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Chamber wall response to target implosion in inertial fusion reactors: new and critical assessments☆,☆☆

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Abstract

The chamber walls in inertial fusion energy (IFE) reactors are exposed to harsh conditions following each target implosion. Key issues of the cyclic IFE operation include intense photon and ion deposition, wall thermal and hydrodynamic evolution, wall erosion and fatigue lifetime, and chamber clearing and evacuation to ensure desirable conditions prior to next target implosion. Several methods for wall protection have been proposed in the past, each having its own advantages and disadvantages. These methods include use of solid bare walls, gas-filled cavities, and liquid walls/jets. Detailed models have been developed for reflected laser light, emitted photons, and target debris deposition and interaction with chamber components and have been implemented in the comprehensive HEIGHTS software package. The focus of this study is to critically assess the reliability and the dynamic response of chamber walls in IFE systems. Of particular concern is the effect on wall erosion lifetime due to various erosion mechanisms, such as vaporization, chemical and physical sputtering, melt/liquid splashing and explosive erosion, and fragmentation of liquid walls.

Keywords: Chamber walls; Inertial fusion reactors; IFE systems

1. Introduction

In inertial fusion systems, the power to the first wall resulting from X-rays, neutrons, energetic particles, and photon radiation is high enough to cause damage and dynamically affect the ability to reestablish chamber conditions prior to the next target implosion. In the case of a dry-wall protection scheme, the resulting target debris will interact and affect the surface wall materials in different ways. This can result in the emission of atomic (vaporization) and macroscopic particles (i.e. liquid droplets or carbon flakes), thereby limiting the lifetime of the wall. The mass loss in the form

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of macroscopic particles can be much larger than mass loss due to surface vaporization and has not been properly considered in past studies as part of the overall cavity response and re-establishment. This could significantly alter cavity dynamics and power requirements.

The overall objective of this work is to create a fully integrated model within the HEIGHTS software package [1] to study chamber dynamic behavior after target implosion. This model includes cavity gas hydrodynamics, the particle/radiation interaction, the effects of various heat sources (e.g., direct particle and debris deposition, gas conduction, convection, and photon radiation), chamber wall response and lifetime, and the cavity clearing. The model emphasizes the relatively long-time phenomena following the target implosion up to the chamber clearing in preparation for the next target injection. It takes into account both micro- and macroscopic particles (mechanisms of generation, dynamics, vaporization, condensation, and deposition due to various heat sources: direct laser/particle beam, debris and target conduction, convection, and radiation). These processes are detrimental and of significant importance to the success of inertial fusion energy (IFE) reactors [2].

The hydrodynamic response of gas-filled cavities and photon radiation transport of the deposited energy have also been calculated in detail by means of new and advanced numerical techniques [3,4]. In addition, fragmentation models of liquid jets as a result of the deposited energy have been developed, and the impact on chamber clearing dynamics has been evaluated [5].

The experience gained from the use of HEIGHTS-MFE package [1], which contains unique models and physics for magnetic fusion energy was applied to simulate the dynamics of chamber behavior in inertial fusion reactors. Various aspects of the HEIGHTS-MFE models have been benchmarked and tested against worldwide simulation devices and tokamak reactors in Japan, Europe, Russia, and the US. Besides magnetic fusion research, the HEIGHTS package has been used and is currently being applied to the space program (Fire & Ice project), high-energy physics program (muon collider and neutrino factory projects), nuclear physics program (RIA project) and medical (isotope production and arc injury), and defense applications.

2. Model considerations

Following the micro-explosion in an IFE reactor, high-energy X-rays and ions are produced and directed toward the chamber wall at high but different velocities. Some of their energy is deposited in the residual or protective chamber gas, and is re-radiated to the wall over a relatively longer time. Fig. 1 shows a schematic illustration of the energy deposition on the chamber wall.

