Summary of the Third APEX Meeting
May 6-8, 1998
UCLA

Content

I. Introduction

The third APEX meeting was held at UCLA, May 6-8, 1998. A summary of the working sessions, prepared by respective chairmen and the Secretary, is given in Section II. Section III lists the action items agreed upon during the meeting. The milestones of Phase I of the APEX study is given in Section IV. For a concept to be further evaluated within the study, it was agreed that there is minimum information that should be provided about the concept, mainly, the Analysis Information (defined in Table 1, Section V) and Planning and Comparison Information (defined in Table 2, Section VI. The meeting agenda is in given in Section VII and a list of attendees is given in Section VIII. Section IX is reserved for Appendices. The presentations given during the meeting, this summary, and other information can be found on the APEX Web Page http://www.fusion.ucla.edu.

II. Summary of Working Sessions

Summary of Session I Status and Rational
Session Chair: Sam Berk, OFES

S. Berk (OFES) presented the current status of the U.S. Fusion Technology Program (USFTP) in relation to the other elements of the Fusion Energy Sciences. The USFTP heavily focused in FY 1998 on ITER-specific tasks. In FY 1999, a transition to broader scope of activities is envisioned (e.g. reduction in ITER-specific tasks but ITER remains the major element of program, increase in effort on enabling technologies for U.S. plasma experiments such as D-DIII, C-MOD, and worldwide plasma experiments such as JT-60, LHD, JET). Emphasis will also be placed on dual purpose tasks that support both ITER and plasma experiments. In addition, the scope will be broadened with innovative technology initiatives where APEX/ALPS studies fall in.
The total of $50 M in FY 1999 will be devoted to (a) Advanced Design/Analysis (ITER + Development Path and Power Plant Studies) - 34%, (b) Enabling Technologies (ITER-specific

and Dual Purpose + U.S. and Worldwide Plasma Experiments) - 35%, (c) Advanced Materials (Structures and Irradiation Facilities and Non-structural and Systems Interactions) - 15%, (d) Advanced Technologies (Power Handling Innovations + Plasma Support Innovations) - 7%, and (e) Management/Close-out/SBIR - 9%. Berk pointed out that enhanced community role will be emphasized through the Virtual Laboratories that are created in many parts of the U.S. DOE. The USFTP Virtual Laboratory will be fully established by the end of 1998.

M. Abdou (UCLA) gave introductory remarks to serve as the opening/guidance of the APEX meeting. He emphasized the long-term objective of APEX as the development of a *vision* for an attractive product with favorable economics, safety, and environmental impact attributes. The economics is the major challenge that requires high-performance plasma and power extraction technology, low failure rates and short maintenance time, high power multiplication and efficient high temperature energy extraction system for favorable thermal efficiency. Both innovative confinement concept initiative in plasma physics and new initiatives in technology are the two-sided coin for this attractive fusion product.

Based on feedback from the community and for self-consistency in the calculations, Abdou indicated that the reference values for the (peak) neutron wall load (NWL) and the surface heat (SHF) have changed for any proposed concept for high power density (HPD) extraction to be 10 MW/m2 and 2 MW/m2, respectively. Additional measure of very high potential of NWL = 20 MW/m2 and SHF = 4 MW/m2 is encouraged, if feasible. Some of the proposed HPD concepts where either abandoned from last meeting (e.g. Heat pipe, Mist flow) or put on hold during this meeting (Porous Wall). In the later case, recent analysis has indicated that the stress and temperature limits of SiC, for example, could be exceeded based on the current data under high NWL. The consensus of the attendees (discussed during the last day, see action items) is to hold the filtrated porous wall concept for the time being. Other concepts that will be pursued are, the thin Convective thin wall concept, the thick liquid wall (free fall and magnetically restrained) concept, the free fall Li2O Particulates with no structural FW concept, and the helium-cooled solid refractory FW concept. The vaporization concept presented by Malang (FZK) was encouraged to be evaluated in-depth. Abdou emphasized that proposals for new concepts will always be welcome throughout the project. Minimum required information about a proposed concept were discussed in details during the last day of the meeting (See Section IV, V, and VI)

During the session it was agreed that steady state operation in Tokamaks is the reference point Advanced Tokamak , ARIES-RS, general parameters will be adopted in the study. Open systems such FRC/Spheromak will also be considered as an alternative confinement system. Ralph Moir (LLNL) will (or find a physicist to) get configuration and boundary conditions of such systems.

The two stages of the study till October 2000 were defined by Abdou. Stage 1 is for the design idea formulation in which an idea for the design concept is evolved followed by supporting analysis to examine the scientific feasibility of the concept. Mechanical design options should also be explored and resources be defined to assist in continuing (or terminating) a concept. The decision will be based on judgment by Project Management (*Steering Committee*). Accomplishing Stage 2 will be the final product of APEX first 3 years study in which a reasonably detailed analysis and mechanical design of a concept is outlined in more details and ranking of each concept will be based on expert judgment and qualitative evaluation. Participants agreed that the completion of Stage 2 will lead to the start of a full-fledged conceptual design of a reactor based on the winning concepts that are highly ranked. The APEX Schedule and Milestones in the present 3-year study were presented by Abdou and are given in Section IV.

Abdou announced that the next APEX meeting will be held in Albuquerque , New Mexico, July 27-28, 1998. Plasma interface issues and plasma confinement concepts will be held July 29, 1998 followed by the ALPS meeting, scheduled July 30-31, 1998, in the same place.

The importance of improving plasma performance and the strong tie between plasma physics and HPD technology was emphasized by Kotschenreuther (UTXS). He presented several options for high power density plasmas in Tokamaks and in spheromaks/FRC. MHD stability codes were reviewed. As was stressed in Berk's presentation, strong interaction between plasma innovative operational scheme and technology innovations should be maintained during the study.

Announcements and review of last APEX meeting's action items were given by Youssef (APEX Secretary, UCLA) as the last presentation in this session (see Appendix I).

Summary of Session II: Analysis of Promising HPD Concepts for APEX
Session Chairmen: Neil Morley and Mahmoud Youssef, UCLA

This was a long session, which took most of Wednesday and part of Thursday, where analyses on previously proposed high power density concepts, and ideas for some new concepts, were reported. One idea that came out of the session was the fact that concepts that tolerate leaks or soft failures, would be very advantage. Also, concepts that radically reduce the primary stress and neutron damage may result in longer lifetime of components and less hard failure, reducing the need for costly and time consuming blanket replacements. The following summary is organized according to design concept.

Convective Liquid Layer
N. Morley (UCLA) gave a presentation looking at the power balance, hydraulics and vacuum drainage of the thin, fast liquid layer concept with integrated droplet divertor. The issues were explored for both lithium and flibe as working liquid. The following conclusions were made.

(1) A 2 cm thickness turbulent flibe flow at 10 m/s is needed to ensure wall adhesion, while the surface temperature rise should be small due to turbulent mixing. A 2 cm thick laminar-MHD lithium flow at 20 m/s is required to keep the surface temperature rise below 100 K.

(2) At these flow rates the overall bulk temperature rise is ~100 K if the entire flow is recirculated to the blanket region. It is desirable to reduce the flow rates to increase the bulk temperature rise, but the amount of any reduction is limited by (1).

(3) Drain from vacuum of lithium at these flow rates may require long, large pipes due to MHD forces. Flibe drainage by gravity is not seen to be a problem.

More detailed calculations are need to really optimize the flow rates in conjunction with other concerns like drainage and bulk temperature rise. The group expressed concerns that the competing goals of low surface temperature and high exit temperatures may make lithium difficult to apply. The question was raised as to what are the real difficulties with flibe. D.K. Sze suggested that fast flowing flibe might be decomposed by the V x B EMF generated in the semi-conductor.

A. Hadid (Boeing) presented some discussion of different techniques for free surface computation and reviewed Rocketdyne's capabilities in this area. He is working with UCLA to analyze both thick and thin liquid flows.

Thick Liquid Walls

A. Ying (UCLA) presented 2D Navier-Stokes solutions where she shows that free thick liquid jets tend to be dramatically thinned due to the acceleration of gravity. This can be overcome by increasing the velocity of the jets, but then the recirculation power is increased while the bulk temperature rise is decreased. Ideas to combat this thinning were discussed including some structure at the rear of the flow which would tend to slow down the flow and maintain the thickness. Also considered are multiple layer slabs, starting at different vertical heights.

