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Materials response modelling is used to determine transient stresses in light ion beam ICF reactor first walls. It is shown that mechanical stress from the dynamic overpressure and thermal stress from the heat flux can be of comparable magnitudes. The maximum values of each and the time at which they occur in the material can be controlled somewhat by small percentages of sodium in the cavity gas. Such characteristics can guide materials selection.

1. INTRODUCTION

Lifetime estimates for first structural walls of proposed inertial confinement fusion (ICF) reactors depend upon many design considerations including assessment of repetitive transient stresses. The work which follows describes the structural and material modelling used for the determination of dynamic mechanical and thermal stresses in the first wall of a light ion beam (LIB) system. The principal characteristics are based upon a LIB/ICF cavity design study of the University of Wisconsin Fusion Engineering Program [1]. The basic configuration is a circular cylinder shell structure charged with a cavity gas. Cavity parameters are listed in Table I.

Table I

Cavity Parameters

Wall
  Radius = 4 m
  Height = 8 m
  Material = HT-9 or 316 SS
  Design = cellular

Gas
  Composition = argon with 0-2% sodium
  Density = 1.8×10^{18} cm^{-3}
  Initial temperature = 0.1 eV

Target
  Yield = 100 MJ
  X-ray + ion debris energy = 30 MJ
  Initial fireball radius = 10 cm
  Repetition rate = 10 Hz

2. BLAST WAVE

The largest potential for damage to the first wall of a LIB fusion reactor is not directly from the target explosion generated ions and X-rays because they will be stopped in the 10-100 Torr of cavity gas provided $Z > 10$. It should be noted that only "soft" X-rays, below about 1 keV, are necessarily stopped this effectively [2]. Higher energy X-rays will tend to penetrate deeper into the gas, possibly reaching the reactor first wall. However, these "hard" X-rays should not greatly damage wall components. The deposition of this energy into the gas creates a fireball which may propagate to the wall as a blast wave [3] with its possibly damaging overpressure and flux of radiant heat. Since the characteristics of the fireball are to a large degree determined by the propagation of radiation through the gas, the heat fluxes and overpressure at the first wall of the reactor may be controlled by the optical properties of the cavity gas. Here we investigate whether a cavity gas of 1.8×10^{18} cm^{-3} argon (50 Torr at 0°C) mixed with 0-2% by volume of sodium vapor can provide adequate protection for a reactor first wall. The argon can easily stop the target generated soft X-rays and ion debris while the sodium controls the opacity of the gas.

To calculate the propagation of the fireball to the first wall of the reactor, it is necessary to first determine the equation-of-state of the cavity gas and its resistance to the flow of photons. This is done with a computer code MIXER [4]. The atomic physics of a monatomic gas is modelled by assuming that the average ionization state follows the Saha formalism at high density and low temperature or the coronal model otherwise and that the six most populous ionization states have densities spread in a Gaussian about the average. The first twenty atomic energy levels are included where their populations are assumed to obey Boltzmann's law. In the Saha model, recombination is through three body recombination so that the ionization state of a minority species, sodium in this case, whose density is much smaller than that of the majority species, is very different from what it would be if the majority species was not present. For this reason, we cannot calculate the properties of the gas separately for each species and then combine them in some manner but must calculate the properties of the combined gases for each different concentration of sodium. Once the equation-of-state of the gas has been calculated, the Rosseland and Planck averaged mean free paths for radiation are calculated considering photo-ionization, inverse Bremsstrahlung, atomic line absorption and Thompson scattering as photon stopping mechanisms [5].

This analysis shows that, as long as one considers photons with energies greater than the first ionization potential, photo-ionization is the dominant mechanism of photon stopping. When the photon energy drops below this energy, the absorption coefficient drops by several orders of magnitude so that the gas is relatively transparent to low energy photons. An inert gas like argon with a high value for the first ionization energy will be transparent to much higher energy photons than an alkali metal vapor like sodium. Thus, the addition of a small amount of sodium will not significantly change the opacity of the gas to higher energy photons but will greatly increase the opacity to low energy photons.

A hydrodynamic radiative transfer computer code, FIRE, has been used to simulate this behavior in fireballs [6]. FIRE is a one-dimensional hydrodynamics code that calculates the dynamics of two fluids; the plasma at its own temperature and the radiation at its own temperature. The transport of the radiation fluid is flux limited and upstream averaged. The equation-of-state of the plasma and mean free paths of radiation in the gas are read from tables of data provided by the atomic physics code MIXER.

