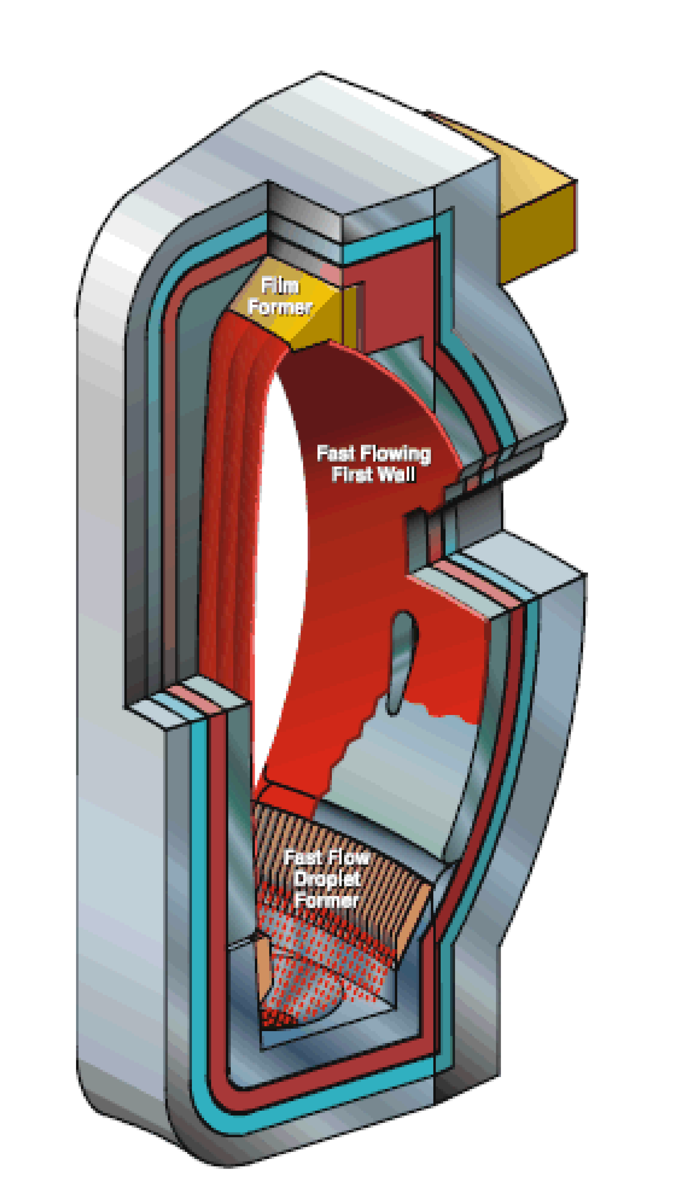
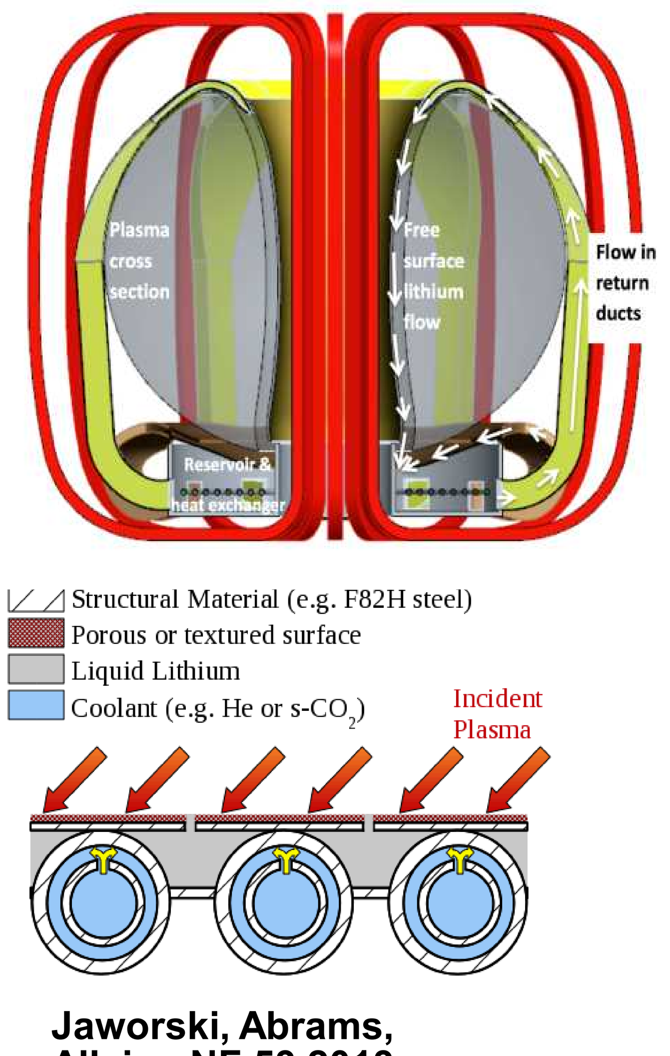
Exceptional service in the national interest

