Summary of the Second APEX Meeting
January 12-14, 1998
UCLA

<u>Content</u>

I. Introduction

The second APEX meeting was held at UCLA, January 12-14, 1998. A summary of the six working sessions is given in Section II. These summaries were written by the respective session chairmen. Section III has a list of action items as compiled by the APEX Secretary (M. Youssef). This list is in addition to the individual action items included in the summaries of the working sessions. The meeting agenda is in Section IV. A list of attendees is given in Section V. The actual presentations can be found on the APEX Web Page (http://www.fusion.ucla.edu, and then click APEX)

II. Summary of Working Sessions

II.1: Study Status (Chairperson: Sam Berk)

Sam Berk summarized the new directions of the restructured fusion energy sciences program. He indicated the importance of APEX as a key element in advanced technology.

Mohamed Abdou made introductory remarks and summarized the status of the project. He noted that APEX is trying to "invent new concepts" and this requires ingenuity and prediction capabilities. The new novel concepts pose interesting issues for which prediction capabilities often do not exist. A combination of modelling, analysis, and experiments will be necessary to fully evaluate concepts.

Abdou encouraged participants to continue to search for new ideas and work hard on evolving the concepts already proposed in the first APEX meeting. The study is open to all concepts. Although a concept is proposed initially by an organization, the entire APEX Team must be committed to support the analysis for all promising concepts regardless of who proposed. The goal of the Team should be to discover and evolve at least one concept that can make a dramatic difference to the improvement of the ultimate fusion product.

Abdou elaborated on three stages for evolving and evaluating a concept: 1) Exploration (scientific evaluation), 2) pre-conceptual design, 3) conceptual design. His presentation indicates the type of work needed for each stage and the requirements for a concept to move from one stage to another.

In the discussion, Abdou encouraged the team to explore concepts in which there are no structural elements inside the vacuum vessel. For example, if there is only liquid inside the vacuum vessel, this would simplify maintenance.

II.2: Mechanical Design, Configuration, Reliability, and First Wall Considerations *(Session Co-chairs: S. Malang, B. Nelson)*

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

- Status of activities for mechanical design and availability group
- General Design Requirements and Considerations
- ITER limiter design (for comparison purposes)
- First Wall thickness considerations and recommendation
- Availability considerations
- Vacuum boundary options

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 (separate vacuum vessel, resistive shield, or other approaches)
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 has just begun operating, and work so far has been limited to developing a list of design criteria and constraints, developing draft criteria for minimum first wall thickness, review of the ITER first wall and limiter designs, and a first pass look at the vacuum boundary options.

General Design Requirements and Considerations

A list of general design requirements was presented as shown in Table 1. It was noted that only confinement boundaries, not containment boundaries, are necessary for fusion safety. In addition, some type of divertor is necessary in each configuration to remove helium. The Plasma Interface Group was tasked with determining what penetration sizes are needed for heating and diagnostics, as well as determining the number of normal pulses and off-normal (disruption) events.

Table 1 General Design Requirements and Assumptions

Function	**Requirement**	**Value/Goal**
Power Extraction	Neutron Wall Load Surface Heat Flux	5 MW/m^2 avg* 7 MW/m^2 peak* 1.5 MW/m^2*
Tritium Breeding	Self Sufficient	TBR > 1
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	~~containment boundaries~~ confinement boundaries	~~1?~~ 2?
Plasma Exhaust	Divertor required?	~~TBD~~ to remove helium
Penetrations	Plasma Heating Power Density - NBI - ICH Diagnostics	 TBD MW/m^2 TBD MW/ m^2 TBD
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

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 (eg, 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

ITER limiter design (for comparison purposes)

The ITER first wall and limiter designs represent the current "state of the art", since these are the first components designed with the intent of fabrication and use in a fusion reactor environment. The heat loads are listed in Table 2, with comparison to the APEX goals.

Table 2 ITER and APEX power handling requirements

Requirement	**ITER FW**	**ITER limiter**	**APEX goals**
Surface flux, (MW/m^2)	.25, avg. .5, peak	8	1.5
Neutron wall load (MW/m^2)	1, avg	1, avg	5, avg 7, peak

The ITER first wall design has heat load requirments at least 5 times less than APEX, but the ITER limiter has a surface flux requirement 5 times more severe. The limiter design uses low temperature water (140C), copper heat sinks with imbedded swirl tubes and minimum distance from the coolant to the plasma facing surface (7mm). This concept meets some of the APEX criteria but not all, and is near the performance limit of this type of "conventional" design.

