

Overview APEX(NucSys)/ALPS(PFCs) 1996-2002 plus transition into the ITER TBM

RE Nygren

Sandia National Laboratories

on behalf of the APEX - ALPS Teams, many collaborators

*and with a special acknowledgement to my friend
Prof. Mohamed Abdou*

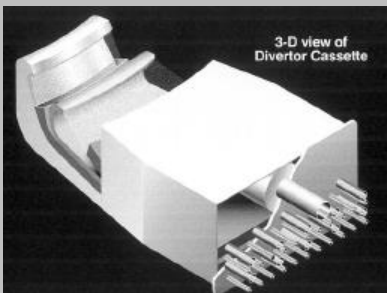
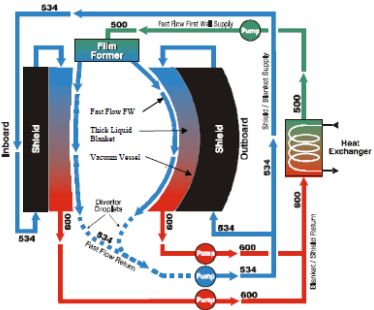
Mohamed was a brilliant steward of APEX.

He recruited excellent foreign collaborators, US experts and bright students. This highly leveraged talent pool delivered a lasting contribution to fusion.

Sam Berk was the FES leader.

US is good at innovation – use this; what is transformative.

Potential Attractiveness for an ALL-LIQUID FW/Blanket



Sandia National Laboratories

Exceptional service in the national interest



U.S. DEPARTMENT OF ENERGY



Historical Perspective on PFC/PMI Development

1980

1990

2000

2010

limiters
isolated core
radiation loss
sputtering

more power/impurities
conditioned/coated wall
erosion-consequence
[CX neutrals, Maxwellian tail]

diverted plasmas
[more core isolation]
[radiative, detached div.]
importance of plasma edge

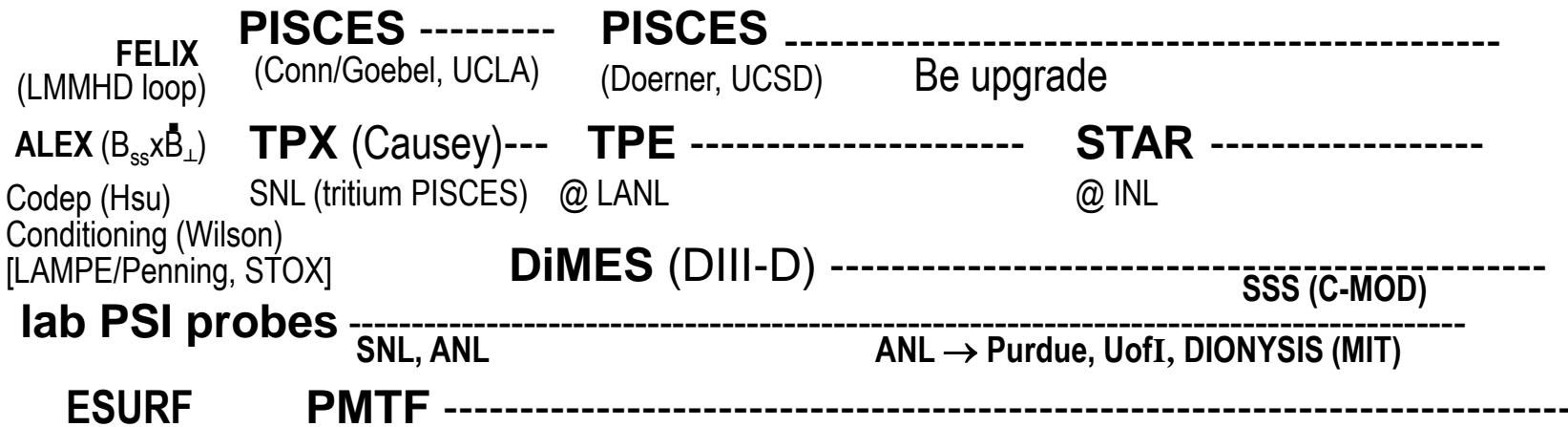
Next Step
(FED/INTOR, CIT, FIRE ..)
ITER

***DT Mat'l Physics Group**
tritium in TFTR

prominence of ITER
tritium retention

limiters → divertors → active cooling
C issues, Be in JET, ITER PFC options

US collaborator-built PFCs  **TEXTOR limiters**
Tore Supra Limiters  **NSTX liquid Li limiter**



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large D/T devices
• exhausted power
• stored energy
?FNSF/DEMO div.