Sandia National Laboratories

SAND2015-3945C

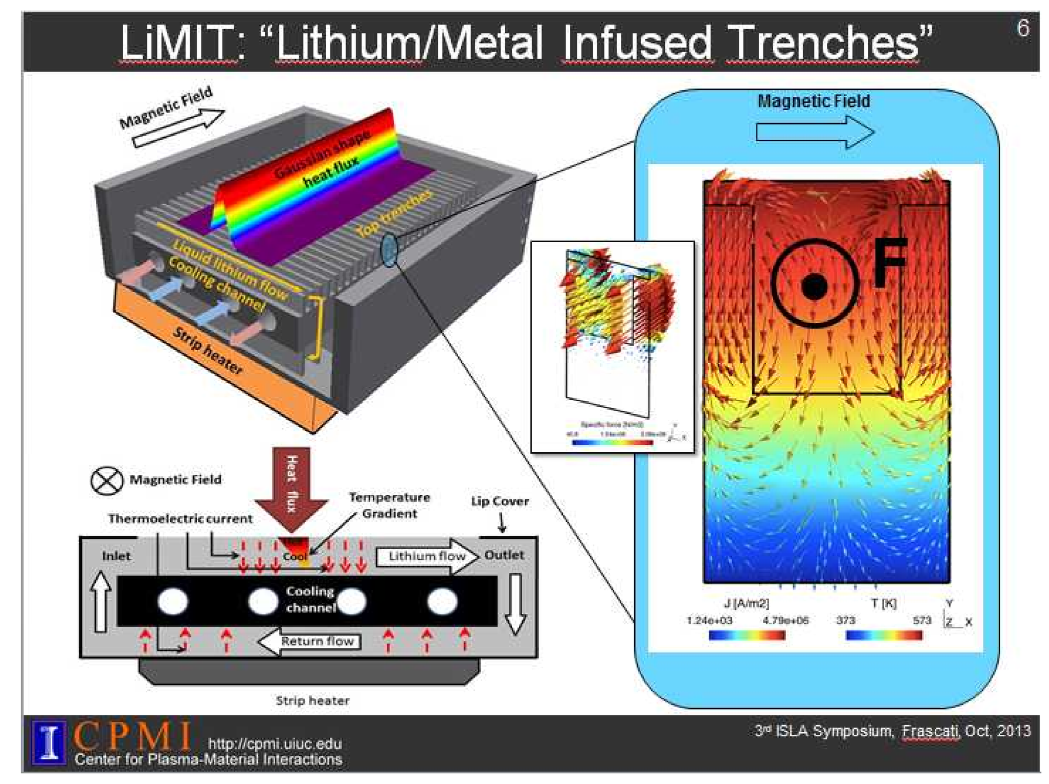


Majeski White Paper



Jaworski, Abrams, Allain ..NF 53 2013

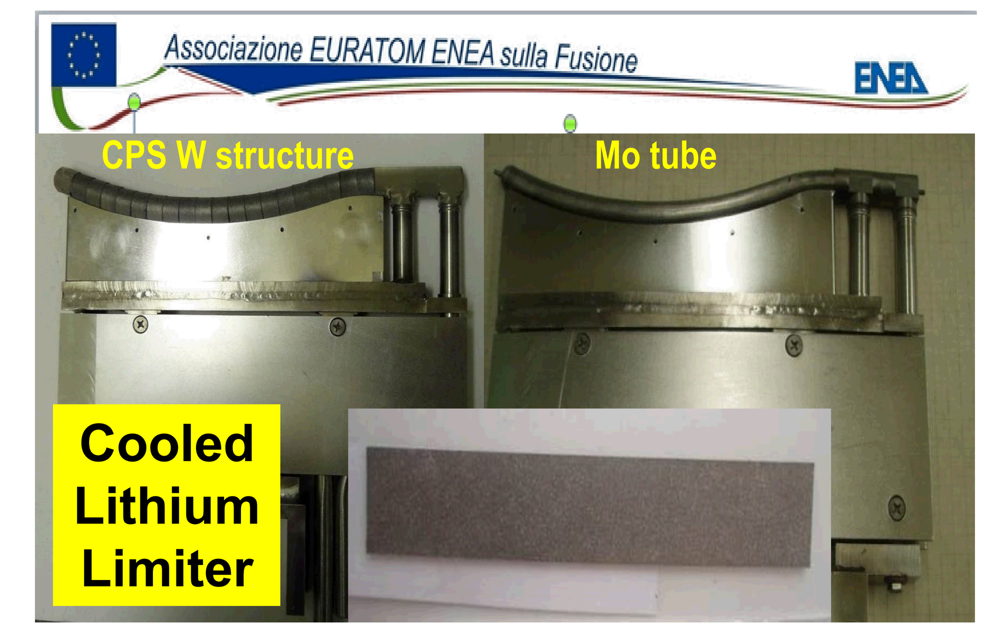
*Figures from presentations at the 3rd International Symposium