First Wall thickness considerations and recommendation

One of the primary obstacles to achieving the APEX goals for conventional designs is the thermal stress limit in the first wall. If this were the only consideration, the first wall could be made arbitrarily thin to reduce the thermal stress. However, thermal stress is not the only consideration. The intent of this part of the presentation was to review the first wall functional requirements, list some of the considerations and limitations on first wall thickness, and recommend some criteria for arriving at a minimum first wall thickness.

Several primary functional requirements exist for the first wall. These requirements must be met during both normal and off-normal operation, including transient thermal events and loss of cooling or flow conditions. These requirements include:

- Intercept lost particles and radiated power
- Withstand normal and off-normal mechanical loads
- Provide coolant boundary
- Minimize trapped gases
- Minimize “high Z” impurities in plasma
- Contribute to Plasma stability
- Accomodate loss of plasma conditions
- Define boundary of plasma during startup/shutdown
- Provide for penetrations
- Maximize availability

The first wall thickness must be selected to meet all the functional requirements listed above, but unfortunately these requirements are often conflicting. For example, a thin first wall may result in a lower thermal stresses, while a thicker first wall will be more resistant to damage from mechanical loads and erosion. The optimum thickness will be different for different materials, and it may be necessary to use more than one material through the thickness. Obviously, the configuration of the first wall is also important, since the geometry and structural constraint is directly related to the thermal and mechanical stress state. Table 3 lists some of the consideration related to first wall thickness, a proposed design criteria, and what functions will be impacted due to a failure of the first wall related to this criteria

The Plasma Interface Group will offer guidance with respect to electrical conductivity, ELMS, plasma transients and startup

Availability considerations

Some general comments on availability were presented that echoed earlier comments by Dr. Abdou.

In order to have reasonable availability, fusion hardware must be both reliable and maintainable, since availability is defined as:

$$\text{Availability} = \frac{\text{Mean Time Between Failures}}{\text{Mean Time Between Failures + Mean time to Replace}}$$

Table 3. First wall thickness considerations and suggested criteria

Consideration	**Relation to thickness**	**Criteria**	**Impacted Functions from failure**

Maximum Temp (normal oper.)	T ∝ thickness	T < T matl.	Plasma contamination Coolant boundary
Maximum Temp (off-normal)	T ∝ thickness	Tcool side < Tcrit Need thermal inertia for high heat flux transients	Coolant boundary
Thermal Stress	Q ∝ thickness	Pm+Pb+Q < 3*Sm	Coolant boundary Surface contour
Pressure load*	Pm ∝ 1/thickness Pb ∝ 1/thickness^2	Pm < Sm Pm + Pb < 1.5 Sm	Coolant boundary Surface contour
Assembly loads	(same as pressure)	Support wt. of person (2*100 kg) standing on FW	Coolant boundary Surface contour
Impact load	(same as pressure)	20 (?) kg object dropped from height of plasma chamber	Coolant boundary Surface contour
Tritiium retention	Vol ∝ thickness Ret. ∝ temperature		
Corrosion	Margin ∝ thickness	1 mm allowance	Coolant boundary
Erosion	Margin ∝ thickness	1 mm allowance	Coolant boundary
Passive stability	Elec.cond. ∝ thickness	~~will not consider~~	Plasma stability
Runaway electrons	Penetration ∝ thickness	will not consider	Coolant boundary
Rad. Effects	variable	material properties	
Fabrication	variable	must be able to integrate first wall with structural and cooling connections	
Margin/tolerance	variable	thickness can vary locally by >20 % of total thickness or 2 mm, whichever is larger	

* Electromagnetic pressure may be inversely proportional to wall thickness if response is

It would be desirable if the design is tolerant of a few failures, potential problems can be predicted and prevented, and any failures that do occur can be diagnosed and corrected quickly. The primary obstacle to availability in conventional designs is the danger of a coolant leak. This makes the liquid metal concepts appear very desirable, since they eliminate this problem altogether.

Some lists of design features to include and avoid were presented, but there was little comment.

Vacuum boundary options
Finally, some information was presented on various options for the vacuum boundary. The conventional design puts the primary confinement boundary, the vacuum vessel, between the blanket and coil set, and the seondary confinement boundary outside the coil set. Various options move the primary boundary outside the blanket and even outside the coil set. One attractive idea is to have the first boundary be the TF coil set, as is the case for the ST version of the VNS, which uses a single turn TF coil winding. In all cases the first wall must be inside the vacuum boundary.