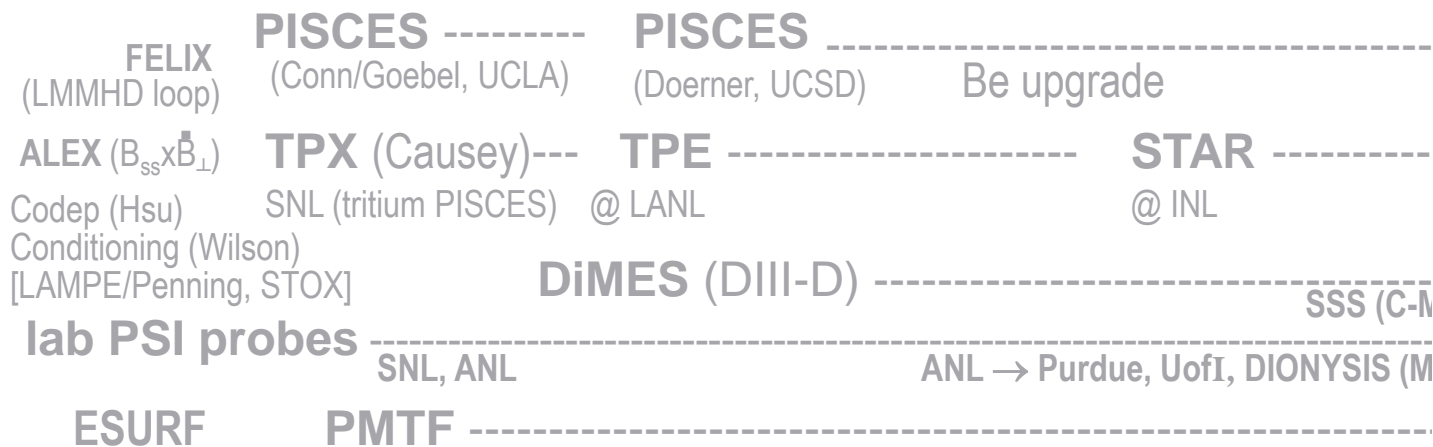
***DT Mat'l Physics Group**
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- Hot walls
- Shaped FW
- ?super-X

US collaborator-built PFCs TEXTOR limiters
Tore Supra Limiters NSTX liquid Li limiter



Upgraded & new capabilities

Presenter: Richard Nygren

- **Hanford Eng. Dev. Lab <1981** radiation damage, **LMFBRs**, fusion
- **Oak Ridge NL 1979-81** materials in **Fusion Eng. Device** (pre-ITER)
- **Argonne NL 1981-85** FW-Blanket-Shield Program Director
- **DOE/OFES 1986** Spec. Ass't. to Dir. US Fusion Program
- **UCLA 1987-88** PSI experiments, PISCES (now at UCSD)

- **Sandia National Laboratories (since 1989)**

Distinguished Member, Technical Staff (1995-2006, 2012-present)

TEXTOR He pumping, **Tore Supra** water-cooled pump limiter, **ITER**

Manager, Fusion Technology Dept. (2006-2011)

Plasma Materials Test Facility: High heat flux testing; water, He, liquid metal coolants; ITER FW R&D; Liquid Li Divertor for NSTX

VLT, USBPO RC, PFC Group, IEA-NFTR Solid Surface PFC Ch., program committees,

Richard F. Mattas (IAEA 1997)

US Assessment of Free Surface Liquid Metal Divertors - Design, Analysis and R&D Needs,

The US Fusion Program was restructured in 1996 to, "Develop fusion science, technology, and plasma confinement innovations as the central theme of the domestic program" [1].

1. "Strategic Plan for the Restructured U.S. Fusion Energy Sciences Program", issued by Office of Fusion Energy Science, DOE, in August 1996

One of the main goals of the program is to **develop a scientific understanding of technologies and materials** required to withstand high plasma heat flux and neutron wall load that at the same time exhibit attractive safety and environmental features.