M. Youssef (UCLA) presented the level of radiation damage in the vacuum vessel for the flowing liquid FW concept. In this concept, the thick liquid layer is assumed to be flowing poloidally on the surface of the V.V. whereas the blanket is outside the vacuum boundary behind the V.V. Material combination considered for the liquid wall/blanket are Li/(Li-V4Cr4Ti,80:20) and Flibe/(Flibe-FS,80:20). Because neutron mean free path (MFP) in Li at energies above ~3eV is larger than those in Flibe by as much as an order of magnitude, the damage to the V.V. (expressed in terms of DPA, he-4, and H production rate) as a function of the flowing layer thickness is noticeably larger than in the Flibe case. Consequently, the 10-fold thickness of the Flibe (the thickness needed to reduce a damage index by an order of magnitude) was shown to be ~25-40 cm while it is about twice as much (~54-80 cm) in the Li case The ratio of the he-4/dpa rate for a bare wall is ~11 in the Li system and ~3 in the Flibe system and drops to ~6 and 1.5 at a layer thickness of 50 cm. It was argued that ratios similar to those found in fission reactors can in principle be achieved by increasing the liquid layer thickness and introducing an appropriate shield. In another presentation given by Youssef, he showed that increasing Li-6 enrichment up to 90% could reduce the DPA rate in the V.V. by only ~15% in the 50 cm-thick Flibe case while the impact is larger (~45% reduction) in the Li case for the same layer thickness. Power multiplication decreased in the Flibe case (M=1.13 to M=1.1) and increased in the Li case (M=1.18 to M=1.19). About 30% of the power is deposited in the first 10 cm of the Li layer whereas ~ 45% is deposited in the Flibe layer for natural Li-6 enrichment

In relation to the above, M. Sawan (UW) presented neutronics results for liquid metal protected ICF chamber and extrapolation to thick liquid metal concept. The results presented were based on the several ICF chamber designs (HIBALL, HYLIFE, LIBRA-LiTE, LIBRA-SP) performed in the past decade. The chamber in these designs is protected by a blanket made of flexible INPORT (Inhibited flow PORus Tubes) tubes in which Li17Pb83 (HIBALL) or (Li or Li13Pb83 (LIBRA-LiTE) flows. The structure in these tubes is SiC (HIBALL) or HT-9 (LIBRA-LiTE) with a ratio of 2% (the .packing factor of the tubes is 33%). The variation of chamber structure dpa and he-4 production with liquid metal protection thickness was used to determine the e-fold and 10-fold distance for Li, Li17Pb83, and Flibe. It was shown that the 10-fold thickness of Li, LiPb, and Flibe is ~ 52 cm, 45 cm, and 31 cm for dpa response with natural lithium. The corresponding thickness for he-4 response is 43 cm, 20 cm, and 30 cm. Thinner thickness (by ~ 6 cm for dpa and ~ 2 cm for he-4) is required if Li-6 is enriched to 90%. These 10-fold thickness' are very similar to the values presented by Youssef when the second order corrections due to geometrical and spectral differences in ICF and MCF systems are taken into consideration.

Khater (UW) presented the specific activity and decay heat in the FW/V.V. after 30 FPY operation and 7 MW/m2 wall load in the three Liquid metal/structure options discussed by Youssef, mainly, Li/(Li-V4Cr4Ti), Flibe/(Flibe-FS), and LiPb/(LiPb-SiC.). A comparison of results was shown for the three cases: bare FW, natural Li in the 50 cm-thick liquid layer, and 90%Li-6 enriched layer. It was shown that using a flowing layer of Li results in a factor of three reduction in the activity and decay heat in the vanadium structure of the FW/V.V. and a further an order of magnitude reduction is obtained with enriched Li. These reduction factors of layer inclusion are more than an order of magnitude in the Flibe/(Flibe-FS) and the LiPb/(LiPb-SiC) system, respectively. It was also shown that the Flibe/FS option provide the TFC with the highest shielding protection. If Fetter waste disposal are used, the inclusion of the flowing layer will allow for the disposal of the FW and blanket structure of the three options as low level waste (LLW). However, if the limits of the NRC are applied, the Li/V option is the only one among the three options that is qualified as LLW. Khater showed also that the off-site dose inventory is significantly reduced when the flowing layer is used to protect the FW/blanket. The LiPb/SiC option produced the least off-site dose inventory.

Liquid-Infiltrated Porous Walls

The idea to use porous walls with infiltrated liquid to create a compliant, high thermal conductivity first wall was put on hold. N. Ghoniem (UCLA) presented some calculations (by A. El-Azab, UCLA) that showed that the SiC-Li system could not meet the NWL requirements of APEX due to decreasing strength of the porous material, and the SiC-Li computability temperature limit of ~600 C. The V-Li system also failed to reach the APEX goals for NWL, being limited by the reduced strength of the V alloy. The group raised questions regarding the definition of strength and failure in a porous material. Ralph Moir urged the group to remember the concept of "soft-failure" in a leaky wall system is an important goal, since small cracks do not shut down reactor operation. The idea of using a porous wall, or flexible woven wall, should still be considered for modified concepts of this type as long as the heat is removed in some clever way (e.g. evaporation) that doesn't rely solely on conduction through a thick (~4 mm) wall.

Li_2O Particulate FW/Blanket – APPLE

D.K. Sze (ANL) reviewed the merits and issues associated with the APPLE concept. He presented results of calculations in the following areas.

(1) Tritium in the form of tritiated water molecules will diffuse out of the Particulates in about 100 s after their birth. About 500 g of tritium will be bred each FPD, releasing 2.5 kg of oxygen as well from the Li_2O.

(2) The amount of evaporated material released to the plasma was estimated to be 86 kg/FPD, along with an additional 2.5 kg of oxygen (discussed above). Sputtering was estimated to be of the same order as Be. The total release of this magnitude requires a plasma edge barrier of ~100 to keep core impurities reasonable.

(3) The heat transfer area in the vacuum heat exchanger was estimated to be 30,000 m^2, which is considered reasonable by current standards. There was some debate by the group whether or not the heat transfer was computed in a realistic way. The assumption that every particulate comes into intimate contact with a fin during the passage through the heat exchanger is implicit in the calculation which determines the required surface area. During that contact time, the particulate cools by radiating to the fin.

The group also expressed concerns over the performance and reliability of the radiation cooled baffles necessary to direct the flow of Particulates in the FW.

M. Sawan presented also the neutronics, shielding, and activation analyses for the Li2O particulate concept discussed in this session by Sze. An overall TBR>1.2 is achievable in this concept. A minimum blanket thickness of 40 cm is required for the structure to be a life-time component. However, if rewelding of the V.V. is allowed, the required total blanket/reflector/shield thickness is ~105 cm. It was shown that more than an order of magnitude reduction in decay heat and short term activity is obtained from placing the structure behind the Li2O particulate blanket. Also, using the low activation ferritic steel (ORNL LAFS 9Cr-2WVTa) as permanent structure behind the Li2O particulate blanket can allow for near surface burial of the waste.

Helium Cooled Refractory FW

C. Wong (GA) reviewed again the requirements of FW/Blanket systems and the benefits of He cooled liquid breeder blankets. R. Nygren (SNL) reviewed high heat flux testing needs, and the results of previous solid wall, high heat flux tests at Sandia. The group commented that the state of understanding of conventional solid wall designs is already considerably more advanced than that of radical liquid or flow solid particulate FWs discussed above. Specific calculations and design data on this concept was promised for the next meeting in ABQ.

Evaporative Spray Cooling of the FW

S. Malang (FZK) proposed a new concept based on the previously (see October meeting) advanced ideas of quasi-heat pipe FW and entrained mist cooling of the FW. Malang's idea improves on these concepts by forcing complete liquid coverage of the FW area by pressurized liquid jets emanating from a delivery tube. The liquid (sodium, lithium or potassium) then vaporizes and flows under its own pressure out of the blanket. The concept is inherently high temperature and requires a refractory metal structure. However, high heat conversion efficiency can be achieved. In addition, low first wall pressure reduce the worry concerning creep rupture (allowing thinner structural walls) and low liquid coolant velocities eliminates the need for electrical insulator coatings. M. Tillack (UCSD), N. Morley and R. Mattas (ANL) and B. Nelson (ORNL) volunteered to investigate this concept further.

