Summary of the APEX6/FHPD Workshop
February 16-19, 1999
University of California, Los Angeles

Content

I. Introduction

The 6th APEX meeting was held at University of California, Los Angeles, in conjunction with the Fusion High Power Density (FHPD) Workshop during the period November 16-19, 1999. The latter, is an on-going co-operative research study between the U.S. and Japan on HPD blanket/divertor concepts with many common objectives with those of the APEX study. In this combined workshop, recent progress in the design of the HPD blanket concepts under investigation in the APEX study, including liquid as well as high refractory solid FW/blankets, were reviewed along with similar activities in Monbushu and JAERI in Japan. Discussion was carried out on the scientific criteria to be used in the evaluation process for APEX FW/blanket concepts and plans were set for the near-term activities. Special session was held on the top "hot issues" to be discussed in Snowmass Summer Study Meeting to be held in Colorado in July of this year (details on http://www.pppl.gov/snowmass/). The presentations given can be viewed from the APEX Web Page http://www.fusion.ucla.edu. The meeting agenda, attendees, contact information and announcements are given in Appendices I-IV. A summary of the working sessions is given in Section II. Section III lists the action items agreed upon during the meeting.

II. Summary of Working Sessions

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

Abdou gave introductory remarks about the APEX study and welcomed the Japanese colleagues from Japan universities and JAERI who participated in the workshop and have common interest in resolving the critical issues pertaining to the HPD in-vessel components. Wong (GA) gave a background of the US/Japan FHPD activities which focus on problem recognition, fundamental studies, innovation, and solution approaches. He gave a chronological history of previous workshops (Dec. 11-15, 1994, San Diego, Feb. 17-21, 1997, San Diego). Toda (Tohoku U.) emphasized the importance of collaboration in this field and he introduced the members of the Japanese group who are from various universities, NIFS, and JAERI.

Berk (DOE) reviewed next the planning activities in 1999 and the basis to prepare new fusion program plan. The review and planning activities, along with the deadlines for report submission are as follows:

(1) Secretary of Energy Advisory Board (SEAB) Task Force will review all of DOE's magnetic and inertial fusion program activities and submit a report by end of May, 1999. Purpose: response to congressional request (House and Senate FY1999) by reviewing DOE programs in four fusion approaches to ignition and energy applications, namely, magnetic fusion and pulse-power, laser, and ion driver concepts for initial fusion.

(2) National Academy of Sciences/National Research Council (NAS/NRC) Panel will assess quality of science in fusion program and review fusion program goals and strategy and submit a report by mid September, 1999.

(3) Fusion Energy Sciences Advisory Committee (FESAC) Review Panel will report in February, 1999 on "opportunities and requirements" of fusion energy sciences program. Following the panel report, FESAC will lead community assessment of fusion program and submit a report by end of September, 1999.

(4) Fusion Summer Study will have a two-week meeting in Snowmass, Co, during July, 1999 to examine opportunities and directions in fusion energy sciences for the next decade and develop community consensus on key issues for plasma science, technology, energy, and environment

Berk also discussed related activities that could impact the decision on the fusion program planning for FY 2000 and FY 2001. They are:

(1) Next Step Option (NSO) Studies on nest step devices that emphasize plasma behavior at high energy gain and long ignition. Interim report on this study is die to SEAB review in March, 1999, draft white papers in July, 1999 (input o Fusion Summer Study), and preconceptual design of advanced physics BPX-like by October, 1999.

(2) Panel of President's Committee of Advisors on Science and Technology (PCAST) Study is conducting a study of international cooperation in energy R&D and developing a strategic framework to meet national and global challenges through international energy R&D. Panel report to PCAST (end of March, 1999); PCAST report to President in May, 1999.

On the international activities, Berk pointed out that there is $12.2 M provided by Congress in FY99 to complete ITER-related activities. If ITER parties will go forward with construction, US will assess opportunities for involvement and evaluate them in light of domestic circumstances. There is a new international agreement on fusion science that DOE called for in September, 1998. The US has proposed annual forum for leaders of four major fusion programs, presented by EU, Japan, and RF during Yokohama Meeting. Draft package is due to DOE in March, 1999 to outlines opportunities of international collaboration in plasma sciences, technology, and energy.

As for APEX budget in FY2000, Berk indicated that it is currently ~ $1.5M (as opposed to $2.17M in FY99) but he anticipated that the number will go up after initial VLT Director recommendations (2/4/99), updated VTL Director recommendations after PAC Input (3/26/99), updated VTL Director recommendations after BPM (4/23/99) and after updated VTL Director recommendations following Snowmass Meeting (7/30/99).

The status of APEX study was next discussed by Abdou. He pointed out that there is currently contradictions in the US Fusion Program: community-wide support and enthusiasm but there is a possibility of budget cuts. He indicated that we need to work harder and double our work on the technical tasks and try to convey the message to Decision Makers. The current status of APEX and directions is given in a presentation by Abdou to VTL/PAC on December, 19998 and is available on the APEX web site (http://www.fusion.ucla.edu). Abdou reviewed the APEX Phase I milestones (Appendix V), the organizational chart of participants by technical area (Appendix VI), and the outlines of APEX Interim report (Appendix VII). The deadlines of this report is firm (See Appendix VI) and it will be distributed to Snowmass Technology participants by July 1, 1999.

The APEX Secretary's announcements were then given by Youssef (UCLA, see Appendix IV). He urged the participants to submit soft copies of their presentations to be posted on the web site and asked Chairpersons to provide summaries of their sessions shortly after the meeting.

Summary of Session II: EVOLVE, APPLE Concepts and Related Japanese Activities

Session Chair: Rich Mattas (ANL)

Mattas (ANL) covered the latest activities pertaining to the EVOLVE design in the areas of power conversion efficiency, design of heat exchangers, tritium system, thermo-mechanical design, and some material issues (helium embrittlement). This concept was presented by Malang (FZK) in May, July and November APEX meetings. A low- and high-temperature lithium-helium HX was shown. Also the parameters of 2-single HX were discussed. The cycle efficiency is ~57.7%. Heat exchanger sizes and pumping power are modest in this design. An acceptable tritium recovery system was identified but tritium containment needs to be addressed in more details. High T creep seems to impose no problem. Finite element analysis for EVOLVE is planned. Mattas also indicated that He embrittlement effects for all high temperature concepts should be carefully analyzed.

Sawan gave the neutronics parameters and shielding characteristics of the EVOLVE design. In addition to the Li in the cups and the front FW tubes, a secondary Blanket is incorporated in the outboard to enhance the TBR. Using W structure (instead of Ta) for the FW and cups resulted in ~10% increase in TBR. The recommended radial build was given in which the overall TBR (after accounting for the coverage of the cups of 72.7% and not breeding in the divertor zone that occupies ~10% of total coverage) was estimated to be ~ 1.34 This was judged to be adequate if Li is enriched to 40%Li-6. It was shown that heating and hot spots occur at parts of the O/B secondary blanket and I/B shield between cups due to neutron streaming and the conservatively high values obtained from 1-D calculations need to be confirmed from multi-dimensional estimates.

Fogarty (BNL) presented the first iteration of the mechanical design of the EVOLVE concept. This included segmentation, FW, cups, vapor manifold configuration, integration of divertor, diagnostics and midplane maintenance cassettes as well as the integration of heat exchangers. The advantage of the design is the low vapor pressure of Li (Temperature ~1200 C), nearly uniform temperature, and low Li liquid flow velocities. The main issues included the fabrication of the refractory materials and the cups design and vapor duct layout for adequate shielding. Future plan includes assessment of the consequences of Li leak with respect to availability and further examination of geometry and configuration.

The applicability of LM mist cooling (LMMC) for high heat flux systems was then described by Toda (Tohoku U.) This method of cooling uses a sprayed mist flow containing liquid droplets in its carrier gas and can be operated at low pressure. Due to its high void fraction (~80%) MHD effects in a strong magnetic field are drastically reduced and can be neglected. In addition, during the deformation of a liquid metal drop impinging on the heated surface, the drop absorbs heat efficiently from the high temperature wall due to its high thermal conductivity. The relationship (from hydrodynamics) of liquid drop (d) and the formation of thin liquid film of width D was described in terms of Re and We numbers and compared to experimental conditions for water, eythyl alcohol, and mercury. At present, there is an experimental apparatus under construction for a sodium loop with argon gas to validate this method of cooling.

Heat flux removal by evaporated fluid in porous media was discussed by Toda/Hashizume (Tohoku U.) Based on heat removal system by latent heat of vaporization can efficiently be used to enhance the heat removal capacity of systems subjected to high heat fluxes. The porous media used in an experimental setup is the sintered metal SUS316L. The porosity (vol.%) varies as 47 and 42% with average pore diameter (μm) of 25 and 9, respectively. The numerical results based on 2-D analysis to simulate the heating boundary conditions give good prediction to the relationship between the pressure drop and mass flux and to the relationship between mass flux and removed heat flux. From the experiment, it was shown that heat flux up to 1.3 MW/m2 could be removed at the present and further development is underway to enhance heat removal capacity above this limit.

