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T.O. Hunter, S.I. Abdel-Khalik and G.L. Kulcinski

Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

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T.O. HUNTER*
S.I. ABDEL-KHALIK
G.L. KULCINSKI

Fusion Research Program
University of Wisconsin
Madison, Wisconsin 53706

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Madison, Wisconsin 53706
U.S.A.

*Member Technical Staff, Sandia Laboratories, Albuquerque, New Mexico 87115

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ABSTRACT

A self consistent analysis of the temperature and displacement histories of inertial confinement fusion reactors first walls was performed. The output spectra from two specific pellets were considered: a bare DT pellet and a structured pellet with a mercury shell surrounding the DT fuel. Results for molybdenum and carbon are presented. Temperature excursions of 2000°K and displacement rates as high as 30 dpa/sec are observed at the front surface of the Mo first wall over a period of 10-20 microseconds following each microexplosion.

Introduction

Inertial confinement fusion reactors (ICFR) produce a unique environment in which materials used for first walls, mirrors, liners, or other components must operate. The pulsed thermonuclear source creates intense radiation fluxes which subject these materials to large energy deposition and radiation damage transients. These transients can induce numerous subsequent responses such as temperature excursions, thermoelastic stresses, and atomic displacements.

The development of analytical tools to assess the effect of transient radiations has played a significant role in conceptual design effort for ICFR's. This paper presents a specific application of some of these models to the performance of candidate materials bombarded with typical pellet output spectra. The objectives of this analysis are to:

(1) Determine the response of unprotected dry walls to thermonuclear radiation from different pellet designs,

(2) Assess synergistic damage in Mo and C and the relative contribution of different radiation components, and

(3) Identify those problem areas requiring further investigation.

Response Models

This analysis is primarily concerned with the determination of the temperature and displacements transients associated with first wall materials. Models have been developed to provide the temporal and spatial variations of these responses for arbitrary radiation spectra.[1-3] These spectra consist of various combinations of photon, ion, and neutron radiation.

The temperature response and associated stress wave generation could have been determined by a combination of various energy deposition codes and material response hydrocodes.[4] These combinations, although quite useful in treating phase changes, and other material nonlinearities, are sometimes awkward and limited in the flexibility of output form. They may also contain significant approximations about absorption processes and can have difficulty in the coupling of phenomena with grossly different spatial extent or time dependence.

In this analysis a different methodology was adopted. A model was developed which incorporates the deposition and response processes so that efficient results are obtained without the complexities and numerical cost of combining large computer codes. This approach allows flexibility in determining the sensitivity of the response to variations in spectra and material properties.

The input to the models is a description of the output spectra from the microexplosion. From these energy spectra the time dependent fluxes may be established at the exposed surface of a material. The energy dependent depositions are then developed for either photon or ion species.

Photon absorption is based on photoelectric and incoherent interaction processes for X-rays or on classical absorption for laser light. Ion deposition is based on either a detailed formulation of the slowing down processes for light ions ($Z \leq 2$) or on the results of ion implantation calculations for heavier ions. For light ions consideration is

given to both high energy and low energy effects. For all ions the deposition functions are transformed into a standard spatial form which is compatible with the temperature response model.

The resulting solutions are closed-form expressions which require only integration over the loading fluxes to incorporate arbitrary spectra. The linearity of the models allow superposition of the response for numerous components. This formulation allows determination of the temperature at any time or location independent of any discretization of space or time.

Displacement transients are derived by determining for each ion species an effective local displacement cross section based on either a binary Rutherford collision model or a nuclear interaction model after Lindhard, et al.[5]

The details of these models are recorded in references 1 thru 3 and are incorporated into a general computer code (T-DAMEN) at the University of Wisconsin.

Application to Specific Pellet Spectra

In this analysis the response models were applied to two radiation spectra which were characteristic of calculations done elsewhere.[6] They represent the mix and proportions of components typical of a bare (D & T only) and a structured (D,T + heavy outer shell) pellet. The spectra chosen are given in Table 1. Several functional fits (e.g., black-body, Maxwellian, Gaussian) to the pellet output spectra were made. The bare pellet output consisted of a small fraction of X-ray output with the remainder of the non neutronic

Table 1

CHARACTERISTIC PELLET SPECTRA (150 MJ)

	Bare Pellet		Structured Pellet	
	ENERGY (MJ)	SPECTRUM	ENERGY (MJ)	SPECTRUM
LASER	0.15	10.6 μ	0.15	10.6 μ
X-RAY	1.5	2 kev-BB	14	20 kev-BB
D	9.5	340 kev-M	0.13	15±9 kev-G
T	12.9	465 kev-M	0.19	20±9 kev-G
He (SLOW)	1.9	240 kev-M	0.25	30±10 kev-G
He (FAST)	6.6	2.4±0.6 Mev-G	---	---
MERCURY	---	---	14.8	3±1 Mev-G
NEUTRONS	120	14±1 Mev-G	120	14±1 Mev-G

BB = Black Body; M = Maxwellian; G = Gaussian

energy carried by the reaction products and the pellet debris. The structured pellet spectra consisted of a large fraction of X-ray energy with the remainder of the non neutronic energy in the high-Z material (Hg) which surrounded the deuterium and tritium.

