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SKIN AND SUBCUTANEOUS TEMPERATURE CHANGES
DURING
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J. A. J. Stolwijk, J. D. Hardy

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SKIN AND SUBCUTANEOUS TEMPERATURE CHANGES
DURING
EXPOSURE TO INTENSE THERMAL RADIATION*

By

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ABSTRACT

Radiometric measurements have been made of the skin temperature changes occurring during irradiation of the body by high intensity thermal radiation with square wave pulses. Quartz lamps operated at 50% overvoltage provided a source of color temperature 2650°K and a uniform ($\pm 5\%$) irradiance of 0.15 gm cal/sec/cm² over areas of 40 x 30 cm. A spring operated focal-plane shutter controlled exposure times from 2-120 seconds with a rise time of 0.01 seconds. The radiometer, mounted between the quartz lamps so as to view the skin from normal incidence, had a 96% response time of 0.1 seconds and a precision of $\pm 0.1^\circ\text{C}$. Significant corrections were necessary to allow for the far infrared reflection from the human skin; a reflectivity of 1.5% was measured for the white skin in the spectral region 3.7 μ to 30 μ . Experimental values of skin temperature rise during irradiation were compared with those calculated by the finite differences method for various skin layers with the best available values for optical and thermal properties of each skin layer, using an analog computer. During the initial 10-15 sec. of irradiation theoretical and experimental values are in agreement, indicating passive responses. For longer exposures, it is concluded that physiological responses such as vasodilatation and sweating slow the skin temperature rise. Subcutaneous temperatures can be calculated from surface temperature data; it is indicated that most of the radiation is absorbed in the first 0.05 - 0.15 mm of skin through combined effects of absorption and scattering. Some of the radiation of wavelength near 1 μ penetrates to a depth of 5 mm or more.

The temperature of the human skin is one of the basic physiological parameters but despite the long interest of physiologists and others in this important variable, its accurate measurement is so difficult that in many instances indices of skin temperature and skin temperature change have been used rather than the skin temperature itself. In view of the urgent requirement for data on skin temperature and the lack of proved experimental methods for obtaining them, the use of indices cannot be criticized severely and it is with this need in mind that we report another advance in the technical methodology which permits the accurate measurement of skin temperature during exposure to intense thermal radiation from a broad spectrum source. As shown by Cobet and Bramig (1) and confirmed by a detailed series of studies (3, 10, 11), the skin temperature can best be determined radiometrically by quantitatively measuring the emitted infrared radiation from the skin by a radiometer at a distance. Such a measurement of skin temperature requires a knowledge of the emissivity of the skin and the penetration of the emitted radiation through the skin. The optical properties of the skin have been the subject of research for the past forty years resulting in general agreement that the human skin in the spectral region beyond 3μ is black (4), emissivity 0.985 irrespective of visual color, and that the skin absorbs within a few microns of the skin surface all of the radiation within its spectral emission band - $4-40\mu$ (7). These facts permit the use of radiometric devices for skin temperature measurement provided the skin is not being irradiated with

significant amounts of visible, near infrared and far infrared radiation. About ten years ago, there was developed a radiometric method which could be used if visible and near infrared were emitted from the source, but no method has been available for skin temperature measurement using irradiation by a broad spectrum source. Also, it is of particular importance to note that an accurate determination of the skin temperature can be used together with the optical and thermal properties of the skin to obtain the best estimate of subcutaneous temperatures.

The problem of skin temperature measurement during exposure to high intensity heat radiation can be visualized from figure 1. Plotted on the abscissa is

FIGURE 1

the logarithm of the wavelength in microns and on the ordinate the logarithm of the energy in $\text{kcal}/\text{M}^2/\text{hr}/\mu$. The energy used to measure the skin temperature is represented by the area under the curve "S" and it can be seen that this energy is small in comparison to that emitted from the source and to that fraction of the source radiation reflected from the skin surface shown as "R". If the source be filtered by glass, plastics, or other ordinary transparent material, the infrared portion of the energy of source beyond 3μ is greatly reduced and thus there is a clear separation between the energy emitted by the skin and that which is incident on the skin surface. This makes it possible to measure skin temperature radiometrically under these special circumstances (5). In the present situation, the source had a significant amount of radiation in the

4-20 μ region and even though the skin reflects only a very small amount of this energy, 0.5% to 1.5%, there is still enough of this reflected energy to cause large errors in radiometric measurement of skin temperature. The problem is thus two fold:-

- 1) the energy in the visible and near infrared region must be completely filtered out of the radiation used for skin temperature measurement;
- 2) a method must be devised to correct the readings of the skin temperature radiometer for the remaining reflected radiation from the source in the 4-20 μ region.

It is the intent of this report to describe a method for accomplishing these aims and to present some experimental data which can be compared directly with theory and to indicate how subcutaneous temperature can be estimated from skin temperature data.