<u>Summary of Session III: Mechanical Design, Configuration, Reliability, and First Wall Considerations</u>

<u>(Session Co-chairs: S. Malang, B. Nelson)</u>

The purpose of this session was to summarize some of the mechanical design issues associated with the APEX blanket and first wall and present the status of design work to date. The presentation included discussions of the following topics:

- Status of activities for mechanical design and availability group
- General Design Requirements and concept information needed
- First thoughts on flowing liquid concept

Status of activities for mechanical design and availability group The Mechanical Design and Availability Group will assist all design conceptualization groups with the mechanical design and integration of their concept. Specifically, the group has responsibility for:

1. Vacuum boundary concept
2. Mechanical configuration
3. Maintenance approach (innovative ideas to enhance maintainability)
4. Reliability (suggestions for reducing failure rates and for fault-tolerant designs)
5. Minimum wall thickness
6. Fabrication techniques

The group includes Brad Nelson, Paul Goranson, Paul Fogarty, John Haines, Dave Lousteau (ORNL); Mark Tillack (UCSD); Siegfried Malang (FZK); M. Dagher, Alice Ying (UCLA); Don Clemens (Rocketdyne); Igor Sviatoslovsky (UW);

The group is still in the formative stages, and work since the last meeting has been somewhat limited. It was suggested at the January APEX meeting that the ARIES RS serve as a baseline configuration for incorporating the various APEX concepts, so the ARIES RS design was reviewed and CAD files were generated for use with the concept development. Additional CAD files in the PRO-E format were obtained from the ARIES RS group

The general approach for the mechanical design group will be to:

1. Develop requirements, both general and concept-specific
2. Identify generic device configurations (such as advanced tokamak, ST, etc) to use in the development of concepts
3. Produce a strawman design for each concept, including a 3-D layout showing the main features of the concept

The group thought that in addition to an advanced tokamak (ARIES RS), an FRC configuration (to be furnished by Ralph Moir) should be included in the study. The ST was judged to be similar enough to the advanced tokamak that separate studies were not required at this time.

General Design Requirements and Considerations

A list of general design requirements was presented again as shown in Table 1, but with changes and comments included from the January meeting. Dr. Abdou suggested that the peak power loading should be increased from 7 to 10 MW/m^2 and the surface heat flux should be increased from 1.5 to 2 MW/m^2. The group decided that the configuration of penetrations for heating and diagnostics is not known, so a generic 1 m^2 opening should be developed for each concept. It was also noted that the tritium breeding ratio should be 1.3 based on 1-D calculations and 1.2 based on more complex calculations.

General Design Requirements and Assumptions

Function	**Requirement**	**Value/Goal**
Power Extraction	Neutron Wall Load Surface Heat Flux	7 MW/m^2 avg* 10 MW/m^2 peak* 2 MW/m^2*
Tritium Breeding	Self Sufficient	TBR > 1.2 (1.3 for 1-D)
Shielding	Radiation exposure of coils (insulation) Nuclear heating of coils (sc cable) Reweldable confinement boundary	< 1×10^{9} Rad < 1kW/m^3 < 1 appm He
Vacuum	Compatible with plasma - Base partial pressure, non-fuel - Base pressure, fuel (H,D,T)	 < 1×10^{-9} Torr < 1×10^{-7} Torr
Safety	confinement boundaries	2
Plasma Exhaust	Divertor required	to remove helium
Penetrations	Plasma Heating Power Density - NBI - ICH Diagnostics Penetration size	 TBD MW/m^2 TBD MW/ m^2 TBD 1 m^2
Operating Parameters	Pulse Length Number of pulses Disruptions	Steady State > 3,000 TBD
Availability	Maximize total availability	$A_{plant} > .75$ $A_{blanket/FW} > .98$

* Values are minimum goals for steady state operation

As was presented in the January meeting, in order to begin the task of assisting with the mechanical design for specific concepts, some information is needed by the design group. This information includes:

• Device type
  - Point design device (tokamak, stellarator, RFP, etc.)
  - Limitations (will only work for _____)

• Configuration
  - General - 1 m^2 chunk of the FW/blanket
  - Integrated - schematic of system for point design device (e.g., tokamak)

• Size/total power:
  - Point design - GW fusion power for developed concept
  - Limits, if any, on maximum/minimum size/power

• Shielding:
  - power deposition profile
  - thickness required for breeding
  - thickness required to limit coil heating/insulator damage

• Coolant parameters:
  - cooling media (lithium, flibe, helium, solid, combination)
  - flow rate per unit FW area or unit power
  - inlet and outlet temperatures
  - inlet and outlet pressure and pumping method

First thoughts on Flowing Liquid concept
Investigations of the flowing liquid concept have begun, with an attempt to illustrate the location and available space for the various concept features. These features include:

• Film forming device
• Film collecting device
• Concept for starting system
• Concept for providing heating and diagnostic penetrations
• Vacuum pumping concept
• Divertor concept

It was apparent that a double null divertor concept would be difficult for this concept, so a single null configuration was assumed. The liquid is introduced at the top of the machine, split into multiple streams by the “film former”, flows down the walls and out the bottom of the torus through the vacuum pumping duct to a separator and pump. The liquid does not fill the duct, so there is not a limit on duct length to provide sufficient head for gravity flow. Penetrations are provided by placing a deflector in the stream on the outboard side. Some of the issues for this concept include:

- How do you move ~10^5 kg/s of Li in and out of the machine?
- How do you separate the thin and thick flow regimes?
- How do you start the two streams?
- Does stream follow field lines and come off of the inboard wall?
- How do the passive stability currents move the surfaces around?
- How do you accommodate a double null configuration?
- What are the failure modes?

A meeting at UCLA is proposed for the week of June 15 or June 22 to further develop this concept.

Summary of Session IV: Materials Data base and Limits
(Chairman: Richard Nygren)

There were six presentations in the Materials Data Base and Limits Session. The first two scheduled presentations, "Neutron Wall Load Limits for Some Refractory Materials" (El-Azab) and "Assessment of High Temperature Refractory Metals" (Ghoniem) were presented by Nasr Ghoniem. Two NWL limits, one based on stress and the other on temperature, were shown for TZM, Nb-1Zr and T111 assuming a primary stress of 20 MPa, expansion but not bending, bulk heating of 10 W/cm^3 per MW/m^2 neutron wall load and a heat flux of 0.2 MW/m^2. A compendium of physical and mechanical properties of Nb and Nb alloys, Mo and Mo alloys, Ta and Ta alloys, W and W alloys and Re and Re alloys, and Ni bearing alloys were presented along with some data on cost and compatibility with Li and interstitial elements. The following comments were offered. The values used for costs of several of the materials appeared to be inaccurate and much too high (several). The DBTT values may be from reduction of area measurements rather than from Charpy tests (Zinkle). From the standpoint of compatibility with He coolant, the Mo alloys appear to be the best choice (Ghoniem/Zinkle). Corrosion will not limit austenitic SS's at ~600°C (Moir per Devan of ORNL). Transmutation of Ta will lead to much higher W content as the alloy is subjected to irradiation, e.g., W increased from 8% to 25% at end of life in STARFIRE (Mattas).

In "Chemical Compatibility and Radiation Effects Issues in High Temperature Refractory Metals" (Zinkle/Ghoniem), recent activities of the APEX Material Group were summarized. Assessments of irradiated and unirradiated properties of low activation structural materials (V-4Cr-4Ti, Fe-8Cr and SiC/SiC) were completed. Information on oxide dispersion strengthened ferritic and martensitic steels is being compiled. A draft report on Ta-111 (Ta-8W-2Hf) has been completed. Information on chemical compatibility of refractory alloys with liquid metals is being compiled; and a limited database on radiation effects on refractory alloys has been assembled. The following comments were offered. Look at Nb-1Zr in range of 700-1000°C (Ghoniem). Look at Al2O3 coating on Ta (Wong). MRS Symposium a couple of years ago may be helpful resource (Zinkle); but now there are new bonding techniques available (Ghoniem). Devan (ORNL) recommends 304SS with flibe (Moir). We should raise the temperature limit of interest for flibe from 650°C max. to 1000°C (Sze); this action was accepted. Look at total ductility and reduction of area (Mattas). At these high temperatures, tritium will diffuse everywhere (Sze).

In "Impact of Ferromagnetism of Materials on Fusion Reactors Design" (Zinkle/Tillack) presented by Brad Nelson, the main message was that, while there is no absolute ban on use of ferromagnetic materials, there has long been a general concern on their use because of error fields during alignment of the coils and field perturbations during operation. Some analytical work disputes the validity of these concerns. Also, the forces on primary structures on piping is a concern and was evaluated in STARFIRE and MARS. The following comments were offered. There are some good but old calculations but few people have looked in detail (Abdou). Physicists are taught to avoid field errors; we need to make calculations for real designs (Meade).

"Risks from Low Activation Materials" (Kotschenreuther) was an overview of concerns regarding activation associated with fusion reactors. The following comments were offered. The EZCOM analysis presents some real problems now since we know more now but this analysis is well publicized and referenced (McCarthy). We must be careful not to overstate what "low activation" means (Abdou).