on Lithium Applicatons in Fusion Devices October 2012 *ENEA Frascati, Roma, Italy*



*Currelli, Ruzic (U. of Illinois)

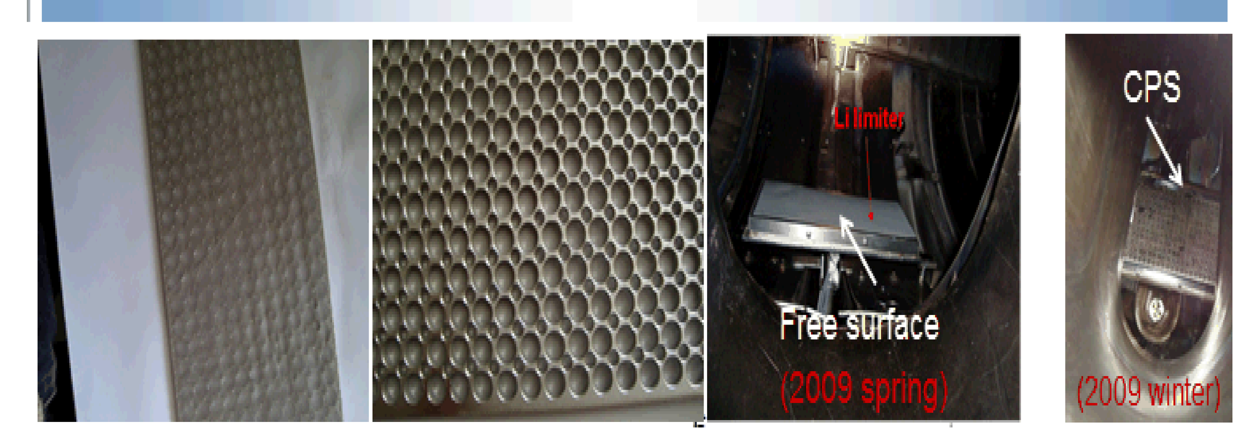
*Zuo, et al.(IPP-CAS), Zakharov (PPPL), Ruzic (U. of Illinois)

*Mazzitelli et al.