METHODS

A lamp bank was constructed consisting of 8 quartz lamps 40 cm long mounted horizontally and spaced 10 cm apart vertically as shown in figure 2. The lamps were of the General Electric type "T-3"

Figure 2

and were provided with parabolic-type, cylindrical, stainless-steel reflectors. The design of the radiator was planned so as to give a uniform irradiance of 0.16 gm cal/sec/cm² over a surface 40 x 170 cm at a voltage of 440 volts. The lamps had a rated voltage of 220 volts and were used in the present

experiments at 300 volts which furnish an irradiance of $0.100 \text{ gm cal/sec/cm}^2$. A focal plane shutter of aluminized fabric was mounted on spring rollers to control the exposure time. As seen from the figure, the entire anterior or posterior body surface could be irradiated at one time with this arrangement. As the present experiments were concerned with the measurement of skin temperature, the upper aperture only was used and the skin area in center of the back just above the tips of the scapulae was selected for study. The value of the irradiance was measured with a carefully standardized radiometer located at the center of the area to be studied. In figure 3 is shown a survey of the irradiated area to indicate the degree of uniformity of the irradiance over the area of study indicated by shadow. It is seen that the maximum variation over the 20 cm diameter area was less than 5%.

Figure 3

In figure 4 is shown the radiometer and the calibrating source in position with respect to the lamp bank. The radiometer consisted of a vacuum thermopile, T, mounted at the focus of an elliptical mirror, M., surrounded with a diaphragmed cover, C, to restrict the scattered radiation coming into the mirror. The mirror itself was adjusted to focus on to the thermopile the rays from a point source placed at the center of the area of study. Thus, the radiometer was "viewing" the skin from behind the lamp bank between the third and second lamps. Immediately in front of the diaphragmed cover was placed a highly polished silver metal chopper which allowed the radiation from the skin to pass into the thermopile on one half of the cycle and reflected the radiation of the thermopile back

Figure 4

on itself during the second half. In this way, the temperature of the chopper itself played no role in the measurement and the cyclic voltage generated by the thermopile is proportional only to the difference in temperature between the thermopile and the skin. The voltage from the thermopile after amplification and mechanical rectification (Perkin-Elmer Corp. U.S.A.) was recorded on a strip chart recorder of response time 0.1 seconds (Kipp and Zonen, Delft).

The calibrating source was mounted in the exact plane of the subject's skin and was about 1.1 meters from the silver chopper. The source was a black body of the type designed by our Laboratory some years ago (4) and contained 60 Kg of water, the temperature of which could be measured and controlled between 60°C and 5°C. The aperture of the cone was 20 cm in diameter which was larger than the skin area to be measured which was about 18 cm in diameter. A calibration curve of the system relating the recorder reading to cone temperature is shown in figure 5. The reproducibility of the radiometer was better than 0.2°C

Figure 5

over the temperature range of 15°C and skin temperature readings were estimated to 0.1°C. It will be noted in Figure 5 that the relationship between temperature and recorder voltage is a straight line whereas one might expect a relationship following more nearly the difference of the fourth powers of the temperatures. The failure to observe the fourth power law was due to filtering of the infra-red radiation. The radiometer was fitted with an Indium-Arsenide filter in order to exclude the large amounts of reflected radiation from the skin in the visible and near infra-red (see curve R - Figure 1). The transmission curve of Indium-

Arsenide is shown in Figure 6 and indicates that this substance is opaque to radiation of wave lengths shorter than 3.7μ but transmits about 40% of the radiation of longer wave lengths.

Figure 6

Transmission Curves of Infra-Red Filters

This filter has a sharp cut-off between 3.7 and 4.0μ and tests with the combination of glass and Indium Arsenide filters together indicated that no significant amount of radiation would pass both filters. Germanium was also tested as a filter but its short wave cut-off was between 1μ and 2μ and thus transmitted unacceptably large amounts of reflected radiation from the skin. The reflected radiation filtered through the Indium Arsenide as shown by curve F in Figure 1 and as this radiation over-laid the emission spectrum of the skin, there was, of course, no way to separate this radiation by filtering. Resort was made, therefore, to separation by time.

In figure 7 is shown four superimposed recordings of skin temperature before, during and after irradiation for 16 seconds with an intensity of $100 \text{ mcal/sec/cm}^2$. At the end of the 16 seconds the two shutters, shown in figure 4 at H.S. by dashed lines immediately in front of the lamps, were quickly moved into place

Figure 7

by hand thus occluding the radiation from the lamps but still allowing the radiometer to view the skin surface. There was a sudden immediate fall in the radiometer reading followed by a slower decrease. At 23 seconds, the power to the lamps was turned off thereby eliminating the visible and near infra-red radiation

from the filaments in the quartz tubes of lamps which are, of course, the major factor in heating the skin. Two seconds later the skin was again exposed to the radiation from the lamps which by this time was due entirely to the longer wave length infrared radiation mainly from the heated quartz tubes but also from the heated mirrors and other structures associated with the lamps. Immediately, there was a marked increase in the radiometer reading due to reflected infrared and due only in minor degree to further skin heating. The hand shutters were operated repeatedly, three times, as shown in the figure. The increased deflection seen in the record when the shutters were opened represent the reflection by the skin of the radiation from the hot lamps which decreased rapidly due to cooling of the lamp structures; the lower part of the curve changed only slowly and represented skin cooling. The correction for reflection was determined by extrapolation of the lamp reflection values to zero time (i.e. when the lamps were cut off). This correction was then subtracted from all the readings made during the irradiation period to determine the true skin temperature.

