Liquid Breeder Blanket Concepts

And Overview of the Dual-Coolant Lead-Lithium Blanket Concept (DCLL)

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Liquid Breeder Blanket Concepts and Overview of the Dual-Coolant Lead-Lithium Blanket Concept (DCLL)

Outline

- Introduction to liquid breeder blankets and issues
- Key aspects of the Design, Technical topics and Issues (e.g. MHD, insulation, tritium extraction and permeation, heat extraction and thermodynamic cycle, compatibility, etc) for various concepts:
 - Self-cooled cooled liquid metal (LM) concepts
 - Separately cooled liquid metal (LM) concepts
 - The Dual-Coolant Lead Lithium (DCLL) Blanket concepts
 - Molten salt self cooled and dual coolant concepts
- DCLL R&D
- Appendix examples of data (thermo physical properties for liquid breeders)

Liquid Breeders

- Many liquid breeder concepts exist, all of which have key feasibility issues. Selection can not prudently be made before additional R&D and fusion testing results become available.
- Type of Liquid Breeder: Two different classes of materials with markedly different issues.
 - a) Liquid Metal: Li, ⁸³Pb ¹⁷Li

High conductivity, low Pr number

Dominant issues: MHD, chemical reactivity for Li, tritium permeation for LiPb

b) Molten Salt: Flibe $(LiF)_n \cdot (BeF_2)$, Flinabe $(LiF-BeF_2-NaF)$

Low conductivity, high Pr number

Dominant Issues: Melting point, chemistry, tritium control

Liquid Breeder Blanket Concepts

1. Self-Cooled

- Liquid breeder circulated at high speed to serve as coolant
- Concepts: Li/V, Flibe/advanced ferritic, flinabe/FS

2. Separately Cooled

- A separate coolant, typically helium, is used. The breeder is circulated at low speed for tritium extraction.
- Concepts: LiPb/He/FS, Li/He/FS

3. Dual Coolant

- First Wall (highest heat flux region) and structure are cooled with a separate coolant (helium). The idea is to keep the temperature of the structure (ferritic steel) below 550°C, and the interface temperature below 480°C.
- The liquid breeder is self-cooled; i.e., in the breeder region, the liquid serves as breeder and coolant. The temperature of the breeder can be kept higher than the structure temperature through design, leading to higher thermal efficiency.



Advantages of Liquid Metal Blankets

LM Blankets have the *Potential* for:

- High heat removal
- Adequate tritium breeding ratio appears possible without beryllium neutron multiplier in Li, PbLi (Pb serves as a multiplier in PbLi). (Note that molten slats, e.g flibe has beryllium part of the salt and generally requires additional separate Be.)
- Relatively simple design
- Low pressure, low pumping power (if MHD problems can be overcome)

See BCSS for review of many possible blanket systems.

Flows of electrically conducting coolants will experience complicated magnetohydrodynamic (MHD) effects

What is magnetohydrodynamics (MHD)?

 Motion of a conductor in a magnetic field produces an EMF that can induce current in the liquid. This must be added to Ohm's law:

$$\mathbf{j} = \boldsymbol{\sigma}(\mathbf{E} + \mathbf{V} \times \mathbf{B})$$

 Any induced current in the liquid results in an additional body force in the liquid that usually opposes the motion. This body force must be included in the Navier-Stokes equation of motion:

$$\frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V} \cdot \nabla)\mathbf{V} = -\frac{1}{\rho}\nabla p + \nu \nabla^2 \mathbf{V} + \mathbf{g} + \frac{1}{\rho}\mathbf{j} \times \mathbf{B}$$

 For liquid metal coolant, this body force can have dramatic impact on the flow: e.g. enormous MHD drag, highly distorted velocity profiles, non-uniform flow distribution, modified or suppressed turbulent fluctuations.

Main Issue for Flowing Liquid Metal in Blankets: MHD Pressure Drop

<u>Feasibility issue</u> – Lorentz force resulting from LM motion across the magnetic field generates MHD retarding force that is very high for electrically conducting ducts and complex geometry flow elements



Inboard is the critical limiting region for LM blankets

- B is very high! 10-12T
- L is fixed to reactor height by poor access
- a is fixed by allowable shielding size
- T_{max} is fixed by material limits

Combining Power balance formula

 $\dot{m} = P_{NWL} La / c_p \Delta T$

With Pipe wall stress formula

$$S \approx pa/t_w$$

With thin wall MHD pressure drop formula (previous slide) gives:

$$S = \frac{P_{\rm NWL} L^2 B^2 \sigma_w}{a \rho c_p \Delta T} \qquad (Sze, 1992)$$

Pipe stress is INDEPENDENT of wall thickness to first order and highly constrained by reactor size and power!



