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UWFDM-233

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# Surface Damage and Thermal Effects from Transient Thermonuclear Radiation in Inertial Confinement Fusion Reactors

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Presented at the

3rd International Conference on Plasma Surface Interaction in Controlled Fusion Devices

UKAEA Culham Laboratory

Abingdon Oxfordshire UK

3-7 April 1978

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Work partially supported by U.S. Department of Energy.

Abstract

A general model for transient deposition of thermonuclear radiation has been developed and applied to calculate the response of copper to a reference spectrum typical of laser fusion reactors. At 7 meters from a 100 MJ pellet, temperature excursions of approximately 700°C above the ambient temperature are noted for both photons and ions, occuring 0.02 and 2 microseconds after the thermonuclear burn respectively. Total displacement rates approach 100 dpa/sec at the surface and 500 dpa/sec at 1 micrometer into the copper. Filling the chamber with Ne at 0.5 Torr was found to be sufficient to reduce the temperature excursion in copper by 50% and the dpa rate at the front surface by 25%. The combination of surface temperature transients and ion bombardment were found to increase the sputtering yield by a factor of 6 over ambient temperature values indicating that previous calculations may have seriously underestimated the sputtering damage in laser fusion first walls.

## INTRODUCTION

Recent successes in the physics of pellet implosion have led to the first conceptual fusion reactors based on the inertial confinement approach.[1,2] Such studies have highlighted not only the physics problems of coupling high intensity laser light, energetic electron beams or high energy heavy ion beams to the pellets, but the technological problems of converting the thermonuclear energy to useable heat as well. One problem, in particular, has been common to all of the designs; the requirement that materials directly facing the plasma withstand high intensity pulses of energy from the pellet. The radiation damage environment associated with the repetitive exposure to photons, unburnt fuel (D,T), reaction products (neutrons and helium atoms) and other pellet debris (C, O, Si, and high Z elements such as Au, Hg, etc.) represents a truly unique problem never before faced by scientists.

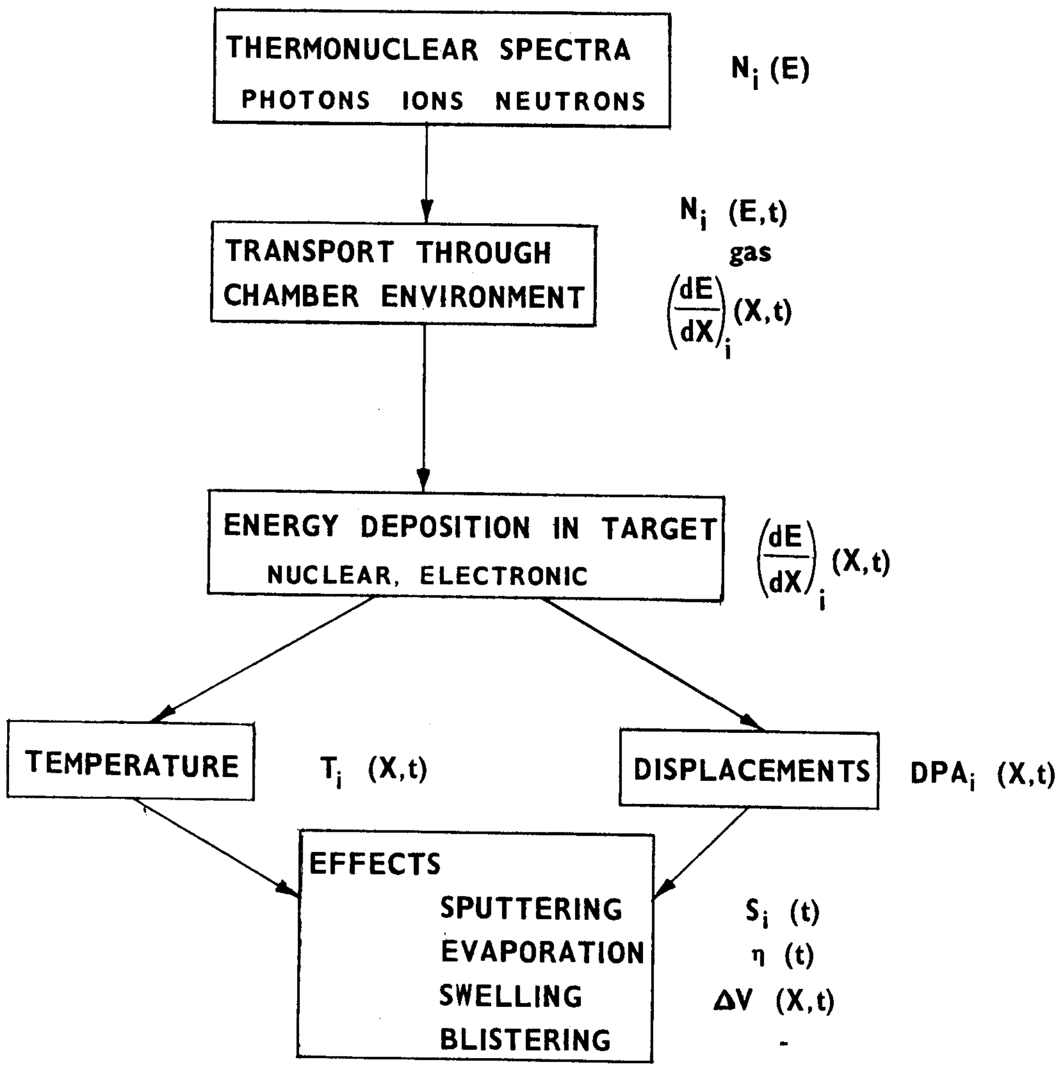
The object of this paper is to analyze this damage process, component by component, in order to clearly establish both the magnitude and chronology of transient temperature and displacement rates that might be experienced by a typical solid component in a laser fusion reactor (e.g., first wall, last mirror, diagnostic equipment, etc.). We have combined several models of radiation damage to calculate the material response to a transient flux of photons or ions with arbitrary energy spectra into a computer code called T-DAMEN [3] and the results will be discussed in the following sections.

## Method of Analysis

The analysis methodology used is outlined in Figure 1 and it begins with the specification of the output spectra from the pellet microexplosion. These various components consist of reflected laser light, X-rays, neutrons,

FIGURE 1

TRANSIENT DAMAGE ANALYSIS



ions from unburnt fuel, reaction products and pellet materials. Each component will transit the reactor chamber and impact the surface of the exposed material at different times and with different energies. In cases where protective mechanisms, such as magnetic fields or gas layers are employed, the spectra and flux will be altered upon arrival at the exposed surface. In a gas filled cavity, a significant portion of the energy can be deposited in the gas, thereby initiating a shock wave and causing a much different spectra to be incident on the wall than was found near the surface of the pellet.

