PRELIMINARY DRAFT FOR DISCUSSION: Version 6/24/99

Chamber Science & Technology Key Question #1:
Liquid Walls in MFE and IFE

What are the merits and issues for liquid walls? What experiments, modeling, and analysis must be done to judge their potential for IFE and MFE? What are the key go/no go issues and how they can be explored quickly?

Group Leaders:

Ralph Moir (LLNL) and Neil Morley (UCLA)

With Contributions from the Core Working Group:

Rich Mattas and Dai-Kai Sze (ANL)
Ed Lee (LBNL)
Steve Payne and Tom Rognlien (LLNL)
Dick Majeski and Dale Meade (PPPL)
Mike Ulrickson (SNL)
Per Peterson (UCB)
Mohamed Sawan (UWM)

And Other Interested Fusion Community Members

Prospectus

For some time now people have thought of liquid walls as an attractive solution to the technology problems of high power density plasma configurations for MFE, and as (nearly) essential for the pulsed wall-loading conditions in IFE. A flowing, renewable surface could be eroded, evaporated and even be broken apart with no permanent adverse effects on a structure requiring frequent maintenance and replacement. Alpha particle energy could be removed without conduction through a solid wall and the associated thermal stress and creep failure modes, and the energy could be extracted at high temperatures for efficient energy conversion. If a liquid wall of sufficient depth could be formed, radiation damage and waste disposal issues for solid structures could be significantly ameliorated.

All these benefits are indeed possible, if only liquid walls could be made to work! As we will see, there are many issues associated with the successful and attractive implementation of liquid walls.

The most obvious issue with liquid walls in MFE, assuming that they can be formed without splash, is that the vacuum required for current successful plasma experiments will be compromised by the relatively high evaporation rate of the hot liquid in the plasma chamber. This concern has led to the formulation of the idea that there is a temperature limit, corresponding to an acceptable evaporation flux, above which liquid walls will kill the operation of the plasma. This temperature limit will be inextricably linked to the ability of the plasma edge to screen neutral atoms and molecules before they enter the core plasma. In determining this screening one must account for the fact that the plasma edge behavior itself will likely be influenced by this large neutral flux.

For IFE, a similar issue stems from the need to clear the chamber of vaporized, splashed, and/or spalled liquid wall material so that targets can be injected and the driver beams can propagate to the targets through the residual vapor and debris at a pulse rate of several shots per second.

Other issues have sprung up as the analysis of liquid walls has advanced slowly over the years, and now more rapidly as part of the APEX and ALPS projects, and IFE development program. For MFE these issues include:

- Feasible liquid flow configurations, including inlet/outlet systems and space for penetrations must be identified

- Conflicting need for low surface temperature for plasma compatibility and high bulk outlet temperature for efficient energy conversion.

- High mass-flow rates needed to form thick liquid walls leads to low bulk temperature rise, and requires large pumping power, significant pumping equipment, and large piping (especially for gravity drainage from the vacuum chamber).

- Electromagnetic fluctuations and currents from the plasma can couple to liquid metal walls and exert a significant influence on its flow behavior. Conversely, stability of core MHD modes and plasma control may be affected differently for conducting and non-conducting liquids

- The liquid walls may act as particle pumps, especially in the limiter/divertor region, which change the effective recycling behavior and plasma-operating regime.

- Effect on other essential reactor systems like vacuum pumping, tritium recovery, plasma fueling, RF antennae, diagnostic and neutral beam penetrations, may require radically redesigned systems.

For IFE the other general issues include:

- Feasible liquid flow configurations, including inlet/outlet systems and space for beam lines must be identified

- Pulsed power deposition can lead to high velocity liquid slugs and droplets that can damage the target chamber structure and beam lines.

- Conflicting need for low surface temperature for driver beam propagation to the target, cryo-target compatibility, and rapid vapor condensation on films and droplet clouds; and high bulk outlet temperature for efficient energy conversion.

- High mass-flow rates needed to form thick liquid walls leads to low bulk temperature rise, and require large pumping power, significant pumping equipment, large piping (especially for gravity drainage from the vacuum chamber), and head recovery systems.

- Effect of liquid and vapor on other essential reactor systems like vacuum pumping, tritium recovery, final optics, diagnostic and driver beam penetrations, may require radically redesigned systems.

Main subtopics:

The subtopic questions posed to the Fusion Community are designed to try to extract from people of various physics and technology backgrounds their views of the precise issues facing liquid walls, and the associated modeling and experiments needed to establish the feasibility and attractiveness of liquid wall concepts as a new paradigm for fusion reactor design.

