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Pre-Shock Soil Temperature Predictions of a Simplified Soil Heating Model

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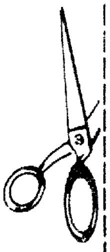

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13 ABSTRACT *(Maximum 200 words)*

This report constitutes an extension and augmentation under contract DNA 001-88-C-0042 of a report initially prepared under contract DNA 001-84-C-0127.

A model of energy transport and temperature evolution in the surface layers of soil subjected to thermal radiation prior to the time-of-arrival (TOA) of the blastwave from a low height-of-burst (HOB) nuclear explosion has been developed and evaluated. Processes taken into account are thermal conductivity, boiling of water, transpiration cooling, and attenuation of thermal radiation in the soil. Calculations were carried out for a range of parameters. We present an analytic fit to the soil temperature profiles for a 1 MT explosion of 200 ft HOB at TOA as a function of ground range.

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SUMMARY

Calculations have been carried out for the pre-shock soil heating expected from a nuclear explosion having a 1 MT yield and a HOB = 2000 ft for several ground ranges. Assumptions made in the calculation favor a lower surface temperature and a rapid decrease with increasing ground range. Additional calculations simulating flash lamp experiments suggest that crucial parameters must be adjusted to obtain qualitative agreement. More experimental data, as well as calculations, are required. Calculations having a larger transmission factor, a larger geometric factor, and possibly a larger soil absorption coefficient (smaller mean-free path), would result in higher peak surface temperatures and probably would correspond to more realistic conditions.

CONVERSION TABLE

Conversion factors for U.S. customary
to metric (SI) units of measurement

To Convert From	To	Multiply By
angstrom	meters (m)	1.000 000 X E-10
atmosphere	kilo pascal (kPa)	1.013 25 X E+2
bar	kilo pascal (kPa)	1.000 000 X E+2
barn	meter^2 (m^2)	1.000 000 X E-28
British Thermal unit (thermochemical)	joule (J)	1.054 350 X E+3
calorie (thermochemical)	joule (J)	4.184 000
cal (thermochemical)/cm^2	mega joule/m^2(MJ/m^2)	4.184 000 X E-2
curie	giga becquerel (GBq)*	3.700 000 X E+1
degree (angle)	radian (rad)	1.745 329 X E-2
degree Fahrenheit	degree kelvin (K)	T_K=(t°f + 459.67)/1.8
electron volt	joule (J)	1.602 19 X E-19
erg	joule (J)	1.000 000 X E-7
erg/second	watt (W)	1.000 000 X E-7
foot	meter (m)	3.048 000 X E-1
foot-pound-force	joule (J)	1.355 818
gallon (U.S. liquid)	meter^3 (m^3)	3.785 412 X E-3
inch	meter (m)	2.540 000 X E-2
jerk	joule (J)	1.000 000 X E+9
joule/kilogram (J/Kg) (radiation dose absorbed)	Gray (Gy)**	1.000 000
kilotons	terajoules	4.183
kip (1000 lbf)	newton (N)	4.448 222 X E+3
kip/inch^2 (ksi)	kilo pascal (kPa)	6.894 757 X E+3
ktap	newton-second/m^2 (N-s/m^2)	1.000 000 X E+2
micron	meter (m)	1.000 000 X E-6
mil	meter (m)	2.540 000 X E-5
mile (international)	meter (m)	1.609 344 X E+3
ounce	kilogram (kg)	2.834 952 X E-2
pound-force (lbf avoirdupois)	newton (N)	4.448 222
pound-force Inch	newton-Ometer (N.m)	1.129 848 X E-1
pound-force/inch	newton/meter (N/m)	1.751 268 X E+2
pound-force/foot^2	kilo pascal (kPa)	4.788 026 X E-2
pound-force/inch^2 (PSI)	kilo pascal (kPa)	6.894 757
pound-mass (lbm avoirdupois)	kilogram (kg)	4.535 924 X E-1
pound-mass-foot^2 (moment of inertia)	kilogram-meter2 (kg.m^2)	4.214 011 X E-2
pound-mass/foot^3	kilogram/meter3 (kg/m^3)	1.601 846 X E+1
rad (radiation dose absorbed)	Gray (Gy)**	1.000 000 X E-2
roentgen	coulomb/kilogram (C/kg)	2.579 760 X E-4
shake	second (s)	1.000 000 X E-8
slug	kilogram (kg)	1.459 390 X E+1
torr (mm Hg, 0°C)	kilo pascal (kPa)	1.333 22 X E-1

*The becquerel (Bq) is the SI unit of radioactivity; Bp = 1 event/s.