... key technical issues

- Sputtering and Redeposition
- Instabilities arising from plasma/liquid interactions (particularly disruptions)
- DT/He Transport (PSI of retention)
- MHD Behavior of Liquid Metal Free Surfaces
- Power Density Limits
- Insulator Coating Development
- Impurity Transport (of influx from liquid surface)
- Materials Activation
- Accident Consequences and Mitigation
- DT Pumping and Fueling

There are three main parts of the program - Concept Evaluation, Plasma Physics/PMI, and Engineering

APEX Approach to Problems

1. Understand the Problem and the Underlying Sciences

2. Search for “Innovative Solutions”

Our Job is “How to Make Things Work”

3. Do good analysis using the best engineering sciences tool available

4. Confirm by “low-cost and fast” experiments

APEX APPROACH

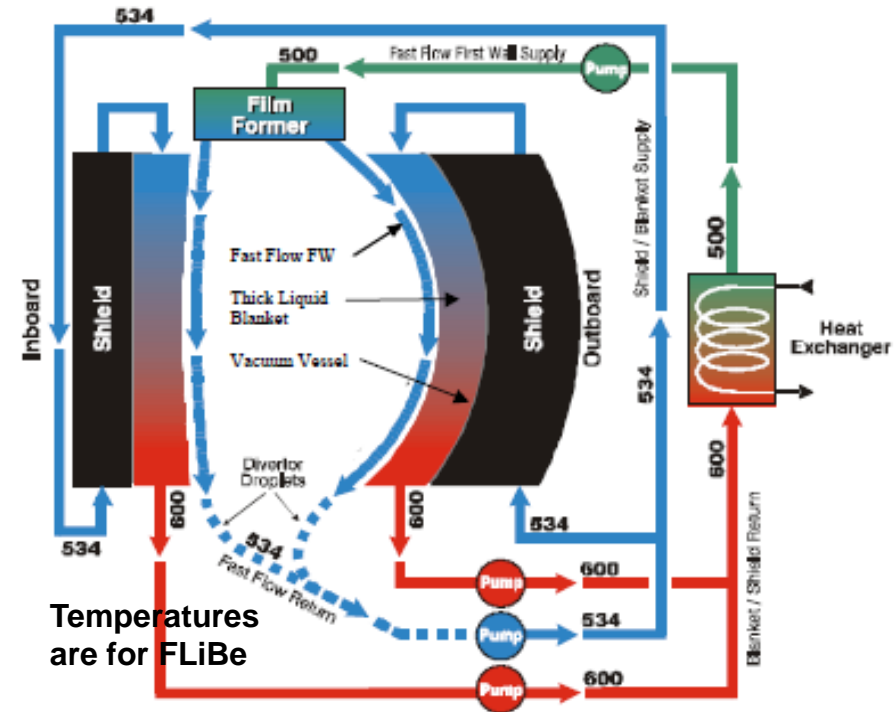
- 1) Foster an Environment conducive to innovation
 - Encourage innovative ideas
 - Opportunities for talented young sci./eng.
- 2) Understand/Advance underlying Eng. Sciences
- 3) Utilize multidisciplinary, multi-institution integrated TEAM to foster collaboration, pool talents, and expand expert and specialty input. Organizations: UCLA, ANL, ORNL, SNL, LLNL, PPPL, GA, LANL, UW, UCSD, INEL
- 4) Provide for Open Competitive Solicitation in 1999
- 5) Close Coupling to the Plasma Community
 - Plasma Interface Group
 - Joint Physics-Technology Workshops
- 6) Direct Participation of Material Scientists and System Design Groups
- 7) Direct Coupling to IFE Chamber Tech. Community
- 8) Encourage International Collaboration
 - Current participation from Germany and Japan

