# Overview of US Liquid Metal Blanket R&D Activities


**Mohamed A. Abdou and the US FNST Team**

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B. Merrill, P. Sharpe, Y. Katoh, D. Sze, N. Morley, C. Wong,
B. Pint, S. Sharafat, H. Zhang, R. Kurtz, M. Sawan, T. Sketchley, M. Wright, R. Munipalli)**



**International Workshop on Liquid Metal Breeder Blankets (IEA)**

**September 23-24, 2010, Madrid, Spain**

# Key Research Areas in the US PbLi based DCLL Blankets

- MHD flow Dynamics for liquid metal blankets (experiments and modeling)
- Interfacial phenomena, MHD Heat and Mass Transfer, Corrosion, Tritium Transport
- Compatibility, Corrosion experiments
- Tritium permeation and recovery experiments and modeling
- Safety analysis and modeling
- FCI material/component development & properties
- Irradiation effects in RAFM steels and SiC
- Integrated modeling / Virtual TBM
- Neutronics

# US Presentations
# IEA Workshop – September 23-24, 2010
# Madrid, Spain

## Thursday, September 23

| | | |
|---|---|---|
| S1-I3 | **Mohamed Abdou:** | “Overview of US Liquid Metal Blanket R&D Activities” |
| S3-O1 | **Pattrick Calderoni:** | “Tritium Transport properties in lead lithium eutectic” |

## Friday, September 24

| | | |
|---|---|---|
| S5-O4 | **Matt Wright:** | “Silicon Carbide Tritium Permeation Barrier for Steel Structural Components” |
| S6-I1 | **Brad Merrill:** | “Safety Analyses for the US DCLL Test Blanket Module” |
| S6-O7 | **Sergey Smolentsev:** | “Integrated Modeling of MHD Flows, Corrosion/Deposition and Tritium Transport in Liquid-Metal Blankets” |
| S7-I2 | **C. Wong/M. Abdou:** | “Status report on the US DCLL ITER TBM” |

# Key Points about US Strategy for FNST Research

- US Blanket R&D is carried out as part of a Broader Program on Fusion Nuclear Science and Technology (FNST)
- US FNST research activities continue to focus on the most important issues with high scientific content and substantial potential for improved vision of fusion energy systems
- The US science-based framework for development of FNST has two key elements
    1. An extensive R&D program of modeling and experiments in non-fusion facilities, e.g. laboratory experiments, fission reactors, and accelerator based neutron sources
    2. Integrated testing of fusion nuclear components in DT plasma-based testing facilities in which a true fusion environment can be simulated
- US views ITER TBM as important, but limited- only for initial exploration
- Fusion Nuclear Science Facility (FNSF) is required for FNST development. FNSF is a small-size, low fusion power, DT, driven plasma (QN3) device
- US DOE/OFES announced 2 top priorities: plasma control and FNST
- FNST-Pathway Assessment study is underway to detail the FNST R&D required prior to DEMO and the mission for FNSF

# Tritium extraction from lead-lithium eutectic: program objective

Experimental determination of hydrogen isotopes solubility in lead lithium eutectic (LLE)

Tritium transport modeling in liquid metal blanket systems

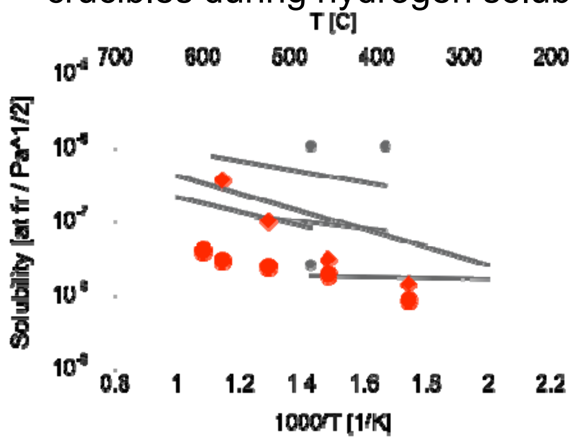
Design and experimental validation of tritium extraction systems for LLE blanket concepts

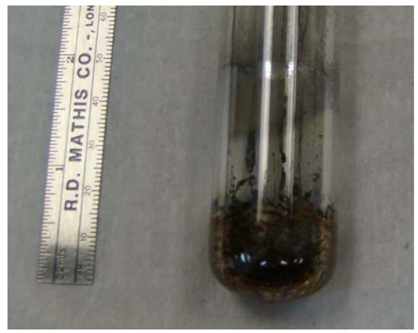
Critical evaluation of completed and operating experiments with hydrogen isotopes and lead lithium alloys

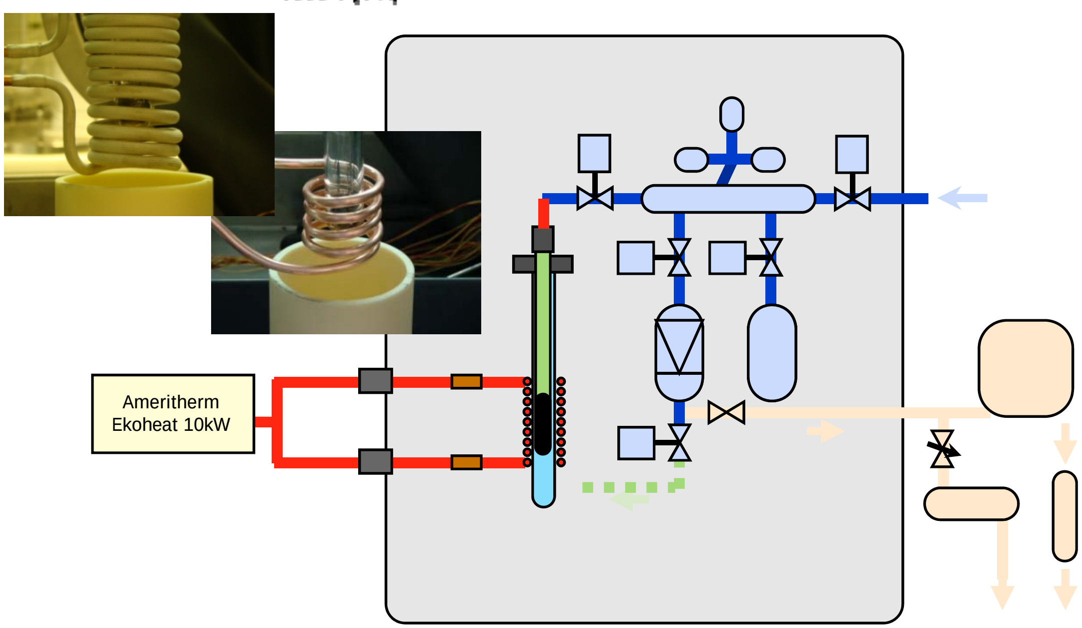
Pre-conceptual design of forced convection liquid metal loop

# Ongoing $H_2$ and $T_2$ solubility experiments

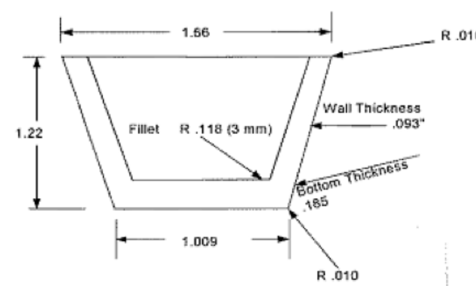
LLE showed evidence of strong interaction in resistive and induction heating configurations with both alumina and quartz crucibles during hydrogen solubility tests




Tritium test configuration:
W crucibles (99.97%, smooth forged)
induction heating




Compatibility of refractory metals and beryllium with molten Pb–17Li

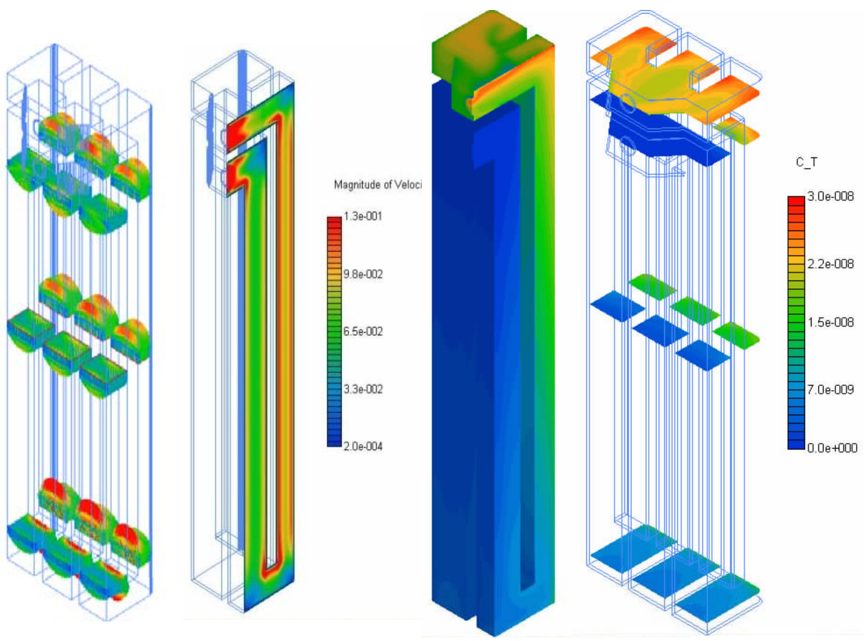
H. Feuerstein *, H. Gräbner, J. Oschinski, S. Horn

Forschungszentrum Karlsruhe GmbH, Postfach 3640, D-76021 Karlsruhe, Germany

# Tritium transport modeling development for LLB

- Develop 3D computational models to characterize diffusive, convective and temperature effects on tritium transport in PbLi blankets (DCLL and HCLL)
  - Integrate the mass transfer model with the thermo-fluid analysis to account for the velocity (ordinary and MHD flow) and temperature profiles
  - Account for the tritium generation rate profile and nuclear heating rate profile.
  - Include complex blanket geometry into analysis domain