The particle arrival flux at a radius of 6 meters is shown in Figure 1. The photons from the source are not shown here but arrive about 20 ns after the burn and are followed by the neutrons and finally by the various ions. The bare pellet ions arrive much earlier than the less energetic structured pellet ions and have pulse durations which are considerably shorter.

The front surface energy deposition in carbon is shown in Figure 2. The total energy deposited by the ions from the structured pellet is higher

FIGURE 1

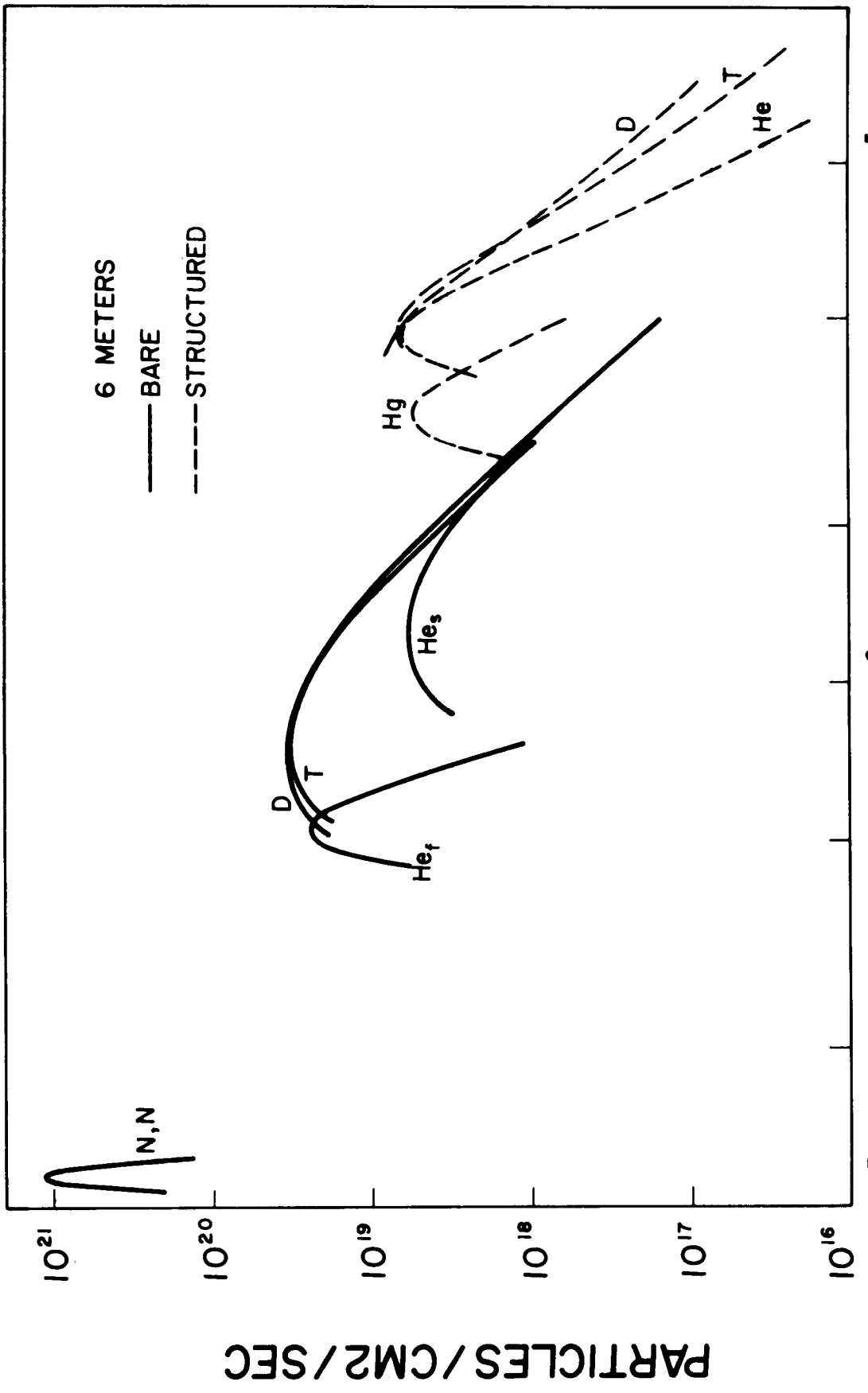
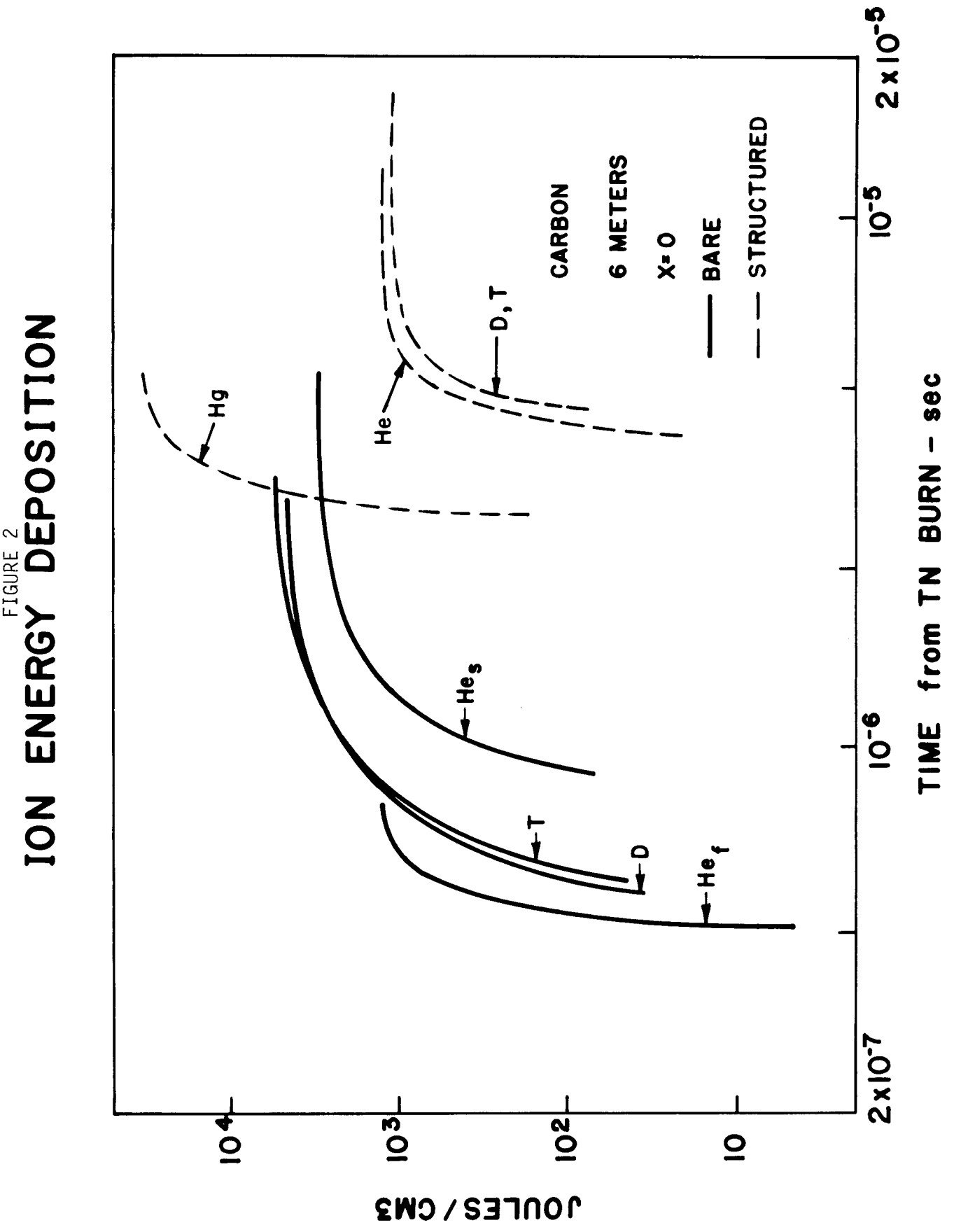