Potential Attractiveness for an ALL-LIQUID FW/Blanket

Liquid Concepts Currently Being Explored in APEX

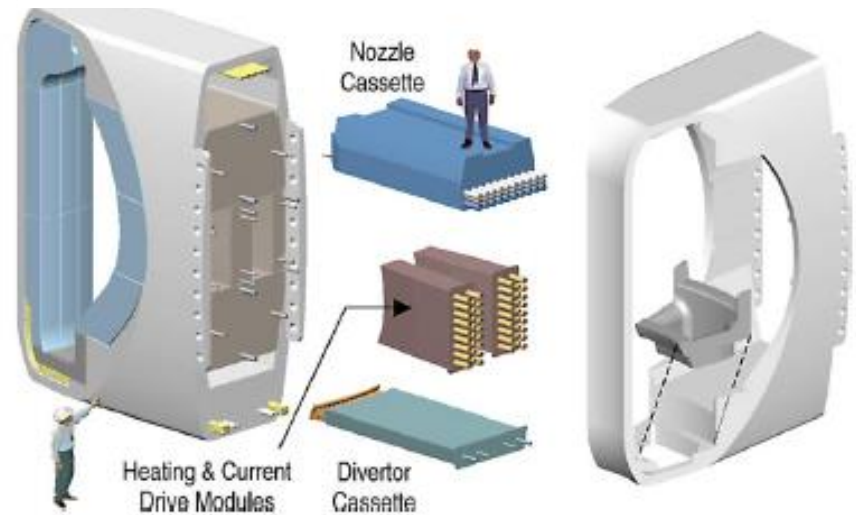
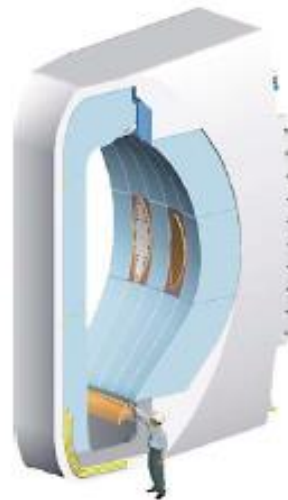
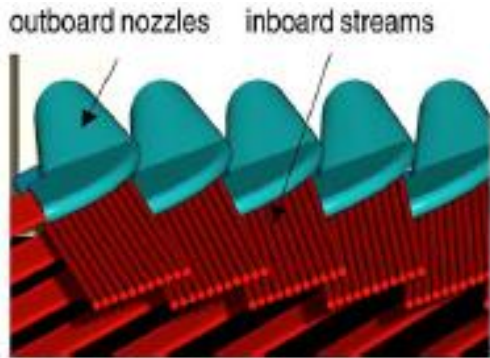
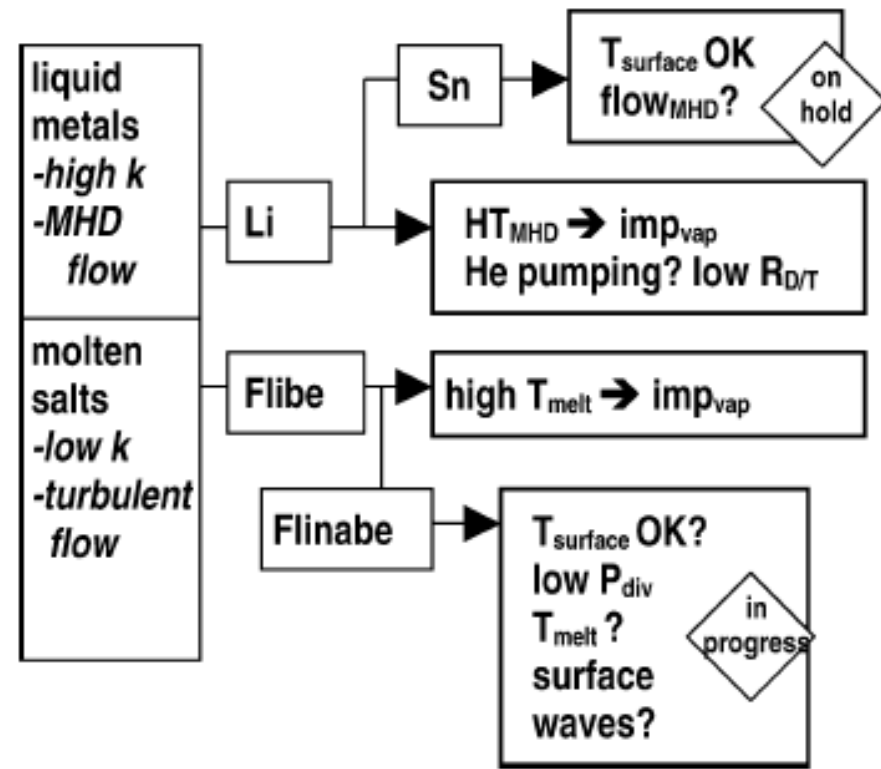
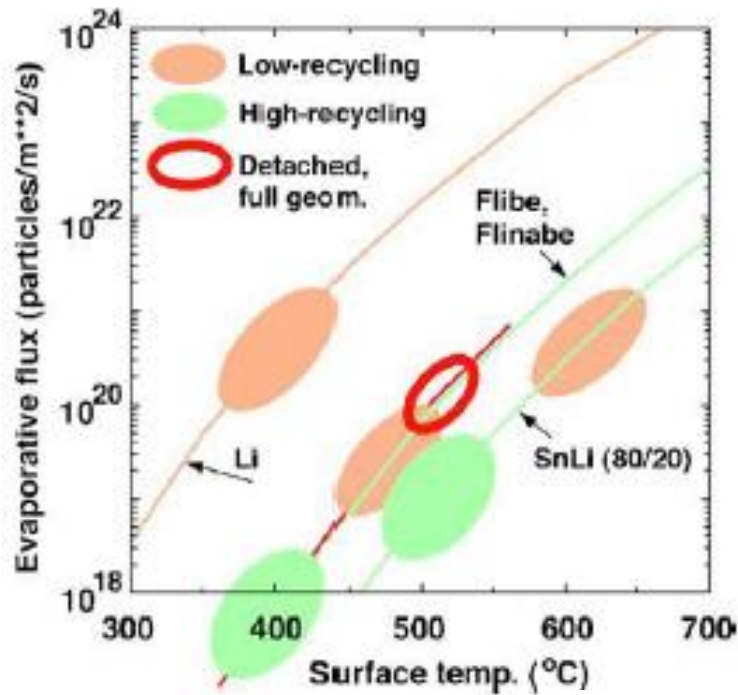
1. Liquid First Wall (CLIFF)
 - 1 cm liquid removes all surface heat
 - Near-Term Applications in Plasma Devices
2. Thick Liquid FW/Blanket
 - Highest Potential, Most Challenging
 - A. EM-Restrained Thick Li
 - B. Contiguous Gravity-Momentum-Rotational Flow
 - C. Separate Liquid FW and Liquid Blanket