RESULTS

Measurements were made on several subjects at room temperatures near 20°C . The low room temperature was necessary to prevent the early onset of vasomotor changes and sweating as it was desired to keep conditions at the skin surface constant for at least one minute. In general, this was not feasible for periods longer than about 10-15 seconds. Figure 8 shows averages of measurements of skin temperature measurements on two subjects for different irradiances. For the first 10-15 seconds the skin temperature elevations were entirely proportional to the irradiance and thus could be expected to be least affected by physiological

Figure 8

changes and therefore should be predicted by theory from straight forward application of standard heat flow equations providing sufficient data on the optical and thermal properties of skin were available.

Inasmuch as a large area of skin was being irradiated, it can be safely assumed that the heat was flowing into the skin in one direction and that the lateral heat flow occurring at the edges can be neglected. Also, the skin is a non homogeneous aggregate composed of horny layers of almost dry protein, cellular layers of water-like materials and wet protein membranes and tissues; vascular layers, similar to the cellular layers in optical characteristics except for the absorption bands due to hemoglobin, and a fatty layer at some depth, estimated in this instance to be at a depth of 1 mm or more below the skin surface. The skin over the body surface has recognized variability and even within an area such as studied in this experiment, complete uniformity could not be expected. However, calculation indicates that except for the most superficial layers, the exact characteristics of the various layers are not important as long as the values of the various heat flow constants do not depart significantly from those of water. Based on these considerations, the skin was visualized as divided into eight overlying layers as shown in Figure 9. Layers 1 and 2, each 50 microns thick, are considered to make up the stratum

Figure 9

corneum and transition layers to the basal layers shown as layers 3 and 4; also 50 microns thick. The most superficial layers are considered to be similar in their properties to dry protein with a transition in layer 3 to wet protein in layers

4 through 7. Beneath layer 7 is assumed to be a fatty like layer extending to a total thickness of 1 cm; the exact thickness and value of the thermal properties of this deepest layer are not important in the thermal exchanges occurring within a few seconds after the beginning of the exposure to thermal radiation. The values of the heat conductivity, density and heat capacity shown in the slide are taken from the work of several authors as being the best values available but exact values for the various tissue layers in the intact man cannot be obtained by present methods and, thus, the values used in the calculations should be considered as only approximate. Fortunately, changes in the values of the constants by 10% - 20% will not greatly change the results.

The absorptivity of the various skin layers has been studied for the spectral range $0.5-2\mu$ and the values are shown in figure 10 for excised white human skin (6). The measurements made with a goniometric spectrometer are given for many specimens of freshly removed skin for four wavelengths. The absorption coefficients

Figure 10

Absorptivity of excised human skin as a function of wavelength and thickness.

are highly variable with depth for energy in the visible spectrum, but for wavelengths as long as 1.2μ , there is no significant change of the absorption coefficient with thickness of specimen studied. For the present source of radiation with a color temperature of 2650°K , the amount of energy in the visible spectrum is 10% whereas the energy in the region $0.8 - 2.5\mu$ is about 70%. For this reason it would be

expected that the tissues would absorb effectively in accord with an absorption coefficient which is constant with depth. It is important to mention that the absorption coefficients as shown in Figure 11 are composed in part by the scattering which takes place when the radiation enters the skin as well as any true absorption as the chemist uses the term in spectrophotometric matches of clear solutions. For example - a clear glass cover slip will have a significant absorption coefficient if its surfaces are roughened with grinding powder. Thus, the very low absorption coefficient for wavelength 1.2μ indicates that the white human skin is almost completely transparent to this energy except for scattering losses in the tissues due to optical irregularities.

With the data outlined in the previous paragraphs, it is now possible to calculate the heat losses and gains for each layer of tissue during an exposure to thermal radiation and to compare the theoretical results with those of the experiments described above. As mentioned before, the calculations we have made can only be applied to the situation in which there are no marked physiological changes such as vasomotor action or sweating. This restriction implies that a comparison of theoretical and experimental results will not be valid after about 15 seconds following exposure to the radiation with the subject precooled.

For each skin layer, it can be stated that the

1) gain in heat = heat inflow - heat outflow.

For each square centimeter of skin surface, the heat gained in a short time is

$$\Delta x \rho c \frac{dT}{dt}$$

where: Δx = layer thickness

ρ = density of tissue on layer

c = specific heat of tissue in layer and

$\frac{dT}{dt}$ = rate of temperature change

The heat flow into the layer is by conduction of metabolic heat from the neighboring layers and the energy absorbed from the radiation. This can be written as follows for a layer of number "n":-

Heat gain from (or loss to) the superficial layer by conduction =

$$\frac{K_{(n-1/2)}}{\Delta X_{(n-1/2)}} [T_n - T_{(n-1)}]$$

in which $K_{(n-1/2)}$ = thermal conductivity of the tissue between the centers of layers "n" and "n-1".