**The Gray (Gy) is the SI unit of absorbed radiation.

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SECTION 1

INTRODUCTION

Soil surface layers exposed to a thermal flux of $\sim 10^2$ cal/(cm^{2}s) are expected to be heated quickly to temperatures in the range of several times $10^{3\circ}$K. Such an environment is anticipated from nuclear explosions having low height-of-burst (HOB) at ground ranges of interest to a hardened mobile launcher system. These conditions can also be created to some degree in thermal layer simulators such as the Thermal Radiation Simulator (TRS) or the condenser discharge simulator (Flash-Bang).

In addition to wanting to know the properties of the vapor layer adjacent to the ground produced by thermal radiation, modelers of the nuclear blastwave desire to incorporate the effects of dust pick-up into their fluid dynamics calculations, including the thermodynamic consequences. Consequently, the energy or temperature resident in the first few millimeters of the soil subject to lofting should be specified. It is expected that a significant temperature gradient will be present in this layer at the time of shock arrival so that temperature profiles at various ground ranges are needed.

Several models of the heating of the soil and adjacent thermal layer have been developed. Predictions were made for cases of interest by H. Carpenter, based principally on heat conduction into the soil. The results generally show surface temperatures toward the upper range of expected results.

Calculations were also made using the S-CUBED THRML model showing much lower surface temperatures under the combined effects of thermal conduction, soil water boiling/transport, dust lofting, and radiation absorption/scattering in the dusty layer. The predictions of THRML are sensitive to the amount of dust lofted by the efflux of steam from the vaporization of free or bound water in the soil.

In order to provide a detailed estimate of soil temperature we have developed a simplified model (described below) to evaluate energy transport in the soil. In addition to the process of thermal conduction included by Carpenter, water boiling and transpiration are taken into account. In addition, the thermal radiation incident on the soil surface is deposited exponentially in the soil. While this model is simpler than THRML, it contains basically the same physical processes in the soil; the effects of the thermal layer above the soil are replaced by an empirically attenuated thermal source incident on the soil surface.

In Section 2 of this report an outline of the formulation is presented. Calculations covering a range of parameters are reported in Section 3. In addition, this section also presents an analytical fit to the calculated soil temperature pro-files at shock arrival for a yield of 1 MT at a height-of-burst of 2000 ft as a function of ground range. Conclusions and a summary are contained in Section 4.

SECTION 2

FORMULATION OF A SOIL HEATING MODEL

The current model is similar in concept to the Analytic Heat Transfer Model of H. Carpenter in that emphasis is placed on processes occurring within the soil. In addition, the model contains empirically-based descriptions of the thermal radiation from the source and processes taking place within the thermal layer itself. In the following sections we outline the treatment of the model for these several processes.

2.1 SOIL ENERGY TRANSPORT.

The calculation of temperature change in the soil accounts for three processes; thermal radiation heating, thermal conduction, and water vapor advection (consisting of the evaporation and heating of water). To describe the evolution of this two-phase system in generality, it would be necessary to solve the mass, momentum, and energy equations for each of the interacting (water, water vapor, and soil matrix) phases. We have simplified this complicated formulation by making several reasonable approximations:

- The water vapor expands at constant atmospheric pressure; it is not necessary to solve a momentum equation for the water vapor and the mass equation can be employed to evaluate the vapor streaming speed.
- The temperatures of the water and soil matrix equilibrate rapidly; it is not necessary to solve separate energy equations for the water and the matrix.
- The soil matrix is not disrupted by thermal expansion, by the transport of small dust particles or by pressure build-up of the water vapor; it is not necessary to solve equations for the motion or density change of the soil matrix since dust lofting is neglected.