Sze (ANL) presented the status of the APPLE concept in which a stream of Li2O particulate is freely fed to the blanket region for cooling and breeding. Two layers are used: (1) a 5-cm thick fast layer in free flowing along the FW for efficient heat removal and (2) second layer confined by SiC structure to reduce velocity and achieve an acceptable coolant. Li2O particulate collected by gravity moved upward by a mechanical conveyor and fed downward to a heat exchanger to transfer the thermal energy to a He stream. While this concept has a potential to alleviate problems such as erosion, blanket replacement, radiation damage, etc., issues of concerns are mainly mechanical and configurational nature. Accommodation of penetrations is also an issue which may require using baffles to prevent bouncing or scattering of particulate above penetrations and deflectors to line up particulate back below penetrations. Cooling such penetration baffles is also an issue. An idea for near elimination of the guide baffles in APPLE was shown in which the upper guide baffle is minimally exposed to surface heating (<1.0 MW/m2 for a 10 MW/m2 wall load). Other key issues pointed out are: (a) electromagnetically levitated Li2O dust, (b) plasma charge-up of particulate and consequent effects, and (c) O2 contamination of plasma.

Tillack (UCSD) presented some results from the particle dynamic simulation code PFC2D applied to the free fall APPLE concept. The code solves for the momentum equations for large assembly of particles by first updating the guiding walls position, particle position and information about the set of contacts between particles, the force-displacement laws are then applied to each contact, the contact forces are updated, and then the laws of motion for each particle are applied to arrive at new set of contacts and the process is repeated. At the moment, heat transfer capability is not included in the code but can be incorporated at later stage. Tillack demonstrated that some bouncing and scattering could occur when the code is applied to surfaces with inclination and curvatures.

The updated neutronics parameters for APPLE concept were given by Sawan (UW). A recommended radial build was described that achieved an overall TBR of 1.22 after accounting for the coverage fraction of the O/B (75%), the I/B (15%) and the divertor (10%). The overall energy multiplication is ~ 1.12. About 94% of nuclear heating is deposited as high-grade heat in the front particulate cooled blanket. It was shown that a minimum blanket thickness of ~40 cm is required for the structure (ferric steel) to be lifetime component.

Shimizu’s presentation not available

Some issues related to the simulation of dense particulate systems were presented by Yokomine (Kyushu U.) These include particle transport (pneumatic or mechanical conveyer, erosive damage to walls, coagulation, attrition, etc), heat removal and recovery from particulate, pressure drop, purification, fragments of particles, etc. Features and the governing equations of dense particulate flow versus dilute particulate flow (gas-solid suspension) were discussed. Equations of translational and rotational motions of particles in contact with one another for examples were shown for the DEM simulation as a function of time with and without the presence of obstacles. Comparison between experimental results and numerical predictions of duct erosion as a result of particle flow was shown were stochastic and deterministic simulation approaches were applied.

.

Summary of Session III, He-Cooled Refractory Metal FW/Blanket/Divertor Concept

Session Chair: Wong(GA)/Nygren (SNL)

Wong reported on the thermal-hydraulics of the helium-cooled design. A 2 GWe design was evaluated at a peak neutron wall loading and surface heat flux of 10.4 and 2.97 MW/m^2, respectively. In order to match the inlet/outlet temperature of 400/1000 C, three different refractory alloys were used. V-alloy is used for the back blanket tubes, Ta-alloy is used for the front blanket tubes and W-alloy is used for the first wall. This resulted in a closed cycle gas turbine gross efficiency of 46%. The total coolant loop pressure drop is quite high at 0.85 MPa but would still be acceptable for a CCGT power conversion system.

Takase's presentation not available

Nygren (SNL) presented the fabrication of the helium-cooled porous metal first-wall heat sink. Based on the experience from Ultramet (Pacoima, California), he showed that commercial Ta and Re metal foam product with different pore size and at 15% dense is already available.

Ulrickson (SNL) presented the performance of the SAES Zr gettering systems, which are used for the semi-conducting industry. These systems are designed to achieve better than 1 ppb purity control. The operating temperature range is 300-700 C. Sandia is planning to install a prototype on the EBTS helium-cooled experimental loop for refractory metal testing.

Fogarty (ORNL) presented the mechanical design for the helium-cooled option. A co-axial plenum piping design connected to FW/blanket tubes was presented. Due to the change from the use of V-, Ta- and W-alloys to W-alloy only FW/blanket design, the cooling routing will be changed and the design will be iterated with the thermal-hydraulics and neutronics design tasks.

Youssef (UCLA) presented the results on damage indices in He-cooled refractory alloys FW/blanket design and comparison for liquid and solid walls. With W, the dpa, helium-production and hydrogen generation rate are lower than TZM and Nb-1Zr cases. It was noted in this case (with W), that the damage parameters at the VV and the TF coil case are similar to the values in the thick liquid FW/blanket concept with Ferritic steel. Youssef also examined these damage parameters when breeders (Flibe, Li-Pb) other than Li were used. He showed that damage parameters at the solid FW are similar among these breeders. At the VV and FT coil, they are higher with the Li than with Flibe by a factor of 6-10. At these locations, the damage parameters with the Li-Sn breeder are larger than with the Flibe by a factor of 1.3-1.7. The advantage of using liquid FW over solid walls was discussed. With a 42-cm thick liquid Flibe breeder in front, the reduction in damage level can be 1-2 order of magnitude.

Summary of Session IV: Materials and data Base Evaluation

Session Chair: Zinkle (ORNL)/Ghoniem (UCLA)

The three presentations in this session focussed on chemical compatibility issues between structural materials and coolants, with an emphasis on oxygen pickup and oxidation in Group V and Group VI refractory alloys. These presentations were given by Zinkle (ORNL), Sharafat (UCLA), and Ghoniem (UCLA)

The key concern regarding oxygen-containing coolants for Group V metals (V, Nb, Ta) is matrix hardening and embrittlement due to oxygen pickup. The matrix oxygen content in V needs to be below ~1000 wt.ppm in order to keep the ductile to brittle transition temperature bellow room temperature. All of the Group V metals have a high affinity for oxygen and unrealistically low oxygen partial pressure ($< 10^{-20}$ atm.) would be required to avoid oxygen pickup based on thermodynamics. In practice, kinetic processes (oxygen diffusion and impingement flux) control the oxygen pickup. The diffusion of oxygen at T<600^{o}C is too slow to be of concern in engineering applications. At T>600^{o}C, pronounced oxygen pickup will occur unless the oxygen partial pressure is low enough to limit the flux of oxygen striking the metal surface. A rough calculation indicated that oxygen pickup of <1000 wt.ppm can be achieved for long-term (10 yr) exposures if the oxygen partial pressure is <10^{-4} torr. The effects of mass transfer limitation through the boundary layer need to be investigated to determine if higher oxygen partial pressures are acceptable.

The oxidation of Group VI metals (Mo, W) was presented by S. Sharafat (UCLA). Formation of volatile oxides can lead to pronounced surface erosion of these metals at elevated temperatures. The evaporation rate increases rapidly up to ~2000K in both Mo and W. If boundary layer scattering effects are ignored, the evaporation rate exceeds 100 µm/y at ~1500 K in both materials for 1 ppm oxygen in He at a pressure of 10 MPa. Boundary layer effects may reduce the evaporation rate by several orders of magnitude. The calculations suggest that limitations on mass transport through the boundary layer may reduce the erosion rate to less than 10 µm/y at wall temperatures up to 2600 K in both Mo and W. Further work is planned.

The limited experimental database on corrosion of structural materials in Sn was reviewed in the 3rd presentation at the session. This information is relevant for the evaluation of Sn and Li as a potential coolant/breeding material in austenitic and ferritic steels which corrode rapidly in Sn at temperature above ~400^{o}C. Additional experimental data are need for other structural materials, although several materials appear to be compatible with Sn at temperatures of interest for APEX. The physical nature of Sn interaction with structural materials needs to be experimentally examined, so as to plan for corrosion control strategies.

Summary of Session V: Plasma Interface Issues

Session Chair: Meade (PPPL)

Two presentations were given in this session by Uchimoto (UCLA) and Ezato (JAERI). Uchimoto investigated the transport of impurities from evaporated liquid wall surfaces and their impact on the plasma heat flux (mainly Bremsstrahlung and line radiation). He estimated the evaporation rate from the surface of FliBe used as the flowing liquid in liquid FW concept as a function of the liquid velocity and poloidal location in ITER-like device. In this assessment, the heat wall distribution on the liquid surface was first estimated using a developed code IONMIX. The radial temperature profiles were then calculated taking into consideration the x-rays attenuation characteristics in FliBe (provided by Youssef) and under the assumption of slug velocity profile and no convection or turbulence flow. As a future work, the accurate profile of the evaporation rate will be introduced to the UEDGE code to perform a comprehensive edge plasma analysis in which the effect of the magnetic field, location of the wall surface from the separatrix, and temperature of the evaporated gas are taken into consideration.

Ezato (JAERI) presented the time dependent temperature rise in the armor of the FW and the divertor as a function of the parameters pertaining to the incident run-away (RE) electrons. They include the incident angle, variation in energy density, location of incidence, and the total incident energy under ITER conditions (10-50 MJ/m2). The 3-D Monte Carlo code for electrons and x-rays (EGS-4) was applied and the volumetric heat deposition rates in the armor (Be for FW, CFC or W for the divertor) and the heat sink (Cu) were calculated followed by thermal response calculations with the ABAQUS code. Under 0.01 deg. Incident angle and toroidal magnetic field of 6T, the melting depth due to the RE is ~0.5 mm in Be case at energy density of 50 MJ/m2, ~0.3 mm in W case at energy density of 20 MJ/m2, a maximum surface temperature in the CFC case of ~2300 oC at energy density of ~75 MJ/m2. No damage to the Cu heat sink in these cases. Future work will include other incident angles and assessment of the proper conditions to avoid melting of the heat sink.

