Plasma Materials Interaction Issues For Burning Plasma Experiments

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Outline

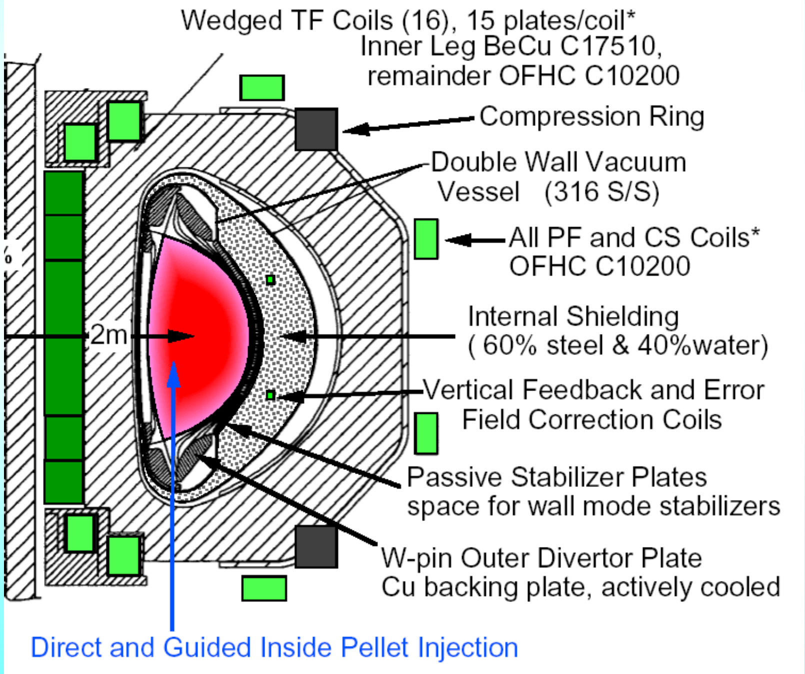
- Introduction to Burning Plasmas
- Plasma Materials Interaction Phenomena
- Materials Issues
- Summary

Benefits of a Burning Plasma Experiment

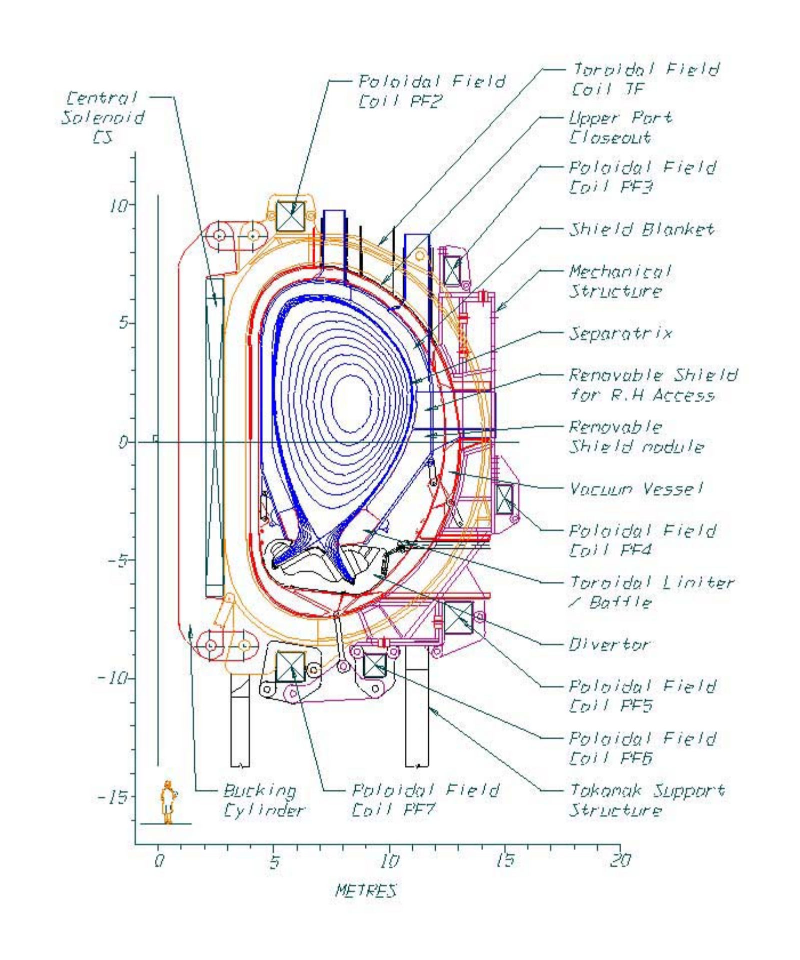
- Study the physics of self heated plasmas
  - Alpha particle heating
  - Alpha energy driven MHD activity
  - Self organized current distribution
- Demonstrate ignition and burn in a magnetic confinement configuration
- Establish the practical components needed for energy production
  - Fueling and particle control
  - Steady-state heat removal
  - Tritium breeding
  - Resistance to neutron damage

The FIRE Burning Plasma Device

- A compact high field and density tokamak machine
- Major radius 2 m
- Minor radius 0.5 m
- Elongation 1.8
- Magnetic field 8 Tesla
- Density $10^{21}/m^3$
- 200 MW fusion power
- 18 s pulse length
- 3000 full power pulses



The International Thermonuclear Experimental Reactor (ITER)

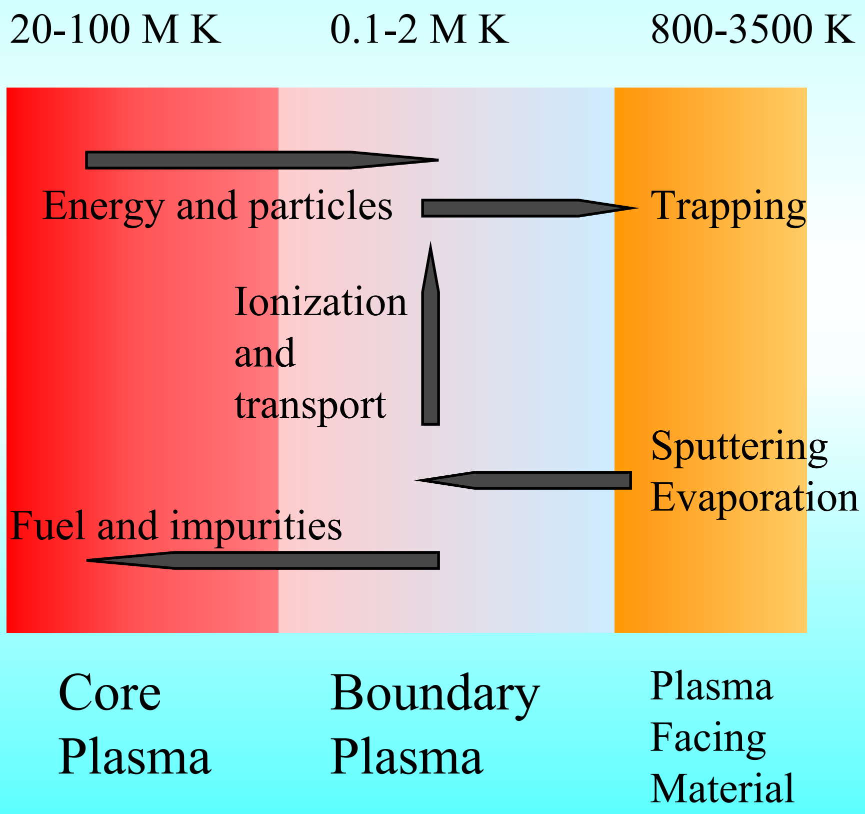


- Joint design by US, Europe, Japan, and Russia (US dropped out in 1998)
- Superconducting magnets
- 500-1000 MW fusion power
- Fusion gain of 10
- Maximum pulse length 1000 s
- Actively cooled internal components
- Designed for full remote maintenance