The result of the above approximations is that a single equation for the total enthalpy change remains. It has the form:

$$\frac{\partial H}{\partial t} + \frac{\partial u H_w}{\partial x} = \frac{\partial}{\partial z} K \frac{\partial T}{\partial z} + \dot{S} \qquad (1)$$

where

z = depth into the soil (measured from the surface),

t = time (measured from onset of thermal radiation),

u = speed of water vapor (possibly including partially unvaporized water) due to vaporization and heating,

H = enthalpy per unit volume of liquid and vaporized water and soil matrix,

H_w = enthalpy per unit volume of water vapor,

T = common temperature of water and soil matrix,

K = thermal conductivity of soil and water,

$\dot{S}$ = volumetric heating rate due to absorption of thermal radiation.

Equation (1) has the form of an advection-diffusion equation. The advected enthalpy, however, differs from that of the time derivative. A complication arises in relating the enthalpy to the temperature due to the phase change of water and the associated large heat of vaporization.

We expect that the effects of water in the soil will be significant in reducing the soil temperature. During the course of soil heating almost all of the soil water in the vaporization zone will be removed from the matrix at temperatures corresponding to the soil surface temperature. The energy expelled from the soil in this manner can be a significant fraction of the energy incident on the surface. We also expect that the obliquity of the thermal radiation at the larger ground ranges, as it affects the transmission and source deposition, will modify the range-dependence of the results.

In the following subsections we describe in greater detail the three processes enumerated above.

2.1.1 Thermal Radiation Heating.

The absorption of thermal radiation by the soil matrix is approximated by a temperature-independent absorption mean-free path, ℓ_0. This coefficient must be determined by transmission experiments or calculated from the estimated index of refraction. For our simplified model, the thermal flux, F, at a soil depth, z, is approximated by the single oblique ray solution:

$$F = F_0 e^{-z/(\mu \ell_0)} , \dot{S} = \frac{dF}{dz} \qquad (2)$$

where

F_0 = flux incident on the soil surface (discussed in Section 2.2).

μ = cosine of the average angle of incidence $\sim \frac{h}{R}$

where

h = height-of-burst (HOB)

R = $(h^2 + r^2)^{1/2}$ = slant range from fireball center to the surface station at ground range r

Such a treatment would require refinement if the fireball HOB were to become appreciably smaller than the radius of the radiating fireball at times of interest.

The energy deposited by thermal radiation is calculated in the finite difference scheme so as to conserve the incident energy. This is accomplished by evaluating radiation fluxes at each of the interzone boundaries.

2.1.2 Thermal Conduction.

The thermal conductivity, K, of typical soils is large enough to be a factor limiting the rise in surface temperature and modifying the profile of soil temperature at the time of shock arrival. Since the thermal conductivity of soils exhibits a range of values, it is desirable to explore the sensitivity of the soil response to this parameter. In addition, it is known that the thermal conductivity depends on the water fraction and temperature of the soil. While we have not found data for soils on the temperature dependence, it is known that the conductivity of SiO_2 increases with temperature. We have neglected any temperature dependence of K at the present time due to lack of data.

Typical dependences of conductivity on soil type and water fraction, X_w, are discussed by W. Sellers, (*Physical Climatology*, University of Chicago Press, 1965). According to Sellers, ". . . . . .thermal conductivity is highest for a soil containing abundant quartz and least for a soil rich in organic matter. It increases with increasing moisture content, since water replaces air in the soil pore spaces, and is higher for frozen soil than for unfrozen soil." Figure 1, taken from Sellers, shows measured conductivity for four soils at temperatures of 4.4°C (Fairbanks Sand), 20°C (Quartz Sand), and 18°C (Clay and Peat).

The figure indicates the volume fraction of soil, X_s, in the dry soil. Curves cover the range from dry to saturated soils (although this complete range is not experienced under field conditions). It is striking that the sands show a five-fold or greater increase in K as water volume fraction increases to a typical value of 8%. K-values of the sands and clay are substantially larger than the value used by Carpenter. We have incorporated the curve for Quartz Sand into some of our calculations. In this case, the value of K decreases for that part of the soil from which the water has been vaporized.