In "An Overview of Safety and Environmental Issues for APEX" (McCarthy), safety goals for fusion and lessons learned were reviewed. Among the many lesson, issues and concerns reviewed was the recommendation that stopping neutrons in a small volume, even if it means generating some greater-than-Class-C waste, is preferable to spreading neutrons out through a very large volume. The scope and depth of the ITER EDA safety effort was unprecedented and provides a valuable resource. In the discussion, Kathy McCarthy noted that Japan is formulating disposal guidelines for fusion and looking at (a) reuse, (b) low level and (c) medium level (but not high level). The issue of W mobilization was raised; Kathy intends to do a parametric study. An action item was reported; 20 experiments were done at the University of Wisconsin in which Li at 527°C was introduced into Therminal 66 (organic coolant) at 300°C. There was no real reaction at 300°C and maybe a very slow reaction below 300°C and some decomposition of Therminal at 400°C.

Summary of Session V: Physics Interface
(Chairman, Dale Meade , PPPL)

Mattas (ANL) gave the latest activities in the ALPS project, particularly the summary of last February 1998 meeting, in the area of physics and engineering. In the physics area, he showed that liquid surfaces (e.g. Li) will significantly affect the plasma edge and core performance by increasing confinement, enhancing DT fusion power and radiation losses (by as much as 100% increase) with high-z impurities. Little or no penetration into plasma core by Li is envisioned with minimal effect on electron temperature. There is unresolved (not understood) phenomenon that was observed from experiment. Instead of plasma cooling in response to the additional radiative power losses due to impurity injection, the electron temperature stayed approximately the same while total stored plasma energy increased. Similar results were observed on other Tokamaks (e.g. ISX (ZMODE), TEXTOR (RIMODE)). Topics discussed by Mattas in the physics area were:

(a) Plasma-Materials Interactions: Li will trap essentially all DT particles striking the surface as predicted by the DIFFUSE model (SNL) - He may be trapped - there could be enhanced sputtering of liquid surfaces due to bubble/droplet formation (SPLASH code).

(b) PMI Experiments: DiMES can be used to test ALPS concept (SNL) - PISCES can offer an experimental verification of liquid metal droplet iteraction in plasmas - The SNL facility can be used to test sputtering of liquid and surface segregation effects while the UIUC facility can be used to study sputtering of solid Li.

In the engineering areas, Mattas discussed the ALPS basic issues on what limits heat removal in liquid surface PFCs. This complex question involves disciplines such as heat transfer, thermal hydraulics and surface stability. Liquid metal film flow in magnetic field is also a complex problem since many factors come together to influence heat transfer at the free surface, and all require modeling to assess their relative importance (i.e. unsteady, 3D, free surface, turbulent, MHD flow analysis is required). This applies as well to liquid metal droplet flows in magnetic field. Li vaporization rate from surfaces is another issue discussed. As for the next steps, suggested screening criteria were outlined for the ALPS study. This includes peak/average heat flux in the divertor of 5/2, useful heat thermal efficiency > 20%, safety (tritium inventory < 500 g -use of reduced activation materials), component should withstand neutron fluence > 10 MW-yr/m2 and lifetime-erosion > 2 MW-yr/m2. The concept evaluation will be based on performance in several areas such as plasma scrape-off & core specifications, surface sciences (e.g. sputtering, DT/He trapping/release), heat transfer characteristics (e.g. thermal response, MHD free-surface flow), X-vessel components behavior (e.g. tritium system, heat exchanger), safety (e.g. accident response, waste disposal issue, recycling), and foundation of the data base (e.g. surface properties, solid and liquid bulk properties).

Plasma operation and interface issues were next discussed by Meade (PPPL). These issues were raised during last APEX meeting and were addressed by this time. As for the liquid surface plasma interface, Meade showed that, based on typical scrape-off parameters of TFTR and ARIES (n_e ~ 1013 cm-3, T_e > 10 eV, width w_{es} ~ 10 cm) and Li surface parameters (SHF ~1.5 MW/m2, $T_{surface}$ ~ 500 °C), the idealized screening estimate is more than adequate. This is consistent with the TFTR Li injection experience where ~< 0.1% Li penetration occurred for 25 MW beam heating. As for the question of whether or not the high influx of wall impurities will quench the screening action of the plasma scrape-off, he showed that this issue “looks OK” and should not raise a concern (power input to scrape-off plasma from core ~ 200 MW and power loss from scrape-off due to ionization and radiation ~ 30 MW, using ARIES-RS parameters). Meade indicated that present codes to model the plasma scrape-off of Tokamaks (e.g. EIRENE + B2.5, UEDGE + DEGAS2) could in principle be modified to model the problems at hand in the APEX study to address the screening and dynamics of the scrape-off for liquid walls. He also addressed the merits/disadvantages of rectangular FW as opposed to FW that follow the contours of plasma edge.

Other presentations in this session were given by Kotschenreuther (Reducing Liquid Wall Surface Temperature with Plasma Instability) and Moir (Edge Plasma calculations). In the first presentation, Kotschenreuther indicated that sources of plasma turbulence are important for liquid walls since they could lead to reducing surface temperature and may cause splashing into plasma. Rippling mode is identified as the most important instability for plasma. It is the resistive MHD instability which produces the most turbulence and heat transport. He pointed out that the differences of the liquid walls from plasma case are in the boundary conditions and that surface tension effect should be included in modeling the liquid FW. In the latter presentation, Moir addressed the same issue discussed by Meade, emphasizing the need for plasma modeling using codes such as UEDGE and DEGAS to estimate how much evaporated liquid materials will penetrate through the edge plasma. He showed rough calculations (most of the parameters used need to be checked) for the evaporation rates in Tokamak and Field Revered Configuration (FRC or Spheromak). Moir presented also some chemical kinetics for Flibe. He concluded by addressing the need for cross section information on D, T, He, Li, BeF2, LiF and UEDGE calculations for open and closed field line edge plasmas. He further emphasized the coupling between plasma physics and blanket technology by addressing the need to *examine for each confinement concept* whether or not a thick liquid layer could replace the usual solid FW.

Summary of Session VI: Parallel Group Meetings

The seven groups of APEX study met in the afternoon of Thursday to discuss key feasibility issues pertaining to the scope of each group. These groups are: Evaluation Criteria, Materials, Mechanical Design and Availability, Plasma Interface and Alternate Confinement, Power Conversion, , Safety and Environment, and the Neutronics Group (the latter three groups have been globally termed as the Analysis Group). Reports from these groups were scheduled for presentation Friday morning.

Summary of Session VII: Group Reporting
(Chair: M. Abdou)

The lead person of each group presented a summary of the key issues/action items in his/her group. Summary of reports are given below for some groups:

Materials Group (Zinkle):
(1) Prepare summary on liquid metal compatibility (Li, Pb-Li, Flibe) with structural materials (F/M steels, V alloys, SiC/SiC, Ta, 300SS, Nb, Mo, W).
(2) Prepare a summary on He coolant compatibility.
(3) Complete property assessment reports on Ta, Mo, W alloys.
(4) Prepare mechanical design report (modification of ITER documentation).
(5) Porous materiel properties: general analysis completed by El-Azab, Further reports are put on hold.
(6) Other issues: tritium permeation, impact of insulating coatings (T2 permeation, etc.), joining techniques (friction welding, etc.), updating cost of materials (7/98), and transmutation effects (through the neutronics group)

Power Conversion Group (Sze)
(1) Don’t use binary cycle. Using regenerator HX is always beneficial.

(2) Keep the coolant exit temperature as high as possible.
(3) Keep the coolant ΔT in the range of 200 to 400 °C, if possible.
(4) Keep the coolant inlet temperature > 300 °C.
(5) The group will work with all blanket concepts to develop the power conversion system as the coolant parameters are defined.

Tritium Issues (Sze)
(1)FW tritium permeation.
(2) Tritium concentration in structure materials.
(3) Tritium clean-up, recovery and processing.
(4) Tritium Safety.
(5) Fueling and vacuum.

Neutronics Group (Youssef)
(1) Attenuation characteristics of liquid FW and (solids, e.g. SiC) to surface wall load (Bremsstrahlung and cyclotron radiation). Impact of impurities in plasma.
(2) Heat deposition profiles in LM/solid FW and blanket from neutrons
(3) System power multiplication and percentage of heat deposited in each component.
(4) Tritium breeding ratio (TBR) and tritium production profiles (TPR). Percentage of T bred in each component.
(5) Radiation damage to structural materials : in FW, blanket, TFC, etc
(6) Impact of Li-6 enrichment on TBR, TPR, and damage parameters.
(6) Shielding design
(7) Transmutation effect and radioactivity inventory.
(8) Decay heat assessment.

