Results from ARIES-IFE Study and Research Activities on IFE Chamber and Optics at UC San Diego

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Electronic copy:  http://aries.ucsd.edu/najmabadi/TALKS
UCSD IFE  Web Site: http://aries.ucsd.edu/IFE
Results from the ARIES-IFE study, Assessment of IFE Chamber Concepts.

IFE Research Activities at UC San Diego:

- Final Optics Experiments
- Chamber dynamics and clearing simulations
- Chamber wall simulation Experiments
Selected Results from ARIES-IFE Study

For ARIES-IFE Publications, see:
http://aries.ucsd.edu/ARIES/DOCS/ARIES-IFE/bib.shtml
ARIES Integrated IFE Chamber Analysis and Assessment Research Is An Exploration Study

Objectives:

- Analyze & assess integrated and self-consistent IFE chamber concepts
- Understand trade-offs and identify design windows for promising concepts.

*The research is not aimed at developing a point design.*

Approach:

- Six classes of target were identified. Advanced target designs from NRL (laser-driven direct drive) and LLNL (Heavy-ion-driven indirect-drive) are used as references.
- To make progress, we divided the activity based on three classes of chambers:
  - Dry wall chambers;
  - Solid wall chambers protected with a “sacrificial zone” (e.g., liquid films);
  - Thick liquid walls.

ARIES-IFE study was completed in September 2003.
Reference Direct and Indirect Target Designs

NRL Advanced Direct-Drive Targets

- 1 µm CH + 300 Å Au
- CH Foam + DT
  - DT Fuel
  - DT Vapor 0.3 mg/cc
- CH foam \( \rho = 20 \text{ mg/cc} \)

- 5 µm CH
- CH Foam + DT
  - DT Fuel
  - DT Vapor 0.3 mg/cc
- CH foam \( \rho = 75 \text{ mg/cc} \)

LLNL/LBNL HIF Target

- Ion beam characteristics:
  - 3.5 GeV Pb\(^+\) ions
  - 3.3 MJ input energy
  - 1.7 mm effective radius spot

• NRL Direct Drive Target Gain Calculations (1-D) have been corroborated by LLNL and UW.
Details of Target Spectra Has A Strong Impact on the Thermal Response of the Wall

- Heat fluxes are much lower than predicted in previous studies:
  - A much smaller portion of target yield is in X-rays.
  - Time of flight of ions spread the temporal profile of energy flux on the wall over several µs.
- A cover gas may not be necessary for protecting the chamber wall.

- Photon and ion energy deposition falls by 1-2 orders of magnitude within 0.1 mm of surface.
Selected Results from ARIES-IFE Study: Dry Wall Concepts
Thermal Response of a W Flat Wall

- NRL direct-drive target in 6.5-m chamber with no gas protection:
  - 3-mm thick W Chamber Wall
  - Evaporation heat flux B.C at incident wall
  - Convection B.C. at coolant wall: \( h = 10 \text{ kW/m}^2\text{-K} \)
  - Coolant at 500°C

- Temperature variation mainly in thin (0.1-0.2 mm) region.
- Margin for design optimization (a conservative limit for tungsten is to avoid reaching the melting point at 3,410°C).
- Similar margin for C slab.
All the Action Takes Place within 0.1-0.2 mm of Surface -- Use an Armor

- Photon and ion energy deposition falls by 1-2 orders of magnitude within 0.1-0.2 mm of surface.
- Beyond the first 0.1-0.2 mm of the surface, the first wall experiences a much more uniform q’’ and quasi steady-state temperature (heat fluxes similar to MFE).

Use an Armor
- Armor optimized to handle particle and heat flux.
- First wall is optimized for efficient heat removal.

- Most of neutrons deposited in the back where blanket and coolant temperature will be at quasi steady state due to thermal capacity effect
- Blanket design can be adapted from MFE blankets
- Significant high-energy ion flux on the armor.

