

# U.S. Assessment of Advanced Limiter-divertor Plasma-facing Systems (ALPS) - Design, Analysis, and R&D Needs

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## Abstract

The purpose of the ALPS program is to identify and evaluate advanced limiter/divertor systems that will enhance the attractiveness of fusion power. The highest priority goals at present are achieving high power density, up to 50 MW/m<sup>2</sup>, and showing compatibility of plasma-facing surfaces with plasma operation. Personnel representing a wide range of disciplines from a number of institutions are engaged in the program, where an evaluation phase of the program is planned for three years. Successful identification of promising concepts in the evaluation phase should lead to an R&D phase that includes proof-of-principle experiments.

## 1. Introduction

The Advanced Limiter-divertor Plasma-facing Systems (ALPS) program began in FY 1998 to evaluate the potential for improved performance and lifetime for plasma-facing systems. At the request of the Office of Fusion Energy Sciences (OFES), an ALPS planning group report was prepared in October 1997 (1), which described the issues, approach, and proposed schedule for the three year evaluation phase. Since that time, the ALPS team has worked together to address key issues through analysis and experimentation, to establish procedures for evaluation of different concepts, and to establish closer ties with the fusion plasma physics community as well as other areas of advanced technology development.

The main goal of the program is to demonstrate the advantages of advanced limiter/divertor systems over conventional systems in terms of

power density capability, component lifetime, and power conversion efficiency, while providing for safe operation and minimizing impurity concerns for the plasma. An initial set of performance goals is shown in Table 1. The minimum goals are those required for systems to be included in the evaluation, and the grand challenge represent goals that would greatly enhance the attractiveness of fusion power. The highest priority goals at present are achieving high power density, up to 50 MW/m<sup>2</sup>, and showing compatibility of plasma-facing surfaces with plasma operation.

Systems being considered include both free surface liquids and advanced solid plasma facing systems. Solid plasma-facing systems were only recently added to the ALPS program, so most of the work to date has focussed on free surface liquid systems. The technical information given below is limited to free surface liquid systems.

The fusion confinement systems being considered are the tokamak, including advanced tokamak configurations, and innovative confinement concepts such as the Field Reversed Configuration (FRC).

## 2. Limiter/Divertor Options

The idea of using liquids for plasma facing components goes back over twenty years [2,3] and, since then, most of the effort to examine these systems has focused on divertors in tokamaks. The liquid options can be divided into

two major classes - concepts with film flow over solid surfaces and concepts with droplets or waterfalls. Film flow concepts are further classified by the speed of flow and by the choice of liquid and backing materials. Droplet concepts are further classified by the droplet size, the method of droplet formation, and the choice of liquid and backing materials. The range of options to be considered is presented in Table 2, which shows the liquids, configurations, and confinement schemes under consideration.

**Table 1. Performance Goals for Attractive Fusion Energy Systems**

Attribute	Minimum Goal	Grand Challenge
Peak / Average Neutron Wall Load (MW/m <sup>2</sup> )	6 / 3	20 / 10
Peak / Average Heat Flux (MW/m <sup>2</sup> )	5 / 2	50 / 20
First Wall Fluence Lifetime (MW-y/m <sup>2</sup> )	10	20
Erosion Lifetime (y)	2	
Coolant Inlet/Outlet Temperature (°C) (goal of 45% conversion efficiency)	250/500	250/1000
Time to Repair/Replace	< 1 month	< 1 week
Average Cost of Core Materials (\$/kg)	100	<50
Waste Disposal Limit	Class C Major Components	Class C All Components
Worst-Case Accident Dose at Site Boundary	1 rem	0.1 rem

**Table 2. Possible Materials, Configuration, and Confinement Options**

<b>Liquid species</b>	Li, FLiBe, Ga
<b>Surface configuration</b>	Fast film, droplets, waterfall, stagnant film, pool, backside impinging jet
<b>Confinement Options</b>	Tokamak, Advanced Tokamak, Spherical Torus, Field Reversed Configuration, Stellarator

## 3. Key Issues

There are a number of key questions that are being addressed in the ALPS program.

- What is the heat flux and power density limits for free-surface liquid systems? Power density limits are influenced by the maximum allowable surface temperature,

which is likely set by the evaporation limits, solid/liquid interface temperature limit, which is likely set by corrosion/impurity considerations, MHD effects on liquid flow profiles, and the thermophysical properties of the candidate liquids. Another important issue for liquid metal systems is the development of

insulator coatings to reduce the MHD pressure drop in heat transfer systems.

