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

Richard F. Mattas

Argonne National Laboratory, 9700 South Cass Ave., Bldg. 207, Argonne National Laboratory, Illinois

Representing the
Advanced Liquid Plasma-facing Surface (ALPS) planning group

One of the objectives of the restructured U.S. Fusion Energy Sciences Program is to: "Identify and evaluate new high performance concepts for advanced technology with high neutron wall load capability and attractive safety and environmental features." One promising technology specified by the Advanced Technologies and Materials Working Group is liquid plasma-facing surfaces for divertors. Some of the possible advantages of using liquid surfaces in divertors, relative to conventional solid surface approaches,include higher surface heat flux capability, continuously renewable surfaces, and higher temperature operation. A planning activity has been undertaken to identify the work to be performed over approximately three years to evaluate liquid surface concepts on the basis of such factors as their compatibility with fusion plasmas, high power density handling capabilities, engineering feasibility, lifetime, safety, and R&D requirements. A group, known as the Advanced Liquid Plasma-facing Surface (ALPS) planning group, was organized to prepare a plan for the activities needed to conduct such an evaluation. This paper will summarize the work of the ALPS group including recommendations on specific activities and a tentative schedule.

1. INTRODUCTION

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]. 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. Among of the most attractive technologies for use in devices that operate in advanced high power density physics regimes are liquid plasma facing systems. Such systems can be divided into two major classes - concepts with film flow over solid surfaces and concepts with free falling droplets or waterfalls. Film flow concepts are further divided by the speed of flow and by the choice of liquid and backing materials. Droplet concepts are further divided by the size of the droplets, the method of droplet formation, and the choice of liquid and backing materials. Candidate liquids for include gallium, lithium, lead-lithium, and FLiBe.

Liquid plasma facing systems potentially offer several advantages over conventional solid systems with internal cooling channels.

- Unlimited Erosion Lifetime The continuously renewable liquid surface eliminates sputtering and disruption erosion as life limiting events. In contrast, the predicted erosion lifetime of a carbon or beryllium coated divertor plate for ITER is < 0.1 MW-y/m2.
- No Neutron Damage Concerns for Liquids The candidate solid plasma facing materials (C, Be, and W) are all strongly degraded by neutron irradiation, and the lifetime of conventional systems can be short even if erosion is controlled. The use of liquids as plasma facing materials eliminates this concern, and the radiation lifetime of the system is then determined by the life of the main structural material, which for the materials in the US program is estimated to be 100-200 dpa (~ 10-20 MW-y/m2).
- High Power Density Capability Devices for testing advanced plasma physics regimes will likely require technologies that can accommodate high surface and neutron power densities. Conventional, water-cooled systems, such as those envisioned for ITER, are limited to peak heat fluxes in the range of 5 - 10 MW/m2. In contrast, liquid metal systems can potentially accommodate very high heat fluxes. As an example, the 14 MeV neutron generator for testing materials, IFMIF, uses a free surface liquid lithium target. The power on target for the latest IFMIF design is

* The submitted manuscript has been authored by a contractor of the U.S. Government under contract No. W-31-109-ENG-38. Accordingly, the U.S. Government retains a no exclusive, royalty-free license to publish or reproduce the published form of this contribution, or alloy others to do so, for U.S. Government purposes.

DISCLAIMER

DISCLAIMER

750 - 1000 MW/m2, CW. Liquid facing systems for fusion are not likely to achieve this level, but 50 - 100 MW/m2 may be possible.

- Active Pumping of Liquid Surface DT and He particles striking the surface will penetrate and possibly be trapped. In solid surfaces, the material will quickly become saturated, and no further net trapping will occur. In continuously renewable liquid surfaces, the material will not become saturated, and trapping can continue. The trapped particles will be removed from the plasma chamber with the liquid flow, and the liquid can therefore act as a pump. This effect may reduce the need for large vacuum pumps and also alter the plasma edge conditions.
- High Temperature Operation Candidate liquids can potentially operate in the plasma chamber at 300 - 1000 C without high vapor pressures. These high temperatures are important for retrieving useful heat for power production.
- High Power Conversion Efficiency The ability of candidate liquids to operate at high temperatures translates into high-energy conversion efficiency. For example, the ARIES-RS blanket and divertor, which uses liquid Li with an outlet temperature of 700 C, has a net system efficiency of ~47%.
- Low Pressure Operation The pressure in the heat transfer system for candidate liquids is typically 1 - 2 Mpa, compared with 5 - 10 Mpa for water and helium heat transfer systems. This low-pressure operation is a significant safety advantage when considering different accident scenarios.