Plasma Materials Interaction Phenomena

Fusion Plasma Materials Interactions

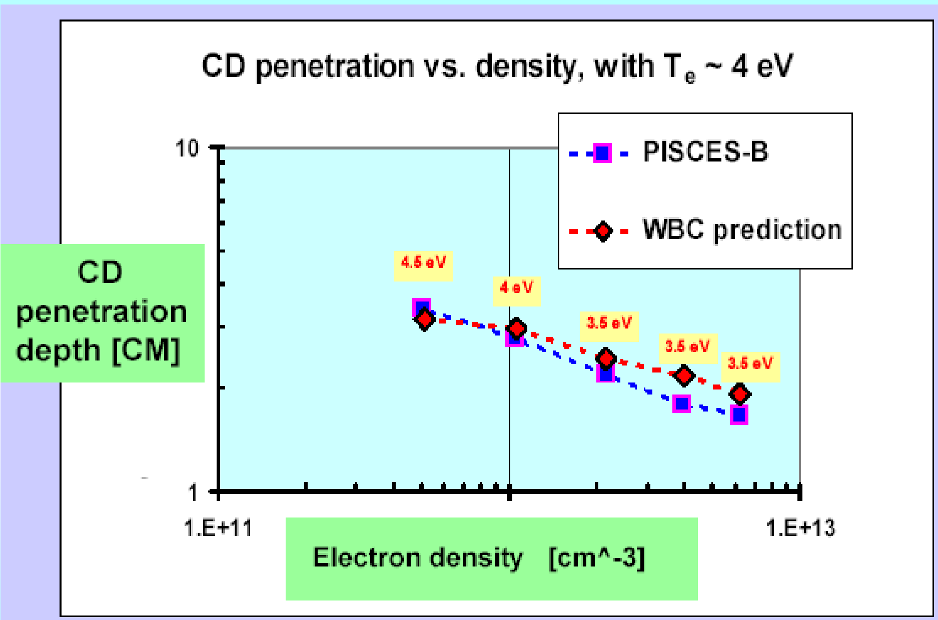
- The core plasma must be kept clean of impurities and He ash
- The plasma facing component surface sees high density and temperature plasma
- Key issues are hydrogen trapping, erosion, and thermal fatigue
- Spans science specialties from ionized gases to materials science

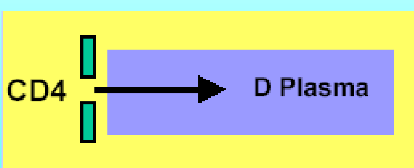


Science Needed for Fusion Plasma Materials Interactions

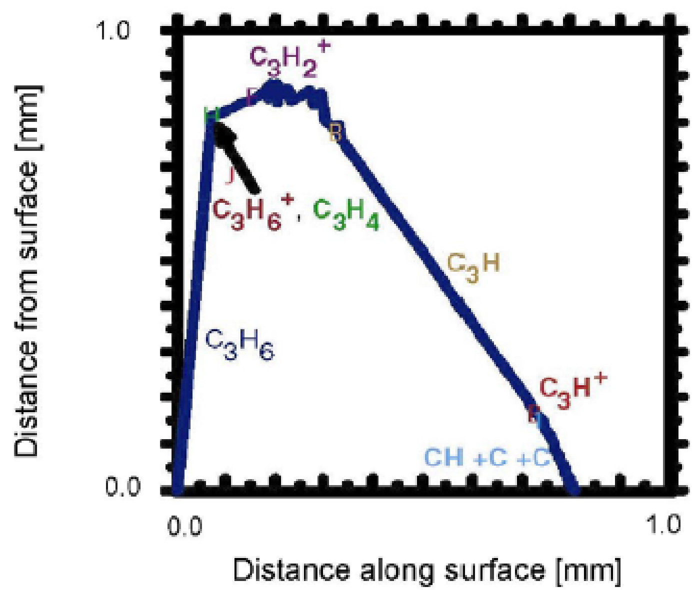
- Atomic and molecular physics for ionization, dissociation, and photon radiation of plasma and impurity species
- Surface physics for sputtering, chemical erosion, hydrogen trapping and release, surface segregation
- Materials science for nuclear radiation damage, thermal fatigue, stress corrosion, creep, bonding, and hydrogen trapping
- Engineering science for stress management, heat transfer, and component design

Understanding of Hydrocarbon Molecule Transport in the Plasma Edge





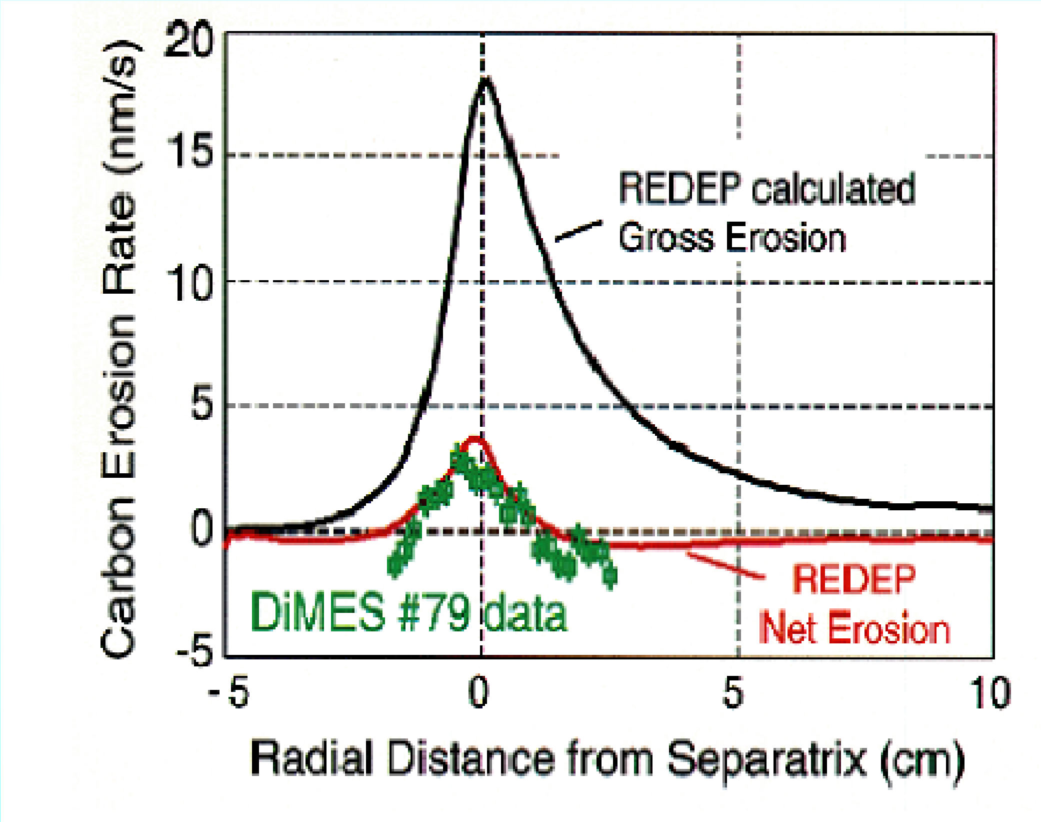
Trajectory of propane molecule dissociation and redepostion in boundary plasma. WBC montecarlo code.



