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TECHNICAL REPORT

MATERIAL LABORATORY

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AFSWP-1144

RESEARCH
on
THE THERMAL CONDUCTIVITY AND DIATHERMANCY OF ALBINO RAT SKIN

Lab. Project 5046-16 Part 4
Final Report

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SUMMARY

In its study of protection against the thermal radiation from nuclear weapons the Naval Material Laboratory has exposed uncovered and covered rat skin to pulsed radiant energy from a carbon-arc thermal radiation source. Some thermal and optical properties of the rat skin employed in these studies have been determined by measuring the temperature of the surface of rat skin during exposure to thermal radiation.

A $k\rho c$ product of $10.6 \pm 0.6 \times 10^{-4}$ cgs units for the denuded blackened skin of anesthetized rat skin was determined for square wave exposures ranging from 1 to 10 seconds in duration. A systemic reaction, probably vasodilation, caused a marked increase in the $k\rho c$ product for exposures longer than 10 seconds. In prior investigations at NML the $k\rho c$ product for human skin was measured to be 8.6×10^{-4} cgs units.

The effective extinction coefficient was found to change from 26 to 6.7 cm^{-1} for 1 to 20 second exposures to carbon-arc radiation and from 32 to 12 cm^{-1} for 1 to 15 second exposures to tungsten lamp radiation. Comparison of the effective extinction coefficients for both media shows that human skin is more opaque than that of the anesthetized rat.

Lab. Project 5046-16 Part 4
Final Report

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INTRODUCTION

The Naval Material Laboratory is studying the protection by various clothing systems against the intense thermal energy released by the detonation of nuclear weapons. The objective of this investigation was the measurement of the kρc (k, conductivity; ρ, density; c, specific heat) and the effective extinction coefficient, γ*, for carbon-arc and for tungsten radiation.

During the exposures of uncovered rat skin and of rat skin under the hot-wet uniform assembly to pulses of thermal radiation it was found that the temperatures of the surface of the rat's skin were lower than the corresponding temperatures of the skin simulant. Since the simulant was matched to human skin the implications were that the temperatures of human skin when irradiated would be higher than those of rat skin under the same conditions. To document this difference the physical and optical constants for rat skin were determined. The parameters for human skin had been measured in previous investigations at the Naval Material Laboratory.[1,2,3,4]

The thermal properties of rat skin have been investigated by other observers. Hardy[5] et al reported the kpc product for male Sprague-Dawley rats to be 8.4×10^{-4} cgs units. Unanesthetized rats, painted with printer's ink, were exposed to thermal radiation with irradiances ranging from 0.05 to 0.5 cal/cm² sec. In another experiment, Hardy[5] determined that the administration of azepetine caused a 20 percent increase in the kpc product and attributed this change to vasodilation.

In order to determine the constants that would apply to the results of the investigation on the uncovered rat and on the protection afforded by the hot-wet uniform the temperatures of the blackened and of the bare rat were combined with the appropriate expressions of heat flow theory. Assuming that blackened shaved depilated rat skin behaves, thermally, as an opaque homogeneous semi-infinite solid, the temperature of the surface may be represented by the equation:

$$\Delta\theta = \frac{2AH\, t_o^{\frac{1}{2}}}{\pi\, k\rho c} \qquad (1)$$

where $\Delta\theta$ is the temperature rise (^{o}C),

A is the radiant absorptance

H is the irradiance (cal/cm²-sec),

t_o is the time of exposure (sec),

k is the thermal conductivity (cal/cm-deg C-sec),

ρ is the density (gm/cm^3), and

c is the specific heat (cal/gm-deg C).

Solving equation (1) for $k\rho c$ yields

$$k\rho c = \frac{4A^2H^2t_o}{\pi\,(\Delta\theta)^2} \qquad (2)$$

The spectral distribution of the thermal radiation emitted during a nuclear detonation is approximated by the carbon arc and in some instances by a tungsten lamp operated at 3000°K. The measured effective extinction coefficients, γ^*, for a medium relative to these sources should provide the order of magnitude of γ for thermal radiation. The temperature rise at the surface of a homogeneous semi-infinite diathermanous medium is expressed as:

$$\Delta\theta = \frac{2AHt^{\frac{1}{2}}}{\sqrt{\pi k\rho c}} \quad 1 + \frac{\sqrt{\pi}\,e^{\gamma 2\,ht}\ \mathrm{erfc}\ \gamma\sqrt{ht}}{2\ \gamma\sqrt{ht}} - \frac{\pi}{2\gamma\sqrt{ht}}, \qquad (3)$$