PARTICLE FLUX
6 METERS
BARE
STRUCTURED
N,N
D
T
He_f
He_s
Hg
D
T
He
10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
10^{-7}
10^{-6}
10^{-5}
PARTICLES/CM2/SEC
TIME FROM TN BURN-SEC

FIGURE 2


ION ENERGY DEPOSITION
JOULES / CM3
10^4
10^3
10^2
10
2x10^-7
10^-6
10^-5
2x10^-5
TIME from TN BURN - sec
Hg
He
D, T
CARBON
6 METERS
X=0
BARE
STRUCTURED
He_s
T
D
He_f

due to the short range of the heavy ions. This energy is however deposited over a much longer period of time. These longer times are sufficient for a considerable amount of the energy to be conducted away from the deposition region. The difference between the energy deposition profiles at the end of the respective pulses is shown in Figure 3 which indicates that the deposition from the Hg ions is about 6 times larger than any component of the bare pellet. The neutron energy deposition is always quite low and is on the order of 1 J/cm^3 even though it is essentially uniformly deposited through the first wall.

The temperature increase over the ambient value is displayed in Figure 4 for each of the components in each spectrum. The initial excursion for the laser light is based on a uniform deposition duration of 1 ns while the X-ray absorbtion is assumed to occur as an impulse in time. Each component of the bare pellet produces a significant ΔT occuring at slightly different times while the structured pellet response is dominated by the heavy Hg ions. The time at which the temperature is elevated at the front surface is longer for the bare pellet due to the larger deposition region and commensurate smaller temperature gradients.

The total temperature increase from all components in each spectrum is shown in Figure 5 for both carbon and molybdenum. In both cases the bare pellet temperature excursion exceeds that of the structured pellet due to the longer time interval over which the deposition took place and the larger gradient associated with the heavy ions. The comparison of molybdenum and carbon indicates that Mo and C show essentially equivalent responses for the bare pellet but a smaller excursion is noted for the former with the structured pellet due to the higher thermal diffusivity of the Mo.

FIGURE 3

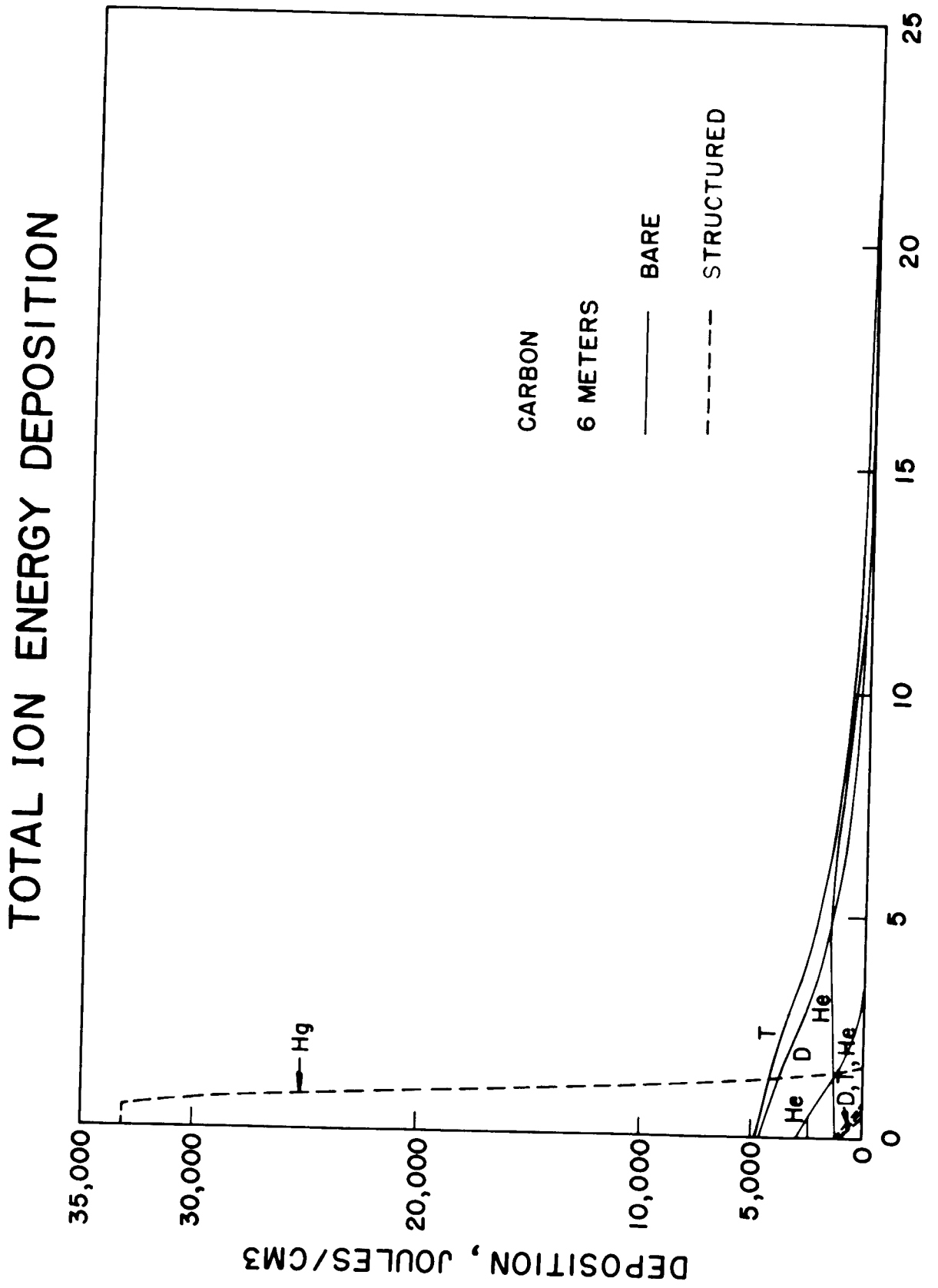

TOTAL ION ENERGY DEPOSITION
CARBON
6 METERS
BARE
STRUCTURED
Hg
T
D
He
He
D, T, He
35,000
30,000
20,000
10,000
5,000
0
0
5
10
15
20
25
DEPOSITION, JOULES/CM3
LOCATION, MICRONS