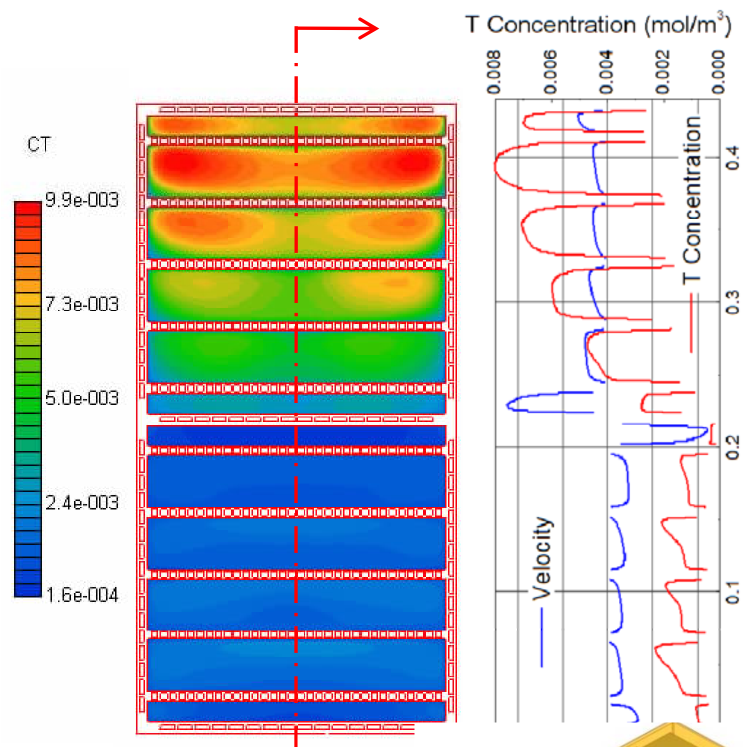
## DCLL Concepts




Velocity Profile  T concentration in PbLi

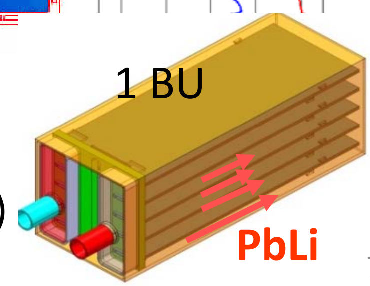
(3 U-bent duct flow with conducting walls connected through inlet/outlet with manifolds)

## HCLL Concepts




**PbLi BU (2)**

1 BU




- Evaluate tritium transport phenomena in PbLi accompanying helium(He) and develop relevant transport models to account for He effects

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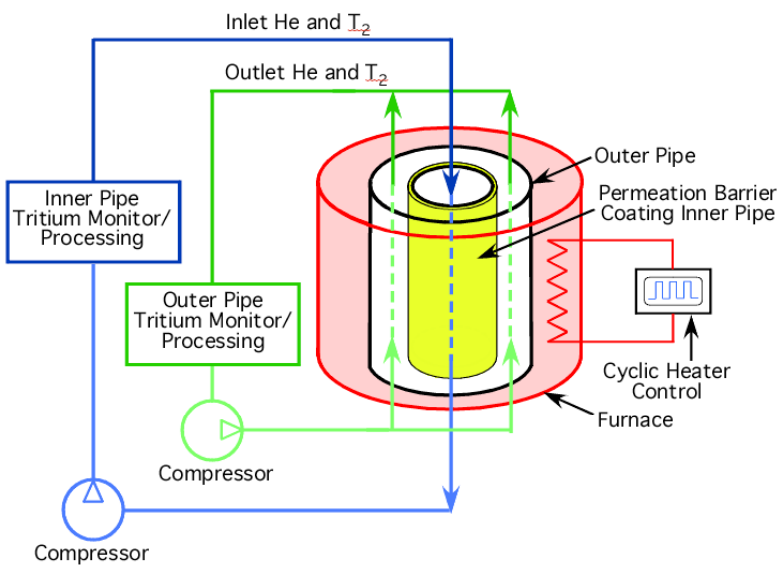
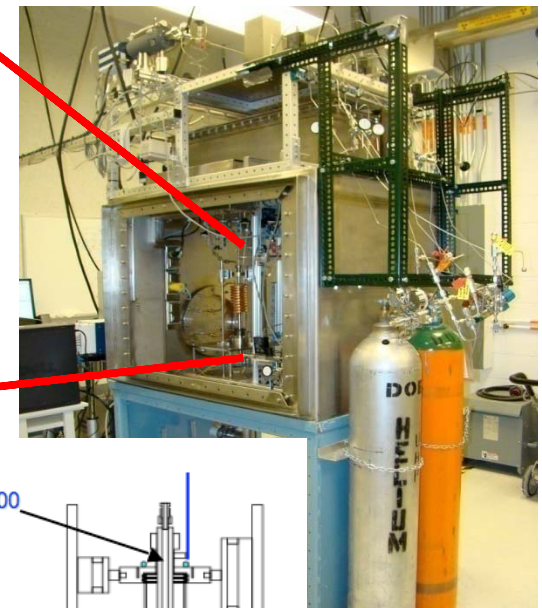
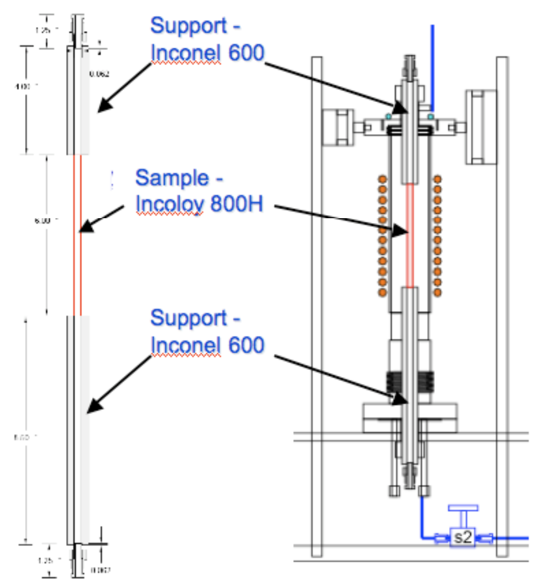
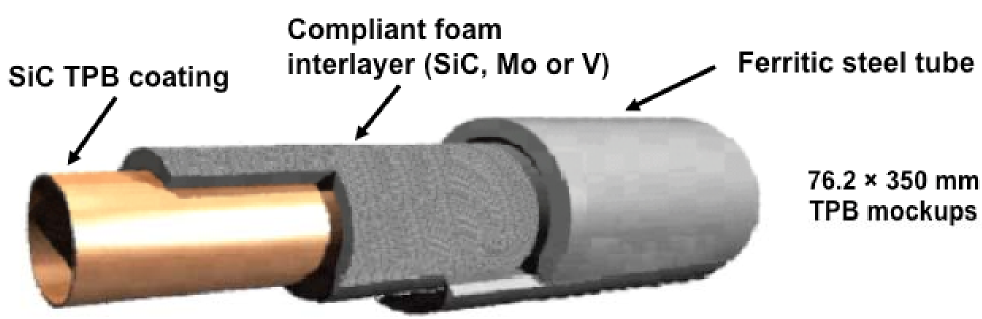
# Tritium Transport Experiments: Tritium permeation in metals and coatings: (experiments for fission reactors at INL – applicable to fusion)

***Pressure-drive permeation system with surface chemistry control: bulk materials and coatings tests***





# Safety Assessment Tools:

## Development and application of MELCOR-Fusion:

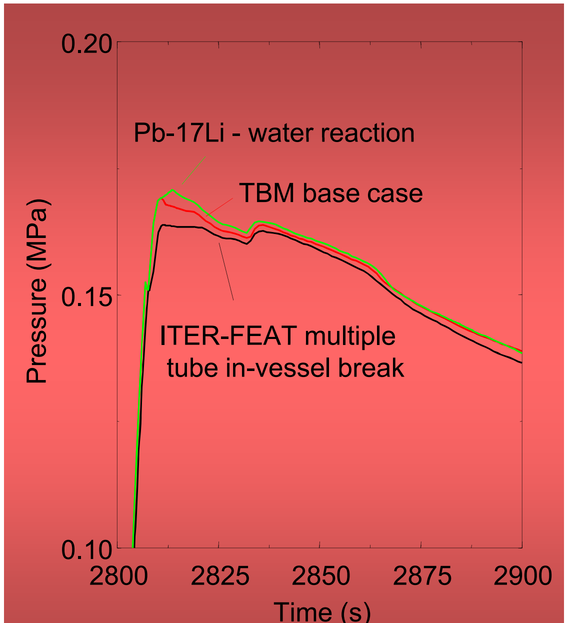
- *Adaptation of fusion-specific thermal hydraulic models*
- *Pedigreed through verification/validation and quality assurance procedures*
- *Utilized by ITER-IO for ITER RPrSand initial licensing submittals*
- *Leverages advances in nuclear safety system code development*

## Example Results from US-DCLL TBM Safety Assessment:

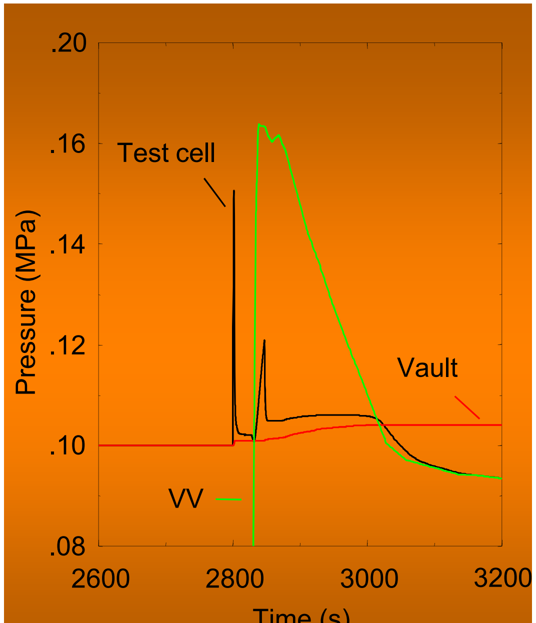
<u>Three base-case LOCA's evaluated:</u>