Summary of Session VII: Resources, Man Power Requirements, and Technical Plans for Design Concept Development and Analysis
(Chair: M. Abdou)

Each concept proponent presented a plan for the concept during the next 12 Month. Summary for each concept is given below. More details can be found on the APEX web site:

Thick Liquid Wall Concepts (A. Ying)
key tasks next 12 months:
(1) Hydrodynamics (free surface flow characteristics and stability
- 1 man (75% from UCLA) on behavior of turbulent liquid jets and films
- 1 man (50% UCLA, 50% Boeing) on behavior of electrically conducting liquid jets
- 0.5 man (UCLA) on liquid jet stability

(2) Heat Transfer
- 0.5 man (30% UCLA) on temperature profiles in liquid jets and film
- 0.5 man (50% UCLA) on identification and characterization of effect of turbulence.

(3) Design and Engineering Configuration (0.5 man)
(4) Supporting analysis
- 0.1 man (neutronics)

- 0.1 man (power conversion)
- 0.1 (man materials)

Convective Liquid Layer Concept (N. Morley)

Analysis needed:

(1) Estimates of allowable FW contamination fluff or LMs and Flibe.

(2) Detailed analysis of film flow behavior including: wall adhesion, film thickness/velocity, wave formation, heat transfer at surface, and evaporation flux from surface.

(3) Analysis of film extraction from vacuum chamber, including possibility of integrated divertor.

(4) Estimates of effects of 3D magnetic field (surface T gradient), temporally and spatially varying magnetic fields, off-normal plasma events.

(5) Thermal hydraulic analysis of system, including feed lines and nozzle, free surface flow, removal from vacuum chamber, recirculation through the blanket, and heat exchanger.

(6) Neutronics analysis with consistent mechanical design.

(Some overlapping analysis with other LM concepts and with ALPS)

Resources

2 man-yr (UCLA) for RIPPLE, MHD tool, thermal hydraulics, neutronics).

0.5 man-yr (Boeing) for MHD tool

0.25 man-yr (ORNL) for mechanical design

0.75 man-yr (ANL/LLNL/PPPL) for disruption and plasma edge modeling

(Total of 3.5 man-yr, about 1.5 man-yr is considered as overlap with other APEX concepts and ALPS)

He-cooled FW/B/Divertor Concept (C. Wong/R. Nygren)

Plan was set from date till Feb. 99. By end of FY98, good idea on how the FW/B/Divertor concept should look and ready to initiate fabrication, reliability, safety, and testing tasks. Tasks fall in the area of evaluation, design/analysis, physics interface, neutronics, safety, fabrication, testing, and compatibility/cleanup/He purification. Design/analysis includes configuration, structural analysis, thermal hydraulics, and stability. Man power requirements are 2 FTE (from GA), 1 FTE +$150 k experiment (from SNL), 0.1-0.2 FTE (from UCLA for neutronics). Support from INEEL (safety) and ORNL (design) is from Task Accounting (TA).

Plans for other concepts will be submitted to APEX management by June 15 (see action items)

Summary of concluding Round-the-Table-Discussion:

In concluding the workshop, a round-the-table discussion was conducted about the important points of concerns raised during the meeting. They are:

(a) Concept evaluation process: The evaluation criteria group is in the process of developing meaningful criteria that emphasize scientific foundations and concept potential for major improvements. Emphasis is on high power density capability, low failure rate, simplicity, and design margin. These criteria are in addition to the usual attributes of economics, safety , and environmental impact. R&D requirements is also an important category. New concepts/ideas will always be welcome. More details on the evaluation process will be discussed in the next meeting.

(b) Concepts present at hand and requirements per concept: Three/four classes of concepts are considered (Porous Walls concept is put on hold). For each concept there are several issues that require should be resolved. The classes of concepts are: (1) Thin and Thick Liquid FW (controlling the trajectory of the liquid is an issue. In the free falling layer, how to get the liquid being formed is an issue), (2) Free falling Li2O Particulates with no solid FW (radiation cooled baffles to direct Li2O Particulates flow and the amount of material evaporation to plasma are concerns), (3) Helium-cooled refractory structural FW and (4) Spray coating FW (who is interested in carrying the evaluation of this concept was tentatively identified after the meeting, namely Malang, Mattas, Tillack, Morley, Wong, Youssef).

Each concept should be presented with supporting analytical results (i.e. each concept should be brought to the same level of analysis to be able to screen among concepts). There was a discussion on what is the minimum information required for each concept's idea to be considered. These requirements should be met before an idea evolves to a concept. Additionally, for planning and comparison purposes, other information are needed such as: crucial issues of the concept to be addressed during the coming 8 months, what are the new models, codes or experiments that are required to investigate these crucial issues, and the needed resources (analysis and experiments) over how long a time are required to investigate these feasibility issues.

Malang (FZK) volunteered to outline the minimum required information for each concept. He distributed this information for comments one week after the workshop. After revisions suggested by some participants (Wong, Sawan, Youssef), these requirements were officially distributed by Abdou along with the milestones for the APEX study. Section VI, V, and VI give the APEX planning milestone, required analysis information and required planning and comparison information, respectively. Abdou requested that the lead person of each concept to submit to APEX management the crucial issues pertaining to the concept to be addressed during the coming 8 months, the new models, codes or experiments that are required to investigate these crucial issues, and the needed resources (analysis and experiments) over specified length of time frame to investigate these feasibility issues.

(c) Formation of a Steering Committee: Abdou suggested a Steering Committee to be formed from people (5-6) who don't have immediate interest in the outcomes from the study and who can best judge, evaluate, and possibly prioritize the proposed concepts based on their expertise and who attend, when possible, all APEX meetings. There was a suggestion (Berk) to have this evaluation/judgment be rendered from within the APEX Planning Group.

III. Action Items

The following action items were agreed upon during the workshop:

(1) The next APEX meeting will be held in Albuquerque , New Mexico, July 27-28, 1998. Plasma interface issues and plasma confinement concepts will be held July 29, 1998 followed by the ALPS meeting, scheduled July 30-31, 1998, in the same place.

(2) The reference values for the (peak) neutron wall load (NWL) and the surface heat (SHF) have changed for any proposed to be 10 MW/m2 and 2 MW/m2, respectively. Additional measure of very high potential of NWL = 20 MW/m2 and SHF = 4 MW/m2 is encouraged, if feasible.

(3) Some of the proposed HPD concepts where either abandoned from last meeting (e.g. Heat pipe, Mist flow) or put on hold during this meeting (Porous Wall). In the latter case, recent analysis has indicated that the stress and temperature limits of SiC, for example, could be exceeded based on the current data under high NWL. The consensus of the attendees was to hold the filtrated porous wall concept for the time being. Other concepts that will be pursued are, the thin Convective thin wall concept, the thick liquid wall (free fall and magnetically restrained) concept, the free fall Li2O Particulates with no structural FW concept, and the helium-cooled solid refractory FW concept. The vaporization concept presented by Malang (FZK) was encouraged to be evaluated in-depth. people who indicated their interest to work on this concept are: Mattas (ANL). Tillack (UCSD), Nelson, Berry (ORNL), Morley, Youssef (UCLA), and Malang (FZK).

(4) Steady state operation in Tokamaks is the reference point. Advanced Tokamak , ARIES-RS, general parameters will be adopted in the study. Open systems such FRC/Spheromak will also be considered as an alternative confinement system. Ralph Moir (LLNL) will (or find a physicist to) get configuration and boundary conditions of such systems. (Suggested person is A. Hoffman, U. Washington). It was a greed to devote time during the next APEX meeting to discuss configuration and parameters of Stellerators (1hr) and FRC (1hr). Meade will look into this arrangement.

(5) Malang (FZK) outlined the minimum required information for each concept. These requirements were officially distributed by Abdou along with the milestones for the APEX study. (see Sections VI, V, and VI). Abdou requested that the lead person of each concept to submit to APEX management by June 15 the crucial issues pertaining to the concept to be addressed during the coming 8 months, the new models, codes or experiments that are required to investigate these crucial issues, and the needed resources (analysis and experiments) over specified length of time to investigate these feasibility issues.

(6) A Steering Committee to be formed from people (5-6) who can best judge, evaluate, and possibly prioritize the proposed concepts based on their expertise and who attend, when possible, all APEX meetings.

Other items are:

(7) Specific calculations and design data on Helium-cooled refractory structural FW concept was promised (Wong) for the next meeting in ABQ.