REACTION PROCESS:

$H^+ + C3H6 = C3H6^+ + H$		PROTON IMPACT IONIZATION
$e^- + C3H6^+ = C3H4 + H2$		DISSOCIATIVE RECOMBINATION
$H^+ + C3H4 = C3H2^+ + H2 + H$		PROTON IMPACT IONIZATION
$e^- + C3H2^+ = C3H + H$		DISSOCIATIVE RECOMBINATION
$H^+ + C3H = C3H^+ + H$		PROTON IMPACT IONIZATION
$e^- + C3H^+ = CH + C + C$		DISSOCIATIVE RECOMBINATION

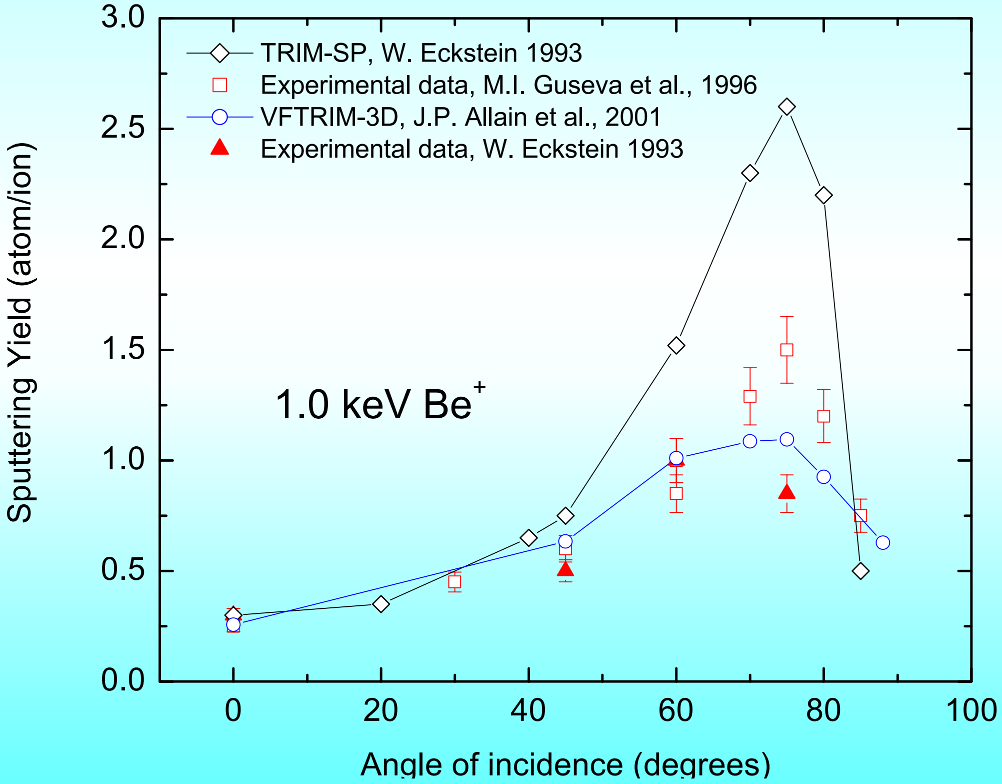
Comparison of Erosion Modeling and Experiment



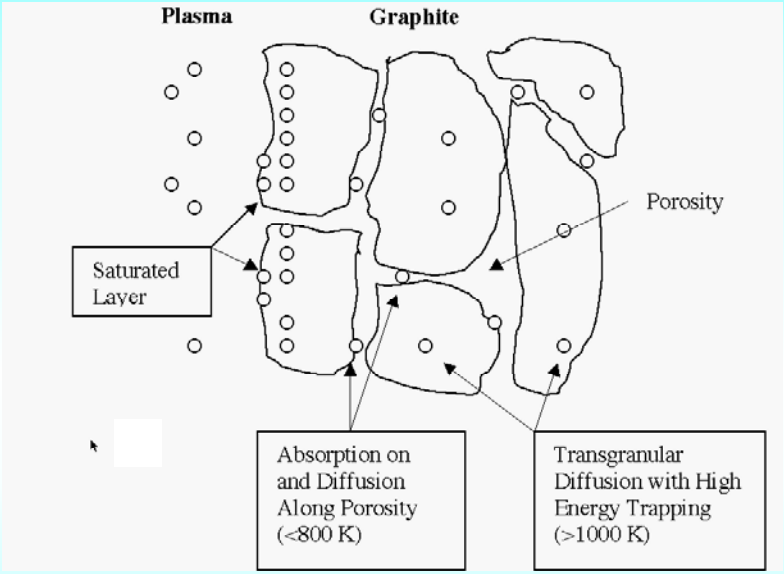
- Erosion data from DIII-D divertor probe under the strike point
- Calculation from the WBC code including sputtering, ionization, transport and redeposition

VFTRIM-3D (Vectorized Fractal TRIM)

- **A binary-collision approximation with atomic-scale surface roughness using a fractal algorithm.**
- **Uses a binary collision based on the Kr-C interaction potential and classical scattering kinematics.**
- **Electronic inelastic energy loss model uses an equipartition between the local Oen-Robinson model and non-local Lindhard-Sharff model.**



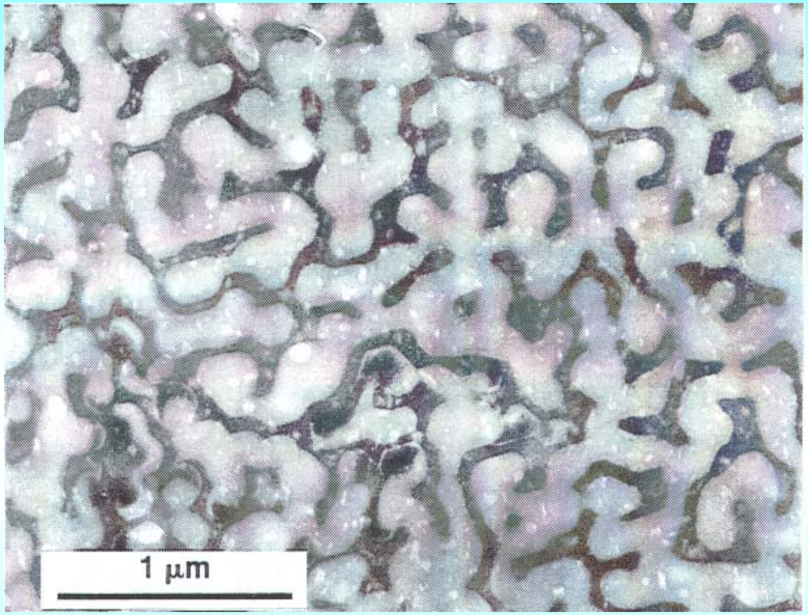
Carbon



- Hydrogen insoluble in carbon.
- Implanted H quickly forms a saturated layer in the implant zone. H atoms diffuse rapidly along the porosity (low T).
- At higher temperatures, the atoms enter into the grains where many are trapped.