- Ex-vessel LOCA
- Coolant leak into TBM breeder or multiplier zone
- In-vessel TBM coolant leak analysis

*Analysis demonstrates the safety function of the ITER VV pressure suppression system was not compromised and the vault design pressure were not exceeded, thus meeting ITER TBM safety requirements*




VV pressure during an in-vessel TBM LOCA




Compartment pressurization during an ex-vessel TBM LOCA

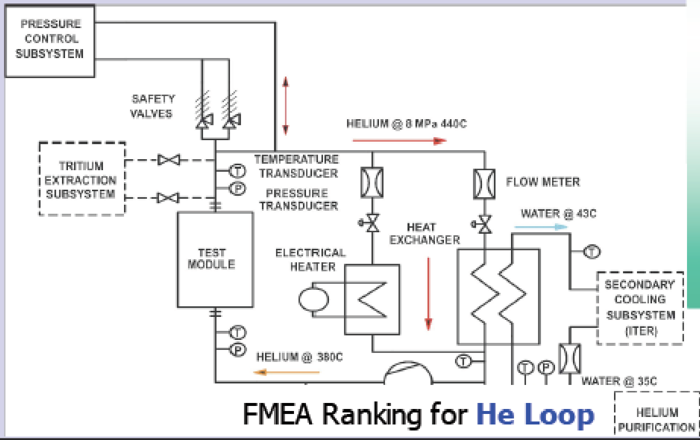
# Strong Expertise in Safety and Reliability Assessments

## US DCLL Test Blanket System (TBS) Comprehensive Preliminary Safety Report (PrSR) was transmitted to the ITER IO on 7/1/2010

### FMEA
(Failure Modes and Effects Analysis)

*3 subsystems evaluated:*
LLE Loop, **He Loop**, and Module Box

Representative details of **He Loop**:



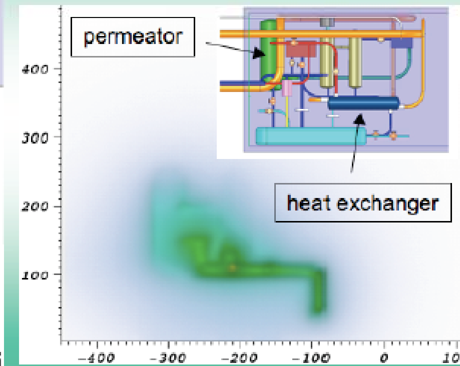

FMEA Ranking for **He Loop**

| Greatest Contributors to PIE frequency | ITER PIE | ITER Frequency Category |
|---|---|---|
| **Piping leaks** | **Small He LOCA into Port Cell** | **Category III** |
| **Piping rupture** (with aggravating TBM FW failure) | **Large He LOCA into Port Cell** | **Category III** (Category IV) |
| **Piping & valve leaks, gas circulator leak** | **Small He LOCA into TCWS vault** | **Category II** |
| **Safety relief valve spurious open, piping & valve ruptures** | **Large He LOCA into TCWS vault** | **Category II** |
| **Heater isolation valve fails open, pressure control fails, HX faults** | **Loss of heat sink for He coolant (He depressurization w/o LOCA included here)** | **Category II** (~ 0.15/year, may be Category I) |
| **Gas circulator seizure, valve fails closed** | **Loss of primary He flow** | **Category II** |

**Note: Category II > 1E-02/year, 1E-02/year ≥ Category III > 1E-04/year, 1E-04/year > Category IV**
**GSSR V10 - US DOE-STD-3009-94 defines Category I > 0.1/year**
**Accident analyzed in DCLL TBM DDD (bounding event for large He leaks into TCWS vault)**

### ORE
(Occupational Radiation Exposure)

QADMOD Results- Permeator cut




Exposure estimate for TBM Replacement

| Task Description | Total Time | Dose |
|---|---|---|
| | hours | p-mSv |
| Remove AEU from Port cell Area | 65.00 | 2.410 |
| Bio-Shield Plug removal | 11.00 | 0.055 |
| Equatorial Port Inter-space Pipe removal | 48.00 | 0.580 |
| Port Flange Preparation | 13.00 | 0.130 |
| Port plug Assembly removal, transportation and insertion into hot cell | TBD by ITER | |
| Port plug testing, and assembly Installation | TBD by ITER | |
| Port Inter-space Pipe and service equipment Installation | 106.00 | 1.470 |
| Bio-Shield Plug Installation | 25.00 | 0.125 |
| AEU installation | 120.00 | 2.620 |
| Total | 388.00 | 7.390 |

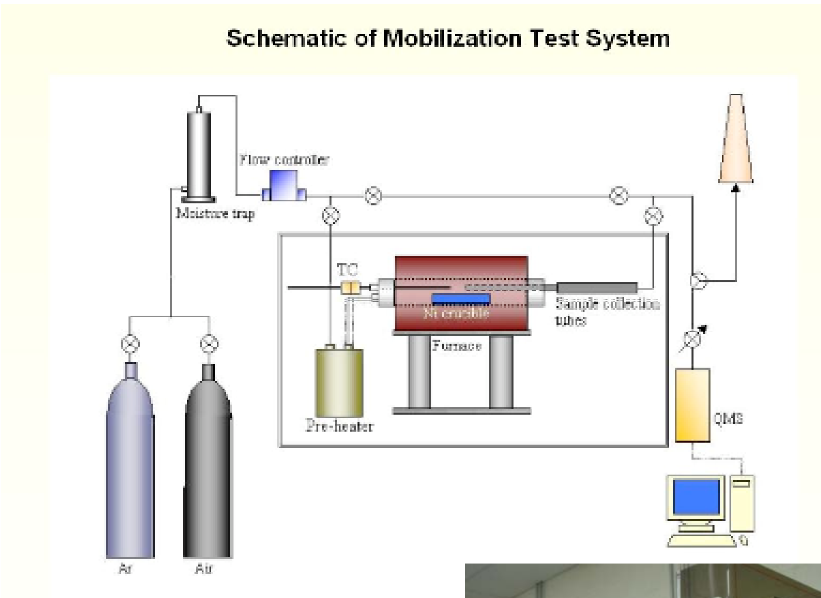
### WDA
(Waste Disposition Analysis)

| US Year | Tokamak | | Hot Cell | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Green Zone | | Amber/Yellow | | | Red | | | |
| | Port | Port Cell | Stand-by (storage < 1 year) | Fresh C Storage (> 1 year ) | Stand-by | Refurbishment | Rad Waste | Stand-by (temporary storage) | Refurbishment* | Rad Waste | Packaging** |
| -2 | | | TBM 1 | | | | | | TBM* 1 to Port Plug 1 | | |
| -1 | | | AEU Tube forest 1 | Dummy TBM | | | | TBM* 1 in Port Plug 1 | | | |
| 1 | TBM 1 | AEU TF1 | TBM 2 | | | | | | | | |
| 2 | TBM 1 | AEU TF1 | Tube forest 2 | | | | | | TBM* 2 to Port Plug 2 | | |
| 3 | TBM 1 | AEU TF1 | | | | | | TBM* 2 in Port Plug 2 | | | |
| Machine down time | | | AEU | | Tube forest 1 | | | TBM* 1 in Port Plug 1 | | | |
| 4 | TBM 2 | AEU TF2 | TBM 3 | | | Tube forest 1 | | | TBM* 1 from Port Plug 1 TBM* 3 to Port Plug 1 | TBM* 1 | |
| 5 | TBM 2 | AEU TF2 | | | Tube forest 1 | | | TBM* 3 in Port Plug 1 | | | TBM * 1 |
| Machine down time | | | | | AEU | | Tube forest 2 | TBM* 2 in Port Plug 2 | | | |
| 6 | TBM 3 | AEU TF1 | TBM 4 | | | | | | TBM* 2 from Port Plug 2 TBM* 4 to Port Plug 2 | TBM* 2 | |
| 7 | TBM 3 | AEU TF1 | Tube forest 3 | | | | | TBM* 4 in Port Plug 2 | | | |
| Machine down time | | | | | AEU | | Tube forest 1 | TBM* 3 in Port Plug 1 | | | |
| 8 | TBM 4 | AEU TF3 | | | | | | | TBM* 3 from Port Plug 1 | TBM* 3 | TBM * 2 |
| 9 | TBM 4 | AEU TF3 | | | | | | | | | |
| 10 | TBM 4 | AEU TF3 | | | | | | | | | TBM * 3 |
| Machine down time | | | | | | | Tube forest 3 | TBM* 4 in Port Plug 2 | | | |
| 11 | | | | | | | | | TBM* 4 from Port Plug 2 | TBM* 4 | |
| 12 | | | | | | | | | | | TBM * 4 |

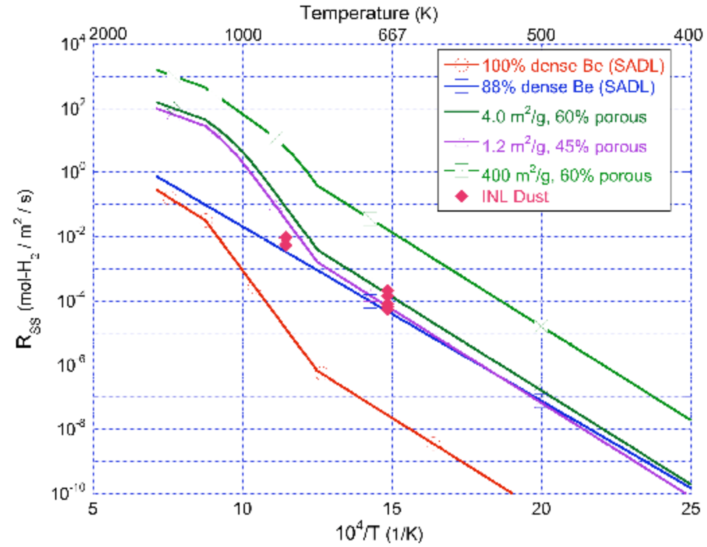
Volumes: TBM shipped - 5.6 $m^3$
Remains onsite - ~180 $m^3$