where $h = k/\rho c$, the thermal diffusivity,

t is the time of reference (sec),

γ is the extinction coefficient (cm^{-1}), and

$$\mathrm{erfc}\ y = \int_0^y e^{-x^2}\,dx.$$

Equation (3) is based on a variation of irradiance with depth given by

$$Hx = AH_o\,e^{-\gamma x},$$

the case of a non-selective and non-scattering medium. Skin is neither non-selective nor non-scattering. The effect of the selectivity of skin has been shown to be a function of exposure time[1,2,3]. The effect of scattering is to change the irradiance-depth relationship. The term, "effective extinction coefficient", is employed in this report as the value of γ in equation (3) which satisfies the experimentally determined temperature-irradiance-time picture at one point and one exposure time. It serves as a ready means of comparing and presenting results, but is useful in precise computations only for the sources, exposure times, and geometric situations involved in its determination.

In addition to changes such as vasodilation induced by anesthetics other factors can change the physical properties of rat skin. The depilatory and its application may remove part of the stratum corneum as well as the hair. Variations in diet and the presence of disease may also influence the physical properties.

The simplified mathematical model of the opaque skin probably is not adequate for times less than 0.5 seconds and will also fail when the time of exposure is long enough to allow systemic response. If the properties of rat skin change with depth the longer exposures will be affected. The deeper portions of the skin would have a greater effect on surface temperatures for long exposures than for short exposures. Unfortunately systemic responses and cooling factors also operate selectively on the longer exposures and may mask the changes of the kρc product with depth.

EXPERIMENTAL APPARATUS AND PROCEDURE

Bare and blackened rats were exposed to square wave pluses of thermal radiation from carbon-arc and tungsten sources with exposures ranging in time from 1 to 25 seconds. During exposure, temperature histories were recorded. Initial skin surface temperatures were recorded. Thermostatically controlled water, passing inside a copper shield, maintained the initial skin surface temperature at 31 ± 1°. Radiant exposures causing maximum temperature rises less than those required to produce burns were normally employed.

A modified 24" carbon-arc searchlight, operated at 60 volts and 87 amperes, provided the carbon-arc radiation for the experiment. A combination electronic and bimetallic-strip feed system maintained the positive carbon at the primary focus of an ellipsoidal mirror whose foci are located at 11 and 52 inches. Specimens were irradiated at the secondary focus. The spectrum of the radiation from this source had been determined in a previous investigation[5].

A 1000-watt biplane tungsten projection lamp, situated at the primary focus of a similar ellipsoidal reflector, and operated at 105 volts, provided the effective 3000°K black-body radiation. Specimens were exposed at the secondary focus.

Copper button calorimeters, whose output was read on a recording potentiometer, measured the radiant output of both sources.

A plated copper-constantan thermocouple in series with an ice point and recording potentiometer measured the skin temperature prior to exposure and the temperature history during exposure. The diameter of the thermocouple was 0.005 cm. Vertical suspension of the thermocouple at 0.5 gm tension maintained good thermal contact between rat skin and thermocouple when the animal was pushed against the thermocouple. The bimetallic junction of the thermocouple was situated at the geometric center of a 12 mm aperture in a copper shield, double-walled to allow passage of the thermostatically controlled water. This aperture was placed in the exposure plane and the animal pushed gently against it.

The animal holder is illustrated in Figure 1. The thermocouple and copper shield are integral parts of this assembly. The platform upon which the rat is placed is made of lucite. An aluminum angle, 1/16 inch thick, padded with foam rubber, maintains the rat at the exposure aperture, thereby establishing thermal contact between rat and thermocouple. Spring-loaded clamps maintain the position of the aluminum angle. The length of the angle was approximately the shoulder-to-pelvic length of the rat.

Twenty-four hours prior to exposure to thermal radiation, female Sprague-Dawley rats, 50 to 70 days old, were shaved and depilated. Forty mg of pentobarbital sodium per kilogram of animal weight were injected intraperitoneally in solution of 1 cc of pentobarbital to 11 cc of saline, prior to depilation. When the rat succumbed to anesthesia, progienic scissors, utilizing a standard head with triple zero cutting assembly, cut the excess hair on the back and flanks from the shoulders to the tail. "Nair" depilatory removed the remaining stubble. The depilatory was kept on for 8 to 10 minutes.