Candidate Liquids: **Li, Sn-Li, Flibe**



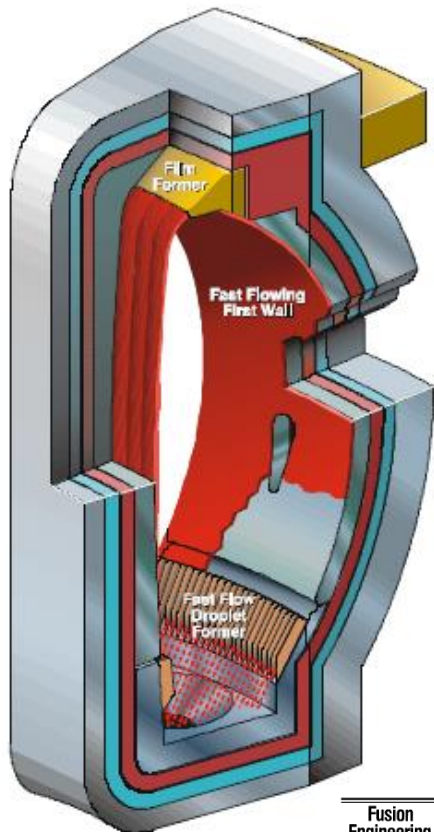
- High Power Density
- High Thermal Conversion Efficiency Dramatic Reduction in Radiation Damage and Activation
- Higher Availability – Lower Failure Rates – Faster Maintenance

Liquid walls concepts have the potential to reduce the volume of radioactive waste materials in the high flux region of the FW/blanket by a factor of 50-100.