Summary of Session VI: Safety, Reliability, and Tritium Issues

Session Chair: Sze (ANL)/McCarthy (INEEL)

Petti (INEEL) presented some LOCA analysis for the He-4 cooled refractory metal high temperature FW/blanket concept in which W is used as the structure material and liquid Li as the breeder (see Session III). The CHEMCON code was used to investigate the peak and long-term temperature during a LOCA. Cases considered are (1) with and without VV cooling, and (2) with and without a gap between the shield and the VV. With no VV cooling. The FW temperature keeps rising and reaches unacceptable peak (~2100 K) after ~ 2 days after shutdown with no VV cooling. This temperature at this time frame is much lower (~1100 K) if VV is cooled, however, a sharp rise in FW temperature (~1700 K) occurs for a few minutes after ~0.03 day (~40 min) from shutdown. The presence of gap between the shield and VV tends to slightly increase the FW temperature if the VV is not cooled (no conduction path to the VV). However, the gap has larger impact (higher FW temperature at later times after shutdown) if the VV is cooled. Petti suggested minimizing the use of structural material with high decay-heat where possible, maximizing heat transfer, segmentation of the cooling loops, and maintaining active cooling to the VV as means to make designs better with respect to accident safety. He also indicated that Tin is an aerosol former and is radiological hazard with potential for mobilization from Sn-Li breeder that needs further investigation.

The reliability issues and available failure and time to repair data were discussed next by Cadwallader (INEEL). He indicated that the most valid data come from the field of experience and that fusion does not have a driving force to rigorously collect such data as fission does. Some data are currently recorded from the operation of DIII, TFTR, and JT-60. Typically, fusion safety analysts use inference and prediction techniques to obtain these data for different or new equipment. The IEA may provide a consensus data for future safety work from a meeting scheduled March 22-26 between US, EU and Japan. Cadwallader gave some failure rate data and representative time to repair for non water cooling loops (liquid metal, molten salt) for centrifugal pumps, EM pumps and motor-operated valves as obtained from fission reactors. He claimed that this data can be used in fusion with proper precautions.

Khater (UW) presented some activation results for the APPLE concept, the He-Cooled Refractory Alloy concept, and for the EVOLVE concept. For APPLE, he showed that the low activation ferritic steel shield will have to be disposed with the VV to meet the limits for class C low level waste (LLW) where as the 316SS shield will not qualify for disposal as class C LLW. For the helium-cooled concept, he showed that TZM ally produces less decay heat (DH) than the W-Re alloy but both are considered to produce relatively high level of DH. TZM alloy results in much higher waste disposal rating (WDR). The two alloys will not qualify for disposal as class C LLW if the waste is compacted. In the EVOLVE concept and after 1 FPY, the FW and cups would not qualify for disposal as LLW if the W alloy contains Nb or Ag impurities. Removing them would allow for the disposal of all components as class C LLW.

A plan of thermofluid safety experiments for fusion reactors was presented by Takase (JAERI). This planned experiments investigate the ingress of coolant event (ICE) in which the pressure rise in the plasma chamber will occur as a result of evaporation of leaked coolant upon encountering a rupture in the coolant channels. Water is considered in the present plan to simulate ITER condition. Main controlling factors are mode of evaporation during and after water injection (flashing and/or pool-boiling), time of injection, injected mass flow rate, volume of water in the containing vessel (VV). The proposed experiments simulate the plasma chamber, and part of the VV. Components that simulate water condensation and collection at the bottom of the VV below the divertor region is part of the planned experiments. The construction of the new test facility will be completed by end of 1999 and the test data will be used for validation of fusion safety analysis.

Summary of Session VII: Liquid wall Concepts

Session Chair: Morley (UCLA)/Nelson (ORNL)

Presentations were made by members of the UCLA team(Gulec, Morley, Smolentsev, Ying, and Youssef), Moir (LLNL), Fogarty (ORNL) and Woolley (PPPL) about the work in progress on the CLIFF concept, the GMD Pocket concept, and other variants of the thick liquid concepts including slow flowing EM restrained FW/Blankets and Swirl flow ideas for FRCs and STs. Work on modeling and analysis is proceeding well, in preparation for the interim report due the end of May. Several important conclusions from the LM-MHD and turbulent flow hydrodynamics analysis are summarized below.

- Simple 1D hydro modeling of CLIFF with Flibe indicates that the toroidal expansion/ contraction of the outboard module does not dramatically impact the flow height/speed (Morley).

- The presence of side walls in a CLIFF-LM module have a dramatic impact on the flow. Analysis indicates that electrically conducting penetrations of any kind are not allowable due to intense drag on the flow (slowing/thickening) and that insulated penetrations or side walls must be 2 m apart (Smolentsev). Penetrations of SiC might be allowable at a greater separation distance, depending of the conductivity of the SiC.

- LM-MHD CLIFF flows is unstable to long waves. The growth rate is slow enough that severe disruption of the flow is not a problem. It appears also that these long waves do not aid greatly in the surface heat transfer (Morley, Smolentsev).

- Thick liquid designs using LM may be attractive since the MHD drag can be tailored to offset acceleration due to gravity. Thick LM flows with velocity 6 m/s would have reduced flow rate compared to 10-15 m/s needed to keep Flibe from thinning (Ying).

- Initial calculations of flow around hydro dynamically shaped penetrations shows that care must be taken to be sure that flow closes in again behind the penetration (Gulec, Moir). Grooves and/or guiding vanes might be required. This is a very important issue for the FRC and Tokamak antennae.

- Progress continues of various attempts at LM-MHD free surface codes with axi-symmetric assumptions and variable magnetic fields (Wooley). This work is important to understand the effect of 1/R toroidal field dependence and time varying plasma events.

- Design drawings showing the CLiFF and GMD sector modules as well as nozzles and drainage system, were presented and discussed (Fogarty). Nozzles for CLIFF with no exposed solid wall were proposed.

- The potential for isotopic tailoring of Sn to improve the neutronic performance of Sn-Li was discussed (Youssef). The objective is to increase tritium breeding while reducing activation. There is a possibility to enhance TBR by 30-35% upon tailoring Sn to one of its natural isotopes which has the lowest absorption cross-section. Among the 10 natural isotopes of Sn, the Sn-116 appears to give the lowest absorption. This is supported by the activation analysis which showed that Sn-116 gives both very low short- and long-term activation in comparison to other natural isotopes of Sn.

In addition to the APEX presentations there were several interesting presentations from Japanese colleagues regarding LM-MHD (Takahashi, *et al.* T.I.T) and Flibe (Toda, Hashizume *et al.* Tohoku U.) research underway in Japan. Of particular interest is the presence of small experimental Flibe loop at Tohoku University. Collaboration with the US on more Flibe loops in currently under discussion as part of the Monbushu collaboration. Professor Kunugi reported extremely interesting ultra fast high heat flux laser melting and evaporation simulations during this session as well

Summary of Session VIII: Special FHPD Session

Session Chair: Toda (Tohoku U.)/Wong (GA)

Kunugi (U. of Tokai) presented a newly developed hydrodynamic code for numerical simulation of melting and evaporation due to ultra-short pulse laser irradiation. The code uses CIP computational method (Cubic Interpolated Propagation) and C-CIP method (CIP-Combined Unified Procedure. The equation of state (EOS) includes 3 phases, solid, liquid, and gas (P-ρ-T). . The governing equation of mass, momentum, energy, interface, and EOS are included. Benchmark problems were tested with the code. Remaining issues to be implemented in the code are: (1) appropriate modeling for laser-plasma interaction (absorption, refraction in a dense plasma), (2) Exact treatment in the solid region (elastic-plastic/viscoelastic model), and validating the code by making comparison to measured data.

Toda (Tohoku U.) presented the technical reasons, history, design and progress of the FliBe loop in Tohoku University for the development of the FliBe blanket. This task is performed in collaboration with NIFS. This loop has a test section of 70 cm in length, with a Flibe flow rate of 10 l/min and an operating temperature range of 773-873 K. The final design of the loop is completed and the fabrication of the loop is about complete.

Toda presented also the present status of liquid blanket chemistry study in Japan and proposal to Japan-US collaboration for Takayuki Terai (U. of Tokyo). He indicated that the critical issues for the NIFS FFHR design are: low tritium breeding ratio, high coolant melting point, heat transfer, tritium control, compatibility with structural material and the needed development of molten salt technology. Under this 5 years program, experiments are being planned and performed to address the issues of compatibility of structural materials, both static and dynamic experiments, and tritium release and extraction. Many items are proposed for the Japan-US collaboration including experiments in the studying of compatibility and chemistry control in Flibe, including the tritium system design and comparison with other liquid blanket designs.

Suzuki (U. Tokyo) presented the results on in-pile experiments on tritium release from Flibe studying the effects between HT and TF. He found that TF has smaller tritium permeation rate but it has issues on corrosion and tritium inventory. HT form will have smaller tritium inventory in Flibe but the tritium permeation rate through metal is much higher. He suggested to use Be as a reducing agent.

Summary of Session IX: Evaluation Criteria for APEX

Session Chair: Sawan (UW)/Malang (FZK)

In this session, Mohamed Sawan presented the evaluation criteria developed for use in the Scientific Evaluation of the APEX concepts. The schedule for the evaluation process was discussed. Mohamed Abdou suggested that because of the very busy summer schedule including Snowmass and ISFNT-5, it might not be practical to schedule the originally planned community workshop. Presentations on APEX in different meetings and conferences will allow us to get feedback from the community. The scientific evaluation should be carried out in September following the release of the interim report on July 1 and receiving community feedback in the Snowmass meeting.