The subject of the vacuum boundary configuration is still open, and additional ideas are solicited.

II.3: Materials Database and Limits *(Chair: M. Ulrickson)*

There were three presentations in this session. Steve Zinkle presented an overview of the sturctural materials database. Rich Mattas presented a summary of the ITER structural materials design criteria. Clement Wong presented an analysis of the wall thickness allowed for helium cooled first wall designs.

For high wall loading concepts, Steve Zinkle showed data on several categories of structural materials. The traditional low-activation materials (V alloys, Ferritic/Martensitic steels, and SiC-SiC) were compared to refractory alloys (Nb-1Zr, T-111, TZM, etc.), Ni based superalloys, intermetallics (TiAl, FeAl, etc.), composites (CFC, metal matrix, etc.), and other porous-matrix metals and ceramics. The refractory alloys offer considerably higher thermal conductivity and a higher maximum operating temperature compared to the low-activation materials. The penalty is higher activation and different safety concerns and design issues. An extensive set of material properties for many alloys were presented in the format of the material property database maintained by John Davis (Boeing- St. Louis). During the discussion, it was pointed out that the ductile-brittle transition temperature was not necessarily a hard limit. In some cases, the materials do not exhibit flow localization and brittle fracture. It is also possible to design for brittle materials if the proper allowables are used. An evaluation of the relative importance of stress limits and temperature limits for various low-activation alloys was presented.

Rich Mattas discussed the content of the ITER Structural Design Criteria. That document is the first comprehensive analysis of structural limits for fusion devices. It is based on the European RCC-MR code but adds radiation effects. The code is primarily aimed at first-wall, blanket and shield components. The code has four classes of criteria with increasing levels of damage allowed as a result of exceeding the criteria. He showed that the code allows consideration of a combination of primary and secondary stresses and the design limits are a complex combination of the two stresses. A logic diagram for determining the actual limits was presented. The code is being revised to include additional material.

Clement Wong presented an analysis of a helium cooled first-wall design based on vanadium. The analysis showed that for a reasonable range of helium coolant parameters and vanadium thickness, the limiting factor was the operating temperature of the vanadium. This again points out the need to consider higher temperature capable materials.

Comments:
Since the objective of the APEX study is to find techniques for removing higher heat flux from the first-wall/shield in a magnetic fusion device, it is important that we not limit ourselves to the lowest-activation materials. The low-activation materials in general have both low thermal conductivity and relatively low temperature limits. Refractory alloys offer higher thermal conductivity (lower operating temperatures) and higher strength at elevated temperature (higher temperature limits). The penalty is higher after-heat and/or higher activation with the associated greater safety risk. The tradeoffs between these effects must be evaluated to see what the optimum solution is for fusion. It may be that we should accept a higher safety risk to find a solution for a higher power density fusion device. The combination of refractory alloys and helium cooling may be an attractive alternative to liquid metal walls.

II.4: Preliminary Analysis for Promising High Power Density Concepts, and New Concepts
(Chairman: Neil Morley)

The morning and early afternoon of Tuesday the 13th of January was taken up with the presentation of analysis of promising HPD concepts put forward in the October APEX meeting, and the presentation of new HPD concept ideas. These concepts are grouped into categories and discussed in detail below. The group concluded that the liquid surface concepts will continue to be pursued by UCLA and others, as they present the greatest possibility for high power density extraction with low failure rates. Issues include interaction of the liquid with the plasma and magnetic field of the reactor. Also, GA/SNL will look into the possibilities of a high temperature tungsten/helium system and ANL/UWM will continue to advance the Li_2O particulate concept. Others will continue to develop new concepts for presentation in the next meeting. All leaders of the continuing concepts will develop a 18 month concept development plan, identifying the issues and needed resources, for presentation at the next APEX meeting in April.

Liquid Wall Concepts
UCLA presented analysis related to three possible concepts: *(1) Convective Liquid Layer* where a 1-5 cm flowing layer of liquid exposed to the plasma removes the surface heat flux by convection, *(2) Liquid-Filled Porous Wall* where a porous FW is infiltrated with high conductivity liquid to improve the thermomechanical performance, and *(3) Thick Liquid FW/Blanket* where one or a series of free surface jets acts as both FW and blanket. Hydraulics heat transfer, surface temperature, and neutronics calculations were presented by Neil Morley, Alice Ying and Mahmoud Youssef for the flowing wall concepts (1) and (3). Anter El-Azab discussed the thermomechanical properties of possible porous wall materials for concept (2).