(8) The configuration of penetrations for heating and diagnostics is not known, so a generic 1 m^2 opening should be developed for each concept.

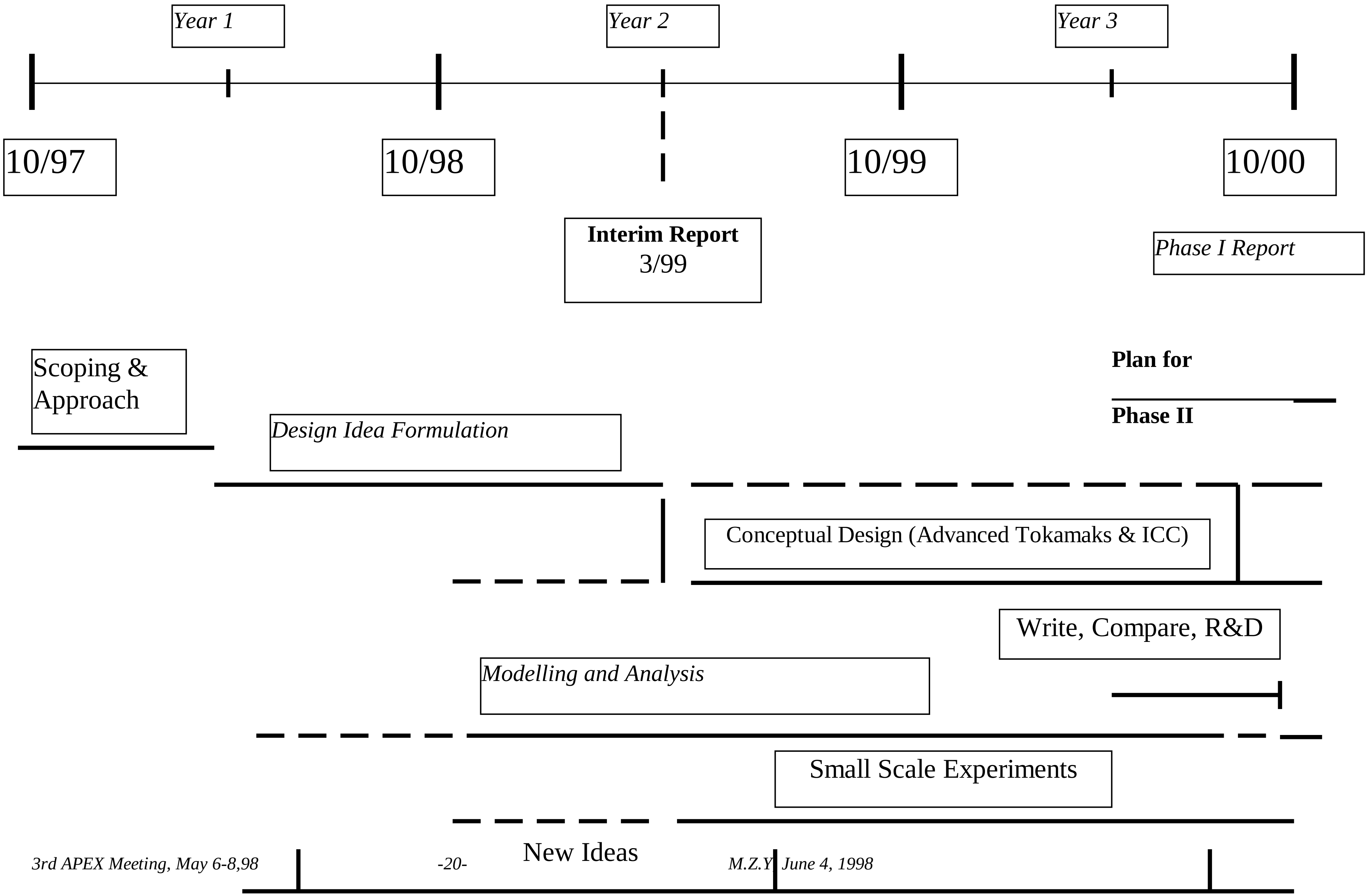
(9) The Mechanical group (Nelson) proposed a meeting at UCLA for the week of June 15 or June 22 to further develop the liquid FW concept.

(10) From the Materials Session, the values used for costs of several of the materials presented by Ghoniem appeared to be inaccurate and much too high (several). He will check these data. Other data to be checked are: Nb-1Zr in range of 700-1000°C (Ghoniem), Al_2O_3 coating on Ta (suggested by Wong), using 304SS with flibe (suggested by Moir). Sze suggested raising the operating temperature limit of interest for from 650°C max. to 1000°C. This action was accepted.

IV. APEX Phase I Milestones

The milestone for the APEX during the 3-years study is outlined in the following Figure presented by Abdou (see summary of Session I)

APEX Schedule and Milestones for Phase I (May ‘98)



V. Requirements for a Concept (Analysis Information)
Table 1
Analysis Information
(Requirements to be met before an idea evolves to a concept)

A) Sketch the geometry of the first wall and blanket components
B) Outline FW/blanket radial build including approximate dimensions
C) Select and present candidate materials for PFC, structure, breeder, and coolant
D) Estimate values of the following parameters, based on a peak neutron wall load of 10 MW/m^2 and first wall surface heat flux of 2 MW/m^2, and a peaking factor of 1.4 for both.

a) Coolant parameters (temperature, pressure) at inlet/outlet of
   - plasma facing surface (liquid FW)
   - FW cooling channel (solid FW)
   - breeding zone

b) Maximum/minimum temperatures of
   - breeder material
   - structural material

c) 1-D maximum primary and total (primary + secondary) stress in the structural material
d) Tritium breeding ratio (1-D calculation)
e) Maximum power density in structure, breeder and coolant material
f) Power multiplication

E) For a typical unit size module, which could be one of the following elements:
(Include the sketch of coolant routing)
- a chunk with a FW surface of $1m^2$
- a cut out of a blanket segment with a poloidal height of 1m
- a sector cut of a segment with full height and a toroidal width of 1m
- a complete outboard segment
- a full sector

estimates for the following parameters have to be provided, assuming the heat loads given under D):
a) total surface heat load
b) total heat load (surface heat load + volumetric heat generation)
c) coolant mass flow rate (either total or for the different zones, depending on the concept)
d) coolant maximum and minimum velocities inside FW and breeding zone
e) coolant inlet and outlet manifold sizes
f) coolant inlet and outlet piping location and sizes
g) coolant pumping power
h) a brief indication of structural support
i) identification of external primary or secondary coolant pumping system

VI. Requirements for a Concept (Planning and Comparison Information)
Table 2
Planning and Comparison Information

(A, B and C are needed by June 15, 1998)

A) What are the crucial issues of the concept to be addressed during the coming 8 months?
B) Which new models, codes or experiments are required to investigate these crucial issues?
C) Which resources (analysis and experiments) over how long a time are required to investigate these hard feasibility issues?

For a first comparison of different concepts, estimates (guesstimates?) should be provided regarding the following issues (first cut by July 27-28 meeting):

D) What is the potential of the concept in regard to the allowable power density and power conversion efficiency?
E) What are the margins of the concept in regard to temperature and stress limits and how do these margins compare to the guesstimated uncertainties in the estimated values?
F) What are the estimated lifetimes of the different elements and what are the limiting factors? (maximum dpa, He-4, and h-production rates)
G) What technology development will be needed or extended for the concept?
H) What are the technical uncertainties of the concept?
I) What are the performance limitations of the concept?
J) What element of the concept has most impact on reliability?