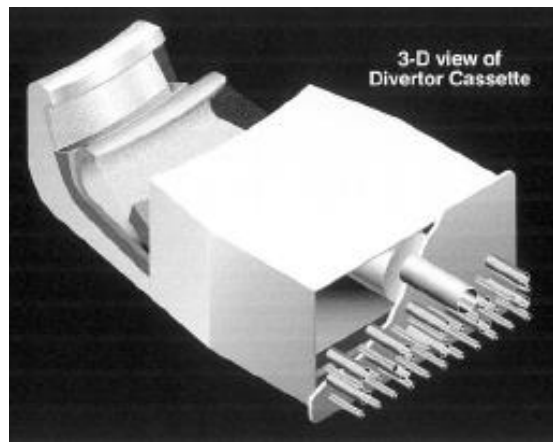
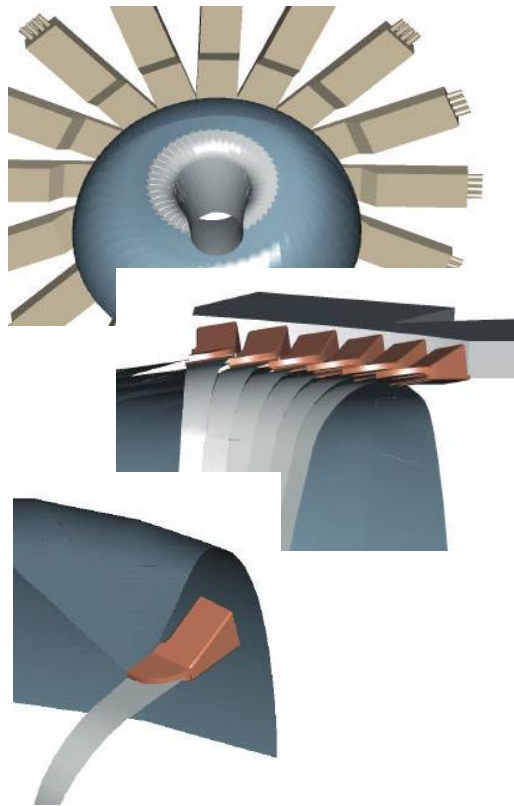
CLIFF Configuration

1/16 Sector - 3D Cutaway



Fusion Engineering and Design

www.dewinter.com/locate/fusionengdes



3-D view of Divertor Cassette

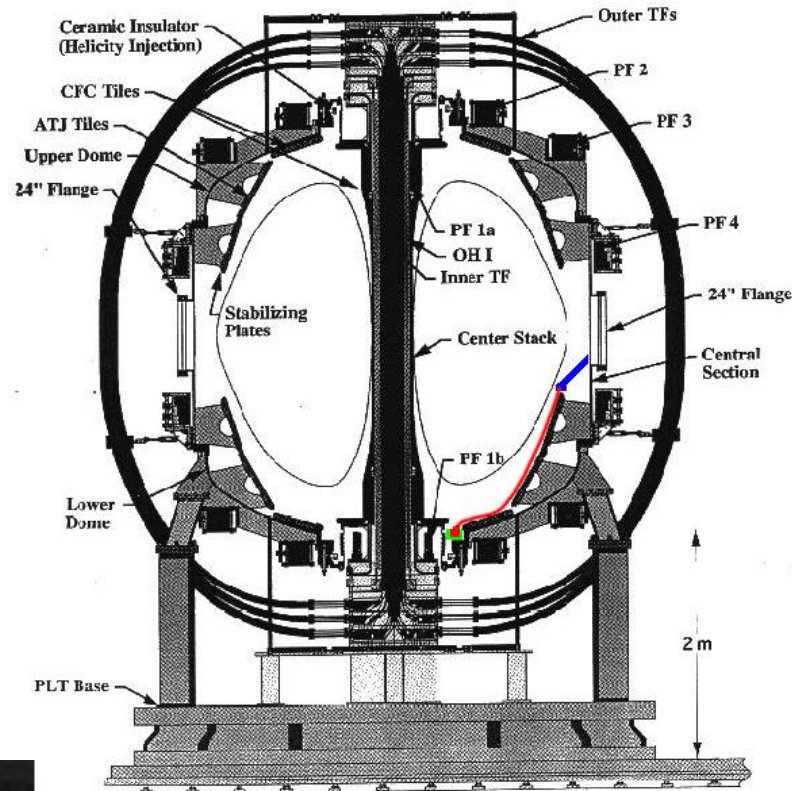


Table 1

Possible materials, configuration, and confinement options

Liquid species	Li, Flibe, SnLi, Ga
Surface configuration	Fast film, droplets, waterfall, stagnant film, pool, backside impinging jet
Confinement options	Tokamak, advanced tokamak, spherical torus, field reversed configuration, stellerator

Merits & Issues for Liquid Wall Concepts Based on the APEX Study - Handout to Aid Snowmass Discussions

A. Ying, M. Youssef, N. Morley, K. Gulec, M. Abdou (UCLA) and APEX Team: UCLA, ORNL, PPPL, LLNL, GA, UCSD, UW, ANL, INEEL, LANL, SNL

