A COMPARISON OF LIQUID AND SOLID SURFACE OPTIONS FOR PLASMA FACING COMPONENTS

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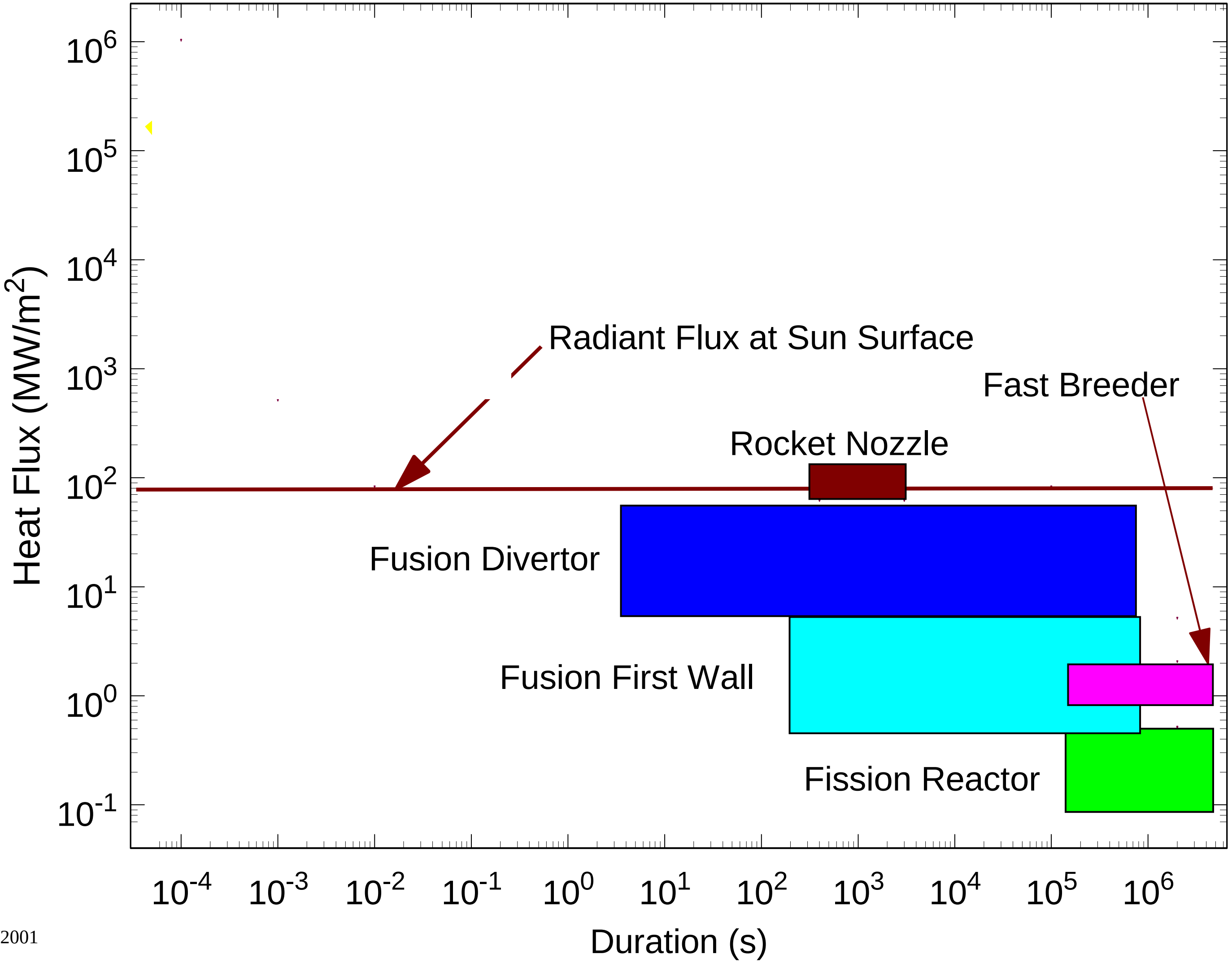
Outline

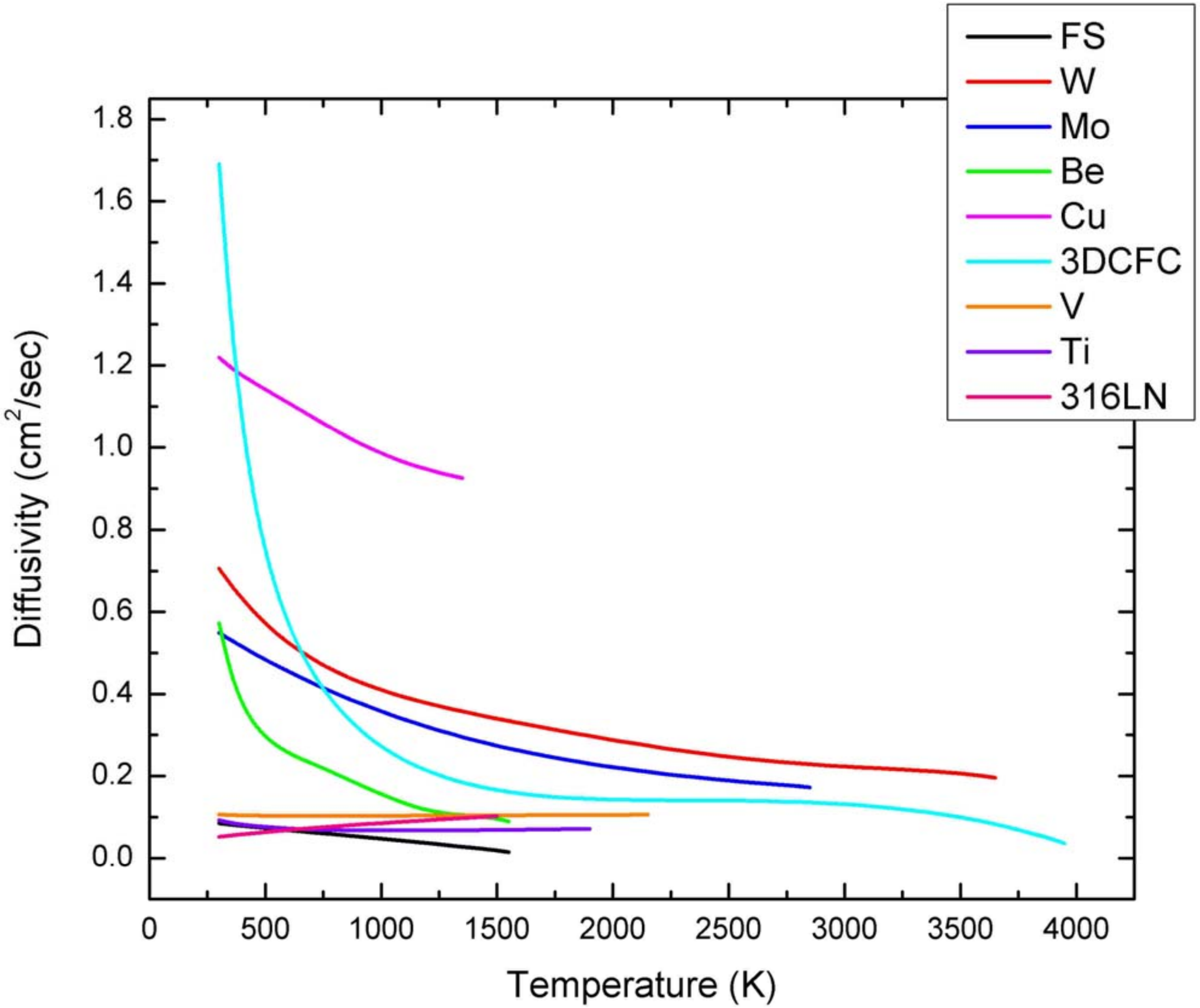
- Solid Plasma Facing Components
  - Heat Flux Limits for actively cooled PFCs
  - Limitations due to ELMs and Disruptions
  - Hydrogen isotope retention
- Liquid Surface PFCs
  - Heat flux limits
  - Response to ELMs and Disruptions
  - Particle retention
  - MHD considerations
- Conclusions