An expanded version of the scientific evaluation criteria was presented. This includes detailed description of the different criteria as contributed by several members of the evaluation group. These criteria fall into four categories as follows:

- Does the concept meet the minimum functional requirements?
- Tritium breeding
- Tritium extraction
- Vacuum and plasma exhaust
- Power extraction
- Does the concept have potential for improved attractiveness?
- High power density and heat flux handling
- High power conversion efficiency
- High availability (low failure rate and short maintenance time)
- High safety & environmental attributes
- Low cost
- What are the design margins and uncertainties?
- What are the major critical issues and R&D needs?

The criteria were discussed and several comments and suggestions were made. These will be included in a revised version which will be made available before the May meeting.

Summary of Session X: "Hot Issues"

Session Chair Abdou (UCLA)

The Fusion Summer Study is scheduled to be held for two weeks in Snowmass, Co, during July, 1999 (details on http://www.pppl.gov/snowmass/). It is organized by community and chaired by Rich Kawryluk, Grant Logan, and Mike Mauel. The study will develop community consensus on (1) key issues for plasma science, technology, energy, and environment, and (2) opportunities and potential contributions of existing and possible future facilities and programs to reduce costs and increase fusion's attractiveness. The working group format will include a Technology Working group which will consist of two subgroups: (1) Chamber Technology (for MFE and IFE), and

(2) Plasma Support Technology. There are questions that will be carefully examined during the study and are common to all Technology subgroups: (A) what are the most important contributions that technology can make over the next 10 years to improve the vision for an attractive and competitive fusion product?, (B) what are the new technology issues that must be solved to allow the continued exploration of “Advanced Tokamaks” and to enable full development of the recently initiated or planned innovative confinement concepts and next step devices, and (C) what constitutes engineering proof of principle and engineering proof of performance for fusion energy systems. For subgroup for the Chamber Science and Technology , the following questions will be addressed:

(1) What are the merits and issues for liquid walls? What experiments , modeling, and analysis must be done to judge their potential for MFE and IFE? (Including plasma-liquid interaction issues). What are the key go/no go issues and how they can be explored quickly?
(2) What advances may be possible for evolutionary concepts (e.g. solid plasma facing materials, traditional blanket concepts)? What are the potential near-term applications for this area? What is the potential for achieving high temperature and high power density?
(3) What should the reliability (MTBF), maintainability (MTTR), and life time goals be to achieve the goal availability? What can we do today, given the lack of fusion testing data, to assess the prospects for various proposed technology concepts and designs? Given the difficult constraints on the program, how can we show that fusion chamber technologies will be able to meet the reliability, maintainability, and availability goals?
(4) When are neutron sources and fusion technology testing facilities needed? What issues differentiate among the various options for testing facilities?
(5) What is the better strategy for fusion waste minimization: hazard versus volume? What are the implications for each strategy for fusion potential R&D? What is the potential for recycling?
(6) What is the potential of current plasma confinement and chamber technology concepts for attaining tritium self-sufficiency? (including issues of tritium fractional burnup in the plasma and tritium permeation, inventory, and processing.)
(7) What advantages may be possible in materials over the next 10 years that can contribute to : 1) improving the vision for an attractive and competitive fusion energy system, and 2) lowering the cost and time for fusion R&D.

Summary of Session XI: Study Direction for APEX and Action Items

Session Chair: Abdou (UCLA)

The outlines of APEX Interim report and schedule were discussed in this session. The latest version of these outlines with lead authors of the various chapters (and sub-sections) can be found in Appendix VII. The report will include 18 Chapters, including an introduction, overview, and study approach Chapters. The other Chapters cover all the concepts under investigation as well as the APEX groups (Plasma Interface, Material, Safety, Activation Consideration, Tritium, Power Conversion, and Evaluation Criteria,) findings. The report will also include a dedicated Chapter on key issues and near- and intermediate-term R&D. The lead author for each Chapter and the core group of co-authors have been assigned (See Abdou’s presentation, November, 1998 meeting). The deadlines of issuing the report are agreed upon as follows:

June 1, 1999: Draft assembly
- section authors send first draft to Chapter key author with copies to other authors.
- Comments to be sent back to authors by June 15
- Second draft to key author by June 30

July 1, 1999: Draft report
- Key authors send Chapters to M. Abdou and to all members of the team
- Comments from team to authors by July 15

July 30, 1999: Final Interim Report
- All Chapters mailed to M. Abdou

August 15, 1999: mail report by UCLA
- UCLA will mail report to community
-

The schedule for the evaluation process was discussed. The scientific evaluation will be carried out in September following the release of the interim report on July 1. Abdou suggested that getting a feedback from people to whom the report will be mailed, and receiving feedback from the participants of the Snowmass meeting, could replace the need to have a community workshop, as was planned earlier.

The process of the competitive proposals for APEX (and ALPS) was given by Berk. The solicitation for Phase I will be in the Summer of 1999. Competition between laboratories, universities, and industry is sought. Ideas about new concepts, key issues of concepts, and the next step towards a proof-of-principle (POP) experiments are in the scope of this open competition. It is anticipated to offer 2-3 awards (~$100K each). There will be muti-phases in the process of POP, namely: (1) pre-conceptual design (define concept, facility, etc..), (2) conceptual design, and (3) engineering design. The pre-conceptual design could start late in 1999, conceptual design could start mid-t-late in year 2000, Engineering design could start late in year 2001, fabrication could start late in year 2002, and testing could start late in year 2003.

Summary of Session XII: Fusion High Power Density Workshop (Cont'd)

Session Chair: Nygren (SNL)/Sagara (NIFS)

Wong (GA) discussed the various factors that affect the cost of electricity (COE) in Tokamaks. He showed the COE for SC coil and normal conducting (NC) coil in Tokamaks. For a SC coil Tokamak with aspect ratio A=4 and major radius Ro=5.9 m, the operating range for key parameters that gives COE 6-8 cents/kWh is: Coil current 26-31 MA/m2, net power 1-2 Gwe, and NWL 4-7 MW/m2. For NC coil in Tokamak with A=1.4 and Ro=3.3 m, the COE is 6.4-8 cents/kWh for net power 1-2 Gwe, water velocity <10m/s, and NWL 4-6.6 MW/m2. The results thus show that 2 Gwe NC or SC Tokamak can have COE ~ or < 65 mill/kWh.

Nygren (SNL) gave a brief review of Sandia's PMTF, previous testing of W brush armor mockups, and recent HHF test of W brush armor performed in 1999. He showed the PW10 Mockup (made by Plasma Processes through DOE's Small Business Innovative Research Program) which has W "brush" embedded in plasma sprayed copper and survived 500 cycles at 30MW/m^2. The rods splayed slightly during testing. In the last 30 cycles (pattern off center), some rods received >30MW/m^2 and melted. The loss from evaporation was evident in these tests.

The development of HHF components in JAERI was then described by Ezato (JAERI). The Particle Beam Engineering Facility (PBEF) at JAERI was upgraded for heating on large components using large ion source. A lower vertical target mockup with a full scale length that simulated ITER divertor cassette was fabricated and thermal cycle tests were performed. It was shown that the mockup satisfied ITER divertor heat load conditions, namely, 5 MW/m2, 30 second for 3000 cycles, and 20 MW/m2, 10 second for 1000 cycles. In the later case, erosion of armor was ~ 1 cm.

Sagara (NIFS) and Motojima (NIFS) discussed the present status and recent studies of LHD type reactors in Japan. This project is a collaboration between NIFS and several universities (Tokai, Tohoku, Kyoto, U. of Tokyo, NRI for metal). The design of FFHR-1 was completed in 1993 and the design of FFHR-2 was completed in 1995. The later in undergoing now processes of optimization. The conceptual design is planned to be completed by year 2005 (Phase II) and the Engineering Design Phase (Phase III) will start thereafter. FFHR-2 has a major radius of 10 m, average plasma radius of 1.2 m, average magnetic field of 10 T (13 T max.) and current/coil of 50 MA. The force-free-like continuous coils with the helical pitch of 1.15 is within the experimental range in HLD. A localized blanket concept is adopted. Under optimization, the current TBR is ~0.8. This raised a concern during the discussion since the goal should be TBR ≥1.1. Nuclear blanket design is optimized but improvements are still needed. Flibe is used as a self-cooling tritium breeder because of its low T solubility, low reactivity and it is compatible with high magnetic fields. Low activation ferritic steel (JLF-1: Fe-9Cr-2W) is the first candidate for structure with V-4Cr-4Ti alloy as a second choice.

The Collaboration work in Japan on Flibe R&D was also described. Material dipping tests on corrosion-resistance and neutron irradiation are done in collaboration with U. of Tokyo. Constructing an active flow loop (~100kg) is done in collaboration with Tohoku university. This area of research is also the subject of collaborative work between the US and Japan.

The work of Baxi and Chin (GA) on the relationship between incident heat flux (IHF) and wall heat flux (WHF) was summarized by Wong (GA). The mockup of the this HHF component is a Glidcop Al-25 with 2mm thick swil tape and is water cooled with inlet condition of ~130 C and 4Mpa.With a uniform heat flux over 100 mm length, the ratio of WHF/IHF is ~ 1.4 up to IHF of 30 MW/m2With peaked HF (peaking factor of 3), This ratio is lower than the uniform HF case. This ration thus depends on the HF profile, HF level, and k of material under consideration. The critical heat flux (CHF) for uniform HF case can be calculated accurately. Good accuracy can also be achieved for the surface temperature for all HF profiles. Post CHF type analysis is required however for non uniform heat flux to accurately predict critical heat flux.

Summary of Session XIII: Fusion High Power Density Workshop (Cont'd)

Session Chair: Toda (Tohoku U.)/Wong (GA)

Professor Saburo Toda and Dr. Clement Wong summarized the observations from the combined APEX project meeting and the US/Japan Fusion High Power Density Workshop. Both expressed thanks to Professor Mohamed Abdou and Dr. Mahmoud Youssef of UCLA of hosting and organizing the successful combined meeting.