As a result of thermonuclear burn in inertially confined fusion (ICF) reactors, the first wall is exposed to photon radiation and ion fluxes with a wide range of energies. The energy deposited in a material can be calculated from various mathematical models for energy loss for each radiation type. Our HEIGHTS contains extensive analysis of these processes, including energy deposition from photons, ions, and laser beams [2].

The thermal response of the chamber wall exposed to thermonuclear radiation is determined if the time- and space-dependent energy depositions are known. Melting can occur in the case of a metallic wall during intense deposition of energy. Complexities in modeling this process arise due to the behavior of melt layers under various forces that can lead to significant wall material loss. Mechanisms that contribute to melt layer loss are partially known and include effects such as splashing due to formation and boiling of volume bubbles that result from continuous heating, and overheating of the liquid and other hydrodynamic instabilities [1–6]. Laboratory experiments on the effects of high heat fluxes and beam deposition on target materials have shown the formation of numerous liquid droplets that are splashed and lost during beam-target interaction [7,8]. Because melt layer thickness is usually much larger than the surface vaporization, splashing erosion of developed melt layer could be quite important in determining the lifetime of IFE chamber walls [9–11]. Although macroscopic erosion is difficult to model because many processes are involved, we

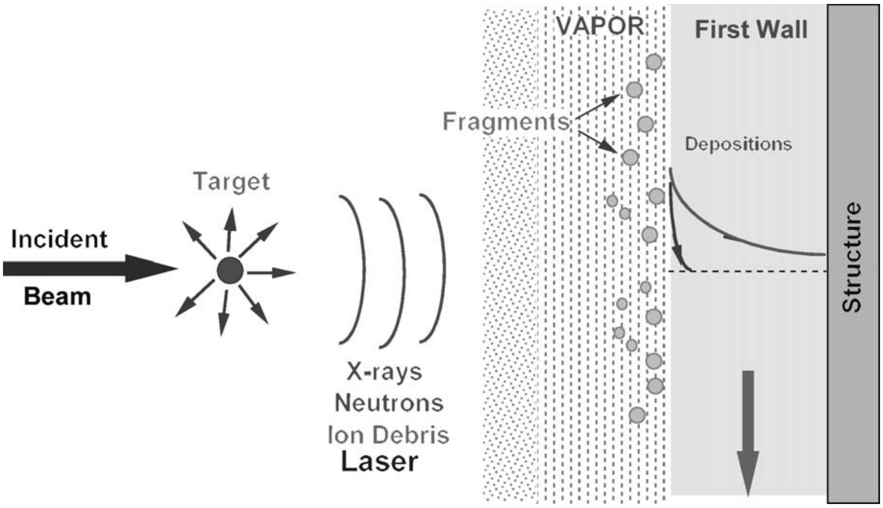

Fig. 1. Schematic of energy deposition on chamber wall.

are developing models that build on the experience gained from magnetic fusion as investigated earlier using the HEIGHTS package [10].

Erosion by particle sputtering can be important depending on the impacting ion energy and chamber conditions [2]. A physical model has been developed to calculate chamber wall erosion due to various debris bombardments. This physical sputtering can be an important erosion mechanism in ICF reactors. Chemical sputtering due to formation of volatile molecules on the wall surface between incident particles and walls made of carbon-based materials (CBMs) can also be an erosion mechanism. In addition, for CBMs, enhanced erosion yields, known as radiation-enhanced sublimation (RES), were observed during ion bombardment at higher wall temperatures above 1200 K. A model has been developed and implemented in HEIGHTS to calculate this effect as a function of wall temperature [2].

The above mentioned erosion mechanisms must be taken into consideration to provide accurate net mass loss during each time step following thermonuclear burn as input for the cavity hydrodynamic response. The actual condensation and redeposition rate of wall material will depend on the cavity conditions, as well as the type of erosion products. The interaction and redeposition of macroscopic erosion products are complicated and initial models are being developed to assess the geometrical effects of the cavity chamber on overall net wall erosion and on cavity clearance before the next target injection.