A series of blast wave calculations have been performed with FIRE. The results obtained are outlined in Table II for sodium concentrations of 0.2% and 2.0%. Notice that the energy radiated and the maximum heat flux to the first wall decrease while the overpressure increases with increasing sodium concentration.

Table II

Results of Fireball Calculations

	Sodium Concentration (%)	
	0.2	2.0
Energy radiated* (MJ)	0.760	0.10
Shock pressure (MPa)	0.296	0.335
Max. heat flux to wall (kW/cm^2)	0.628	0.035

*Energy radiated to first wall in the first 2.5 ms following the target explosion

Clearly, by adjusting the sodium concentration, one can maximize the total effect of the overpressure and heat flux on the first wall. Figure 1 shows the time development of the heat flux and overpressure for a 0.2% concentration of sodium. In this case, the peak heat flux occurs in coincidence with the maximum overpressure. In pure argon, similar calculations have shown the heat flux reaches the wall much sooner than the shock.

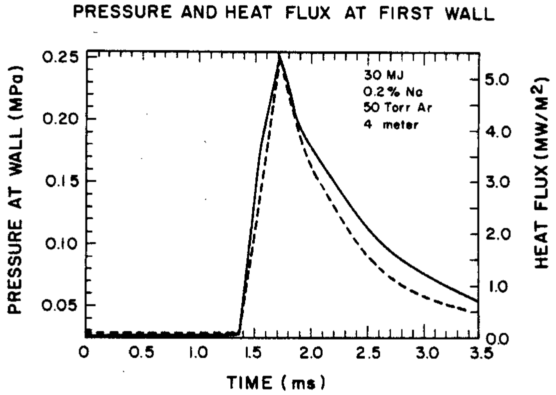

Figure 1. Pressure and heat flux at first wall.

3. CAVITY STRUCTURAL SYSTEM

While the general shape of the cavity is cylindrical, the first wall is not considered as a simple structural shell but instead made up of plate-like components supported by a frame of axial stringers and circumferential ribs (Figure 2). Since the design lends itself well to modular construction, a single panel may be of this size but still span many members of the supporting gridwork. The plate units sustain the dynamic overpressure primarily by flexural action, transmitting radial loads to the frame. In flexure, hollow plates have much higher ratios of strength to weight and stiffness to weight. First walls of this type are also naturally well suited for internal coolant flow and the low structural mass is an advantage for a higher level of tritium breeding.

4. MECHANICAL STRESSES

The primary loading on the first structural wall is the dynamic overpressure. A typical pressure pulse is shown in Figure 1. As it loads the cavity side of the plate, tensile stresses develop near the supports while the state of stress in the central region of the face is compressive. The stresses reverse signs cyclically as the plate responds dynamically as shown in Figure 3. It can be seen that forced vibration takes place for a very short time with free vibration characterizing the greater portion of the response period. Additional details of dynamic stress calculations can be found in [7]. The plate geometry is the same for the various examples: height and span are 200 and 63 cm, respectively; the inner and outer faces are each 0.5 cm thick while the total plate thickness is 4.4 cm. Damping is

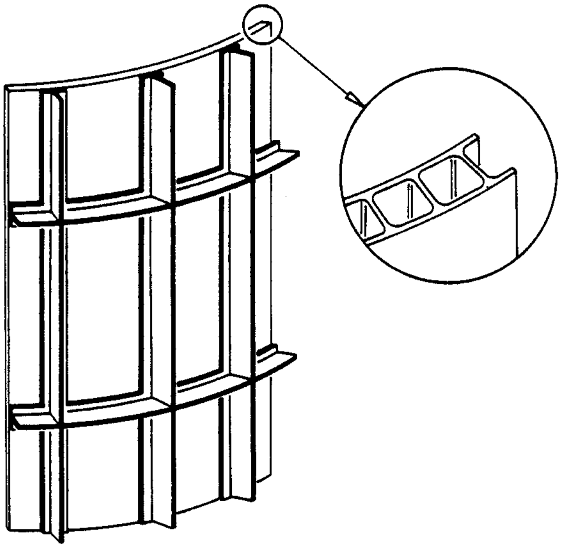

Figure 2. Conceptual first wall structural system.