On the day of the thermal exposures the animal was anesthetized with the same dosage as described for depilation. When the rat succumbed the depilated area was divided into twelve areas, six on either side of the animal. If the skin were to be laid out in a plane, the grid would be composed of three lateral by four transversal. The areas were designated numerically R-1, R-2, R-3 running along the back from shoulder to tail and R-4, R-5, R-6, on the flanks from the first rib to the shank. The left side was divided accordingly. The animal was then ready for exposure.

In a previous investigation[8] the diffuse spectral reflectance of rat skin was measured. The total radiant absorptance was computed to be 0.66 for carbon-arc radiation and 0.72 for 3000° K black-body radiation.

For the animals to be exposed in an essentially opaque situation a blackening agent was prepared and applied. The blackening agent was a commercial stove polish with the trade name of "Vulcanol". It is graphite suspended in an oil emulsion. For ease of application it was diluted with water to a light cream consistency and applied with a brush. The application was dry in a few minutes and left a matt coating about 0.001 cm thick which flexed with the skin and remained opaque. Such a coating has been measured to be neutral at least to 2.8 microns with an absorptance of 0.95.

RESULTS

The temperature rises of the irradiated, blackened rat skin, as determined from the recorder traces, are shown plotted as a function of time in Figure 2. The data are given in terms of unit irradiance for ease of comparison of exposures of differing irradiance and are plotted on logarithmic scales to facilitate comparison with the relationship given by the simplified theoretical model. The data represent points from 15 temperature histories on two rats obtained with essentially different sets of apparatus for each rat.

The temperature rise maxima ranged from 5 to 31 °C, corresponding to maximum skin surface temperatures of 36 to 62°C. Even though the temperature associated with irreversible tissue damage were exceeded no lesions resulting in scabs were found. Because of the obscuring effects of the blackening, scabs might not have been noticed. The small numbers of exposures involved preclude conclusions on this point.

The kpc product was computed for each of the temperatures corresponding to exposure times less than ten seconds; an average value of 10.6×10^{-4} cgs units was calculated. The line representing an ideal solid with the average kpc product is shown in Figure 2. The 95 percent confidence limit was calculated to be 0.6×10^{-4}. The experimental data were found to be significantly different for the longer times. It was postulated that kρc would change as the exposure time is increased; it was considered possible that kρc would change because of the higher temperatures associated with the longer exposures. Both theories were investigated.

Figure 3 is a plot of the kρc product for the temperature rises ranging to 31°C. The change with temperature is considered insignificant for surface temperatures up to 62°C. Plotting the values of kρc against exposure time as in Figure 4 reveals a significant change for exposures longer than 10 seconds. While the kρc product in cgs units averaged 10.6×10^{-4} for times less than 10 seconds, it increased to 15×10^{-4} for the temperature rises measured at 24 seconds. This change in kρc value could be a result of a systemic reaction to temperature such as an increase in blood flow or it could result from an inhomogeneity in the skin's thermal properties with depth. The variability in the temperature data includes an uncertainty of approximately 5 percent in source irradiance for an individual exposure, and an error of 10 percent in the indicated temperature, due to uncertainty in thermocouple contact as well as to real differences in the physical properties of the individual rat.

The temperature data for the surface of the bare rat skin are plotted in Figure 5. One rat was exposed to carbon-arc radiation for a total of six exposures with temperature rises ranging from 12 to 26°C, with one scab lesion occurring at the highest temperature. The second rat was exposed to the tungsten radiation, also for six exposures, resulting in the same temperature range, with, however, no lesions. Again, because of the limited number of exposures, no conclusions as to temperatures would have meaning. Lines representing the average of the temperatures measured are shown in Figure 5 for the two sources. The higher transparency for the carbon-arc radiation, with its greater proportion of visible over infrared energy, is apparent.

The effective extinction coefficients of rat skin for the two sources investigated in this study were computed employing the average temperatures, equation (3), and the kρc's just determined. Table I lists the data thus obtained; the data for human skin from a previous investigation[1] are also included.

TABLE I

THE EXTINCTION COEFFICIENTS FOR RAT AND HUMAN SKIN

Rat Skin			Human Skin	
Time	Carbon-arc	Tungsten	Carbon-arc	Tungsten
sec	cm^{-1}	cm^{-1}	cm^{-1}	cm^{-1}
0.5			188	64
1	26	32	80	45
2	20	23	45	30
5	15	17	31	22
10	12	14	23	21
15	8	12		
20	7			26
35	5			

DISCUSSION

The confidence interval, as computed for the kρc product for exposures less than 10 seconds, was ± 0.6 cgs units, which corresponds to a surface temperature uncertainty of ± 3 percent. In computing the temperatures associated with burns, this error is insignificant, compared with that which is involved in determining radiant exposure levels. While the value of the kρc product represents the properties of the rat skin actually employed in the NML burn studies with the Hot Wet uniform it may not be adequate for experiments employing other rat types or sizes and other preparation and anesthesia techniques.

