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COATING REQUIREMENTS FOR AN ICF DRY-WALL DESIGN

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MASTER

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COATING REQUIREMENTS FOR AN ICF DRY-WALL DESIGN

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A new concept for protecting the first wall of an ICF reactor has been developed which relies heavily on a coating to protect the steel tubes which comprise the first wall. This coating must survive the pellet explosion, be ductile, and be compatible with the materials in the ICF pellet. Calculations indicate that tantalum is the best choice for the coating material and that tantalum coated steel tubes can handle fusion thermal powers of 3500 MW in a 10 m radius spherical chamber.

1. INTRODUCTION

The essential engineering problem to be solved in an ICF reactor chamber is to design a first wall which can carry away the steady state average surface heat and at the same time survive the transient temperature increases generated by x-rays and ions from the pellet explosion. Conditions for transmission of a laser beam and a heavy ion beam to the target require cavity pressures to be $\leq 10^{-1}$ Torr and $\leq 5 \times 10^{-4}$ Torr respectively. While the presence of 10^{-1} Torr background gas in the laser cavity does offer some protection to the first wall against low energy x-rays and ions, it is not effective against the high energy x-rays and ions expected from high gain pellets. Thus, any design for the first wall must solve essentially the same problems for both laser and heavy ion beam drivers.

A new concept for protecting the first wall has been developed which relies on three methods of protection: (1) the construction of the first wall from thin steel tubes which carry flowing liquid lithium to remove the steady state heat flux, (2) a coating on the tube surface facing the explosion whose melting temperature is above the peak temperature transients caused by the x-rays and ions, and (3) an effective design of pellets. Calculations have shown that this coated thin tube wall design can handle fusion thermal powers of 3500 MW produced by 350 MJ yield pellets exploded every 0.1 second in a 10 m radius spherical chamber.

The requirements for a viable coating material are severe. It must form a very good bond with the steel tubes, it must be ductile and, upon cooling, any melted or evaporated material must maintain its integrity with the original coating material. Furthermore, it must be compatible with whatever pellet debris may be deposited on it. This paper examines the requirements placed on the coating material and shows that tantalum appears to be the best candidate for the coating.

2. PELLET DESIGN

A typical CO₂ laser-driven pellet design [1] is shown in Figure 1 where the CH₂ represents a plastic shell. This cryogenic pellet features a double-shell exploding pusher design and has been scaled to a gain of 175 for an incident energy of 2 MJ. This scaled pellet is assumed to achieve its high gain by highly compressing the fuel to a ρR_f value of 6 g/cm² where ρ is the mass density and R_f is the radius of the compressed fuel. At this high compression 55% of the yield will be in the kinetic energy of the thermonuclear neutrons and 45% will be in x-rays and ions [2]. This high percentage of energy in the x-rays and ions is in sharp contrast to the 20% valid for present-day microballoons and emphasizes the need for good first wall protection concepts when reactor-sized pellets are used.

Figure 1. A typical CO₂ laser-driven pellet design

In general, there are two basic components of the x-ray spectrum: thermonuclear and blackbody. The thermonuclear radiation is produced as the thermonuclear burn front travels through the compressed fuel. It has the blackbody temperature of the heated fuel, i.e., around 20 keV, and is very short lived, typically tens of picoseconds [3]. On the other hand, the blackbody radiation lasts for nanoseconds and is simply the thermal radiation from the hot pellet debris as it cools down by expansion.

In contrast to the x-rays, the ions travel with a Maxwellian velocity distribution. They arrive at the first wall coating much later than the x-rays and last for microseconds [3].

The material composition of the pellet is determined by the implosion requirements and is therefore not subject to significant change. The one exception is the high-Z component which reduces electron preheat problems and provides much of the mass required for ablation or pushing. The only requirement on this material component is that it have a high atomic number. This latitude in material selection is important because the reactor conditions which must exist for the coating to survive also guarantee that the pellet debris will condense on the coating, i.e., irrespective of the original coating material, the surface layer of the coating will eventually be composed of pellet debris. Therefore, to avoid potentially deleterious material mismatches, the original coating material should be the same material as that used in the pellet, or vice versa. This explains the use of tantalum for the high-Z component in Figure 1 instead of the more conventional gold or tungsten [1].

3. COATING HEATING

The high energy x-rays (20 keV) will penetrate deeply into the coating and heat a volume of the coating. The range of an x-ray at a particular energy is well defined, but a strong function of the energy. However, an average range, R_x , of x-rays can be defined as the distance (in cm) at which the total energy in the x-ray spectrum is reduced to e^{-1} of its original value. The temperature rise due to these x-rays is given by

$$\Delta T_d = 7.958 E_x (1 - e^{-d/R_x}) / \rho C_v R^2 d \quad (1)$$

where E_x is the incident x-ray energy in MJ, C_v is constant volume specific heat in J/g deg, ρ is the coating density in g/cm³, R is the chamber radius in m, and d is the depth in cm at which the temperature rise is calculated. This expression is valid when the energy deposition time is too short for significant thermal conduction within the coating.