$\Delta X_{(n-1/2)}$ = distance from center of layer "n" to center of layer "n-1"

T_n and $T_{(n-1)}$ = temperatures at the centers of layers "n" and "n-1". Actually in this approximate analysis, all of the layer "n" is assumed to be at temperature T_n ; and all of layer "n-1" to be at temperature $T_{(n-1)}$.

A similar equation can, of course, be written for the exchange of heat by conduction with layer "n + 1" as

$$\frac{K_{(n+1/2)}}{\Delta X_{(n+1/2)}} [T_{(n+1)} - T_n] .$$

The energy absorbed by the layer "n" will depend on the thickness of the layer; its absorption coefficient and the amount of energy which is transmitted to the layer from the layers more superficial to it. To make this calculation, we consider Figure 1, which shows the spectral emission of the source for many wave lengths

and the reflectivity of the skin over the same spectral range. Also, we consider Figure 11, which gives the information regarding the absorption coefficients of the various skin layers. The standard equation for absorption within a layer of thickness ΔX and absorption coefficient μ is -

$$\text{Absorbed Energy} = I_0 (1 - e^{-\Delta X \mu})$$

in which I_0 is the radiant flux entering the layer. What is then required is the systematic computation for each small spectral band of wave lengths (0.1μ was the width of the band used in the present calculations) of the energy received at the surface of each layer, the amount of energy absorbed in the layer, and the amount of energy transmitted to the next layer. The sum of all the contributions from each wave length band is the total energy absorbed by the particular layer.

The heat stored in layer "n" during a small interval of time can thus be written as -

$$2) \Delta X_n \rho_n c_n \frac{dT_n}{dt} = E_n + \frac{K_{(n+1/2)}}{\Delta X_{(n+1/2)}} [T_{(n+1)} - T_n] - \frac{K_{(n-1/2)}}{\Delta X_{(n-1/2)}} [T_n - T_{(n-1)}]$$

in which E_n = radiant energy from the source absorbed in layer "n". There are eight of these equations, one for each layer, and it is assumed that before the radiation pulse the skin layer is at 30°C losing heat to the environment by radiation conduction and convection and insensible evaporation at the rate of $40 \text{ kg cal/m}^2/\text{hr}$. The temperature at the center of layer 8 is assumed initially to be 33.5°C . There will thus be an initial linear gradient through the tissues from 33.5°C in layer 8 to 31°C at the skin surface before the radiation pulse. Using the values from Figure 11, the heat balance equations for the eight layers are as follows:-

$$\frac{dT_1}{dt} = -0.032 (T_s - T_a) + 19.2 (T_2 - T_1) + 0.00890$$

$$\frac{dT_2}{dt} = -19.2 (T_2 - T_1) + 27.0 (T_3 - T_2) + 0.00803$$

$$\frac{dT_3}{dt} = -27.0 (T_3 - T_2) + 36.5 (T_4 - T_3) + 0.00687$$

$$\frac{dT_4}{dt} = -36.5 (T_4 - T_3) + 15.4 (T_5 - T_4) + 0.00645$$

$$\frac{dT_5}{dt} = -3.87 (T_5 - T_4) + 2.42 (T_6 - T_5) + 0.0201$$

$$\frac{dT_6}{dt} = -2.42 (T_6 - T_5) + 2.42 (T_7 - T_6) + 0.0132$$

$$\frac{dT_7}{dt} = -2.42 (T_7 - T_6) + 0.387 (T_8 - T_7) + 0.00806$$

$$\frac{dT_8}{dt} = -0.00159 (T_8 - T_7) + 0.00111 + 0.0128$$

A review of the calculations indicated that certain simplifications could be made regarding the particular source used in these experiments. For example, since nearly 65% of the energy falls in the spectral range of $0.9 - 2.5\mu$, an average value of the absorption coefficient for skin of 22 cm^{-1} can be used for all wave lengths without changing the calculations significantly.

The solving of Equations 1 through 8 for the temperature in each layer can be done more rapidly by the use of an analogue computer of standard design. The diagram for the solution is shown in Figure 11 for the completion of the analysis. It is very useful to maintain an analogue of the skin for comparison of theoretical and experimental results and for calculation of the subcutaneous temperature changes associated with various experimental procedures.

Figure 11

Electrical analogue of heat exchange in the human skin

For example, the thermal situation for artificially blackened skin and for naturally pigmented skin can be quickly evaluated. By appropriate modification of the constants in the equations, the temperature changes in other tissues, for example, the eye, can be explored. In Figure 12 is shown the change in the skin and subcutaneous temperature following irradiation from the lamps set for an irradiance of $0.12 \text{ gm cal/cm}^2 \text{ sec.}$ at the skin surface. It is seen that layer 8 at the center does not change temperature during the first 4 seconds of irradiation and the line joining the centers of all the layers represents the approximated gradient through

Figure 12

the tissues. It is not felt that a more elaborate analogue, dividing the skin into a larger number of layers to thereby more closely approximate the gradient would be useful with the present state of our knowledge of the thermal and optical properties and the physiology of the human skin.