The kρc product found, 10.6 x 10^{-4} cgs units, is significantly different than the value of 8.6 x 10^{-4} found for human skin. This difference means that for many burn situations the temperatures for human skin will be higher than those of rat skin by 10 percent. Temperatures in depth will have second order differences caused by differences in thermal diffusivity (kρc) as well as those resulting from differences in kρc.

The values of kpc for rat and human skin can be used as a basis for computing the radiant exposures to cause burns to humans in terms of the equivalent radiant exposure to cause burns to rat skin. For the case of the cloth in contact or spaced, the radiant exposures for human skin are computed to be 10 percent less than those for rat skin.

The data show a gradual increase in kpc as the time of exposure is lengthened to more than 10 seconds. The value of 15×10^{-4} calculated for the temperatures found after 24 seconds of exposure resulted from temperatures which were 13 percent lower than those which would have been predicted from exposures of less than 10 seconds. If the change is caused by a systemic reaction the skin has different physical properties for extended exposures than those calculated on the basis of no time dependence. The applicability of the kpc product under these for other than demonstration purposes is questionable. The situation calls for an analysis involving systemic reactions or non-homogeneous thermal properties.

Most exposures of skin covered with cloth which result in burns involve temperature histories which are longer than 10 seconds, even for very short thermal pulses. Analysis of situations involving temperature histories longer than 10 seconds should include consideration of the changes in skin properties which result from the skin's reaction to sustained elevated temperatures. Comparison between burn data on individual subjects and between species implies similarity in the skin's reaction to sustained temperatures.

The data for the blackened rat skin are considered reliable to within 5 percent; the data given in Figure 4 for the bare rat skin should have a similar certainty since the data were obtained in the same manner as those for the blackened rat.

The time variation of the effective extinctive coefficient as given in Table I is most probably caused by the wave length selectivity of the rat skin to the penetration of the radiation from the carbon arc source. The effect would be similar to that noted for human skin in an earlier investigation.[1,2,3] The effect of the preparation of the anesthesia on the diathermancy of the skin is not known but is probably of less importance than the effect of anesthesia on the thermal properties.

As shown in Table I, the temperatures of the rat skin were higher for the tungsten radiation than for the carbon-arc radiation. The lower extinction coefficient for carbon-arc radiation indicates relatively greater penetration than by tungsten radiation. For human skin the carbon-arc radiation was less penetrating than tungsten. The difference in temperature caused by the two spectra is probably caused by the higher penetration of radiation in the blue part of the visible spectrum, a fact which may be deduced from the higher reflectance of rat skin over human skin in this spectral region.

To calculate equivalent radiant exposures for human skin burns from data obtained by exposing uncovered rat skin, a first order correction can be computed employing the temperatures for bare skin. For carbon-arc radiation the ratio varies with exposure time but averages approximately 0.66. That is, since human skin has temperatures on the surface which are 50 percent higher than those for rat skin, the radiant exposures to cause equal temperatures in human skin are 66 percent of those for rats. This correction compensates for kpc differences as well as optical differences. While the ratio corrects for surface temperatures differences, the temperatures in depth might not follow and would require further study.

Approved:

