THE RESPONSE OF STAINLESS STEEL TO THE PELLET DEBRIS IN A LASER FUSION REACTOR

T. J. McCARVILLE, A. M. HASSANEIN, G. L. KULCINSKI
University of Wisconsin, Nuclear Engineering Department, 1500 Johnson Drive, Madison, Wisconsin 53706, U.S.A.

Abstract
Stainless steel has been suggested as a potential first wall material for near term fusion reactors. This work examines the thermal and displacement response of stainless steel at 7 meters from a 100 MJ pellet. For a vacuum chamber the temperature pulse from the photons and charged particles produce a temperature increase in excess of the melting temperature. This increase can be reduced by a factor of 2 with 0.5 torr of neon buffer gas. The evaporation rate can approach several millimeters per year without gas protection and is reduced to 0.03 mm/yr with gas protection. It was found that 0.5 torr of neon could reduce the total dpa at the surface due to ion debris from about $2 \times 10^{-4}$ to $1 \times 10^{-4}$ dpa per pulse for the spectra chosen. A parameter study examining the response of stainless steel to variations in X-ray spectra and gas parameters show that more than 5.0 torr of xenon gas almost eliminate the temperature rise from soft X-rays and provides some reduction for harder X-rays. The X-ray temperature response is found to be a weak function of the burn time since the thermal diffusivity of stainless steel is low.
1. Introduction. An analytic technique has been recently developed to calculate the time and spacial variations of the temperature and displacement transients associated with a radiation spectra on laser reactor first wall materials [1,2,3]. It was found that laser fusion pellet debris could promote very large temperature excursions in copper, molybdenum and carbon and that displacement rates could approach several hundred dpa/s in the near surface region. The object of the present study is to extend the previous investigations to another possible first wall construction material, stainless steel, which has a particularly low thermal conductivity. Specifically, the main objectives of this analysis are:

1. To study the displacement, thermal response, and surface evaporation of stainless steel as a first wall material.

2. To study the effect of an inert buffer gas to protect stainless steel from X-rays and ions.

We will use one pellet spectra for this analysis which might be typical of near term, low yield pellets, but the reader should be cautioned that many other spectra are possible. Where possible the results from this study will be normalized to the energy per unit area.

2. Calculation Descriptions. The computer code used for this work, T*DAMEN [4], calculates spacial and temporal energy deposition from a given pellet spectra, and uses the result as a heat source from which the spacial and temporal temperature response can be calculated. The displacement damage from each component of the spectra is also calculated. The consequences of significant energy deposition into the first wall has been shown to enhance sputtering, evaporation, and other effects detrimental to first wall life so it is important to understand the primary energy deposition profiles.

The results of two separate sets of calculations will be presented here. Both have assumed a spherical reactor geometry and a bare first wall having the thermal properties of stainless steel and the stopping power of nickel. At the present time these calculations do not incorporate changes in thermal constants with temperature and no latent heat melting is included. Therefore, the validity of the results become questionable near the melting point. We have chosen to analyze a large cavity (7 meters in radius) to avoid temperatures significantly above the melting point for long periods of time.

The first set of data presented considers a complete pellet spectrum consisting of light and heavy ions, reflected laser light, and X-rays. These calculations will illustrate the effect that 0.5 torr of neon gas can have on the total damage and temperature excursions at the first wall. A description of the pellet spectrum, before modification by the gas, is given in Table 1. The energy dependence of the spectra at the first wall and slowing down effects of gas are calculated by the code, with the exception of reflected laser light, which is monenergetic and assumed to be unaffected by the gas. Although the neutrons possess most of the energy released by the microexplosion, very little of that energy is deposited at the first wall and for this reason temperature excursions from neutrons can be neglected for this study.

The time of arrival of 7 meters, and the effect that 0.5 torr of Ne gas has on that time, is represented in Figure 1. X-rays arrive at the first wall a few nanoseconds after the burn (not shown in Figure 1), whereas ions arrive at times on the order of 500 ns after the burn.

The second set of results presented in this paper is a parameter study showing the relative effectiveness of Xe, and He as a buffer gas for X-rays at 0.5 torr and 10 torr. Energy dependent absorption cross-sections of Biggs [5] are used for all the calculations.
3. **Energy Deposition.** The total energy deposition of X-rays and ions is shown as a function of distance into the material in Figure 2. All the laser light is assumed to be absorbed in a thin region near the surface. The exponential X-ray attenuation is attributed to photoelectric absorption and incoherent scattering, assuming in the calculation that a spectrum of secondary photons is not created. When 0.5 torr of neon gas was included, the total energy deposited within the first few microns was reduced by almost a factor of two, with the largest reduction in the heavy ion component. The ion energy loss models employed in these calculations are approximations to the more elaborate models formulated by Brice [6].