- What are the maximum allowable evaporation/sputtering rates for liquids that still ensure stable plasma operation? The allowable evaporation/sputtering rate is greatly influenced by the interaction of evaporated/sputtered particles with the sheath and plasma scrape-off layer (SOL). Particles can enter the SOL where they can possibly become ionized. They can then enter the plasma core, or be swept along field lines into the divertor. In multi-element liquids, e.g. FLiBe or liquid metals with impurities, minor constituents may segregate to the surface and alter the evaporation/sputtering behavior.
- How will the liquid free-surface systems alter the plasma edge conditions? DT and He particles striking a moving liquid surface may become trapped and be removed from the plasma chamber and not recycled in the plasma edge. It is possible that these conditions will lead to low edge density, high particle energy conditions, which are substantially different than those encountered in present devices. The fact that trapped particles are removed from the plasma chamber by the liquid flow means that the liquid surface can act like a pump for the particles. This effect, if properly exploited, may reduce the need for large vacuum pumps.
- How stable is the liquid surface during normal and off-normal conditions? The surface stability of a large area of liquid can be influenced by several effects including the force of the plasma wind striking the surface, the velocity of flow, gravitational effects, MHD forces, etc.
- How will the liquid free-surface affect other fusion systems? The limiter/divertor system interacts with other components including the first wall/blanket, the vacuum system, the tritium recovery and separation system, the fuelling systems, and the cooling and heat exchange systems.
- What effect will the liquid surface have on tritium recycling and inventory? The possible removal of DT particles by a flowing liquid surface would likely result in a decreased tritium inventory in the plasma vessel, but it could significantly increase the requirements on the tritium processing system and increase the required rate of refueling.

#### 4. Vapor Pressure Considerations

The possible loss of material from liquid surfaces due to vaporization is a key concern for plasma operation. The vaporized particles can possibly make their way into the plasma edge or core and degrade plasma performance. The permissible level of impurities in the plasma depends sensitively on the atomic number. The amount of material that enters the plasma core depends on both the rate of vaporization and the effectiveness of the sheath and SOL to prevent penetration. The rate of vaporization with temperature is well known for candidate liquids, and is illustrated in Fig. 1 (4,5).

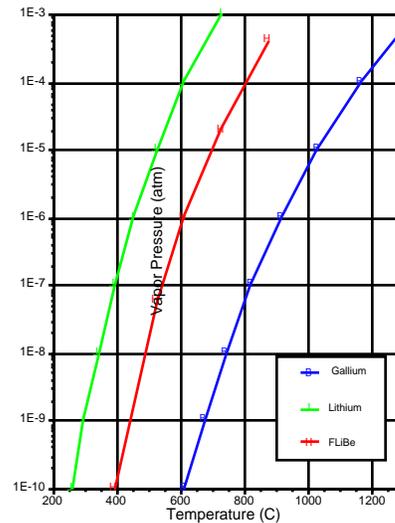


Figure 1. Vapor pressure of gallium, lithium, and FLiBe

The vapor pressure of Li is the highest of the candidates while the vapor pressure of gallium is the lowest. If all of the vaporized material enters the plasma, the allowable surface temperatures would be severely limited. The effectiveness of the plasma scrape-off in preventing the influx of vaporized material is not well understood, however, and there is an ongoing activity in ALPS to address this issue. Initially, existing computer codes for tokamaks will be used to analyze the plasma edge, and it is proposed that tokamak experiments be conducted to validate the models.

#### 5. Sputtering Considerations

For liquids at low temperatures and for solids, sputtering becomes the dominant erosion mechanism. 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 the hydrogen isotopes, helium, and self-sputtering. In the case of Li self-sputtering at oblique angles of incidence, yields greater than unity are calculated for bombardment energies extending below 100 eV. Experimental measurements of Li self-sputtering are being planned to confirm this. 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 or impurity release rates will be evaluated as part of the ALPS program.

## 6. Tritium Recycle Considerations

A flowing liquid surface can potentially trap impinging particles and remove them from the plasma chamber. In contrast, a solid surface can trap impinging particles until the trapping sites become saturated, at which point particles are released at the same rate as they strike the surface. The main concern with solid surfaces is the total inventory of tritium that can build up prior to reaching saturation. Tritium inventory is expected to remain low in flowing liquid surfaces, since the flowing liquid is continuously recycled and processed. The level of tritium being recycled, however, may reach high enough levels that the tritium processing systems and fuelling systems are affected.