Upon determination of the flux, spectra, and impact time of the various species at the exposed surface, the spatial distribution of deposited energy must be determined. These distributions are partitioned into nuclear or electronic deposition rates commensurate with each component of the spectrum.

Such energy deposition rates then become the driving forces for large temperature excursions which occur simultaneously with high damage production rates at the front surface. The synergism of these phenomena can result, as we shall see later, in significant modification to the damage rates in fusion devices; e.g., sputtering, blistering, evaporation, and swelling.

Subsequent sections will describe the specific modeling used in this analysis in more detail and present the results for the response of a copper surface at 7 meters exposed to a "typical" pellet spectrum. The choice of copper is arbitrary but it could be considered as a last mirror or part of some diagnostic equipment.

## Output Spectra

The composition and distribution of energy from a single microexplosion varies considerably depending on the pellet design and desired yield. We have chosen a simple reference spectrum typical of a low yield bare DT pellet [4] with the addition of a higher Z component, Si, to simulate the pellet coating and demonstrate the effect of higher mass in the damage process. The response of an exposed surface is extremely sensitive to the details of these spectra and the reader should view the results of this work only in a very general sense. When more detailed pellet designs are generally available to the public all the principles included in T-DAMEN can be applied equally well giving more specific results.

The spectrum chosen for this work (see Figure 2) has a total energy of 100 MJ of which 77 percent is in neutrons, 2 percent in X-rays characterized by a 1 KeV black body, and the balance distributed between reaction products, unburnt fuel, pellet material, and reflected laser light. The helium distribution is chosen to be bimodal with a high energy component and a thermalized component even though in practice there is likely to be a more complex coupling between the down scattered spectra.

Transport to the Exposed Surface

Each ion or photon component will arrive at the exposed surface at different times resulting in varying fluxes. These fluxes are shown in Figure 3 after transiting 7 meters of a vacuum for each of the components in the spectrum. Calculations were also performed for the modification of the spectra and fluxes if the chamber were filled with 0.5 Torr of neon but they are not repeated here for sake of brevity. The neutron flux is assumed to be unaffected by the gas layer and the photons from the source are not shown but they arrive at about 23 ns after thermonuclear burn. It is assumed that the time of the X-ray production is very short compared to the cavity transit time, hence an impulse model is used for deposition and response. Laser light is assumed to be deposited over a period of 10 ns.

FIGURE 2

## REFERENCE PELLET ENERGY SPECTRA

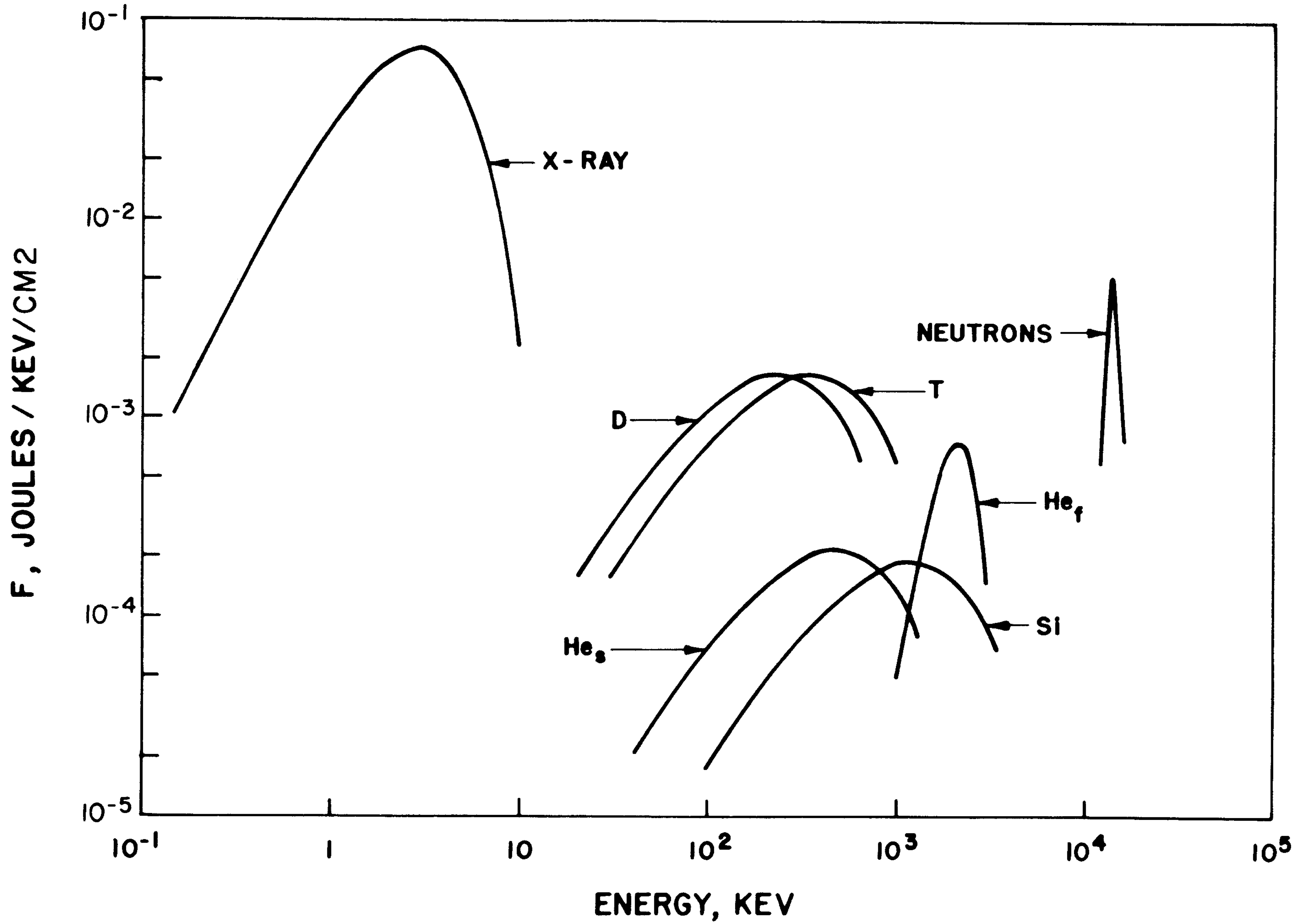
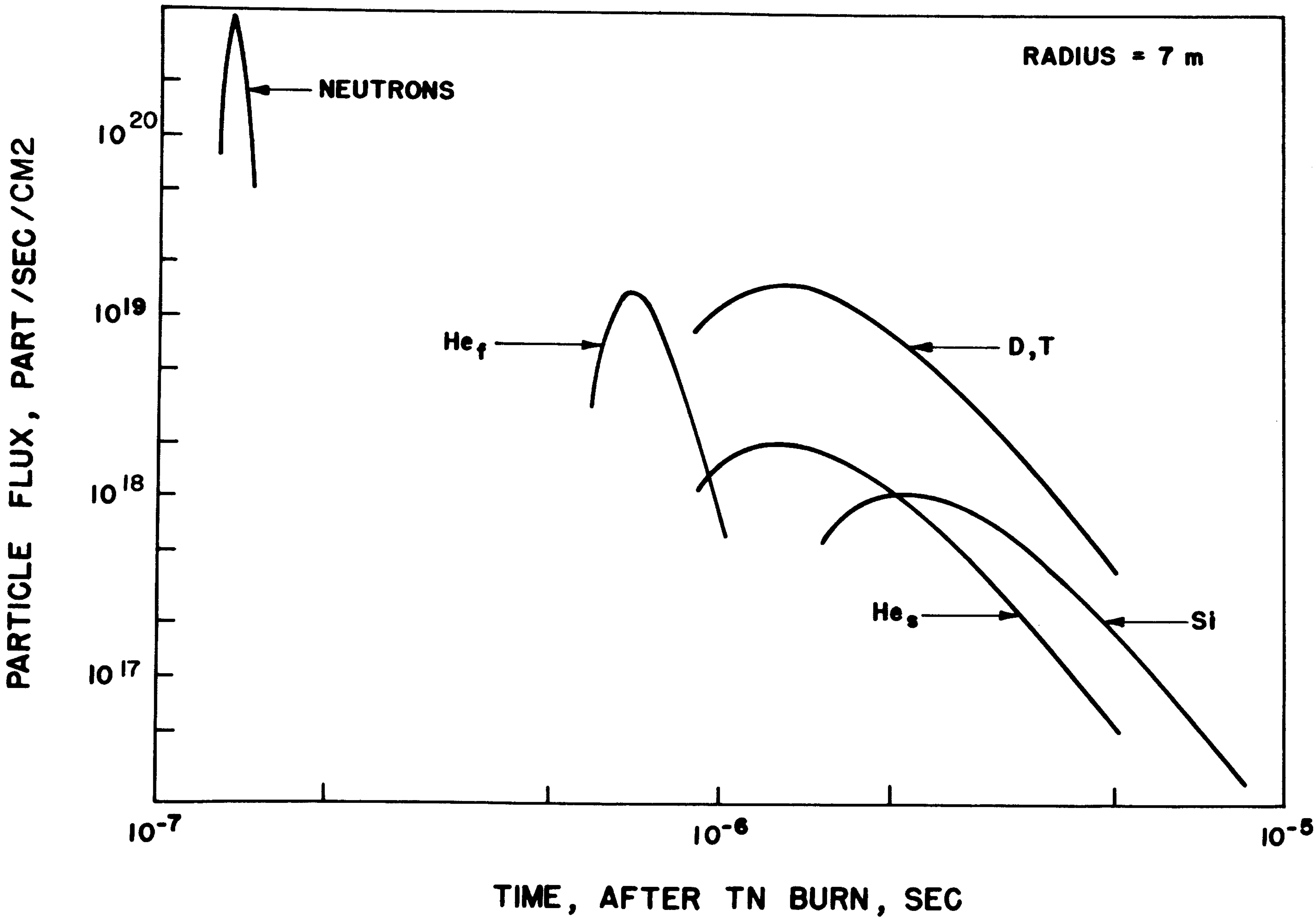