The energy released to the wall during thermonuclear burn is partitioned among different species: reflected laser light, X-rays, neutrons, and plasma debris [2]. The plasma particles consists of both fast and debris ion fluxes. In the case of a laser-driven system, the reflected laser light from target surface can contribute to the total energy released to the wall. The energy released and spectra of the X-rays can vary over a wide range depending on target design and driver beam. Energy deposition from X-ray and fast ion and debris particles occurs near the wall surface whereas the energy of neutrons is deposited through relatively much larger material volumes.

A major goal of HEIGHTS analysis is to evaluate fine details of the near surface evolution of the chamber wall which includes temperature rise, erosion rate, physical and chemical sputtering, radiation-enhanced sublimation, evaporation, and melting. Therefore, the spatial mesh distribution is treated very carefully and great attention is paid to the thermal evolution near the surface, particularly when significant wall vaporization and melting occurs. The wall temperature distribution is computed in great detail as a function of space mesh size to ensure accurate calculations. Previous calculations of wall surface temperatures by other authors are believed not to be correct due to this particular point [12,13].

3. Photon interaction

The primary interaction of photons with materials includes the photoelectric effect, coherent and incoherent scattering, and pair production. Cross sections for each of these reactions have been tabulated in various forms and are available for numerical calculation [2].

The HEIGHTS-IFE package calculates the volumetric energy deposition for a given X-ray spectrum or monoenergetic photons. Photon spectra may be specified as blackbody or in histogram form. Deposition is based on general photoelectric and incoherent cross section libraries that have been incorporated into the package. The wall thermal response to photon deposition can be determined if the photon spectrum is specified [2]. The deposition of X-rays into first wall materials will strongly depend on the energy spectrum of these X-rays. Soft X-rays deposit their energy within a micrometer of the wall's surface, very rapidly heating a thin layer of the first wall to a higher temperature. Harder X-ray energy spectra penetrate relatively longer distances into material, therefore heating a larger mass to a lower temperature.

HEIGHTS-IFE numerical simulation results of target implosion were obtained using the NRL direct drive target spectra [14] deposited in both a carbon-fiber-composite (CFC) and tungsten wall materials. As shown in Fig. 2, the CFC (low-z) allows X-rays to penetrate much deeper than in tungsten (high-z) and as a result, a lower temperature rise is expected. The package can also represent the chamber wall in a multi-component structure. Fig. 3 shows results of X-ray deposition calculation in a composite Li/Pb film on carbon structure. For the Li film case, most of the X-ray energy is penetrated through while for the Pb film most of the energy is absorbed in the 1 mm thick film.

4. Ion interaction and deposition

Ion deposition calculations are performed using several models to predict the behavior and the slowing down of incident ion fluxes in various candidate materials. Incident ion spectra can be approximated using Maxwellian, Gaussian, or histogram distributions.

The interaction of charged particles with materials is primarily due to two processes [15–18]. The first is between the incident ion and the electrons of the wall material, which is an inelastic collision. The second interaction is collision of the ions with wall material nuclei, which is an elastic interaction. The dominant mechanism of ions slowing down in materials is dependent upon the instantaneous energy of the moving ion. Several extensive methods are used in our HEIGHTS calculations for deposition and interaction of fast and slow debris ions in various wall materials. These methods have been compared, and the range of validity of each method is well-established [2].

Fig. 4 shows HEIGHTS-IFE calculations for the energy loss of fast and debris ions in a tungsten wall. HEIGHTS-IFE was able to simulate ion deposition in other uniform (CFC) or composite wall structures [2]. Particular attention must be taken when computing the total ion deposition function since each separate ion species arrives and deposits its energy at different times.

5. Thermal evolution of the chamber wall

The detail thermal evolution of a wall material exposed to thermonuclear radiation can be determined when all the time- and space-dependent energy-deposition functions are known. HEIGHTS-IFE solves the heat diffusion equation subject to several moving and boundary conditions. All thermal properties of the composite wall structures are assumed to vary with temperature.

