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C.P.C. WONG reporting for SAM BERK,[†] M. ABDOU,[‡] R. MATTAS,[◊]
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APEX and ALPS, High Power Density Technology Programs in the U.S.*

Clement Wong† reporting for Sam Berk,‡ M. Abdou,# R. Mattas,+ and the APEX and ALPS teams

Abstract

In fiscal year (FY) 1998 two new fusion technology programs were initiated in the United States, with the goal of making marked progress in the scientific understanding of technologies and materials required to withstand high plasma heat flux and neutron wall loads. APEX is exploring new and "revolutionary" concepts that can provide the capability to extract heat efficiently from a system with high neutron and surface heat loads while satisfying all the fusion power technology requirements and achieving maximum reliability, maintainability, safety, and environmental acceptability. ALPS program is evaluating advanced concepts including liquid surface limiters and divertors on the basis of such factors as their compatibility with fusion plasma, high power density handling capabilities, engineering feasibility, lifetime, safety and R&D requirements. The APEX and ALPS are three-year programs to specify requirements and evaluate criteria for revolutionary approaches in first wall, blanket and high heat flux component applications. Conceptual design and analysis of candidate concepts are being performed with the goal of selecting the most promising first wall, blanket and high heat flux component designs that will provide the technical basis for the initiation of a significant R&D effort beginning in FY2001. These programs are also considering opportunities for international collaborations.

1. INTRODUCTION

Next-step toroidal concepts, such as ITER (at an average neutron wall loading of about 1 MW/m^2), have an average fusion core power density that is over two orders-of-magnitude less than in present-day water cooled fission reactors and a peak-to-average steady state and transient surface heat flux that is over an order-of-magnitude greater than in present-day water cooled fission reactors. These characteristics can lead to significant economic and technological challenges to the design of fusion power plants. Longer-term concepts of an EVOLUTIONARY nature (i.e., based on ferritic steel, vanadium alloy, or silicon carbide composite structural materials) may not be able to handle the average fusion core power densities and peak-to-average heat fluxes needed for competitive economics.

The above observation is in concert with one of the three U.S. Fusion Energy Sciences Program policy goals, which is to develop fusion science, technology, and plasma confinement innovations as the central theme of the domestic program. In response to this policy goal two new fusion technology programs were initiated in the United States, with the intention of making marked progress in the scientific understanding of technologies and materials required to withstand high plasma heat flux and neutron wall loads. The Advanced Power EXtraction program[1] (APEX) and The Advanced Limiter-Plasma-facing Surface[2] (ALPS) programs are created to specify requirements and criteria for and then evaluate revolutionary approaches including liquid plasma-facing surface concepts in first wall, blanket and high heat flux component applications. These programs consist of three sequential phases: a planning phase, already completed in 1997, an evaluation phase, beginning in FY98 and an R&D phase. The

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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. In addition to the tokamak concept, these programs are to extend the experience to evaluate alternate confinement concepts like the Field Reversed Configuration (FRC), the Spherical Torus and Stellerator.

These three-year programs have the participation of a multi-disciplinary team involving several organizations including UCLA (leading the APEX program), ANL (leading the ALPS program), ORNL, SNL, LLNL, GA, UCSD, PPPL, INEL, UI at Urbana and UW at Madison. These programs are also considering opportunities for international collaborations.

2. THE TECHNICAL GOAL AND APPROACH OF APEX

Along these lines, the U.S. Department of Energy, Office of Fusion Energy and Science decided that there should be an element of fusion research that nurtures creativity and innovation toward exploring REVOLUTIONARY power extraction concepts that may be of high technical risk, but have high payoff performance characteristics, such as:

high bulk and surface heat flux handling capability
large design margins
assured fuel self-sufficiency
low failure rates
high thermal efficiency

Focused on the first wall and blanket design, the above form the technical goal of the APEX program. However, research on evolutionary concepts will continue toward proof-of-principle experimentation and determination of performance limits. The proposed research on revolutionary concepts, which will be of more fundamental nature moving toward feasibility assessment, will stimulate the conception of new ideas that utilize fundamentally different approaches and offer order-of-magnitude higher payoffs, even if the development risks appear high.