The following topics will be explored in more detail before and during the Snowmass sessions on this topic. All ideas will be heard and discussed and will be incorporated into the final report along with the opinion (not always unanimous) of the core working group.

1. Do liquid walls really have the potential to yield a more attractive fusion energy product? What is the research and development path required to address feasibility and, subsequently, engineering design issues in a timely, economically realistic manner? What is the real impact on other reactor technology systems? (Moir, Sawan)

2. What modeling and experiments are required to establish the hydrodynamic feasibility of various thick liquid wall configurations for MFE and IFE? (Morley, Peterson)

3. What plasma modeling and experiments are required to determine the criteria of compatibility of liquid walls with acceptable tokamak or emerging concepts plasma operation (*e.g.* allowable surface temperature?) Will plasma operation with liquid walls be fundamentally different than with dry walls? Does it make sense to have a liquid divertor only, with solid first walls or solid divertor with liquid walls? (Rognlien, Majeski, Meade, and Ulickson,)

4. Are there driver propagation, focusing modes, and final optics more compatible with liquid walls? Will residual liquid vapor and droplets affect target and driver propagation? What modeling and experiments are needed to determine the real limits on residual amounts of vaporized wall material in IFE reactors? (Lee, Moir, Payne)

5. Is there a clearly superior choice of working liquid? Is Flibe a feasible liquid based on plasma contamination (MFE), molecular recombination and condensation (IFE), tritium breeding, and structural material compatibility? Is lithium vapor pressure simply too high to make an attractive liquid wall? Will MHD effects and interaction with the plasma exclude either Flibe or liquid metals as viable working liquids? How important are activation and chemical reactivity properties in affecting materials compatibility, waste disposal, and accident response? (Mattas, Sze)

Three 1-hour 45-minute discussion periods during the first week of Snowmass (Tuesday, Wednesday, and Thursday afternoons, July 13th, 14th, and 15th in the *Top-of-the-Village* Tent) are anticipated for the subtopics. Moir and Morley will act as chairmen for these two discussion sessions.

- Each subtopic is allotted 45 minutes.

- Statements not to exceed 10 minutes in length precede each subtopic discussion. These remarks will introduce the issues associated with the subtopics and state the opinion of the core working group on these questions, and will be given by the core working group members assigned to each subtopic (above)

- Guided discussion will continue after the introductory remarks for 35 minutes. The chairmen will have the option of extending the length of the discussion period if it seems particularly useful.

- If there is time remaining near the end of each two-hour period, the chairmen will bring up any additional points for consideration gleaned from the discussions.

A summary of key issues and required modeling and experiments will be prepared by R. Moir and N. Morley and will be presented at the end of the second session and during the second week of Snowmass. Before the one-hour session in the second week, the core working-group will modify the preliminary report to reflect the conclusions (or opinions) of the discussion sessions. Following the summer study, the final report will be prepared based on the discussion at Snowmass, with contributions accepted from ALL interested community members.

Preliminary Report Outline:

A draft of the core working group opinion on the above subtopics is given on the following pages and has been distributed before the meeting so as to elicit comments from the community. Comments can be registered via the Snowmass technology website hosted by UCLA at www.fusion.ucla.edu/Snowmass. Look in “Hot Topics and Commentary” to see all Chamber Technology Hot Topic Questions, and use the “view comments | add comments” link under each question to register your opinions via email. Your comments will be automatically posted on the website and distributed to the core working group. Please feel free to contact Neil Morley (morley@fusion.ucla.edu) directly if you have any problems with the website system.

Philosophy

This particular question is specifically about liquid walls and their potential attractiveness in fusion power plants. Other questions on different technologies are being held as part of the afternoon Cross-Cutting sessions and can be viewed at the Snowmass technology website cited above. It should also be noted that there are other Snowmass sessions with overlapping interest in liquid walls, especially the morning IFE session headed by Craig Olson (www.columbia.edu/~mem4/wg_ife.html).

The discussion here is meant to be frank and honest about the potential and problems of liquid wall concepts for MFE and IFE power reactors, and the R&D necessary to substantiate this potential. Many variants of liquid wall systems are possible that capitalize differently on the potential strengths outlined in this prospectus. They are not discussed here in detail. Many variants of advanced solid wall and particulate wall systems are also possible which may also be attractive for energy producing reactors. They also are not discussed here. But, some information is available at the APEX website at www.fusion.ucla.edu/APEX. All participants are encouraged to educate themselves on the current state of plasma chamber technology research.