The rapid heating of first-wall components due to X-ray and ion debris deposition in ICF reactors may lead to melting and subsequently to surface evaporation. As a result, an accurate analysis of this heat conduction problem initially requires the solution of at least two moving boundary pro-

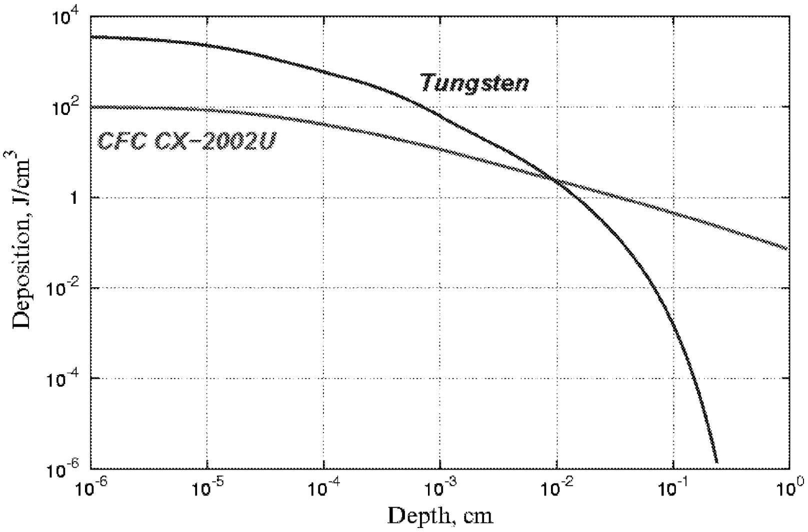

Fig. 2. X-ray deposition in graphite and tungsten walls.

blems. A moving front where vaporization occurs becomes one boundary and a second moving boundary is internal between the liquid and solid interface. Because of moving boundaries and the temperature dependent properties of both the liquid and solid states, the problem is highly nonlinear.

HEIGHTS-IFE calculates the wall thermal evolution in fine detail. The time evolution starts from the arrival of the X-rays, then the reflected laser lights, then the neutrons, then the fast and slow ion debris. In the case of a gas-filled cavity, the re-radiated absorbed gas energy in form of soft X-ray energy is also taken into account [3]. The surface temperature is determined both from boundary conditions and kinetics of the evaporation process. Correct boundary conditions entail partitioning of the incident energy flux into conduction, melting, evaporation, and possible radiation flux. The kinetics of evaporation establishes the connection between the surface temperature and the net atom flux, leaving the surface taking into account the condensation flux.

The surface temperature of the carbon and tungsten wall materials is presented in Fig. 5. This calculation is for a bare-wall concept with no protection and for the lower yield NRL direct target spectra. Fig. 5 also shows the time evolution

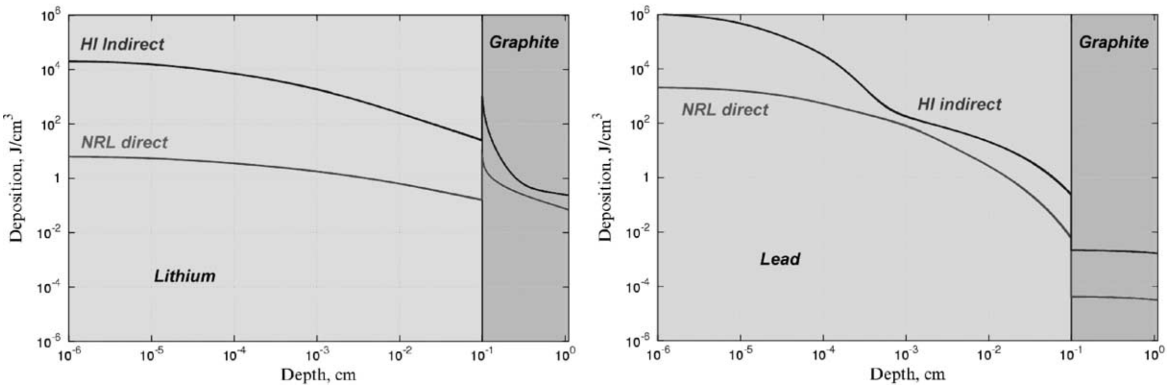

Fig. 3. X-ray deposition in composite wall structure.