In Figure 13 is shown a comparison of the experimental data for the rise in skin temperature with the calculate rise in temperature of layer 1 (i.e. 25μ depth). The agreement between these values is good and serves as the basis for computing

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Figure 13

the temperature of the subcutaneous layers. There is a marked penetration of the radiation so that layers 1, 2 and 3 are practically at the same temperature and indeed about 10% of the total irradiance from the source penetrates to a depth of 6 mm in the tissues. The spectral quality of the transmitted radiation changes markedly with depth and only the most penetrating rays ($1-2\mu$) reach the deeper layers. Thus for very high temperature sources, i.e. 6000°C for which 55% of the radiation is in the ultra-violet and visible spectral regions, a much larger percentage of the radiation would be absorbed in the very superficial layers. The radiation from sources of low temperature (i.e. 1000°C) also will be nearly completely absorbed by layers 1-4. The benefits to be derived from filtering of sources to prevent overheating of the skin by allowing a large degree of penetration is seen from this study. By filtering out the green, blue and yellow portions of the visible spectrum and the infrared radiation longer than 1.8μ , a marked degree of "protection" can be realized by encouraging both the reflection from the skin and the penetration into the skin. Such filtering will reduce significantly the accumulations of heat in the superficial skin layers and the rise temperature in these layers (pigmented or not) to injurious levels during exposure to high intensity heat radiation.

FIGURES

Figure 1

Spectral Distribution of Skin Reflectance R, and Emission Spectrum, S.
Emission Spectrum of Quartz Lamp Source Q (Color Temperature 2650°K) and
Emission Spectrum of Source filtered by 0.5 mm Indium -Antimonide.

Figure 2

Diagrammatic Representation of Subject being irradiated by Quartz Lamp Radiator

Figure 3

Survey of irradiance over Experimental Area Irradiance expressed in Milli-calories per second per square centimeter ($m \text{ Cal/sec.}^2$) 1 gm cal = 1000 mcal.

Figure 4

Diagram of Radiometer and Calibrating Source in Relation to Quartz Radiator.

Figure 5

Calibration of the radiometer with Black Body Source

Figure 6

Transmission Spectrum for Indium - Arsenide Filter used in the Experiments in comparison to the transmission spectra of Germanium and optical glass (Corning No. 970).

Figure 7

Radiometer Records of Skin Temperature before, during and after irradiation. Error due to reflected radiation from the skin shown after Quartz Lamps were turned off.

Figure 8

Elevations of temperature caused by exposure to Quartz Lamp Source at different intensities.

Figure 9

Diagramatic Representation of the Skin for Analysis of Heat Flow during Irradiation together with Thermal Constants for Various Skin Layers (See references 2, 8, 9).

Figure 10

Absorption coefficients including scattering at four wavelengths for skin of different thickness.

Figure 11

Electrical analogue of Equations 1 - 8 for the heat exchange in the human skin. Potentiometer coefficients based on time scaling of 1 second real time = 10 seconds recorder time.

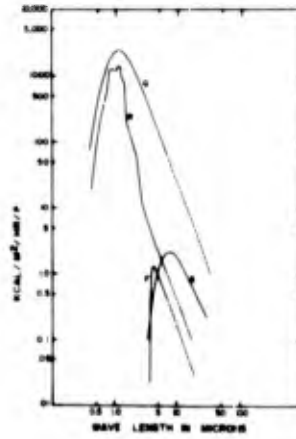
Figure 12

Calculated subcutaneous temperatures before and 4 seconds after the start of irradiation at $120 \text{ mcal/sec. cm}^2$.

Figure 13

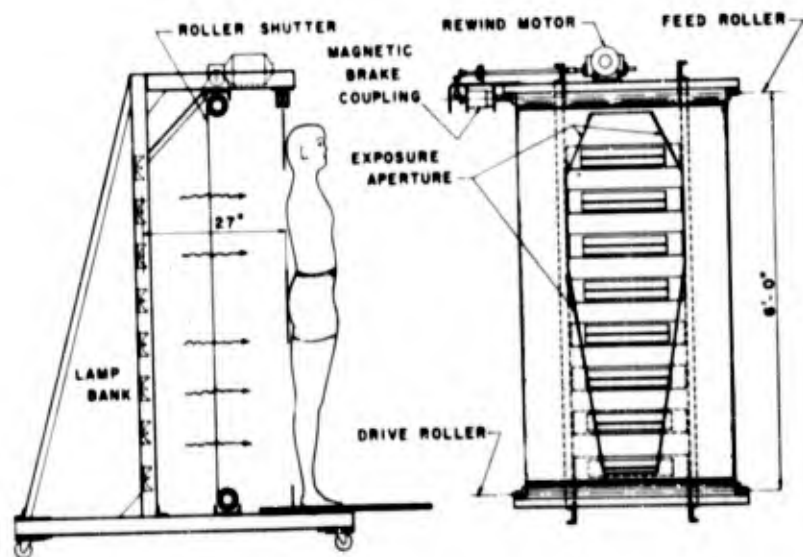
Comparison of experimental values of Skin Temperature rise (shown as solid circles) and theoretical values (line 1) during irradiation with $120 \text{ mcal/sec. cm}^2$ from Quartz Lamp Bank.