The thermal flux, ϕ, is evaluated at an interface between soil cells by a centered difference approximation to the following expression

$$\phi = -K\frac{\partial T}{\partial z} \ .$$

The resulting difference equations for Eq. (1) are solved explicitly, requiring the observance of a time-interval restriction

$$\Delta t < \frac{(\Delta z)^2}{2K} \ , \tag{3}$$

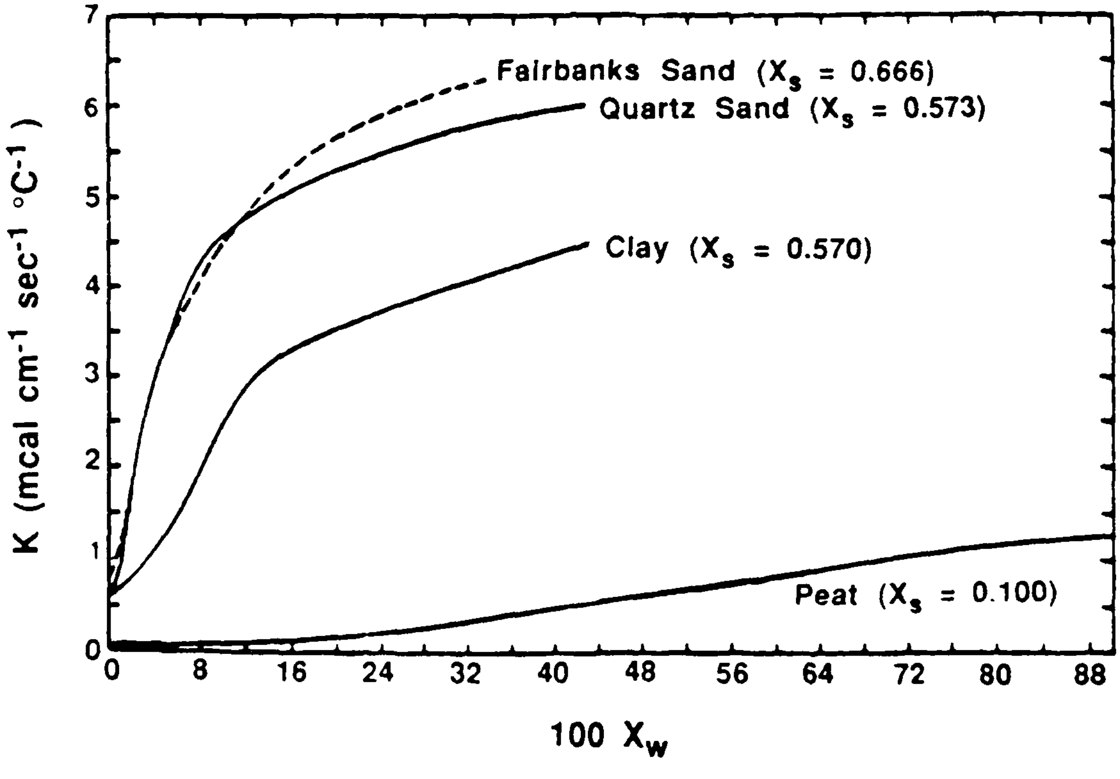


Figure 1. Dependence of thermal conductivity, K, on the volume fraction of water, X_w, for four different soil types.

where

Δt = time-interval

Δz = space-interval

K = thermal diffusivity

2.1.3 Energy Advection by Water Vapor.

Vaporization of water during soil heating results in vapor escaping from the soil into the atmosphere; it carries with it the latent and sensible heat it has acquired within the soil. A comprehensive calculation of this problem requires evaluation of effects of flow through a porous medium, temperature equilibration and the erosion and lofting of soil particulates. While some of these effects can be treated in a more sophisticated formulation than this one, we did not have the time required to develop and test such a formulation for our present purposes. We believe that the predominant processes are the ones included in the formulation.

The approximations made in this code are:

1. Water vapor streaming through the soil is able to reach complete thermal equilibrium with the soil,
2. The water vapor is able to expand rapidly enough to reach ambient pressure (1 atmosphere) throughout the vaporization zone and to stream freely into the atmosphere above the surface.

These approximations make unnecessary a solution of a water vapor momentum equation or the evaluation of an exchange term between the water vapor and the soil in the energy equations. Further, assuming that thermal conduction and thermal radiation absorption take place primarily in the soil, we solve a mass conservation equation for advection of the water vapor and an advection-diffusion equation for the energy.