Depth (mm):
- 0
- 0.02
- 1
- 3

Typical T Swing (℃):
- ~1000
- ~300
- ~10
- ~1

~ 0.2 mm Armor

3-5 mm Structural Material

Coolant
IFE Armor Conditions are similar to those for MFE PFCs (ELM, VDE, Disruption)

<table>
<thead>
<tr>
<th></th>
<th>ITER Type -I ELM’s</th>
<th>ITER VDE’s</th>
<th>ITER Disruptions</th>
<th>Typical IFE Operation (direct-drive NRL target)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>&lt;1 MJ/m²</td>
<td>~ 50 MJ/m²</td>
<td>~ 10 MJ/m²</td>
<td>~ 0.1 MJ/m²</td>
</tr>
<tr>
<td>Location</td>
<td>Surface near div. strike points</td>
<td>surface</td>
<td>surface</td>
<td>bulk (~µm’s)</td>
</tr>
<tr>
<td>Time</td>
<td>100-1000 µs</td>
<td>~ 0.3 s</td>
<td>~ 1 ms</td>
<td>~ 1-3 µs</td>
</tr>
<tr>
<td>Max. Temperature</td>
<td>melting/sublimation points</td>
<td>melting/sublimation points</td>
<td>melting/sublimation points</td>
<td>~ 1500-2000 °C (for dry wall)</td>
</tr>
<tr>
<td>Frequency</td>
<td>Few Hz</td>
<td>~ 1 per 100 cycles</td>
<td>~ 1 per 10 cycles</td>
<td>~ 10 Hz</td>
</tr>
<tr>
<td>Base Temperature</td>
<td>200-1000 °C</td>
<td>~ 100 °C</td>
<td>~ 100 °C</td>
<td>~ &gt;500 °C</td>
</tr>
</tbody>
</table>

- There is a considerable synergy between MFE plasma facing components and IFE chamber armor.
Direct-drive targets (initial T=18K) are heated during their travel in the chamber by:

- Friction with the chamber gas (mainly through condensation heat flux) requiring
  - Lower gas pressure
  - Slower injection velocity
- Radiation heat flux from hot first wall, requiring
  - Lower equilibrium temperature
  - Faster injection velocity
- Addition of a thin (~70µm) foam improves the thermal response considerably.
Design Windows for Direct-Drive Dry-wall Chambers

**Thermal design window**
- Detailed target emissions
- Transport in the chamber including time-of-flight spreading
- Transient thermal analysis of chamber wall
- No gas is necessary

**Target injection design window**
- Heating of target by radiation and friction
- Constraints:
  - Limited rise in temperature
  - Acceptable stresses in DT ice

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**Graphite Chamber Radius of 6.5m**

**Xe Density (Torr)**

**Max Equilibrium Wall Temp. to Avoid Vaporization (°C)**

- Laser propagation design window
- Experiments on NIKE
Selected Results from ARIES-IFE Study: Wetted Wall Concepts
Aerosol Generation and Transport is the Key Issue for Thin-Liquid Wall Concepts

A renewable thin-liquid protection resolve several issues:

- It can handle a much higher heat fluxes compared to solid surfaces;
- It will eliminate damage to the armor/first wall due to high-energy ions.

A renewable thin-liquid protection, however, introduces its own critical issues:

- Fluid-dynamics aspects (establishment and maintenance of the film)
  - “Wetted wall:” Low-speed normal injection through a porous surface
  - “Forced film:” High-speed tangential injection along a solid surface
- Chamber clearing (recondensation of evaporated liquid)
  - “Source term:” both vapor and liquid (e.g., explosive boiling) are ejected
  - Super-saturated state of the chamber leads to aerosol generation
  - Target injection and laser beam propagation lead to severe constraints on the acceptable amount and size of aerosol in the chamber.
Two Methods for Establishment of Thin-Liquid Walls Have Been Proposed

- X-rays and Ions
- Forced Film
- Injection Point
- Detachment Distance $x_d$
- Wetted Film
- First Wall
We Have Developed Wetted-Walls Design Widows for Establishment & Stability of the Protective Film

- Developed general non-dimensional charts for film stability over a wide variety of candidate coolants and operating conditions.
- Model predictions are closely matched with experimental data.
We Have Developed Design Widows for The Forced-Wall Concepts