- Sputtered carbon can join with D/T to form a stable film on surfaces (codeposition)
- Codeposition traps as much as 40% of all D/T

Beryllium

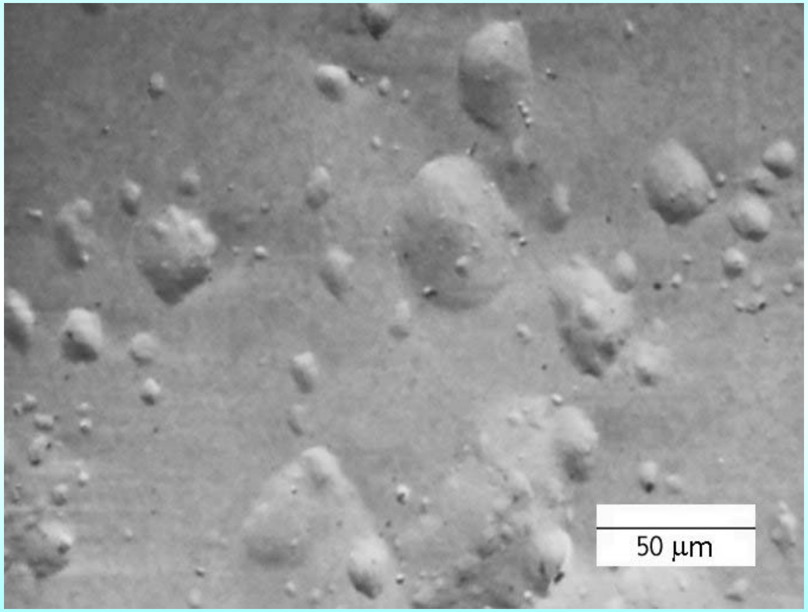


Russian Academy of Sciences

- Hydrogen isotopes are insoluble in beryllium.
- Implanted H comes out of solution to form a "worm-like" structure several microns deep.
- All H subsequently implanted is released.

- T bred in the beryllium due to n reactions is trapped.
- This T stays in the Be until removal from the reactor.
- A T inventory in the hundreds of grams is possible.

Tungsten

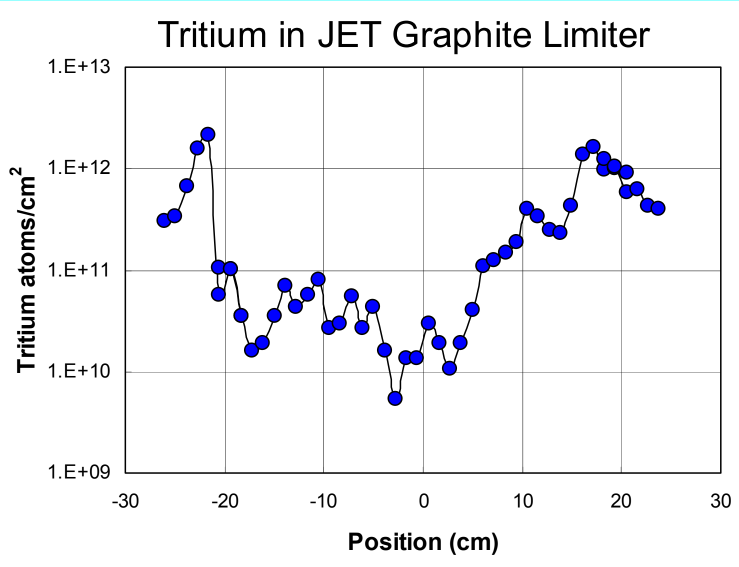


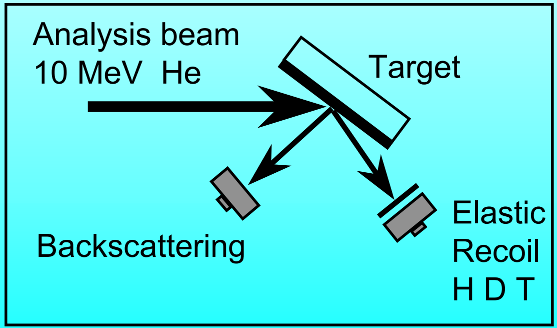
Blisters on W after exposure on the Tritium Plasma Experiment

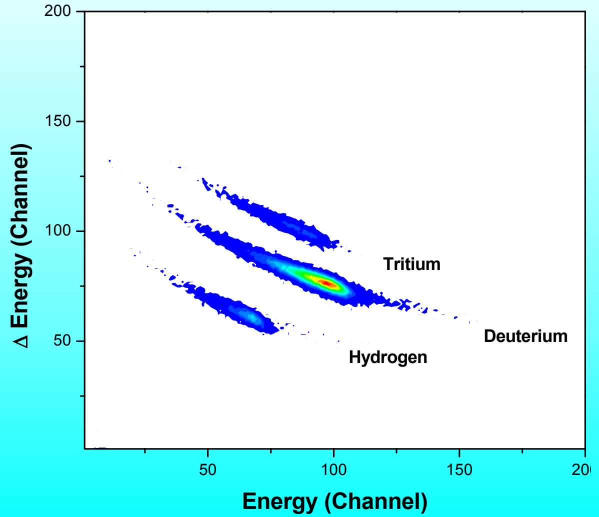
- Rapid diffusion and release of tritium prevent significant buildup of tritium in tungsten.
- The low solubility of the hydrogen isotope in the tungsten can result in bubble and blister formation for intense plasma exposure.
- Blister formation could result in the deposition of tungsten into the plasma (flaking and melting).

Measurement of Tritium

- Count betas using a PIN diode.
  - Beta energy is low (<18 keV), short range, only detects near-surface T.
  - Sensitive ~ 10^8 T/cm^2 or 0.1 Bq/cm^2.
- Elastic Recoil Detection using MeV ions or neutrons.
  - Measures H,D and T
  - Greater range but less sensitive than beta counting.