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No pipe stress window for inboard blanket operation for Self-Cooled LM blankets (e.g. bare wall Li/V) (even with aggressive assumptions)

- Pipe stress >200 MPa will result just to remove nuclear heat
- Higher stress values will result when one considers the real effects of:
 - 3D features like flow distribution and collection manifolds
 - First wall cooling likely requiring V ~ 1 m/s





What can be done about MHD pressure drop?

 $\Delta P = cL\sigma_l VB^2$

c represents a measure of relative conductance of induced current closure paths

- Lower C
 - Insulator coatings
 - Flow channel inserts

Break electrical coupling to thick load bearing channel walls

– Elongated channels with anchor links or other design solutions
Force long current path

- Lower V
 - Heat transfer enhancement or separate coolant to lower velocity required for first wall/breeder zone cooling
 - High temperature difference operation to lower mass flow
- Lower B,L
 - Outboard blanket only (ST)
- Lower σ (molten salt)

A perfectly insulated "WALL" can eliminate the MHD pressure drop. But is it practical?

Conducting walls



Lines of current enter the low resistance wall – leads to very high induced current and high pressure drop

> All currents must close in the liquid near the wall – net drag from jxB force is zero

Insulated walls



- Net JxB body force ∇p = cσVB² where c = (t_w σ_w)/(a σ)
- For high magnetic field and high speed (self-cooled LM concepts in inboard region) the pressure drop is large
- The resulting stresses on the wall exceed the allowable stress for candidate structural materials

- Perfect insulators make the net MHD body force zero
- Insulator coatings were proposed
- But insulator coating crack tolerance is found to be very low (~10⁻⁷).
 - It appears impossible to develop practical insulators under fusion environment conditions with large temperature, stress, and radiation gradients

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 Self-healing coatings have been proposed but none has yet been found (research is on-going)

Example of Self-Cooled Blanket :Li/Vanadium Blanket Concept

Vanadium structure



Self-cooled Lithium with Vanadium Alloy

- Self-cooled Lithium with Vanadium Alloy Structure was the U.S. choice for a long time, because of its perceived simplicity. But no more.
- Russia still has Li/V option (there is interest in some Japanese universities)
- Li/V Conceptual Designs were developed in the US:
 - Blanket Comparison and Selection Study (BCSS 1983-84)
 - ARIES-RS (in the 1990's)





Fig. 3. Outboard blanket and shield.

Issues with the Lithium/Vanadium Concept

Li/V was the U.S. choice for a long time, because of its perceived simplicity. But negative R&D results and lack of progress on serious feasibility issues have eliminated U.S. interest in this concept as a near-term option.

Issues

- Insulator
 - Insulator coating is required
 - Crack tolerance (10⁻⁷) appears too low to be achievable in the fusion environment
 - "Self-healing" coatings can solve the problem, but none has yet been found (research is ongoing)
- Corrosion at high temperature (coupled to coating development)
 - Existing compatibility data are limited to maximum temperature of 550°C and do not support the BCSS reported corrosion limit of 5µm/year at 650°C
- Tritium recovery and control



- Li REACTIVITY with air and water is very serious; precludes use of water anywhere
- Vanadium alloy development is very costly and requires a very long time to complete

Conducting wall

Insulator coating main focus Li/V

- Ideal coatings are the ideal solution to the MHD pressure drop problem
 - All surfaces covered by insulator coatings AIN, YtO3, ErO3
 - Self healing paradigm assumed where cracks and spalls are quickly healed
- However, Tolerable crack fraction (assuming Li wetting) appears to be quite low, well below that achievable with *real* coatings
 - How well does the lithium penetrate small cracks and electrically contact the pressure bearing wall as a function of time?
 - What is the crack fraction, size, distribution as a function of time?
 - Can self-healing work?
- US materials people pessimistic about self-healing, suggestion has been made to move to multi-layer insulating barriers – alternating layers of insulator and metallic protection layer
 - Metal layer seals underlying insulator so insulator cracks have no effect.
 - Thickness of metal layer will govern pressure drop

"in-situ" coating test measure resistance of coating in contact with Li



All tests with bare insulator in contact with Li showed immediate electrical shorts upon Li melting, and often removal of large areas of the coating.

Multiple Layer Insulating Barriers Coatings

- Thin metal layer protects underlying insulator coating.
- The layer must be thin to keep MHD pressure drop acceptable 10-100 microns.
- Corrosion and integrity of this layer is an important potential issue.
- Russian research in this area going on for several years, having difficulty achieving dense metallic layers on top of AIN insulator coatings by spraying technique
- Considering separate metallic liners or baked on foils.