- Developed non-dimensional design widows for longitudinal spacing of injection/coolant/removal slots to maintain attached protective film;

\[
\delta = 1 \, \text{mm} \\
\theta = 0^\circ
\]

\[
|\text{Plexiglas}|
\]

\[
\{ 
\begin{array}{c}
\text{Flat} \\
\text{Curved}
\end{array}
\]

- 1 mm nozzle
- 8 GPM
- 10.1 m/s
- 10° inclination
- \( Re = 9200 \)
Most of Ablated Material Would Be in The Form of Aerosol

- FLiBe aerosol and vapor mass history in a 6.5-m radius following a target explosion (ablated thickness of 5.5 mm)
- Most of ablated material remains in the chamber in aerosol form;
- Only homogeneous nucleation and growth from the vapor phase.

![Graph showing mass in chamber over time](image-url)
There Are Many Mechanism of Aerosol Generation in an IFE Chamber

- Homogeneous nucleation and growth from the vapor phase
  - Supersaturated vapor
  - Ion seeded vapor
- Phase decomposition from the liquid phase
  - Thermally driven phase explosion
  - Pressure driven fracture
- Hydrodynamic droplet formation (May be critical in Thick-liquid Wall concepts)
Selected Results from ARIES-IFE Study:
Thick Liquid Wall Concepts
Aerosol Generation and Transport is also the Key Issue for Thick-Liquid Wall Concepts

- Studies of structural materials choices and limits
  - If a 300 series SS is required as a near-term base line for the design, then Ti-modified 316SS (PCA) should be used. Chamber vessel would not be a life-time components.
  - However, it was strongly recommended to consider alternate structural material candidates (ferritic steels and SiC/SiC composites) offering the possibility of higher operating temperature & performance. In this case, chamber vessel may be a life-time component.

- Aerosol concerns (similar to thin liquids) were highlighted.
  - Hydrodynamic droplet formation is a key issue. Flow conditioning and careful nozzle design are needed to control the hydrodynamic source.
Studies of Ion Transport Modes Indicate Several Options are Feasible

<table>
<thead>
<tr>
<th>Chamber Concept</th>
<th>Transport Mode</th>
<th>Ballistic Transport</th>
<th>Pinch Transport</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>chamber holes ~ 5 cm radius</td>
<td>chamber holes ~ 0.5 cm radius</td>
</tr>
<tr>
<td>Dry-wall</td>
<td>Vacuum-ballistic chamber</td>
<td>Preformed channel (&quot;assisted pinch&quot;) laser + z-discharge</td>
<td>Self-pinched only gas</td>
</tr>
<tr>
<td>~6 meters to wall</td>
<td>vacuum</td>
<td>ARIES-IFE (2002) Possible option: but tighter constraints on vacuum and beam emittance</td>
<td>ARIES-IFE (2001) OPTION: uses 1-10 Torr 2 beams</td>
</tr>
<tr>
<td></td>
<td>Neutralized-ballistic plasma generators</td>
<td>ARIES-IFE (2001) OPTION: uses 1-100 mTorr ~2-100 beams</td>
<td></td>
</tr>
<tr>
<td>~4-5 meters to wall</td>
<td></td>
<td>PROMETHEUS-H (1992) ARIES-IFE (2001) OPTION: uses 1-100 mTorr ~2-100 beams</td>
<td></td>
</tr>
<tr>
<td>Thick-liquid wall</td>
<td>Not considered: needs ≤ 0.1 mTorr</td>
<td>HYLIFE II (1992-now) ARIES-IFE (2002) Main-line approach: uses pre-formed plasma and 1 mTorr for 3 m ~50-200 beams</td>
<td>ARIES-IFE (2002) OPTION: uses 1-100 mTorr ~2-100 beams</td>
</tr>
</tbody>
</table>

- Ion-transport modes compatible with dry- and thin-liquid walls (larger chambers) are feasible.
- May require significantly smaller number of beams simplifying the system.
IFE Research at UC San Diego: Final Optics Research & Development