# Safety Experiment: Beryllium Reactivity Testing *(Experimental setup can be used to study Air/moisture interactions with liquid breeders simulating LOVA conditions)*

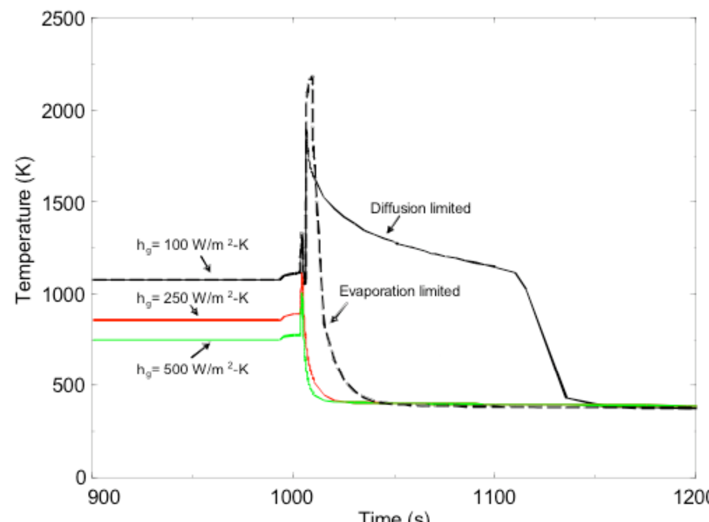
**Various forms of beryllium- bulk, dust, mixed dust, and pebbles (including irradiated materials)**




**$H_2$ generation rate for bulk and granular Be**




**Dust reaction in ITER wet bypass accident scenario**




*(Be-dust explosion testing to be started in FY10)*

# MHD, heat & mass transfer Research highlights

- **MODELING** – we expanded our research from purely MHD flows to coupling between MHD and heat & mass transfer, including *tritium transport*, *corrosion, deposition* and *buoyancy-driven flows*
- **EXPERIMENT** – from simulants (In-Ga-Sn, Hg) to "real" liquid (PbLi). Hot PbLi loop is under construction at UCLA to address interfacial phenomena and to test new materials (e.g. SiC).
- **DESIGN** – modeling/experimental results are used to improve blanket designs (e.g. nested FCI)

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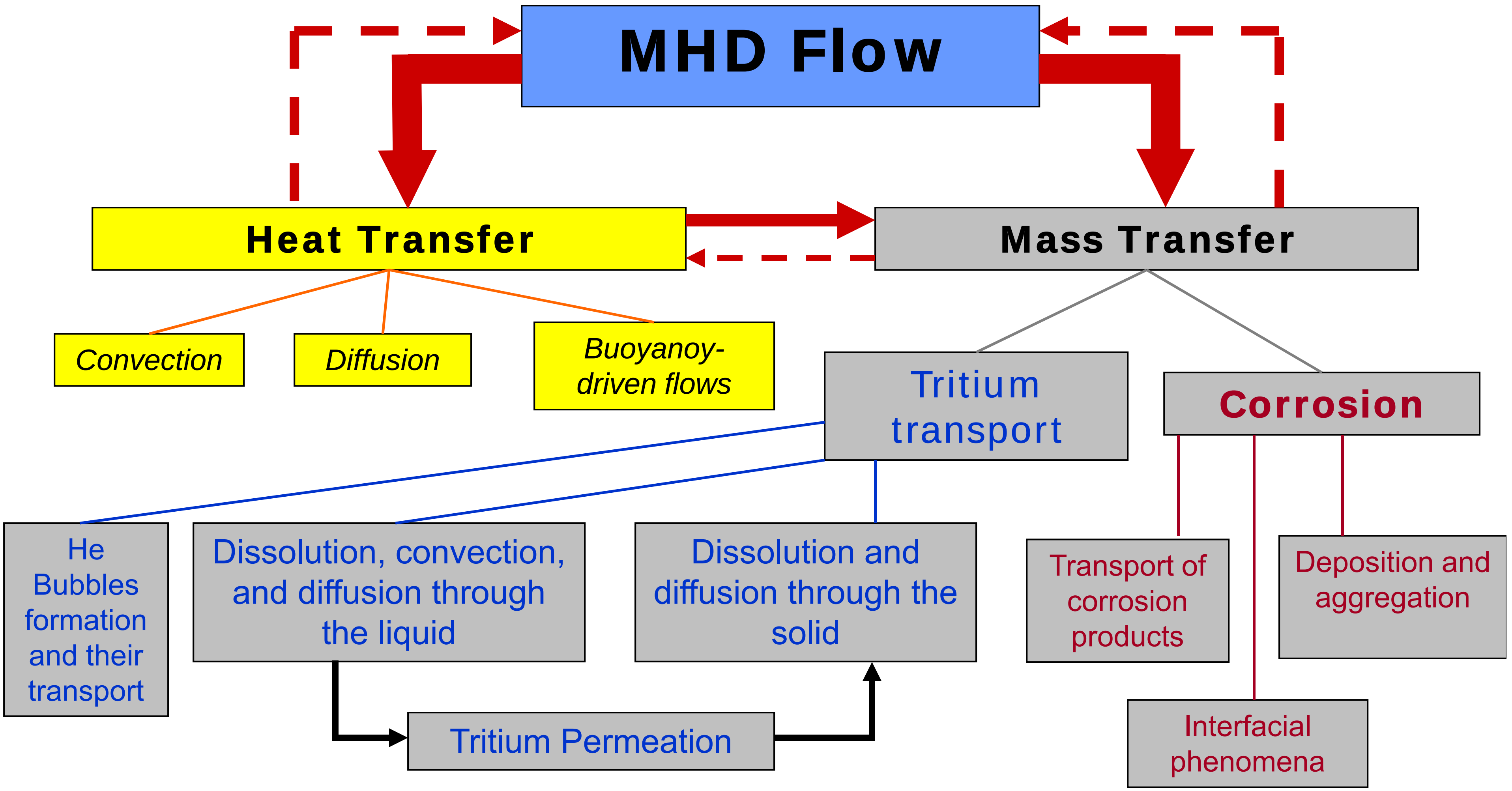
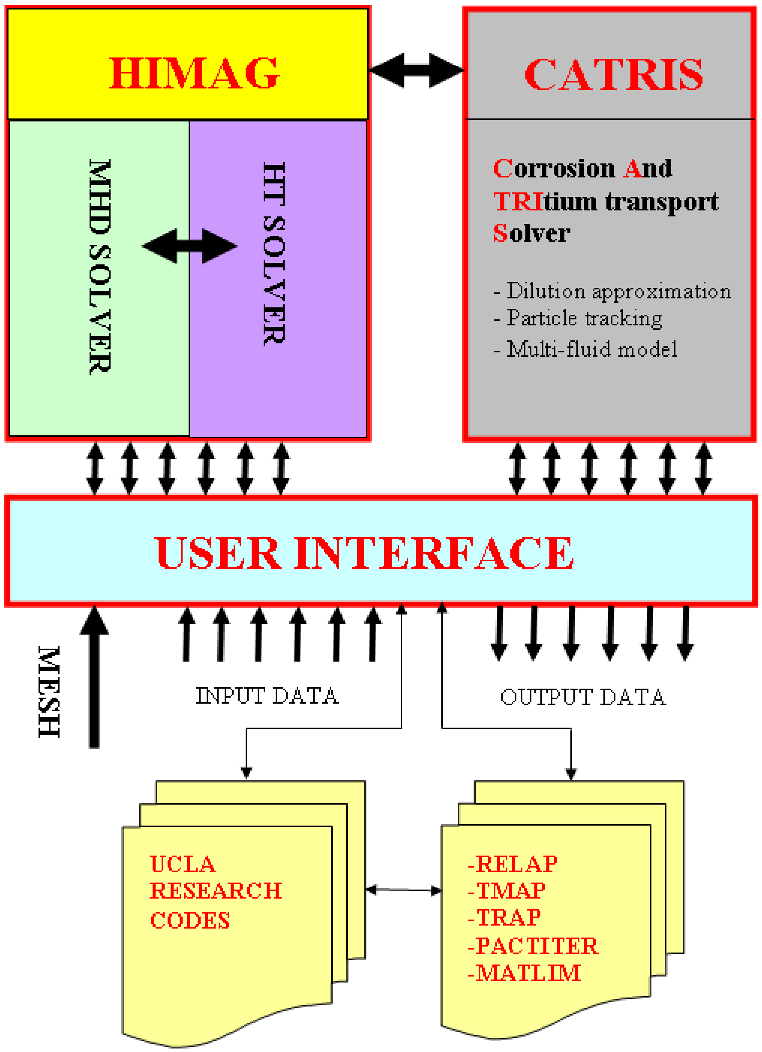
# Integrated, multi-physics modelling of MHD flow dynamics and heat and mass transfer in blanket flows




Coupling through the source / sink term, boundary conditions, and transport coefficients

# Development of computational tools




- Continuing to develop **HIMAG** as a basic MHD/Heat Transfer solver – *code acceleration* is the major objective. Recent implementation of "wall functions" allows for code acceleration by factor 5-20 !
- **CATRIS** is a *new mass transfer solver* coupled with HIMAG – just started. Various models from "dilution approximation" to "multi-fluid models" are being included
- **New PHENOMENOLOGICAL MODELS** for tritium transport, interfacial phenomena and corrosion and deposition are being developed