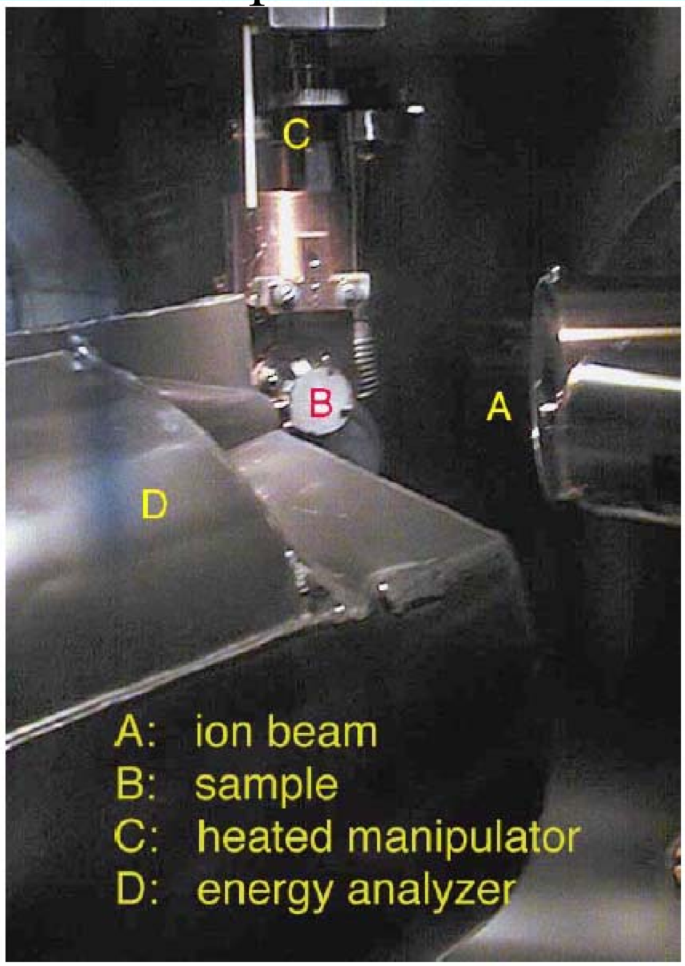




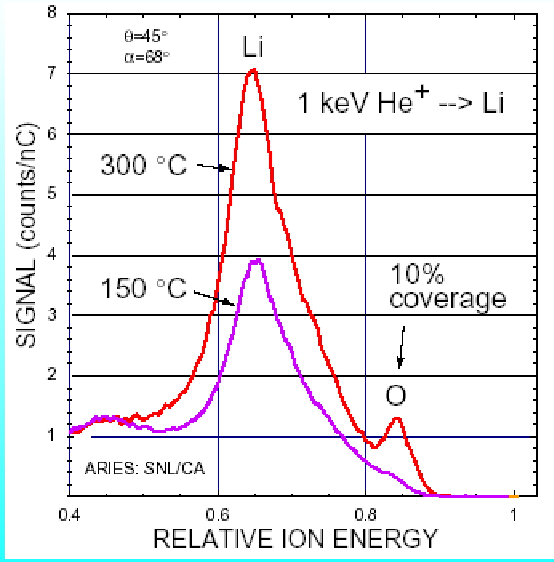


Liquid Surface Composition

Experiment

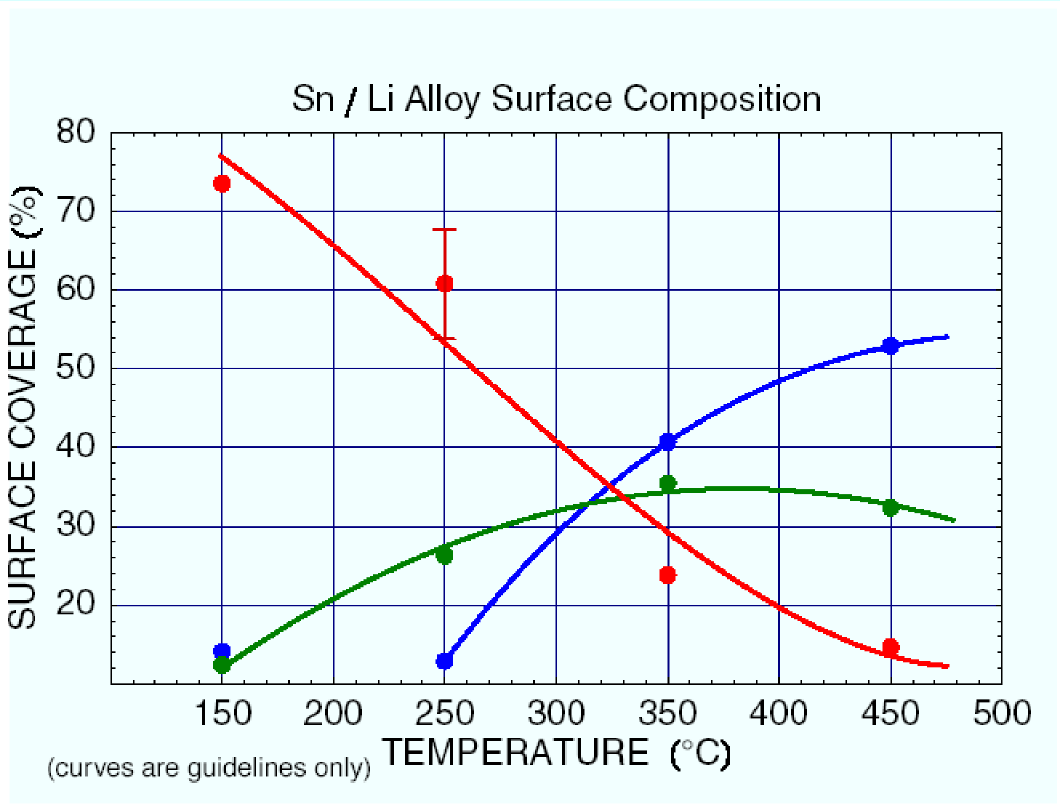


Liquid Lithium



Oxygen segregates to the surface upon melting

Variation of Sn/Li Liquid Surface Composition



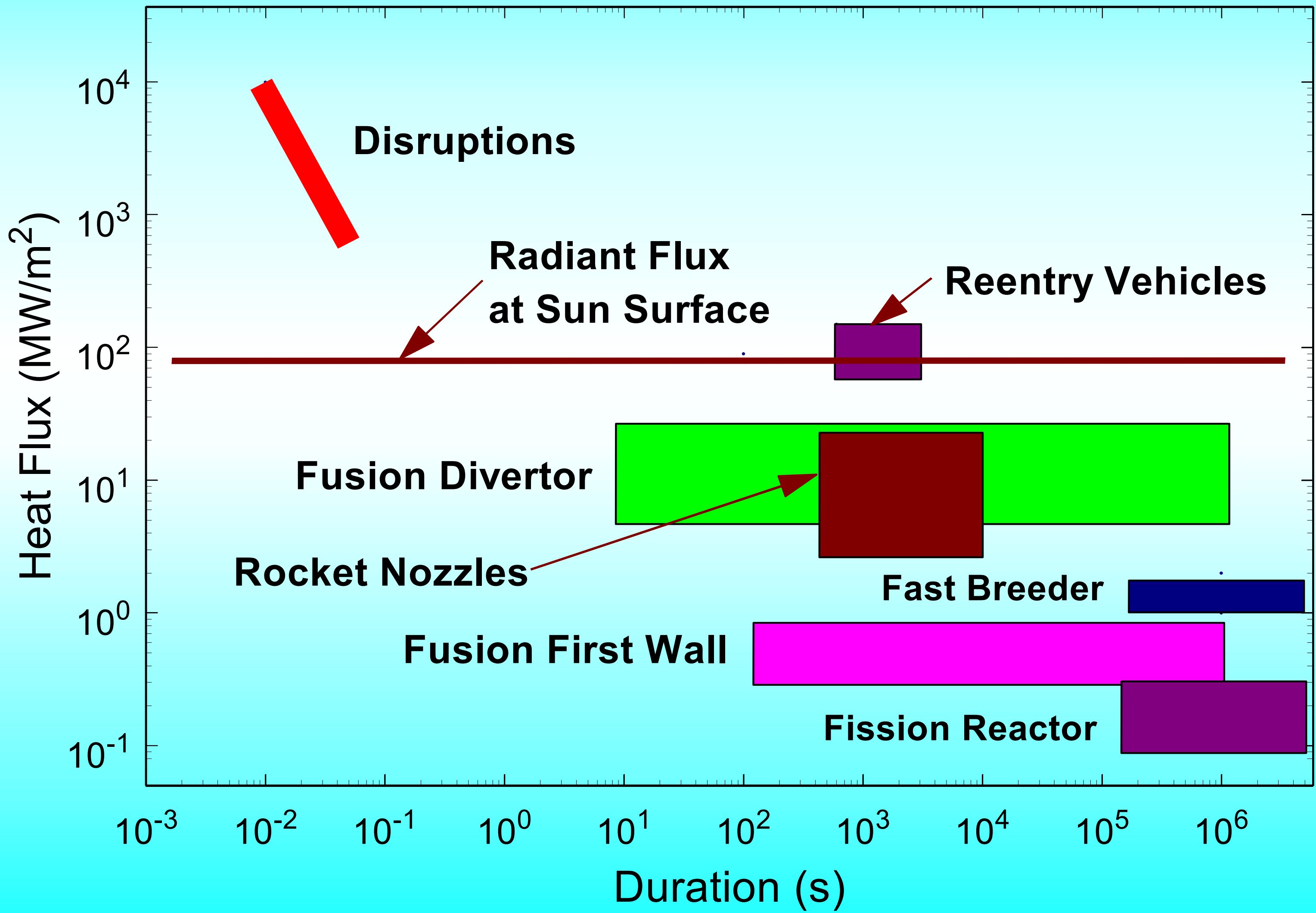
- Sn80Li20 liquid
- Composition measured by small angle scattering
- Red is Sn, blue is Li and green is O
- Segregation of Li on the surface is clearly seen above the melting point