Liquid Walls Subtopic 1

Do liquid walls really have the potential to yield a more attractive fusion energy product?

What is the research and development path required to address feasibility and, subsequently, engineering design issues in a timely, economically realistic manner?

What is the real impact on other reactor technology systems?

Ralph Moir and Mohamed Sawan

Liquid Walls Subtopic 1 – R. Moir and M. Sawan

Do Liquid Walls have the Potential to be Attractive?

Yes

Attractive Liquid Wall Features

- Elimination of first wall (divertor, and blanket) structure resulting in reduced thermo-mechanical problems related to thermal stress, embrittlement, and creep, *etc.*

- Neutron attenuation by liquid in front of most (possibly all) solid structures, reduced parasitic capture of neutrons in solid structure

Potential Impact on Attractiveness (compared to generic solid wall)

- Higher power density capability – results in smaller and lower cost components (magnets, chambers, vacuum vessel)
- Elimination of erosion lifetime limitations at divertor and FW/Limiter surfaces
- Reduced volume of radioactive waste (reduced size, increased lifetime)
- Reduced radioactive hazard from accidental releases
- Increased tritium breeding potential without the use of massive amounts of Beryllium multiplier
- Higher availability due to increased lifetime and reduced failure rates
- Lower capital cost by reduction in first wall and blanket replacement, number of hot and cold cells, amount of handling equipment, *etc*. (Highly design dependent)
- Reduction in costly materials development needs with expensive 14 MeV neutron testing facilities (IFMIF = ~$1B, VNS=~$3B, Operation=~$.25B/yr, *etc*.)

IF WE ARE CLEVER – The above attractive features could lead to significantly lower COE

How much: by ~30%? ~50%?

Liquid Walls Subtopic 1 – R. Moir and M. Sawan

Can Liquid Walls be made to work and still remain attractive?

There are serious issues needing resolution by R&D before we can say yes.

Primary Issues needing R&D:

- Evaporation threatens to put out plasma burn in MFE systems limiting the blanket operating temperature and affecting the attractiveness of the power conversion system. Low temperature operation of liquid walls may be feasible, but might not be attractive.

- Evaporation and liquid debris threatens pulse rate in IFE systems. Limits on pulse rate and liquid temperature will impact the attractiveness of liquid walls designs. Low temperature low pulse rate operation of liquid walls may be feasible, but might not be attractive.

- Nozzles must form the liquid flow pattern required and exit nozzles (or drains) must receive the flow without drips and other liquid debris that threatens the plasma burn or chamber clearing.

- MHD effects with liquid metals might preclude the desired open channel flows for MFE systems and insulators are integral parts of the concept.

- Penetrations for MFE systems and beam port protection for IFE systems have serious design issues

Feasibility and attractiveness is not assured and may come out negatively, different conclusions are possible for different plasma confinement schemes (MFE) and drivers (IFE).

Rethinking of optimum plasma confinement and driver propagation should proceed hand-in-hand with liquid wall development to achieve both a feasible and attractive vision of a fusion reactor

Liquid Walls Subtopic 1 – R. Moir and M. Sawan

APEX and ALPS Projects and IFE Program are taking the right steps toward establishing feasibility.

Some questions are being addressed in the APEX project (for liquid walls) and ALPS project (innovative divertors) and as part of the IFE development path

- Various designs implementations for liquid walls and divertors have been proposed and explored
- Information available at APEX website www.fusion.ucla.edu , and as part of the interim APEX report due out in August
- IFE plan described by W. R. Meier, editor, "Chamber and target technology development for heavy-ion inertial fusion," UCRL-ID-133629 (draft Mar 15, 1999).

At this point the ultimate feasibility and attractiveness of liquid walls has not yet been shown.

The Modeling and Experimental R&D program needed to resolve the issues will be part of the continuing APEX, ALPS programs

- Hydrodynamic feasibility
- Plasma operation and interaction with liquid walls
- Surface and bulk temperature control
- Fundamental data measurements: sputtering and recycling rates from the liquids, dissociation cross-sections for molecules such as those from Flibe, liquid vapor pressure and composition

and IFE program

- Hydrodynamic feasibility
- Chamber clearing ready for the next shot in about 1/5 s

Liquid Walls Subtopic 1 – R. Moir and M. Sawan

What is the Needed R&D do demonstrate the attractiveness of Liquid Walls

Must demonstrate feasibility - R&D needs for various feasibility issues are described in the following subtopics

- Hydrodynamic Feasibility
- Plasma Compatibility
- Driver Compatibility
- Choice of Working Liquid

R&D needs to demonstrate ultimate Attractiveness

- System code for liquid walls in Tokamak, Emerging Concepts, and IFE: with specific assumptions for liquid wall issues. Where do Liquid Walls optimize?