After some experimentation with numerical methods, we adopted an explicit scheme in which the Eulerian finite-difference mesh attached to the soil is dominant. Within the zone of vaporizing or vaporized water, the following calculations are performed:

A. Form the vapor velocity due to vaporization and heating in the vapor region using mass conservation and the assumption of atmospheric pressure. Calculate the displacement of zone interfaces at the end of the time-interval in question.

B. Form the water vapor mass and energy density in these displaced zones (Lagrangian phase of the calculation).

C. Interpolate the water mass and energy density onto the original Eulerian zones by a remapping technique.

D. Recalculate the zone temperature.

These steps complete the advection calculation for a cycle; all quantities are now associated with the Eulerian zones and are ready for the calculation of the next time-cycle. The advantage of the above procedure is that the computational mesh remains associated with the soil so that the soil temperature profile is well resolved.

2.1.4 Equation-of-State for Water Vapor.

Using the assumption that pressure is maintained at one atmosphere, water vapor density data obey a perfect gas equation to within a few percent:

$$\rho_o = 5.8 \; x \; 10^{-4} \left(\frac{373^\circ K}{T} \right) gm/cm^3$$

Assuming that the vapor fills the pore space of the soil, we obtain an effective water vapor density taking account of the pore volume fraction of the soil:

$$\rho_v = (1 - X_m - X_o)\,\rho_o$$

where the soil is composed of mineral and organic components having

X_m = volume fraction of mineral component.

X_o = volume fraction of organic component.

The specific heats (cal/(cm^3 °K)) of mineral and organic components are taken to be 0.46 and 0.60, respectively.

2.2 SOURCE DESCRIPTION.

The thermal radiation flux component normal to the ground has been taken from an analytic fit to calculated data of the RECIPE code. This expression is

$$F_R = 10^4 \frac{h}{R} \left(\frac{100\ YS}{R - 50\ YS} \right)^2 f(\tau)\ cal/(cm^2 s)\ , \tag{4}$$

where

YS = $Y^{1/3}$ = cube-root-scaled yield (Y in kT)

h = HOB (ft)

R = slant range (ft)

$f(\tau)$ = $2\tau^2/(1 + \tau^4)$ and τ = 10 t/YS

t = time after explosion (s)

Since this expression obeys cube-root scaling, it presumably is quite limited in the yields to which it is applicable. It appears to fit the RECIPE data for Y = 1 MT (Carpenter) at peak fluxes, and underpredict the flux at earlier times. These data can be replaced (as in the THRML code) by a more accurate prescription for the thermal flux using a table of the RECIPE calculation of the specific source and a geometric model of the fireball thermal flux.

The factor accounting for the oblique incidence of the radiation (= h/R) is also an approximation when the fireball comes into contact with the ground. As the fireball after contact grows more rapidly into the upper hemisphere, the geometric factor becomes larger than that of Eq. (4). For the case evaluated in the sample calculation (Y = 10^3 kT, HOB = 2000 ft) the fireball is expected to make surface contact during the later part of the thermal pulse. Improved geometric factors are available.

We modify the source thermal flux by an assumed atmospheric transmission factor, T, due to air absorption or scattering, and a surface albedo, A, due to diffuse reflection. Values of these quantities employed in the calculations are discussed in Section 3. In addition, the transmission factor is reduced by an empirical factor to account for thermal layer absorption or simulator geometry. We also permit the surface to re-radiate in the IR due to the surface temperature, Ts. The resulting net incident flux is

$$F_o = F_R\ T(1 - A) - \sigma\ T_s^{\ 4}\ . \tag{5}$$

This expression is used in Eq. (2) of Subsection 2.1.1

SECTION 3

RESULTS OF CALCULATIONS

3.1 NUMERICAL CALCULATIONS.

The model described in Subsection 2.2 has been applied to several cases of interest in the modeling of the shock precursor of a 1 MT nuclear explosion. In order to compare results with those of Carpenter we have evaluated soil heating at ground ranges of 3000 to 8000 ft, using increments of 1000 ft, for an assumed HOB = 2000 ft. As a first case we selected a value of the soil thermal radiation mean-free path, ℓ_0 = .04 cm. Each of the calculations was carried out to the time-of-arrival of the shock wave without precursor: these ranged from ~0.7 sec to ~3.0 sec. Properties of the soil at earlier times corresponding to the arrival of a shock precursor were also available.