At the surface ($d = 0$), where the maximum temperature exists, the feature of interest is this temperature rise relative to the rise, ΔT_m , needed to bring the coating to its melt

temperature:

$$\Delta T_o / \Delta T_m = 7.958 E_x / K_v R^2 \quad (2)$$

where

$$K_v = \rho C_v R \Delta T_m \quad (3)$$

is the volumetric heating constant for the coating. To survive repeated pellet explosions the coating must never reach its melt temperature, i.e., Eq. 2 must be less than unity. The volumetric heating constant for the coating should therefore be large. This requirement favors low-Z coating materials since R_x is a strong function of the atomic number. However, calculations for reasonable pellet spectra indicate that volumetric heating is not the biggest problem and the coating material should be selected to minimize the surface heating caused by the low energy ions and blackbody x-rays.

The range of low energy ions and x-rays is quite small (less than 1 μ m) which means that the energy absorbed by the coating goes mostly to heating the surface. A conservative estimate of the heating is to assume that the absorbed energy goes entirely into heating the surface of a semi-infinite solid. In this case, the surface temperature rise, ΔT_s , for a square pulse lasting τ_n sec and having an energy of E_n MJ is given by [4]:

$$\Delta T_s = 0.1114 \frac{E_n}{R^2} \sqrt{\frac{\rho k C_p}{\tau_n}} \quad (4)$$

where k is the thermal conductivity of the coating in W/cm deg and the subscript n represents either the low energy ions ($n = i$) or the low energy x-rays ($n = x$). The feature of interest is again this temperature rise relative to the rise needed to bring the coating to its melt temperature which can be written as:

$$\Delta T_s / \Delta T_m = (K_p / K_s) / R^2 \quad (5)$$

where

$$K_p = E_n / \sqrt{\tau_n} \quad (6)$$

$$K_s = 0.1114 \Delta T_m \sqrt{\rho k C_p} \quad (7)$$

By writing Eq. 5 in this form the influence of the reactor size, the pellet explosion, and the coating material are separated into the three parameters R , K_p , and K_s , respectively. The latter two parameters may be considered as figures of merit for the pellet and coating. Although small changes in the pellet figure of merit may be possible, we are concerned here with the figure of merit for the coating, K_s , which is a strong function of the coating material. Nine potential materials are listed in Table 1 with their material constants [5] and figures of merit. Lead is not included because its melting temperature is below the 773 K steady state temperature assumed for the coating.

TABLE 1.
MATERIAL CONSTANTS AND FIGURES OF
MERIT FOR NINE COATINGS

Material	ρ g/cm ³	k W/cm deg	C_p J/g deg	ΔT_m K	K_s MJ/m ² sec ^{1/2}
Al	2.7	2.22	0.90	220	57
Ag	10.5	4.08	0.23	460	163
Au	19.3	2.97	0.13	560	171
Fe	7.9	0.75	0.46	1040	191
Be	1.8	1.59	2.18	780	220
Cu	9.0	3.93	0.38	580	239
Ta	16.6	0.54	0.15	2500	325
C	1.9	2.08	0.69	3200	589
W	19.4	2.01	0.13	2880	733

From this table, it can be seen that the figure of merit for aluminum is very low. On the other hand, tantalum, graphite, and tungsten have high figures of merit. However, tungsten is extremely difficult to fabricate and until that problem is solved, tungsten cannot be considered a serious candidate for the coating material. In addition, graphite has serious problems in that it is difficult to bond to steel, forms acetylene with the hydrogen from the pellet debris, swells a great deal under large thermal excursions with subsequent spallation, and cannot be used as the high-Z material in the pellets.

The most promising candidate for the coating material thus appears to be tantalum with a high figure of merit of 325. Tantalum is an average material to chemically process and purify, has average radioactive waste products, and is average in costs. It is relatively easy to fabricate, to bond to steel, and to remove from the first wall. It is also relatively available in large quantities, is a very good getter at high temperatures but chemically inert at low temperatures, and is a very good high-Z material for pellet designs.

Although the temperature rise at the tantalum coating surfaces can be rather large as long as it does not exceed 2500 K, the temperature excursions at the tantalum-steel interface must be limited to small values to minimize thermal fatigue of the bond. A conservative estimate of this excursion is given by applying Eq. 1 in the limit of a large depth d . The result for a tantalum coating exposed to E_x and E_i MJ of x-ray and ion energy, respectively, is

$$\Delta T_D = 3.175 (E_x + E_i) / R^2 D \quad (8)$$

where D is the coating thickness in cm. With 45% of the pellet yield in x-rays and ions, and with a chamber radius of 10 m, this expression gives a temperature rise of 50 K for a coating thickness of 0.1 cm. This value is an acceptable temperature excursion at the interface and shows that a tantalum coating need not be very thick.