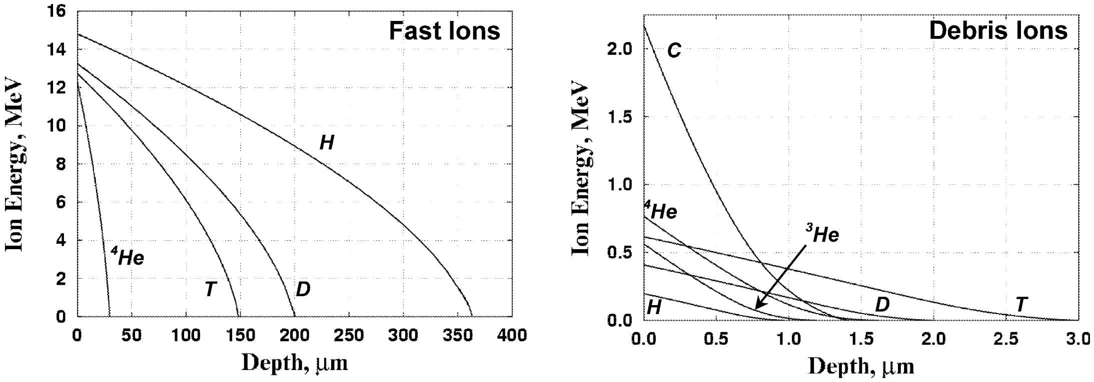

Fig. 4. Ranges and stopping power of fast and debris ions in tungsten.

of the wall thermal response due to the sequence of different incident species. The 3-D distribution of the surface temperature in both time and depth is shown in Fig. 6 for a tungsten wall.

6. Erosion processes

The erosion mechanisms of debris/surface interaction include physical sputtering, chemical sputtering, and radiation-enhanced sublimation. High-z materials, such as tungsten, show low effective sputtering yield at low ion energies and, therefore, may be the preferred choice. For higher ion energies and low-z materials, such as lithium or CBMs, the sputtering is less critical, but chemical erosion may become important and cause additional wall erosion.

Physical sputtering erosion is measured by a sputtering yield Y, defined as the mean number of atoms removed from the surface layer of the wall per incident ion. Sputtering yields and their dependence of the incident ion energy, mass, and angle have been studied theoretically, experimen-