Fig. 2. AlN+Cr coating on VCrTi, $h_{AlN} = 5.5 \ \mu m$, $h_{Cr} = 5.5 \ \mu m$, $h_{Cr} = 5.5 \ \mu m$, $h_{Cr2O3} = 3 \ \mu m$ (sample No. 7.1).

Vitkovkski et al. FED, v. 61-62 (2002)

Other LM blanket issues: Pressure drop effect on flow balance

- Changes in insulator can also have large effects on the flow balance between parallel channels.
 - Velocity varies linearly with the pressure difference, so $v_1/v_2 = c_2/c_1$ for thin walled channels.
 - This is a significant issue for liquid metal blankets, even if the overall pressure drop is acceptable.





- It is desirable to choose and insulation scenario where small changes in insulation do not produce large changes in pressure drop.
- Another possible mitigation technique is to force some degree of flow balancing by electrically connecting the channels in clever ways.

Other LM blanket issues: Velocity Profiles and Impact on Heat Transfer

- □ The velocity itself is modified by the MHD forces it creates via JxB force.
- Typical MHD velocity profiles in ducts with conducting walls include the potential for very large velocity jets near or in shear layers that form parallel to the magnetic field.
- In channels with insulator coatings these reversed flow regions can also spring up near local cracks.
- □ The impact that these velocity profiles have on the thermal performance can be strong.
- Reversed or stagnant flow can lead to hot spots, especially for self-cooled designs where the LM flow must cool the heated walls.



Reversed flow jets in region near cracks in insulator – Local reversed velocity *10x* the average forward flow

Other MHD phenomena affecting heat transfer, corrosion, and tritium transport

- Natural convection and degree of MHD damping
 - MHD can act to suppress natural convection, but
 - Concepts with large thermal gradients and slow liquid breeder velocity will likely be affected by natural convection phenomena
- MHD Turbulence and degree of damping
 - Turbulence is damped by magnetic field in conducting channels
 - Turbulence may persist in modified form even for strong magnetic fields in insulated channels
- Natural convection and turbulence can strongly affect the ultimate temperature profiles



Mixing in LM flow with 2D MHD Turbulence – UCLA model

Separately-cooled LM Blanket Example: PbLi Breeder/ helium Coolant with RAFM

- EU mainline blanket design
- All energy removed by separate He stream
- The idea is to avoid MHD issues. But, PbLi must still be circulated to extract tritium
- ISSUES:
- Low velocity of PbLi leads to high tritium partial pressure , which leads to tritium permeation (Serious Problem)
- T_{out} limited by PbLi compatibility with RAFM steel structure ~ 500C (and also by limit on Ferritic, ~550C)
- Possible MHD Issues :
- A- MHD pressure drop in the inlet manifolds
- B- Effect of MHD buoyancy-driven flows on tritium transport



EU-PPCS B

Drawbacks: Tritium Permeation and limited thermal efficiency

rad

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EU – The Helium-Cooled Lead Lithium (HCLL) DEMO Blanket Concept



He-Cooled PbLi Flow Scheme



Dual-coolant Blanket Concept Example: Dual Coolant Lead-Lithium Concept (DCLL)

The structure is cooled by helium, while the Breeder region is "self cooled", i.e. the liquid breeder is circulated to also transport the volumetric nuclear heating generated within the breeder.

- It is an attempt to get a much better performance than HCLL, while 1avoiding the serious MHD problems of a fully self-cooled blanket, and 2- using ferritic steel and not relying on advanced structural materials.
- Note that "Surface Heating" on the first wall in fusion blankets is high, requiring high coolant speed. To cool the first wall with LM results in challenging MHD problem.
- Thus, cooling the FW with helium reduces considerably the MHD problem in breeder selfcooled zones.
- But the DCLL needs SiC insert for thermal and electric insulation.



DCLL Basic Idea – Push towards high $T_{out} (\Rightarrow High Efficiency)$ with present generation materials

How can high outlet temperature be reached?

- Cool all steel structures, including first wall, with He (Tin/Tout ~ 350/450C, carries 50% of the total energy)
- Have a PbLi breeding zone that is flowing and self-cooled (Tin/Tout ~ 450/700C, carries other 50% of the total energy)
- Isolate the hot PbLi from the cooler structure by use of a non-structural liner (e.g. SiC) called a Flow Channel Insert (FCI) that:



- Prevents leakage of volumetric nuclear heat deposited in the PbLi from entering the (lower efficiency) He coolant stream
- **Provides nominal electrical insulation** to keep MHD pressure drop manageable
- ✤ Is compatible with PbLi at elevated temperatures ~800C.