W. A. Utley

W. A. UTLEY, COMMANDER, USN
Assistant Director

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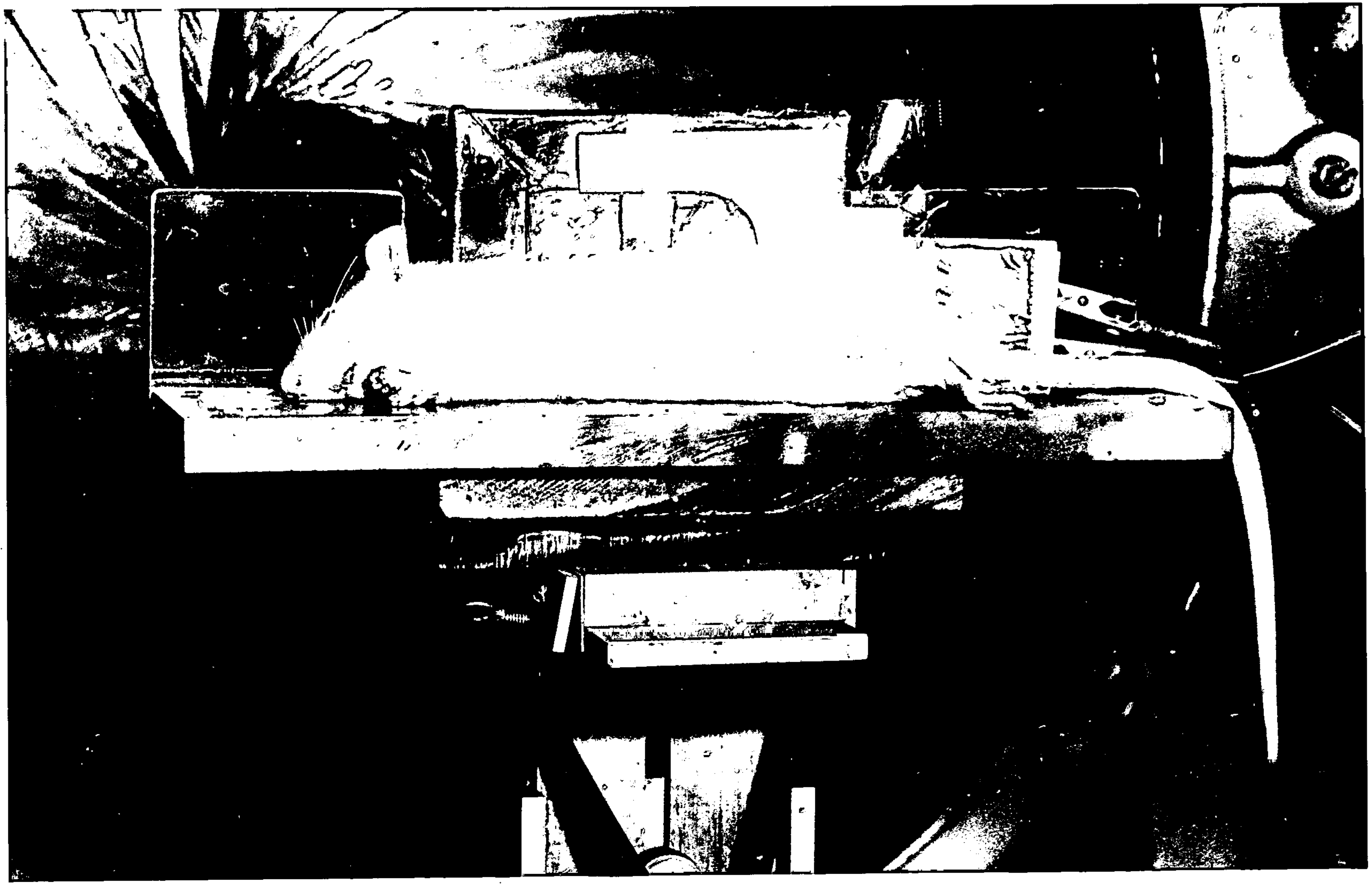