The total energy deposition into the front surface (X=0) of the first wall for each ion as a function of time is given in Figure 3. There is a substantial slowing down of the ions (with the exception of fast He) due to electronic interactions in the gas, and, in the case of the heavy ions, nuclear energy deposition. Although D and T deposit the same total energy into the first wall without gas, the gas slows down the D ions more efficiently than the T ions, so their temporal depositions into the first wall are no longer superimposed after the gas is introduced.

4. **Temperature Response.** The solution for the spacial and temporal temperature response of an arbitrary spectrum is described in detail in references (1,2). The response for one microexplosion will be discussed here, although the code can use LaPlace transform techniques to calculate the response after any number of pulses.

Figure 4 shows the temperature response at the front surface (X=0) for each component of the spectrum if there is no gas. The initial large temperature rise is due to the X-rays (assumed to be emitted with a pulse width = 10^-9 sec) and the reflected laser light. Before the heat from the photons is completely diffused from the surface the ions arrive and deposit all their energy within the first 5 microns. The temperature rise from each component is not predictable by the magnitude of the total energy deposition alone. Shorter deposition times tend to increase the temperature rise and can play a more important role in the thermal response than the total energy deposited, a fact illustrated by the fast He. It is also noticed that although D and T ions deposit the same total amount of energy at the same time, their temperature responses at the front surface are not identical because the energy loss rates are different at the front surface.

The temperature rise at the front surface from each component was also calculated for a chamber containing 0.5 torr Ne. The decrease in magnitude of the temperature rise from each ion as compared to the case with no gas is mainly due to the extraction of energy by the buffer gas, but it is also reduced by broadening of the deposition times. Reradiation of energy from the gas to the first wall is not considered in these results but it will occur on a millisecond time scale, which will considerably reduce its impact on the first wall temperature.

The temperature curves with and without the gas are quite similar except that the ordinates differ by a scale factor of 1/2, as illustrated in Figure 5 for the total temperature rise. The temperature response from this spectrum on stainless steel with 0.5 torr neon is approximately the same as the response observed for copper with no gas layer [3], a reflection of the differences in thermal diffusivity and energy deposition.

5. **Effects on Evaporation.** Since stainless steel is a combination of different elements and current evaporation models are not sophisticated enough to make accurate predictions for such materials, the accuracy of the estimates presented here should only be considered as order of
magnitude indications. The model used in this analysis to estimate the evaporation rate from the equilibrium vapor pressure is that given by Behrish [7]. The heat of sublimation of nickel, needed to relate the vapor pressure exponentially to temperature, was used since it is characteristic of the major components of stainless steels. Recondensation of surface atoms is not considered. The ambient temperature of $600^\circ\text{C}$ was chosen to be representative of a potential reactor configuration.

The photons evaporate a negligible number of atoms during the time that they are responsible for heating and this is illustrated by the evaporation curves in Figure 6. This means that the large X-ray cross sections of the heavy inert gases would not be a major consideration in choosing a buffering gas from the standpoint of evaporation. The curve also shows how the number of evaporated atoms per pulse can be reduced by over four orders of magnitude with 0.5 torr neon in the chamber. Without a gas, the evaporation rate could be a limiting factor in first wall life. When 0.5 torr neon is included, for a pulse rate of 10 Hz, 70% plant factor, the maximum evaporation rate (without recondensation) is only $0.03\text{ mm/year}$. For the purposes of reducing evaporation and surface temperature, it is desirable to use as high a gas pressure as possible; however, even 0.5 torr might be too high from the standpoint of laser breakdown or hot gas removal requirements. The heavier inert gases, in particular Xe, are the most promising due to their large ion stopping powers.

6. Displacement Response. The displacement rates in inertial confinement systems are expected to depart from the familiar radiation environments in fission and magnetic fusion devices ($\approx 10^{-6}\text{ dpa/sec}$) partly because the ions are deposited over 10 usec, and partly because of the pellets heavy ablator ions. To estimate the displacement response of stainless steel, stopping power input parameters for nickel were used since they were readily available and should closely resemble those of the major components. Lindhard theory is used at low energies and a modified Rutherford interaction incorporating a screening function is used at higher energies to calculate the displacement response for light ions [8,9]. For heavy ions, T*MENDEN combines the IAEA standard defect production model with a nuclear energy deposition function that is the output of an ion implantation code [6] to determine the displacement response.

The total displacement rate at the surface with 0.5 torr neon is plotted in Figure 7 to show the relationship of the displacement spike from the ions with the temperature spike. The superposition of these spikes in time is known to affect the point defect cluster behavior [10]. The calculations revealed that a 0.5 torr neon gas fill reduces the temperature by a factor of 1/2, and the total dpa rate by $\sim 30\%$.