FIGURE 3

# PARTICLE FLUX TO EXPOSED SURFACE



The modification of the spectra due to the presence of an intermediate gaseous layer is based on a diffusion approximation to ion transport in continuous media. [5] This model allows for a simple estimation of ion spatial distributions at intermediate energies between the pellet and the copper surface from which the flux and spectra at any position can be determined.

## Energy Deposition

Each component will deposit its energy by an appropriate distribution between nuclear and electronic processes. In our model we assume photon absorption by photoelectric or incoherent scattering processes. For light ions the model accounts for electronic stopping power both in the low energy region where stopping power increases with energy and at high energies where the converse applies.

All ion spatial energy distributions are processed into a standard polynomial form whose energy dependent coefficients are analogous to cross sections used in transport processes. In the case of heavy ions these cross sections are derived from processing the result of the ion implantation codes developed by Brice. [6] This formulation allows for partitioning between electronic and nuclear processes and accounts for redistribution of energy at the front surface due to PKA recoil.

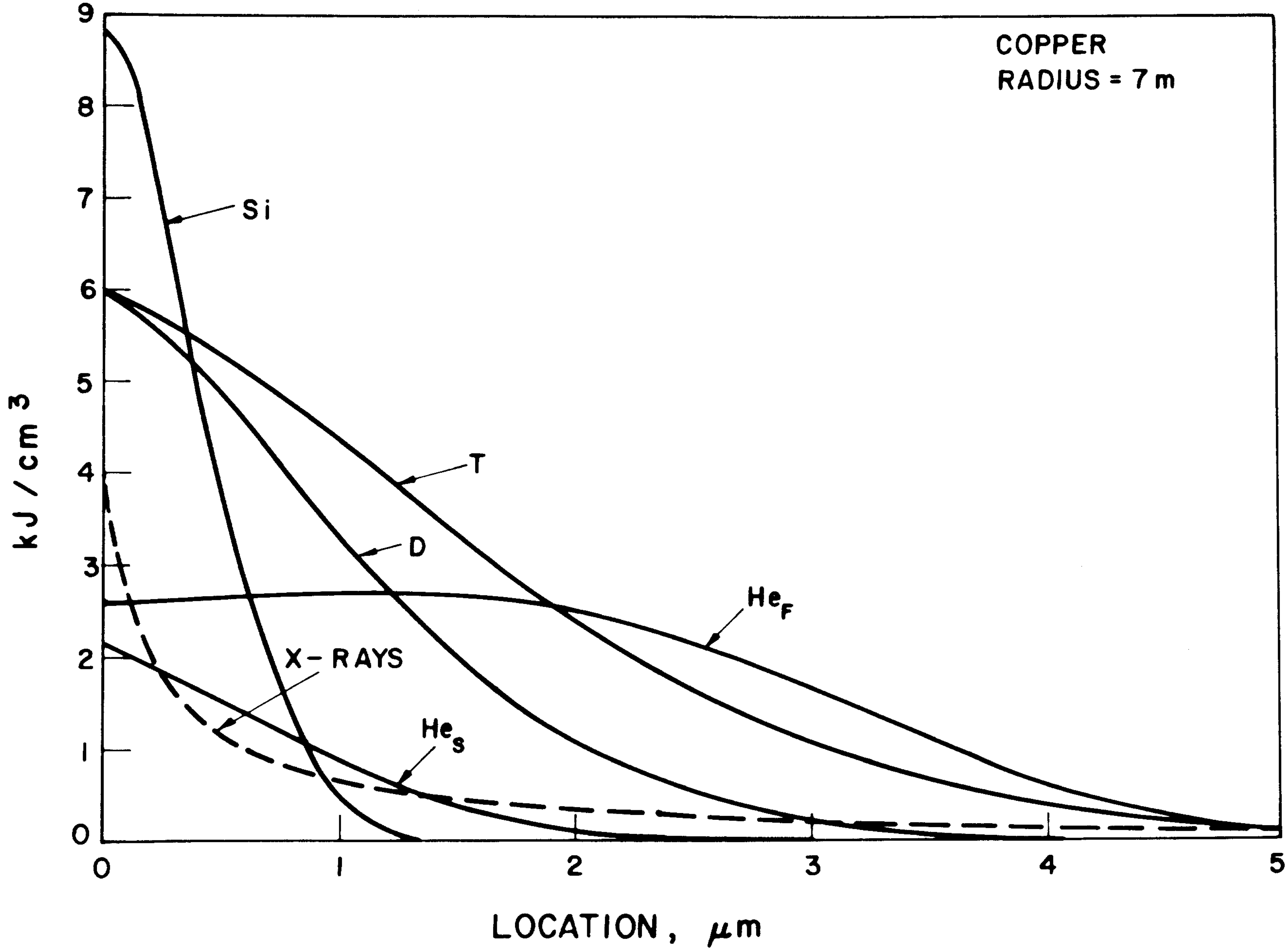
The time integrated spatial distribution of deposited energy for each component in the reference spectrum is shown in Figure 4. The time history for each component is proportional to the flux displayed in Figure 3.