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Figure 1 - Animal Mount

PHOTO 17244-13

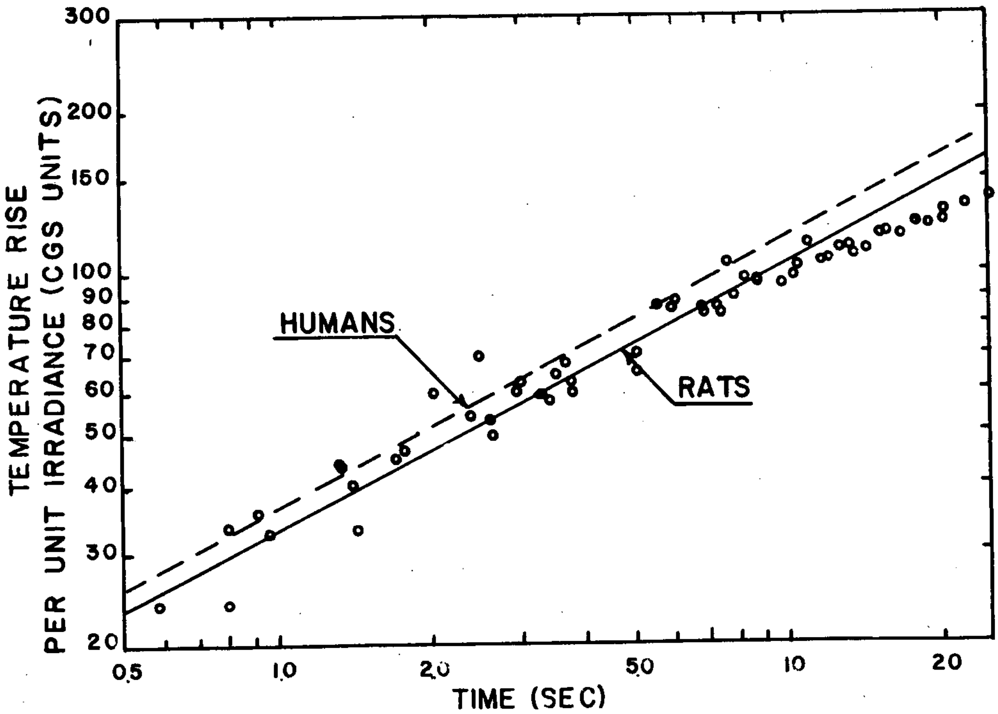

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Figure 2 - Temperature Rise per Unit Irradiance of Irradiated Opaque Rat Skin

PHOTO 18228-1

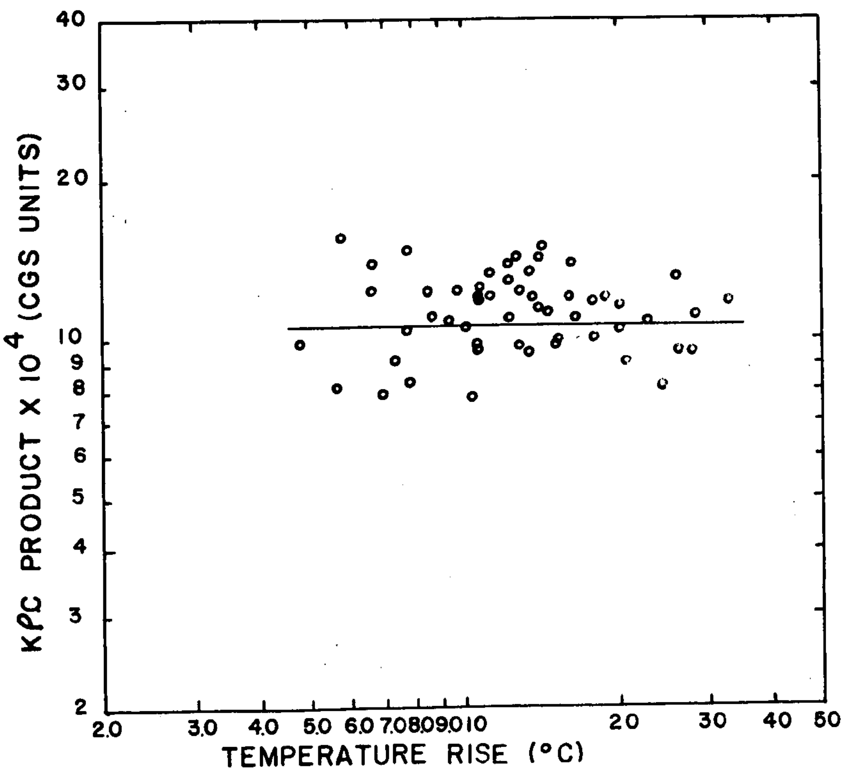

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Figure 3 - The Effect of Temperature Rise on the kρc Product