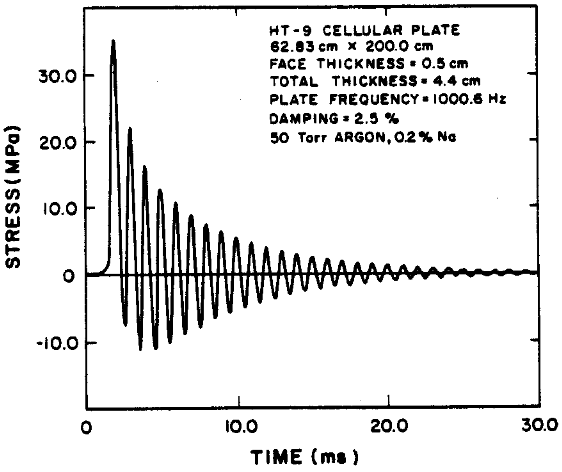

Figure 3. Compressive flexural stress vs. time.

equivalent to 2.5% of the critical value. This corresponds to the mean value of tests on pressure vessels and tanks at stresses less than 10% of the yield [8]. It is desirable to have the stress and motion damped out between pulses. This is a function of the repetition rate, plate natural frequencies, as well as the damping level. Figure 4 can be used as a guide for this purpose. For example, with a repetition rate of 10 Hz and a fundamental plate frequency of 1000 Hz (ω/R = 100), the amplitude at the end of the repetition period is 1/1000 of the value initially for damping slightly larger than 1%. If the damping and repetition rate are fixed in a particular case, it may be necessary to design the plate geometry to have a vibrational frequency high enough to allow the system to come to rest between pulses.

5. THERMAL STRESSES

The large heat fluxes on the first wall can cause large temperature gradients through the first wall material. These temperature gradients can cause correspondingly large stresses due to differential expansion of the material. The stress state may also be altered by membrane loads, irradiation induced differential swelling, and residual stresses caused by thermal and irradiation creep-induced stress relaxation. Residual stress may be especially important to wall lifetime because it can cause the total stress on the inner face of the cavity wall to change from compression to tension. This may cause the growth of cracks and lead to failure of the wall [9].

The transient stress code TSTRESS [10] has been developed to provide stress histories for given temperature profiles. The effects of expansion,

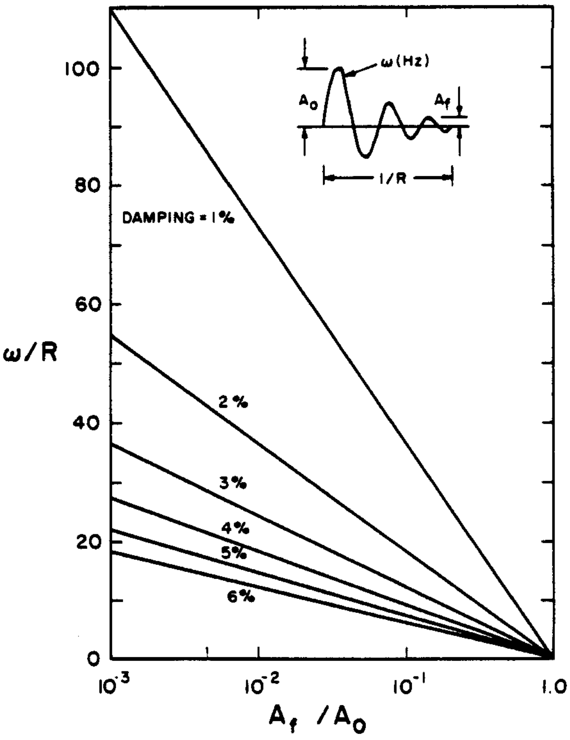

Figure 4. Plate frequency/repetition rate vs. final amplitude/original amplitude for various percentages of damping.

external membrane loads, swelling and creep are included in the code. A temperature diffusion code PELLET has been developed to take the heat fluxes generated in FIRE and create a series of temperature profiles across the width of the first surface for various times. This information is then used in TSTRESS to generate the thermal stress histories, shown for example in Figures 5 through 8.

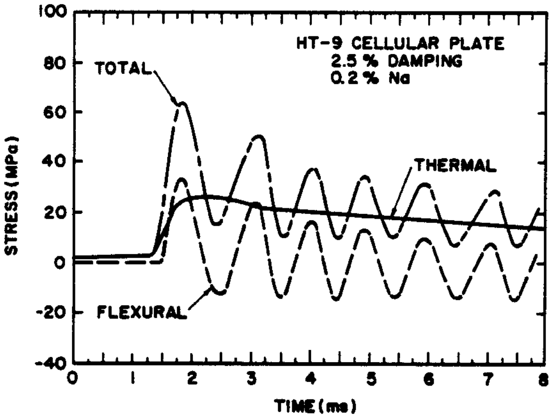

Figure 5. Combined compressive stress vs. time.