4. RESULTS

The previous discussion has focused on an analytical understanding of the coating requirements and has resulted in the selection of tantalum for the coating material. This section presents results of a more complete analysis of the interaction between the 350 MJ yield from classified pellets and the tantalum coating in a 10 m radius spherical reactor chamber filled with 0.1 Torr of Xe gas.

The volumetric absorption of the x-rays by the Xe gas and by the tantalum coating was estimated by combining analytical absorption coefficients [6] with the blackbody radiation function. The effect of this absorption on the coating was studied with the CHART D computer program developed at the Sandia Laboratories [7]. This code calculates the hydrodynamic and radiation transport associated with the time-dependent deposition of energy into a set of elastic-plastic or porous materials. The Lagrangian equations of motion with energy transport terms are solved in one-dimensional spherical coordinates. Thermal and electron conduction, as well as spall and rejoin processes are included. One of the main features of the program is the inclusion of realistic equations of state for the materials. To save time and money, the less dangerous heating by the ion pulse was analytically modeled from the heat conduction equations describing the surface heating of a semi-infinite solid [4].

The temporal behavior of the tantalum surface temperature during the simulated square wave x-ray and ion pulses is shown in Figure 2. The x-rays come in a very short burst which heats the surface to 2870 K. The temperature then decreases until the ion pulse arrives and again heats the surface, but this time to only 2050 K. The effect of the gas pressure is relatively minor; the maximum coating temperature increases from 2870 K at 0.1 Torr to 2960 K at pressures below 0.01 Torr of Xe. Because these temperatures are always below the melting point of tantalum, significant evaporation and spallation do not occur. However, at these relatively low temperatures the target debris will condense onto the coating.

The penetration of the heating into the tantalum coating is shown in Figure 3. Curve 1 is shortly after the x-ray pulse and curve 2 is just before the arrival of the ion pulse. Curve 3 is shortly after the ion pulse and curve 4 is a significant time after the ion pulse. In these calculations the tantalum is assumed to be a semi-infinite solid, i.e., the cooling effect of the flowing lithium in the steel tubes has not been included. These results show that high temperatures do not penetrate deeply into the coating and that there should be minimal thermal cycling of the steel-tantalum interface for relatively thin coatings.

Figure 2. Time history of surface temperature.

Figure 3. Temperatures in the tantalum coating.

5. DISCUSSION

These results indicate that, to first order, the tantalum coating should survive repeated 350 MJ explosions in a 10 m radius reactor chamber without significant evaporation or spallation losses. However, many more aspects of this dry wall concept must be examined before its viability is assured. First, the numerous stress waves produced in the coating by each pellet explosion may eventually fatigue the tantalum-steel bonding. Second, although the absorbing surface layer does not become hot enough to melt or spall, it does become hot enough to engage in plastic flow. This action will subsequently lead to thermal fatigue of this surface layer and possibly to surface crazing to relieve the stresses. It is not clear what effect the fatigue will have on the coating since the fatigued material is in such a small

volume at the surface. However, if plastic flow should prove to be a problem, the stresses can be restricted to the elastic regime by reducing the pellet energy yield to 175 MJ per pellet and increasing the repetition rate to 20 Hz to maintain the original thermal power of 3500 MWt.

The deposition on the tantalum coating of the tantalum in the pellet debris will tend to compensate for variations in coating thickness. The thinner portions will be nearer the cooler liquid lithium in the steel tubes and will therefore be at a lower temperature than the thicker portions. The Ta in the pellet debris will more likely stick to a cooler surface than to a hotter surface. The final result will be a uniform thickness of tantalum.

The continual deposition of pellet debris onto the coating complicates the analysis of this dry wall concept and presents new problems. For example, the deposited debris may form a protective layer over the original coating. However, the deposited tantalum may not have the same crystalline structure or be as pure as the original tantalum. The result may be modified material properties in the surface layer and a poor bond between the deposited debris and the original coating. This could cause a randomly distributed flaking of the deposited material--hopefully without tearing off any of the original coating. On the other hand, if flaking did not occur, the buildup of the debris may become too heavy for the tubes to support. In this case the excessive buildup could be periodically removed by injecting a pellet with a modified yield to evaporate the debris which could then be removed by the gas pumping system.

It thus appears that this dry wall concept has considerable promise for ICF reactors although many questions remain concerning its lifetime. The concept has the advantages of being simple and of being compatible with the cavity atmosphere requirements for all drivers.

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