## Surface Temperature Response

With the models developed in this study the temperature response can be evaluated at any position in the exposed material for each component of

FIGURE 4

TOTAL DEPOSITED ENERGY



the radiation spectrum. A superposition technique can then be used to evaluate the response to the total spectrum.

The temperature analysis is based on the formulation of the spatial form of the deposition in terms of energy dependent polynomials for ions and exponentials for photons. The heat conduction is then solved by a Green's function technique for an arbitrary deposition. The solution is obtained by evaluating the spatial contributions of the forcing function analytically while the temporal contribution is integrated numerically to allow arbitrary specification of spectra. [7] The equilibrium temperature after any number of pulses can also be evaluated using the same deposition formulation and an eigenvalue solution with a Laplace transform technique.

Results of the temperature response of the exposed surface of copper at 7 meters are shown in Figure 5. The dominant response for this spectrum at early times is due to the X-ray component but this temperature falls significantly before the arrival of the ions. The temperature increase due to each ion is observed to peak, then subside during the time interval of energy deposition as energy is escaping by conduction faster than it is being deposited. The fact that the helium component yields the maximum response is primarily due to the shorter time duration of the deposition.

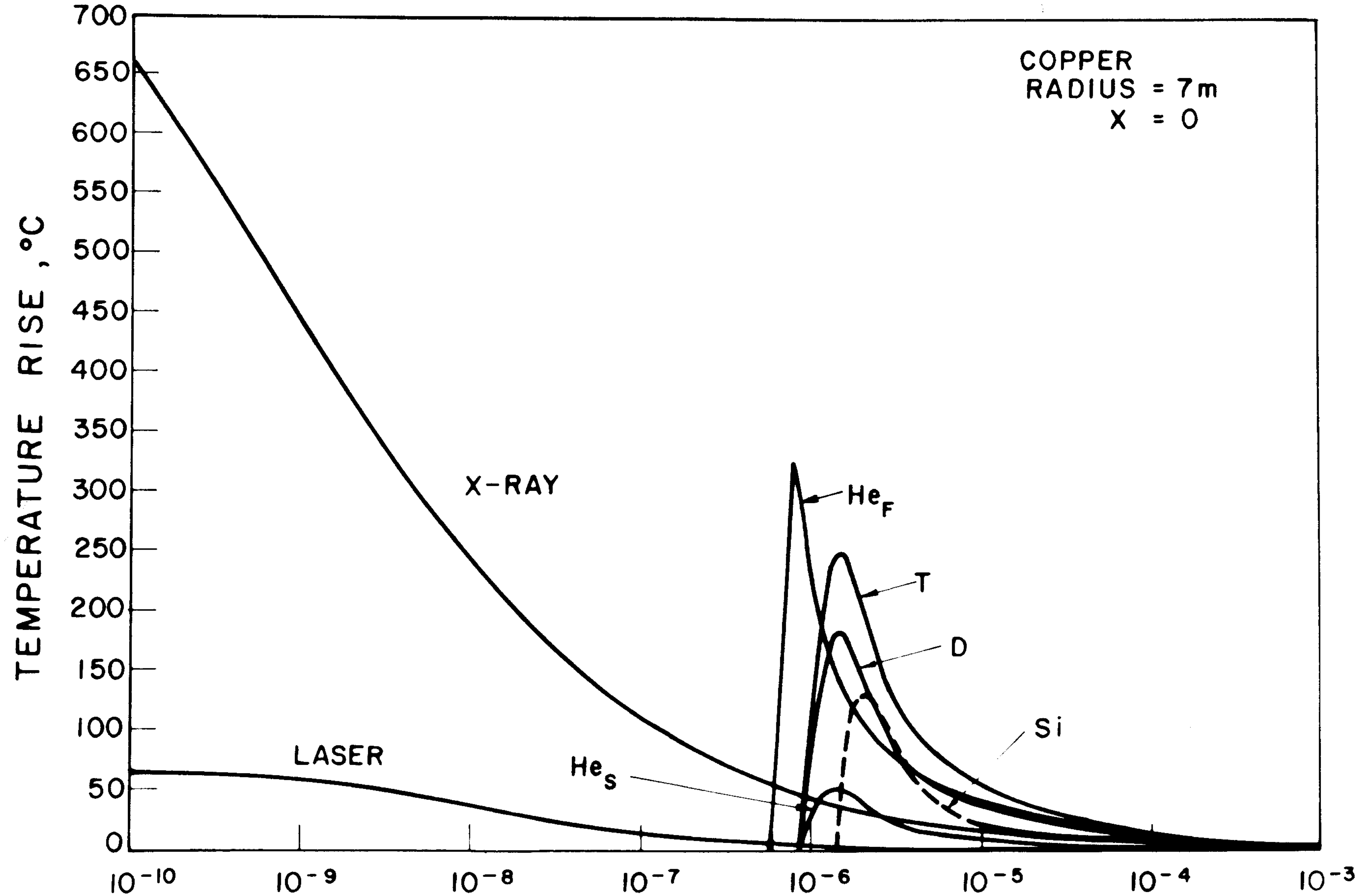
The total thermal response from all components is given later in Figure 8 and shows that the maximum temperature excursion due to all the ions is equivalent to that of the photons.