Common areas of interest from the two meetings were identified as follows:

- ·Research in the high performance FliBe coolant/breeder
- Study of particulate and liquid mist design to enhance heat transfer at low system pressure
- ·MHD research for liquid metal on both free surface and channel flow designs
- Conceptual reactor and high heat flux components design
- Fundamental studies in neutronics
- Fundamental studies in thermal fluid and high heat flux heat transfer
- Material research
- .Safety and accident analysis

These are crucial elements that we need to understand in making progress towards the goal of coming up with highly reliable high power density fusion components.

A short discussion took place and the US and Japan delegations recommended that the next FHPD workshop to be held in Japan in the year 2000 and the time and place would be determined later this year.

III: Action Items

(1) The next APEX meeting will be held: May 12-14, 1999, Princeton University.

(2) The deadlines of issuing the APEX Interim Report were agreed upon as follow:

June 1, 1999: Draft assembly
  - section authors send first draft to Chapter key author with copies to other authors.
  - Comments to be sent back to authors by June 15
  - Second draft to key author by June 30

July 1, 1999: Draft report
  - Key authors send Chapters to M. Abdou and to all members of the team
  - Comments from team to authors by July 15

July 30, 1999: Final Interim Report
  - All Chapters mailed to M. Abdou

August 15, 1999: mail report by UCLA
  - UCLA will mail report to community
  -

(3) The scientific evaluation will be carried out in September following the release of the interim report on July. Getting a feedback from people to whom the report will be mailed, and receiving feedback from the participants of the Snowmass meeting, could replace the need to have a community workshop, as was planned earlier, but this will be decided soon.

(4) The solicitation for Phase I of the process of the competitive proposals for APEX (and ALPS) will be in the Summer of 1999. Competition between laboratories, universities, and industry is sought. Ideas about new

concepts, key issues of concepts, and the next step towards a proof-of-principle (POP) experiments are in the scope of this open competition.

(5) It was agreed to continue establishing collaboration between Japan and the U.S in common areas of interest including research in the high performance FliBe coolant/breeder, Study of particulate and liquid mist design to enhance heat transfer at low system pressure, MHD research for liquid metal on both free surface and channel flow designs, conceptual reactor and high heat flux components design, fundamental studies in neutronics, fundamental studies in thermal fluid and high heat flux heat transfer, material research, and safety and accident analysis

(6) The US and Japan delegations recommended that the next FHPD workshop to be held in Japan in the year 2000 and the time and place would be determined later this year.

Appendix I

Agenda for APEX-6/FHPD Workshop at UCLA

February 16-19, 1999

Faculty Center (Feb. 16-18)

(Note that only Friday Feb. 19 will be in Engr. IV Bldg., Room 37-124)

Tuesday, February 16, 1999

Hacienda Room, Faculty Center

8:30 a.m.	Coffee/Muffins	

Session I: Study Status and Direction (Chair: Berk)

9:00 a.m.	Welcome and Opening Remarks	Abdou
9:10 a.m.	*Introduction and Background of the US/Japan FHPD Workshop*	Wong
9:20 a.m.	*Introduction of Japanese Participants*	Toda (Tohoku U.)
9:30 a.m.	**OFES Remarks**	Berk
9:50 a.m.	Status and Direction of APEX Study	Abdou
10:20 a.m.	APEX Secretary's Announcements	Youssef
10:30 a.m.	Coffee Break	

Session II: EVOLVE, APPLE Concepts and Related Japanese Activities (Chair: Mattas)

10:40 a.m.	EVOLVE Concept:	
	Overview and Status	Mattas/Malang
	Heat Transfer Considerations	Mattas/Mogahed
	Shield Requirements and Neutronics Parameters	Sawan
	Configuration	Fogarty/Nelson
	Structural Considerations	Najumdar/Mattas
11:50 a.m.	*Applicability of Liquid Metal Mist Cooling for High Heat Flux Systems*	Toda/Hashizume (Tohoku Univ.)
12:15 p.m.	Lunch	
1:30 p.m.	*High-Heat-Flux Heat Removal by Evaporated Fluid in Porous Media*	Toda/Hashizume (Tohoku Univ.)
2:00 p.m.	Group Discussion	
2:15 p.m.	APPLE Concept:	
	Recent Development on the APPLE Concept	Sze/Tillack
	Configuration	Sze/Igor
	Updated Neutronics Parameters	Sawan
3:00 p.m.	*Perspective of Forming High Efficiency Energy Conversion System Using Particulate or Suspension Medium*	Shimizu (Kyushu Univ.)
	Coffee Break	
3:30 p.m.	*Some Issues Related to the Simulation of Dense Particulate Systems*	Yokomine
3:45 p.m.		(Kyushu Univ.)
4:15 p.m.	Group Discussion	

Session III: He-Cooled Refractory Metal FW/Blanket/Divertor Concept (Chair: Wong/Nygren)

4:30 p.m.	Thermal Hydraulics of the APEX He-cooled FW/Blanket Design	Wong
4:50 p.m.	*Heat Transfer Characteristics in Helium-Cooling Porous Channels*	Takase (JAERI)
5:10 p.m.	Update on Design and Manufacturing Plan for He-Cooled Heat Sink	Nygren
5:30 p.m.	Mechanical Design for Helium-Cooled Refractory Material FW/Blanket Concept	Fogarty/Nelson
5:50 p.m.	Damage Indices in He-Cooled Refractory Alloys FW/Blanket - Comparison for Solid and Liquid Walls	Youssef
6:10 p.m.	Group Discussion	
6:30 p.m.	Adjourn	

Wednesday, February 17, 1999

California Room, Faculty Center

8:00 a.m.	Coffee/Muffins	

Session IV: Materials and Data Base Evaluation (Chair: Zinkle/Ghoniem)

8:30 a.m.	Oxygen Pressure Limits for V, Nb and Ta alloys	Zinkle

8:45 a.m.	Overview of Experimental Data Base on Sn Corrosion	Zinkle
9:00 a.m.	Oxygen Pressure and Temperature Limits for Mo and W Base Alloys	Ghoniem
9:15 a.m.	Group Discussion	

Session V: Plasma Interface Issues (Chair: Meade)

9:30 a.m.	Self-Consistent Transport Analysis of Impurity from Liquid Wall Surface	Uchimoto (UCLA)
10:00 a.m.	*Numerical Analyses of Run-away Electrons onto Plasma Facing Components, Ezato (JAERI)*	Ezato (JAERI)
10:20 a.m.	Coffee Break	

Session VI: Safety, Reliability, and Tritium Issues (Chair: Sze/McCarthy)

10:35 a.m.	Progress in Understanding Safety Issues in Various APEX Designs	McCarthy/Petti
11:00 a.m.	Recent Evaluation of Sn-Li from Safety Viewpoint	McCarthy/Petti
11:15 a.m.	Fusion Components Reliability Issues	Cadwallader
11:45 a.m.	Activation Analysis of Several HPD Concepts	Khater
11:55 a.m.	*Thermal-Hydraulic Characteristics During Transient Events in Fusion Reactors*	Takase (JAERI)
12:15 p.m.	Lunch	

Session VII: Liquid Wall Concepts (Chair: Morley/Nelson)

1:30 p.m..	Progress on CliFF Concept for Advanced Tokamaks	Morley
2:00 p.m.	Studies of MHD Film Flows and Heat Transfer and their Applications to CLiFF Concept	Smolentsev
2:30 p.m..	Initial Exploration of Rotational Flow in an Advanced Tokamak Configuration	Gulec
2:50 p.m.	Progress on the Minimum Structure GMD Thick Liquid Wall Concepts for Advanced Tokamak Configurations	Ying
3:20 p.m.	Coffee Break	
3:35 p.m.	Electromagnetic Liquid Metal Wall Phenomena	Woolley
4:05 p.m.	Liquid Walled FRC Progress Report	Moir
4:30 p.m.	Progress on SWIRL Concepts for FRC and ST	Gulec
5:10 p.m.	*Enhanced Heat Transfer for FLiBe Blanket System Using Swirl Flow Method*	Toda/Hashizume (Tohoku Univ.)
5:40 p.m.	Flowing liquid: GMD, CLIFF , and FRC CAD Modeling and Concepts	Nelson
6:00 p.m.	Can We Improve the Potential of Li-Sn Liquid for Tritium Breeding?-Activation Issues Involved.	Youssef
6:15 p.m.	Group Discussion	
6:30 p.m.	Adjourn	

Thursday, February 18, 1999

Downstairs Lounge, Faculty Center

8:00 a.m.	Coffee/Muffins	

Session VII: Liquid Wall Concepts (Chair: Morley/Nelson) (Continued)

8:30 a.m.	*Recent Research Activities on Liquid Metal MHD Phenomena in Japan*	M. Takahashi (TIT)
8:55 a.m.	*Liquid Metal MHD Flow and Heat Transfer*	M. Takahashi (TIT)
9:20 a.m.	Group Discussion	

Session VIII: Special FHPD Session (Chair: Toda/Wong)

9:30 a.m.	*Numerical Simulation of Melting and Evaporation Due to Ultra-Short-Pulse Laser Irradiation*	Kunugi (Univ. of Tokai)
10:00 a.m.	*A High Temperature FLiBe Loop Developed in Tohoku University in Collaboration with NIFS*	Toda/Hashizume (Tohoku Univ.)
10:30 a.m.	Coffee Break	
10:45 a.m.	*Present Status of Liquid Blanket Chemistry Study in Japan and Proposal to Japan-US Collaboration*	Written by Terai (Univ. of Tokyo), Presented by S.Toda
11:15 a.m.	*In-pile Experiments on Tritium Release from Flibe*	Suzuki
11:35 a.m.	Group Discussion	