Figure 1



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Figure 2



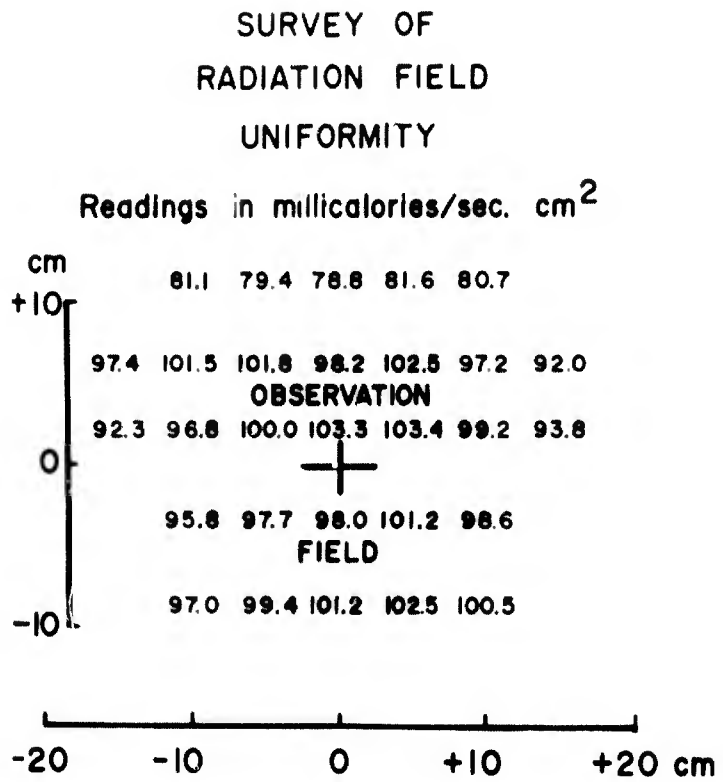


FIGURE 4

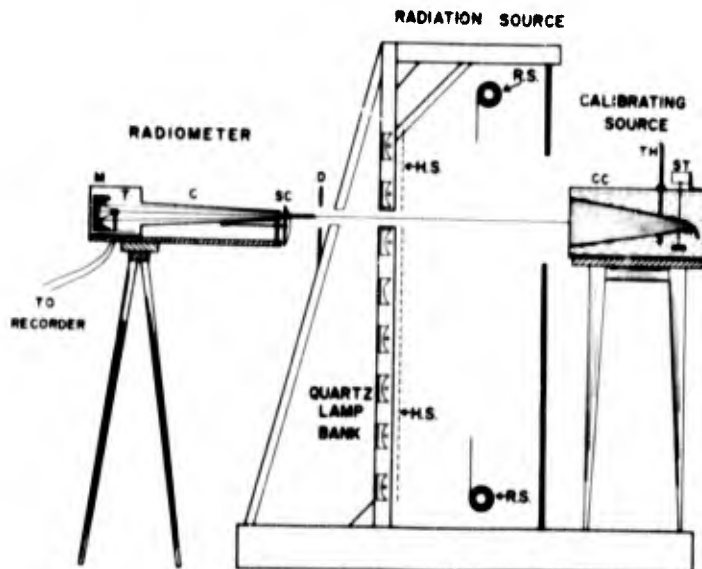


Figure 5 -5-