Magnetic Fusion Energy Heat Fluxes Are Very Challenging

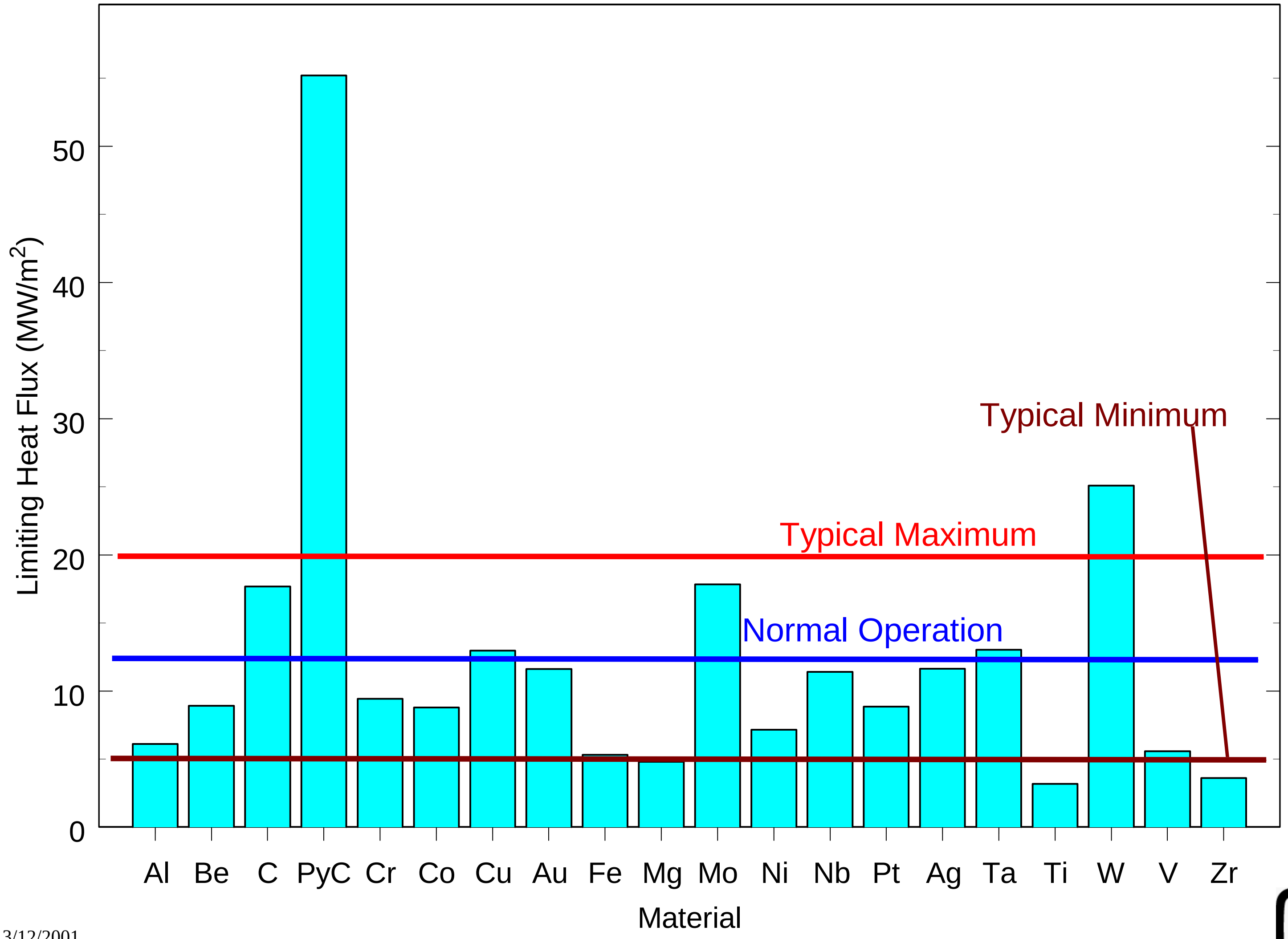


Solid Plasma Facing Components

Typical Thermal Properties



Heat Flux Capability

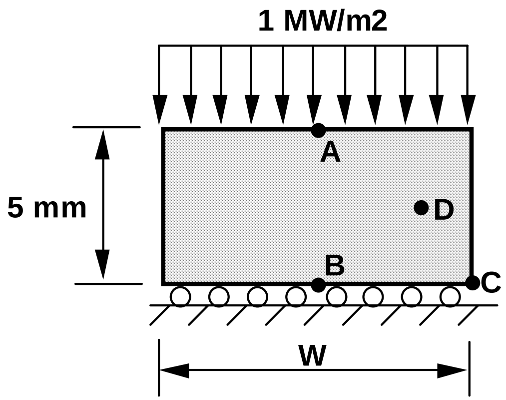


Status of PFC research

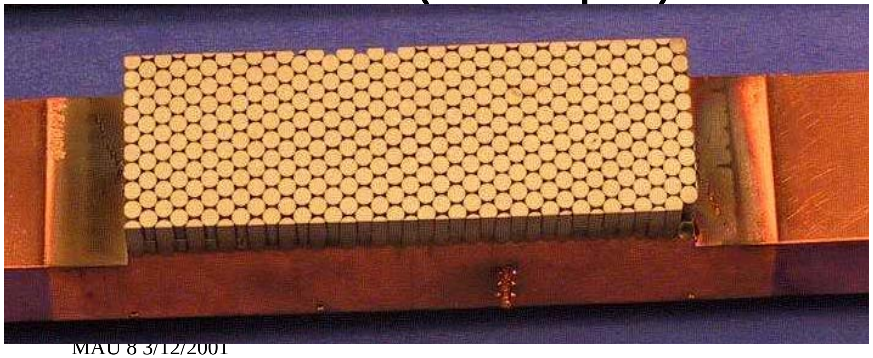
- ITER PFC design
  - Water cooled Cu Alloy heat sinks with CFC or W plasma facing surface in the divertor region (10-15 MW/m^2 steady state)
  - Water cooled Cu Alloy heat sinks with 316LN insert and Be plasma facing surface on the first wall (0.5 MW/m^2 steady state)
  - Full size prototypes have been fabricated and tested
  - Scaling of fabrication to large area is unfinished

Castellation Reduces Stress

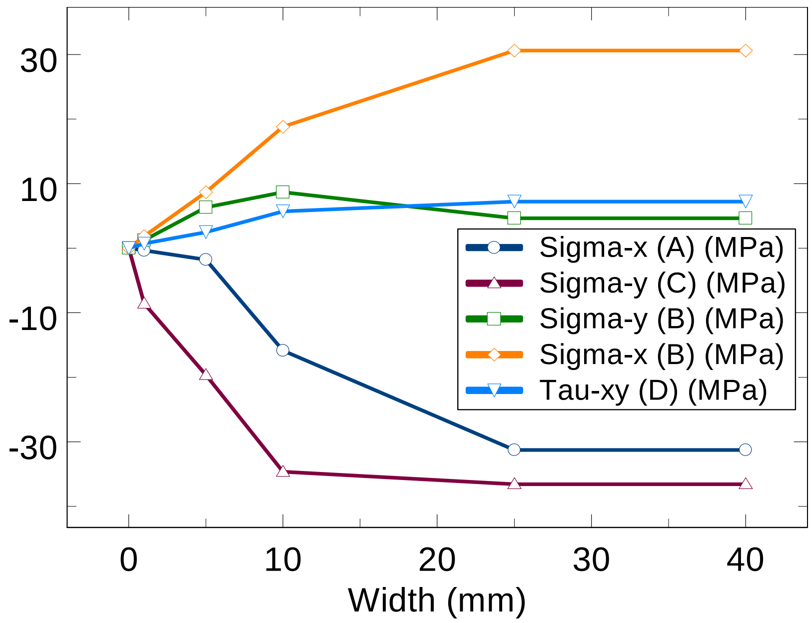
ABAQUS Finite Element Model



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



Tungsten, 5 mm thick



Status of PFC research

- **Existing fusion devices**
  - **Most use passively cooled carbon based PFCs (one with W coating and one with molybdenum)**
  - **Very few actively cooled PFCs**
  - **Extensive time is spent conditioning the walls (relative to plasma on time)**
  - **Some experiments have active particle control (cryo-pumps)**

Status of PFC research

- **Off Normal events must be controlled**
  - – **Disruptions**
    - **Disruption mitigation using massive gas puff is demonstrated on some machines**
    - **Reduced current decay rate and thermal loads on divertor (increases first wall energy deposition)**
    - **Reliable detection and triggering is being investigated (neural networks)**

Status of PFC research

- **Off Normal Events II**
  - **Edge Localized Modes (ELMs)**
    - **Present the greatest threat to PFC survival**
    - **The highest performance plasmas have the largest ELMs (>1 MJ/m^2 in a few hundred μsec at a few Hz)**
    - **Melting is predicted on the divertor high heat flux region (and possibly on the first wall)**
    - **The key issue is loss of melted material (determines PFC lifetime)**
    - **Mitigation through double null, high triangularity, edge magnetic perturbation, etc. is partially successful**

Needs for Devices Beyond ITER

- Assume long pulse, high power density, high duty factor
- Improved radiation damage resistance for materials meeting PFC requirements.
- Understanding of radiation effects on PFC joints
- Mitigation and control of off normal events
- New coolant and material combinations compatible with tritium and high power for large numbers of cycles

Key Issues

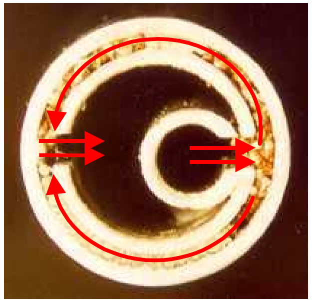
- For divertor PFCs
  - High thermal conductivity
  - Joints between PFM and heat sink
  - Coolant compatibility
  - Most likely He gas cooled
  - Liquid metal PFCs are high risk, high potential alternative

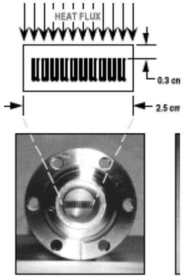
Heat Sink Development

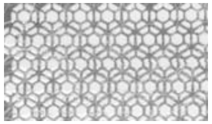
- Coolant Choices
  - Water is primary now but has future issues of steam interactions with hot refractory metals
  - Helium gas is the prime candidate in the future
- Heat sink designs
  - For water swirl tapes, hypervapotron, screw tube are all well established
  - Porous metal heat sinks are in the initial stages of development for He gas cooling (Cu alloys now)

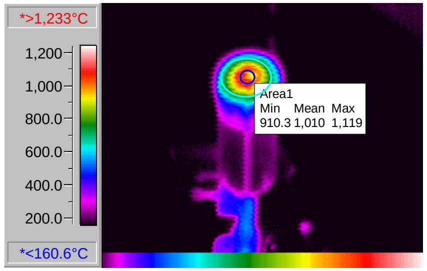
Porous Metal Heat Sinks (He)