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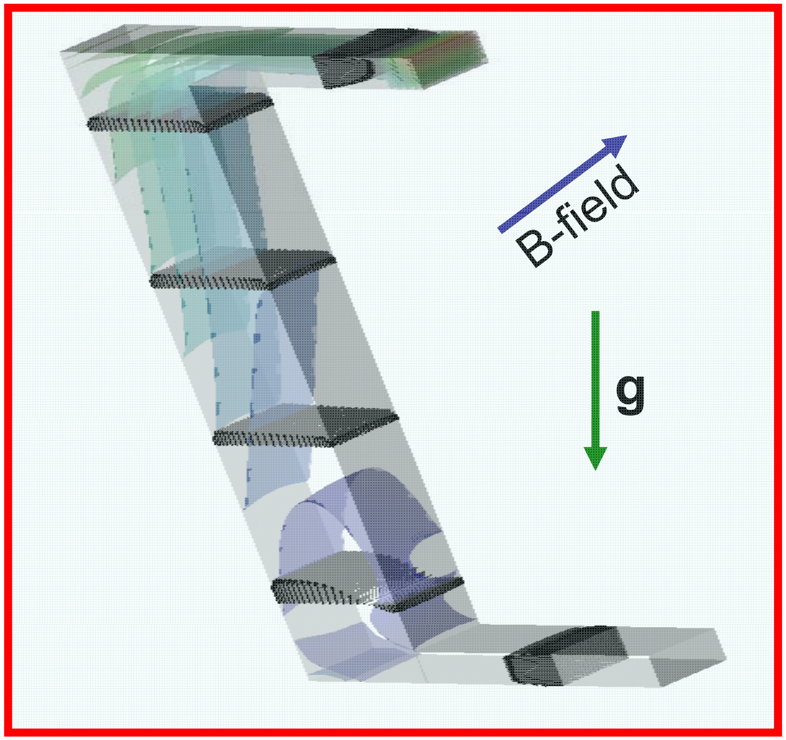
# Buoyant flows are dominant in DCLL and HCLL blankets

***Volumetric heating causes strong Archimedes forces in LM flows, resulting in buoyancy effects***

DCLL: **FORCED flow** ~ *10 cm/s*, **Buoyant flow** ~ *30 cm/s*




**Ha=1000 Re=10,000 Gr=$10^7$**

The buoyant flows affect the temperature field in the liquid and solid, interfacial temperature, heat losses and tritium transport – all IMPORTANT!

*Recent 3D computations in the DCLL blanket conditions with HIMAG have confirmed importance of mixed convection effects and demonstrated a strong tendency to a quasi-two-dimensional state as well as reduction of 3-D effects as Ha number is increased*

(Note: DEMO will have higher Ha and Gr than used in the figure. In DEMO, Ha ~12000, Gr ~$10^{12}$ )



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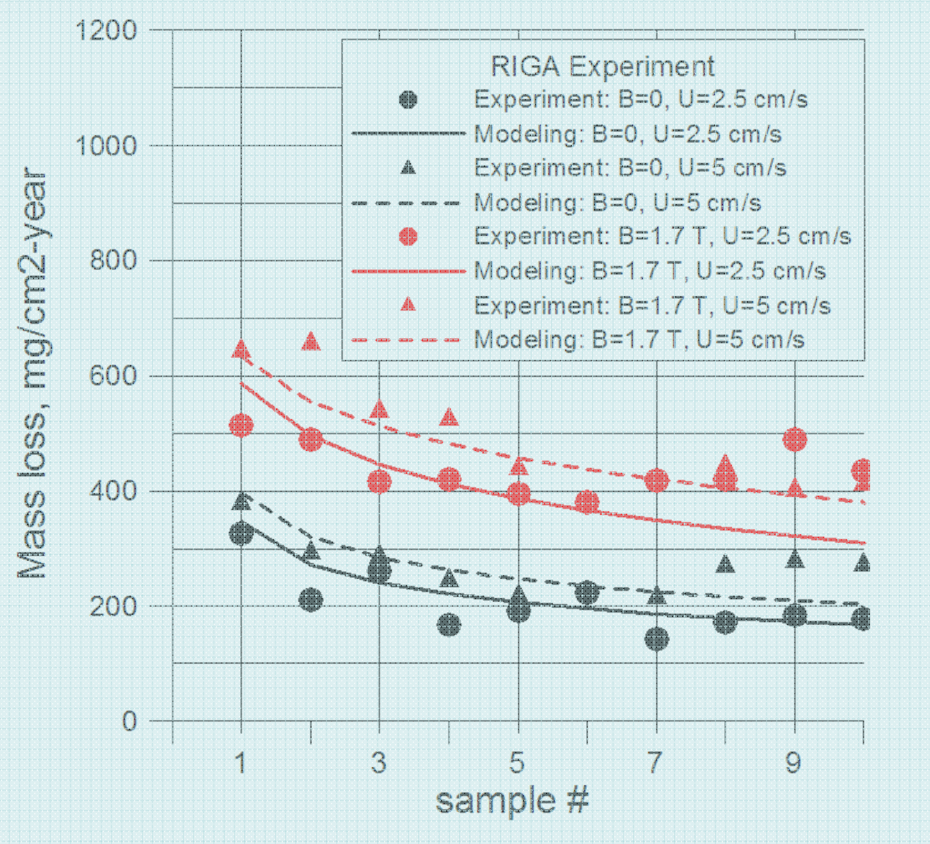
# Corrosion/Deposition severely limits the interfacial temperature

- Recent experiments (Riga) for MHD corrosion in PbLi-EUROFER (*laminar flow, 550°C, 3000 hrs, 1.7 T*) have demonstrated that the corrosion rate in the presence of a magnetic field can be doubled
- 3D computations using HIMAG/CATRIS are in fair agreement with the experiment

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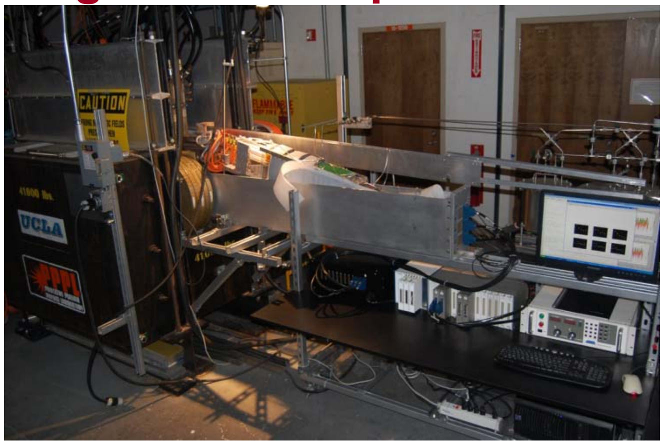
# Experiments with simulants (Hg)

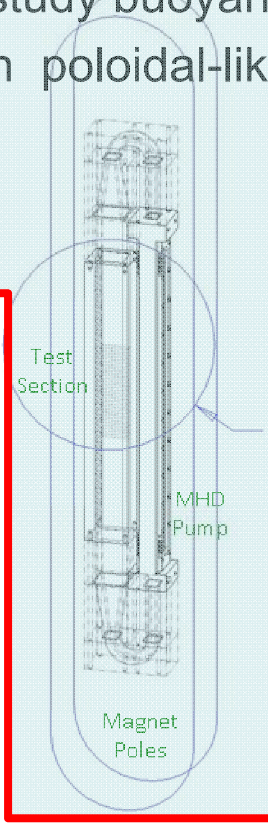
**Prequalification experiment:** to test new MHD flow diagnostics and to address 3D->2D transitions in duct flows in a strong magnetic field

## UCLA MHD facilities

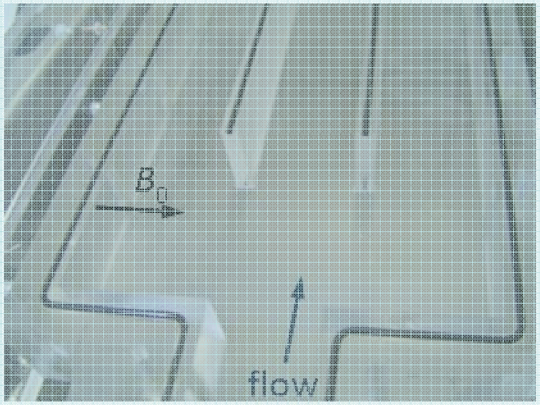
**Magnetic field up to 1.7 T**

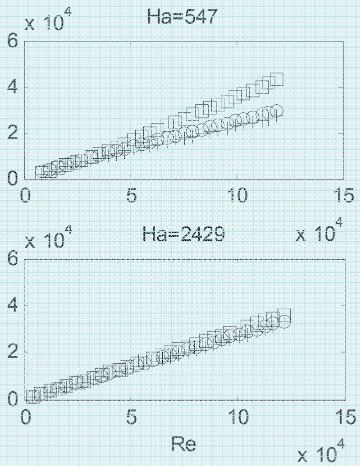


**Mixed convection experiment:** the magnet will be turned vertically to study buoyant MHD flows in poloidal-like channels



