempting to read or to perform any visual task requiring high acuity of vision. If, however, one's gaze has been averted even by a small angle, say 3° or more, the after-image would have decayed in a short period—seconds rather than minutes—and little more than temporary annoyance would have been felt.

The visual hazards have been assessed critically by the Atomic Weapons Research Establishment (AWRE) using the parameters established by Dr. J. J. Vos of the Netherlands Institute of Perception. The more serious damage is when the retina is burned by massive over-exposure at any wavelength transmitted to it, i.e. within the range of 0·4 to 1·4 μm, whereas flash-blindness can be caused only by that light to which the retina is sensitive, effectively 0·4 to 0·7 μm. The energy needed for permanent damage is higher than for visual saturation, and the threshold energy is a function of retinal image size, period of exposure, and source temperature. For sources subtending an angle greater than $\frac{1}{2}$°, and for exposures greater than about 0·1 seconds in duration, the threshold energy is about 1cal/cm^2 at the retina. The eye has a natural defence mechanism against over-exposure—the blink. Because the response time for blinking is about 0·1 seconds, the critical question is that of assessing the energy transmitted to the retina during this time.

In the day time, the pupil of the eye is contracted and will not transmit sufficient power to create a permanently damaging hazard. At night, however, the pupil is enlarged and may transmit a hazard at close ranges to a burst.

TABLE I—*Radiant exposures for burns under clothing*

Clothing	*Degree of burn*	*Weapon yield*		
		40kt	1Mt	10Mt
		Radiant exposures[1] [2]		
Bare skin	none	2·0	2·6	2·9
	first	2·6	3·1	3·5
	second	4·6	6·3	7·0
Summer uniform—2 layers of light porous fabric	none	5	6	7
	first	10	16	21
	second	12	20	26
Winter uniform—2 to 5 layers of tightly woven fabric	none	7	10	12
	first	13	21	29
	second	16	26	36
Sub-arctic and arctic—3 to 8 layers of tightly woven fabric[3]	none	15	25	40
	first	15	25	40
	second	15	25	40

[1]Expressed in cal/cm^2 incident on skin or outer surface of clothing when the inner layer of the clothing is spaced 0·5cm from the skin and when at least the first 70 per cent. of the thermal pulse is normal to the surface.
[2]These values are sensitively dependent on many variables and are probably correct to within ± 50 per cent. for the range of normal military situations.
[3]Burns to personnel wearing these heavy uniforms will occur only by contact with flaming or glowing outer garments. Some systems require in excess of 100 cal/cm^2 to produce burns by direct transmission of heat through the fabrics.

TABLE II—*Effectiveness of thermal shield materials*

Material	*Weapon yield*		
	1kt	100kt	10Mt
	Incident energies*		
Vinyl poncho	6	10	18
Neoprene poncho	8	13	23
Cotton sateen, 9oz	7	12	21
Cotton duck, 12oz	8	13	23
Wool blanket	14	25	43

*Energies below which no burn occurs expressed in cal/cm^2.

Protection against Burns

Clothing contributes to the protection afforded against skin burns. Cotton, synthetic, and woollen clothing have a high resistance to destruction and, consequently, skin burns seldom occur beneath these materials when they are undamaged. TABLES I and II attempt to show a comparison of the radiant exposures necessary to cause burns under different types of clothing and shielding materials.

Evasive action by personnel is not considered very effective for detonations up to 100kt endo-atmospheric bursts due to the very rapid delivery of the thermal pulse of such yields. Megaton yield weapons (which are usually exo-atmospheric) allow some evasive action as the pulse is delivered over a period of seconds.

Protection against Eye Damage

Protection can be divided into two broad types: individual protection where each man is fitted with his own goggles or visor, and collective protection where an attempt is made to protect the openings in a ship, armoured vehicle, or building in such a way that all personnel within are sheltered. This eliminates the need for personnel to have individual eye protection, leaving them more free to move about the better to perform their duties. Additionally, it affords a measure of protection to instrumentation within the collective protection, e.g. a ship citadel.

Work is now proceeding at AWRE and elsewhere on protection, both individual and collective. It takes advantage of the ultra-violet (UV) content of the light emitted from a nuclear detonation, and the reaction of photochromic components to UV.

The word 'photochromic' derives from the Greek χρωμα (colour) and φως (light) and means literally the effect of light upon colour. It has been found that certain molecules, when exposed to ultra-violet light, become excited into a higher energy band and in doing so change colour and become opaque. The degree of opacity depends upon the intensity of the UV light and the particular molecules used. Removal of the UV light results in the recovery of the molecules to their original state. This phenomenon is very rapid (about 10 nanoseconds), with recovery taking perhaps a few milliseconds.

The initial investigation of photochromic compounds and systems was conducted by Applied Photophysics Ltd. at the Royal Institution in London. AWRE has made a study of the practicability of using a mixture of photochromics proposed by APL in protective systems. AWRE has shown that it is possible to make sheets of perspex (polymethylmethacrylate) in which the photochromic compounds are held in solid solution, and that these sheets can be formed into visors or used as windows.

SCRDE have summarized the work done by Applied Photophysics Ltd. up to April 1973, giving a brief statement of the principles and operational characteristics of the photochromic compounds considered most worthy of attention. Other plastic-based materials with better physical properties are being investigated.

Photochromic compounds require to be stimulated by ultra-violet illumination before any substantial absorption in the visible spectrum is shown. The generation of this simulation in the molecule is very rapid (times of the order of 10 nanoseconds have been mentioned) but decay back to its original state is much slower, relaxation times of about one second are noticed. The rate at which a photochromic component embodying photochromic compounds darkens in the visible spectrum depends on the intensity of the ultra-violet illumination. Provided the UV illumination is applied in a small fraction of a second, it is possible to ignore the effect of relaxing back to the ground state when estimating the optical density achieved. Tests at AWRE made with a typical photochromic component show that visual density of 1·0 is achieved by illuminating it with UV to about 0·03 J/cm^2 whilst a density of 2·0 needs about ten times that illumination.

The thickness of photochromic material required to give maximum effect depends on the concentration of the photochromic compounds which can be achieved in the matrix. For the compounds dissolved in perspex investigated by AWRE, it appears that, provided the material is at least 5mm thick, extra substance adds little to the photochromic efficiency. Such a thickness is acceptable for visors (although somewhat thinner material would be preferred) and as such it could be built into sandwich windscreens and goggle lenses.

The major disadvantages of perspex are that it suffers massive shrinkage (about 20 per cent. change in volume) during polymerization, and it allows oxygen to permeate it leading eventually to quenching of the photochromic effect. Other plastic-based materials are much less sensitive to oxygen ingress.

For some Service users, perspex is not considered hard enough and polycarbonate plastics are preferred. However, as an experimental matrix for demonstration purposes, perspex is satisfactory and undoubtedly there are applications for which it would be suitable, e.g. goggles and visors. Photochromic compounds can, however, be incorporated successfully in other plastics. Further work is required to establish which is the most suitable.

The photochromic compounds proposed remove effectively only the visible radiation; there is a residual amount of red light and some infra-red transmitted, even when the absorbing states are fully activated. These wavelengths should be filtered out by a secondary filter; the violet and ultra-violet fluorescence should also be removed. If the photochromic material is to be built into a sandwich, these secondary filters can be attached as a cladding on the observer's side of the sandwich. The provision of these secondary filters would be more difficult; surface dyes have been suggested, but not yet investigated for feasibility.

Further development and research support work is required to optimize practicable Service devices to perfect the protection needed against damage to the eyes.

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