As an example, liquid lithium is known to have an affinity for hydrogen isotopes. Lithium has an exothermic heat of solution for hydrogen, and it is a hydride former. Lithium exposed to a flux of hydrogen particles may be converted into a combination of liquid lithium, liquid lithium with dissolved hydrogen, and liquid lithium with lithium hydride. The phase diagram for Li-LiH is shown in Figure 2 (6). The different phases that are present in a fusion system will depend on the impinging particle flux, the temperature of the lithium surface, the diffusion rate of hydrogen in liquid lithium, the time of exposure to the particle flux, and the recombination and release rate of hydrogen particles from the surface. There are uncertainties in the hydrogen behavior in several areas, but an initial assessment for typical fusion conditions indicates that 1) nearly all

incident DT particles will be trapped by the lithium, and 2) lithium hydride formation is unlikely, i.e., the trapped hydrogen is expected to be in the form of a Li-H solid in solution.

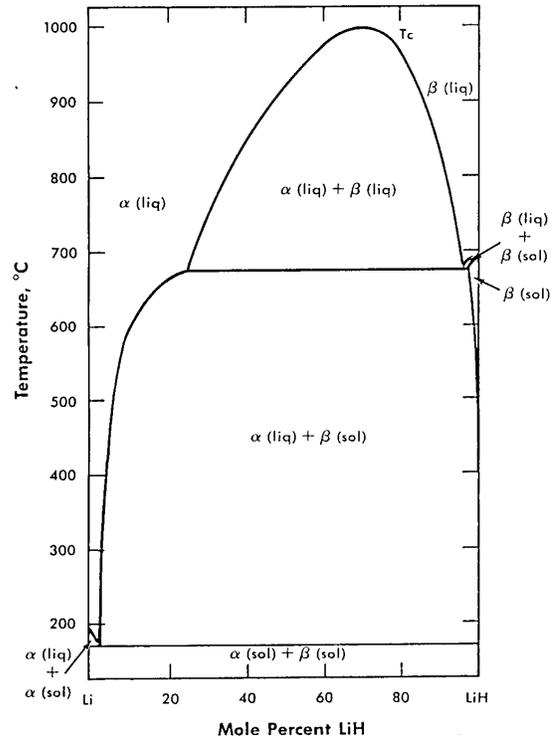


Figure 2. Li-LiH phase diagram (6)

The amount of tritium removed can be estimated using the assumption that all impinging DT particles are trapped in the lithium surface. The total number of DT particles in the plasma is approximately  $10^{23}$  (a core average density of  $10^{20}/\text{m}^3$  and a total plasma volume of  $1000 \text{ m}^3$ ). If the particle confinement time is 5 seconds, then the number of DT particles lost from the plasma is  $\sim 2 \times 10^{22}/\text{s}$ , all of which is trapped and removed by the lithium. This amount translates to  $\sim 50 \text{ mg/s}$  of tritium that needs to be processed and then recycled back into the plasma through the fuelling system. This level of tritium throughput, although high, is believed to be within acceptable limits for both the tritium processing and fuelling systems. A possible consequence of a high surface trapping efficiency is tendency towards low edge recycling and high particle energies in the scrape-off and divertor plasmas. Other liquids could easily trap less DT than lithium, so that their impact on the tritium processing and fuelling systems should be reduced.

## 7. Heat Transfer Considerations

The candidate liquids can potentially accommodate very high heat loads (8). As an example, the liquid lithium target proposed for the IFMIF neutron source is projected to have a steady state heat load of  $\sim 1000 \text{ MW/m}^2$  (7). This heat load is over a relatively small area of  $200 \text{ cm}^2$ , and there are no magnetic fields that can affect the flow, so it is expected that larger limiter/divertor surfaces will not achieve this high level. The goal for ALPS is to achieve a level of  $50 \text{ MW/m}^2$ .

There are a number of items that influence the heat transfer capability of free-surface liquids in a fusion environment, including flow rate, heat deposition area, flow configuration, magnetic field strength and orientation, and material properties. For liquid metals, MHD effects are expected to dominate heat transfer and to control overall pressure drop. In order to minimize pressure drop, it will also be necessary to incorporate insulator coatings on the coolant duct surfaces due to the high pressure drop associated with bare metal walls. For liquid metals, the effect of MHD is to produce laminar (slug) flow with no turbulence. The heat transfer rate perpendicular to the surface is then set by the thermal diffusivity of the candidate coolant. For high surface heat loads, laminar flow will likely result in a steep temperature gradient through the liquid. Turbulent mixing may be possible in liquid metals, but R&D is required to investigate this possibility. For non-conducting liquids or low electrical conductivity liquids, like FliBe, turbulent mixing is more likely which would aid in heat transfer and reduce peak surface temperatures.

