Assessment of Carbon and Tungsten Dry Chamber Walls under IFE Energy Depositions

A. R. Raffray, M. S. Tillack, X. Wang, M. Zaghloul
University of California, San Diego

ARIES Meeting
Livermore
March 8-9, 2001
Outline of Presentation

• Thermal analysis
  – Consider C and W
  – Refined mesh for more accurate energy deposition calculations
  – Use material properties as a f(T), in particular k(T)
  – Inclusion of sublimation
  – Refined mesh for more accurate fiber analysis
  – Sensitivity analysis (total energy, ion energy deposition calculations)

• Lifetime issue
  – Identify possible erosion mechanisms
  – Assess relevance and order of magnitude for IFE application

• Concluding remarks
  – Status based on analysis
  – Remaining issues
Lifetime is a Key Dry Chamber Wall Issue

• Material Option (C, W, SiC ...)

• Material Configuration to Help Accommodate Energy Deposition

• Protective Chamber Gas, e.g. Xe
  - Effect on target injection
  - Effect on laser
  - UW has performed detailed comparative studies for different materials and gas pressures (R. Peterson/D. Haynes)

• Goal

  Dry wall material configuration(s) which can accommodate energy deposition and provide required lifetime without any protective gas in chamber
X-ray and Charged Particles Spectra

NRL Direct-Drive Target

1. X-ray (2.14 MJ)
2. Debris ions (24.9 MJ)
3. Fast burn ions (18.1 MJ)

(from J. Perkins, LLNL)
Energy Deposition Calculations

- **X-ray energy deposition through attenuation calculation**

- **Ion energy deposition dependent on energy level**
  - Electronic stopping power + Nuclear stopping power
  - Model uses spectra to follow ions at each energy level though the material slab until all energy is deposited

- **1-D radial geometry**
  - Very fine mesh at wall surface
  - No protective gas

\[
E_j(r_i) = E_j(r_1) - \sum_{i=1}^{i} \left[ \frac{d E_j(x)}{dx} \right]_i \Delta E_i
\]

A. R. Raffray, et al., Assessment of Carbon and Tungsten Dry Chamber Walls under IFE Energy Depositions
Ion Energy Deposition Calculations

Electronic stopping power
- Bethe model for $E > 1$ MeV/amu
- Lindhard model for $E < 1$ MeV/amu

Nuclear stopping power
- Important at low energy ($\sim$keV/amu)

Example case for $^4$He

Moses & Peterson (Laser and Particle Beams, 1994)
This analysis (Mohajerzadeh & Selvakumar, J. Appl. Phys., 1997)
Photon and Ion Attenuation in Carbon and Tungsten
Temporal Distribution of Energy Distribution from Photons and Ions Taken into Account

- Dramatic decrease in the maximum surface temperature when including temporal distribution of energy deposition
  - e.g. $T_{\text{max}}$ for carbon reduced from $\sim 6000^\circ C$ to $\sim 1400^\circ C$ for a case with constant $k_{\text{carbon}}$ (400 W/m-K) and without protective gas, presented at the Dec. 2000 ARIES meeting

Example Photon Temporal Distribution

From R. Peterson and D. Haynes’s presentation
At ARIES meeting September 2000.

Time-of-Flight Ion Power Spread

Temporal Distribution for Ions Based on Given Spectrum and 6.5 m Chamber

March 8, 2001

A. R. Raffray, et al., Assessment of Carbon and Tungsten Dry Chamber Walls under IFE Energy Depositions
Sublimation Can Be Estimated from the Vapor Pressure by Equating the Sublimating Flux to the Condensing Flux at Equilibrium

- From the kinetic theory of gases and using the Clausius-Clapeyron, the condensing flux, $G$ (kg/m$^2$-s) can be expressed as:

$$G = \alpha P \sqrt{\frac{M}{2\pi RT}}$$

Where $\alpha$ = coefficient of evaporation, or accommodation coefficient (conservatively set to 1 in our calculations)

- The evaporation heat flux, $q_{ev}$'' (W/m$^2$) can be estimated as:

$$q_{ev} = GH_{ev}$$

Where $H_{ev}$ = Latent heat of evaporation (J/kg)