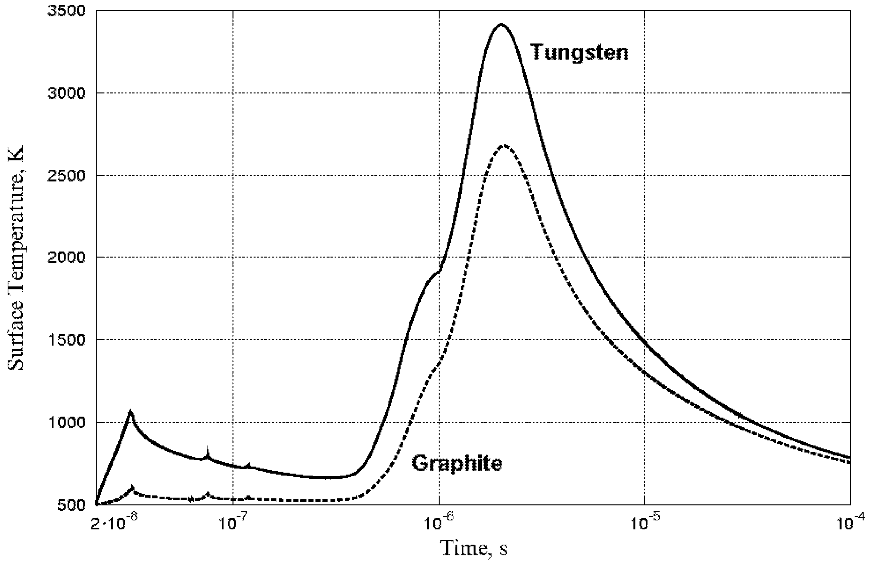

Fig. 5. Surface temperature rise due to direct drive target in graphite and tungsten.

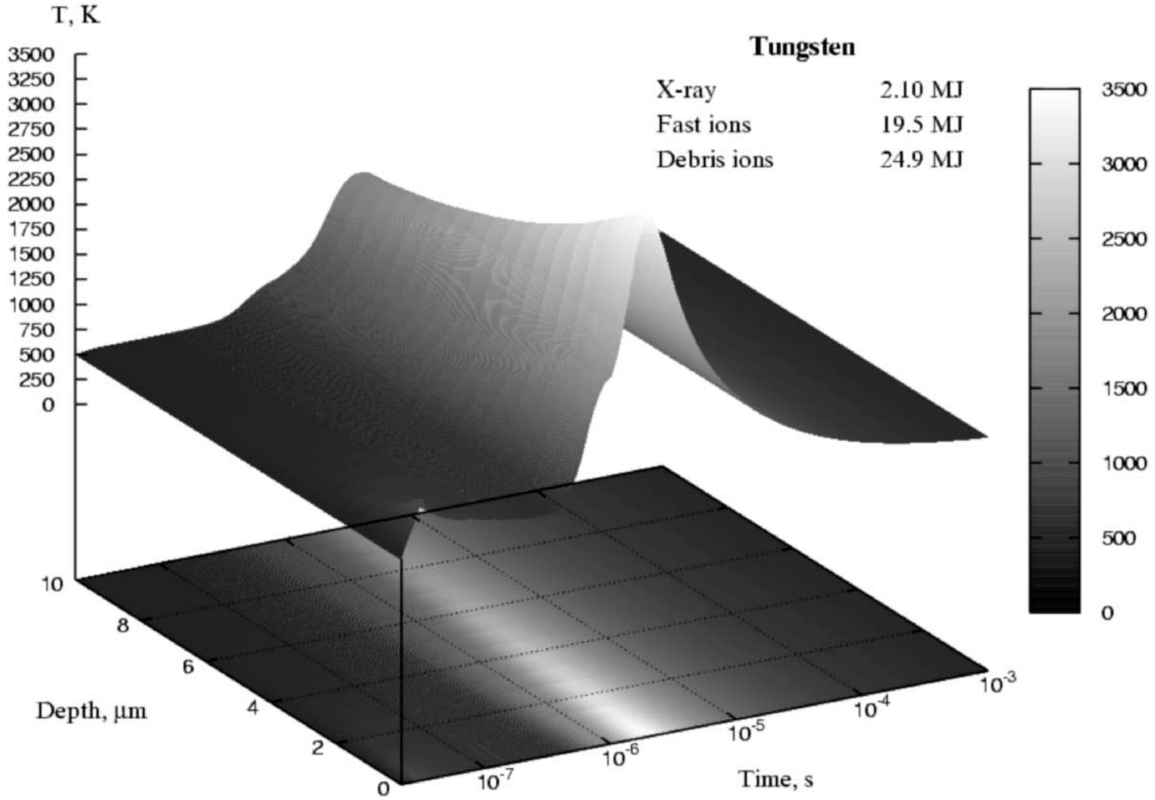

Fig. 6. Temperature rise due to laser, X-ray, and ion depositions.

tally and by computer simulation programs, such as the ITMC Monte Carlo code (part of the HEIGHTS package) [1].