As mentioned above, the vaporization rates will limit the allowable surface temperatures, which will in turn limit allowable heat flux. These temperature limits are not yet established, and they may vary from one plasma configuration to another. At this time, scoping calculations are underway. The top priorities are to perform preliminary liquid flow calculations, heat transfer calculations, and estimates of liquid temperature limits. As specific heat transfer concepts are identified and analyzed, experiments will be performed to establish the power density limits.

## 8. Experimentation

Coupled with the design and analysis of advanced concepts, R&D is planned to either supply data needed for the analysis or to demonstrate component of material behavior. The types of

experiments being considered include plasma/surface experiments using existing laboratory facilities, plasma edge experiments using existing fusion devices, and engineering and technology experiments in existing MHD and heat transfer facilities.

Laboratory experiments can provide measurements of the sputtering yield at the liquid surface by oblique-incidence hydrogen, helium, and the substrate species (self-sputtering yield). Suitable facilities are located at SNL and the University of Illinois. As an example of such a facility, one apparatus at the low-energy ion beam laboratory at SNL/CA, is shown in Figure 3.

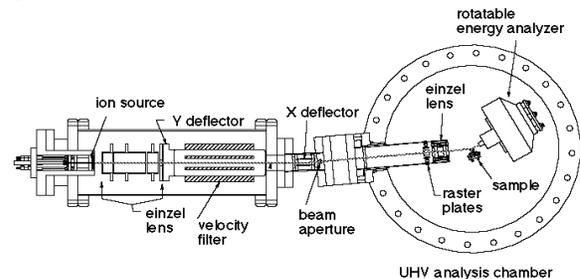


Fig. 3: Diagram of the ion-energy spectrometer located at SNL/CA which can be utilized to determine self-sputtering yields as a function of temperature, angle of incidence, and incident energy.

Integrated tokamak testing of liquid surface material erosion and transport can be performed at the Divertor Material Evaluation System (DiMES) at DIII-D (9). Fig. 4 shows a possible specimen holder configuration for a liquid surface test. The 4.7 cm diameter sample can be inserted and aligned to the surrounding graphite tiles to within 0.25 mm vertical distance and 0.1 degrees horizontal orientation. Erosion rates of solid target materials viz. C, Be, W, V and Mo have already been measured under different plasma operation conditions.

The DiMES samples would consist of thin films of candidate liquids deposited on appropriate substrates. Experiments can be performed in the dedicated mode with control of the DIII-D machine, and the piggy back mode with the requirement of not disturbing the assigned physics experiment. During the three year initial phase of ALPS program, the focus would be on the design of the liquid film sample and the exposure of samples in the study of material erosion and redeposition, material vaporization and ionization.

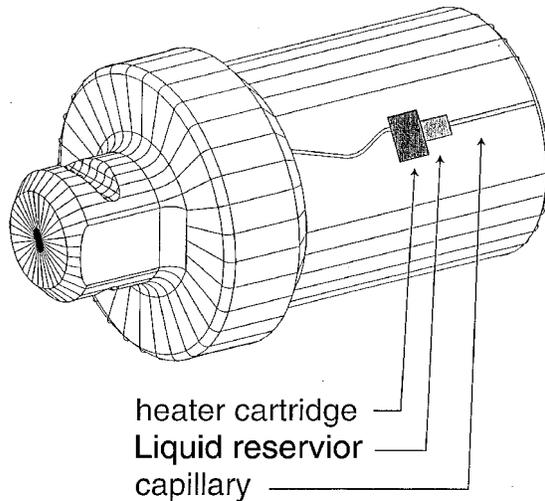


Figure 4. DiMES Test Vehicle for Tests in DIII-D

PISCES at UCSD can be used for laboratory testing of candidate liquid targets and systems on integrated high heat and particle flux testing in the early phase of ALPS. The following experiments can be performed in the initial three year phase of ALPS: 1. plasma experimental testing of candidate liquid target materials including gallium, and possibly lithium using static liquid targets; 2. modify PISCES test source for vertical orientation of plasma onto liquid target and carry out first plasma-liquid target compatibility experiments and characterize erosion/evaporation rates under high plasma flux conditions; 3. complete characterization of plasma boundary phenomena of static liquid target and develop and test dynamic liquid targets, investigate high heat flux and pumping issues; and 4. carryout integrated plasma/boundary tests of dynamic liquid target system, aiming to provide basis for tokamak tests of flowing liquid facing system.