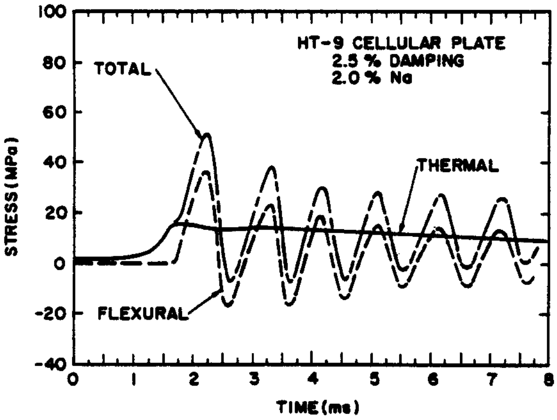

Figure 6. Combined compressive stress vs. time.

6. TOTAL STRESS

The thermal stress histories from TSTRESS can be combined with the flexural mechanical stress to give the total stress needed for fatigue lifetime analysis. Figures 5 through 8 show the thermal, mechanical and total stresses at the center of the inside face of the wall panels plotted against time for a number of cases. Figures 5 and 6 show stress histories for an

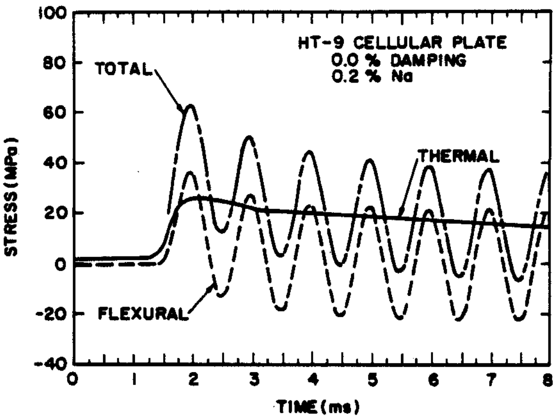

Figure 7. Combined compressive stress vs. time.

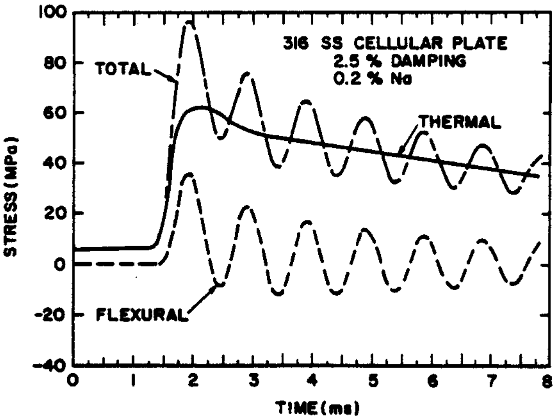

Figure 8. Combined compressive stress vs. time.

HT-9 plate with 2.5% damping for cavity gases with 0.2% and 2.0% sodium, respectively. Table II shows that the heat flux is much lower and the overpressure is larger in the latter case. The effect of this is seen in Figure 6 where the total stress is dominated by the mechanical stress while the mechanical and thermal stresses are approximately equal in Figure 5. The total stress is slightly higher in the 0.2% sodium case. A similar plot for pure argon would show the thermal stress dominating. Figure 7 is the stress history for 0.2% sodium with no damping. Notice that there is a significant difference between the damped and undamped flexural and total stresses by the sixth oscillation. Figure 8 shows the 2.5% damped behavior of a 316 stainless steel wall for a 0.2% sodium cavity gas. The thermal stress in this case is much higher than for HT-9 because the lower conductivity of 316 stainless steel results in larger temperature gradients.

7. CONCLUSIONS

It has been shown that the total stress state in first wall materials of LIB/ICF reactors depends upon many parameters. These include not only cavity gas composition, but also the thermal, mechanical and inertial characteristics of the materials. The combined stress is oscillatory in nature following each power pulse. Thus, the determination of this response is necessary in order to assess fatigue degradation of the wall. These analyses then become the basis for more accurate lifetime predictions.

ACKNOWLEDGMENT

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