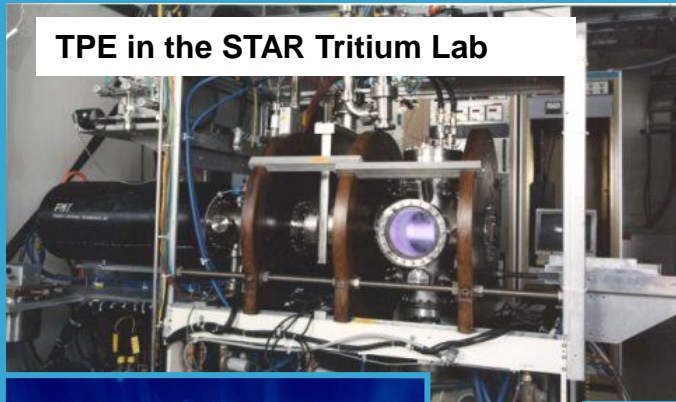
FED 49-50 (2000) 127-134
ALPS-advanced limiter-divertor plasma-facing systems

R.F. Mattas, J.P. Allain, R. Bastasz, J.N. Brooks, T. Evans, A. Hassanein, S. Luckhardt, K. McCarthy, P. Mioduszewski, R. Maingi, E. Mogahed, R. Moir, S. Molokov, N. Morely, R. Nygren, T. Rognlien, C. Reed, D. Ruzic, I. Sviatoslavsky, D. Sze, M. Tillack, M. Ulrickson, P.M. Wade, R. Wooley, C. Wong

Multiple-Effects, Synergistic Phenomena

Neil Morley will cover this

TPE in the STAR Tritium Lab

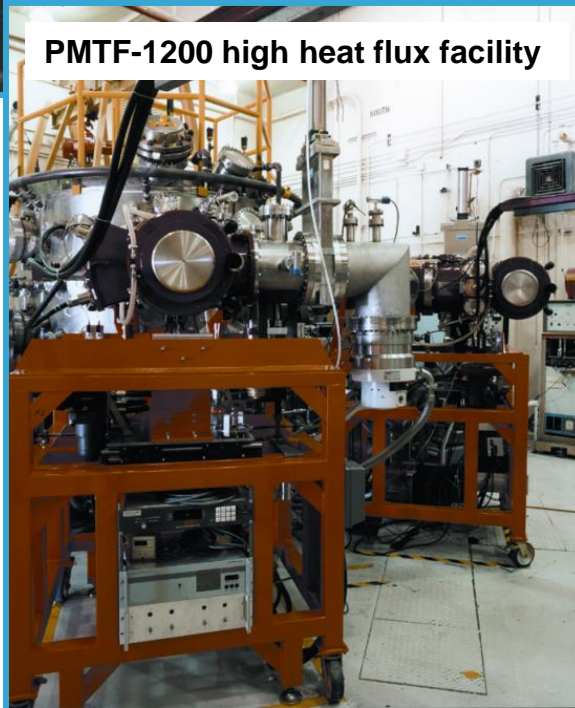


- PISCES - UCSD
- SNL, U-IL
Surface sci. labs
- Purdue labs
- U Illinois labs

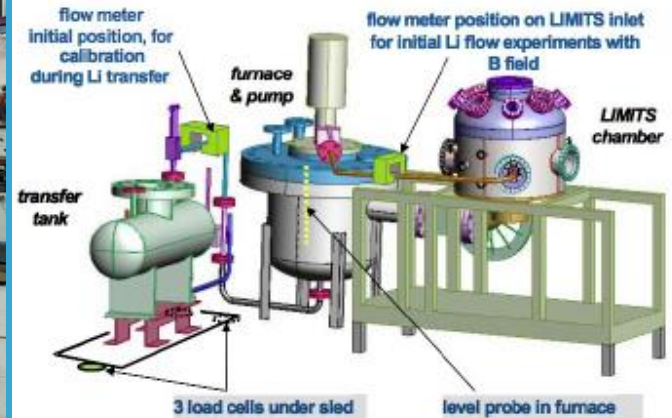
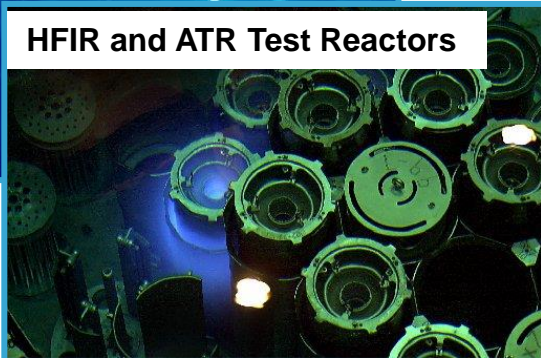
MTOR Thermofluid/MHD facility