The APEX deliverables up to the year 2000 are:

Understanding of technological limits and how to extend them
Identification and preliminary design of the most promising innovative concept(s)
Recommendation on R&D requirements, proof-of-principle experiments, and further design conceptualization effort
Provision of new models and data for advanced fusion technology (and advances in engineering science)

3. THE PURPOSE AND GOAL OF ALPS

Complement to the APEX program, the purpose of the ALPS program is to identify and evaluate advanced limiter and divertor systems that will enhance the attractiveness of fusion power systems. The highest priority goals at present are handling high surface heat flux up to 50 MW/m^2, and showing compatibility of plasma-facing surfaces with plasma operation.

The main goal of the program is to demonstrate the advantages of advanced limiter and 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 concept evaluation, and the grand challenge represent goals that would greatly enhance the attractiveness of fusion power.

Table 1. Performance Goals for Attractive Fusion Energy Systems

Attribute	Minimum Goal	Grand Challenge
Peak/Average Neutron Wall Load (MW/m^2)	6/3	20/10
Peak/Average Heat Flux (MW/m^2)	5/2	50/20
First Wall Fluence Lifetime ($MW\text{-}y/m^2$)	10	20
First Wall Erosion Lifetime (y)	2	8
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

4. APPLICATION OF LIQUID PLASMA FACING SURFACES

Following a planning workshop by the U.S. fusion community and OFES to chart the future of the fusion program, the Advanced Technologies and Materials Working Group was formed and elaborated further on the need for the evaluation of REVOLUTIONARY concepts. The following statements were stated on the working group March 1997 draft report:

"Even in a highly funding-limited program, resources should be set aside to continue to explore high payoff innovative concepts with reasonable chance of success. For example, liquid plasma-facing surfaces could radically alter the critical issue of damage erosion and high heat flux removal, even though numerous concerns need to be addressed to establish their feasibility."

4.1. Advantages of Liquid Plasma Facing Surface

The idea to use liquids for plasma facing components goes back over twenty years.[3,4] Some of the possible advantages of using liquid surfaces in divertors, first wall and blanket applications relative to conventional solid surface approaches are: higher surface heat flux and neutron wall load handling capabilities. These capabilities are necessary to exploit advanced plasma modes that allow high power density operation. Additional potential advantages are: continuously renewable surface, which could significantly enhance limiter and divertor lifetime by reducing concerns about surface material sputtering and disruption erosion, and higher temperature operation, which could significantly improve thermal power conversion efficiencies.

4.2. Issues for Free-surface Liquid Systems

Power density limits are influenced by the maximum allowable surface temperature, which is likely set by the evaporation limits of the plasma surface interface material. To understand this material interface limit, a number of fundamentally coupled questions are being addressed in the ALPS program and the results are also applicable to the APEX program:

1. What is the heat flux and power density limits for free-surface liquid systems, and what are the MHD effects on liquid flow profile? The answer to these questions will be different for different materials of interest between lithium, Flibe and Ga.
2. What are the maximum allowable evaporation/sputtering rates for liquids and can still insure scrape-off-layer stability and optimum plasma operation? This will need to be investigated for different advanced plasma confinement regimes.

3. When lithium is used as the liquid material, due to its affinity to hydrogen, a low recycling plasma edge will be formed, how would this edge condition affects plasma confinement, plasma density and temperature distribution and the performance of different current drive options?

These plasma and liquid surface interaction issues are being addressed by the ALPS physics group composed of plasma core and edge modelers, experimentalists and divertor design engineers.

Additional impact on the vacuum system design, tritium fueling, re-cycling, recovery and separation are being addressed.