A Brief History of the DCLL

- A less ambitious version of the DCLL, (the outlet temperature for the PbLi and He stream are the same) was proposed in the 1980s in the EU
 - Ease the FW cooling problem with LMs by using separate FW coolant
 - Use RAFS-clad Alumina FCIs to further control MHD pressure drop
- The high PbLi outlet temperature DCLL first proposed in the 1990s
 - Tillack MS, Malang S. "High performance PbLi blanket." 17th IEEE/NPSS Symposium Fusion Engineering, New York, NY, USA. IEEE. Part vol.2, 1998, pp. 1000-4 vol.2.
- The high PbLi outlet temperature DCLL was further advanced in the US-ARIES and EU-PPCS studies
 - ARIES-ST (FED, 65, 2003)
 - EU PPCS C (FED, 61-62, 2002 or FZKA 6780)
 - A. R. Raffray and the ARIES Team, "Engineering Design and Analysis of the ARIES-CS Power Plant," TOFE-17, Albuquerque, NM, 2006
- The DCLL has also been adopted and advanced as a Primary US concept for ITER testing
 - Ying et al. "Overview of US ITER test blanket module program" (FED, 81, 2006)
 - Abdou and US ITER TBM Team , "Overview of the US ITER Test Blanket Module (TBM) Technical Plan" (17th ANS TOFE, Albuquerque, NM November , 2006)

US DCLL DEMO Blanket Module



Proposed US DCLL TBM Cutaway



Simplified DCLL Blanket Module Flow Scheme



- All structural walls are RAFS actively cooled by He
- Cold PbLi flows up the FW (where volumetric heating is strongest), turns, and flows back down the back of the blanket module
- SiC FCIs separates and insulates the flowing PbLi from the RAFS walls
- FCIs are loosely slip-fit together, and GAPs between FCIs and structure is filled in by nearly stagnant PbLi

SiC FCIs

Gap between FCI and Structure (Filled with nearly stagnant PbLi)

 The interface temperature between the RAFS structure and gap PbLi is controlled by the He cooling, and kept < 500C.

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A Simplified DCLL DEMO System



Another Look at the DCLL Unit Cell



Flow Channel Inserts are a critical element of the high outlet temperature DCLL

- FCIs are roughly box channel shapes made from some material with low electrical and thermal conductivity
 - SiC/SiC composites and SiC foams are primary candidate materials
- They will *slip* inside the He Cooled RAFS structure, but not be rigidly attached
- They will slip fit over each other, but not be rigidly attached or sealed
- FCIs may have a thin slot or holes in one wall to allow better pressure equalization between the PbLi in the main flow and in the gap region



 FCIs in front channels, back channels, and access pipes will be subjected to different thermal and pressure conditions; and will likely have different designs and thermal and electrical property optimization

DCLL should be effective in reducing MHD pressure drop to manageable levels

- Low velocity due to elimination of the need for FW cooling reduces MHD pressure drop.
- <u>Higher outlet temperature</u> due to FCI thermal insulation allows large coolant delta T in breeder zone, resulting in lower mass flow rate requirements and thus lower velocity.
- <u>Electrical insulation</u> provided by insert reduces bare wall pressure drop by a factor of 10-100.



Idea of Coaxial Pipe for PbLi feedlines similar to TBM – use FCI to insulate hot leg from cold



- Same principle can be applied for TX and HX outer shells
- Allows use of ordinary RAFS for almost all structure



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Why did the US choose the DCLL?

- Self-Cooled Li/V had been primary US LM Blanket option for ~20 years
 - US invested many millions of dollars in Vanadium research and insulator coating development
 - US materials experts concluded that bare coatings are unlikely ever to work, primary option now is coatings with metallic overlayers – integrity of thin overlayers is a serious concern
- DCLL offers a more attractive pathway to high outlet temperature Materials issues appear more tractable!
 - Combination of FW structure cooling by He, and partially insulating FCI, effectively addresses MHD pressure drop concerns
 - FCIs made of SiC appear more feasible and robust than multi-layer coatings
 - Fabrication of current generation RAFS structures, even with embedded cooling channels, appears more feasible than simpler Vanadium structures but with multi-layer insulating barriers
 - PbLi is much less violently reactive with air and water than Li (although heavier and with increased tritium control issues)
 - PbLi database and technology is large with significant investment by the EU international synergy possible
 - Dual-coolant strategy inherently safer against LOCAs and more flexible in thermal control of the system

Molten Salt Concepts: Advantages and Issues

Advantages

- Very low pressure operation
- Very low tritium solubility
- Low MHD interaction
- Relatively inert with air and water
- Pure material compatible with many structural materials
- Relatively low thermal conductivity allows dual coolant concept (high thermal efficiency) <u>without</u> the use of flow-channel inserts