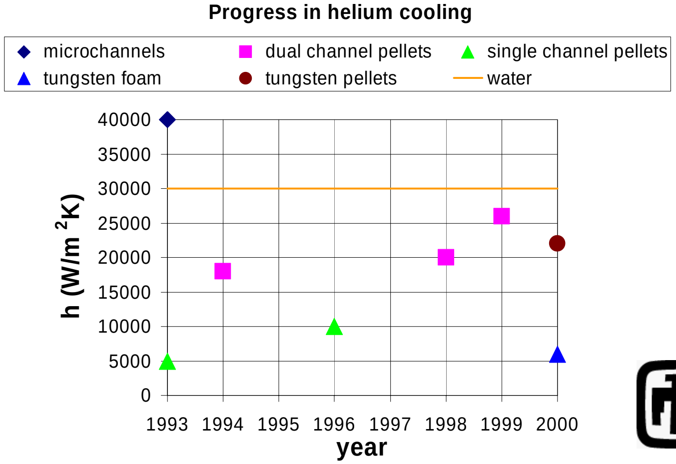
- **Promising designs have been found for Cu alloys**
- **Heat removal is approaching water values**
- **Pressure drop is ok.**
- **Refractory metal research just starting.**
- **Helium gas purity is a key issue but there appear to be solutions.**
- **Refractory alloy development is needed.**







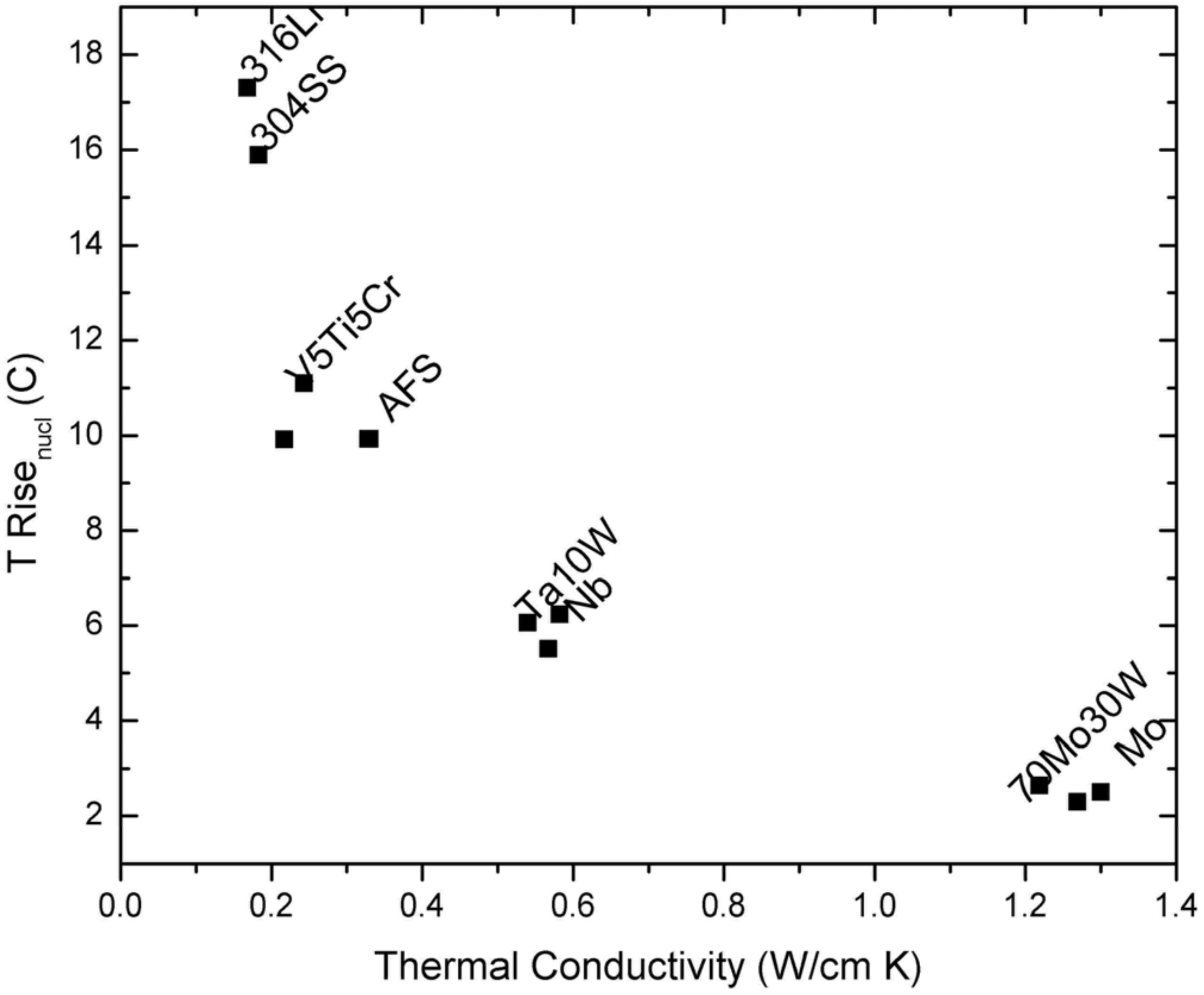




Key Issues

- For first wall PFCs
  - Material selection must be compatible with breeding blanket
  - Very large area implies constraints on fabrication methods
  - Coolant compatibility and joints to heat sink
  - Plasma facing material (plasma prefers low Z and this is reinforced by fast radial transport)
  - Radiation damage resistance and activation