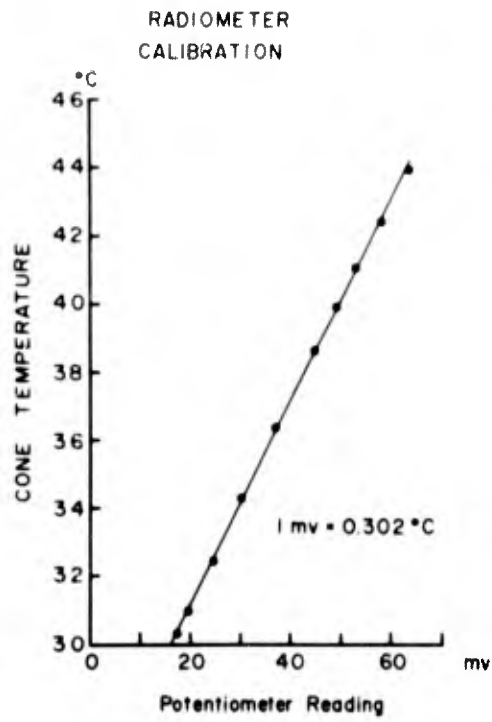


Figure 6

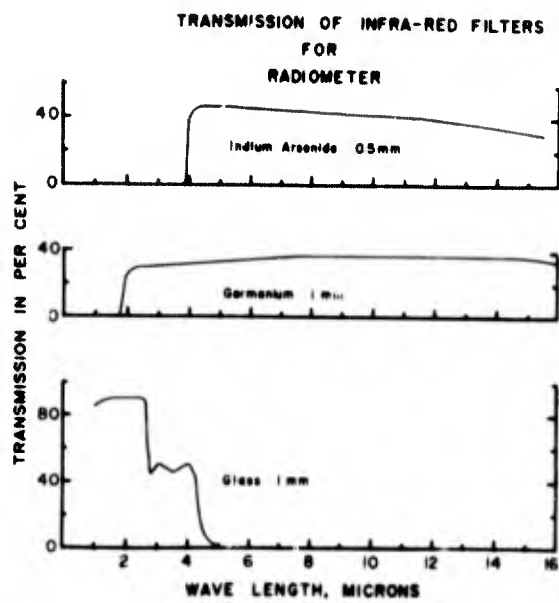


Figure 7

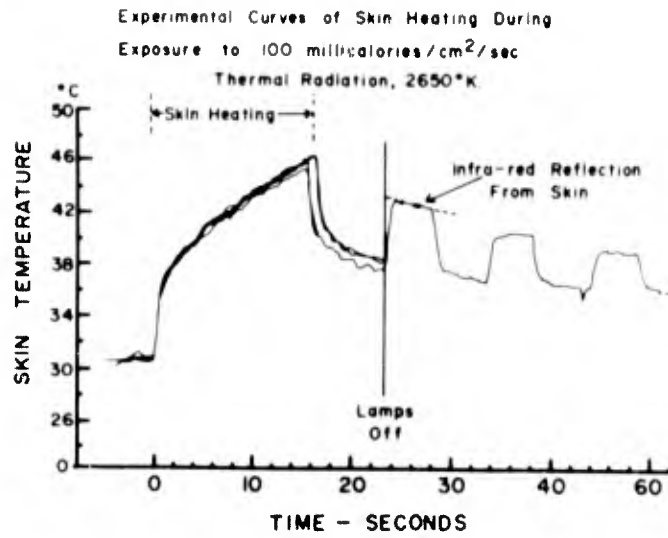
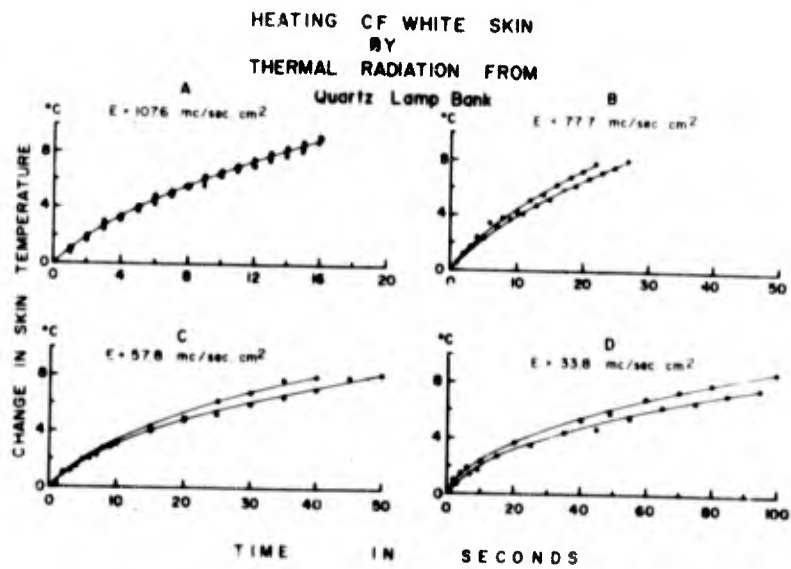