FIGURE 4

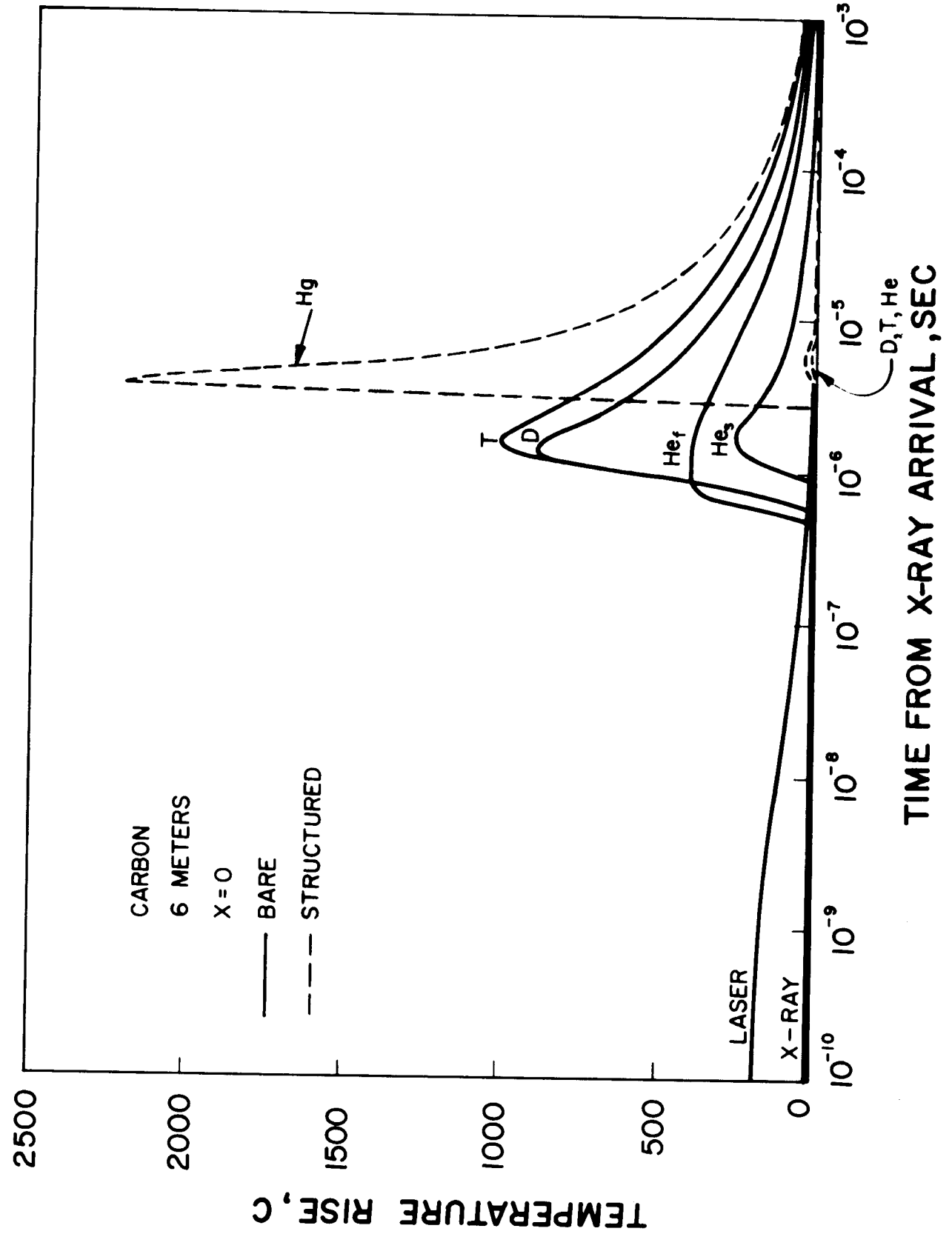