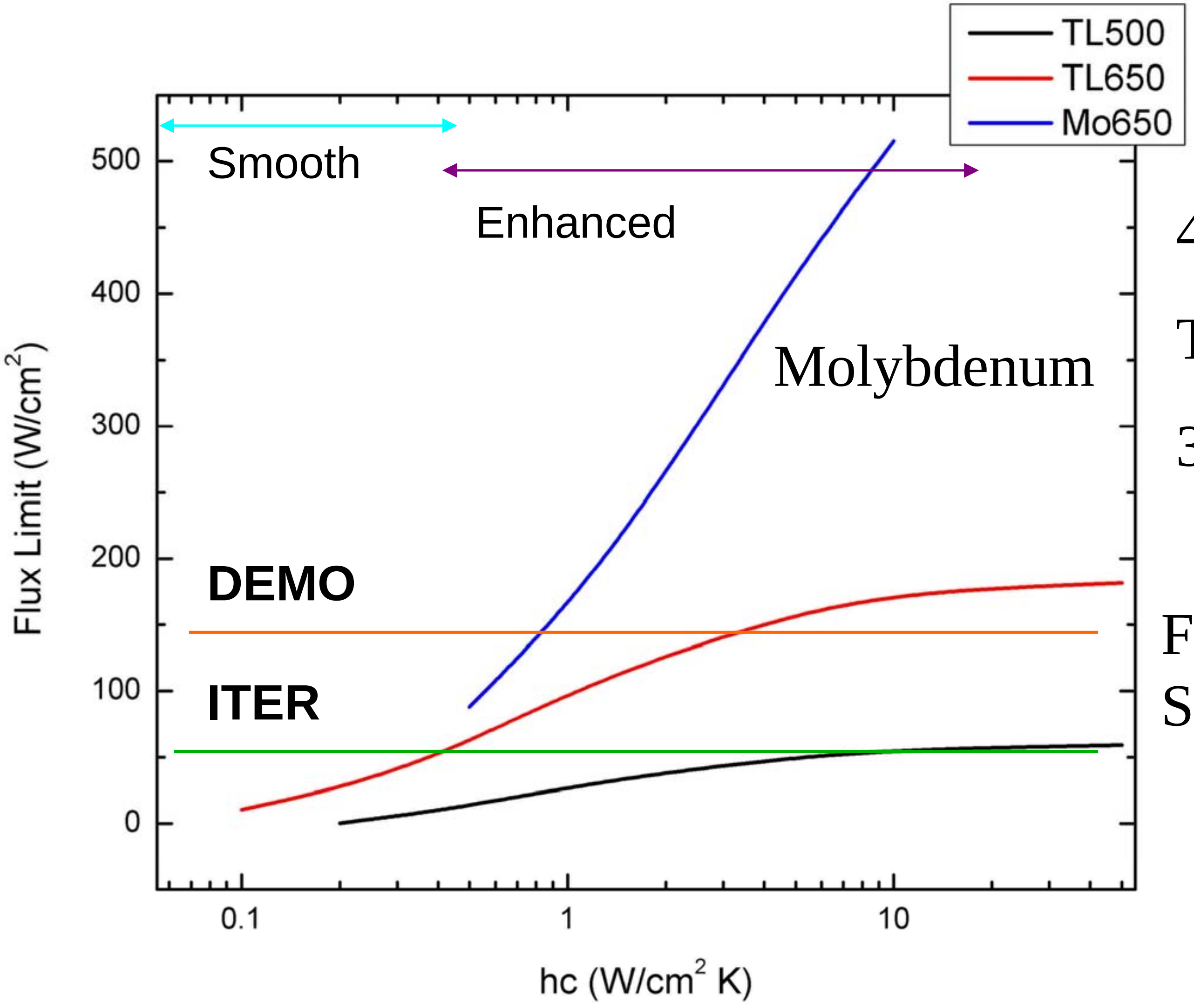
T Rise Due to Nuclear Heating



3 MW/m^2

4 mm thick

Heat Flux Limits



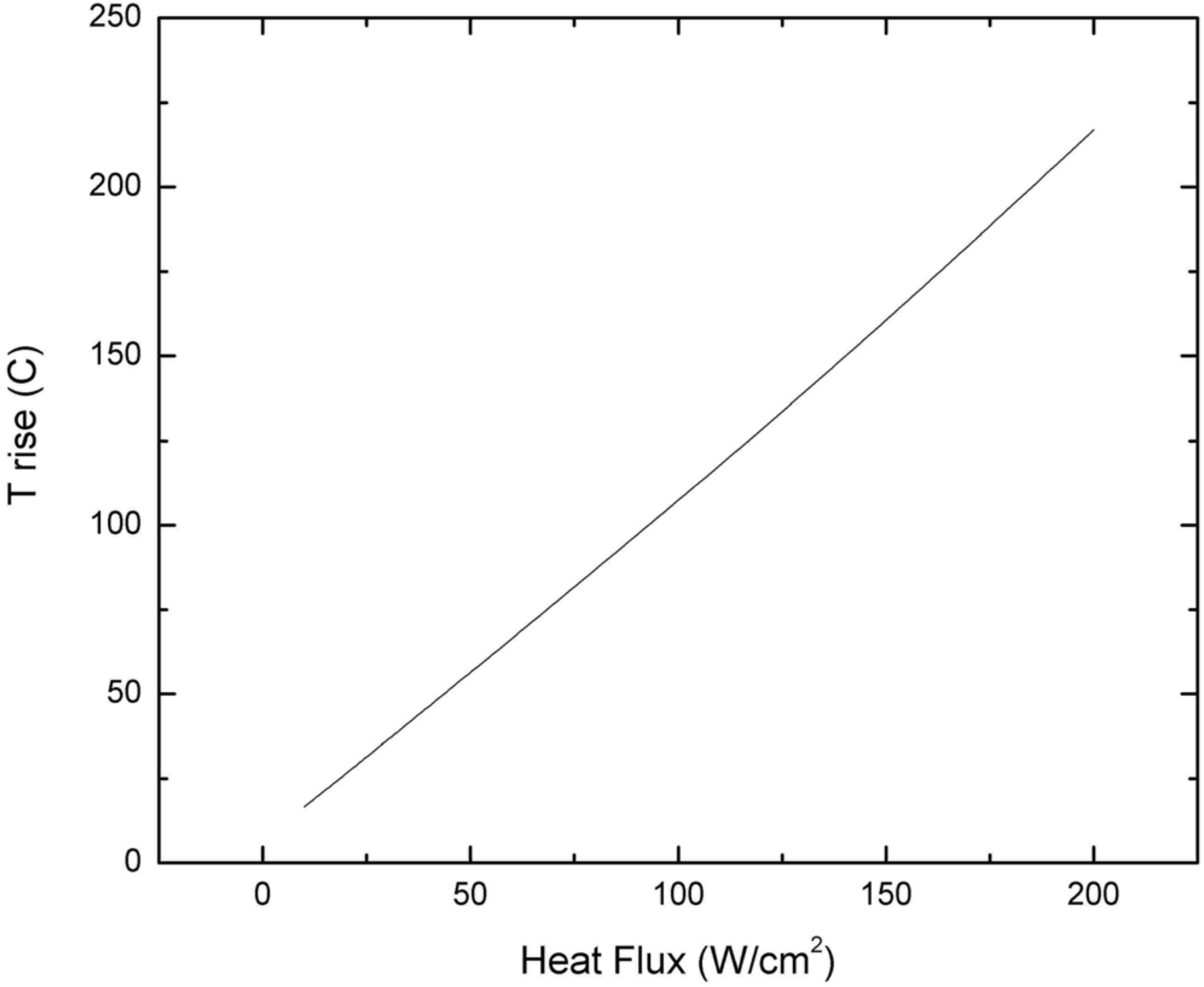
4 mm

Tcool = 420 C

3 MW/m^2

Ferritic
Steel

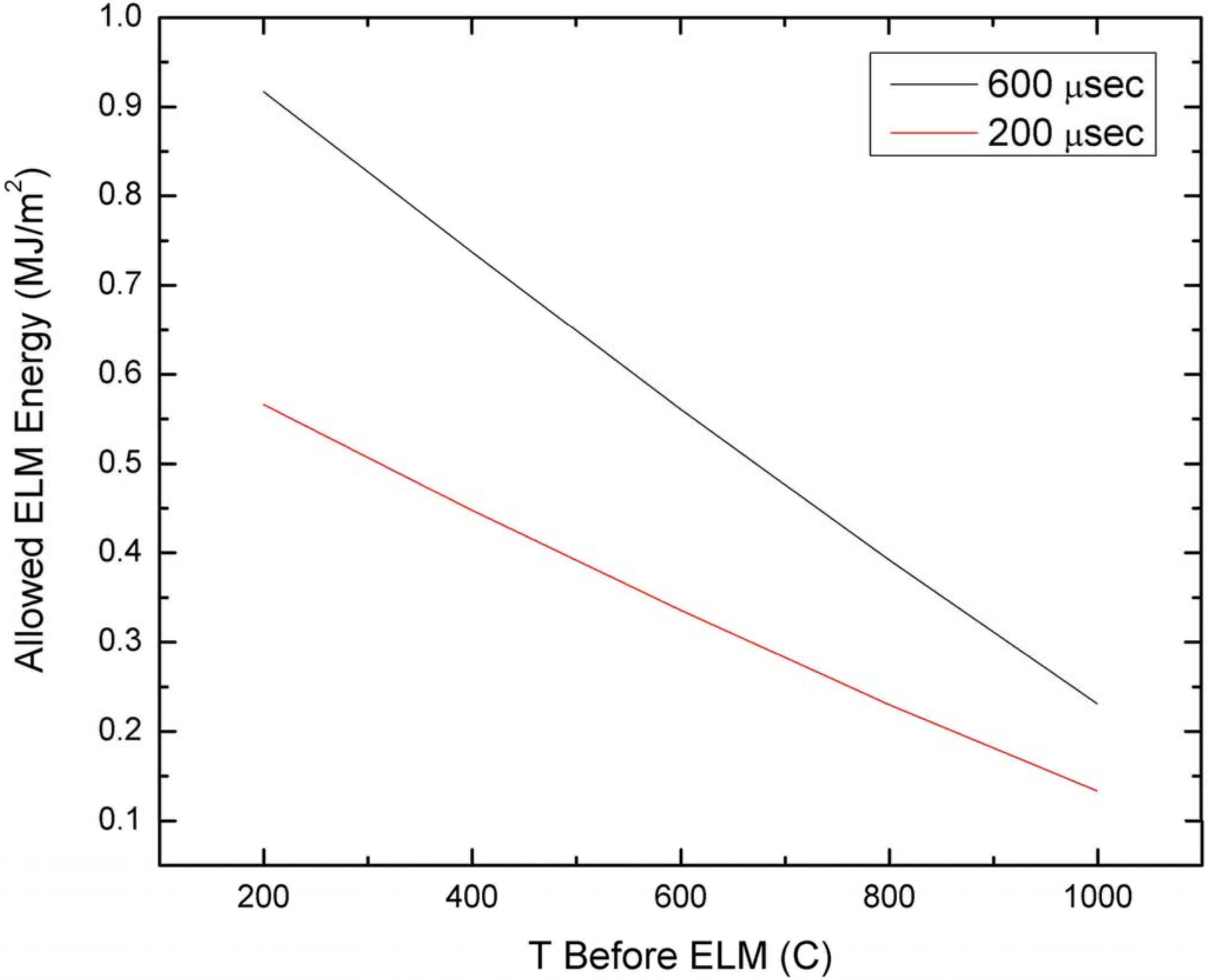
Be T Rise for 10 mm



Limitations Due to ELMs and Disruptions

- For solid surface PFCs, some thermal margin must be allowed for ELM heat loads to prevent excessive melting of the surface.
- The limitation on the normal operation surface temperature reduces the heat flux that can be accepted even with active cooling.
- For an ITER like device the flux limits on a Be first wall are approximately consistent with the expected ELM deposition but for a DEMO this is unlikely to be the case.

ELM Energy Density Limits for Be



Hydrogen Isotope Retention

- There is a wide variation in inferred H retention in eroded and redeposited carbon on fusion devices
  - 10-40% on JET and TFTR (only T machines)
  - Few percent or less in recent measurements (higher T, different configurations, etc.)
  - ITER needs less than 0.1% for no cleaning
- Existing methods for removing codeposits are inadequate
- Even if solutions are found for ITER, C is unlikely to be used in the future.
- Potential problems with other systems (e.g., Be/W) need to be studied just in case there is no solution for C

Liquid Surface Plasma Facing Components

Key Issues for Liquid Surfaces

- Is the heat and particle removal adequate?
- Can the flow be maintained in a tokamak environment?
- Are there practical engineering designs for the required systems?
- Is it safe to use free surface liquid flows in fusion devices?

Surface Temperature Limits

- **Lower end limits were taken from the UDEDGE Modeling (Rognlien) for high and low recycling (most applicable for the first wall). (Li - 400C, Sn & Ga - 600C, In - 500C, SnLi - 600C)**
- **High end limits were taken from the WBC Code (Brooks) for the divertor where sheath considerations dominate (Sn - 1300C, Ga - 1000C, In - 800C, Li 500C, SnLi - 700C)**
- **Ga and In were scaled from Sn the vapor pressure curves using Z^{-3} for the allowed flux.**