PHOTO 18228-2

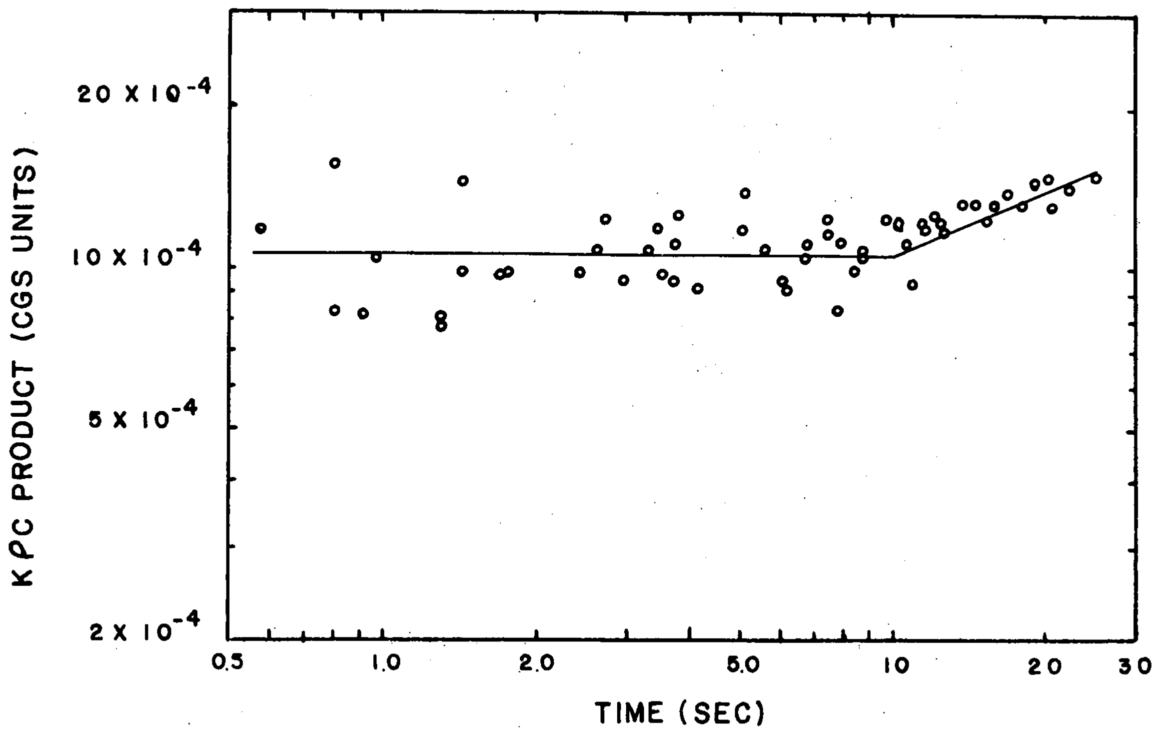

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Figure 4 - The Effect of Time on the kρc Product