- $P = 10^{(A - \frac{B}{T})}$

- $P = \text{Vapor pressure (Pa)}$ of material at temperature $T$(K)
- $M = \text{Molecular weight of material}$
- $R = \text{Universal gas constant (J/kmol-K)}$
- $A$ and $B$ are experimentally determined constants Consistent with several references, we use
- For C: $A = 14.8$ and $B = 40181$
- For W: $A = 12.74$ and $B = 44485$
Sublimation is a Temperature-Dependent Process Increasing Markedly at the Sublimation Point

**Carbon**
Latent heat of evaporation = $5.99 \times 10^7$ J/kg
Sublimation point ~ 3367 °C

**Tungsten**
Latent heat of evaporation = $4.8 \times 10^6$ J/kg
Melting point ~ 3410 °C

Use evaporation heat flux as a f(T) as surface boundary conditions to include evaporation/sublimation effect in ANSYS calculations

March 8, 2001

A. R. Raffray, et al., Assessment of Carbon and Tungsten Dry Chamber Walls under IFE Energy Depositions
Consider Temperature-Dependent Properties for Carbon and Tungsten

- C thermal conductivity as a function of temperature for 1 dpa case (see figure)
- C specific heat = 1900 J/kg-K
- W thermal conductivity and specific heat as a function of temperature from ITER material handbook (see ARIES web site)

Calculated thermal conductivity of neutron irradiated MKC-1PH CFC
Example Temperature History for Carbon Flat Wall Under Energy Deposition from NRL Direct-Drive Spectra

- Coolant temperature = 500°C
- Chamber radius = 6.5 m
- Maximum temperature = 1530 °C
- Sublimation loss per year = $3 \times 10^{-13}$ m (availability=0.85)

3-mm thick Carbon Chamber Wall

Coolant at 500°C

Energy Front

Evaporation

heat flux B.C at incident wall

Convection B.C. at coolant wall:

$h = 10$ kW/m²-K

March 8, 2001

A. R. Raffray, et al., Assessment of Carbon and Tungsten Dry Chamber Walls under IFE Energy Depositions
### Summary of Thermal and Sublimation Loss Results for Carbon Flat Wall

<table>
<thead>
<tr>
<th>Coolant Temp. (°C)</th>
<th>Energy Deposition Multiplier</th>
<th>Maximum Temp. (°C)</th>
<th>Sublimation Loss per Shot (m)</th>
<th>Sublimation Loss per Year (m)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>1</td>
<td>1530</td>
<td>1.75x10^{-21}</td>
<td>3.31x10^{-13}</td>
</tr>
<tr>
<td>800</td>
<td>1</td>
<td>1787</td>
<td>1.19x10^{-18}</td>
<td>2.25x10^{-10}</td>
</tr>
<tr>
<td>1000</td>
<td>1</td>
<td>1972</td>
<td>5.3x10^{-17}</td>
<td>1.0x10^{-8}</td>
</tr>
<tr>
<td>500</td>
<td>2</td>
<td>2474</td>
<td>6.96x10^{-14}</td>
<td>1.32x10^{-5}</td>
</tr>
<tr>
<td>500</td>
<td>3</td>
<td>3429</td>
<td>4.09x10^{-10}</td>
<td>7.73x10^{-2}</td>
</tr>
</tbody>
</table>

* Shot frequency = 6; Plant availability = 0.85

- Encouraging results: sublimation only takes off when energy deposition is increased by a factor of 2-3
- Margin for setting coolant temperature and chamber wall radius, and accounting for uncertainties
Example Temperature History for Tungsten Flat Wall Under Energy Deposition from NRL Direct-Drive Spectra

Key issue for tungsten is to avoid reaching the melting point = 3410°C

- Coolant temperature = 500°C
- Chamber radius = 6.5 m
- Maximum temperature = 1438 °C

3-mm thick W Chamber Wall

Coolant at 500°C

Energy Front

Evaporation heat flux B.C at incident wall

Convection B.C. at coolant wall:

h = 10 kW/m²-K

W compared to C:

- Much shallower energy deposition from photons
- Somewhat deeper energy deposition from ions