Disadvantages

- High melting temperature
- Need additional Be for tritium breeding
- Transmutation products may cause high corrosion
- Low tritium solubility means high tritium partial pressure (tritium control problem)
- Limited heat removal capability, unless operating at high Re (not an issue for dual-coolant concepts)

Molten Salt Blanket Concepts

- Lithium-containing molten salts are used as the coolant for the Molten Salt Reactor Experiment (MSRE)
- Examples of molten salt are:
 - Flibe: $(LiF)_n \cdot (BeF_2)$
 - Flinabe: (LiF-BeF₂-NaF)
- The melting point for flibe is high (460°C for n = 2, 380°C for n = 1)
- Flinabe has a lower melting point (recent measurement at SNL gives about 300°C)
- Flibe has low electrical conductivity, low thermal conductivity

Concepts considered by US for ITER TBM (but were not selected):

- Dual coolant (He-cooled ferritic structures, self-cooled molten salt)
- Self-cooled (only with low-melting-point molten salt)

Dual Coolant Molten Salt Blanket Concepts

- He-cooled First Wall and structure
- Self-cooled breeding region with flibe or flinabe
- No flow-channel insert needed (because of lower conductivity)



Example: Dual-Cooled FLiBe + Be Blanket Concept

Self-cooled – FLiNaBe Design Concept Radial Build and Flow Schematic



Key DCLL DEMO R&D Items

- PbLi Thermofluid MHD Key impacts on thermal/power extraction performance, FCI load, safety
- SiC FCI development including irradiation effects Key impacts on DCLL lifetime, thermal and power extraction performance
- RAFS/PbLi/SiC compatibility & chemistry control Impacts DCLL lifetime and thermal performance
- Tritium extraction and control Critical element for PbLi which has low T solubility
- High temperature heat exchanger system
 Critical element for high temperature DCLL operation
- He distribution and heat transfer enhancement
 Key impacts on DCLL thermal and power extraction optimization
- RAFS fabrication development and materials properties Critical for any RAFS system
- Integrated behavior leading to Test Blanket Module testing in ITER Critical for any blanket system performance and reliability
- Brayton Cycle optimization for DCLL parameters Key impacts on thermal/power extraction performance

Thermofluid/MHD issues of DCLL

DCLL PbLi flows and heat transfer are strongly affected by MHD, current blankets designed with 2D simulations only

Main Issues:

- Impact of 3-D effects on pressure drop & flow distribution
 - Flows in the manifold region
 - Flows in non-uniform, 3-component B-field
 - Pressure equalization via slots (PES) or holes (PEH)
 - FCI overlap regions
 - FCI property variations
- o Coupled MHD Flow and FCI property effects on heat transfer
 - MHD turbulence and natural convection
 - Cracks, FCI movements
 - Heat leakage from PbLi to He coolants
- o Flow distribution, heat transfer, and EM loads in off-normal plasma conditions

Temperature, ITER DT



High Ha number flow computation DEMO: Ha=15,000; Re=84,000; σ=100 S/m



US strategy for DCLL Thermofluid MHD R&D

Two goals:

- 1. To address ITER TBM issues via experiments and modeling
- 2. To develop a verified PC, enabling design and performance predictions for all ITER TBMs and DEMO blanket

Two lines of activity:

- Experimental database. Obtain experimental data on key MHD flows affecting operation and performance of the blanket for which there is little/no data available.
 - Flow distribution in manifolds
 - FCI effectiveness & 3D issues
 - Coupled heat transfer / velocity field
- 2. Modeling tools. Develop 2D and 3D codes and models for PbLi flows and heat transfer in specific TBM and DEMO conditions.
 - HIMAG arbitrary geometry 3D fully viscous and inertial parallel MHD solver
 - 2D models and codes for specific physics issues – MHD turbulence and natural convection



3D Simulation of flow profiles through a distribution manifold at Re=Ha=1000. Resultant flow is 15% higher in center channel

DCLL Temperatures strongly influenced by MHD effects and FCI design/properties



Temperature near the FW for different FCI electrical conductivity based on laminar, fully developed MHD simulations – turbulent decay of velocity jets and buoyancy effects can strongly change this picture and must be investigated

Flow Channel Insert Requirements

- 1. Transverse thermal conductivity of the FCI should be as low as possible (in the range 1-2 W/mK) to provide effective thermal insulation and reduce heat loss from the PbLi hot leg to the cooler He.
- Transverse electrical conductivity of the FCI should be low enough to provide some electrical insulation (current MHD estimates indicate a range of 1-100 S/m is acceptable – some debate remains over ideal value).
- 3. The inserts have to be compatible with PbLi up to ~800 °C.
- 4. Liquid metal must not "soak" into any internal pores to avoid increased electrical conductivity and high tritium retention. In general, dense SiC layers are required on all surfaces of the inserts.
- 5. Primary stresses caused by MHD effects, and secondary stresses and deformation caused by temperature gradients must not endanger the integrity of the FCIs.
- The insert shapes must be fabricable and affordable thicknesses ~3 to 10 mm, box channel shapes, pressure equalization slots and holes, slip fit features, etc.
- 7. Maintain 1-6 in a practical operation environment
 - Neutron irradiation
 - Developing flow conditions, temperature & field gradients
 - Repeated mechanical loading plasma VDE and disruption events