The attractive features and scientific challenge offered by liquid plasma facing systems make them strong candidates for development in the restructured Fusion Program. In June 1997, the Office of Fusion Energy Science within the US Department of Energy requested that a planning group, known as the Advanced Liquid Plasma-facing Surface (ALPS) planning group, be organized to plan a three year program to evaluate these systems for advanced fusion devices. The following guidelines were made for this activity.

- The ALPS program will be carried out in 3 sequential phases: a planning phase, beginning as soon as possible and lasting for about 3 months; an evaluation phase, beginning in FY 1998 and lasting for about 3 years; an R&D phase, beginning after the evaluation phase.
- The group should have representation from US fusion community institutions with capabilities and interests toward addressing feasibility issues of liquid plasma-facing surfaces. Membership includes representatives from ANL, GA, INEEL, ORNL, PPPL, SNLA, SNLL, UCLA, and UCSD.
- The ALPS planning group will carry out the planning phase effort by preparing a plan for the evaluation phase effort, which should begin in early FY 1998 and provide the technical basis for initiation of a significant R&D effort beginning in FY 2001. The activities in the evaluation phase effort are suggested to include the following:
  - Specification of requirements and evaluation criteria for liquid plasma-facing surface concepts in divertor applications
  - Conceptual design and analysis of candidate concepts; selection of most promising concepts
  - Identification of generic experimental research that could be conducted in parallel with design activities
  - Detailed design and evaluation of the most promising concepts; identification of feasibility issues and assessment of overall attractiveness
  - Description of R&D required to resolve feasibility issues of the most promising concepts
- The group should consider opportunities for international collaborations and make recommendations accordingly.

Over the past three months, the ALPS group has worked together closely to identify the key issues and development needs for liquid plasma facing systems and to develop a comprehensive plan for the Evaluation Phase.

2. TECHNICAL ISSUES TO BE ADDRESSED

The challenge of the program will be to develop systems with the advantages described above and at the same time resolve the key technical issues. These issues are briefly described.

- Sputtering and Redeposition While a large data base exists for the sputtering of solid plasma-facing materials, less is known about the sputter erosion of liquid surfaces exposed to the particle fluxes and energies expected in the divertor. Of immediate need is the assessment of sputtering yields at liquid surfaces by hydrogen, helium, and self-sputtering. Such data are needed to validate models, originally developed for solid surfaces, which calculate material transport (erosion/deposition) in the divertor. Some effects may occur in liquids that are attenuated or absent in the solid phase. Possibilities include the emission of clusters or droplets, enhanced evaporation, and rapid segregation to the liquid surface of bulk impurities or alloying components. The degree to which these effects occur and whether or not these processes can lead to unacceptably high erosion rates or impurity release rates need to be evaluated within the initial three years of the ALPS project.
- Instabilities arising from plasma/liquid interactions (particularly disruptions) Plasma effects on liquid metal surface will need to be evaluated. These include: 1. pulse divertor thermal and momentum inputs, e.g. ELMs, edge MHD instabilities, and disruptions that may cause instabilities in the liquid metal surface, 2. steady divertor momentum (plasma wind) may cause instabilities in the liquid metal surface shape (analogous to ocean waves), and 3. Electrical currents that can be generated on the liquid surface may be another cause of liquid surface instability. These will have to be studied.
- DT/He Transport The rate of D, T and He uptake by a liquid surface in the plasma operation environment needs evaluation. As an example, lithium has an exothermic heat of solution for hydrogen isotopes and forms a hydride under certain temperature - pressure regimes. Therefore lithium will absorb tritium due to plasma-material interactions and from the neutral gas pressure, but the magnitude of the effect is not known. R&D needs to be conducted on tritium interaction with candidate liquids.

