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Estimated radiactive and shock loading of fusion reactor armor

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Estimated radiative and shock loading of fusion reactor armor

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Abstract

Estimates are given for the loading induced in the wall armor of the fusion chamber caused by ablative thermal radiation from the fusion plasma and by the hydrodynamic shock. Taking a version of the LIFE design as an example, the ablation pressure was estimated to be ~0.6 GPa with an approximately exponential decay with time constant ~0.6 ns. Radiation hydrodynamics simulations suggested that ablation of the W armor should be negligible.

Introduction

Inertial confinement fusion (ICF) is of interest as a source of neutrons for proliferation-resistant and high burn-up fission reactor designs. ICF is a transient process, each implosion leading to energy release over a short period, with a continuous series of ICF operations needed to drive the fission reactor.

ICF yields energy in the form of MeV-range neutrons and ions, and thermal x-rays. These radiations, particularly the thermal x-rays, can deposit a pulse of energy in the wall of the ICF chamber, inducing loading by isochoric heating (i.e. at constant volume before the material can expand) or by ablation of material from the surface. The explosion of the hot ICF system, and the compression of any fill material in the chamber, may also result in direct mechanical loading by a blast wave (decaying shock) reaching the chamber wall.

The chamber wall must be able to survive the repetitive loading events for long enough for the reactor to operate economically. It is thus necessary to understand the loading induced by ICF systems in possible chamber wall designs, and to predict the response and life time of the wall.

Configuration

The ICF-driven fission configuration considered here is a version of the LLNL LIFE reactor, at August 2008.

ICF system	Indirect drive
Yield	26 MJ
Drive energy (assumed)	1 MJ

Component masses (assumed)	Dominated by high-Z hohlraum: 0.3 g Au
Dimensions	Cylinder: 2.5 mm radius x 10 mm high
Chamber and fill	2.25 m radius, 2.5 g/m^3 Ar
Chamber wall	0.3 mm W, 3 mm steel

Estimated x-ray and shock loads

Capsule/hohlraum condition after fusion burn

For a simple estimate, the state of the ICF system after thermonuclear burn was taken to be spherical with the same volume as the original hohlraum. The hohlraum wall material was assumed to be distributed uniformly over this volume, with a constant temperature. This model is reasonable in the sense that ablated hohlraum wall material expands to fill the hohlraum, and is a limiting factor in the minimum size and drive energy necessary to achieve thermonuclear ignition. Any hohlraum fill (e.g. gas or foam), the fuel capsule, and the thermonuclear fuel itself were ignored: their mass is far lower than that of the hohlraum wall.

The thermonuclear fuel was taken to be DT, where ~20% of the fusion energy is carried by charged particles, which have a much shorter range than the neutrons. Much of this energy is deposited within the hohlraum. Thus the state of the ICF system immediately after thermonuclear burn was taken to be a uniform sphere of Au (mass density 1532 kg/m^3 i.e. ~8% of solid) with a thermal energy of 6.4 MJ. Using the SESAME EOS for Au, the temperature would be 334 eV and the pressure 8.7 TPa.

At this temperature, and assuming black body emission (which should be accurate to a few percent), the cooling radiance would be 1.28 x 10^{19} W/m^2 over the surface of the hohlraum. The radiance falls rapidly as the plasma cools, but a rough estimate of the characteristic cooling time can be obtained by cooling at this rate until the thermal energy is exhausted, which would take ~2.5 ns. (A more accurate cooling calculation is given below.) For comparison, the time for a release wave from the outside of the ICF system to penetrate to the center of the uniform plasma would be ~43 ns, so the explosion of the plasma is unlikely to reduce the energy available for thermal emission.

A more accurate calculation of the thermal emissions takes into account the decrease in emission – and thus cooling rate – as the plasma cools (Figs 1 and 2). The radiance falls faster than the simple calculation, roughly exponentially, with a time constant of ~0.6 ns, but lasts much longer at a lower level.