Plasma Interaction With a Liquid Li Surface

- PISCES plasma device
- Lithium light from the interaction of the incident plasma with the evaporated or sputtered Li from the liquid surface
- Studies of erosion rates, temperature limits and hydrogen isotope retention in Li have been conducted.

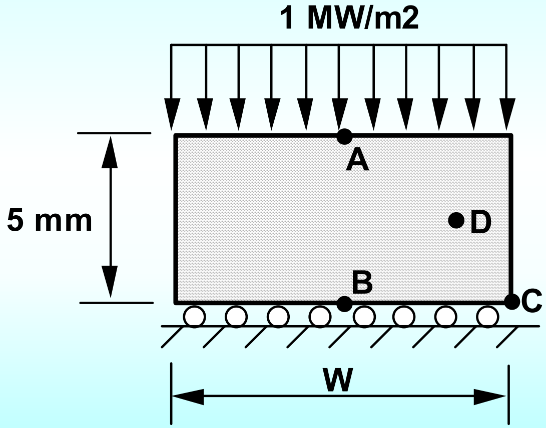
Materials Issues

Magnetic Fusion Energy Heat Fluxes



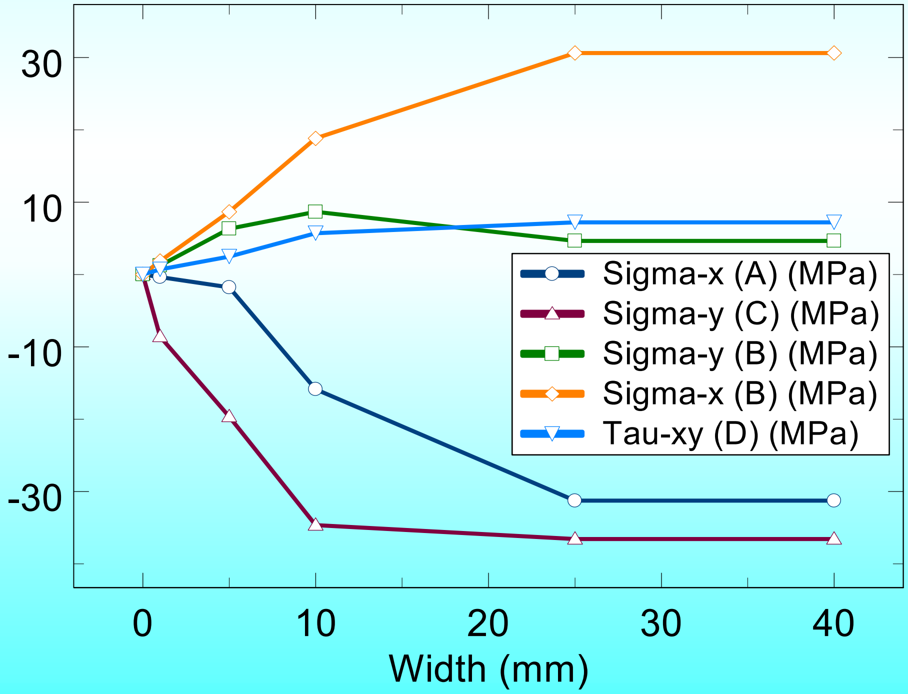
Stress Minimization Analysis

ABAQUS Finite Element Model

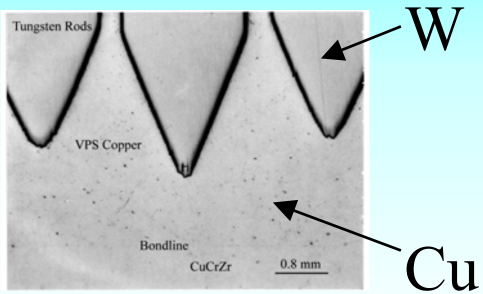


- 2-D plane stress
- Elastic behavior
- Temp. dependent props.
- 2000 elements (8-node quad)