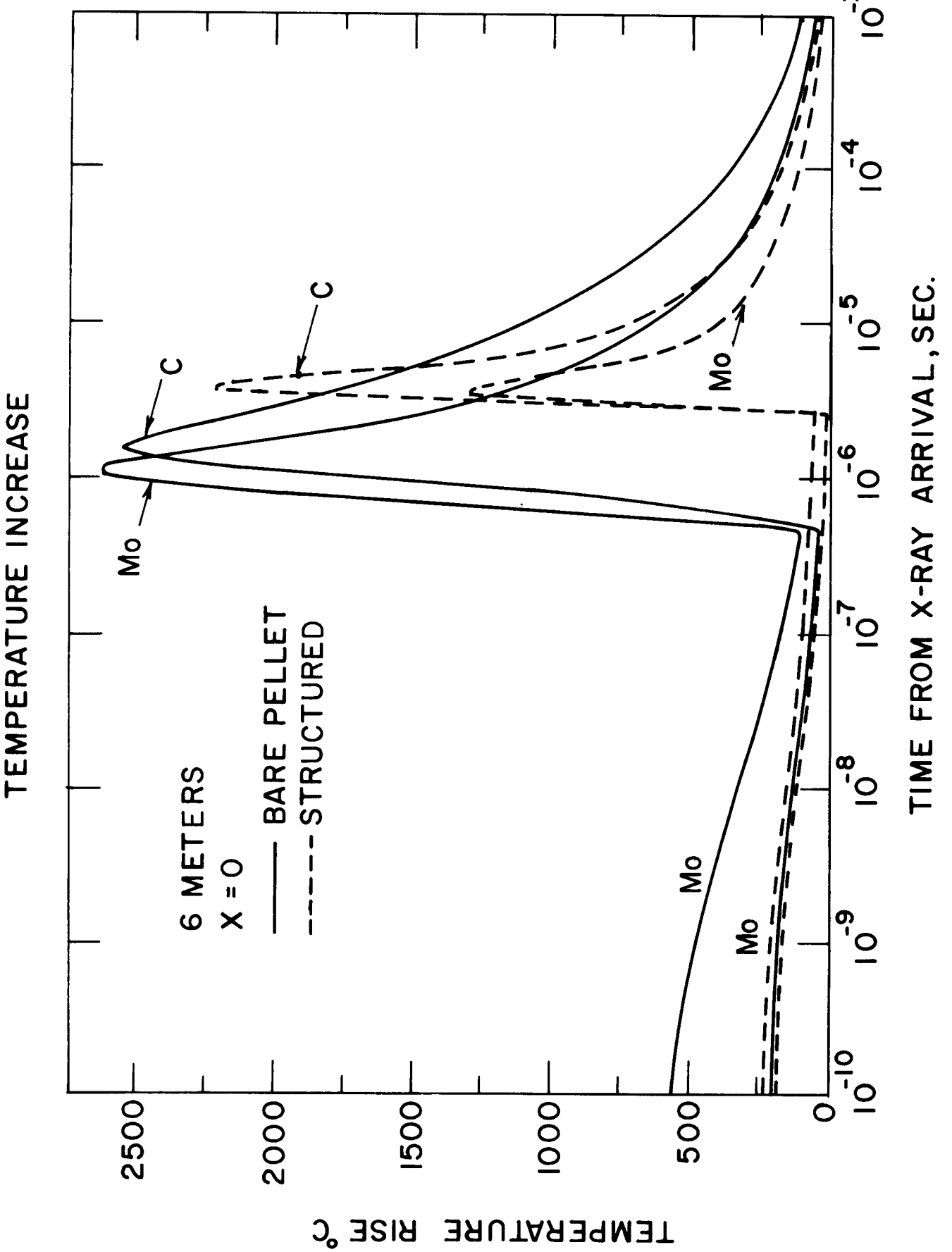