Material properties of the soil were selected to correspond to "Quartz Sand" of Figure 1, initially containing a water volume fraction, $X_w = 0.07$. The thermal radiation source was calculated from the prescription of Section 2.2, which approximates the results of the RECIPE Code. The radiation source was reduced to account for effects of surface albedo and transmission through the atmosphere and lofted dust. Each of these factors was assumed to be constant (although it is expected that they will change during the course of the interaction). The albedo (= 0.25) was taken from the work of Carpenter. This value is typical of undisturbed light soils. Thermal layer transmission was estimated from the experimental data of Versteegen, (*SAIC Flash Lamp Tests*, in Proc. of Thermal Layer Review Meeting, October 18, 1984). Making use of his calorimeter measurements for Yucca soil, we assume that about 0.5 mean-free paths of attenuation are present in the atmosphere of the flash lamp test cell. Since the radiation is substantially normally incident in this case, a greater attenuation may be expected in the burst geometry at larger ground ranges. Consequently, we employ a time-independent thermal layer transmission factor, $T = \exp(-0.5\ R/h)$, where R = slant range, and h = HOB. Clearly, more information is needed to clarify the dependence of flux-reducing factors on system parameters.

Incorporating the above parameters, calculations were carried to the time of shock arrival for a series of ground ranges. The peak surface temperature achieved during the calculation, and corresponding time of peak temperature, are shown as a function of ground range in Figure 2. At GR = 3000 ft the peak temperature is still rising rapidly at the end of the calculation (0.7 s), while at the largest ground ranges, the temperature is falling slowly. These results show a rapid decrease with ground range primarily due to the assumed decrease of transmission and, perhaps, are representative of a weak precursor case.

3.2 ANALYTIC FITS.

The peak temperature (T_{MAX} with units of °K) can be represented analytically as a function of ground range (GR with units of ft) with excellent accuracy by

$$T_{MAX} = 300 + 2400 \exp\left[-\left(\frac{GR - 2500}{3140}\right)^2\right] . \tag{6}$$

In Figure 3 we show profiles of the soil temperature at the times of ideal shock arrival for several values of ground range. These profiles are characterized by a rapid decrease from the peak in a depth of < 1 mm. At the water boiling temperature, they show a transition to a much more slowly decreasing curve. For convenience in incorporating these results into hydrodynamic calculations, we have obtained analytic expressions approximating the curves of Figure 3. The fit consists of two branches:

$\underline{T > 373°K}$

$$T = \frac{(1+F)\ T_{MAX}E}{1+FE^4} \quad . \qquad (7a)$$

where

T_{MAX} = Peak surface temperature as a function of GR given by Eq. (6),

F = $0.8/(1 + 2 \times 10^{-4}$ GR),

E = exp [- 1.1×10^5 z /(1000 + GR)],

GR = ground range (ft),

z = soil depth (cm).

$$T \leq 373°K \qquad (7b)$$

$$T = 300\ °K + 73° exp(-(z - z_o)\ /\ D)\ ,$$

where

$$z_o = 0.17/(1 + 2.5 \times 10^{-4}\ GR),$$

$$D = .05 + .021\left(\frac{GR}{3000}\right)^2 \ .$$

The flash lamp experiments of SAIC show evidence of surface melting of the soil samples. This is suggestive that the surface has achieved at least a temperature in the range of 1000-1500 °K. In order to compare with the SAIC data, we calculated several cases in which the obliquity of the thermal radiation was neglected in the transmission function and the source deposition. The soil thermal radiation absorption coefficient retained the value, ℓ_o = 0.04 cm, used in previous calculations. At GR = 7000 ft (corresponding to the SAIC simulation), the resulting surface flux is ~ 28 cal/(cm^2 s). We also used several values of the soil water volume fraction, X_w, and obtained the following peak surface temperatures:

X_w	T_{MAX} (°K)
0.035	1385
0.07	1318
0.14	1215

The peak temperatures display a weak dependence on soil water in this range.