Morley showed calculations demonstrating that it may be possible to flow a 2 cm layer of electrically conducting lithium at 20 m/s over a 10 m wall arc if the channel walls are electrically insulating and any side walls are spaced more than 2 m apart toroidally. For electrically non-conducting Flibe, the turbulent friction with the back plate leads to 6 cm thick layers at 20 m/s, independent of side wall spacing and magnetic field. In both cases the layer remains adhered to a back wall by a centrifugal force ten times the acceleration of gravity. Questions were raised about the validity of these simple MHD calculations in the complex magnetic environment of the first wall. In particular, how would the film (or layer) respond to toroidal field ripple, radial dependence of toroidal field, and time dependent field shifts needed for plasma control. Flibe is unaffected by these concerns, but the presence of fluorine in the chamber and vacuum system was a serious concern of the group.

Youssef analyzed the absorption of bremsstrahlung radiation in the bulk of the liquid layer, instead of as a surface heat flux. He found that for characteristic plasma radiation spectra corresponding to 10 keV plasmas that the power deposition is spread over a centimeter of so in lithium, and several millimeters in Flibe. The volumetric heating rate from the “surface” heat flux exceeds that due to neutrons in the first few millimeters for lithium, and for about 1 mm for Flibe. This penetration is not yet significant enough to reduce the surface temperature of Flibe. Youssef also performed some 1D TBR analysis and showed that having lithium or Flibe directly facing the plasma without structural material markedly improves the tritium breeding characteristics over conventional blanket/FW designs. Questions were raised by the group concerning the real spectrum and amount of alpha heat coming out as bremsstrahlung radiation, as opposed to softer line and synchrotron radiation, or charge-exchange neutrals.

Heat transfer calculations by Ying were presented that show the possibility of keeping the surface temperature of the first wall liquid layer below 325°C for lithium, and thus minimizing evaporation from the surface. With the spectra considered, Flibe surface temperatures were much higher, due to the low thermal conductivity and high melting point of Flibe, but could be improved by taking into account turbulent mixing. The turbulence characteristics will differ depending on the concept geometry. Questions were raised about a realistic limit on surface temperature considering the possible beneficial effects of lithium in plasma experiments at TFTR. Lower flowrates for the surface layer (and so higher surface temperatures) may be required in order to optimize the power conversion by achieving higher bulk temperatures. Yet, the calculations showed that the evaporation flux limit for lithium, according to Moir’s 1997 paper, could be met.

El-Azab gave some information related to determining effective properties of porous materials used by concept (2). In particular, the elastic modulus and Poisson ratio for porous V-alloys and SiC composites were presented and discussed. The group comments included material compatibility issues that may result in blockage of the pores, and time-scale questions for the response of the material.

Bob Woolley presented a review of his concept where >1 m of flowing free-surface lithium is pushed against a confining wall by flowing an electric current along the direction of the flow, which interacts with the toroidal field to produce the radial force. He described work in progress to solve the MHD equations in an axi-symmetric approximation in order to predict the behavior of his proposed system. The group had many questions concerning startup and stability of this flow. Some of these questions overlap with the UCLA concepts discussed above, including the heat transfer and neutronics, in addition to the MHD concerns. UCLA will work with Woolley in these areas.

Some other free surface liquid ideas adapted from Inertial Fusion experience were presented by Igor Sviatoslavsky from UWM. These include thin fans of sprayed liquid, which overlap and completely cover the walls, and curved plates cooled from behind by fast flowing liquid. UWM proposes to develop these ideas further for MFE application. Additionally, UWM reviewed their general capabilities in hydraulics, neutronics and fluid mechanics to make the group aware of possibilities for collaboration.

Evaporating liquid wall

Nasr Ghoniem of UCLA discussed the possibility of using the latent heat of vaporization of a free surface liquid to carry the surface heat to a new energy extraction cycle. The use of a porous material saturated with the liquid and exposed to the plasma would maintain a continuous supply of liquid for evaporation. The question as to how to remove this evaporated vapor from the plasma chamber without going to the divertor was a serious concern of the group. The group also wondered if the energy of ionization of the vapor would aid in the removal of surface heat, or would recombination just reradiate the energy to the wall.