Displacement Response

The flux history can be combined with the slowing down properties of light ions and with a local displacement cross section based on the energy of the ions to provide the displacement production at any position in the

FIGURE 5

## COMPONENT TEMPERATURE RESPONSE




TIME AFTER X-RAY ARRIVAL, sec

material. Our model provides for a cross section based on the theory of Lindhard, [8] et al., (LSS), or a modified Rutherford interaction incorporating electron screening [9]. For heavy ions ($Z > 2$) the displacement responses can be determined from the spatial form of the nuclear energy deposition and a modified Kinchin Pease defect production model.

The displacement production rates for each of the radiation components are shown in Figure 6. In this case the damage is dominated by the heavy ion, Si. The peak damage production from the neutrons is due to the source neutrons and is significantly lower than the other components. Transient neutronics calculations [10] reveal that the contribution of the backscattered flux is at a much lower rate and accounts for only 30-40% of the total displacements due to neutrons.

The composite spatial distribution of displacement damage per pulse for all the radiation components is shown in Figure 7. The peak of $10^{-3}$ dpa at approximately the 0.5 micron depth is due to the silicon ions while the lighter, more penetrating ions yield $10^{-4}$ dpa per pulse for several microns from the surface.

The relation between surface temperature excursion and displacement production is displayed in Figure 8. At 1 micron depth the maximum dpa rate is about 500 dpa/sec but is shorter in duration. The damage is produced during a period of large temperature transients which will result in a significant alteration of both point and clustered defect behavior.

The effect of the addition of 7 meters of neon at 0.5 Torr between the pellet and the surface is shown in Figure 9. The modification of the spectra and arrival times for both ions and X-rays results in a 50% reduction in temperature excursion at the surface. The same amount of chamber gas