Relatively high incident particle energies in the ICF condition will likely to cause lower sputtering yields. However, if a gas is employed for cavity protection without sufficient density to stop these energetic ions, it may result in higher sputtering erosion. The HEIGHTS-IFE package is able to study that in detail [2].

Chemical sputtering due to the formation of volatile molecules on wall surface is especially observed for hydrogen and oxygen bombardment of CBMs. This is especially important for hydrogen isotope and oxygen bombardment of graphite and CBMs due to the formation of hydrocarbon molecules (e.g. CH_4) and CO. In contrast to physical sputtering, chemical erosion strongly depends on the wall surface temperature. For oxygen irradiation of carbon, erosion yields close to unity are found basically independent on the incident energy and target temperature. For hydrogen irradiation of carbon, the chemical sputtering significantly depends on wall temperature and the incident energy. Chemical erosion yield reaches its maximum around 800 K. At low ion energies (<100 eV) the maximum decreases and the temperature dependence becomes broader such that at room temperature the chemical sputtering yield may exceed the values of physical sputtering [19]. The exact values of chemical sputtering of hydrogen isotope ions incident at very high energies is not known due to the deep penetration of these ions into wall materials.

For graphite, however, besides erosion by chemical sputtering enhanced erosion yields were measured for any ion bombardment at target temperatures above 1200 K [20–22]. This RES

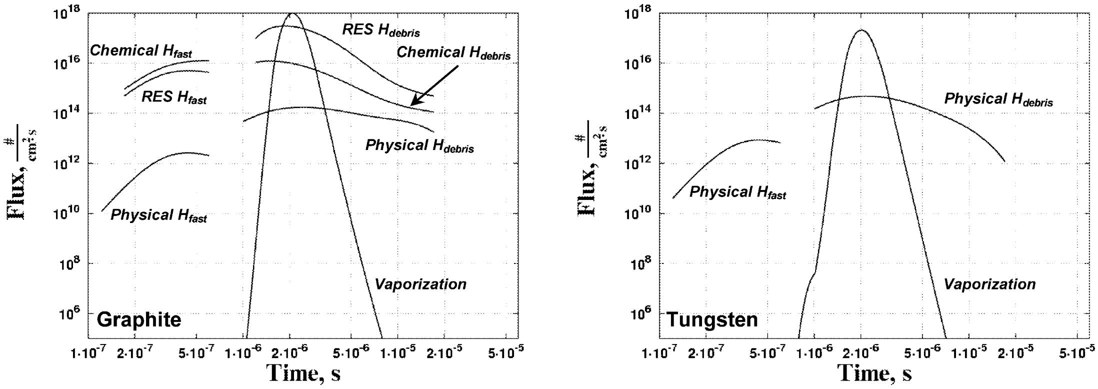

Fig. 7. Various erosion fluxes of graphite and tungsten.

occurs when interstitial atoms formed by the incident particles diffuse to the surface and then sublimate.

Fig. 7 presents results of HEIGHTS-IFE numerical simulation of various erosion mechanisms of both graphite and tungsten for the NRL direct target case [2]. Shown separately are the erosion rates caused by both fast and debris protons. It can be seen that for graphite, erosion by physical sputtering is at least two orders of magnitude lower than chemical erosion and RES. Fig. 8 compares the chemical, radiation-enhanced sublimation, and physical sputtering to incident particle flux of carbon and tungsten. In the case of graphite wall, chemical erosion and RES remain major erosion mechanisms, more than two orders of magnitude higher than erosion by physical sputtering. Despite the tungsten wall lacks both chemical sputtering and RES, its physical sputtering erosion is significant and can play a very important role in the total erosion yield.

7. Macroscopic erosion and brittle destruction

Modeling predictions indicate that surface vaporization losses of metallic materials can be lowered by different protection schemes. However, for liquid metal surfaces, ablation is predicted theoretically to be in the form of macroscopic metal droplets due to splashing of the molten layer.