Latest results were reported at IFSA 2003:
Paper: http://aries.ucsd.edu/LIBREPORT/CONF/IFSA03/GIMM.pdf
Presentation: http://aries.ucsd.edu/LIB/TALK/MST/
Grazing incidence metal mirror: Design concept and key issues

Key Issues:
- Shallow angle stability
- Damage resistance/lifetime
  Goal = 5 J/cm², 10⁸ shots
- Fabrication & optical quality
- Contamination resistance
- Radiation resistance

The reference mirror concept consists of stiff, light-weight, radiation-resistant substrates with a thin metallic coating optimized for high reflectivity (Al for UV, S-pol, shallow θ).
We Have Tested Several Al Fabrication Options

- Thin films on superpolished substrates
  - CVD SiC, 2-3Å roughness, 2-3 nm flatness over 3 cm
  - magnetron sputtering up to 250 nm
  - e-beam evaporation up to 2 mm

- Solid polycrystalline metal
  - Polished
  - diamond-turned

- Electroplated and turned Al

- Testing was performed with 25-ns, 248-nm pulses in a controlled environment
Review of Progress: 
Accomplishments and Findings

1. No signs of a “shallow angle instability” under any conditions tested to date

2. Testing of diamond-turned surfaces showed high damage threshold at 532 nm, but much lower threshold at 248 nm

3. UV damage observed in air, requiring testing in vacuum
4. All evidence suggests that weakly attached contaminants are tolerable due to strong cleaning by laser.

5. Thin film coatings have been difficult to produce with sufficient quality, and have a lower damage resistance than Al plates.

6. Perturbations to transmitted light are measured in-situ using bright-field, dark-field and direct imaging.
8. Our best results have been obtained with thick (50-100 mm) electroplated coatings that are diamond-turned
   ✓ 100,000 shots at 3-4 J/cm² with no discernable change to the surface

9. Scale-up and system integration (with driver and target injector) work has begun
IFE Research at UC San Diego: Chamber Dynamics and Clearing Simulation
Response of Chamber to Target Explosion Covers Two Vastly Different Time Scales

**SPARTAN Code**

- **“Pre-shot” Chamber Environment**
- **Non-Equilibrium Environment**

**“Slow” time-scale:**
- Processes

**“Fast” time-scale:**
- Processes
  - First pass of X-ray and ions through the chamber (a few µs)
  - 1-D Codes such as Bucky

**Target injection, Laser propagation, ...**
We Have Developed SPARTAN Chamber Dynamics and Clearing Code

- 2-D Transient Compressible Navier-Stokes Equations.
  - Extension to 3-D and cylindrical geometry is straight-forward.
- Second order Godunov method, for capturing strong shocks.
- Diffusive terms (conductivity, viscosity) can depend on local state variables.
- Adaptive Mesh Refinement employed to secure the uniform accuracy throughout the fluid domain.
- Arbitrary boundary resolved on a Cartesian grid with Embedded Boundary method.
### Initial Conditions:
- Xenon gas at 50 mTorr, room temperature;
- 160MJ NRL Direct drive target;
- Chamber condition from BYCKY at 500 µs.

### Boundary Condition:
- Zero mass flux;
- Reflective velocity;
- Energy:
  - Zero energy flux (“insulated wall”)
  - Conduction to the wall (wall temperature is fixed at 700 °C).
Reference Case: No Viscosity, No Conductivity

Pressure:

- $t = 0.5\text{ ms}$
  - $p_{\text{max}} = 1117.8\text{ Pa}$
  - $p_{\text{min}} = 175.36\text{ Pa}$

- $t = 5\text{ ms}$
  - $p_{\text{max}} = 1580\text{ Pa}$
  - $p_{\text{min}} = 126.8\text{ Pa}$

- $t = 50\text{ ms}$
  - $p_{\text{max}} = 812.41\text{ Pa}$
  - $p_{\text{min}} = 272.65\text{ Pa}$

Temperature:

- $t = 0.5\text{ ms}$
  - $T_{\text{min}} = 1.66 \times 10^4\text{ K}$
  - $T_{\text{max}} = 5.37 \times 10^4\text{ K}$