FIGURE 6

COMPONENT DISPLACEMENT RATE

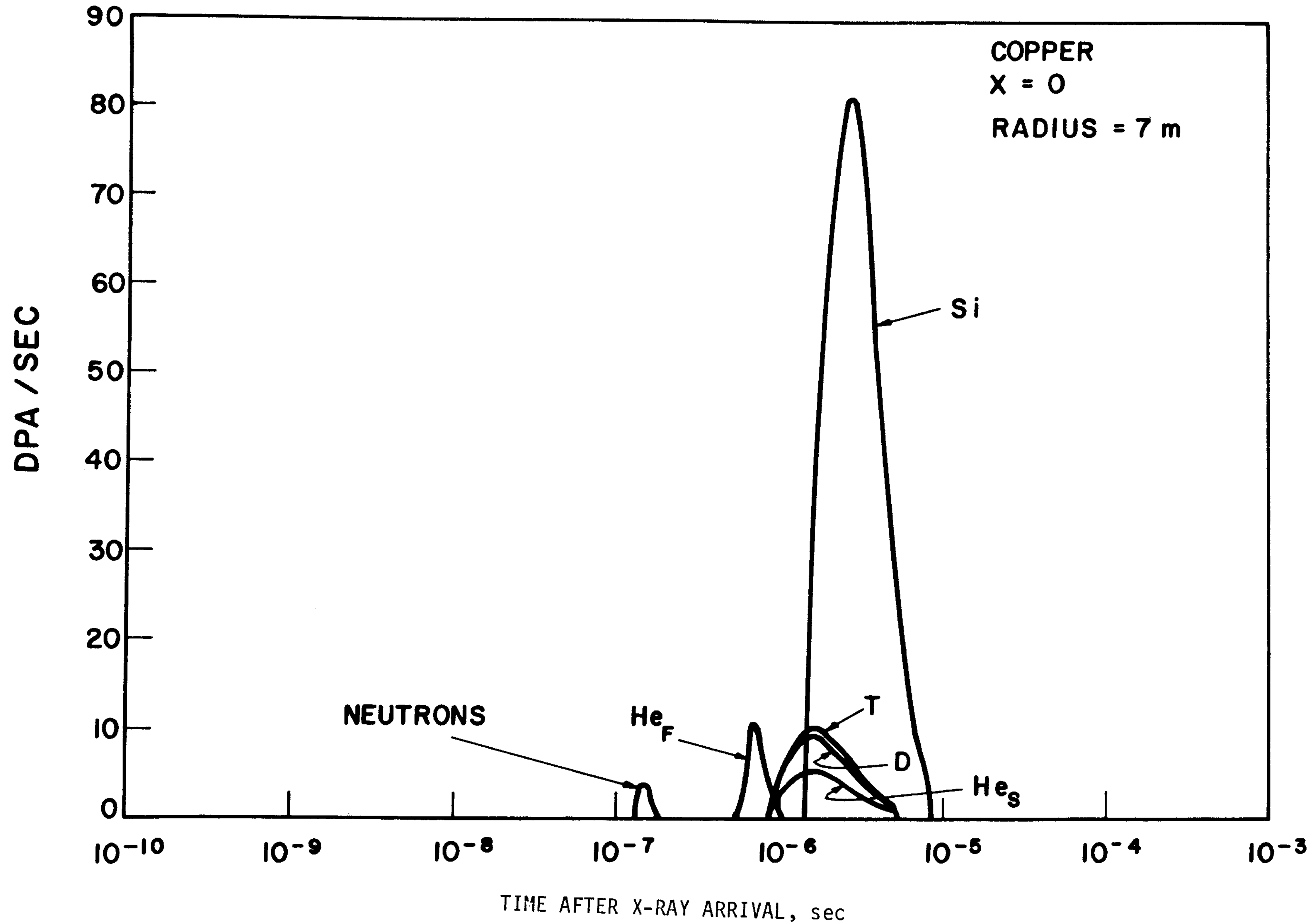


FIGURE 7

SPATIAL DISTRIBUTION OF DISPLACEMENT DAMAGE PER PULSE

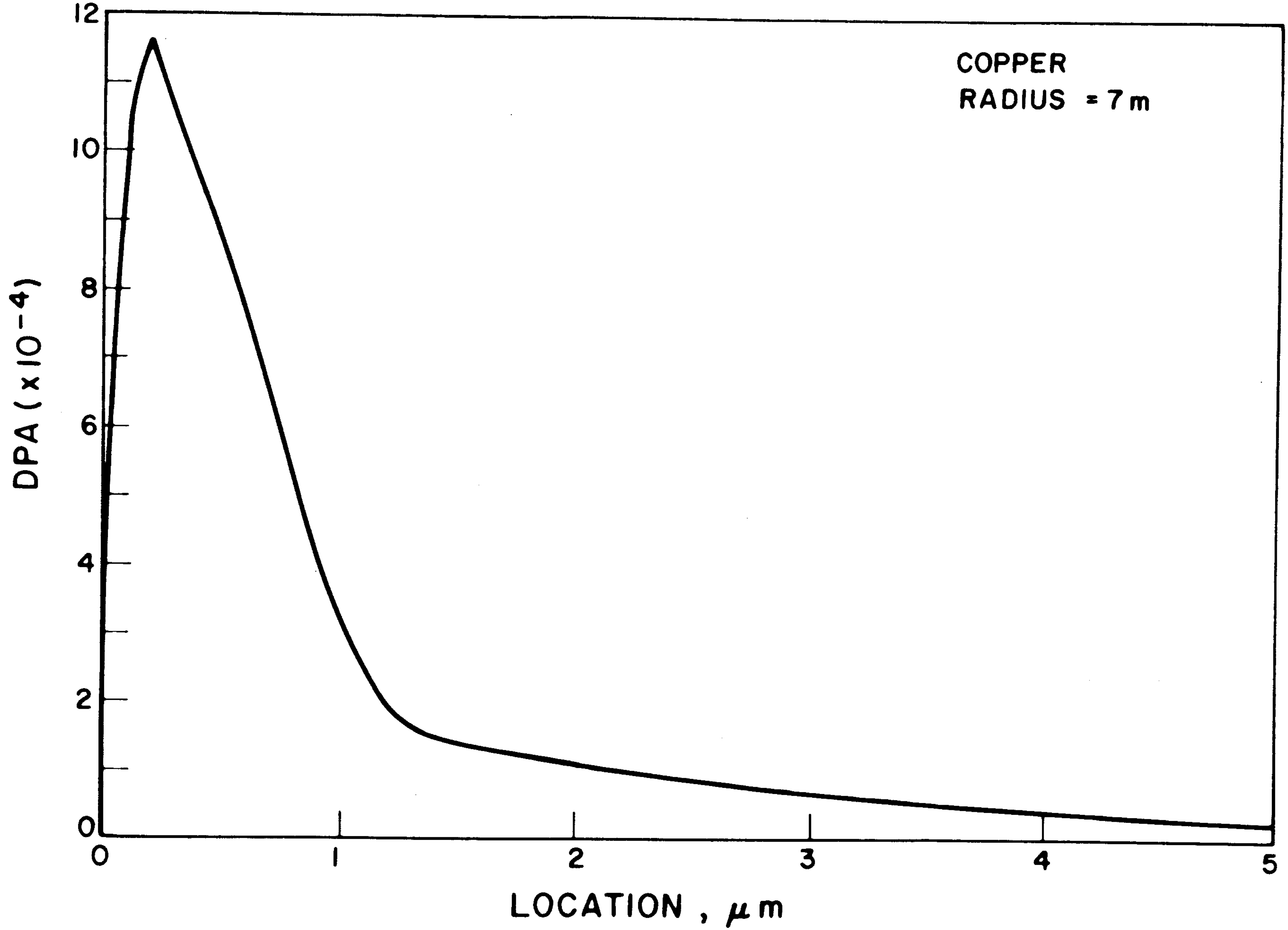


FIGURE 8

TEMPERATURE AND DISPLACEMENT RATE

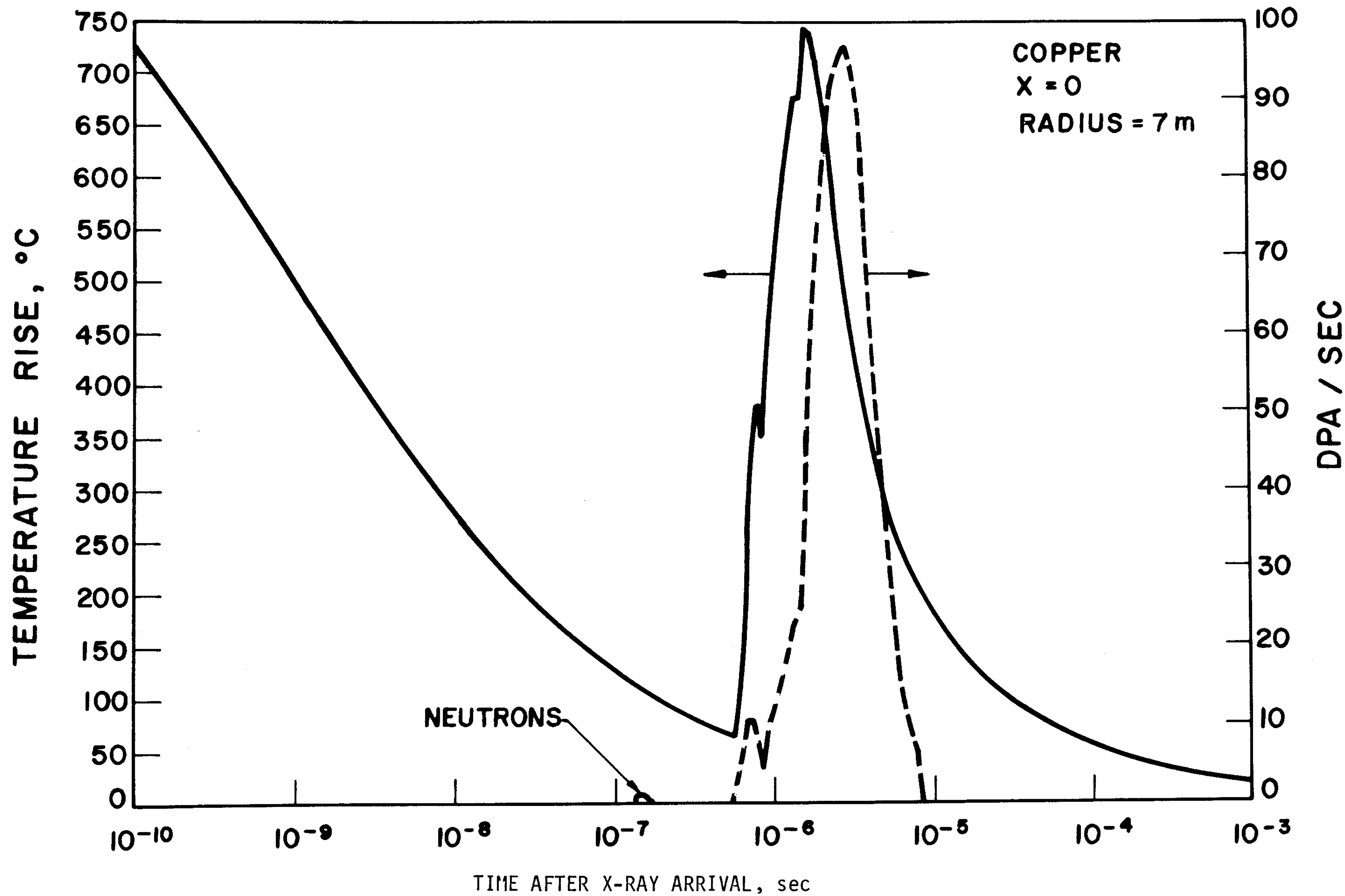
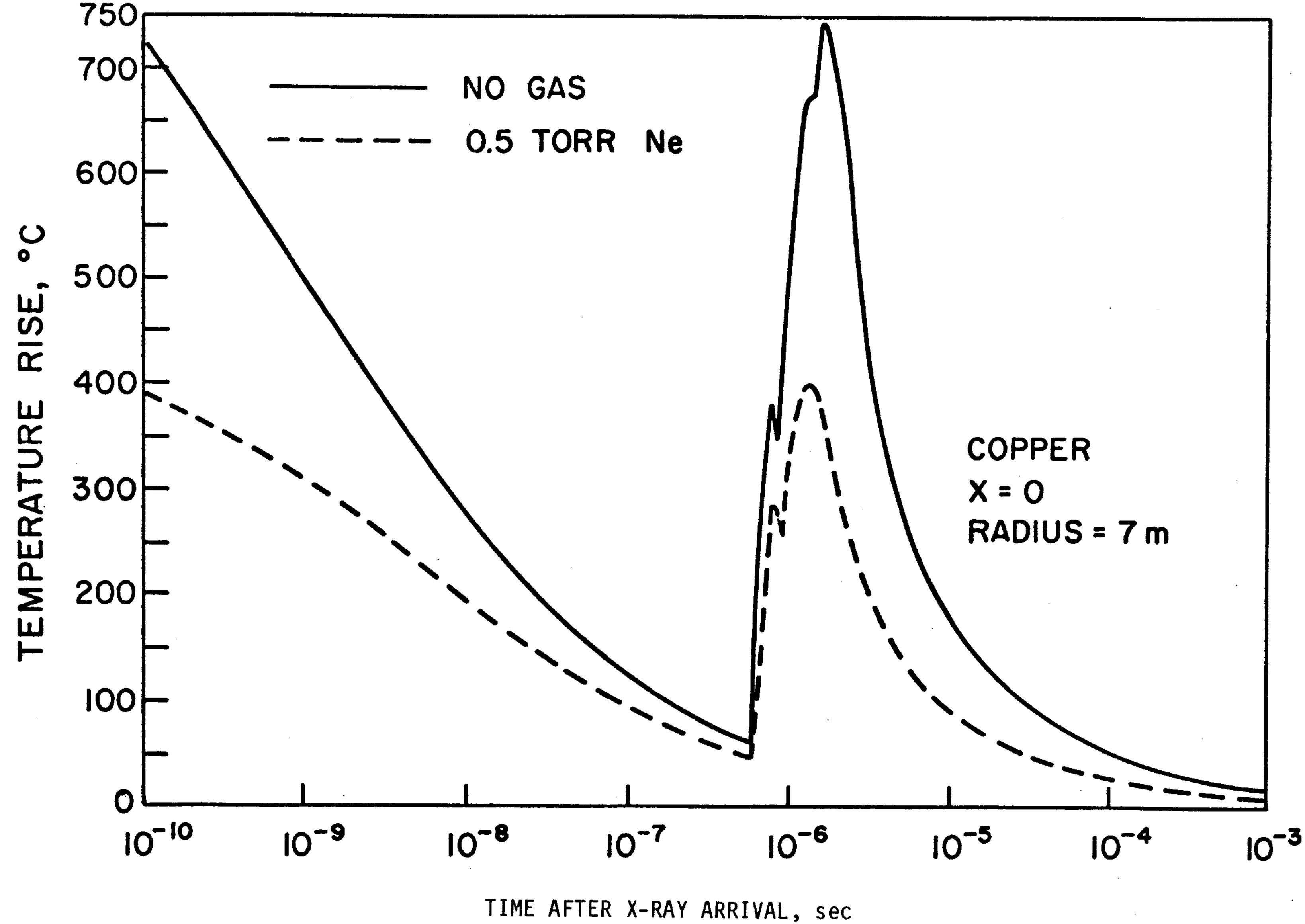


FIGURE 9

EFFECT OF CHAMBER GAS ON TEMPERATURE



results in only a 25% reduction in dpa rate at the surface but at the 1 micron depth the displacement rate is significantly reduced due to the elimination of the higher energy ions in the silicon spectrum.

The displacement rates observed in this example reveal the departure from standard radiation environments which are encountered in inertial confinement fusion. In addition to the temperature excursions, displacement rates for unprotected walls are noted to range from 10 dpa/sec to 1000 dpa/sec which should be compared with $10^{-6}$ dpa/sec in fission and magnetic confinement fusion devices and $10^{-4}$ to $10^{-1}$ dpa/sec in electron and ion simulation devices.