TEMPERATURE INCREASE
CARBON
6 METERS
X = 0
BARE
STRUCTURED
Hg
T
D
He f
He 3
D, T, He
LASER
X-RAY
TEMPERATURE RISE, C
TIME FROM X-RAY ARRIVAL, SEC
2500
2000
1500
1000
500
0
10^-10
10^-9
10^-8
10^-7
10^-6
10^-5
10^-4
10^-3

FIGURE 5


TEMPERATURE INCREASE
6 METERS
X = 0
BARE PELLET
STRUCTURED
C
C
Mo
Mo
Mo
Mo
2500
2000
1500
1000
500
0
TEMPERATURE RISE °C
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
TIME FROM X-RAY ARRIVAL, SEC.

This effect has been noted to be even more significant in material of higher thermal conductivity.

The displacement production for light ions like those of the bare pellet is determined by the local energy of the ion as it slows down in the material. The displacement cross section in general is inversely proportional to the ion energy. Consequently the dpa rate increases with distance into the material. The displacement rate for each ion species at the front surface is shown in Figure 6. The dpa rate for neutrons were developed from neutron fluxes determined from time dependent neutronics calculations[7] and are noted to be an order of magnitude lower than any of the ion species.

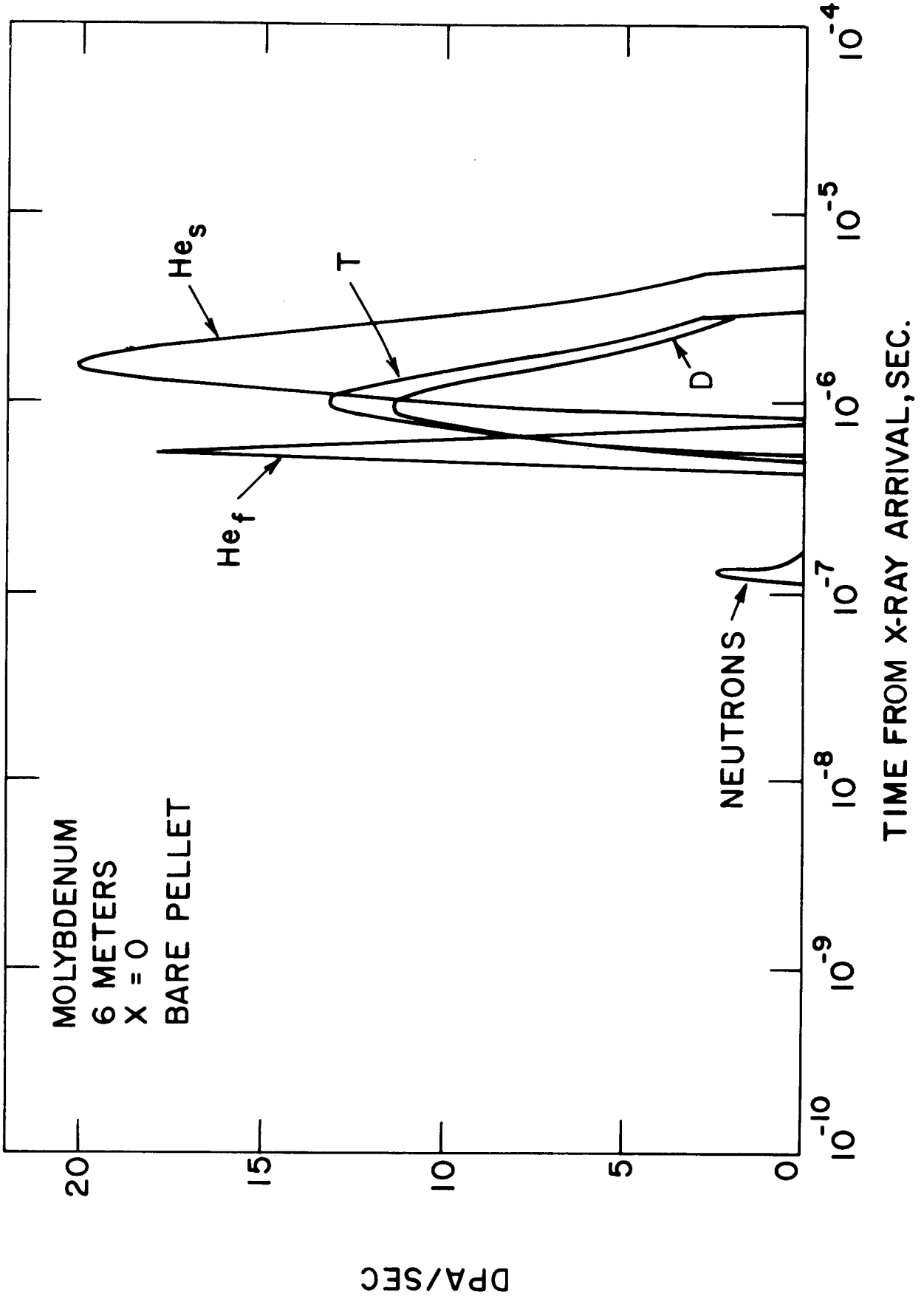
The total displacement rate and the commensurate temperature excursion in molybdenum for the bare pellet is shown in Figure 7. The maximum dpa rate exceeds 30 dpa/sec which is a factor of 10^7 higher than that observed in fission reactors and 100 times larger than ion simulation facilities. The displacement rate at a position 1 micron from the surface is a factor of 5 higher than the front surface values.

Implications

These large temperature and displacement transients will have significant implications on the phenomena which determine the performance of a material in these radiation environments. Among these are the following:

Thermal Ablation - A coupling of these temperature excursions with the evaporation rates for carbon indicates that significant erosion rates (>1 cm/year) could be anticipated.

FIGURE 6


DISPLACEMENT RATE
MOLYBDENUM
6 METERS
X = 0
BARE PELLET
He_s
T
D
He_f
NEUTRONS
DPA/SEC
20
15
10
5
0
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
TIME FROM X-RAY ARRIVAL, SEC.