- Design study exploring impact of liquid walls on all reactor systems with detailed COE calculations with both conservative and liberal assumption sets

- **Liquid Wall DEMO**

Liquid Walls Subtopic 2

What modeling and experiments are required to establish the hydrodynamic feasibility of various thick liquid wall configurations for MFE and IFE?

Neil Morley and Per Peterson

Liquid Walls Subtopic 2 – N. Morley and P. Peterson

So What is Hydrodynamic feasibility for MFE Liquid Walls?

- Can you form it?
- Can you drain it?
- Can you maintain it?

What are the Primary Hydrodynamic Feasibility Issues that Must Be Addressed for MFE?

- Basic MFE Geometry - Free surface flow over flat or concave structures with constant surface heat flux from plasma
  - Back-wall and nozzle turbulence generation in a magnetic field and the effect on hydrodynamic drag and surface heat transfer (mainly for Flibe)
  - Free surface flow across temporally and spatially variable magnetic fields without significant thickening and slowing due to MHD effects (mainly for LMs but concerns exist for free surface Flibe as well)
  - Acceptable surface stability due to finite inlet and vibrational disturbances
  - Flow around necessary penetrations
  - Dripping due to surface boundary layer instabilities near inlet nozzles
  - Head recovery nozzle systems that don't splash
  - High heat flux removal in divertor without excessive evaporation
  - Effect of plasma momentum and currents in divertor region
  - Response to induced currents and forces in back-wall and/or in the liquid itself during disruption, start-up, and other plasma events.
  - Acceptable pressure losses in supply piping including need for insulator coatings and effect of 3D pressure drops due to entrance into magnetic field

- Other MFE geometries are possible which might have issues that vary slightly
  - The idea of free jets arrays forming a rectangular space for the plasma has been advanced.
  - Swirling flows inside cylindrically shaped chambers are considered for FRC and some IFE configurations
  - Magnetized target fusion with chambers similar to IFE
  - Others are possible

Liquid Walls Subtopic 2 – N. Morley and P. Peterson

So What is Hydrodynamic feasibility for IFE Liquid Walls?

- Can you form it?
- Can you drain it?
- Can you clear it?

What are the Primary Hydrodynamic Feasibility Issues that Must Be Addressed for IFE?

- Basic thick-liquid IFE Geometry – Stationary and oscillating jet arrays of various cross-sectional shape with impulsive surface heat and neutron loading
    - Creation of stationary, oscillating, and deflected free liquid jets at high Reynolds numbers and Weber numbers, with suitable surface smoothness and other geometric characteristics
    - Design of multiple nozzle systems to form dynamically clearing pockets with access for target and beam injection
    - Response of liquid pocket systems to x-ray ablation and pocket pressurization impulse loading and neutron isochoric heating, droplet and slug formation, momentum redistribution in thick liquids, pocket clearing and regeneration
    - Rapid condensation of vaporized liquid onto droplets and jets
    - Dripping and surface boundary layer instabilities near inlet nozzles
    - Head recovery nozzle systems that don't splash (too much)

- Basic thin-liquid IFE Geometry – Flowing or stationary liquid films on porous walls and tubes
    - Flow guiding around beamline penetrations and adherence to inverted surfaces. Control of layer thickness
    - Rapid surface heat transfer via turbulent surface renewal (flowing) and conduction
    - Standoff distance to avoid breakup and droplet ejection from rapid surface ablation and isochoric heating
    - Reduction in cyclic loading of back-wall structure and fast replacement

- Other IFE geometries are possible which have similar issues
    - Vortice flow in a cylindrical or cusp-like chamber
    - Others?

Liquid Walls Subtopic 2 – N. Morley and P. Peterson

What can CFD Modeling do towards establishing Hydrodynamic Feasibility?