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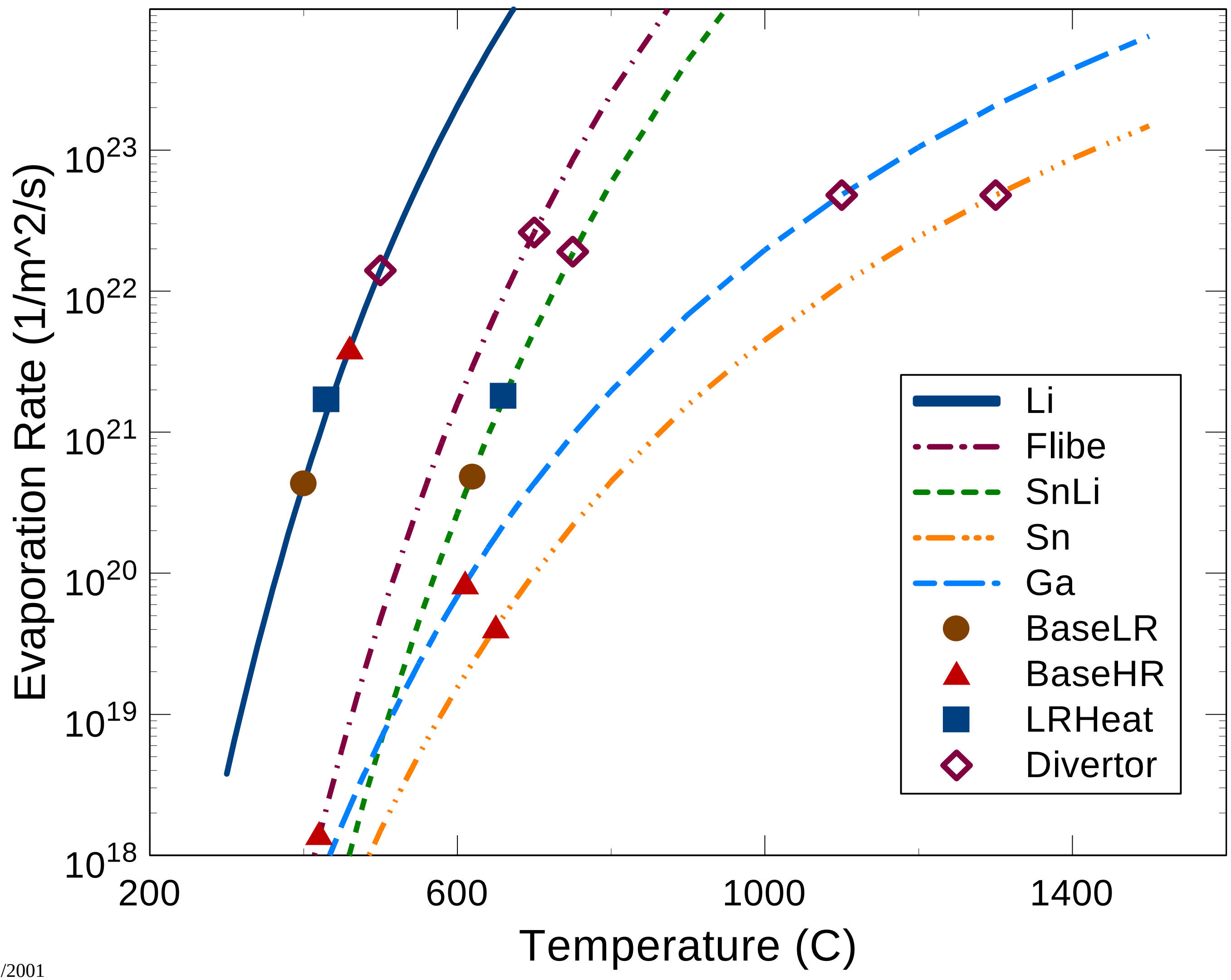