PHOTO 18228-3

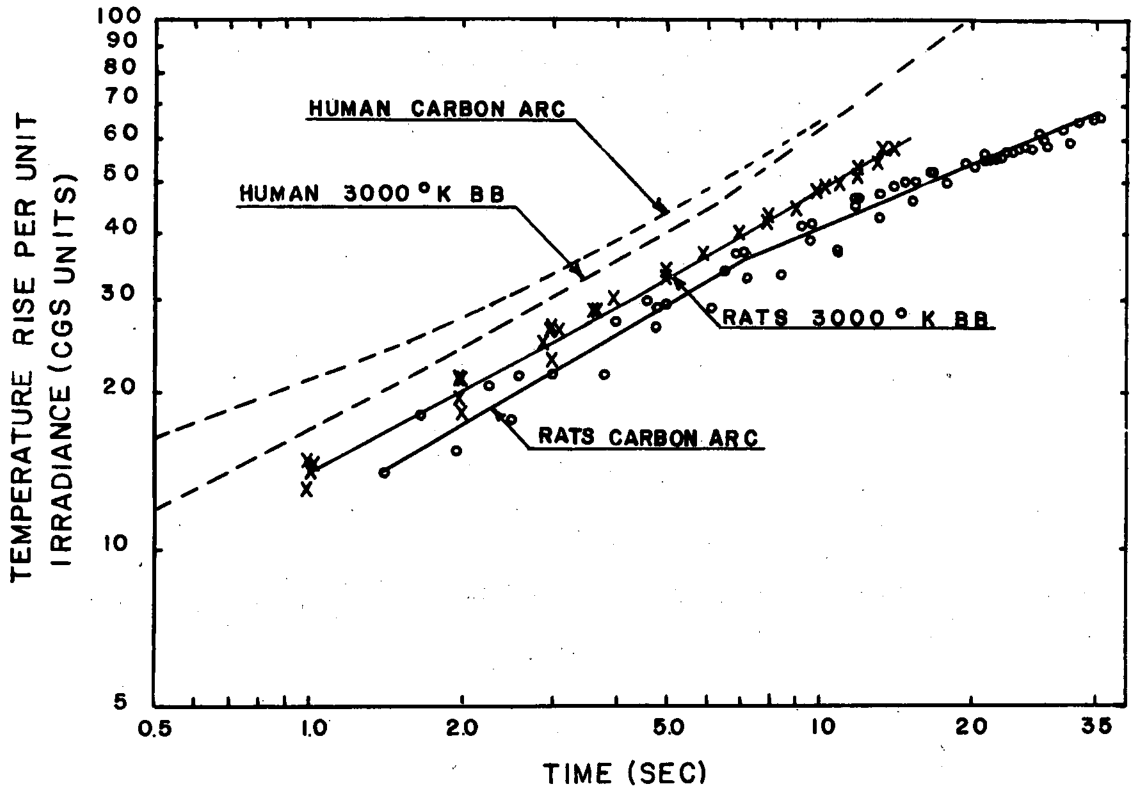

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Figure 5 - The Temperature Rise per Unit Irradiance of Diathermous Rat Skin

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Commander-in-Chief, Strategic Air Command, Offutt AFB, Nebraska, ATTN: OAWS		1
Commander, Tactical Air Command, Langley AFB, Va., ATTN: Doc Security Branch		1
Commander, Air Defense Command, Ent AFB, Colorado, ATTN: Atomic Energy Division, ADLAN-A		1
Commander, Hq Air Research & Development Command, Andrews AFB, Washington 25, D.C., ATTN: RDRWA		1
Commander, Air Force Ballistic Missile Division, Hq ARDC, Air Force Unit Post Office, Los Angeles 45, California, ATTN: WDSOT		1
Commander-in-Chief, Pacific Air Forces, APO 953, San Francisco, Calif., ATTN: PFCIE-MB, Base Recovery		1
Commander, Air Force Cambridge Research Center, L.G. Hanscom Field, Bedford, Mass., ATTN: CRQST-2		1
Commander, Air Force Special Weapons Center, Kirtland AFB, Albuquerque, New Mexico, ATTN: Tech Info & Intel Div		1
Director, Air University Library, Maxwell AFB, Alabama		1
Commander, Lowry AFB, Denver, Colorado, ATTN: Dept of Sp Wpns Tng		1
Commandant, School of Aviation Medicine, USAF Randolph Air Force Base, Texas, ATTN: Research Secretariat		1
Commander, 1009th Sp Wpn Squadron, Hq USAF, Washington 25, D.C.		1
Commander, Wright Air Development Center, Wright-Patterson AFB, Ohio, ATTN: WCOSI		1

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Director, USAF Project Rand, VIA: U.S. Air Force Liaison Office, The Rand Corporation, 1700 Main Street, Santa Monica, California	1
Commander, Air Defense Systems Integration Division, L.G. Hanscom Field, Bedford, Mass., ATTN: SIDE-S	1
Commander, Air Technical Intelligence Center, USAF, Wright-Patterson AF Base, Ohio, ATTN: AFCIN-4Bla, Library	1
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Director of Defense Research & Engineering, Washington 25, D.C., ATTN: Tech Library	1
Director, Weapons Systems Evaluation Group, Room 1E880, The Pentagon, Washington 25, D.C.	1
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Chief, Defense Atomic Support Agency, Washington 25, D.C.,	5
Commander, Field Command, DASA, Sandia Base, Albuquerque, New Mexico	16
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Chief, Classified Technical Library, Technical Information Service, U.S. Atomic Energy Commission, Washington 25, D.C. ATTN: Mrs. Jean O'Leary	1
Manager, Albuquerque Operations Office, U.S. Atomic Energy Commission, P.O. Box 5400, Albuquerque, N.M.	1
Sandia Corporation, Sandia Base, Albuquerque, N.M. ATTN: Classified Document Division	1
Commander, ASTIA, Arlington Hall Sta, Arlington 12, Va, ATTN: TIPDR	15

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THE THERMAL CONDUCTIVITY AND DIATHERMANCY OF ALBINO RAT SKIN, by G.P. deIhery, W.L. Derksen and T.I. Monahan. Final Report. 29 Apr. 1959. 13 p. figs. (AFSWP-1144). UNCLASSIFIED

In previous investigations uncovered and cloth covered rats were exposed to intense thermal radiation for flash burn studies. Pertinent thermal and optical properties of the rat skin employed in these studies were determined by measuring the temperature of the skin surface during irradiation. A kpc product of 10.6×10^{-4} cgs units was determined for the skin of an anesthetized rat. Exposures longer than 10 seconds produced a change in the kpc product. Albino rat skin was more transparent than human skin.

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2. Thermal radiation-Physiological effects
3. Skin-Effects of Radiation
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II. Derksen, W.L.
III. Monahan, T.I.
IV. AFSWP-1144
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