- Provide preliminary check on feasibility of configuration and ballpark estimates on flow parameters
- Allow screening of concepts and variations
- Be tuned to address specific problems identified with various designs, *e.g.* heat transport at free surfaces, wave instability at free surfaces, breakup of liquid jets due to rapid bulk heating and surface shocks, *etc.*
- Must be checked with appropriate experiments

Concept Exploration Experiments must be Undertaken

- Simulate various design ideas and benchmark CFD modeling (Experiments performed at reduce geometric scale can preserve key hydraulics phenomena at reduced cost)
- Investigate basic critical issues for MFE codes
  - Free surface flow and heat transfer for Flibe
  - Free surface MHD flow and heat transfer for LMs
- Investigate basic critical issues for IFE
  - Dynamics and surface stability of stationary and oscillating liquid jets of various cross-sectional shapes
  - Disruption of partial liquid pockets to demonstrate droplet clearing and pocket regeneration
  - Dynamics of flowing liquid films on porous structures
  - Liquid fracture simulation due to impulsive loading
  - Condensation rates of vaporized material in characteristic IFE geometry
- Allow down-selection of promising configurations

Ultimately - Proof of Principle Experiments Required

Liquid Walls Subtopic 2 – N. Morley and P. Peterson

What kind of POP facilities are we talking about for Hydrodynamic Feasibility?

One that can demonstrate feasibility of Flibe and LM flows in a partially integrated fusion environment with appropriate simulant liquid and WITHOUT nuclear heating

Thermal-Fluid Integral Test Facility for Flibe Hydrodynamics and Heat Transfer

- Flow and surface heat transport in complex flow geometries including penetrations are the primary feasibility issues for MFE
- Flow and response to scaled impulse loads are primary feasibility issues for IFE (disruption using scaled fuel-oxidizer charges will require qualification).
- Simulant should be acceptable for establishing hydrodynamic feasibility. Water has good scaling properties as a simulant

  Advantages: Water is fairly easy to pump, transparent, cheap, and can be tailored to improve characteristics for tests
  - Add electrolyte for non-zero electrical conductivity.
  - Add surfactants for modified surface tension characteristics
  - Control Temperature for modified viscosity characteristics
  - Add dyes for preferential adsorption of radiation at select frequencies

  Disadvantages: Water has vapor pressure issues and can not simulate MHD or heat transfer in high electrical conductivity, low Prandtl number LMs
  - Can flash when exiting contraction nozzles and when pumped from vacuum vessel
  - Lower atmospheric pressure limit can result in non-characteristic levels of finite surface shear (affecting surface heat transfer)
  - Boiling point is low so allowable surface heating is limited
- Facility size estimate with water < 10M$

Thermal-Fluid MHD Test Facility for LM Free Surface MHD and Heat Transfer

- Lithium and Sn-Li may require different low melting point simulant LMs
- Flow interaction with magnetic field is a primary feasibility issue
- Long pulse, high magnetic field facility (possibly toroidal) required
  - Strong toroidal field with characteristic 1/R dependence
  - Temporally varying OH, equilibrium, and plasma current fields with characteristic time response to simulate start-up, steady state plasma control, and disruption
- Facility size estimate depends on magnets and simulant, but should be in the ~$20M range.

Liquid Walls Subtopic 3

What plasma modeling and experiments are required to determine the criteria of compatibility of liquid walls with acceptable tokamak or emerging concepts plasma operation?

Will plasma operation with liquid walls be fundamentally different than with dry walls?

Does it make sense to have a liquid divertor only, with solid first walls or solid divertor with liquid walls?

Tom Rognlien, Dick Majeski, Dale Meade, Mike Ulrickson

Liquid Walls Subtopic 3 – T. Rognlien, D. Majeski, D. Meade, M Ulrickson

What plasma modeling and experiments are required to determine the criteria of compatibility of liquid walls with acceptable tokamak or emerging concepts plasma operation?

Analysis of the Edge Plasma Required:

The edge plasma provides the interface between the hot core plasma and the liquid first-walls and divertor plates. The liquid surfaces can impact the edge and core plasmas by releasing impurities through sputtering, recycling, and evaporation. Such impurities degrade fusion core performance through enhanced radiation loss and fuel dilution. The edge plasma, in turn, influences the liquid surfaces through particle bombardment and line radiation from excited ions. The bombardment leads to sputtering and recycling, and both bombardment and radiation heat the surface leading to increased evaporation.

Key Issues for Edge and Core Plasma:

- What is the maximum liquid surface temperature that gives tolerable impurity influx to the core from evaporation? What are the differences between the species from various candidate coolants and their effects on the plasma?