Laboratory simulation experiments to predict erosion of candidate wall materials during a plasma disruption in magnetic fusion systems have also shown that erosion of metallic materials (such as W, Be, Al, and Cu) can be much higher than mass losses due only to surface vaporization.

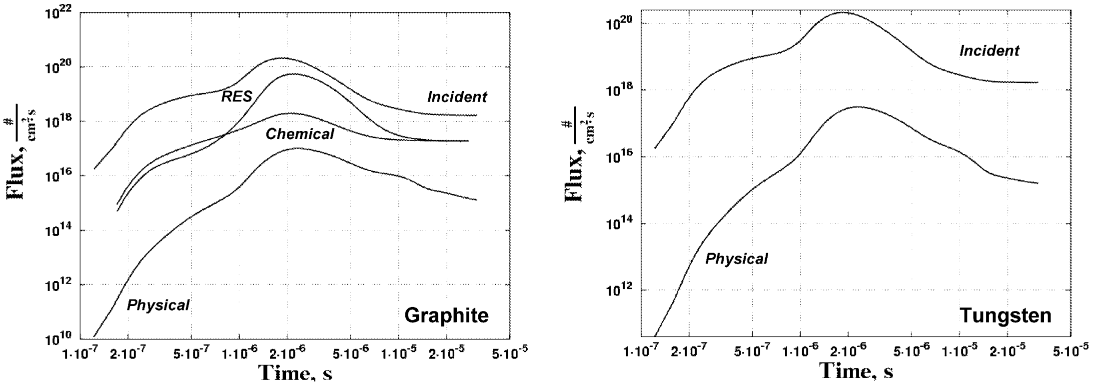

Fig. 8. HEIGHTS-IFE calculation of various wall erosion mechanisms.

The mass losses are in the form of liquid metal droplets. Such ablation occurs as a result of splashing of the liquid layer, mainly caused by boiling and explosion of gas bubbles in the liquid, absorption of debris momentum, and hydrodynamic instabilities developed in the liquid layer.

Nonmetallic materials such as graphite and CBMs have also shown large erosion losses, significantly exceeding that from surface vaporization. This has been observed in different laboratory simulation facilities such as electron beams, lasers, plasma guns, and other devices. This macroscopic erosion of CBMs depends on several main parameters, such as net power flux to the surface, exposure time, and threshold energy required for brittle destruction. Therefore, more relevant experimental data and additional detailed modeling are needed for inertial fusion devices to evaluate the erosion of CBMs, which strongly depends on the type of carbon material.

The ejected macroscopic particles from CBMs or splashed droplets from liquid surfaces will also form an aerosol cloud near the target surface. Therefore, accurate calculations of mass losses require full description of the media near the wall surface, which consist of a mixture of vapor and droplets/macroscopic particles moving away from the surface. These processes are quite important in evaluating chamber cavity clearing conditions prior to next target injection.

8. Conclusions

Models have been developed to study the dynamic behavior of ICF cavities following target implosions. These models take into account energy deposition from the reflected laser light, emitted photons, neutrons, and target ion debris and the interaction/thermal evolution of chamber gas/wall components. The models are implemented in the comprehensive HEIGHTS-IFE package. The hydrodynamic response of gas-filled cavities and photon radiation transport of the deposited energy can also be accurately calculated as well as models for fragmentation of thick or thin liquid jets as a result of the deposited energy.

Several erosion-causing mechanisms are modeled and evaluated for assessing chamber wall lifetime. These erosion mechanisms include vaporization, chemical and physical sputtering, radiation-enhanced sublimation, melt/liquid splashing, and macroscopic erosion. Depending on target yield and cavity gas pressure, most of these erosion mechanisms could be important factors in determining the best choice material and the overall lifetime of chamber walls in IFE reactors.

Acknowledgements

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