Liquid Lithium Surface Control and Its Effect on Plasma Performance in HT-7 Tokamak

ASIPP



Understanding Design Integration to Confirm the Credibility of Liquid Surface PFCs

R.E. Nygren *renygre@sandia.gov*

Sandia National Laboratories, Albuquerque, New Mexico, USA

The approach is to study requirements on liquid surface concepts from basic features related to design integration:

1) ***A liquid FW is an integral structure with that of a breeding blanket; and***
2) ***Managing flow for a liquid divertor or FW brings implicit requirements for manifolds, for filling and draining, and for interfaces with systems to recover power (electricity) and tritium fuel.***

The benefits of LSPFCs come from several motivations.

Specific to Li is the improvement in plasma performance observed with Li at the plasma edge. (Two excellent recent reviews with emphasis on Li by Jaworski and by Hirooka.)

The self-replenishing surface (implicit in LSPFCs for DEMO) could eliminate melting/recrystallization, ion damage, etc. associated with solid surfaces. This benefit was recognized much earlier, e.g., 1974 UWMAK design and Wells's 1981 paper. Mirnov summarized the early efforts (ref above).

A new motivation, quite speculative but with a big impact, is:

LSPFCS - only solution* for conforming walls?

If significant power convected to the wall remains as a threat for FNSF/DEMO, this may require shaped solid walls (e.g., poloidal limiters), and bring related issues.** However the understanding of the behavior of the plasma edge is still emerging and how to incorporate a quiescent edge plasma into a workable confinement scheme is not yet clear.

*MIT researchers have invented a clever innovative approach that uses a unibody vessel created by additive manufacturing that eliminates leading edges but depends upon demountable superconducting coils for its implementation. [see Whyte, FES_PMI Workshop].

**The issues such as restricted breeding volume, remote maintenance and challenges for injecting and exhausting power never evaluated in earlier design studies.

FWs are likely to have more technical challenges than divertors because long flow paths are necessary for fast flowing systems and the FW-blanket is an integral structure.

Maximum tolerable heat loads are a critical concern for DEMO.

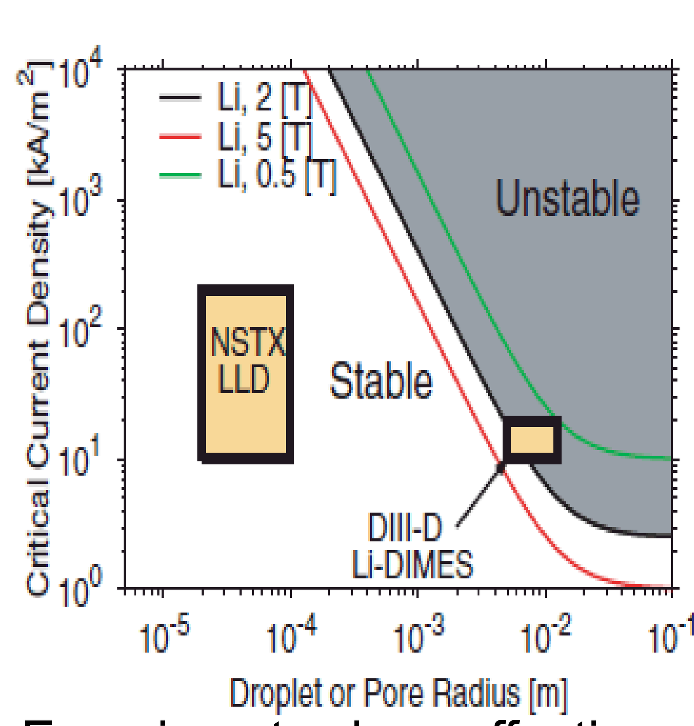
A fast flowing system would seem to have an advantage, since CPS PFCs must transfer heat through the lithium and its host structure to the coolant in the substrate. However the slow flow in CPSs diminishes liquid metal MHD forces, but only at the wall.