- Does sputtering from hydrogen and impurity ions give tolerable impurity influx?

- Is the optimal liquid for the first wall the same as for the divertor (if one exists)? Can one be a solid surface and one a liquid surface?

- Does vapor from liquid walls modify the hydrogen edge-plasma sufficiently that core operation is affected? For example, core-edge profile changes could alter H-mode and ELM behavior in tokamaks. Lower edge density from low recycling lithium could improve current drive efficiency. Does a moving conducting liquid wall, or a non-conducting liquid wall, affect MHD instabilities in the plasma?

- Do configuration difference for various confinement concepts make one clearly superior for minimizing impurities from liquid walls, e.g., short connection length or no divertor?

- What are the characteristics of turbulent cross-field transport in an impurity-dominated edge plasma? Does parallel transport remain classical?

- How are the impurity ions/neutrals exhausted from the system?

Liquid Walls Subtopic 3 – T. Rognlien, D. Majeski, D. Meade, M Ulrickson

Theory/Modeling and Experimental Work - Present Status and Needs

Plasma Modeling Activities Underway

- Many of these issues are being investigated with simulation codes.
  - The transport of hydrogen and impurity ions in the edge region is modeled by the 2-D transport code UEDGE that includes both the hydrogenic plasma from the core and impurities
  - The MCI Monte Carlo code can use the hydrogenic UEDGE profiles and then follow impurities in the whole edge region
  - Near-surface interactions with the vapor and sheath formation are studied with the WBC and BPHI Monte Carlo ion codes
  - The effect on core plasma performance is simulated by a systems code used for the ARIES studies and the ONETWO core transport code

- There is a very important need to couple these various calculations together in a self-consistent manner.
  - Work has begun in that output from UEDGE is feed into WBC and ONETWO, and will then be feed back
  - However, if the physical coupling is very strong, there will be a need to couple these models more directly

Surface Properties from Experiments and Codes Underway

- The behavior of the liquid materials, including some sputtering rates, are being measured in stand-alone experiments at Sandia and UIUC, and in plasma devices in DIII-D at General Atomics and PISCES at UCSD.

- Monte Carlo surface codes such as TRIM are benchmarked by these experiments, and then used for more extensive parameterization. More work is needed to determine dissociation cross-sections.

Liquid Walls Subtopic 3 – T. Rognlien, D. Majeski, D. Meade, M Ulrickson

Related Experimental Tests in Tokamaks are NEEDED

There is experimental evidence to suggest that a strongly radiating edge region can coexist with a hot core plasma

- Radiating impurity (RI) mode studied in TEXTOR, and to a lesser extent in DIII-D and TFTR, show that a moderate-Z impurity such as neon can surround the core plasma at the edge at sufficient density that nearly all of the escaping core power is finally radiated at the edge, but the core remains hot with a good energy confinement time

- TFTR experiments with lithium pellet injection shows that a substantial amount of lithium can be injected without a radiative collapse owing to the low Z of lithium

- However, for a reactor, fuel dilution will limit the permissible amount of lithium.

It is necessary to conduct whole-device tests where liquid divertors and/or walls comprise a significant portion of the active surface area

- Only here can the impact of the liquid surface on core performance be realistically studied. Existing machines like CDX-U, DIII-D and C-MOD could do much towards investigating liquid wall plasma feasibility

- Such experiments would provide important data to benchmark model calculations and possibly uncover unanticipated problems

- For a tokamak device, one must address the following issues:
    - Is there sufficient impurity shielding?
    - Is core performance changed - L-H transition, ELMs, disruptions? Is it changed for the better?
    - Is the temperature rise of the liquid in accord with heat transfer models?
    - Is there a clear choice of working liquid - conducting/non-conducting, recycling/non-recycling?
    - Can the plasma be started up in the presence of the liquid?

- Issues for FRC or other innovative confinement should be similar

Liquid Walls Subtopic 4

Are there driver propagation, focusing modes, and final optics more compatible with liquid walls?

Will residual liquid vapor and droplets affect target and driver propagation?

What modeling and experiments are needed to determine the real limits on residual amounts of vaporized wall material in IFE reactors?

Ed Lee, Ralph Moir, Steve Payne

Liquid Walls Subtopic 4 – E. Lee, R. Moir, S. Payne

Are there driver propagation, focusing modes, and final optics more compatible with liquid walls?