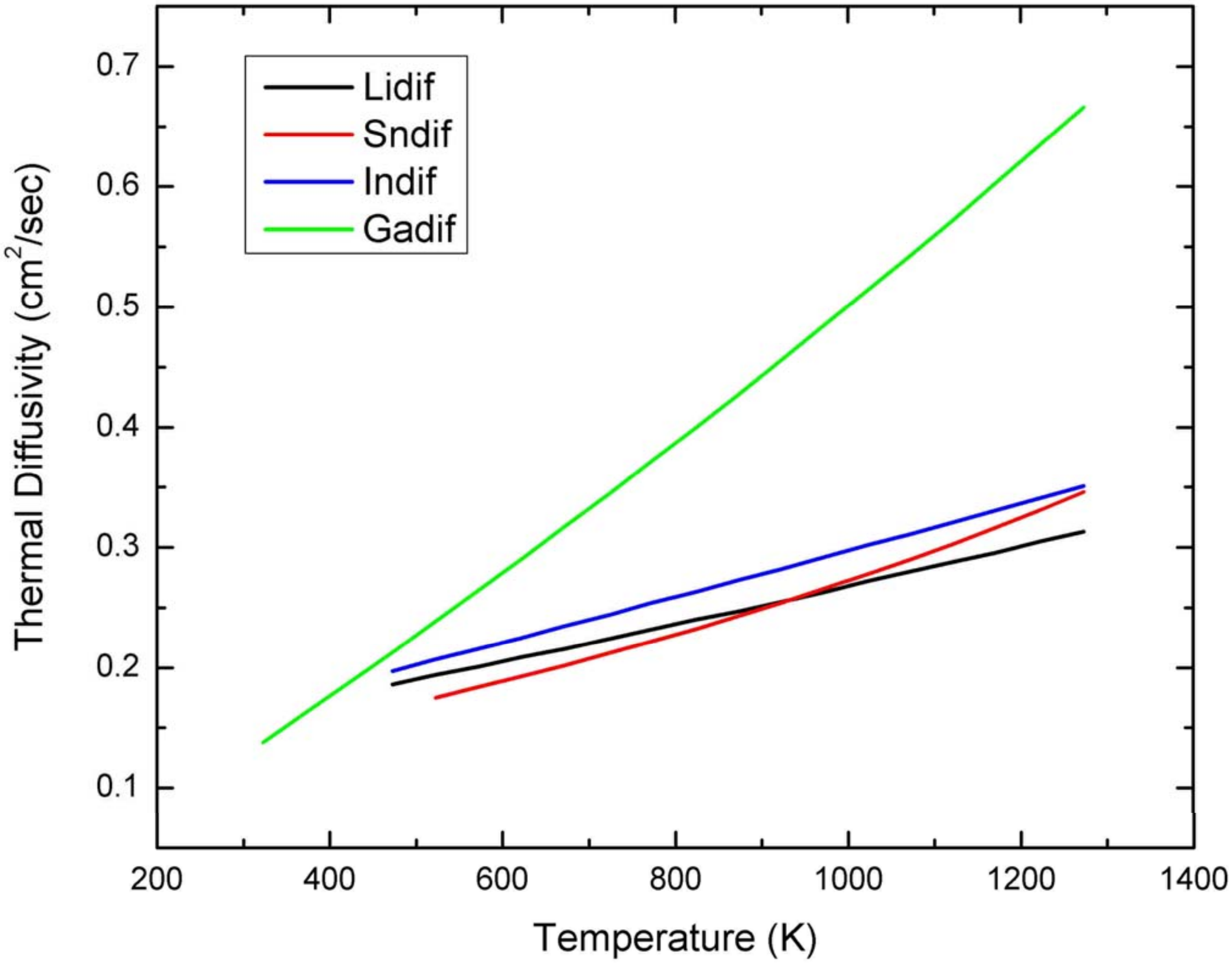
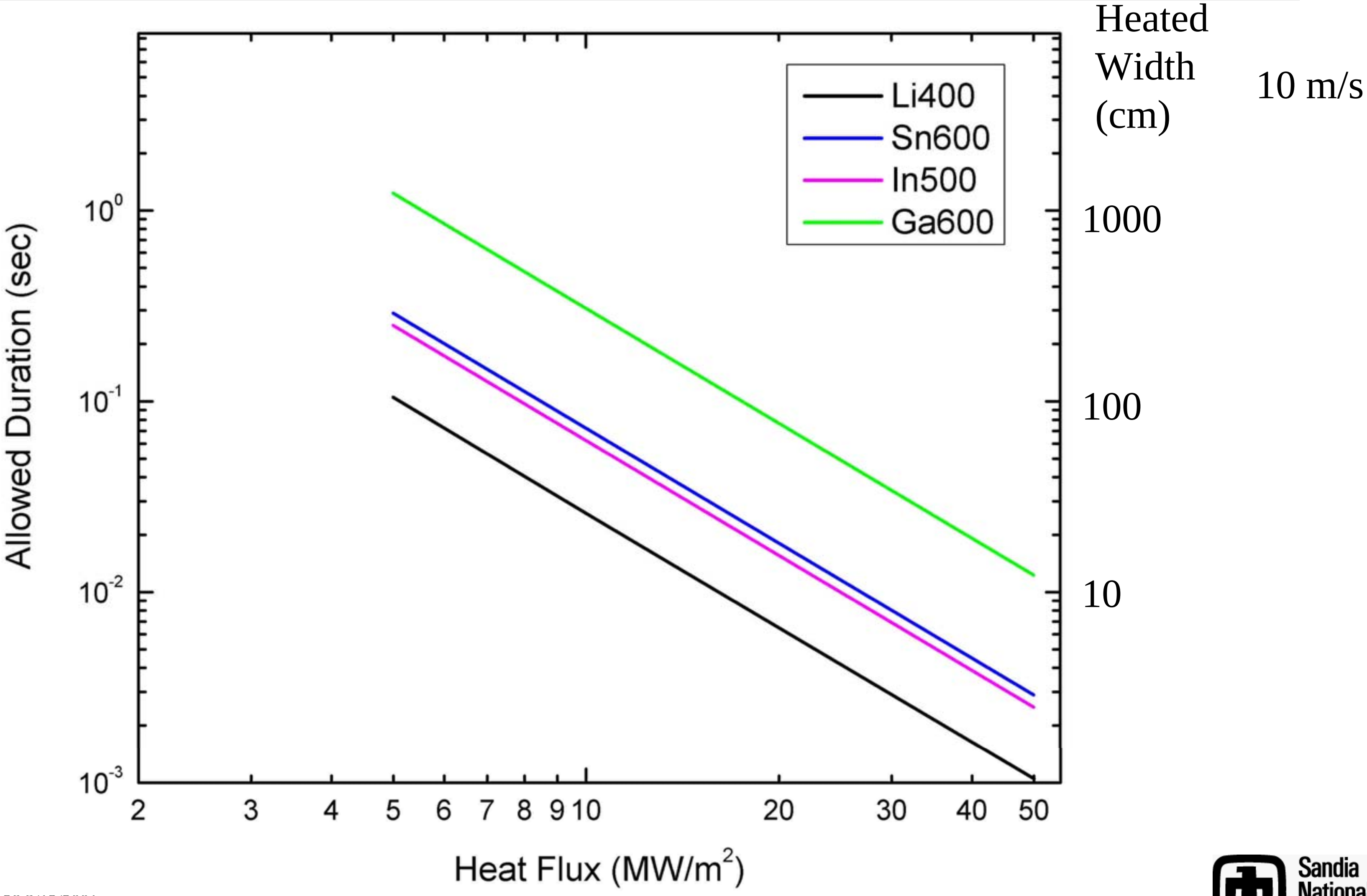
Temperature Limits