- MHD Behavior of Liquid Metal Free Surfaces For concepts with liquid metal (in a strong magnetic field), liquid metal magnetohydrodynamic (LMMHD) effects can control the flow and drastically alter the heat transport. The primary effects are (1) the suppression of turbulence that would more rapidly distribute heat throughout the bulk of the flowing liquid metal in the absence of a magnetic field, (2) increased pressure to drive flow, (3) large effect on velocity profiles which could result in hot spots due to decreased heat transfer in specific areas. Designing reasonable experiments to measure this capability is challenging and will require thoughtful development, and in particular, modeling of and experiments on LMMHD effects. Although an understanding of the integrated LMMHD and heat transport effects are desired, it will be necessary and useful initially to include some analysis and testing of their separate effects.
- Insulator Coating Development It is probable that self-healing insulator coatings will be required in order to utilize a quickly flowing (self-cooled) liquid metal (LM) as the working surface in an ALPS concept. The coating will be necessary in supply and drainage lines in order to reduce pressure drop to an acceptable engineering level [2]. In addition, for films, a coating or non-conducting material liner will likely be necessary to produce thin, fast equilibrium film flows desirable for high heat removal at relatively low flowrates [3].
- Impurity Transport Based on experimental results it is assumed that a fraction of the liquid surface material released through sputtering, evaporation and other processes will migrate as impurity to the core plasma. This leads to fuel dilution, a reduction in reactivity and increase of line and continuum radiation, and high enough impurity levels, the plasma cannot be sustained. The limits of candidate liquid impurities in the scrape-off and plasma core need to be established. Once the acceptable concentration of impurity in the plasma core has been determined and a sputtering database has been established, the physics of impurity transport, ionization and entrainment in the core, scrape-off-layer (SOL) and divertor need to be understood to predict the possibility of achieving the operating fraction with different liquid surface materials.
- Power Density Limits Heat transfer in these systems depends on a number of interrelated areas including MHD effects on flow, allowable temperature limits of the candidate liquids, structural material temperature limits, material thermophysical properties, etc. Both modeling and experiments to determine heat flux limits will need to be performed.
- Materials Activation To accurately assess waste management (including disposal and recycling/reuse potential) and accident safety of a particular concept, appropriate activation cross section libraries and dose conversion factors must be known. Both waste management and accident safety are important factors in the

evaluation of a candidate concept because of the importance of the safety and environmental attributes of fusion. Impurities tend to affect waste management issues, while the base material tends to be more important in accident safety.

- Accident Consequences and Mitigation There is the potential for accidents when the liquids are directly exposed in the plasma chamber. The types of accidents that can occur need to be examined, and ways of reducing the consequences to acceptable levels need to be identified.
- DT Pumping and Fueling The liquid surface can act as an effective pump for DT and He particles, which will affect the DT throughput rates and may lead to greater demands on the tritium separation systems and the fueling system.

3. OVERVIEW OF SCHEDULE

There are three main parts of the program - Concept Evaluation, Plasma Physics/PMI, and Engineering - as shown in the attached Figure. These three areas are closely integrated throughout the program.

The early stages of the program will emphasize concept evaluation. Concept evaluation begins with a scoping phase that includes the definition of design criteria, selection of different concepts and materials to be included in the evaluation, identification of the level of detail that is required to perform a meaningful evaluation, definition of the plasma parameters to be used in the evaluation, and initial definition of generic R&D needs. The different phases of the concept evaluation are expected to overlap to some degree, and the bulk of the evaluation effort is expected to be completed by the end of the Evaluation Phase in 2000. The design criteria are needed at an early stage so that all concepts can be later compared on the same basis and advantages and disadvantages can be clearly specified. In addition to the other activities, a comprehensive materials database will be organized, and the database will continue to be updated during the entire program. The evaluation of all concepts will make use of this central materials database.

Concept comparison will begin in mid-1998 and continue for approximately one year. All concepts selected for review in the scoping phase will be analyzed to the same degree in several key areas to address feasibility and attractiveness. At the end of this phase, one or two lead concepts will be selected for more detailed design. The detailed design activity is necessary to investigate overall system response and to address system interface issues. This work is a prelude to ultimately performing design specific experiments towards the end of the Evaluation Phase and during the R&D phase. Finally, new concepts may be identified through this work, and they would be evaluated in the latter stages of the work.

Plasma Physics/PMI includes investigation of the physics of the scrape-off layer, impurity transport into the core plasma, erosion/redeposition, disruption effects, and surface recombination and release. This area is divided into a modeling effort and an R&D effort. The modeling represents to main interface with the concept evaluation. The response of the candidate concepts will be modeled using state of the art codes, and these codes will be validated improved through the R&D portion of the program. The evaluation effort will also identify those R&D areas where data is required to complete the evaluation and to identify key feasibility issues that need to be addressed through near term R&D. Both the modeling and the R&D are expected to continue beyond the Evaluation Phase.