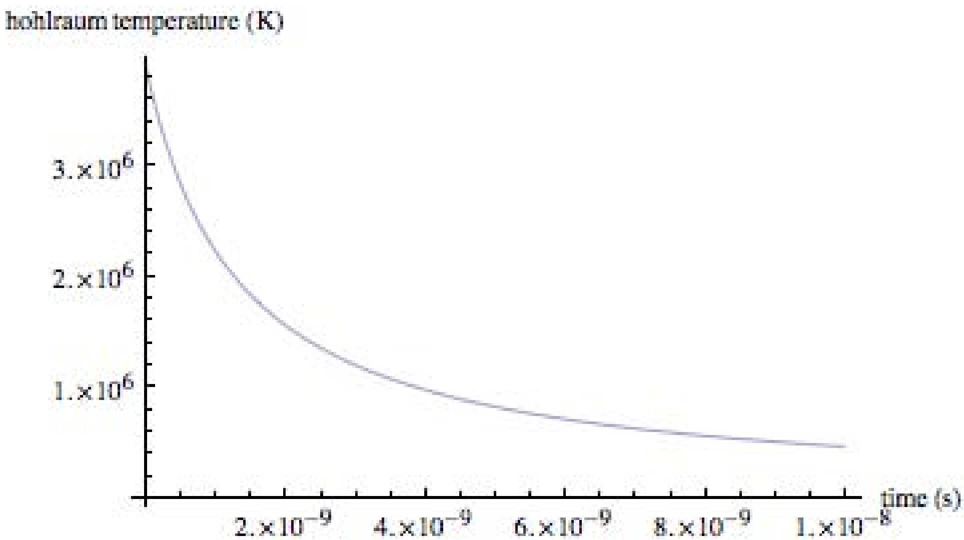

Figure 1: Calculated temperature history of ICF plasma during cooling.

The thermal energy is in the form of soft x-rays, which are absorbed within ~0.1 μm of the surface of the W armor. Soft x-rays should give a more efficient coupling than optical radiation to ablation pressure in the W. A conservative estimate of the ablation pressure is to use the irradiance-pressure relation for laser ablation. (A more accurate calculation, with less experimental validation, is given below). Distributing the thermal emission from the ICF system uniformly over the surface of the W armor, the initial irradiance would be ~40 TW/m^2, giving an ablation pressure ~0.7 GPa. This is a factor of 3 less than the observed flow stress for W initially at room temperature on microsecond time scales (2.2 GPa), but is a concern for material at elevated temperatures and with repetitive loading.

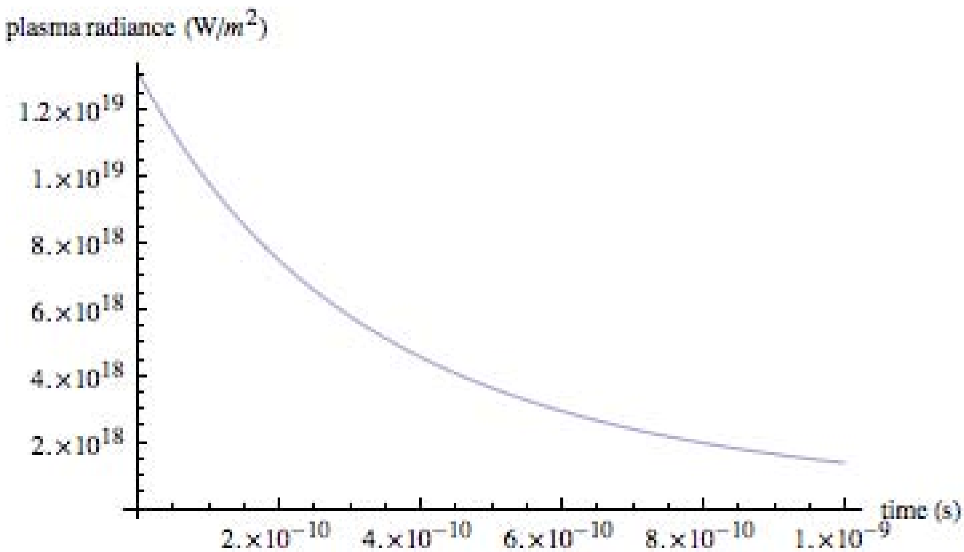

Figure 2: Calculated irradiance history from the ICF plasma.