- $t = 5\text{ ms}$
  - $T_{\text{min}} = 0.14 \times 10^5\text{ K}$
  - $T_{\text{max}} = 2.0 \times 10^5\text{ K}$

- $t = 50\text{ ms}$
  - $T_{\text{min}} = 0.19 \times 10^5\text{ K}$
  - $T_{\text{max}} = 2.0 \times 10^5\text{ K}$

- Convergence of shock waves sets up hot spots in the chamber.
- Flow mixing is too slow to equalize the temperature.
Viscosity and Conductivity Significantly Change the Chamber Condition

No Diffusion

$t = 5$ ms

- $T_{\text{min}} = 0.14 \times 10^5$ K
- $T_{\text{max}} = 2.0 \times 10^5$ K

$t = 50$ ms

- $T_{\text{min}} = 0.19 \times 10^5$ K
- $T_{\text{max}} = 2.0 \times 10^5$ K

$t = 100$ ms

- $T_{\text{min}} = 0.19 \times 10^5$ K
- $T_{\text{max}} = 1.87 \times 10^5$ K
- $T_{\text{avg}} = 5.14 \times 10^4$ °C

Viscosity Only

$t = 5$ ms

- $T_{\text{min}} = 0.14 \times 10^5$ K
- $T_{\text{max}} = 1.96 \times 10^5$ K

$t = 50$ ms

- $T_{\text{min}} = 0.18 \times 10^5$ K
- $T_{\text{max}} = 1.67 \times 10^5$ K

$t = 100$ ms

- $T_{\text{min}} = 0.19 \times 10^5$ K
- $T_{\text{max}} = 1.41 \times 10^5$ K
- $T_{\text{avg}} = 6.36 \times 10^4$ °C

Conductivity Only

$t = 5$ ms

- $T_{\text{min}} = 0.11 \times 10^5$ K
- $T_{\text{max}} = 1.5 \times 10^5$ K

$t = 50$ ms

- $T_{\text{min}} = 0.06 \times 10^5$ K
- $T_{\text{max}} = 1.09 \times 10^5$ K

$t = 100$ ms

- $T_{\text{min}} = 0.58 \times 10^4$ K
- $T_{\text{max}} = 7.92 \times 10^4$ K
- $T_{\text{avg}} = 3.79 \times 10^4$ °C
Chamber Conditions at 100 ms

**No Diffusion**

\[
T_{\text{avg}} = 5.14 \times 10^4 \, ^{\circ}\text{C}
\]

\[
T_{\text{min}} = 0.19 \times 10^5 \, \text{K}
\]

\[
T_{\text{max}} = 1.87 \times 10^5 \, \text{K}
\]

**Viscosity only**

\[
T_{\text{avg}} = 3.79 \times 10^4 \, ^{\circ}\text{C}
\]

\[
T_{\text{min}} = 0.19 \times 10^5 \, \text{K}
\]

\[
T_{\text{max}} = 1.41 \times 10^5 \, \text{K}
\]

**Conduction Only**

\[
T_{\text{avg}} = 6.36 \times 10^4 \, ^{\circ}\text{C}
\]

\[
T_{\text{min}} = 0.58 \times 10^4 \, \text{K}
\]

\[
T_{\text{max}} = 7.92 \times 10^4 \, \text{K}
\]

**Full Navier Stocks**

\[
T_{\text{avg}} = 3.88 \times 10^4 \, ^{\circ}\text{C}
\]

\[
T_{\text{min}} = 0.5 \times 10^4 \, \text{K}
\]

\[
T_{\text{max}} = 8.57 \times 10^4 \, \text{K}
\]
Evolution of Chamber Condition
(Full Navier Stocks)

Pressure

Temperature

Density
Chamber Evolution Occurs In Two Phases

Evolution of Temperature of the Center of the Chamber

- Flow is dominated by shock bouncing
- Large scale eddies is setup and gas parameters evolve “smoothly.”
Turbulence Induced By Beam Channels Reduces The Chamber Temperature Significantly

Ref. Case

$T_{\text{min}} = 1.1 \times 10^4 \text{ K}$
$T_{\text{max}} = 14.3 \times 10^4 \text{ K}$
$t = 5 \text{ ms}$