Heat transfer and liquid flow tests can be conducted at facilities at SNL, ANL, and UCLA. The SNL facilities can be used for high heat flux testing, without a magnetic field. The engineering of useful small experiments that combine high heat flux with a magnetic field is by no means straightforward since an impinging heat source must be used with a free surface. Initially, it will be prudent to do some HHF testing without a magnetic field using an e-beam; three cases of interest are (1) heating of droplets, (2) lateral heat transfer in a film with laminar flow and a thermally insulating backing plate,

and (3) heating and circulation in a quasi-static pool.

The ALEX facility at ANL plus the MEGA facility at UCLA can be used to test MHD effects on the flow of liquid metals. The flow configurations of interest are droplets, jets, and flowing films. Coupled with these experiments, 3D MHD modeling of the liquid flows is required and should begin early in the evaluation phase.

Existing facilities can provide key data used in development of codes for safety analyses. These codes are extremely important for analysis of designs under development to ensure that safety is incorporated into design. For example, facilities at the University of Wisconsin exist for testing the chemical reactivity of liquids (liquid metals, organic coolants, etc.), and facilities exist at the INEEL for testing the chemical reactivity and volatility of solids

## 9. Schedule

The ALPS program consists of 3 sequential phases: a planning phase, already completed; an evaluation phase, beginning in FY 1998 and lasting for about 3 years; and an R&D phase, beginning after the evaluation phase. The exact nature of the R&D phase depends on the results of the evaluations phase, and it is expected to include design specific experiments leading to proof-of-principle R&D for one or more systems identified during the evaluation phase.

The general approach to evaluation advanced limiter/divertor concepts is shown in Figure 5. There are two major steps envisioned in the evaluation process; 1) an initial evaluation phase, and 2) a detailed evaluation phase. Initial evaluation begins with a scoping effort that includes the definition of screening 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 design of each concept will be developed to the point where performance parameters can be scoped out, key issues can be identified, and required types of analyses can be identified. The initial evaluation will begin in mid-1998 and continue for approximately one year.

At the end of this phase, several lead concepts will be selected for more detailed evaluation. The detailed evaluation activity is necessary to

investigate overall system response and to address system interface issues. Experts on the team will make use of state-of-the-art models and codes to examine the key issues and to help determine the viability and advantages of each concept. During this time, results of near term R&D initiated during the scoping phase could help provide answers to important questions on performance. This work is a prelude to ultimately conducting more design specific experiments towards the end of the Evaluation Phase and during the R&D phase.

performance. Personnel representing a wide range of disciplines from a number of institutions are engaged in the program. Coupled with the concept evaluations are experimental programs which will address generic critical issues and which will supply data needed to complete the evaluations. Successful identification of promising concepts should lead to an R&D phase that includes proof-of-principle experiments.

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## ALPS Concept Evaluation Process

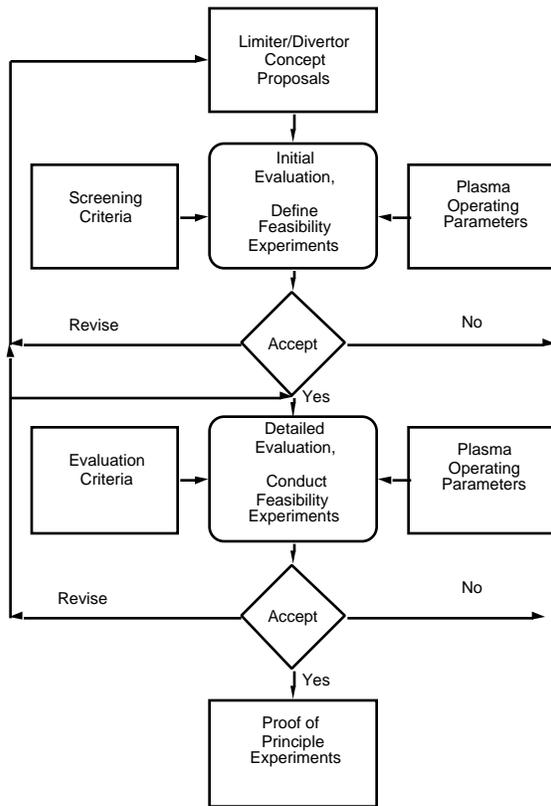


Figure 5. Flowchart of ALPS Concept Evaluation Process

## 10. Conclusions

The ALPS program is in the early stages of the planned three-year evaluation phase. Advanced limiter-divertor concepts are now being identified, and they will then be evaluated to determine their potential for enhancing fusion power