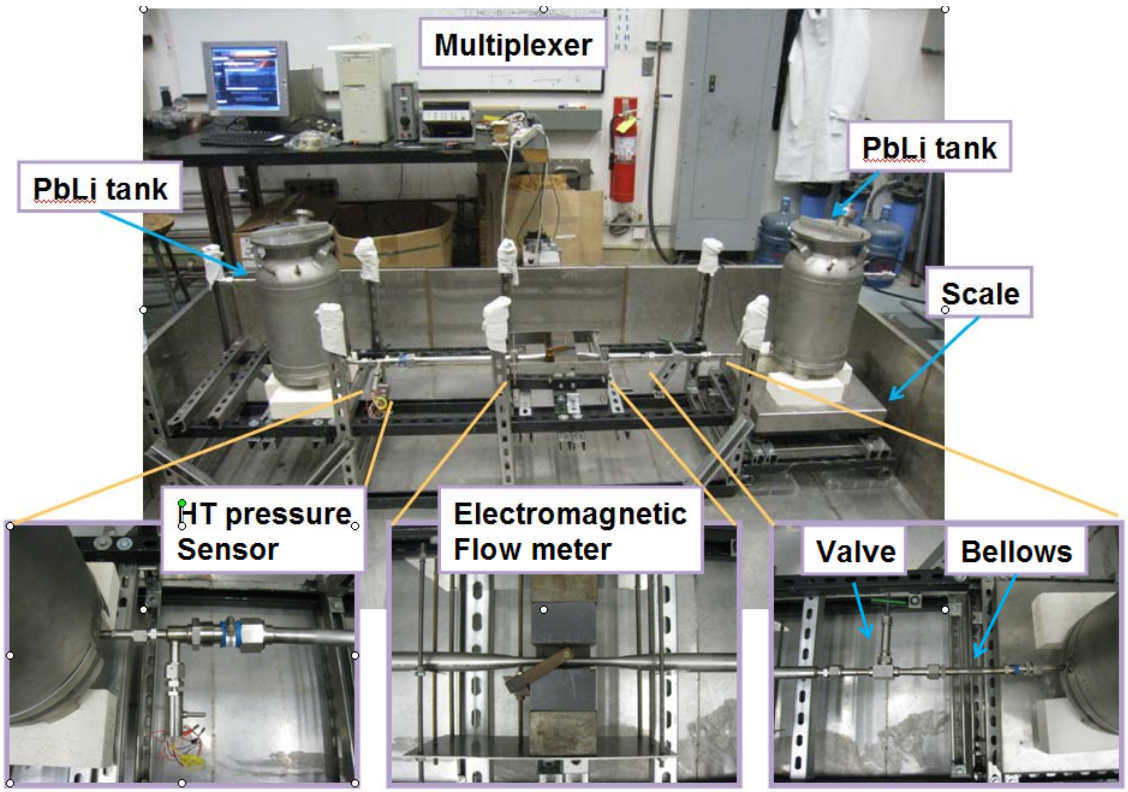

**Manifold experiment:** to address flow distribution in a complex 3D geometry, where the LM flow from the inlet splits into 3 poloidal channels – *tendency to more uniform flow as Ha and Re numbers change*



# New PbLi loop is under construction at UCLA

## The loop components are being tested




*magnetic field ~ 2 T*
*space inside the magnet ~ 1 x 0.2  x 0.2 m*
*temperature ~350-400°C*
*pumping capacity ~ 0.5 L/s, 0.15 MPa*

The loop will be upgraded in 2012 to increase pumping capacity (1 L/s, 0.3 MPa), and temperature (500°C)

- *MHD testing*
- *Heat transfer testing*
- *Mass transfer testing*
- *New material testing*

Current goals of the PbLi loop under construction: PbLi technology experience, develop and test diagnostics, foam-based SiC FCI exposure, etc.

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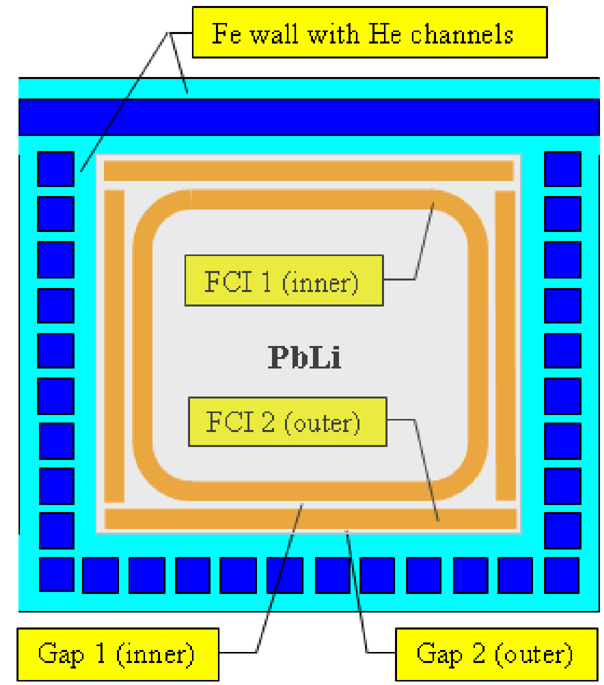
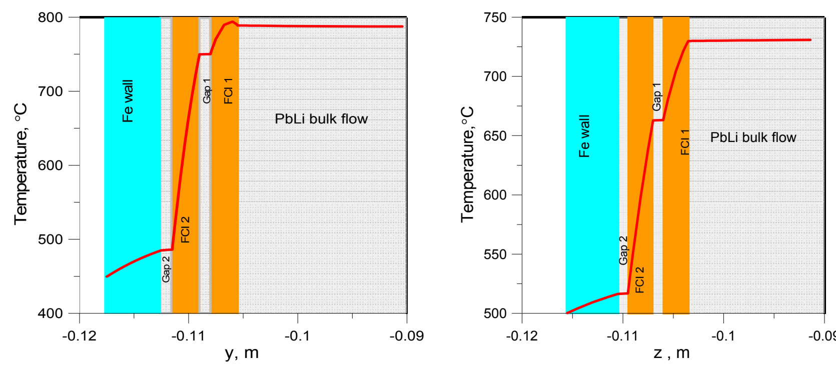
# Nested FCI– new approach to mitigate thermal stress in the FCI

- Current analysis shows that conventional single-layer SiC FCI will experience unacceptable thermal stress (DCLL DEMO)
- Nested FCI - new engineering solution to mitigate thermal stress
- Internal layer serves mostly as electrical insulator
- Thermal insulation is shared between the two layers
- No stringent requirements on electrical or thermal conductivity. Changing FCI properties by irradiation does not affect the FCI performance




S. SMOLENTSEV, S. MALANG, Double-Layer Flow Channel Insert for Electric and Thermal Insulation in the Dual-Coolant Lead-Lithium Blanket, <u>Fus. Sci. Technol.</u>, 56, 201-205, 2009.



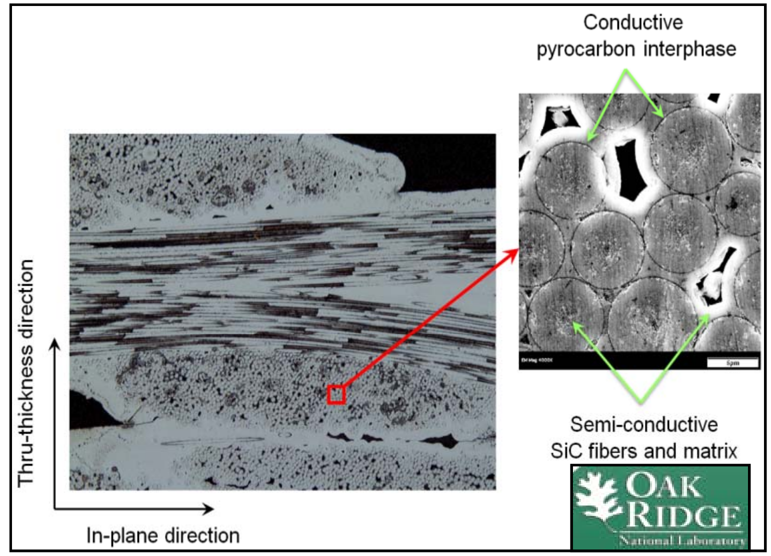



Calculations are for DEMO conditions assuming fully developed velocity profile

# SiC Based FCI Fabrication & Testing

- FCI Samples and Mockups Fabricated:
  - Open-cell CVD-SiC foam based FCI prototypes fabricated and tested (650 $^oC$ static PbLi)
  - Closed-cell CVD SiC foam under development
  - $SiC_f/SiC_m$ Composites under development
- Property Measurements Conducted:
  - Thermal, Electrical, Mechanical
- Performed PbLi exposure and heat load testing of FCI prototype

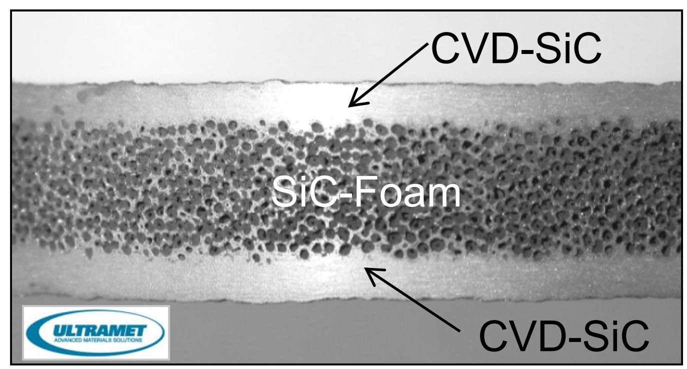
SiC-fiber/SiC-matrix composites are promising candidates





Fabrication, testing and modeling of foam based FCI Prototype

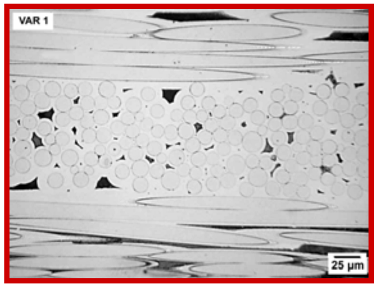
CVD SiC
Closeout Layers/SiC foam (5X)



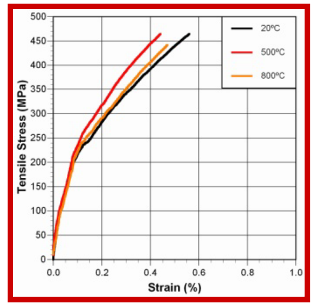
# SiC/SiC Composites for Flow Channel Inserts

DoE funded SBIR with Hyper-Therm HTC examining the feasibility of SiC/SiC composites for flow channel inserts

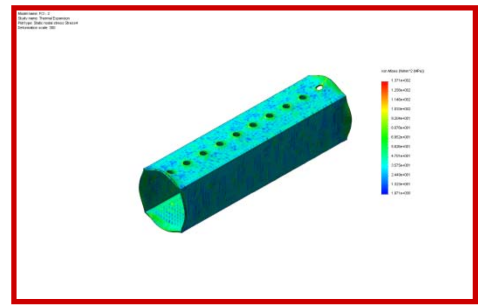
## Benefits:




SiC/SiC composites produced from near stoichiometric SiC fibers and a CVI SiC matrix have demonstrated excellent stability under neutron radiation similar to monolithic CVD SiC



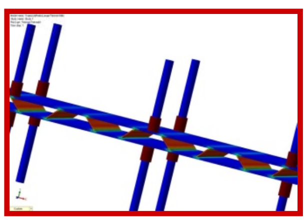

SiC/SiC composites possess pseudo-plasticity because reinforcing fibers provide a high strain to failure (compared to monolithic ceramics). An insensitivity of the mechanical properties to temperature also exists