Table 1. PFC-Blanket Cases

Fast Flow FW & Divertor			Blanket				
FW	Div.	Press.	breeder	coolant	P	structure	
Li	Li	L	Li-Pb	He	H	RAFS	1*
Li-Pb	Li	L	Li-Pb	He	H	RAFS	2
Li	Li	L	Li-Pb	He	H	RAFS +SiC	3
Li	Li	L	solid	He	H	RAFS	4
Li +HX	Li	H (HX)	solid	He		RAFS	5
Ga	Ga	L	solid	He	H	RAFS	6
salt	salt	L	salt	salt	L	RAFS	7
Slow Flow FW & Divertor			**Blanket**				
Li-CPS	He	H	solid	He	H	RAFS	8
Li	Li	L	application for hybrid				9

Table 2. Cases for Parallel Conductance

A	R-Li	0.36	10	27.8	77%
	R-FS	0.60	5	8.3	23%
B	R-Li	0.36	10	27.8	53%
	R-FS	0.60	15	25.0	47%
C	R-Li	0.36	10	27.8	88%
	R-Inc	1.30	5	3.8	12%
D	R-Li	0.36	10	27.8	22%
	R-W	0.05	5	100.0	78%



Experiments show effectiveness of host structure in retaining stable surface of Li. *Jaworski, Abrams, Allain ..NF 53 2013 ,* also *Mirnov, .. JNM 390–391 (2009) 876–85*

***1. JxB drive** – Most current stays in the fluid if the resistance (resistivity*cross-section) along other paths is much higher.

The FW–blanket structure provides another path unless it is insulated. Relying simply on the higher resistance may not be sufficient. (Table 2, resistivities of Inconel 600 (Inc), ferritic steel (FS) and Li are ~1.30, 0.6 and 0.36 micro-ohm-m.)

2. Li Segregation – With a Li layer on the free surface (due to Gibb's free energy), Pb-Li could serve for the FW and blanket (idea proposed in the APEX Program). But the huge cross sectional area of the blanket walls plus the liquid breeder would be a low resistance current path in parallel with the FW.

3. SiC Inserts - The US developed SiC flow channel inserts for a dual coolant Pb-Li blanket to provide thermal and electrical isolation for the Pb-Li and permit lower FW temperatures. These might limit parallel conductance for a JxB-driven liquid wall (need detailed 3-D flow model with LMMHD effects).

4. High P – A low-pressure FW combined with a blanket cooled with He (most blankets) is a high pressure (P) system. The high pressure gives sufficient mass flow for efficient cooling.

5. Internal Li loops* – Majeski's concept has an in-vessel heat exchanger (HX), partial coverage of the FW with liquid and an open toroidal slot for injection of power and for diagnostics.

6. Ga Divertor - Ga has excellent heat transfer properties but lacks lithium's beneficial effect at the plasma edge. Use of Ga adds another working fluid and the complication of systems separate from the FW and blanket to exchange heat and to extract tritium.

7. Molten Salts have been studied for fission reactors. The case here, with mixed Li, Na and Be fluorides studied in the APEX Program**, is the only low pressure system listed.

8. Capillary Pore System (CPS) has been in development since 1994 as a divertor and perhaps FW application. Since many favor solid breeders over liquid breeders, e.g., in ITER TBMs, The case here is represents that combination.

9. Zakharov Gravity Flow System* - Zakharov proposes a clever and simply executed lithium film divertor along with a concept in which Li at the plasma edge radically improves confinement. A divertor module was deployed in EAST.