Heavy-ion beams: YES

Ideal Propagation mode → partially neutralize beam without striping in ballistic focus to reduce space charge

- This mode required that you preionize small fraction of background gas to get an electron density >10 times the beam density
  - use RF; for example a whisler mode in low field ~20 G to accomplish preionization
  - other techniques possible

- For Flibe: gas density $< \sim 3 \times 10^{13}$ BeF_2 molecules/cm^3 is acceptable
  - This is 2.7 mTorr of vapor pressure
  - Corresponds to 614 °C Flibe surface temperature

- Droplets may be harmless up to few % opacity in neutralized mode with the need to oversize the beams by a few %.

- Other propagation modes are possible with liquid walls, but neutralized ballistic focusing is the most promising near term possibility.

What are the issues (that R&D must address?)

- Effect on beam power coupling and spot size of various vapor and liquid droplet densities in the beamline (contributed by Morley)
- Effectiveness of final focussing magnet shielding by liquid and solid systems, and effect on minimum stand-off distance (contributed by Petereson)
- Others????

Liquid Walls Subtopic 4 – E. Lee, R. Moir, S. Payne

R&D necessary to establish the feasibility of partially neutralized ballistic focusing for IFE power plants

Need numerical simulation of neutralization process

- uniformity and controlled for small spot
- others??

Experiment on creation of ionization

- uniformity, persistence benchmark with modeling predictions
- near term: LBNL small scale final focus experiment (with introduced vapor and liquid droplets)

IRE experiments and modeling needed

- Integrated research experiment IRE proposes to build models of beam lines and study the issues related to propagation through realistic chamber environments to final illumination of the target
- 2003—2011 IRE high current from multiple beams

Liquid Walls Subtopic 4 – E. Lee, R. Moir, S. Payne

Laser beams (1/4 or 1/3 micron)

- Propagation expected through low Z gases up to a Torr (~$3x10^{16}$ BeF_2 or Li molecules/cm^3) so no problem expected from vapor from liquid walls (vapor density from hot Flibe is a thousand times lower than this limit)

- Propagation through medium Z xenon gas for x-ray protection at a few Torr·m thickness appears feasible even for ¼ micron laser light. More experiments and analysis should be done on:
  - hot xenon gas handling
  - preventing turbulence from scattering beam

- Effects of droplets on beam propagation needs study; probably harmless up to a few % opacity with the need to oversize the beams. Allowed nonuniformity from beam to beam will have to be studied

- Ablation of, and condensation on, final optics components must be prevented

- Temperature of final optics components must be controlled.

- Experiments in IRE will allow demonstration of the operation and resolve many issues

(aside: this issue of propagation is always a big one for MFE criticism. Why is it that here is appears to be no problem? What are the real difficulties? I think we need to be more explicit about what needs to be studied. Any suggestions?? Should we add cryo-target propagation to this subtopic??)

Liquid Walls Subtopic 5

Is there a clearly superior choice of working liquid?

Is Flibe a feasible liquid based on plasma contamination (MFE), molecular recombination and condensation (IFE), tritium breeding, and structural material compatibility?

Is lithium vapor pressure simply too high to make an attractive liquid wall?

Will MHD effects and interaction with the plasma exclude either Flibe or liquid metals as viable working liquids?

How important are activation and chemical reactivity properties in affecting materials compatibility, waste disposal, and accident response?

Dai-Kai Sze and Rich Mattas

Liquid Walls Subtopic 5 – D.K. Sze and R. Mattas

All working liquids must also be breeding materials (containing Li)

- Lithium
- Flibe
- Sn-Li
- Pb-Li

Different Candidates have different Key Features

- Lithium: Best breeding material
- 83Pb-17Li: Less reactive when comparing to lithium
- Flibe: Low electrical conductivity
- 75Sn-25Li: Low Z, low vapor pressure

Relative Comparison

	Lithium	Pb-Li	Flibe	Sn-Li
Breeding	++	++	+	+
Activation	++	–	–	—
Chemical reactivity	—	+	+	+
Vapor pressure	–	—	–	++
Electrical conductivity	—	—	++	—
Thermal conductivity	+	-	(1)	++
Tritium recovery, inventory	–	+	+	+
Tritium recovery, pressure	+	–	–	–
Material compatibility	+	–	(2)	(3)
Key impurities	N	O	F, TF	O
Need for coating				
MHD Insulation	Yes	Yes	No	Yes
Tritium Permeation (4)	No	Yes	Yes	Yes

(1) The thermal conductivity of Flibe is very low. However, the heat transfer will be by convection. The low thermal conductivity is not a severe issue.