VII. Agenda of the Meeting

Agenda for APEX Study Meeting
UCLA
ACKERMAN, Room 2408
May 6-8, 1998

8:30-9:00 a.m.	Continental Breakfast	

Wednesday, May 6
Session I: Study Status and Rational
(Session Chair: Sam Berk)

9:00 a.m.	Introductory Remarks	Berk
9:10 a.m.	Status and Progress	Abdou
9:35 a.m.	Designs for High Power Density Devices	Kotschenreuther
9:50 a.m.	Secretary's Announcements	Youssef

Session II Analysis of Promising HPD Concepts for APEX
(Session Chair: Neil Morley)

10:00 a.m.	Analyses of Liquid Wall Concepts	Morley

10:30 a.m.	Fluid Stability Issues	Gulec
10:45 a.m.	Analysis and Modeling of Thick Liquid Wall Concept	Ying
11:15 a.m.	Mechanics of Porous Materials and Assessment of Porous FW Concept	El-Azab (Ghoniem)
11:40 a.m.	Structure Damage Rates in Liquid Layer Concepts	Youssef
12:10 p.m.	Free-Surface LM Flow in Tokamaks	Woolley
12:35 p.m.	Lunch	
1:45 p.m.	CFD Development for Free Surface Liquid Flows in APEX	Hadid
2:00 p.m.	The Li2O Particulate Blanket Concept and Power Cycle/ Configuration and Maintenance	Sze
2:30 p.m.	Nuclear Analysis of the Li2O Particulate Concept	Sawan/Khater
3:00 p.m.	He-Cooled FW/Blanket Concepts - Functional Requirement/Critical Issues	Wong
3:30 p.m.	Innovative Vaporization Concepts - Spray Cooling of the First Wall	Malang
4:00 p.m.	Coffee Break	
4:15 p.m.	Issues in FW/Divertor He-Cooled Design for HPD	Ulrickson/ Nygren
4:45 p.m.	Liquid Wall Considerations	Kotschenreuther
5:00 p.m.	Impact of Li-6 Enrichment on Heating and Damage Rates in Structure of Thick LM Concepts	Youssef
5:15 p.m.	Extrapolation of ICF Chamber Neutronics to Thick LM Concept	Sawan
5:40 p.m.	Activation Analysis for Thick LM Concept	Khater
6:00 p.m.	Group Discussion	
6:15 p.m.	Adjourn	

Thursday, May 7

Session III: Mechanical Design, Configuration, Reliability, and First Wall Considerations
(Session Chair: Nelson/Malang)

8:00-8:30 a.m.	Continental Breakfast	
8:30 a.m.	APEX Mechanical Design Considerations	Nelson
9:15 a.m.	Group Discussion	

Session IV: Materials Data Base and Limits
(Session Chair: Richard Nygren)

9:30 a.m.	Neutron Wall Load Limits for Some Refractory Materials	El-Azab (Zinkle)
9:55 a.m.	Properties of High Temperature Refractory Metals	Ghoniem/Zinkle
10:20 a.m.	Coffee Break	
10:35 a.m.	Chemical Compatibility and Radiation Effects Issues in High Temperature Refractory Metals	Zinkle
11:00 a.m.	Impact of Ferromagnetism of Materials on Fusion Reactors Design	Nelson/Zinkle/ Tillack
11:20 a.m.	Risks from Low Activation Materials	Kotschenreuther
11:30 p.m.	An Overview of Safety and Environmental Issues for APEX	McCarthy
12:00 Noon	Group Discussion	
12:30 p.m.	Lunch	

Session V: Physics Interface
(Session Chair: Dale Meade)

- Dependence of Physics Boundary Conditions on Confinement Scheme
- Transient Conditions
- Temperature Limits of Liquids on Plasma-side of FW - Impurity Control and Exhaust Scheme to Relax Limits
- Fraction of alpha Power and Bremsstrahlung Radiated to FW

1:30 p.m.	Summary of Alps Activities	Mattas
2:00 p.m.	Reducing Liquid Wall Surface Temperature with Plasma Instability	Kotschenreuther
2:15 p.m.	Plasma Operation and Interface Issues	Meade

2:45 p.m.	Edge Plasma Calculations	Moir
3:00 p.m.	Group Discussion	
3:45 p.m.	Coffee Break	

Session VI: Parallel Group Meeting

4:00-6:00 p.m.	Evaluation Criteria Group (members: Please stay in the same conference room for the meeting)	(Abdou)
4:00-6:00 p.m.	Materials Group (members: Please Meet in Room 44-139A)	(Zinkle)
4:00-6:00 p.m.	Mechanical Design and Availability Group (members: Please meet in Room Fusion Lab- 4th Floor)	(Nelson)

- *Other Groups (Power Conversion, Plasma Interface and Alternate Confinement, Safety and Environment, and Neutronics: can meet at this time (4:00-6:00 p.m., Rooms available are 37-124 and 43-133) if they have no conflict with other groups, or they can meet early Friday morning, or Friday afternoon)*

6:00 p.m.	Adjourn	
7:15 p.m.	Group Dinner (No-Host)	

Friday, May 8
Session VII: Group Reports
(Session Chair: Mohamed Abdou).

8:00-8:30 a.m. Continental Breakfast

8:30 a.m. - Evaluation Criteria Group
- Materials Group
- Mechanical Design and Availability Group
-Power Conversion Group
- Plasma Interface and Alternate Confinement Group
- Safety and Environment Group
- Neutronics

9:40 a.m.	Impression from ICC Workshop	Moir/Meade Morley/Nygren
9:55 a.m.	Plans for Joint APEX - Plasma Confinement in Summer	Moir/Meade/ Abdou

Session VIII: Resources, Man Power Requirements, and Technical Plans for Design Concept Development and Analysis
(Session Chair: Mohamed Abdou)

10:05 a.m.	- Li2O Particulate Concept	Sze
10:15 a.m.	- Thick Liquid Metal Concept	Ying
10:25 a.m.	- Thin Liquid Metal Concept	Morley
10:35 a.m.	- He-Cooled Concept	Wong/Nygren
10:45 a.m.	- Porous/Foam Wall Concept	Ghoniem/Azab
10:50 a.m.	- LM Thick Free Flow	Woolley
11:00 a.m.	- Other Concepts	Malang, Others ..

11:10 -Noon   Discussion, Action Items, and Plan for Next Meeting

12:00 p.m.   Close of the Meeting

VIII. List of Attendees

UCLA - APEX Planning Group Contact Information

Name	Office Phone	Facsimile	E-mail
Mohamed Abdou	(310) 206-0501	(310) 825-2599	abdou@fusion.ucla.edu
Mohamad Dagher	(310) 787-7097	(310) 787-7099	mdagher@engineer.com
Anter El-Azab*	(310) 825-7421	(310) 825-2599	anter@seas.ucla.edu
Nasr Ghoniem	(310) 825-4866	(310) 206-4830	ghoniem@seas.ucla.edu
Karani Gulec	(310) 206-7726	(310) 825-2599	karani@fusion.ucla.edu
Neil Morley	(310) 206-1230	(310) 825-2599	morley@fusion.ucla.edu
Tetsuya Uchimoto	(310) 794-5354	(310) 825-2599	tetsuya@fusion.ucla.edu
Alice Ying	(310) 206-8815	(310) 825-2599	ying@fusion.ucla.edu
Mahmoud Youssef (Group's Secretary)	(310) 825-2879	(310) 825-2599	youssef@fusion.ucla.edu

* Did not Attend Meeting

APEX Planning Group Contact Information

Charles Baker* (UCSD)	(619) 534-5260	(619) 534-5440	cbaker@iter.ucsd.edu
Sam Berk (Monitor, OFES)	(301) 903-4171	(301) 903-1233	sam.berk@mailgw.er.doe.gov berk@er.doe.gov
Lee Berry (ORNL)	(423) 574-0998	(423) 576-7926	berryla@ornl.gov
Don Clemens (RIC)	(818) 586-1433		donald.d.clemens@boeing.com
Ali Hadid (Boeing)	(818) 586-0385	(818) 586-0588	ali.hadid@west.boeing.com
John Haines* (ORNL)	(423) 574-0966	(423) 576-7926	hainesjr@ornl.gov
Ahmed Hassanein* (ANL)	(630) 252-5889	(630) 252-5287	hassanein@anl.gov
Hesham Khater (UWIS)	(608) 263-2167	(608) 263-4499	khater@engr.wisc.edu
Mike Kotschenreuther (UTXS)	(512) 471-4367	(512) 471-6715	mtk@pauling.ph.utexas.edu
Siegfried Malang (FZK)	49-7247-82-4101	49-7247-82-4837	malang@iatf.fzk.de
Rich Mattas (ANL)	(630) 252-8673	(630) 252-5287	mattas@anl.gov
Kathy McCarthy (INEL)	(208) 526-9392	(208) 526-0528	km3@inel.gov
Dale Meade (PPPL)	(609) 243-3301	(609) 243-2749	dmeade@pppl.gov
Ralph Moir (LLNL)	(510) 422-9808	(510) 424-6401	moir@llnl.gov
Brad Nelson (ORNL)	(423) 574-1507	(423) 576-0024	ban@ornl.gov
Richard Nygren (SNL)	(505) 845-3135	(505) 845-3130	renygre@sandia.gov
Mohamed Sawan (UWIS)	(608) 263-5093	(608) 263-4499	sawan@engr.wisc.edu
Dai-Kai Sze (ANL)	(630) 252-4838	(630) 252-5287	sze@anl.gov
Mark Tillack (UCSD)	(619) 534-7897	(619) 534-7716	tillack@fusion.ucsd.edu
Mike Ulrickson* (SNL)	(505) 845-3020	(505) 845-3130	maulric@sandia.gov
Scott Willms (LANL)	(505) 667-5802	(505) 665-9132	rsw@lanl.gov
Clement Wong (GA)	(619) 455-4258	(619) 455-2266	wongc@gav.gat.com
Robert Woolley (PPPL)	(609) 243-3130	(609) 243-3248	rwoolley@pppl.gov
Jim Yuen* (RIC)	(818) 586-2820	(818) 586-9481	jlyuen@rdyne.rockwell.com
Steve Zinkle (ORNL)	(423) 576-7220	(423) 574-0641	zinklesj@ornl.gov

* Did not Attend Meeting

IX. Appendices

Appendix I

SECRETARY's ANNOUNCEMENTS

SUMMARY OF LAST MEETING

- Distributed to participants. Thanks for Sessions Chairs who provided summaries of their sessions. Action Items was developed during the meeting.
- e-mail list is updated to include more participants/interested individuals in the study.