A. R. Raffray, et al., Assessment of Carbon and Tungsten Dry Chamber Walls under IFE Energy Depositions
Example Temperature History for Tungsten Flat Wall Under 5 x Energy Deposition from NRL Direct-Drive Spectra

- Illustrate melting process from W; melting point = 3410°C
- Include phase change in ANSYS by increasing enthalpy at melting point to account for latent heat of fusion (= 220 kJ/kg for W)
- Melt layer thickness ~ 1.2 μm

Separation = 1 μm
Summary of Thermal Results for Tungsten Flat Wall

<table>
<thead>
<tr>
<th>Coolant Temp. (°C)</th>
<th>Energy Deposition Multiplier</th>
<th>Maximum Temp. (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>1</td>
<td>1438</td>
</tr>
<tr>
<td>800</td>
<td>1</td>
<td>1710</td>
</tr>
<tr>
<td>1000</td>
<td>1</td>
<td>1972</td>
</tr>
<tr>
<td>500</td>
<td>2</td>
<td>2390</td>
</tr>
<tr>
<td>500</td>
<td>3</td>
<td>3207</td>
</tr>
<tr>
<td>500</td>
<td>5</td>
<td>5300</td>
</tr>
</tbody>
</table>

- Encouraging results: melting point (3410°C) is not reached even when energy deposition is increased by a factor of 3
- Some margin for setting coolant temperature and chamber wall radius, and accounting for uncertainties
Consider Engineered Surface Configuration for Improved Thermal Performance

- **Porous Media**
  - Fiber diameter ~ diffusion characteristic length for 1 µs
  - Increase incident surface area per unit cell seeing energy deposition

\[ \phi_{\text{fiber}} = \phi_{\text{incident}} \sin \theta \]

**ESLI Fiber-Infiltrated Substrate**

Large fiber L/d ratio ~100
Modeling Porous Fiber Configuration

Probability for energy front to contact fiber:
- over first unit cell, \( P_1 = \frac{d}{y} \)
- over second unit cell, \( P_2 = \frac{(1-P_1) \cdot d}{(y-d)} \)
- over third unit cell, \( P_3 = \frac{(1-P_1 \cdot P_2) \cdot d}{(y-2d)} \), etc...
up to \( P_n=(1-P_1 \cdot P_2 \cdot \ldots \cdot P_{n-1}) \cdot \frac{d}{(y-(n-1)d)} \)
where \( n=\frac{y}{d} \)

\[ y_{\text{eff}} = yP_1 + 2yP_2 + 3yP_3 + \ldots + nyP_n \]

Fiber Density, \((1-\varepsilon) = \pi d^2 / 4y^2\)
For \( \varepsilon=0.9 \) and \( d=10\mu m \), \( y=28\mu m \), \( y_{\text{eff}} = 54\mu m \)
For \( \varepsilon=0.8 \) and \( d=10\mu m \), \( y=19.8\mu m \), \( y_{\text{eff}} = 29.6\mu m \)
Photon+Ion Energy Deposition In Fiber

Example case
- Incidence angle = 30°
- Porosity = 0.9
- Fiber Length = 1 mm
- Fiber diameter = 10 μm
- Unit cell dimension = 28 μm
- Effective fiber separation = 54 μm
Example Thermal Analysis for Fiber Case

- Incidence angle = 30°
- Porosity = 0.9
- Effective fiber separation = 54 μm
- Sublimation effect not included

Convection B.C. at coolant wall:
- \( h = 10 \text{ kW/m}^2\text{-K} \)
- Coolant at 500°C

A. R. Raffray, et al., Assessment of Carbon and Tungsten Dry Chamber Walls under IFE Energy Depositions
Temperature Contour of Example Fiber Case at 2.5 μs

- Incidence angle = 30°
- Porosity = 0.9; Effective fiber separation = 54 μm
- Sublimation effect not included

Carbon Fiber

1 mm

10 μm

Coolant at 500°C

Convection B.C. at coolant wall: h = 10 kW/m²-K
Summary of Thermal Results for Carbon Fibrous Wall