SiC has good potential for FCI Material

SiC/SiC is primary candidate

- Long development in fusion as potential structural material (FCI has reduced requirements compared to structural material)
- Industrial maturity, radiation-resistance, PbLi chemical compatibility, etc.
- Complementary qualification work as the control rod material in US-DOE Next Generation Nuclear Power program

Sealed SiC Foam is an alternate

- Low k and e, low cost, no CTE mismatch
- But potential issues with "soaking"
- Metal-clad alumina or SiC is a 3rd option

– W for high temp, FS for low





Transverse electrical conductivity measurements in 2D composite

10³ Data for in-plane σ of typical 2D SiC composite, in-plane fusion grade 2D-SiC/SiC shows relatively high values ~500 S/m, 10^{2} **Monolithic SiC** likely due to highly conducting carbon inter-phase New measurements on same material shows SIGNIFICANTLY lower σ in transverse direction – 2 to 3 orders lower at 500C The low σ transverse apparently reflects the extreme anisotropy of the CVI-deposition process form **DCLL TBM Target** 20 S/m 10^{1} 2D SiC composite, transverse 10[°] Pacific Northwest ပ္ရ National Laboratory 10⁻¹ Operated by Battelle ku the 500 5. Department of Groups - in-plane, pre C burn out

10⁻²

10 ⁻³

0

200

400

- SiC/SiC composite made with 2D-woven fabric layers.
 Thermal conductivity still a challenge
- For SiC Foams, σ is also low (.1-1 S/m)
- DC electrical conductivity measurements of 2D-Nic S/CVI-SiC composite. Measurements were made in both argon-3% H2 or dry argon. Vacuum-evaporated Au-electrodes on disc faces.

Temperature (°C)

- in-plane, C burn out

600

transverse, 6-ply in argon+3% H2

800

1000

thansverse, 8-ply in dry argon CVD-SiC Bar (Weber)

CVD-SiC Bar (Hi-Purity)

Withstanding Deformation and Thermal Stress are Key Issues for the DCLL FCI

- FCI should ideally withstand:
 - 200-300K temperature difference from inside to outside
 - 100K difference along length and from front to back
- FCI and channel design features that reduce stress and accommodate movement must be considered FCI development
 - FCI corner rounding, Slip fit features that allow motion, Sufficient gap space
 - Optimal tradeoff in material design between thermal conductivity, modulus, radiation resistance and strength



R&D Needs for SiC/SiC FCI

	Present Status (Radiation-resistant SiC/SiC)	R&D Goal (Property-adjusted SiC/SiC)	
Thermal insulation	 Insufficient unirradiated insulation (5-10 W/m-K) Substantial change during irradiation 	 Maintain 2 - 5 W/m-K throughout operation Validate radiation effect model 	
Electrical insulation	 May meet requirement (<~ 20 S/m) Controllability questionable Radiation effect unknown 	 Establish control scheme Address radiation effect 	
Chemical compatibility	- <u>Testing</u> underway - Results so far promising	- Perform validation	
Liquid Metal Leak Tightness	 No serious concern for composites, Concern for foam 	- Perform validation	
Mechanical integrity	 Cracking stress likely limits ⊿T < 100K Stress induced by differential swelling may dictate secondary stress 	 Survive ∆T > 200K throughout operation Determine differential swelling effect and irradiation creep Confirm other radiation effects 	

Static compatibility of SiC With PbLi up to 1100C looks acceptable



Before/During Test

Test	Li	Si	С	0	N			
Starting	n.d.	<40	<170	1270	<40			
1000 h								
800°C	17.49%	<30	1850	4090	100			
1100°C	16.27%	<30	1160	3550	90			
1200°C	15.62%	370	2690	16620	450			
2000 h								
1100°C	15.99%	185	1025	7890	200			
5000 h								
800°C	18.55%	<60	650	2580	90			

Concentrations in appm

• No significant mass gains after any capsule test.

- Si in PbLi only detected after highest temperature tests.
- Si could come from CVD SiC specimen or capsule.
- Results suggest maximum temperature is <~1100°C
- Research Needs:
 - Testing in flowing LiPb environment.
 - Testing of SiC composites with sealing layers.