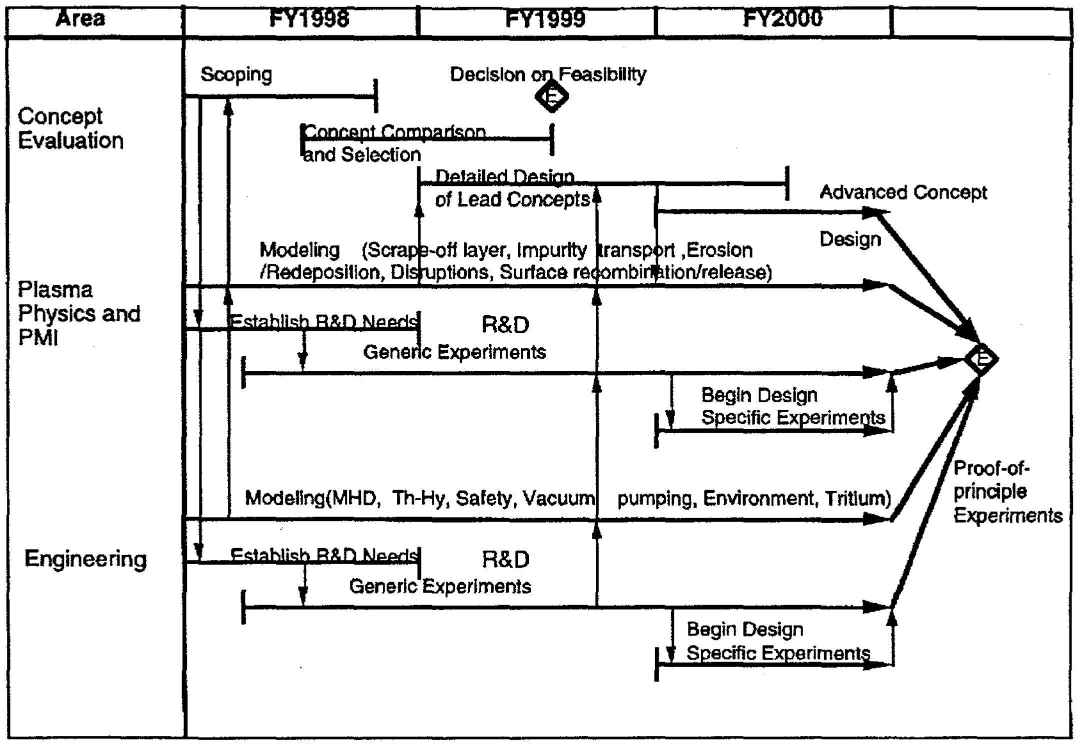
The Engineering area includes MHD effects on the flow behavior of liquid metals, thermalhydraulics behavior, safety and environmental issues, insulator coating development, materials compatibility and corrosion, vacuum pumping, and tritium behavior and system development. This area, like the Plasma Physics/PMI area, is divided into a modeling effort and an R&D effort. The overall approach to the modeling and R&D is similar to that given above for Physics/PMI.

At the end of the Evaluation Phase, a decision will be made whether to proceed to proof-of-principle testing. In order to proceed the concept evaluation should lead to one or more concepts that exhibit no insurmountable technological barriers and continue to demonstrate advantages over conventional systems. To the degree possible key feasibility issues should be resolved through the modeling and R&D efforts.

4. CONCLUSIONS

- Free surface liquid, plasma facing systems offer several potential advantages over conventional systems for use in advanced fusion power reactors.
- The evaluation of free surface concepts will begin in October, 1997 and continue for approximately three years.
- Near term work will emphasize concept evaluation, modeling, and generic R&D.
- People from a number of major US institutions will be participating in the program.

Evaluation Phase Schedule
Free Surface Liquid Plasma Facing Systems



The author gratefully acknowledges the contributions of members of the ALPS planning group. They are Bob Bastasz (SNL), Jeff Brooks (ANL), Stan Luckhardt (UCSD), Yoshi Hirooka (UCSD), Kathy McCarthy (INEEL), Peter Mioduszewski (ORNL), Ralph Moir (LLNL),Neil Morley (UCLA), Richard Nygren (SNL), Dai Kai Sze (ANL), Mark Tillack (UCSD), Mike Ulrickson (SNL), Ken Wilson (SNL), Bob Woolley (PPPL), and Clement Wong (GA).

REFERENCE

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