$T_{\text{min}} = 0.5 \times 10^4 \text{ K}$
$T_{\text{max}} = 11.3 \times 10^4 \text{ K}$
$t = 50 \text{ ms}$

$T_{\text{min}} = 0.5 \times 10^4 \text{ K}$
$T_{\text{max}} = 8.57 \times 10^4 \text{ K}$
$t = 100 \text{ ms}$

$T_{\text{min}} = 1.03 \times 10^4$
$T_{\text{max}} = 13.5 \times 10^4$
$t = 5 \text{ ms}$

$T_{\text{min}} = 0.51 \times 10^4$
$T_{\text{max}} = 9.01 \times 10^4$
$t = 50 \text{ ms}$

$T_{\text{min}} = 0.44 \times 10^4$
$T_{\text{max}} = 6.28 \times 10^4 \text{ K}$
$t = 100 \text{ ms}$

$T_{\text{min}} = 1.0 \times 10^4 \text{ K}$
$T_{\text{max}} = 15.5 \times 10^4 \text{ K}$
$t = 5 \text{ ms}$

$T_{\text{min}} = 0.36 \times 10^4 \text{ K}$
$T_{\text{max}} = 8.15 \times 10^4 \text{ K}$
$t = 50 \text{ ms}$

$T_{\text{min}} = 0.32 \times 10^4 \text{ K}$
$T_{\text{max}} = 6.48 \times 10^4 \text{ K}$
$t = 72 \text{ ms}$
Observation from Recent SPARTAN Simulations

- Chamber evolution occurs in two phases:
  1) Flow is dominated by shock bouncing (first ~30-50 ms);
  2) Large scale eddies is setup and gas parameters evolve “smoothly.”

- Diffusive processes lead to a more uniform chamber environment. Peak temperatures, pressure, and velocity are reduced by a factor of two or more compared to the case with no conductivity/viscosity.

- Laser beam channels seed large scale eddies in the chamber. The resulting flow mixing leads to further reduction of peak temperatures, pressure, and velocity. It also enhances heat transfer to the wall.

- Peak temperature in the chamber is still too high. But:
  ✓ Geometrical effects will further reduce the peak temperatures: more beam channel, a cylindrical chamber to shorten shock bouncing period.
  ✓ Effects of background plasma (conductivity, viscosity, and radiation)
SPARTAN Research Plan for 2003-2004

- Incorporate cylindrical symmetry.
  - Completed. We are performing convergence studies at present.

- Implement and test contributions of viscosity, thermal conductivity, and radiation from background plasma.
  - Models are incorporated and tested in SPARTAN.

- Implement multi-species capability.

- Implement of Equation of State.

- Parametric investigation of chamber dynamics with different gas, gas pressure, target yield, chamber size, beam ports, etc.

- Parallelization and extension to 3-D geometry.
IFE Research at UC San Diego:
Chamber Wall Response Simulation Experiments
Thermo-mechanical Response of the Wall Is Mainly Dictated by Wall Temperature Evolution

- Most phenomena encountered depend on wall temperature evolution (temporal and spatial) and chamber environment except sputtering and radiation (ion & neutron) damage.
- Lasers can be used to simulate IFE Chamber Wall Response.

**NRL Target, X-ray Only**
1 J/cm², 10 ns Rectangular pulse

**Laser**
0.24 J/cm², 10 ns Gaussian pulse

- Only laser intensity is adjusted to give similar peak temperatures.
- Spatial temperature profile can be adjusted by changing laser pulse shape.
Thermo-Mechanical Response of Chamber Wall Can Be Explored in Laser Simulation Facilities

Requirements:

- Capability to simulate a variety of wall temperature profiles

A suite of diagnostics:
- Real-time temperature (High-speed Optical Thermometer)
- Per-shot ejecta mass and constituents (QMS & RGA)
- Rep-rated experiments to simulate fatigue and material response
  - Relevant equilibrium temperature (High-temperature sample holder)