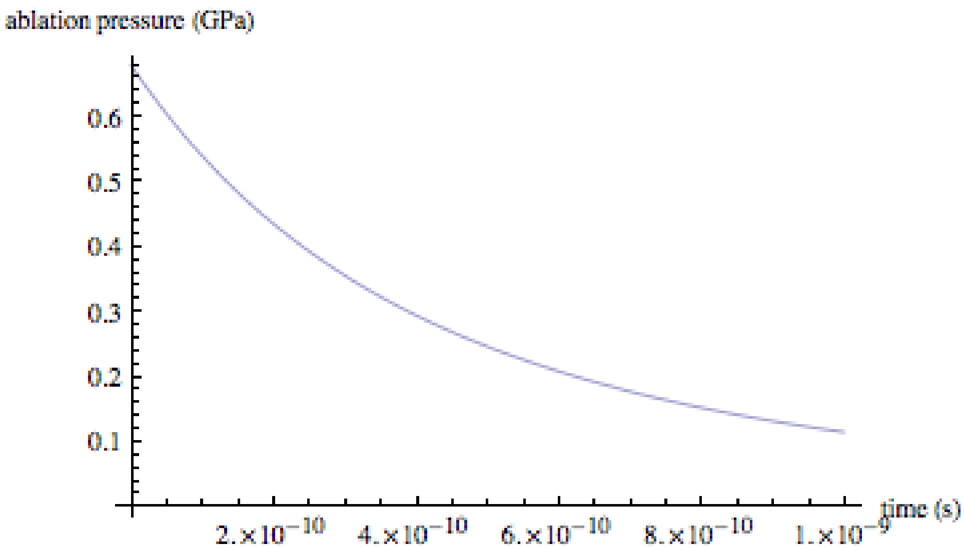

Figure 3: Estimated ablation pressure history applied to the W armor.

A more accurate estimate of the ablative loading uses the thermal spectrum of the plasma, and radiation hydrodynamics to simulate the deposition of thermal energy in the armor and thus its ablation.

Any departure from a spherical distribution would give spatial variations in the thermal emissions from the ICF system, which could easily cause radiation-induced loading an order of magnitude greater over some parts of the chamber wall.

Radiation hydrodynamics simulations were performed using the estimated irradiance on the W armor. As usual in such simulations, an exponentially expanding spatial mesh was used, the first zone in this case being ~2×10^{-13} m wide. The EOS of W was taken from the SESAME database, and the opacity from ZOT calculations. The simulations suggested that the thermal energy was simply absorbed and then transported by conduction and the motion of stress waves, rather than raising the surface temperature high enough to cause ablation. The spatial resolution exceeds the limits of the deposition scale and of the continuum approximation, so it can be concluded that the ablation rate is negligible, to the accuracy of the thermal source and radiation hydrodynamics models used.

Gas shock in chamber

Although the ICF plasma appears likely to cool rapidly by thermal emission, some energy is certainly expended in the hydrodynamic expansion of the plasma. This expansion drives a shock into the chamber fill gas, which will ultimately be transmitted into the chamber wall. However, the initial density of the Ar fill gas is extremely low compared with the ICF plasma, and the compression leads to a high degree of shock heating of the Ar. Hydrocode calculations are quite difficult because of the large density difference and high compression, but the shock temperature in the Ar was calculated to be similar to (or even higher than) the post-burn temperature in the ICF plasma: ~350 eV. The areal mass of Ar is too low to absorb this radiation effectively. Thus it seems likely that almost all of the non-neutron energy from the ICF system appears within ~10 ns as soft x-ray ablation of the W armor.

Wave interactions in chamber wall

The impedance mismatch between the W armor and the steel wall affects causes a lower amplitude shock to be transmitted into the wall, and a release wave to be reflected back into the armor. If, as estimated above, the loading applied to the armor is less than its flow stress, the loading wave should be transmitted through the armor with essentially no attenuation. The peak stress of ~0.7 GPa in the armor should be transmitted as ~0.3 GPa in the steel. This is in the range of flow stresses reported for steels, and is a possible concern for repetitive loading at elevated temperatures. Since the wave profile is a decaying stress, the reflected release wave will interact with the incident wave to induce a tensile stress of ~0.4 GPa. This is less than the reported spall strength of 0.9 GPa [Steinberg, 1996], but as with the compressive wave this is a potential concern for repetitive loading at elevated temperatures.

The compressive and tensile waves will reverberate through the thickness of the chamber wall, potentially many times if they remain elastic. Subsequent interactions could induce higher peak stresses.

Normal modes of chamber

(not estimated)

Conclusions

Trial calculations were made of the loading induced in ICF reactor walls by the explosion of the ICF system. Peak stresses were estimated to be lower than dynamic compressive and tensile stresses typical of W and steel initially at room temperature, but may cause problems for repetitive loading and walls at elevated temperature. Ablation of the W armor was estimated to be negligible.

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