Figure 8



-7-
FIGURE 9

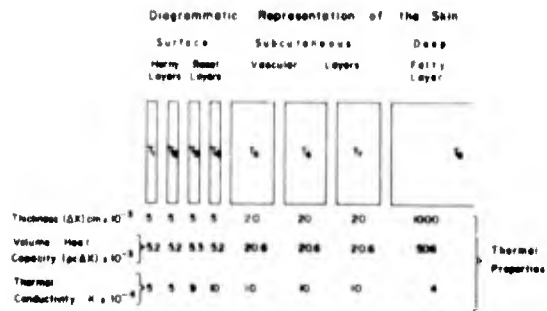


FIGURE 10

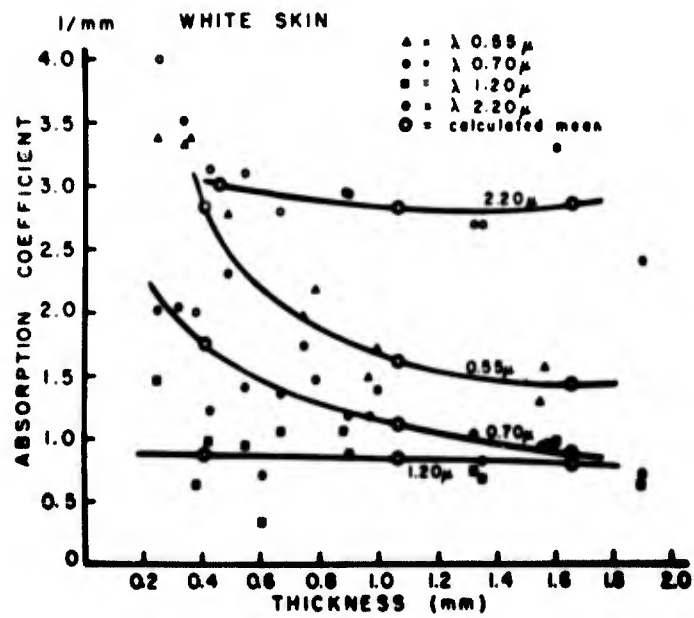


FIGURE 11

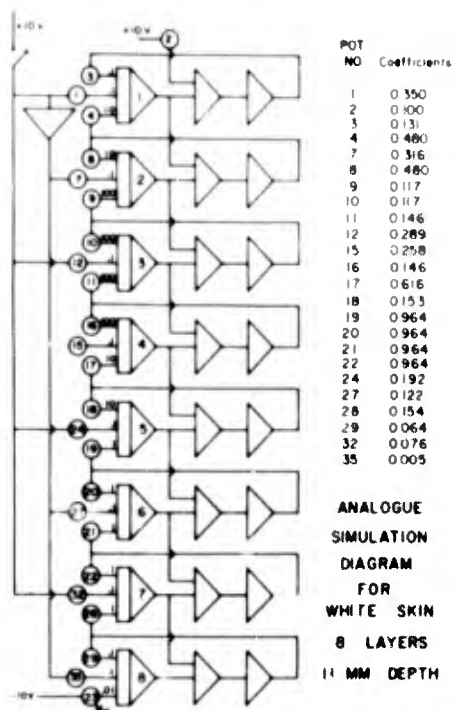
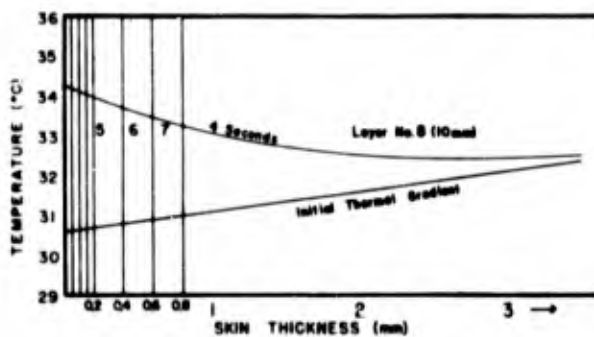


FIGURE 12

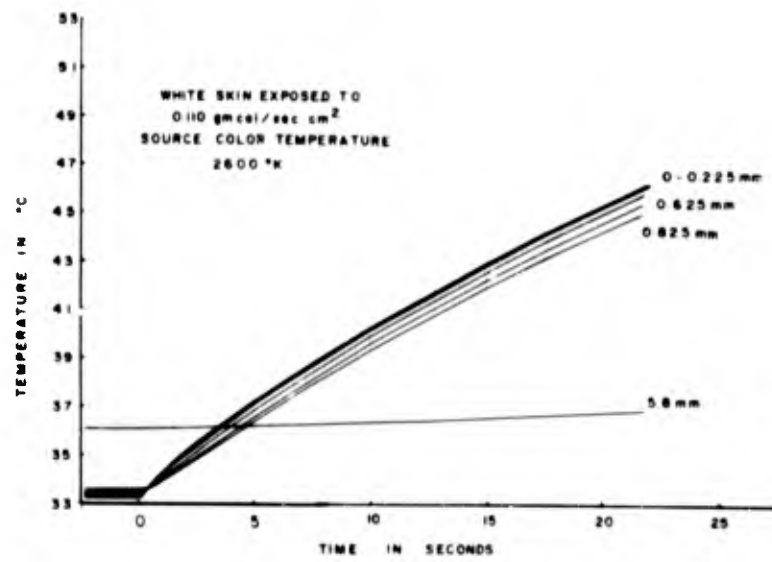
THERMAL GRADIENTS IN THE SKIN FOLLOWING
IRRADIATION BY 0.12 gm cal/cm². sec



LAYER No.	1	2	3	4	5	6	7	8
Δx (mm)	.05	.05	.05	.05	.2	.2	.2	.10
ρ	1.2	1.2	1.2	1.2	1.2	1.2	1.2	0.92
C	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86
K	0.0005	0.0005	0.0005	0.001	0.001	0.001	0.001	0.0004
C mm ⁻¹	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2

Physical Properties of Skin Layers

FIGURE 13



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