Thermal Diffusivity of Liquid Metals



Very Good Power Handling



Particle Pumping by Liquid Li

- H in Li can do one of two things
  - Exist as H atoms at concentrations up to 2-10% for temperatures between 200 and 650 C
  - Form LiH at higher concentrations (kinetics unknown)
- H atoms have a diffusivity of about 10^{-4} cm^2/s
- To leave Li the H atoms must recombine into molecules
- Measurements have found nearly 100% retention in liquid Li
- Liquid Li is a good pump for H,D, T (Too good?)

He Atom Pumping

- Helium does not need to recombine on the surface
- Helium retention is determined by the range of He in Li and the diffusivity
- If the residence time of He is long enough to reach the liquid collector, He pumping may be sufficient
- Measurements on flowing liquid Li are inconclusive
- Modeling suggests bubble formation may be important in higher Z liquids

Response to ELMs and Disruptions

- ELM or disruption heat loads will cause evaporation of the liquid but the motion will move the heat liquid from the heat flux in approximately the duration of an ELM.
- Will excessive metal flux cause contamination and ruin the plasma?
- Disruptions are likely to cause large displacement of liquid. Can the liquid be recovered?

MHD Considerations

- The flowing liquid metal will see both spatially and temporally varying magnetic fields.
- Both will induce currents in the liquid and cause forces.
- Experiments have shown that the shape changes in the liquid can be quite large
- MHD model development is still in progress
- It is too soon to tell if MHD will permit use of liquid surfaces in fusion devices.

Conclusions

Conclusions (Solid Surfaces)

- Control or mitigation of ELMs and disruptions is essential
- For divertor applications there is a need for:
  - High thermal conductivity refractory alloys compatible with He gas cooling
  - Joining methods for a high temperature radiation environment
  - Practical enhanced heat transfer method
- For the First Wall there is a need for:
  - Improved thermal conductivity
  - Practical enhanced heat transfer methods
  - Joining methods for a high temperature radiation environment

Conclusions (Liquid Surfaces)

- Flowing liquids have an advantage for heat removal (50 MW/m^2 is possible)
  - Gallium is the best for heat removal
  - Lithium may lead to low recycling (He pumping?)
- MHD stability of flowing liquids is an open question (could be a fatal flaw)
  - MHD model development is progressing and comparison to experiment is starting
- Need materials for pipes, insulators, etc.