Coolant temperature = 500 °C
Energy deposition multiplier = 1

<table>
<thead>
<tr>
<th>Porosity</th>
<th>Fiber Effective Separation (µm)</th>
<th>Incidence Angle (°)</th>
<th>Maximum Temp. (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>29.6</td>
<td>5</td>
<td>654</td>
</tr>
<tr>
<td>0.8</td>
<td>29.6</td>
<td>30</td>
<td>1317</td>
</tr>
<tr>
<td>0.8</td>
<td>29.6</td>
<td>45</td>
<td>1624</td>
</tr>
<tr>
<td>0.9</td>
<td>54</td>
<td>30</td>
<td>1318</td>
</tr>
<tr>
<td>C flat wall as comparison:</td>
<td></td>
<td></td>
<td>1530</td>
</tr>
</tbody>
</table>

- Initial results indicate that for shallow angle of incidence the fiber configuration perform better than a flat plate and would provide more margin
- Statistical treatment of incidence angle and fiber separation would give a better understanding
Sensitivity Analysis for Ion Energy Deposition Calculations

Comparison with NIST Data for He ion (ASTAR database)

Electronic stopping power
- Our values from the Bethe model for $E > 1$ MeV/amu are similar to NIST’s values
- Our values from Lindhard model for $E < 1$ MeV/amu are lower than the semi-empirical values of NIST (by a factor of up to ~10)
(They are lower than the NIST proton results (PSTAR) by a factor of up to ~5)

Nuclear stopping power
- Our values are the same as NIST’s values

- Perform a sensitivity analysis by conservatively multiplying the stopping power from Lindhard model by a factor of up to 10 and compare the resulting maximum temperature and sublimation to the previous results

March 8, 2001
A. R. Raffray, et al., Assessment of Carbon and Tungsten Dry Chamber Walls under IFE Energy Depositions

UCSD
Maximum Temperature History for Carbon Flat Wall for a case with 4 x Stopping Power of Lindhard Model

- The increase in stopping power results in higher ion energy deposition close to the surface and higher temperature
## Thermal and Sublimation Analysis Results for Carbon Cases with Artificially Higher Stopping Power in Lindhard Model

<table>
<thead>
<tr>
<th>Coolant Temp. (°C)</th>
<th>Stopping Power Multiplier</th>
<th>Maximum Temp. (°C)</th>
<th>Sublimation Loss per Shot (m)</th>
<th>Sublimation Loss per Year (m)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>1</td>
<td>1530</td>
<td>1.75x10^{-21}</td>
<td>3.31x10^{-13}</td>
</tr>
<tr>
<td>500</td>
<td>4</td>
<td>1950</td>
<td>2.25x10^{-17}</td>
<td>4.26x10^{-9}</td>
</tr>
<tr>
<td>500</td>
<td>10</td>
<td>3097</td>
<td>2.5x10^{-11}</td>
<td>4.7x10^{-3}</td>
</tr>
</tbody>
</table>

* Shot frequency = 6; Plant availability = 0.85

- The increase in stopping power results in higher ion energy deposition close to the surface and higher temperature
- However, even with a conservative factor of 10 increase in stopping power, the resulting temperature and sublimation loss are probably acceptable (although very marginal)
- We have to be vigilant with the design analysis of the dry wall but it appears that a design window is available based on sublimation loss (in particular when considering engineered surface)
Chamber Wall Erosion Lifetime for Dry Wall Concepts Potentially Dependent on a Number of Phenomena

• Main mass transfer mechanisms for carbon (in addition to sublimation)
  – Physical Sputtering
  – Chemical Sputtering
  – Radiation Enhanced Sublimation (RES)
  – Other (including macroscopic erosion due to thermo-mechanical effects under highly pulsed, irradiated conditions)
  – Condensation/redeposition

• Key parameters
  – Ion energy
  – Ion flux
  – Temperature
  – Angle of incidence
  – Surface characteristics (e.g. contaminants/dopants, smoothness..)

