Simulating thermo-mechanical interaction between a xenon gas-filled chamber and tungsten first-wall armor for the LIFE reactor design using the BUCKY 1-D radiation hydrodynamics code

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Abstract. The BUCKY 1-D radiation hydrodynamics code has been used to simulate the dynamic thermo-mechanical interaction between a xenon gas-filled chamber and tungsten first-wall armor with an indirect-drive laser fusion target for the LIFE reactor design.

Two classes of simulations were performed: (1) short-time (0–2 ms) simulations to fully capture the hydrodynamic effects of the introduction of the LIFE indirect-drive target x-ray and ion threat spectra and (2) long-time (2–70 ms) simulations starting with quiescent chamber conditions characteristic of those at 2 ms to estimate xenon plasma cooling between target implosions at 13 Hz.

The short-time simulation results reported are: (1) the plasma hydrodynamics of the xenon in the chamber, (2) dynamic overpressure on the tungsten armor, and (3) time-dependent temperatures in the tungsten armor. The ramifications of local thermodynamic equilibrium (LTE) vs. non-LTE opacity models are also addressed.

1. Introduction
The BUCKY 1-D radiation hydrodynamics code has been used to model the chamber conditions subsequent to the implosion of an indirect-drive DT target for the LIFE reactor study [1]. This analysis is crucial for estimating the survivability of a tungsten-armored oxide dispersion strengthened (ODS) ferritic steel first wall material. The results presented here address the long-term survivability of the tungsten wall, which is evaluated by determining the maximum temperature excursion of the tungsten surface facing the xenon chamber fill gas. The design criteria for survivability is set at 2400°C, the temperature limit for arresting cyclic stress crack propagation through the tungsten armor [2]. Other chamber design issues and feasibility of rep-rated ICF reactors are discussed in detail in Ref. 2.

2. Simulation Setup
2.1. Ion and X-ray Source
The LIFE indirect-drive target integrated yield is given to be 37.5 MJ — 4.5 MJ in x-rays, 3.8 MJ in ions and 29.2 MJ in neutrons and gamma rays [3].

For an indirect-drive target, the majority of the mass is located in the hohlraum surrounding the DT capsule. For the LIFE reactor, the hohlraum has a total mass of 230 mg. The chamber simulation used this mass at a Maxwellian temperature of 20 keV to create a kinetic energy distribution of the gold ion population. This ion source was launched at $t = 0$ seconds in the simulation.
The x-ray spectra was divided into 300 photon energy groups, ranging from 0.01 keV to 200 keV. Figure 1 shows the x-ray power vs. time, normalized to a 1 MJ total x-ray yield. Figure 2 shows the x-ray photon energy spectrum as emitted by the target and at the xenon-tungsten interface.

2.2. Chamber and Armor Characterization
The chamber fill gas is xenon at 226.6 Pa (1.7 torr) with an ambient temperature of 600°C [3]. The radius of the gas-armor interface is 2.5 m from the center of the target chamber. The simulation results reported here include a local thermodynamic equilibrium (LTE) EOS and opacity model and a non-LTE coronal model for the xenon chamber gas generated by the IONMIX code [4]. The chamber gas was partitioned into 450 hydrodynamic zones and a mass-matching boundary condition was used on the ten zones closest to the gas-armor interface.

The first-wall armor consists of a 308 μm layer of tungsten over a first-wall consisting of ODS low-activation ferritic steel at an ambient temperature of 600°C [3]. For the simulation results reported here, the tungsten-steel interface is treated as a fixed-temperature boundary condition of 600°C. YAC non-LTE data are used for tungsten armor opacities [5]. The armor material was partitioned into 50 finite-difference zones with logarithmic spacing and first-zone thickness of 100 nm.

For the solid and liquid phases of tungsten, the temperature-dependent values of thermal conductivity were obtained from the ITER Material Properties Handbook. The temperature dependent values for the specific heat capacity of tungsten were obtained from the NIST Standard Reference Database in the form of the Shomate equation. Phase changes were incorporated into the specific heat data by dividing the latent heats of fusion and vaporization by 232 K and inserting the resulting top hat functions into the specific heat data set with the midpoints on the melting and vaporization temperatures, respectively.