The surface temperatures obtained in all of these cases are comparable with the minimum temperature indicated by the data. There are several effects which, in fact, should result in higher calculated temperatures.

1. The peak flux attributed by SAIC to GR = 7000 ft [> 85 cal/(cm^2 s)] is substantially larger than that given by the source prescription (59 cal/cm^2 s) used in the calculations.

2. We may have reduced the flux too much by assuming both an albedo and a transmission factor.

3. The mean-free path may be significantly smaller than the selected value.

Assuming that the peak surface flux (for a soil like the Yucca Flats sample) should be approximately the observed 48 cal/cm2 s, we should have increased the flux by almost a factor 2. This would increase the peak surface temperature to approximately 2000°K.

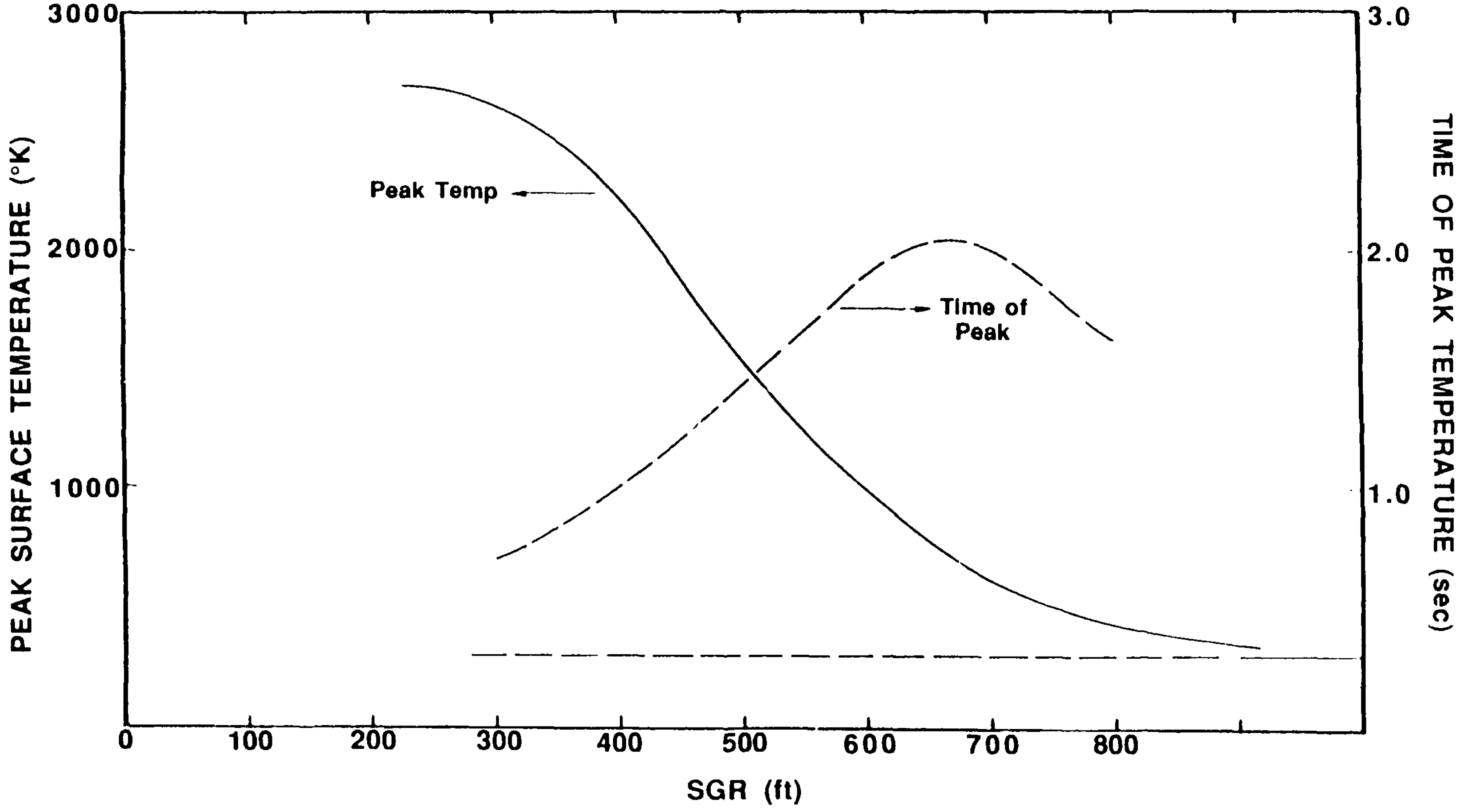
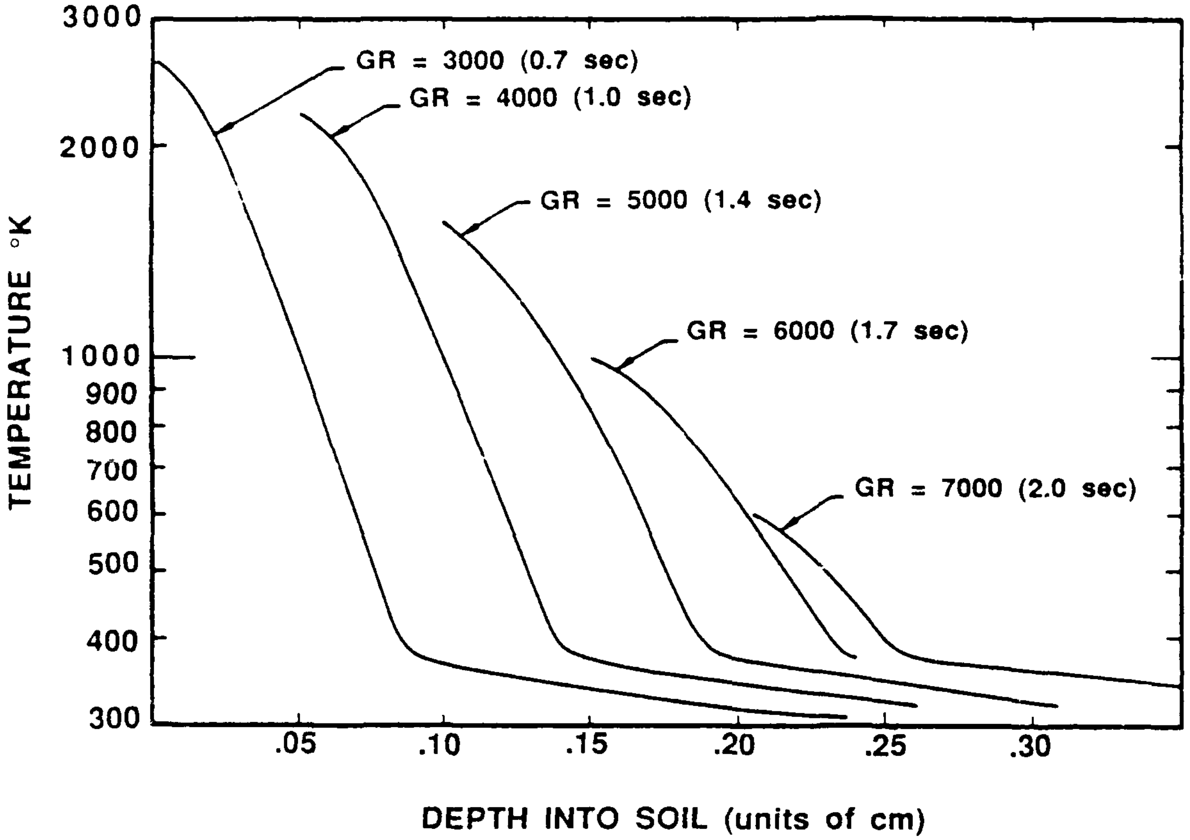


Figure 2. Peak surface temperature *versus* ground range (left scale) during the calculation of surface thermal irradiation by a 1 MT explosion at HOB = 2000 ft. Corresponding time of peak surface temperature (right scale).



NB: For clarity, each curve is displaced from that of the next smaller ground range by z = 0.05 cm.

Figure 3. Profiles of soil temperature for selected ground ranges from a 1 MT explosion having HOB = 2000 ft. Corresponding TOA's are in parentheses.

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