ACTION ITEMS FROM LAST MEETING (Attached):

PLEASE REVIEW THE ITEMS IN YOUR AREA AND BE PREPARED TO UPDATE GROUP ON STATUS.

-Several documents and Technical Memos were provided to Secretary and added to APEX Web Site (*http://www.fusion.ucla.edu)*::

- Thermophysical and Mechanical Properties of V-(4-5)%Cr-(4-5)%Ti Alloys (S. J. Zinkle)
- Thermophysical and Mechanical Properties of Fe-(8-9)%Cr Reduced Activation Steels (Steve Zinkle, J.P. Robertson and R.L. Klueh)
- Thermophysical and Mechanical Properties of SiC/SiC Composites (S. J. Zinkle, L.L.Snead)
- Damage rate in V.V. as a Function of Convective Layer Thickness (M.Z. Youssef)
- Impact of Li-6 Enrichment of the Convective Layer on Damage and Heat Deposition rate in V.V. (M.Z. Youssef)
- Results n NML Limits for the Porous Solid Wall-Liquid Lithium Concept (A. El-Azab)
- Porous FW Concepts (A. El-Azab)

Prepared and sent to UCLA. Will be discussed this meeting.

APEX WEB SITE:

PLEASE MAKE SURE TO GIVE SECRETARY A COPY OF YOUR PRESENTATION FOR THIS MEETING. A COPY ON A DISC OR SENT AS A SOFTWARE DOCUMENT IS PREFERABLE.

PUBLICATIONS:

An Overview paper on APEX will be presented by M. Abdou at 1998 ANS Annual Meeting and Embedded Topical Meeting: June 7-11, 1998

APEX Secretary
M. Youssef, May 6, 1998

III. **Action Items From Last Meeting** (compiled by M. Youssef)

(Taken from Summary of APEX Planning Group Meeting, January 12-14, 1998)

General Action Items or Observations

1) APEX will look at all magnetic confinement schemes. It is not limited to tokamaks.

2) The type of Tokamak (along with its design parameters) to be adapted as guidance in the APEX study was chosen to be ARRIES-RS since it has high power density characteristics. (Alice to check with Mark Tillack (UCSD) and compile typical dimensions and parameters)

3) Plasma disruptions, and other plasma transients, will be considered as a non-limiting factor (free factor) in the APEX study. However, any concept to be developed should at least take few (~2) disruptions and demonstrate that plasma startup can be performed. In general, concepts that can accommodate easily off-normal conditions will get credit for this.

4) Dai Kai Sze will work with each group concept to construct and identify an efficient power conversion system.

5) Questions regarding safety should be directed to the Safety Group (K. McCarthy) once they arise (by e-mail, no waiting)

6) Perform nuclear analysis to assess guidelines for concept developers with regard to damage, after heat, activation, etc. (M. Youssef, M. Sawan). Also, agree on methodology to be used in the more detailed stage to evaluate tritium self sufficiency. In particular, agree on what type of 3-D heterogeneous calculations to be done for tritium breeding.

7) Several P/FW/B/VV/C configurations to be explored and evaluated. These are

a.	Conventional:	P/FW/B/VV1/C/VV2	
b.	Variation 1:	P/FW/VV1/B/C/VV2	Blanket outside VV
c.	Variation 2:	P/FWCB/B/VV1/C/VV2	FW is a conductance barrier
d.	Variation 3:	P/FW/B/C/VV1/VV2	VV outside coil
e.	Variation 4:	P/FW/B/VV1/C/VV2	Vacuum Vessel is TF Coil

Specific Action Items

1) Mohamed Abdou suggested that Protecting FW Liquid could be the only material inside the VV in order to simplify maintenance. He requested evaluation of the various areas related to this:

   The protection requirements of the VV in this geometry (e.g. 1 ppm He, dpa limits, etc.) will be checked through nuclear analysis (M. Youssef).

   Mechanical Design Group (Brad Nelson) will examine how this configuration simplifies maintainability and how the protecting liquid layer could be formed.

The kind of coolant in the VV will be explored (H2O, He, hydrogen-bearing material, Li, etc.). Kathy McCarthy will talk about hydrocarbons next meeting.

2) Steve Zinkle will provide M. Youssef with "Tables of Materials Properties" to be put on the Web. Included with these tables are the properties of Foams (Nasr Ghoniem)

3) Anter El-Azab will find the limits (stress, temperature) of the materials provided by S. Zinkle. (e.g. Cu-Ni-Be, T-111, Nb-1Zr, TZM, etc.). Hydrogen content in material (e.g. Vanadium) will be considered in affecting these limits.

4) Explore the possibility of forming gaps in the flowing protecting liquid which could be used for penetration. Additionally, the instability of the magnetic field in the toroidal direction could be a limiting factor to be examined (Neil Morley).

5) Next APEX Meeting is scheduled to be April 29- May 1, 1998 at UCLA. Alternate magnetic Confinement Meeting will be held April 27-28, 1998 and arranged by Dale Meade. A person per concept will attend this meeting. Mohamed Abdou will draft a letter about APEX study to this group.

6) Mike Ulrickson (SNL) and Clement Wong (GA) will examine a base FW of Tungsten and Vanadium with Helium cooling system and assess the merit of these combinations on carrying away HHF. UCLA will assist in the analysis as needed.

7) Perform elastic-plastic analysis for stress evaluation and operating limits (Anter El-Azab).

8) Brad Nelson will assist each concept group to develop a design that incorporates reasonable margins and simplifies maintainability. He will stay with UCLA group after this meeting for that purpose.

9) The Physics Interface Group (Dale Meade) will do the following:

- Critical review of impact of evaporated liquid (lithium, lead) on plasma performance. Examine allowable evaporation rate and sputtering limits (there is a sputtering report about lead on the web, Mike Ulrickson)

- Define the plasma functional requirements that should be met to start plasma. (heating, fueling, control field, removing alpha particles, etc.)

- Provide UCLA (and others) with a representative Bremsstrahlung spectrum with typical line radiation from impurities (agree on a standard temperature profile and categorize/parameterize it for impurities). Currently, M. Youssef (UCLA) is using ITER plasma radiation for surface heating and will compare impact of various spectra on volumetric heat deposition in Li, Flibe, and Li17Pb83 liquid layers.

- Provide definition of representative physical penetration (circular, rectangular, triangular shape and dimension) for heating, fueling, and diagnostics.

- Merits/disadvantages of using rectangular FW as opposed to FW that follows the contours of plasma edge. Examine the issue of the need to have a conducting FW (a trade-off question).

10) The concepts that will be further examined/discussed next meeting are:

UCLA: (1) Convective Liquid wall (Li, Flibe)
(2) Porous FW filtrated with liquid (non-evaporated)
(3) Thick non-conducting FW
PPPL: (4) Magnetically restrained thick FW of Lithium (conducting)

- UCLA (N. Morley) will examine the EM forces on the moving liquid (i.e. include MHD in the analysis) which could lead to instabilities. Consider turbulence in the falling liquid layer.
- UCLA (Alice Ying) will examine evaporation of falling liquid as a mechanism to remove heat. Will work with PPPL (Bob Woolley) as needed on its concept.

ANL: (5) Free Falling Li2O Particulates.

- Dai kai Sze will perform more detailed thermal analysis of that concept by next meeting, including heat exchangers.

(6) Purse using foams in FW (Nasr Ghoniem) and examine evaporation of liquid from FW. Develop a complete thermal hydraulic cycle for that concept by next meeting and improve thermodynamic efficiency.

UW: (7) Sprayed-FW concept