Laser pulse simulates temperature evolution

Vacuum Chamber provides a controlled environment

Capability to isolate ejecta and simulate a variety of chamber environments & constituents
High Temperature Sample Holder is Designed and is in Fabrication

- Sample holder is made of Mo
- Specimen
- Ceramic Insulator
- Copper conductor with set screw
- S.S. vacuum seal
- Air cooling inlet
- Thermocouple feed through
- Power feed through
Real-time Temperature Measurements Can Be Made With Fast Optical Thermometry

Spectral radiance is given by Planck’s Law (Wien’s approximation):

\[ L(\lambda, T) = C_1 \varepsilon(\lambda, T) \lambda^{-5} \exp\left(-\frac{C_2}{\lambda T}\right) \]

Since emittance is a strong function of \( \lambda, T, \) surface roughness, etc., deduction of temperature from total radiated power has large errors.

**Temperature deduction by measuring radiance at fixed \( \lambda \)**

- One-color: Use tables/estimates for \( \varepsilon(\lambda_1, T) \)
- Two colors: Assume \( \varepsilon(\lambda_1, T) = \varepsilon(\lambda_2, T) \)
- Three colors: Assume \( \frac{d^2 \varepsilon}{d\lambda^2} = 0 \) [usually a linear interpolation of \( \ln(\varepsilon) \) is used]

**Our observations**

- Two-color method achieves sufficient accuracy (~1%). Three-color method is too difficult.
Schematic of Multi-Color Fiber Optical Thermometer

System is configured as three independent two-color thermometer.
Temperature is calculated from measurement of radiated energy at two wavelengths:

\[ T = \left[ c_2 \left( \frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right) \right] = \left[ c_2 \left( \frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right) \right] \ln \left( \frac{\lambda_2}{\lambda_1} \frac{L_{\lambda_2}}{L_{\lambda_1}} \right) \ln \left( \frac{\lambda_2}{\lambda_1} \frac{C_2 V_2}{C_1 V_1} \right) \]

Calibration of Thermometer

Thermometer is calibrated with a tungsten lamp (calibrated for 7 temperatures in the range 1,500-3,500 K)

Calibration is difficult because the lamp filament is discontinuous – image point should be exactly on the lamp filament.

We developed the protocol to reliably calibrate the thermometer (in <5 minutes).

Calibration is so accurate that one point calibration is sufficient to ensure < 1% accuracy over T=1,500-3,500 K.
We Have Measured Temperature Response of W Samples with ns Resolution

"Noise" in measured temperature is due to low signal level.

PMT pulse is much sharper than laser or temperature pulse because $L \sim \exp \left(-\frac{c}{\lambda T}\right)$

$t = 0$ is the Data Acquisition trigger point
Temperature Measurements of “Thermal Diffusion” Agrees with ANSYS Results

The peak temperature of the sample depends on thermophysical property of the sample (mainly $\rho C_p$) and laser pulse shape.

Thermal Diffusion time constant, $k/\rho C_p$, of the sample, however, should be close to pure W.

Temperature measurements are compared with ANSYS calculations with similar “peak” sample temperature and good agreement has been found.

Temperature rise time is sharper than ANSYS because of difference in laser pulse shape.
Melting of Sample Surface is Captured by the Fast Optical Thermometer

3700 K: Melting temperature of W

Sample surface has melted

Time (ns)

Temperature (K)

600 mJ

500 mJ
Initial Scan of Sample Peak Surface Temperature with Optical Thermometer
We have developed the software for downloading, post processing, and plotting of the thermometer data. Same interface is used for both calibration and data acquisition.
Thermometer Reliability

- Test 1: Successive calibration: the basis for developing calibration protocol.

- Test 2: Chamber installation test: thermometer is removed from calibration stand, mounted in the chamber, returned to calibration stand.
  - Calibration held in repeated tries

- Test 3: Long-term reliability, i.e., how long the calibration is holding.
  - Successive calibration was performed repeated in a 10 days period.
  - Calibration held within 1.5%.
Sample Exposure Experiments Will Begin in December 2003

We are in the process of moving our laboratory into a much larger area.

- September
- 30 October
- December