5. THE APEX CONCEPTS

The APEX program is exploring new and "revolutionary" concepts that can provide the capability to extract heat efficiently from a system with high neutron and surface heat loads while satisfying all the fusion power technology requirements. The approach for APEX is such that new ideas are encouraged from all interested parties. Some of the innovative concepts being evaluated are:

Liquid Wall Concepts: 1. The convective liquid flow first wall (CliFF) concept represents the poloidal downward flow of a relatively thin layer of liquid in a toroidal geometry. Different back structure approaches are being evaluated for the ease of maintenance. 2. The electromagnetically restrained (EMR) first wall blanket concept uses the introduction of a poloidal flow current in the liquid metal to interact with the confinement magnetic field to form the $J \times B$ body force to hold a thick (~1 m) electrically conducting fluid to the chamber wall. The physics of this concept in a toroidal geometry is being modeled. An option with discrete liquid pockets formed by mechanical chambers is also proposed. A 3-D fluid code is being used to evaluate the flow pattern of the fluid pocket concept. 3. A concept with the introduction of liquid surface by impinging jet nozzles is also proposed.

Solid Lithium Oxide Particulate — A free falling solid lithium oxide particulate concept is being considered.

Solid wall concepts: 1. Evaporative Spray Cooled First Wall concept is a pool boiling concept with spraying liquid metal (e.g. Li or K) to cool the first wall, coupled with a liquid metal blanket. This can have the benefit of removing high surface heat flux with low operating internal blanket pressure of about 2 MPa. 2. The He-Cooled Refractory Metal First Wall Blanket concept is an extension of the conventional helium-cooled nested shell design,[5] with the use of high performance refractory alloy. At an allowable temperature of 1400 (°C, an 8 MPa helium-cooled, W-alloy first wall blanket system is being evaluated.

5.1. Supporting Areas

In preparation for the evaluation of different innovative first wall blanket concepts, support areas under the APEX program are: Configurational design, Materials and Data base Evaluation, Fusion Structural Design Criteria, Neutronics, Thermal Hydraulics, Tritium Recovery and Control, Safety Evaluation and Power Conversion system. As an example on the advanced structural evaluation, for the operating temperature limits, it was shown that W-Re, Mo-Re, TZM, Ta-8W-2Hf, Nb-1Zr, and V-4Cr-4Ti alloys have high operating limits and are ranked in the above order. W-Re alloy has the highest maximum allowable limit at 1400°C and the V-4Cr-4Ti alloy has a relatively lower limit of 700°C

6. THE ALPS CONCEPTS

The types of concepts being considered by the ALPS program include both free surface liquids and advanced solid plasma facing systems. 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 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. The range of options to be considered is presented in Table 2, which shows the liquids, configurations, and confinement options under consideration.

Table 2. Possible Materials, Configuration, and Confinement Options

Liquid species	Li, FliBe, Ga
Surface configuration	Fast film, droplets, waterfall, stagnant film, pool, backside impinging jet
Confinement Options	Advanced Tokamak, Spherical Torus, Field Reversed Configuration, Stellerator

6.1. Supporting Experiments

Coupled with the design and analysis of advanced concepts, R&Ds are planned to either supply data needed for the analysis or to demonstrate behavior of material interaction. The types of experiments being considered include plasma/surface experiments to obtain liquid surface sputtering data (e.g. The Low-Energy Ion Beam Facilities (LEIBF) at SNL/CA), existing laboratory facilities to obtain plasma material surface interaction data (e.g. PISCES experiment at UCSD) and integrated tokamak testing (e.g. Divertor Material Exposure System "DiMES" experiment at DIII–D/GA). Heat transfer and liquid flow tests will be conducted at facilities at SNL, ANL, and UCLA.

7. CONCLUSIONS

The APEX and ALPS programs are in the early stages of performing the three-year evaluation. Advanced first wall and blanket concepts and Advanced limiter-divertor concepts are now being identified, and they will then be evaluated to determine their potential for enhancing fusion power performance. Personnel representing a wide range of disciplines from a number of institutions are engaged in the programs. Coupled with the evaluations are experimental programs which will address 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. Advanced concepts evolved from the APEX and ALPS programs that can handle higher neutron wall loading and surface heat flux will enhance the likelihood of fusion to be an economical energy source.

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