Tungsten, 5 mm thick

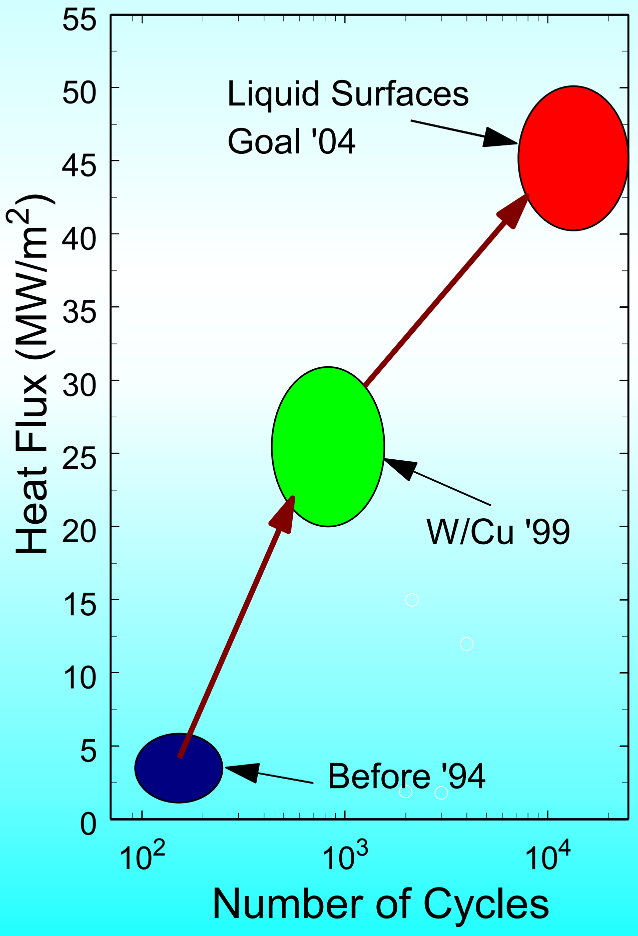


Progress in PFC Capability



Tungsten rod component

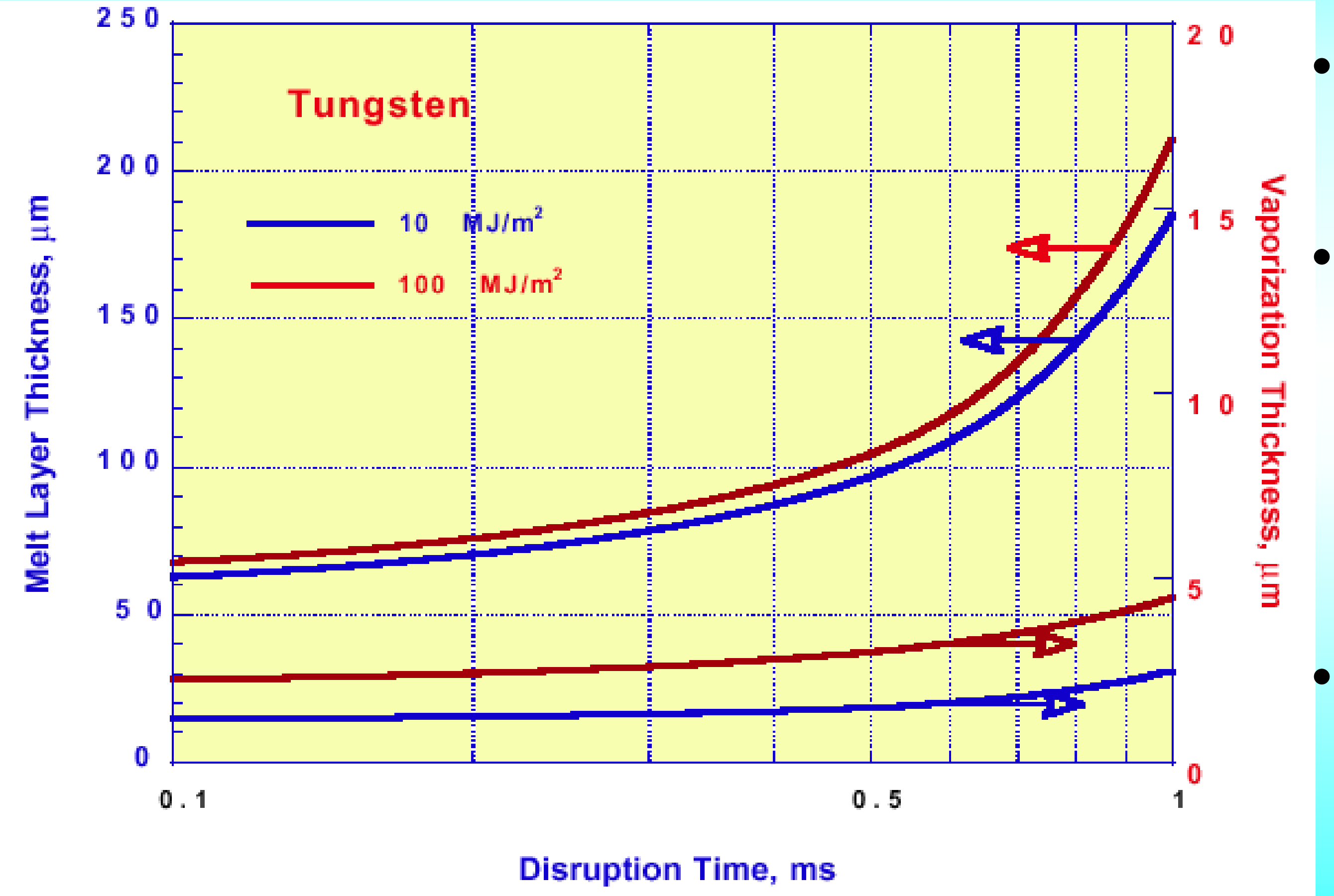
Progress in Heat Removal Capability



Progress:

- **Reduction of stress using rods on the surface**
- **Low temperature joining**
- **Improved heat transfer enhancement**