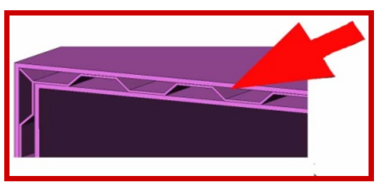


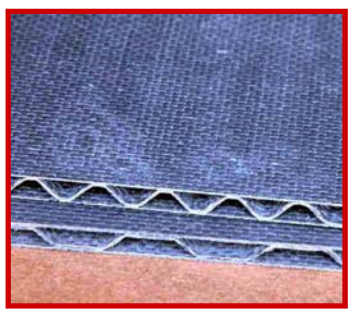
**Two properties identified do not meet requirements:** 1. Unacceptably high through thickness thermal conductivity (15-23 W/m/K in 800ºC-ambient prior to irradiation) would result in too high of a heat loss and/or insufficient thermal protection of the ferritic steel flow channel; 2. High interlaminar shear stresses at corners due to through thickness thermal gradient may cause matrix cracking and Pb-Li permeability

**Solutions:** 1. Architectural construction of the SiC/SiC composite to reduce through-thickness thermal transport

FEA modeling indicates fluted core SiC/SiC can achieve equivalent through thickness thermal conductivity of 1.4 W/m/K

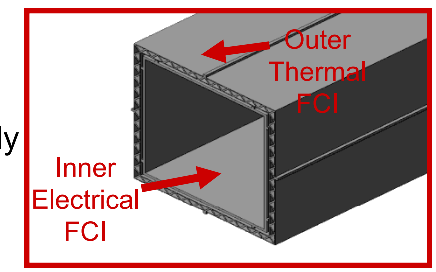






Two fluted core technology demonstrators

2. Eliminate interlaminar shear stresses at corners of FCI insert by using continuous inner electrical FCI with minimal temperature drop through-thickness & outer architecturally designed thermal FCI composed of non-rigidly attached corners (Smolentsev and Malang )



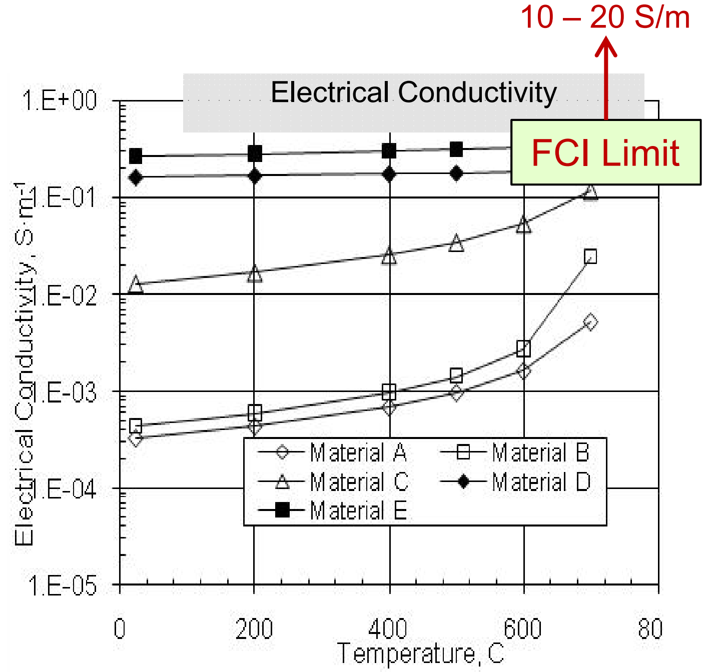
# Recent Progress on SiC-Foam Based FCI

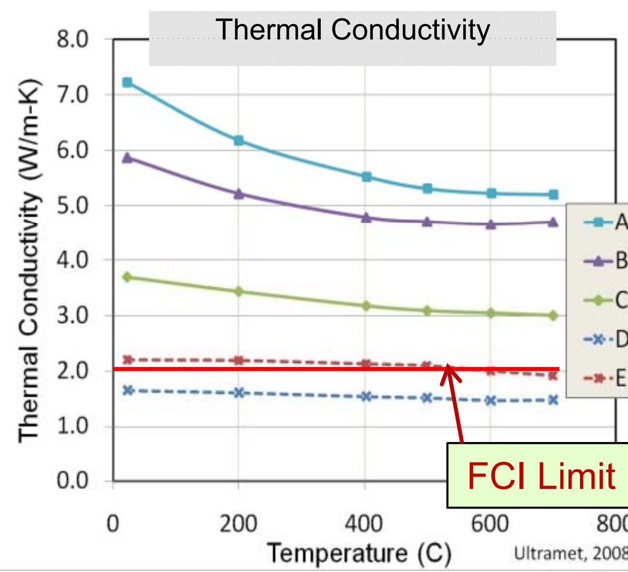
**Objective, using silicon carbide, open-cell-foam-core develop FCI prototype that:**

- Provides thermal insulation between high temperature liquid Pb-17Li tritium breeder and structural material
- Provides electrical insulation between Pb-17Li and structural material to mitigate MHD effects

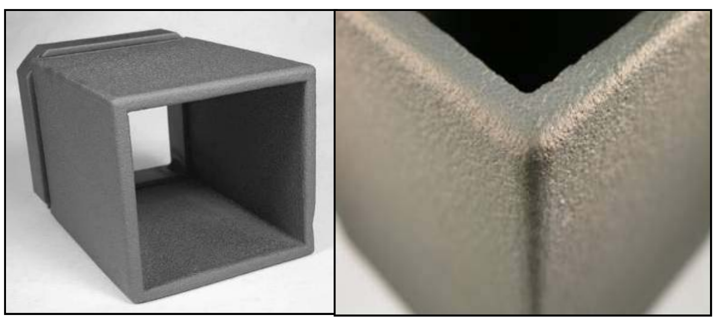
**Results:**

- Comprehensive thermo-mechanical modeling was performed and correlated with experimentally derived performance.
- At 700 °C the open-cell foam structure exhibited low thermal (~ 3 to 6 W/m-K) and electrical conductivity (< 0.1 S/m).
- Immersion testing of development specimens in PbLi for 100 hours at 0.7 MPa and 600ºC resulted in no metal ingress.
- FCI prototype segments up to 100 x 100 x 300 mm long were successfully fabricated along with a segment joint coupling
- FCI prototype thermal testing showed a high thermal gradient across the wall at steady-state with 600ºC ID and 453°C OD.
- Immersion testing of a FCI prototype in PbLi at 560°C, at ambient pressure, for 6 hours resulted in no metal ingress.

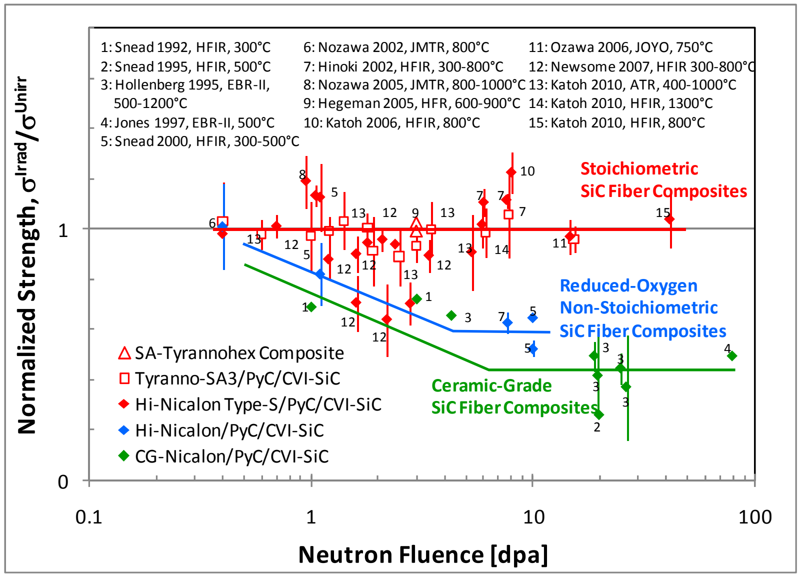


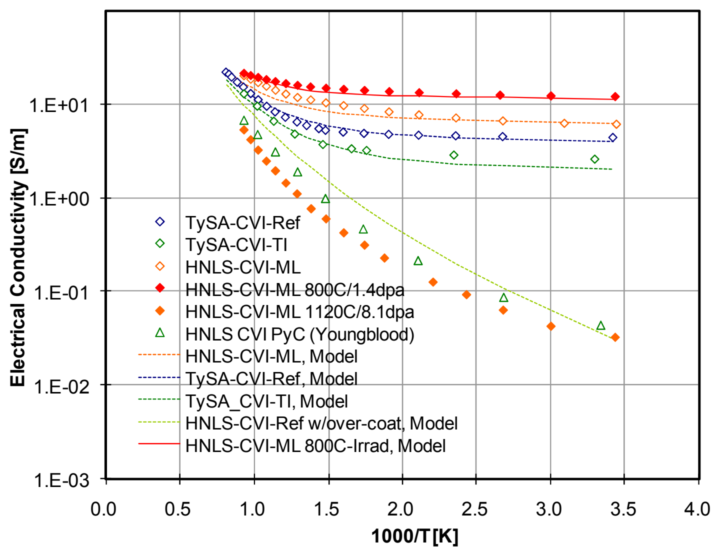




SiC Foam/SiC Facesheet
**FCI Prototype** Segment
(100 x 100 x 300 mm long)