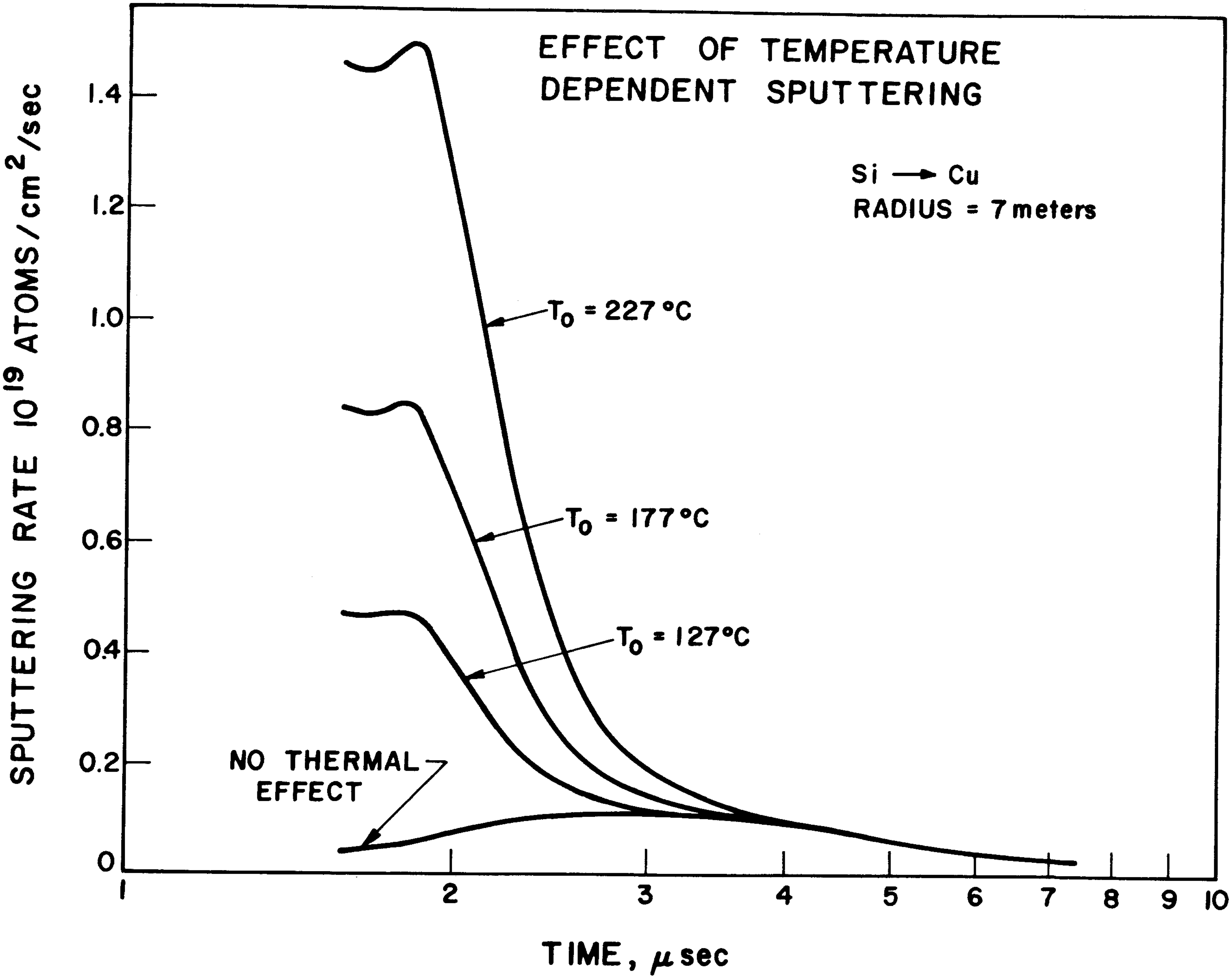
## Effects

### Sputtering

The combination of high ion fluxes and large surface temperature excursions may result in a modification of the sputtering rate observed in constant temperature ion bombardment. In this analysis we have allowed the sputtering rate to be a function of surface temperature. Data for this effect are developed from the work of Nelson [1] in assessing the role of "thermal spikes" on sputtering. In general, Nelson found that the sputtering ratio for heavy ions increases from values near 1 at room temperature to ~30 at 90% of the melting point. The surface temperature increase from the previous analysis can then be combined with the particle arrival flux and spectra to determine the temperature dependent sputtering rate. Figure 10 shows the effect of this analysis for the sputtering of copper due to the silicon ions at various ambient temperatures.

At an ambient temperature of 227°C the total sputtering yield due to the silicon ions was $1.5 \times 10^{13}$ atoms per pulse or a 0.0174 Å per pulse erosion when the surface temperature effect is considered. For a 1000 $MW_t$ reactor operating at a 80% plant factor, this would correspond to surface erosion rates of .439 mm per year. This is in contrast to about 0.00481 Å per pulse and a wall erosion rate

FIGURE 10


EFFECT OF TEMPERATURE
DEPENDENT SPUTTERING
Si → Cu
RADIUS = 7 meters
T0 = 227 °C
T0 = 177 °C
T0 = 127 °C
NO THERMAL EFFECT
SPUTTERING RATE 10^19 ATOMS/cm^2/sec
TIME, μsec
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1
2
3
4
5
6
7
8
9
10

of .121 mm per year when the sputtering is based on ambient temperature only. This comparison indicates that previous sputtering calculations which do not consider the surface temperature may have seriously underestimated the wall erosion rates in inertial confinement systems.

Blistering

In contrast to typical blistering experiments in which the implanted helium distributions are due to monoenergetic ions, the helium atom distributions in inertial confinement systems are determined by all the energies of the ion spectra arriving at the front surface. In addition, the helium atoms come to rest in regions of high lattice distortion which are subject to high temperature fluctuations for about 10 microseconds.

Our analysis allows the determination of the approximate implantation distribution, the damage distribution, and the spatial temperature profile from an arbitrary spectrum of ions. The implantation distributions from the reference spectra which contains a fast and a thermal component are not shown but were found to have peak concentrations of $2 \times 10^{16}$ atoms/cm$^3$ located approximately 1 micron into the copper for each pulse.

The severity of blistering in these environments can be estimated from the data of Bauer and Thomas [12] who have reported significant increases in the re-emission in niobium at fluences of approximately $10^{18}$ He ions/cm$^2$ at 300 KeV. Ignoring the difference between copper and niobium and assuming their data are indicative of spallation thresholds, our calculations indicate that equivalent peak concentrations will be achieved in a laser fusion device after about 80 hours at 1000 $MW_t$. This concentration is achieved, however, after a fluence which is about 10 times greater than required for a monoenergetic spectrum due to the width of the He spectra.

## Conclusions

This analysis revealed that the radiation damage environment in inertial confinement fusion systems is significantly different from their magnetic confinement counterparts. Large temperature excursions accompany the rapid deposition of energy by ions and photons. The displacement rates associated with ion deposition can be as high as 1000 dpa/sec at near surface locations.

The synergism of high damage rates and high temperature transients can enhance the sputtering considerably. Increases in sputtering yields of factors of 6-8 over the ambient temperature calculations were observed in copper. In addition, significant evaporation can be produced at temperatures from 70 to 100% of the melting point.

Conditions for development of blistering are also different in the transient case since high dpa rates and large temperatures are observed in the helium implantation zone. The nucleation and growth of clustered defects such as loops and voids will also be altered by annealing due to large temperature excursions during the periods of damage production.

All these effects can limit the life of components which are exposed to the radiation transients. These effects can however be mitigated by the use of protective mechanisms such as gas protection or magnetic fields. Our analyses reveal that significant reduction in both temperature excursion and displacement damage can be provided by gases such as neon at pressures considerably below that required to stop all ions released from the pellet.

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