Analysis of Disruption Heating

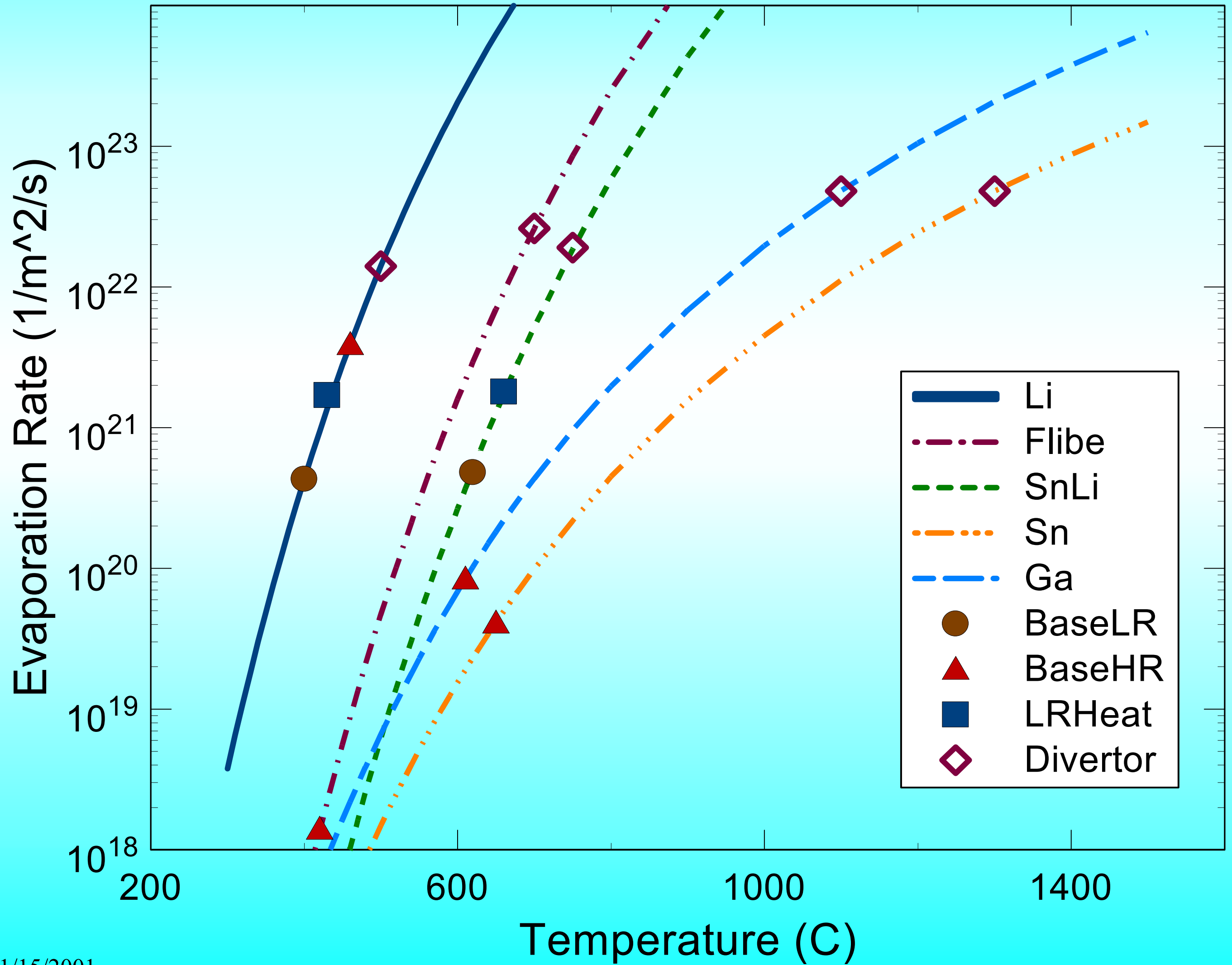


- Heights code package
- Includes evaporation and plasma shielding effects
- Experimentally verified

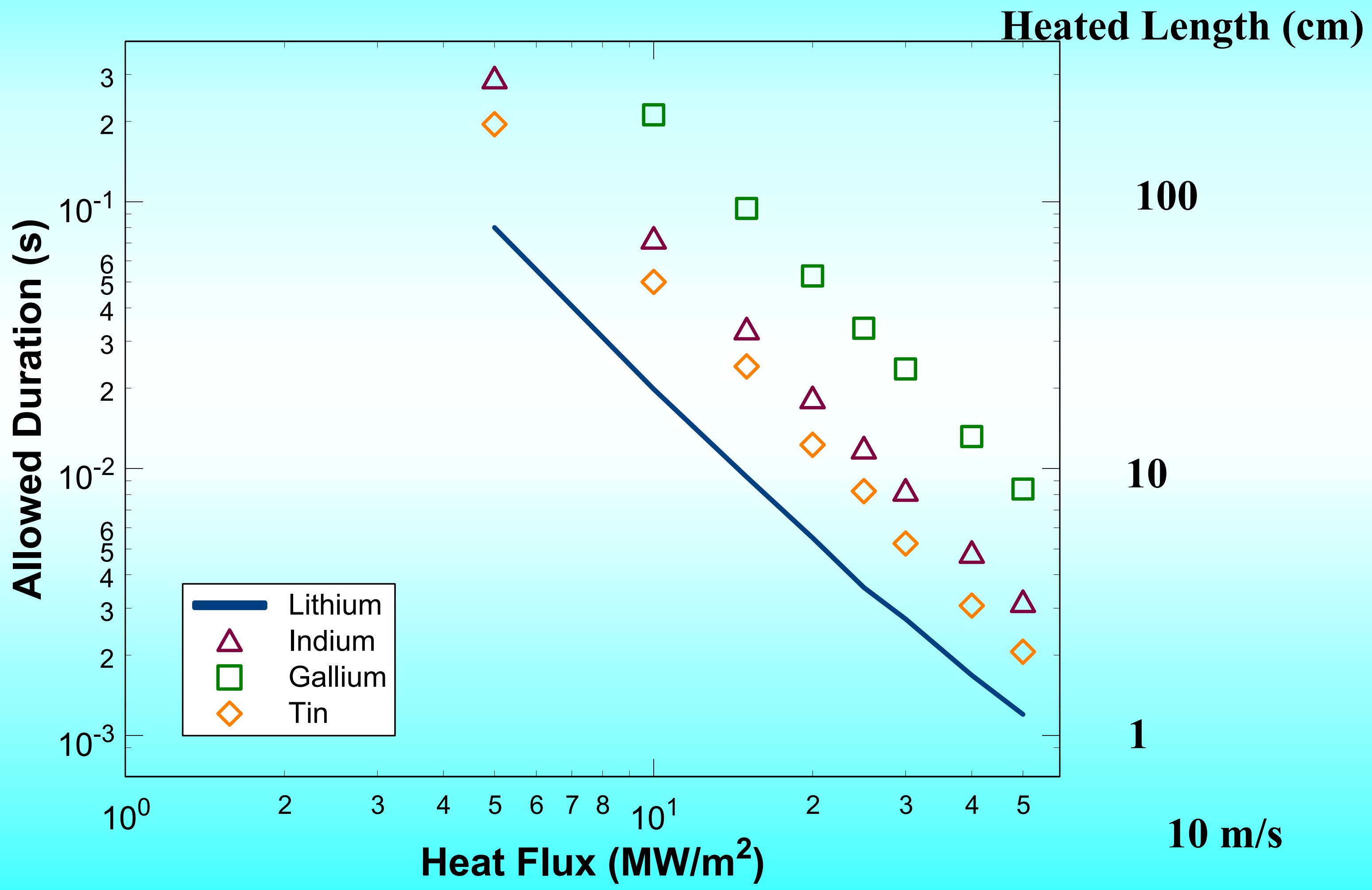
Liquid Surfaces for Fusion Devices

- Eliminates the erosion issue for component lifetime
- No thermal stress issues
- Some liquids offer particle removal capability
- No neutron damage issues
- Complicated MHD effects (3D magnetic fields that are time varying, fast moving conducting liquids, etc.)
- Temperature limits may be low (heat flux limits)

Temperature Limits



Allowed Duration for High T Limit



Particle Pumping by Liquid Li

- The recombination rate for H on Li is very small (10^{-27} to 10^{-31} cm^4/s)
- Several experiments have confirmed nearly 100% retention
- An area of flowing lithium has a large capacity for pumping H isotopes
- 1 m^2 Li flowing at 10 m/s can pump up to 10^{23} particles/s
- This particle removal capability is attracting the interest of even existing fusion machines.

Summary

- The plasma materials interaction issues for a burning plasma device are well defined
  - Tritium retention (hydrogen in materials)
  - Erosion of plasma facing materials (sputtering and chemical)
  - Transport of eroded material (atomic and molecular physics)
  - Cyclic thermal stress (materials and engineering science)
- A substantial experimental database exists to calibrate physics models of the important phenomena

Summary

- Physics and engineering based models of the important phenomena are being developed and compared to the experimental data
- The extrapolation to a burning plasma device is less of a step than was made when designing the last generation of fusion devices.
- Three potential solutions for PFCs exist and research is being conducted to verify those solutions.

Potential Solutions for PFCs

- All metal water cooled solution
  - W rod surface divertor targets and Be first wall
  - Water cooled copper substrates
  - Nearly completely demonstrated on existing devices (lowest risk)
- Helium gas cooled all refractory metal solution
  - Relies on impurity seeding in the divertor to reduce heat loads (may have no erosion)
  - Uses refractory metal improvement from material program
  - High temperature gas turbine cycle

Potential Solutions for PFCs

- Liquid metal plasma facing components
  - Least developed and greatest risk of insurmountable problems
  - Requires solution of very difficult MHD problems
  - No erosion issues
  - Some materials can pump particles
  - No thermal stress issues
  - Robust to transients
  - Long term, high risk, high payoff research