12:00	Lunch	

Session IX: Evaluation Criteria For APEX Concepts (Chairs: Sawan/Malang)

1:30 p.m.	Evaluation Criteria	Sawan
2:00 p.m.	Discussion on Evaluation Criteria	

Session X: "Hot Issues" (Chairs: Abdou)

3:00 p.m.	• Discussion of Three Issues of High Priority for APEX • Discussion on "Snowmass-type" Hot Topics	

Session XI: Study Direction for APEX and Action Items (Chair: Abdou)

4:00 p.m.	• Interim Report Outline and Schedule • Competitive Proposals Process • Future Directions and Comments • Next Meeting Plans	
5:00 p.m.	Status of "FIRE" (Seminar in Hacienda Room)	Meade
6:00 p.m.	**Adjourn**	
7:00 p.m.	**Dinner**	

Friday, February 19, 1999

Engr. IV Bldg., Room 37-124

8:00 a.m.	Coffee/Muffins	

Session XII: Fusion High Power Density Workshop (Cont'd):(Chair: Nygren/Sagara)

8:30 a.m.	*The Meaning of High Power Density for Tokamak Reactors*	Wong
9:00 a.m.	*Development of Tungsten Brush Armor*	Nygren
9:20 a.m.	*Development of High Heat Flux Components in JAERI*	Ezato (JAERI)
9:40 a.m.	*Recent Studies of LHD Type Reactor*	Sagara (NIFS)
10:05 a.m.	*Present Status of LHD*	Motojima (NIFS)
10:40 a.m.	Coffee Break	
10:55 a.m.	*Relationship Between Incident Heat Flux and Coolant Channel Heat Flux for Peaked Profiles*	Baxi
11:15 a.m.	Group Discussion	
12:15	Lunch	

Session XIII: Fusion High Power Density Workshop (Cont'd):(Chair: Toda/Wong)

1:30 p.m.	• FHPD Workshop Collaboration	Toda/Wong
2:30 p.m.	• US-Japan Collaboration	Berk/Sze/Motojima
3:30 p.m.	**Adjourn**	

Appendix II

ATTENDEES

U.S.A.

Mohamed Abdou (UCLA)
Sam Berk (Monitor, OFES)
Leslie Bromberg (MIT)
Lee Cadwallader (INEEL)
Edward Cheng (TSI Research)
V Dhir (UCLA)
Paul Fogarty (ORNL)
Nasr Ghoniem (UCLA)
Karani Gulec (UCLA)
Hesham Khater (UW)
Siegfried Malang (FZK)
Rich Mattas (ANL)
Dale Meade (PPPL)
Ralph Moir (LLNL)
Neil Morley (UCLA)
Richard Nygren (SNL)
David Petti (INEEL)
Mohamed Sawan (U.WIS)
Shahram Sharafat (UCLA)
Sergey Smolentsev (UCLA)
Dai-Kai Sze (ANL)
Mark Tillack (UCSD)
Tetsuya Uchimoto (UCLA)
Mike Ulrickson (SNL)
Scott Willms (LANL)
Clement Wong (GA)
Robert Woolley (PPPL)
Alice Ying (UCLA)
Mahmoud Z. Youssef (UCLA)
Steve Zinkle (ORNL)

Japan

Koichiro EZATO (JAERI)
Hidetashi HASHIZUME (Tohoku U.)
Tomoaki KUNUGI (Tokai U.)
Osamu MOTOJIMA (NIFS)
Akio SAGARA (NIFS)
Akihiko SHIMIZU (Kyushu U.)
Akihiro SUZUKI (U. of Tokyo)
Minoru TAKAHASHI (T.I.T.)
Kazuyuki TAKASE (JAERI)
Saburo TODA (Tohoku U.)
Takehiko YOKOMINE (Kyushu U.)

In addition to Graduate Students from UCLA

Appendix III

UCLA - APEX Planning Group Contact Information (rev. 11/10/98)

Name	Office Phone	Facsimile	Email
Mohamed Abdou	(310) 206-0501	(310) 825-2599	abdou@fusion.ucla.edu
Mohamad Dagher	(310) 787-7097	(310) 787-7099	mdagher@engineer.com
Vijay Dhir	(310) 825-8507	(310) 206-4830	vdhir@seas.ucla.edu
Nasr Ghoniem	(310) 825-4866	(310) 206-4830	ghoniem@seas.ucla.edu
Karani Gulec	(310) 206-2560	(310) 825-2599	karani@fusion.ucla.edu
Neil Morley	(310) 206-1230	(310) 825-2599	morley@fusion.ucla.edu
Sergey Smolentsev	(310) 794-5366	(310) 825-2599	sergey@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

APEX Planning Group Contact Information (rev. 11/10/98)

Name	Office Phone	Facsimile	Email
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 (BOEING)	(818) 586-1433	(818) 586-9481	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 (U.WIS)	(608) 263-2167	(608) 263-4499	khater@engr.wisc.edu
Mike Kotschenreuther (U.TXS)	(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)	(925) 422-9808	(925) 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
John Santarius (U.WIS)	(608) 263-1694	(608) 263-4499	rantarius@engr.wisc.edu
Mohamed Sawan (U.WIS)	(608) 263-5093	(608) 263-4499	sawan@engr.wisc.edu
Igor Sviatoslavsky (U.WIS)	(608) 263-6974	(608) 263-4499	igor@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
Steve Zinkle (ORNL)	(423) 576-7220	(423) 574-0641	zinklesj@ornl.gov

Appendix IV

SECRETARY'S ANNOUNCEMENTS

APEX 6th Meeting

UCLA, November 2-4, 1998

SUMMARY OF LAST/PRESENT MEETING

- Summary of last meeting was distributed to participants and posted on the APEX web site . (http://www.fusion.ucla.edu)
- Session Chair Person(s): Please provide a summary of your session within 10 days after the conclusion of the workshop. Let Secretary knows if you can't meet this deadline.

Please provide Secretary with copy of your presentation before you leave UCLA. On the other hand, forward electronically your presentation, preferably in pdf or postscript form.

OUTLINES OF APEX INTERIM REPORT (ATTACHED)

Need Input from Meade, Zinkle, and Abdou

ACTION ITEMS FROM LAST MEETING (ATTACHED)

GENERAL ANNOUNCEMENT:

A Shuttle Bus will take participants from Double Tree Hotel to Workshop Location (Faculty Center Feb. 16-18, Engr. IV Building Feb. 19): as follows

Leaves Hotel: 8:15 am (Feb. 16), 7:45am (Feb. 17-19)
Leaves Workshop Location to Hotel: 6:45 pm

APEX Secretary
M. Youssef, February 16, 1999

Action Items from November 2-4, 1998 APEX Meeting

(1) M. Sawan (UW) now leads the Evaluation Criteria Group.

(2) Dai-Kai Sze will lead the "Tritium and Liquid Coolants/Breeders Data Base" group and that the scope of the Flibe group is expanded to address Li, Flibe, Li-Sn, and other options.

(3) Forming a new group (Led by McCarthy) that examines the issues associated with low activation goals and the role of high temperature refractory alloys in the context of APEX,

(4) The outlines of the Interim report has been developed. The reports will include 18 Chapters, including an introduction, overview, and study approach Chapters. The other Chapters cover all the concepts under investigation as well as the APEX groups (Plasma Interface, Material, Safety, Activation Consideration, Tritium, Power Conversion, and Evaluation Criteria,) findings. The report will also include a dedicated Chapter on key issues and near- and intermediate-term R&D. The lead author for each Chapter has been assigned. The deadlines of issuing the report are:

- February 15, 1999: finalize report outline (Draft of outlines written by lead author is due by Mid January, 1999
- June 1, 1999: Draft assembly
- July 1, 1999: Draft report
- July 30, 1999: Final Interim Report
- August 15, 1999: mail report by UCLA.

(5) Submission of abstract to the upcoming ISFNT-5 is encouraged. Abstracts due January 19, 1999. Titles of abstracts and list of authors are due to M. Abdou by December 15.

(6) Next APEX meeting will be during February, 1999, either 9-12 or 16-19. Final date will be announced soon.

(7) There is a plan to hold an APEX workshop for the community to report progress, new ideas, and results of analysis and to receive feedback from the community. The date of the workshop will be after the issuance of the Interim Report (suggested dates: September 8-10, October 19-21, 1999). The final date will be announced soon.

(8) The Evaluation Group will convene after the community workshop to evaluate the concepts based on information from the interim report and feedback from community. Experts from outside the APEX team might be added to the evaluation group during the concept evaluation.