3. Simulation Results
3.1. Short-time Simulation
BUCKY was used to simulate the chamber for times 0 to 2 ms to capture the threat spectra and hydrodynamic effects on the chamber armor (figure 3). The dynamic surface temperature response and overpressure of the tungsten armor are reported in figure 4. The surface temperature response is driven primarily by the arrival of the unattenuated prompt x-rays of the target threat spectra (figure 2). The secondary rise in surface temperature observed at later simulation times is due to re-radiation from the xenon plasma. The overpressure data show chronologically distinct features, such as (i) the rise in overpressure due to x-ray heating of the xenon gas near the surface of the tungsten at approximately 20 ns, (ii) the steep rise in overpressure due to the arrival of the Marshak wave at approximately 4 μs, (iii) the arrival of the hydrodynamic shock wave driven by the ion energy deposition in the gas near the center.
Figure 3. The hydrodynamic zone radius vs. time (RT) plot of the xenon fill gas for the short-time simulation. For clarity only zones $1 + 10 \times (n - 1)$ $(n = 1, 2 \ldots 45)$ are plotted.

Figure 4. The overpressure and temperature at the xenon-tungsten interface.

...of the chamber at approximately 0.7 ms, and (iv) the arrival of a second hydrodynamic shock, which is a rebound shock as the gas “sloshes” around at approximately 1.9 ms. This is an artificial shock inherent to 1-D simulations, where multi-dimensional non-uniformities cannot defocus shocks rebounding from the solid interface.

The choice of opacity model (LTE vs. non-LTE) for xenon has an impact on the plasma properties and its ability to attenuate ion and x-ray energy. The plasma opacity model has the greatest impact in the hydrodynamic zones near the center of the chamber, as shown in the average charge state and ion temperature (figure 5), which are the values of the first hydrodynamic zone. Although the plasma properties are vastly different, the effect at the armor interface is minimal. The differing opacity models yielded no change in the x-ray heating temperature spike and the re-radiation temperature rise was increased by 50°C when using the non-LTE opacity model.

3.2. Long-time Simulation

The BUCKY results at the end of the 2 ms LTE simulation were used as initial conditions for an idealized 1-D thermodynamic analysis of the evolution of the xenon gas and tungsten surface temperatures to 70 ms. This analysis was predicated on the assumption that at 2 ms the xenon gas is at a uniform temperature with no hydrodynamic motion. A second was that the xenon gas and tungsten were in quasi-steady-state, allowing the use of classical thermal transport equations. The quasi-steady-state assumption is that the radiative heat transfer rate of the xenon gas is equal to the heat transfer rate via conduction through the tungsten layer. The radiative heat transfer rate for the sphere of xenon gas is given by

$$Q_R = 4\pi r_s^2 \varepsilon \sigma \left( T_g^4 - T_s^4 \right)$$  \hspace{1cm} (1)

where $r_s^2$ is the radius of the inner surface of the tungsten region, $\varepsilon$ is the emissivity of the body, $\sigma$ is the Stefan-Boltzmann constant, $T_g^4$ is the temperature of the xenon gas and $T_s^4$ is the temperature of the tungsten at the surface exposed to the xenon gas. The approximate heat transfer rate via conduction through a thin spherical shell is given by

$$Q_C = 4\pi \left( \frac{r_s r_b}{r_b - r_s} \right) k_W \left( T_s - T_b \right)$$  \hspace{1cm} (2)

where $r_b$ is the radius of the outer surface of the tungsten region, $k_W$ is the thermal conductivity of the tungsten layer and $T_b$ is the temperature of the outer surface of the tungsten layer. Using (1) and (2) the
value for \( \varepsilon \) can be calculated by
\[
\varepsilon = \frac{k_w}{\sigma} \frac{r_b / r_s}{T_s - T_b} \frac{T_s - T_g}{T_s^4 - T_g^4}.
\]

Using the temperatures reported by BUCKY at 2 ms, the value for \( \varepsilon \) is 3.16062 \times 10^{-3}. A simple 1-D finite-difference algorithm using (1) and (2) was used to calculate the chamber cooling. The calculation was performed using the NIST/ITER thermophysical data for tungsten, an initial gas temperature of 1.5 eV and initial surface temperature of 642.4°C. For xenon temperatures in excess of 6000 K, the specific heat evaluated at 6000 K was used. Figure 6 shows the temperature evolution of the xenon gas and tungsten surface calculated with a fixed \( \Delta t \) of 10 \( \mu \)s.

4. Conclusion
The temperature rise in the tungsten surface due to the x-ray flash brings the temperature at the interface to 2260°C, below the maximum design limit of 2400°C. This result confirms that the specified 1.7 torr of xenon chamber fill gas is sufficient to protect a 2.5 m tungsten-armored ODS ferritic steel first wall. However, an analysis of the 70 ms temperature shows that while the tungsten armor returns to the 600°C initial condition, the xenon gas temperature only relaxes to 2200°C. This result requires that analysis be conducted over many target shots to ascertain the self-consistent cyclic steady-state values for the xenon gas and tungsten armor.

Acknowledgments
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