(2) Material compatibility between pure Flibe and structural material is usually not an issue. The impurities in Flibe, such as TF and F2, may cause severe corrosion issues.

(3) There is no database on material compatibility between Sn-Li and structural materials.

(4) See discussion on following pages for clarification

Liquid Walls Subtopic 5 – D.K. Sze and R. Mattas

Is there a clearly superior choice of working liquid? <u>No</u>

- There is not sufficient database to make this choice. Even if all data base are in, there is trade off from different requirements

Is Flibe a feasible liquid based on plasma contamination (MFE), molecular recombination and condensation (IFE), tritium breeding, and structural material compatibility: <u>Yes</u>?

- On plasma contamination, Flibe is most likely better than lithium (high vapor pressure) and Pb-Li (high Z vapor). We certainly can not rule out Flibe on this issue.
- There is not sufficient information on the kinetics of molecular recombination of Li, Be and F, back to Flibe. Thermodynamically, it is very favorable.
- Flibe can breed if there is large first wall coverage, and very low structural fraction. If there are penetrations and modest structural fraction, additional Be will likely be required for breeding.
- Flibe is expected to be compatible to most structural material if impurities, such as TF and F, can be properly controlled. If TF and F can not be properly controlled, material compatibility will be a severe issue.

Is lithium vapor pressure simply too high to make an attractive liquid wall? <u>Maybe</u>.

- We do not know yet what will be the limiting vapor pressure. Although lithium vapor pressure is high, its Z is much lower than Pb-Li and Flibe.
- Clever designs may be possible that take advantage of the low vapor pressure of lithium near the melting point, but still have reasonable bulk outlet temperatures

Will MHD effects and interaction with plasma exclude either Flibe or liquid metals as viable working liquids for MFE? <u>Unknown</u>

- Development of a reliable insulating coating, 3-D (entrance effects and variable field effects) on very high LM flowrates, Flibe flow laminarization and heat transfer degradation are all under investigation.

How important are activation and chemical reactivity properties in affecting materials compatibility, waste disposal, and accident response? <u>Not at all</u>

- Activation, chemical reactivity properties have no impact on material compatibility, waste disposal *etc*.

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Feasibility Issues for Liquid Breeders

Insulating coating development (for LMs in MFE only)

- There is no design window for MFE, with a self-cooled liquid metal design, if an insulating coating can not be developed
- The coating has to be compatible with the liquid metal, radiation, thermal cycling, and be reliable or renewable over many years of operation
- This maybe the most demanding engineering development for chamber technology.
- The development of an insulating coating is in the very early stage

Even with a insulating coating, there are still key MHD effects

- For liquid metal breeders, the 3-D MHD effects, particularly the entrance effect with velocity ~ 10 m/s, has to be assessed
- For Flibe, the key issue is the effect of MHD suppression of the flow turbulence and subsequent reduction of convective heat transfer and surface renewal
- MHD enhanced molecular dissociation may limit the allowable Flibe flow velocity

Tritium diffusion barrier

- A reliable tritium diffusion barrier will be necessary with any liquid breeders (with the possible exception of Li) for both IFE and MFE, unless an tritium recovery system to process the entire HX flow with >99.99 efficiency can be developed
- The development of this coating maybe not be as challenging as the MHD coating, because it can be outside of the radiation environment, and not necessarily in contact with the liquid breeder
- The development of tritium diffusion barriers is in the very early stage

Impurities transport into plasma

- Atoms (or ions) from the coolant liquid can be released by either evaporation or sputtering which may contaminate the plasma. Methodology of impurity transport, and its effect to the plasma operation, has to be developed
- The allowable rate of the impurity transport to the plasma sets an upper temperature limit on the coolant. This temperature limit will determine both the power conversion efficiency and the allowable neutron wall load limit of the first wall/blanket
- MFE and IFE both have limitations, but they are different

Flibe chemistry control

- Impurities in all liquid breeders have to be controlled to below an acceptable limit
- While impurities in other breeding materials are true impurities, the key impurities in the Flibe are transmutation by products, such as TF and F.
- For IFE operation, target material will introduce other impurities.
- Both concentrations of TF, and free fluorine, have to be controlled to very low limits.

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Required R&D

- **Tritium Chemistry Flibe Loop**
- **Tritium Recovery System for Lithium**
- **Others???? Suggestions appreciated**