Moving Solid Particulate

Dai-Kai Sze of ANL presented a refined description of the flowing Li_2O particulate FW blanket concept. The advantages to this “flowing solid” are the elimination of MHD and vapor pressure problems that confront liquid concepts. Based on a 1000 C temperature limit, and free gravitational acceleration, the FW flow should be able to take 2.5 MW/m^2. The group questioned the reliability of a radiation cooled SiC baffle which directs the flow of particulates, and the sputtering of Li_2O in the divertor region. In addition, the actual speed and packing of the FW region is a concern.

Neutronics analysis of this concept by Mohamed Sawan of UWM indicates the possibility of tritium self-sufficiency and the application of 316SS as a lifetime structural material. The blanket thickness in this case is ~70 cm of Li_2O.

Moving Belt

Yoshi Hirooka for UCSD presented a moving belt concept for divertor application, and discussed the possibility of redesigning this for a FW. The SiC belt is reconditioned each pass to remove implanted tritium and deposited heat, and replenish a beneficial getter coating.

High Pressure/Temperature Helium/Vanadium or Helium/Tungsten

Clement Wong of GA discussed again the possibility of using high pressure/temperature helium in conjunction with the good thermomechnical properties of V-alloys for a FW. By increasing the pressure and using swirl tubes, he estimates a thin V (2 mm) FW will meet the minimum APEX goals. The group speculated that use of a higher temperature material like Tungsten alloys would yield even more attractive concepts. Mike Ulrickson of SNL plans on pursuing such a design concept with GA.

II.5: Plasma Interface Issues *(Chair: Dale Meade)*

Achieving the APEX goal of developing a first wall with the capability to a 7.5 MWm-2 of total flux depends on the ability of the first wall to absorb surface heat loads of 1.5 MWm-2. The surface heat load is determined by the surface temperature, the impurities that a get into the plasma.. Several proposals for APEX involve liquid lithium surfaces, mists or JETS. D. Meade described operational experience with the injection of lithium into the limiter scrapeoff region of D-T plasmas in TFTR. The lithium injection was accomplished by directing a rapidly pulsed YAG laser at a pool of molten lithium at the bottom of the TFTR vacuum vessel. The ejected lithium was effectively ionized in the limiter scrapeoff and transported to plasma contact regions on the carbon limiter. This lithium layer on the limiter had the beneficial effect of reducing the influx of carbon impurities as well as reducing hydrogen recycling which reduced the Zeff in the plasma and improved plasma performance. These results suggest that some evaporation of a liquid lithium surface would be allowed in APEX. A future task for the APEX plasma surface participants is to develop a model that relates the lithium levels utilized in TFTR to the maximum lithium emission levels that might be allowed from a plasma facing lithium surface. R. Moir's previous analyses will be a starting point for development of a model. C. Wong described the capabilities of DIII-D for additional studies of plasma surface interactions that would be of interest to APEX.

A significant fraction of the alpha particle heating will be incident on the first wall as photons. The surface temperature will depend on the photon absorption depth which in turn depends on the energy. Some sample photon spectra from ITER were provided by D. Post and some additional representative spectra have been requested. D. Meade also presented TFTR results using a radiating Krypton mantle which radiated 100% of the plasma loss power and still allowed high performance D-T plasmas. A future task is to relate the high Z radiating mantle results to possible plasma operating modes in APEX and to examine the sensitivity to representative photon spectra.

The first wall requirements are to include a range of operating conditions including: nominal steady-state, plasma start-up/shut-down, plasma disruptions/instability and localized alpha loss. Other requirements to be analyzed include first wall electrical conductivity/connectivity requirements that are related eddy currents induced by control fields or required for wall stabilization of plasma instabilities.

The plasma interface participants are also requested to develop nominal configuration requirements for interfacing the first wall with penetrations for plasma heating, current drive, diagnostics, etc.

The highest priority need is for the plasma interface group to provide guidance on the amount of first wall material ejected into the plasma and hence the surface temperature.

III. **Action Items** (compiled by M. Youssef)

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

- UW will purse this concept with analysis to be presented next meeting.

11) By next meeting, each concept proponent (s) will present a plan (~ 18 Months period) on the technical approach and resources needed to develop and analyze the proposed concept.