• Need to assess importance of different mass transfer mechanisms for IFE chamber conditions
Physical Sputtering Peaks at a Certain Ion Energy Level and is Independent of Temperature

- Sputtering yield peaks at ~1 keV and decreases with increasing ion energy level
  - Could be important for debris ions but not for fast ions
- High carbon self-sputtering yield
  - Small factor for IFE
- Sputtering yield peaks at an angle of incidence of ~80°
  - IFE case closer to normal incidence (0°)

Dependence of the physical sputtering yield of graphite on energy for H, D, He and C ions at normal incidence

Chemical Sputtering Depends Strongly on Temperature and to a Lesser Extent on Ion Energy Level

- Chemical sputtering is linked with formation of volatile molecules such as CO, CO$_2$ and/or C$_x$H$_y$

- Chemical sputtering yield peaks at ion energy level of ~0.5 keV and temperature of ~800K

  - Should not be a major factor for IFE
Radiation Enhanced Sublimation Observed in Carbon-Based Materials

Hypothesis

- Vacancy-interstitial pairs created by nuclear collisions
- Diffusing interstitials reach the surface and sublimate thermally with low binding energy

- Process increases dramatically with temperature
- Peaks with ion energies of ~1 keV

Rough Estimate of Radiation Enhanced Sublimation as Compared to Regular Sublimation

- Use extrapolation from sputtering yield vs ion energy results to estimate RES for carbon under IFE conditions (NRLdirect-drive spectra) for 1870 K
- Use extrapolation from RES sputtering yield vs temperature data to estimate effect of temperature

Results indicate that for this case regular sublimation is more important than RES above ~2600°C

Also, for our case with higher ion energies (>> 1 keV) it is possible that deeper penetration leaves longer diffusive paths for interstitial C and higher probabilities of recombination with vacancies.
A reasonable lifetime limit should be a few mm per year, less than $10^{-10}$ m a shot.

Depending on the chamber radius, an overall average sputtering yield of 1 could be accommodated, much larger than what is expected. For example, RES estimate for C under IFE conditions (NRL direct-drive spectra) for 1870 K corresponds to an average sputtering yield of 0.05.

It would be prudent to have measures for (infrequent) in-situ coating of chamber wall to guard against unforeseen local losses.

Shot frequency 6 Hz
Availability = 0.85
Total number of ions per shot = $1 \times 10^{21}$

Chamber radius = 3 m
Chamber radius = 6.5 m
Conclusions: Cautious Optimism for IFE Dry Chamber Wall Without Protective Gas

- Analysis results indicate that a design window exists for flat wall for reasonable chamber radius
  - Fine mesh provides more accurate results for energy deposition and thermal analyses
  - Sensitivity studies indicate that substantially higher heat deposition (2-3 times) could be accommodated for both C and W armor
  - However, uncertainty in ion energy deposition calculations could reduce this margin
  - Fiber surface would provide additional margins depending on angle of incidence (in particular for shallow angle of incidence)

- No data is available for C sputtering and RES under high energy ion fluxes and high temperature. However, based on existing data and extrapolation:
  - It appears that carbon sputtering would not be a problem since it peaks at energy ~ 1 keV, lower than most IFE ions
  - RES would be lower than regular sublimation for NRL-type direct drive spectra
  - Also, it is speculated that higher energy ions will create interstitial C and vacancies deeper in the C material. Longer diffusive path for the interstitial to reach the surface provides more chance for recombination with vacancies and lower RES
  - This needs to be confirmed through R&D and analysis
Conclusions: Cautious Optimism for IFE Dry Wall, but Important Issues Remain

- **Must separate thin armor region from structural backbone**
  - Most issues linked with armor itself
  - Possibility of repairing armor (in-situ)

- **Still many unknowns**
  - How to understand and apply properties and parameters derived for equilibrium conditions for highly-pulsed, irradiated IFE conditions (thin region (~10's of μm) of C (or W...)) which gets to high temperature (~2000 °C) in a highly cyclic manner, ~6 s⁻¹)
  - Erosion
    - Sublimation- and sputtering-based, but also
    - Macroscopic erosion (thermo-mechanical + irradiation effects on armor under IFE operating conditions)
  - Tritium inventory in carbon armor under high-temperature cyclic operation
    - It is thought that any implanted tritium within the thin armor layer would diffuse out to the high temperature, high diffusivity surface region and escape
    - Importance of irradiation trapping?
    - Co-deposition should not be a problem at high temperature but colder surfaces (e.g. in penetration lines) could be a problem
  - Prudent to have more than one option in case C is unacceptable (e.g. W)

- **Important not to underestimate issues and effort to resolve them**
  - Development of material configuration and resolution of these issues will take resources and time