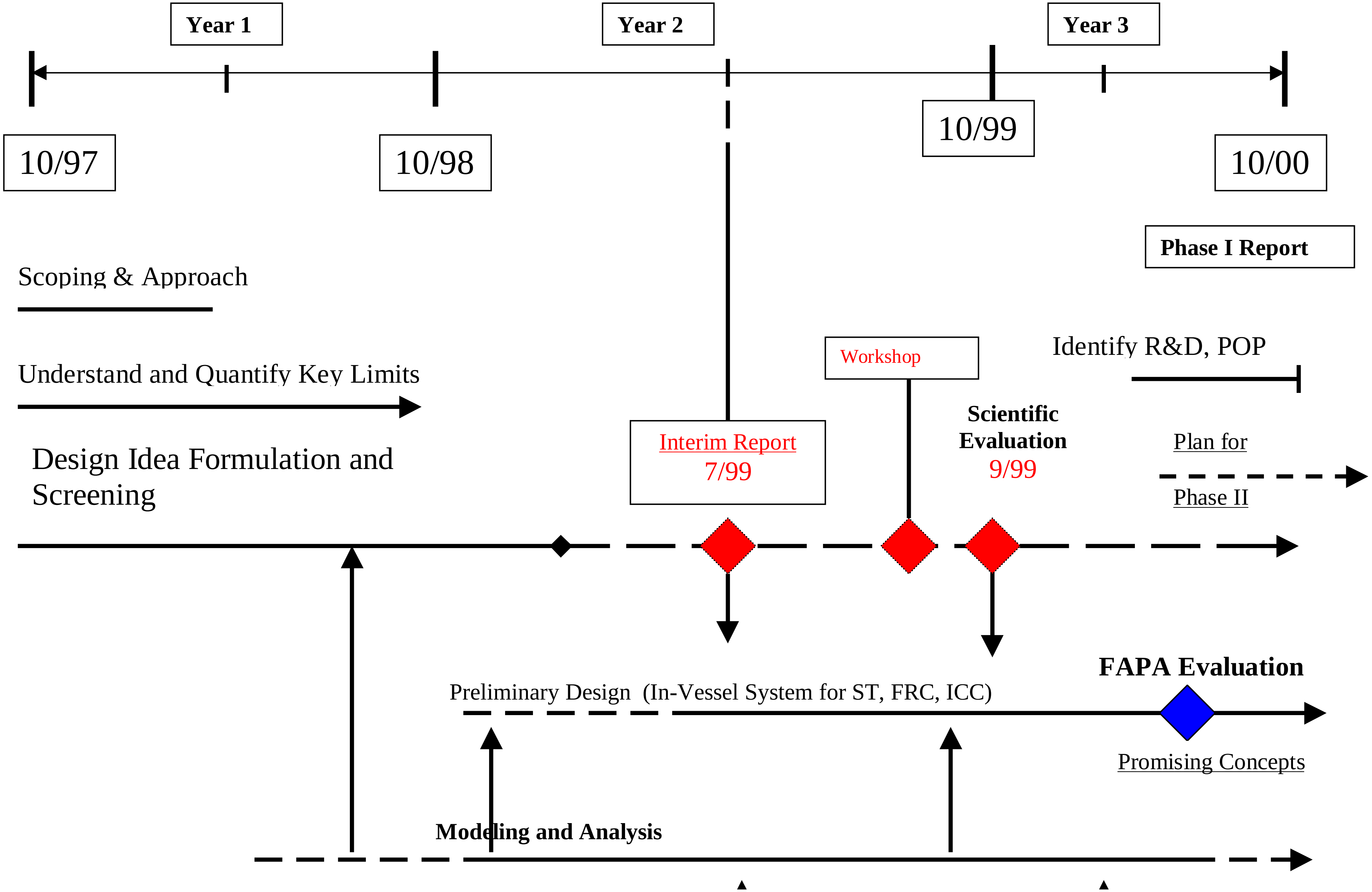
(9) The APEX schedule and modified organizational chart are given in Appendix V and VI, respectively.

(10) Conference calls are to be established for each concept at least once a month.

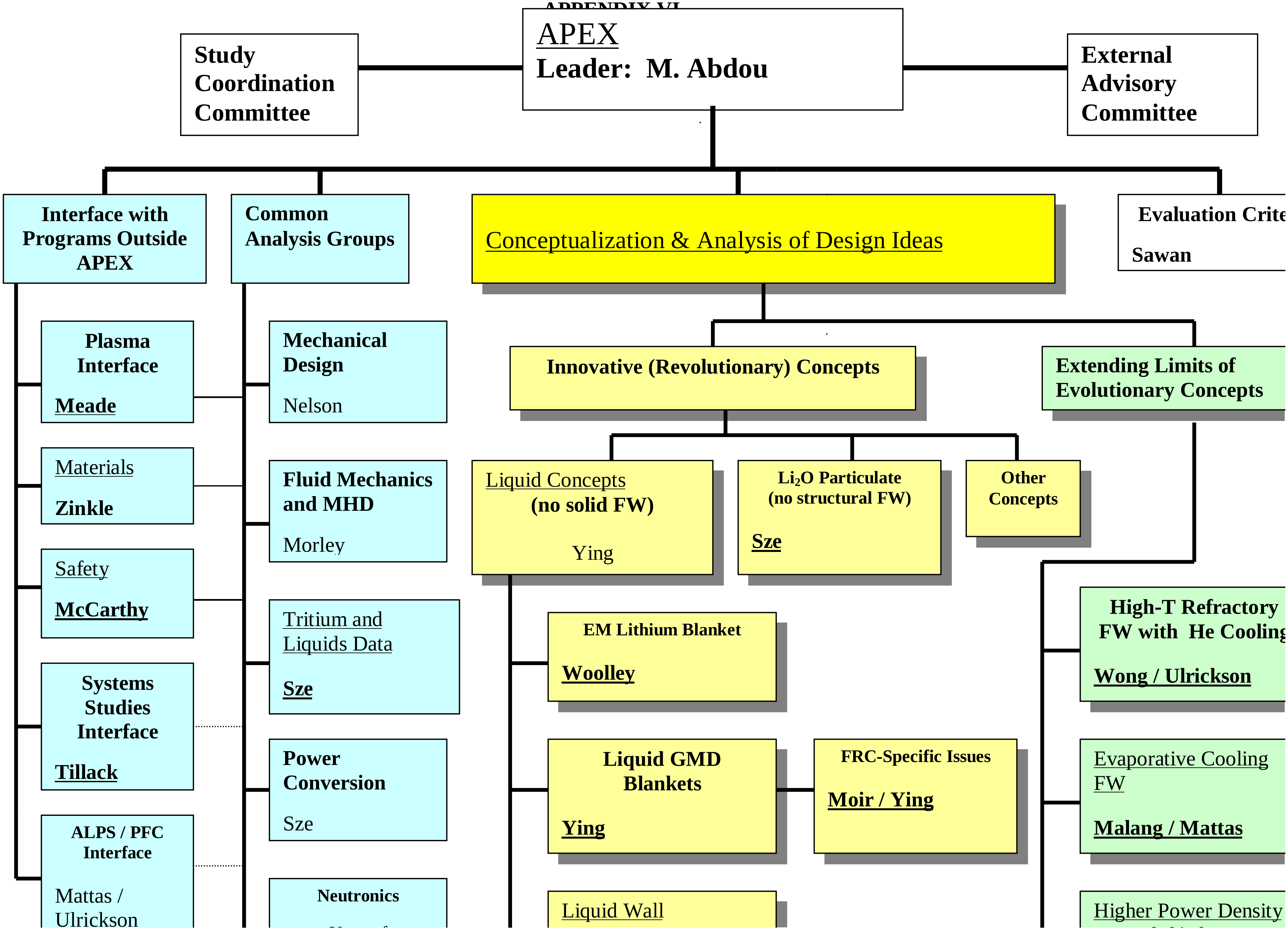
Project conference calls will also be established. The first project conference call is scheduled after Thanksgiving (between December 5-10). Final date will be announced soon.

APPENDIX V

APEX Schedule and Milestones for Phase I



APPENDIX VI



APEX
Leader: M. Abdou

- **Study Coordination Committee**
- **External Advisory Committee**
- **Interface with Programs Outside APEX**
  - **Plasma Interface** — **Meade**
  - Materials — **Zinkle**
  - Safety — **McCarthy**
  - **Systems Studies Interface** — **Tillack**
  - **ALPS / PFC Interface** — Mattas / Ulrickson
- **Common Analysis Groups**
  - **Mechanical Design** — Nelson
  - **Fluid Mechanics and MHD** — Morley
  - Tritium and Liquids Data — **Sze**
  - **Power Conversion** — Sze
  - **Neutronics**
- Conceptualization & Analysis of Design Ideas
  - **Innovative (Revolutionary) Concepts**
    - Liquid Concepts **(no solid FW)** — Ying
      - **EM Lithium Blanket** — **Woolley**
      - **Liquid GMD Blankets** — **Ying**
        - **FRC-Specific Issues** — **Moir / Ying**
      - Liquid Wall
    - **Li$_2$O Particulate (no structural FW)** — **Sze**
    - **Other Concepts**
  - **Extending Limits of Evolutionary Concepts**
    - **High-T Refractory FW with He Cooling** — **Wong / Ulrickson**
    - Evaporative Cooling FW — **Malang / Mattas**
    - Higher Power Density
- **Evaluation Crite**
  - **Sawan**

APPENDIX VII
Outline of the APEX report. (Revised February 26, 1999) and Deadlines