The 0.5 torr of neon has a much larger affect on displacement response farther into the first wall as seen in Figure 8. Not only is the magnitude significantly reduced everywhere in the first wall, but the total dpa peak position is shifted closer toward the surface. This is mainly due to the heavy ions, which give rise to a large percentage of the displacement peak. The silicon energy spectrum is reduced (see Figure 1) and the end-of-range for the heavy ions, where the nuclear damage occurs, is closer to the surface.

7. Parametric Analysis of X-ray Response. A parameter study was conducted examining the response of stainless steel to variations in X-ray spectra and gas parameters. A representative portion of the results are condensed into Figure 9. Figure 9(a) approximates the temperature response for a vacuum chamber. The temperature response is normalized to the total X-ray energy of the pellet and the first wall area. The variables are the time over
which the X-ray energy is emitted and the characteristic energy of those X-rays.

It was found that increasing the source duration time of a 1 keV blackbody source from $10^{-9}$ seconds to $10^{-7}$ seconds reduces the temperature rise by a factor of about 3, but it has no affect on the hard X-rays (larger than 1 keV). The irregularity in the xenon curve at higher gas density is due to a combination of absorption edges in the gas and stainless steel. It is evident from the calculations that for hard X-ray spectra there is almost no reduction in the adiabatic response as the source duration time increases. For soft X-ray spectra, the reduction is still very small due to the poor thermal conductivity of stainless steel. For materials with higher thermal conductivity (like copper), significant temperature reductions have been found as the source duration increases [3]. It is important to note that helium provides only a small reduction in the thermal response (about 30% for 0.5 torr) for blackbody spectra at 0.1 keV and almost no reduction for blackbody spectra greater than 0.5 keV. On the other hand, xenon almost eliminates the X-ray temperature response for soft spectra, and provides some reduction in response for the harder X-rays. It is clear that high atomic number gases (xenon) offer significantly more protection against temperature increases due to X-rays, particularly for softer spectra.

8. Conclusions. These calculations have shown that the large temperature excursions in metal from the rapid deposition of X-rays and ions can approach or exceed the melting point in stainless steels. It was found that 0.5 torr of neon reduces the temperature and displacement damage pulse by a factor of 2 when compared to the case of no gas, reiterating the role of a buffer gas as a first wall protection scheme. Not only is the magnitude of the damage reduced, but the spacial profile is significantly modified. The peak damage region now occurs closer to the surface. The gas protection scheme described here shows stainless steel reactor chambers of about 7 meters could be used for the pellet spectra given here if at least 10-torr meters of high atomic number gas is used.

When comparing the inert gases, He and Xe, one finds that helium is relatively transparent to most of the thermonuclear X-ray radiation at gas pressures compatible with laser fusion (i.e., less than 10 torr). On the other hand, the use of Xe at pressures greater than a few torr can effectively stop all the X-rays below 1 keV. It was found that variations in X-ray pulse duration of less than $10^{-9}$ seconds were not important in determining the final temperature increase in steel. This conclusion differs from the conclusion drawn for higher thermal diffusivity metals like Cu.

Acknowledgement

The authors would like to acknowledge the partial support of the Division of Laser Fusion, U.S. Department of Energy under contract number ET-77-5-02-4296.

References


May 1978.


Table I. Reference Spectra (100 MJ)

<table>
<thead>
<tr>
<th>Energy (MJ)</th>
<th>Spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser</td>
<td>0.2</td>
</tr>
<tr>
<td>X-ray</td>
<td>2</td>
</tr>
<tr>
<td>D</td>
<td>4.6</td>
</tr>
<tr>
<td>T</td>
<td>6.9</td>
</tr>
<tr>
<td>He (Slow)</td>
<td>1.2</td>
</tr>
<tr>
<td>He (Fast)</td>
<td>5.4</td>
</tr>
<tr>
<td>Silicon</td>
<td>2.7</td>
</tr>
<tr>
<td>Neutrons</td>
<td>77.0</td>
</tr>
</tbody>
</table>

BB = Blackbody  M = Maxwellian  G = Gaussian

![Image 1](image1.png)

**Figure 1.** Particle flux vs. arrival time.

![Image 2](image2.png)

**Figure 2.** Total energy deposition vs. wall penetration distance without 0.5 torr of neon.
Figure 3. Total energy deposition vs. arrival time with and without 0.5 torr of neon.

Figure 4. Surface temperature rise from each ion type vs. arrival time with no gas.

Figure 5. Total surface temperature rise vs. arrival time with and without 0.5 torr of neon.

Figure 6. Surface evaporation vs. arrival time with and without 0.5 torr of neon.
Figure 7. Surface temperature and displacement rate vs. arrival time with 0.5 torr of neon.

Figure 8. Total DPA vs. surface penetration with and without 0.5 torr of neon.

Figure 9. Normalized surface temperature rise due to X-rays vs. temporal width and blackbody temperature for helium and xenon.