IV. Meeting Agenda

Agenda for APEX Study Meeting
UCLA, Engineering IV, Room 37-124
January 12-14, 1998

Monday January 12
Session I: Study Status

1:00 p.m.	Introductory Remarks	Berk
1:10 p.m.	Status and Issues	Abdou
1:40 p.m.	Secretary’s Announcements	Youssef

Session II: Mechanical Design, Configuration, Reliability, and First Wall Considerations

(Session Chairs: Brad Nelson/Siegfried Malang)

1:45 p.m.	APEX Mechanical Design Considerations	Nelson
2:30 p.m.	Group Discussion	

Session III: Materials Data Base and Limits

(Session Chair: Mike Ulrickson)

3:30 p.m..	Structural Materials Database and Operating Temperature Limits	Zinkle
4:15 p.m.	Break	
4:30 p.m.	Properties of Metallic Foams and Operating Limits	ElAzab
5:00 p.m.	Evaluation of Heat Load Limits	Majumdar/Mattas
5:30 p.m.	Simple Analysis of Wall Thickness Versus Heat Flux of He-Cooled Tube	Wong
6:00 p.m.	Adjourn	

Tuesday January 13

Session IV: Preliminary Analysis of Promising High Power Density and New Concepts

(Session Chair: Neil Morley)

9:00 a.m.	Design Issues and Analysis of Liquid Wall Concepts Protection	Morley
9:40 a.m.	Surface and Volumetric Heat Deposition in Liquid-Protected FW	Youssef
10:00 a.m.	Thermomechanical Benefits of Porous/Liquid FW Structure	ElAzab
10:15 a.m.	Coffee Break	
10:30 a.m.	Dependence of Liquid Surface Temperature on Turbulence Enhancement and Radiation Penetration	Ying
11:00 a.m.	Numerical Simulation of Free-Surface Liquid Lithium Flows in Tokamak Toroidal Geometry	Woolley
11:30 a.m.	The Li2O Particulate Blanket Concept	Sze
12:00 p.m.	New Ideas for First Wall Cooling	Sviatoslavsky/Sawan
12:30 p.m.	Lunch	
1:30 p.m.	New First Wall Design Concepts Utilizing Porous Structure	Ghoniem
2:00 p.m.	Group Discussion on Concepts	

Session V: Physics Interface

(Session Chair: Meade/Ulrickson)

- 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

3:00 p.m.	Plasma Operation and Interface Issues	Meade
3:30 p.m.	Discussions on Plasma Interface	
4:00 p.m.	Coffee Break	
4:15 p.m.	Steady State Particle Control and Heat Removal by Moving Belt PFCs	Hiroaka/Tillack/ Grossman

Session VI: How to Stimulate New Concepts and Innovation

4:35 p.m.	Invited Remarks – S. Malang – M. Ulrickson – M. Tillack – M. Sawan – Others
5:30 p.m.	Group Discussion
6:15 p.m.	Adjourn
7:15 p.m.	Group No-Host Dinner

Wednesday January 14
Session VII: Tasks and Planning Group
(Session Chair: Mohamed Abdou)

8:30 a.m.	Reports From Other Groups	
	– Power Conversion Group	Sze
	– Safety & Environment	McCarthy

9:30 a.m.

- General Study Directions and Approach

- Working Groups Directions and Focus:

Group 1: Design Conceptualization and Analysis
Group 2: Mechanical Design and Availability
Group 3: Materials
Group 4: Power conversion system
Group 5: Physics Interface
Group 6: Safety & Environment
Group 7: Alternate Confinement Concepts
Group 8: Judgment & Selection

- Task Assignments and Schedule

12:30 p.m.	Close of the Meeting

IV. List of Attendees

Mohamed Abdou (UCLA)
Sam Berk (OFES)
Lee Berry (ORNL)
Anter El-Azab (UCLA)
Nasr Ghoniem (UCLA)
Yoshi Hirooka (UCSD)
Siegfried Malang (FZK)
Rich Mattas (ANL)
Kathy McCarthy (INEL)
Dale Meade (PPPL)
Neil Morley (UCLA)
Brad Nelson (ORNL)
Mohamed Sawan (UWM)
Igor Sviatoslavksy (UWM)
Dai-Kai Sze (ANL)
Mike Ulrickson (SNL)
Clement Wong (GA)
Robert Woolley (PPPL)
Alice Ying (UCLA)
Mahmoud Youssef (UCLA)
Steve Zinkle (ORNL)