PMTF-1200 high heat flux facility



HFIR and ATR Test Reactors



What has happened since ALPS/APEX

Nuclear Materials and Energy

International R&D on Liquid Surfaces for Fusion
Plasma Facing Components - Part I: Physics and PSI

RE. Nygren, FL Tabares

- ITER Project
- TBM development
- ITER FW (redesign, convected power)
- ReNeW, FNSPA, FESAC Mat'ls
- (greater) Importance of ELMs
- Detached plasma solution hard
- EU DEMO program
- Strength of Chinese program
- W microstructure issues
- Computing power (mat'l modeling)
- Additive Manufacturing
- NSTX-U, LTX
- Strength of LM PFC, Li edge
- Li vapor shielding results
- Fukushima

... still cannot state categorically ..
..(LM PFCs) .. potential for successful
development .. for a CTF or DEMO.

.. general concern about solid wall
PFCs for .. fusion reactor.

And **collective research worldwide**
.... (LM PFCs) ... moving toward a
tipping point in the near future.

... the **aggregated evidence** will
motivate **much stronger initiatives**
for liquid surfaces as a **believable**
approach and an alternate to
realizing a robust high power fusion
device.

Table 4. Critical Issues

Features for suitable physics regime

Liquid surface is stable when exposed to plasma over reasonably long times.
 Plasma wets enough area of liquid surface that the effects dominate the behavior of the plasma edge.
 Power, fueling rate and surface temperature of the walls (and surface chemistry for interactions) are prototypic for the intended application in CTF/DEMO.

Features in ongoing experiment efforts

C and O in confinement devices interact with Li.
 Interaction of plasma with liquid surface affects but does not dominate the behavior of the plasma edge.
 Wall temperatures are far below those in a DEMO.

Features in technology R&D

Environment damages structure in liquid surface PFCs
 Fluid streams are chemically compatible with structure.
 Wetting, pumping and drainage are adequate for PFCs and integrated systems connected to PFCs.
 Replenishment and cleaning of PFC surfaces, tritium retention in PFCs is acceptable, and tritium recovery from PFCs is adequate

critical issues or topics

- Stability of flowing liquid including liquid metal MHD and instabilities from rapid heating
 - Li chemistry and PSI (evaporation, vapor shielding, temperature-enhanced erosion and suppressed erosion, D/T retention & recycling)
 - Coronal radiation
 - Fueling, pumping, particle balance (and recycling), burnup
-
- Intercalation, Li-O-C chemistry and recycling
 - Wetted area, recycling
 - Temperature dependence in chemistry of liquid surface
-
- Tritium recovery
 - Effects of liquid metal MHD on heat and mass transfer
 - Corrosion and mass transfer, liquid metal embrittlement
 - Neutron damage, distortions (thermal stress, creep), EM loads
 - Integration of liquid surface first walls with blanket structure and cooling

**Strong
PSI-MAT
coupling**

**Strong
PSI-MAT
coupling**

Integration of liquid surface PFCs into DEMO or FNSF

Richard E Nygren

Table 1. PFC-Blanket Cases.

Fast flow FW/Div.			Blanket				
<i>FW</i>	<i>Div.</i>	<i>Press.</i>	<i>breeder</i>	<i>coolant</i>	<i>P</i>	<i>structure</i>	
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	H	RAFS	5
Ga	Ga	L	solid	He	H	RAFS	6
salt	salt	L	salt	salt	L	RAFS	7
Fast Flow FW/Div.			Blanket				
Li-CPS	He	H	solid	He	H	RAFS	8

LM PFCs

location	type	rationale
wall	CPS	good for large areas, moderate heat load and as integrated FW
deep divertor target	"gas box"	high heat removal , achieves detachment, radiates power
Other, divertor surfaces	fast flow	good heat removal, pumping and tritium removal

Count number of fluid streams

Thanks