Fuel Cycle Dynamics

The D-T fuel cycle includes many components whose operation parameters and their uncertainties impact the required TBR



Tritium extraction and control are key linked issues for the DCLL DEMO

- DCLL strategy is develop an efficient tritium extraction system that can keep the tritium partial pressure low (<100 mPa) and thus reduce permeations issues
 - An advantage of the DCLL, large PbLi thru-put allows better control of T conc.
 - US Program in this area is just now being considered

Solubility in PbLi

- Typical measurements performed at relatively high hydrogenic partial pressure (~10¹-10⁵ Pa) are extrapolated to much lower partial pressures required for tritium inventory control
- Deviance from Sievert's Law is possible at extremely low concentrations requires tritium for measurements

Recovery methods from PbLi and He flows – vacuum permeators

- Determine operational limits on the impurities in PbLi and mass transport across liquid-vapor interface
- Maintenance of extremely low impurity level on vacuum side
- Determine impact of different materials in the primary PbLi loop: RAFS, SiCcomposite, Nb-or Ta permeator tubes, HX tube material.
- Permeation behavior at very low partial pressures over metals
 - linear vs. Sievert's behavior? transport related to dissociation/recombination rates becomes non-equilibrium?

– influence of surface characteristics and treatment and barriers

Strong program for RAFS Fabrication R&D is required for any real blanket development program – in collaboration with industry



US Industry are showing strong capabilities and interest in FS fabrication



Partially-Integrated Mockup Testing is a key part of qualification of experimental components for ITER



US Testing Facilities considered for various partially integrated testing prior to ITER TBM



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US TBM R&D Task List is somewhat different and more focused than for DEMO



Many R&D tasks are highly interactive, and collectively, they provide information critical to design, procurement specifications, qualification/acceptance tests, and definition of operating conditions



VTBM

Integrated Data/multi-code multi-physics modeling activities, or Virtual TBM, is key for ITER TBM R&D activity.



Ripe areas for India R&D and design contributions to the DCLL

- DCLL TBM consortium
 - Development of non-destructive testing techniques and benchmark test samples for TBM fabrication qualification
 - Tritium removal techniques from 500C, 8MPa, He coolants
 - Be joining to RAFS technology
 - PbLi/Water hydrogen generation based on likeliest TBM accidental contact modes
 - RAFS coaxial pipe mechanical disconnects and valves for PbLi and He lines, transporter cask design integration
 - Loop control systems, local and interfaces with ITER CODAC
 - Particular diagnostics and sensor attachments
 - Fission reactor In-pile PbLi flow capability for
 - investigating irradiation assisted corrosion
 - T/He micro bubble formation and effect on permeation
- DEMO Relevant
 - 700C PbLi flow facility
 - High temperature PbLi heat exchanger and efficient tritium extraction technology development
 - SiC behavior in flowing PbLi at high temperature
 - Brayton-Cycle optimization for DCLL

Abdou Lecture 3

APPENDIX

- Much information can be found in literature
- In particular the UCLA website www.fusion.ucla.edu
- Presentations and publications are given in open form on the web site

www.fusion.ucla.edu/abdou

 The following tables of useful thermo physical properties for liquid breeders are examples of important data and information that can be found on the above web sites.

Physical Properties of Molten Natural Li (temperature in degrees Kelvin) Valid for T = 455-1500 K

Melting Temperature: 454 K (181°C) Density [1] ρ (kg/m³) = 278.5 - 0.04657 · T + 274.6 (1-T/3500)^{0.467} Specific heat [1; see also 2] C_{p} (J/kg-K) = 4754 - 0.925 · T + 2.91 x 10⁻⁴ · T² Thermal conductivity [1] K_{th} (W/m-K) = 22.28 + 0.0500 · T - 1.243 x 10⁻⁵ · T² Electrical resistivity [1] ρ_{a} (n Ω -m) = -64.9 + 1.064 · T - 1.035 x 10⁻³ T² + 5.33 x 10⁻⁷ T³ - 9.23 x 10⁻¹² T⁴ Surface tension [1] γ (N/m) = 0.398 - 0.147 x 10⁻³ · T **Dynamic viscosity** [1] **note**: $\eta = \rho \upsilon$ where $\upsilon =$ kinematic viscosity (m²/s) $\ln \eta$ (Pa - s) = -4.164 - 0.6374 ln T + 292.1/T

<u>Vapor pressure</u> [1] In P (Pa) = 26.89 - 18880/T - 0.4942 In T

References:

- [1] R.W. Ohse (Ed.) Handbook of Thermodynamic and Transport Properties of Alkali Metals, Intern. Union of Pure and Applied Chemistry Chemical Data Series No. 30. Oxford: Blackwell Scientific Publ., 1985, pp. 987.
- [2] C.B. Alcock, M.W. Chase, V.P. Itkin, J. Phys. Chem. Ref. Data 23 (1994) 385.