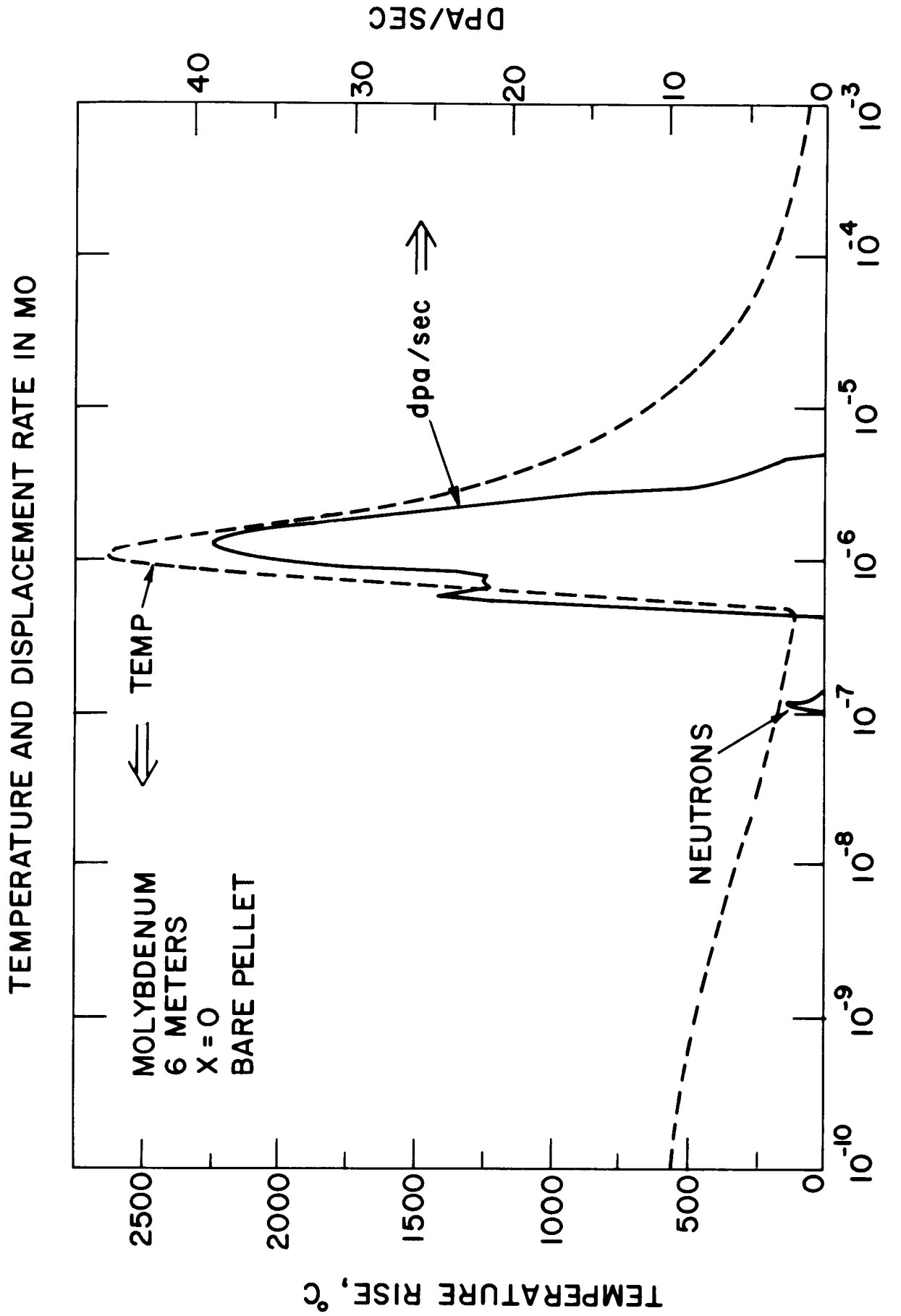

TEMPERATURE AND DISPLACEMENT RATE IN MO
MOLYBDENUM
6 METERS
X = 0
BARE PELLET
TEMP
dpa/sec
NEUTRONS
TEMPERATURE RISE, °C
DPA/SEC
TIME FROM X-RAY ARRIVAL, SEC
2500
2000
1500
1000
500
0
40
30
20
10
0
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}

FIGURE 7

Sputtering - The enhancement of sputtering yield as the temperature approaches the melting temperature[8] will result in a similiar rapid erosion.

Spallation - The spectra in this study did not result in the generation of significant thermoelastic stress waves since the deposition time for the ion was very long compared to the time for acoustic relief and the deposition resulting from the x-rays was low due to the high energy spectra considered.[2]

Swelling - A material in these radiation environments would likelly show a reduced level of swelling from a similiar material in a steady state environment.[9] This would be expected from the enhanced recombination during the high displacements and the significant annealing during the 10 micro-seconds of elevated temperature.

Conclusion

A few general conclusions from these calculations are:

.Unprotected dry walls operating at >30% of their melting point will not survive both of the pellet spectra in this study at economically attractive wall loadings (>1MW/m^2).

.The large spread in ion energies will significantly reduce temperature transients especially in materials of higher thermal diffusivity.

Both conclusions indicate that the response of the first wall is strongly dependent on the pellet output spectra; consequently, protective means for accommodating variation in spectra are desirable.

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