Executive Summary (**Abdou**)
1. Introduction (**Abdou**)
2. Overview (**Abdou**, et al)
3. Study Approach (**Abdou**, et al)
4. Evaluation Criteria (**Sawan**, et al)
    4.1 Introduction
    4.2 Evaluation Plans and Schedule
    4.3.Information Required for Scientific Evaluation
    4.4 Scientific Evaluation Criteria
        4.4.1 Minimum Functional Requirements
        4.4.2 Potential for Improved Attractiveness
            4.4.2.1 High Power Density and Heat Flux Handling
            4.4.2.2 Power Conversion Efficiency
            4.4.2.3 Availability
            4.4.2.4 Safety and Environmental Attributes
            4.4.2.5 Cost
        4.4.3 Design Margins and Uncertainties
        4.4.4 Critical Issues and R&D Needs
5. Thick Liquid Blanket Concept
    5.1 Introduction **Ralph Moir**
    5.2 Idea Description and Rationale **Alice Ying/ Ralph Moir/ Karani Gulec**
        5.2.1 General Perspective
    5.2.2 Applications to Tokamaks
        5.2.3 Applications to ST
        5.2.4 Applications to FRC
    5.3 Neutronics **Mahmoud Youssef**
        5.3.1 Energy Deposition due to X-ray Penetration
        5.3.2 Nuclear Heat Generation within Blankets
        5.3.3 Tritium Breeding and Power Multiplication
        5.3.4 Decay Heat and Activation **Hesham Khater**
    5.4 Hydrodynamics Analysis **Karani Gulec/Neil Morley/ Sergey Smolentsev**
        5.4.1 Hydrodynamics Characteristics of Tokamaks Thick Liquid Blankets
        5.4.2 Hydrodynamics Design of ST **Karani Gulec**
        5.4.3 Hydrodynamics Design of FRC Intake and Outlet **Karani Gulec**
        5.4.4 Flow Around Penetrations **Karani Gulec**
        5.4.5 Hydrodynamics Instability **Karani Gulec**
            5.4.5.1 Source of Instabilities
            5.4.5.2 Effects of Various Parameters on Flow Instability
    5.5 Heat Transfer and Thermal-Hydraulics **Alice Ying**
        5.5.1 Free Surface Temperature Evaluations
            5.5.1.1 Turbulence and MHD Effects **Sergey Smolentsev**
        5.5.2 Temperature Distribution in Blanket Core
        5.5.3 Temperature Distribution in Support Structural Elements
        5.5.4 Pumping Rate/Power and Temperature Control
    5.6 Material and Thermomechanical Analysis **Steve Zinkle/Lu Zi**
        5.6.1 High Temperature Materials for Support Structures
        5.6.2 Thermal and Pressure Stresses
    5.7 Mechanical Design and Maintenance Approach **Brad Nelson/Paul Fogarty**
        5.7.1 Mechanical Design Features and Configuration Layout
        5.7.2 Maintenance
        5.7.3 Considerations for Heating and Diagnostic Penetrations
    5.8 Evaluation of Liquid Options (Li, Flibe, SnLi) **Dai-Kai Sze**
    5.9 Performance Summary and Tables (Tables per Evaluation Criteria Requirements)

Alice Ying

  - 5.10 Key Issues and R&D. **Alice Ying**
- 6. Electromagnetically Restrained Lithium Blanket (**Woolley**, et al)
  - 6.1 Introduction
  - 6.2 Comparison with other Thick Liquid Blanket Concepts
  - 6.3 Flow Phenomena with Injected Electric Current
  - 6.4 Axisymmetric LMMHD Analyses
  - 6.5 Electromagnetic Interactions with Tokamak Plasma
  - 6.6 Necessary Departures from Axisymmetry
  - 6.7 Optional Design Features and Synergies
  - 6.8 Power Conversion Options
  - 6.9 A Design Example Summary - Tables and Sketches
  - 6.10 Performance Summary and Tables
  - 6.11 Key Issues and R&D.
- 7. Liquid Wall Concept, CLIFF (**Morley**, et al)
  - 7.1 Introduction (morley)
  - 7.2 Idea Description and Rationale (morley)
    - 7.2.1 General Perspective and Preliminary Design Description (morley)
    - 7.2.2 Applications to Tokamaks (morley)
    - 7.2.3 Applications to Other MFE Confinement Schemes (morley)
  - 7.3 Hydrodynamics Analysis (morley)
    - 7.3.1 Fast Liquid Layer Hydrodynamics for Turbulent Flibe Flow (morley)
      - 7.3.1.1 Hydraulics (morley)
      - 7.3.1.2 Surface and Boundary Layer Instabilities (gulec)
    - 7.3.2 Fast Liquid Layer Magnetohydrodynamics for Lithium and Sn-Li Flows (smolentsev)
      - 7.3.2.1 Hydraulics (smolentsev)
      - 7.3.2.2 Surface and Boundary Layer Instabilities (smolentsev)
  - 7.4 Neutronics (youssef)
    - 7.4.1 Energy Deposition due to X-ray Penetration (youssef)
    - 7.4.2 Nuclear Heat Generation in Blankets (youssef)
    - 7.4.3 Tritium Breeding and Power Multiplication (youssef)
    - 7.4.4 Irradiation Damage of the Support Structures (youssef)
    - 7.4.5 Decay Heat and Activation (khater)
  - 7.5 Heat Transfer and Thermal-Hydraulics (morley)
    - 7.5.1 Free Surface Temperature Evaluations (ying)
      - 7.5.1.1 Turbulence and Wavy Flow (ying)
      - 7.5.1.2 MHD Effects on Flibe and LMs (smolentsev)
    - 7.5.2 Temperature Distribution in Blanket and Support Structures (morley)
    - 7.5.3 Pumping Rate/Power and Temperature Control (morley)
    - 7.5.4 Power cycle and balance of plant (sze)
  - 7.6 Mechanical Design and Maintenance Approach (nelson/fogarty)
    - 7.6.1 Mechanical Design Features and Configuration Layout (nelson/fogarty)
    - 7.6.2 Thermal and Pressure Stresses (morley)
    - 7.6.3 High Temperature Materials for Support Structures (zinkle)
    - 7.6.4 Maintenance (nelson/fogarty)
    - 7.6.5 Considerations for Plasma Heating and Diagnostic Penetrations (nelson/fogarty)
  - 7.7 Safety and Failure Analysis (mcarthy, cadwaller)
  - 7.8 Evaluation of Liquid Options (Li, Flibe, Sn-Li) (Sze)
  - 7.9 Performance Summary and Tables (Tables per Evaluation Criteria Requirements)
  - 7.10 Key Issues and R&D (morley, et al).
- 8. Data Base for Liquid Breeders and Coolants, Li, Flibe, LiPb, and SnLi (**Sz**e, et al)
  - 8.1 Data base for Li **Zinkle**
  - 8.2 Data base for Flibe **Sze, Wang**
  - 8.3 Data base for LiPb **Zinkle**
- 9. Li2O particulate Flow Concept, APPLE (**Sze**, et al)
  - 9.1 Introduction **Sze**

- 9.2 Rational and design description **Sze**
- 9.3 Mechanical design **Igor**
- 9.4 Tritium breeding, shielding and activation **Sawan**
- 9.5 Flow modeling **Tillack**
- 9.6 Tritium control and power conversion **Sze**
- 9.7 R/D issues

10. Evaporative Cooling Concept, EVOLVE (**Mattas,** et al)
11. High-T Refractory Alloys FW/Blanket with He-Cooling Concept (**Wong,** et al)
    - 11.1 Introduction (**Wong**)
    - 11.2 Material selection and compatibility (**Zinkel**)
    - 11.3.Mechanical Design and Reliability (**Nelson/McCarthy**) This will probably be in section 14
    - 11.4 Blanket Thermal-hydraulics Design and Analysis (**Wong**)
    - 11.5 First wall Design and Analysis
        - 11.5.1 Porous Medium (**Nygren**)
        - 11.5.2 Helical insert (**Wong**)
    - 11.6 Neutronics (**Youssef**)
    - 11.7 Coolant impurity control (**Ulrickson**)
    - 11.7 CCGT Power conversion (**Wong**)
    - 11.8 Tritium migration and control (**Sze**)
    - 11.9 Safety calculations specific to this design (**McCarthy**)

- LOCA calculation
- Assessment of oxidation-driven mobilization

    - 11.9 Performance Summary and Tables (Tables per Evaluation Criteria Requirements) (**Wong**)
    - 11.10 Key Issues and R&D. (**Wong**)

(For contributions from Zinkel, Sze, and McCarthy, I am looking for summaries relevant to the helium-cooled design and specific topic chapters can be referred. Thanks, Clement.)

12. Plasma-Interface Issues and Edge Modeling (**Meade**, et al)
13. Materials Considerations and Data Base (**Zinkle,** et al)
14. Safety and Environment Considerations and Analysis (**McCarthy,** et al)

- General discussion of safety issues
- Effect of materials choice on safety
- Liquid breeder/coolant
- Structural material
- Parametric study of LOCA
- Reliability issues
- Waste management issues

~~15. Activation Considerations for Materials (**McCarthy**, et al)~~

16. Tritium (**Sze,** et al)
    - 16.1 Design constraints
    - 16.2 Possible tritium recovery methods
        - Li
        - Flibe
        - Pb-Li
        - Sn-Li
        - He
    - 16.3 Tritium inventory and pressure
    - 16.4 Tritium control
    - 16.5 Key issues
17. Power Conversion (**Sze**, et al)
    - 17.1 Advanced Steam cycle
    - 17.2 Close cycle gas turbine
    - 17.3 open cycle
18. Key Issues and R&D near term and intermediate term (**Abdou**, et al)

Schedule for writing the Interim Report (From APEX5 Summary)

The outlines of the Interim report has been developed. The reports will include 18 Chapters, including an introduction, overview, and study approach Chapters. The other Chapters cover all the concepts under investigation as well as the APEX groups (Plasma Interface, Material, Safety, Activation Consideration, Tritium, Power Conversion, and Evaluation Criteria,) findings. The report will also include a dedicated Chapter on key issues and near- and intermediate-term R&D. The lead author for each Chapter has been assigned. The deadlines of issuing the report are:

February 15, 1999: finalize report outline (Draft of outlines written by lead author is due by Mid January, 1999)
June 1, 1999: Draft assembly
July 1, 1999: Draft report
July 30, 1999: Final Interim Report
August 15, 1999: mail report by UCLA.