***US FES-PMI Workshop, PPPL May 4-7, 2015** – white papers are to be posted on USBPO website in near future.

****APEX** – see fusion.ucla.edu/APEX

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

33 H x 44 W

Consider the points below.

- We are now far beyond early simplistic concepts. Russians have pursued capillary pore system (CPS) since 1994 with tests in several tokamaks.
- Clever ideas are emerging, many since ReNeW, and being refined. However, the schemes are often at the cartoon stage.
- Deployments, including US modules for Asian tokamaks, are important steps. However the modules cover small areas.

We lack evidence that the schemes can be successfully integrated into the subsystems for an FNSF or a DEMO.

Slow Flow Systems

Two examples of slow flowing systems are (1) the Capillary Pore System or CPS, and (2 the simple lithium surface on a plate as advanced by Zakharov. Russian researchers began developing the CPS systems started development in Russia in 1994 and are continuing, and CPS PFCs have been deployed in tokamaks in Russia Italy and Kazakstan.[15-19] The concept by Zakharov uses a thin film of lithium that adheres to a plate and flows slowly downward drawn by gravity and a clever idea to initiate the pneumatically driven flow. This idea was deployed for tests in the EAST tokamak.[20]

CPS PFCs must transfer heat through the liquid (lithium) and its host structure to the primary coolant in the substrate that supports the CPS although some heat may be transported by evaporation at one location and deposition elsewhere. In the substrate, walls for gas cooling channels must handle the combination of gas pressure (4-10 MPa) and thermal stresses. The flow needed to replenish the liquid at the surface of a CPS is sufficiently slow as to mitigate significant LMMHD concerns at the plasma facing surface.

Fast Flow Systems

A FW with fast flowing liquid system continuously accumulates heat as it flows along a relatively long flow path. A complication is that liquid metal magneto-hydrodynamics (LMMHD) dominates the flow characteristics. These systems propel and stabilize the flowing liquid using electric currents and JxB forces, as in a system proposed by Majeski[13]. A concept by Ruzic and co-workers[14] also uses thermo-electric currents and a module of this type has been exported for use in Chinese tokamaks.

In fast flow systems, LMMHD effects dominate the flow and are used to drive flow. Without the use of electrically insulated flow channels, the driving current also flow in the wall, as do the MHD-generated currents. Electrically insulated walls would reduce the effect but robust coatings self-healing coatings were found hard to develop.

Design integration of such systems must deal with these factors as well as the complications of flow redirection and redistribution in manifolds and with gradients in the magnetic fields. After the flow down (or across) the FW, the flow path must either (a) return within the vessel and transfer heat to another coolant through a heat exchanger, as proposed by Majeski[13], or (b) exit the vessel and transport the heat to an external heat exchanger. The latter option requires flow across both the strong toroidal field and the poloidal field as well as through field gradients. Even with the return flow path inside the vessel, LMMHD effects will dominate the flow during the redistribution of flow through the heat exchanger and manifolds. Also, altered flow distributions can affect not only the required pressure to drive flow but also heat transfer and corrosion.

A first wall with fast flowing liquid system continuously accumulates heat as it flows along a relatively long flow path. A complication is that liquid metal MHD (LMMHD) dominates the flow characteristics and these systems require propulsion and stabilization using electric currents and JxB forces and, in some proposed applications, thermo-electric currents.

The altered flow distributions affect not only the required pressure to drive flow but also heat transfer and corrosion. Design integration of such systems must deal with these factors as well as the complications of flow redirection and redistribution in manifolds and with gradients in the magnetic fields.

After the flow down (or across) the first wall, the flow path must either (a) return within the vessel and transfer heat to another coolant through a heat exchanger, as proposed by Majeski[4], or (b) exit the vessel and transport the heat to an external heat exchanger. The latter option requires flow across both the strong toroidal field and the poloidal field as well as through field gradients.

Even with the return flow path inside the vessel, LMMHD effects will dominate the flow during the redistribution of flow through the heat exchanger and manifolds.