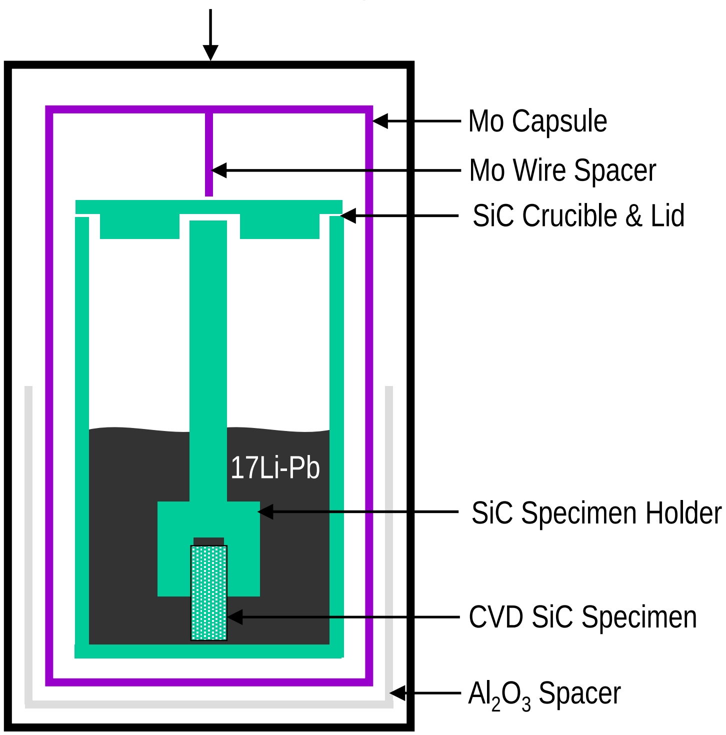
# ORNL Program is Addressing Key Fundamental Performance Issues for SiC-based FCI Development




- Fundamental radiation effects
  - Mechanical properties
  - Thermo-physical properties
  - Dimensional stability
  - Microstructures and micro-mechanics composite constituent properties
- Key design properties for FCI
  - Electrical and thermal transport properties; irradiation effects and constitutive modeling
  - Effects of steep temperature gradient
  - Irradiation creep and stress relaxation phenomena
- Chemical compatibility issues
  - PbLi corrosion of SiC and steels
  - Mass transport in PbLi-SiC-steel system

# Compatibility of SiC FCIs & RAF/M Steel with PbLi



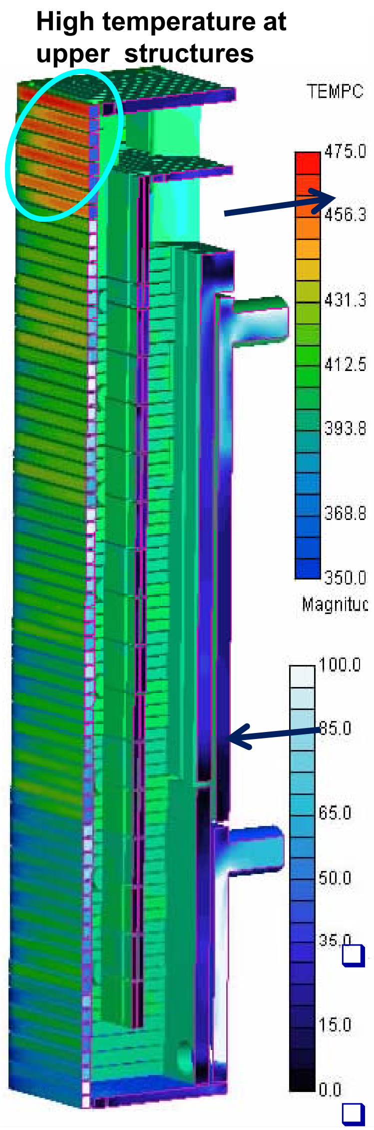
Before/During Test

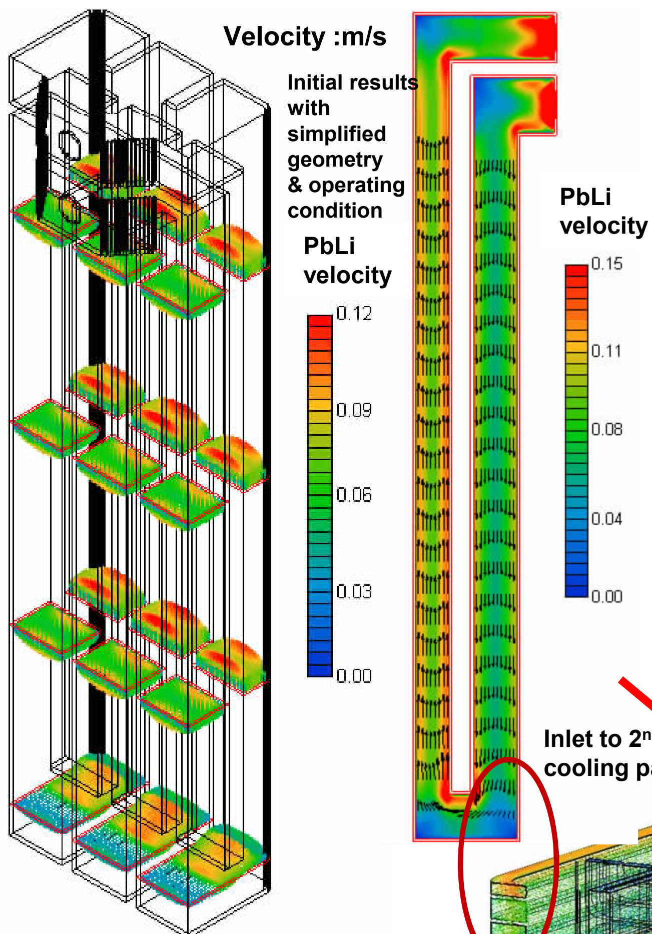
Static capsule testing shows good compatibility up to ~1100°C

- Small scale experiments have been performed at ORNL on SiC/PbLi and structural alloys/PbLi compatibility and surface effects.
- Small scale experiments on aluminized alloys for better PbLi resistance.
- Strong interest to broaden this research to include a more complete system:
  - Testing of more SiC composites and foams with sealing layers.
  - Testing in flowing PbLi-MHD environment.
  - PbLi/SiC/FS/Refractory system.
  - Coupled to the Thermofluid MHD / mass transfer modeling.

## The US has initiated an important program on integrated multi-physics simulation

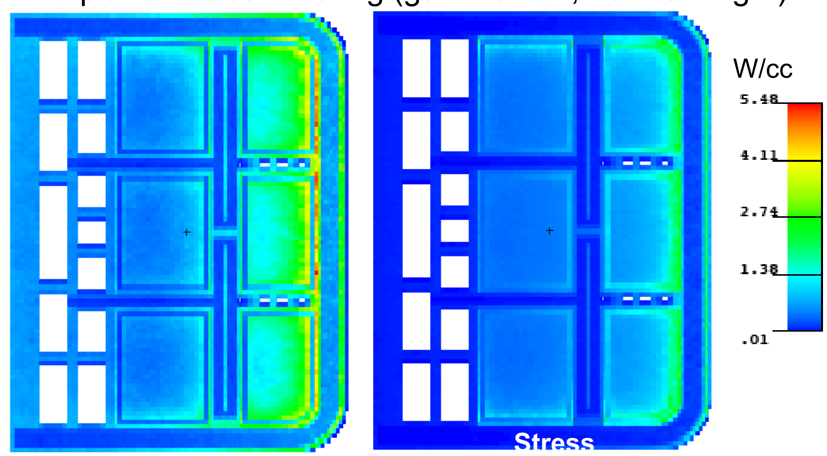
- Important tool to model complex systems, explore design options and guide R&D
- It will evolve as the “FNST Predictive Capability” with advances in modelling of subsystems and with experimental validation



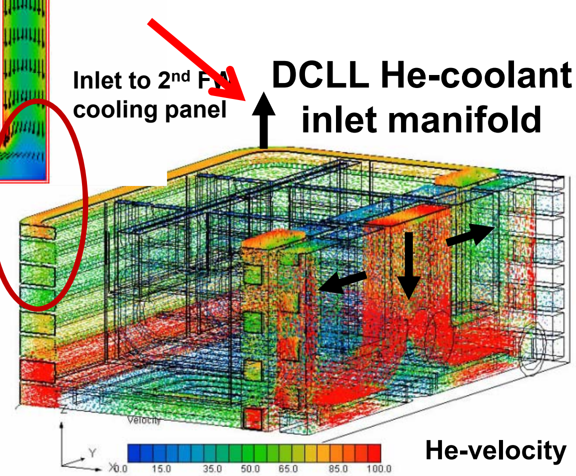



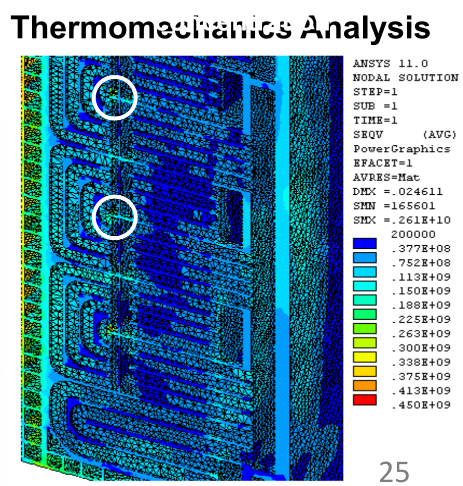

- Location of the instrument and the associated perturbation to the data
- Analysis with a detailed geometric drawing with instrumentations in-place needed

Mid-plane nuclear heating (gamma: left; neutron: right)




- Proper manifold designs to provide uniform flow distributions among many parallel flow paths
- Adequate cooing to all parts



# Summary

- US has strong Research Program on Fusion Nuclear Science and Technology (FNST)
- Blanket R&D is carried out as part of the broader FNST
- Both solid breeders and liquid breeders are pursued as two classes of concepts that have distinct and different feasibility and attractiveness issues
- Larger share of R&D is on liquid metal PbLi blankets. DCLL is selected as an example of a pathway toward higher temperature/higher efficiency but with current generation of ferritic steels
- R&D on Liquid breeders covers many important areas: MHD fluid flow / heat transfer / mass transfer modeling and experiments, tritium extraction / transport / permeation / processing, safety, FCI material / component development, radiation effects in FS, integrated modeling
- US participates in ITER TBM. FNST is one of the top two goals for fusion development. FNSF is the key facility in FNST pathway