Physical Properties of Pb-¹⁷Li

<u>Melting Temperature</u> : T _M = 507 K (234°C)	
<u>Density</u> [1] ρ (kg/m³) = 10.45 x 10³ (1 - 161 x 10 ⁻⁶ T)	508-625 K
<u>Specific heat</u> [1] C _P [J/kg-K] = 195 - 9.116 x 10 ⁻³ T	508-800 K
<u>Thermal Conductivity</u> [1] K _{th} (W/m-K) = 1.95 + 0.0195 T	508-625 K
<u>Electrical resistivity</u> [1] ρ _e (nW-m) = 10.23 + 0.00426 T	508-933 K
<u>Surface tension</u> [2,3] γ(N/m) =0.52 - 0.11 x 10 ⁻³ T	520-1000 K
<u>Dynamic viscosity</u> [1] η (Pa - s) = 0.187 x 10 ⁻³ exp [1400./T]	521-900 K
<u>Vapor pressure</u> [2-4] P (Pa) = 1.5 x 10 ¹⁰ exp (-22900/T)	550-1000 K

References:

- [1] B. Schulz, Fusion Eng. Design 14 (1991) 199.
- [1] B. Schulz, Fusion Eng. Besign 14 (1997).
 [2] H.E.J. Schins, Liquid Metals for Heat Pipes, Properties, Plots and Data Sheets, JRC-Ispra (1967).
 64
- [3] R.E. Buxbaum, J. Less-Common Metals 97 (1984) 27.
- [4] H. Feuerstein et al., Fusion Eng. Design 17 (1991) 203.

Physical Properties of Molten Flibe $(LiF)_n \cdot (BeF_2)$

<u>Melting temperature</u> [1] T _M (K) = 636 K (363°C) T _M (K) = 732 K (459°C)	n=0.88 n=2	(TM=653 K for n=1)
<u>Density</u> [2] ০ (kɑ/m3) =2349 – 0.424 · T	n = 1	930-1130 K
ρ (kg/m3) =2413 – 0.488 · T	n = 2	800-1080 K
Specific heat [3]		
C _P (J/kg-K) ≈ 2380	n=2	600-1200 K ?
Thermal conductivity [3]		
K _{th} (W/m-K) = 1.0	n=2	600-1200 K ?
Electrical resistivity [2]		
ρ _e (Ω-m) = 0.960 x 10 ⁻⁴ exp (3982/T)	n=1	680-790 K
$\rho_{\rm e}$ (Ω-m) = 3.030 x 10 ⁻⁴ exp (2364/T)	n-2	750-920 K
Surface tension [2,4]		
$\overline{\gamma}$ (N/m) = 0.2978 - 0.12 x 10 ⁻³ · T	n = 1	830-1070 K
γ (N/m) = 0.2958 - 0.12 x 10 ⁻³ · T	n = 2	770-1070 K
Dynamic viscosity [2]		
n(Pa - s) = 6.27 x 10 ⁻⁶ exp (7780/T)	n = 1	680-840 K
η(Pa - s) = 5.94 x 10 ⁻⁵ exp (4605/T)	n = 2	740-860 K
Vapor pressure [3]		
P (Pa) = 1.5 x 10 ¹¹ exp (-24200/T)	n = 2	770-970 K

References:

- [1] K.A. Romberger, J. Braunstein, R.E. Thoma, J. Phys. Chem. 76 (1972) 1154.
- [2] G.J. Janz, Thermodynamic and Transport Properties for Molten Salts: Correlation equations for critically evaluated density, surface tension, electrical conductance, and viscosity data, J. Phys. Chem. Ref. Data 17, Supplement 2 (1988) 1.
- [3] S. Cantor et al., Physical Properties of Molten-Salt Reactor Fuel, Coolant and Flush-Salts, ORNL-TM-2316 (August 1968).
- [4] K. Yajima, H. Moriyama, J. Oishi, Y. Tominaga, J. Phys. Chem. 86 (1982) 4193.

Liquid Breeders Summary of some physical property data



COMPARISON OF THE THERMAL CONDUCTIVITY OF LIQUID COOLANTS

COMPARISON OF THE ELECTRICAL RESISTIVITY OF LIQUID COOLANTS





COMPARISON OF THE SPECIFIC HEAT OF LIQUID COOLANTS

COMPARISON OF THE SURFACE TENSION OF LIQUID COOLANTS





• Some key physical property data for Flinabe are not yet available

– (melting temperature measurements for promising compositions are in progress. Measurement at Sandia in early 2004 shows ~ 300°C)

 Physical property data for Flibe are available from the MSR over a limited temperature range