Summary of the Fourth APEX Meeting
July 27-29, 1998
Sandia National Laboratory

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I. Introduction

The fourth APEX meeting was held at Sandia National Laboratory, Albuquerque, July 27-29, 1998. The first two days were scheduled to discuss concepts under study, distribution of effort, and responsibilities. The third day (July 29) was dedicated to plasma interface issues common to APEX and ALPS study. The ALPS meeting was held during the period July 30-31, 1998, in the same place. The presentations given in the first two days can be viewed from the APEX Web Page http://www.fusion.ucla.edu and those given on the third day are in the process of being posted on that site. The meeting agenda, attendees and APEX study participants, contact information and announcements are given in Appendices I-IV, respectively, of Section IV. A summary of the working sessions, prepared by some of respective chairmen and the Secretary, is given in Section II for the first two days. 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

S. Berk (OFES) presented the current status of the U.S. OFES Technology Program That consists of four elements, namely:

(1) Enabling Technologies (Domestic plasma Experiments, Worldwide Plasma Experiments, Burning Plasma Experiments)
(2) Advanced Design (Burning Plasma Experiments and Energy Source Studies: ITER Design, ITER JCT, ITER JWS and system studies)
(3) Advanced Materials (Structural and Non-Structural Materials)
(4) Advanced Technologies (Energy Source Technology Evolution, High Power Density Concept Innovation and Plasma Support Technology Innovation). Energy extraction, safety and environment, tritium systems, vacuum vessel and remote handling are categorized under

Fusion Technologies. Magnets, PFC, ICH, ECH, fueling, and diagnostics are categorized under Plasma Technologies

The request for FY99 for OFES Technology Program is $50M: Enabling Technology (37%), Advanced Design (34%, Advanced Materials (6.72%), and Advanced Technologies (8%) with 8% devoted for other activities. The requested FY99 allocation for APEX and ALPS is $2.3M and $1.5M, respectively. This is the sraw man FY99 budget plans issued prior to VTL meeting (June 24-25, 1998) which were revised following the VTL meeting based on APEX/ALPS preliminary task-performer-effort matrices. In the VTL meeting, the following action items were developed in relation to APEX/ALPS activities:

(1) Update and finalize white paper on Advanced Technology (Abdou)
(2) Propose work scope and resources requirements for plasma modeling needed under ALPS and APEX (Mattas/Abdou)
(3) Prepare APEX and ALPS plans for start of competitive, peer-reviewed activities by end of FY99 (Berk, Abdou/Mattas)
(4) Prepare guidelines competitive, peer-reviewed activities for all areas of Technology Program and start some activity in all areas in FY99 (Berk).

Regarding the competitive, peer-reviewed activities, Berk emphasized the importance of the APEX and ALPS team input to merit review through evaluation processes and criteria for scientific and technical merit and quality of ideas and concepts. The FY99 funding is devoted to merit review of grant applications and national laboratories proposals received *prior* to special solicitation and announcement. The FY2000 funding *after* announcement for competition will follow similar procedure, namely: proposal application, merit review, and final selection based on established criteria. In addition, Berk announced that another route for competition for new ideas and concepts for advanced technology will be followed through Small Business Innovative Research (SBIR) Program. Grant applications for this program will close around March, 1999, merit review and selection processes will be during the April-June, 1999 time frame , and funding can start around October, 1999.

As for this meeting (including ALPS), Berk acknowledged that the focus should be on:

(1) Developing WBS task list for FY99
(2) Prioritizing tasks for FY99
(3) Developing proposed task-performer-effort matrices based on task priorities and funding constraints, and
(4) Developing work scope and resource requirements for plasma modeling needed under ALPS/APEX and prepare plan for approaching Science Division with request for “voluntary” support.

Abdou explained the purpose of this meeting as: (1) to report on technical progress (Monday and early Tuesday), (2) to discuss in details APEX process, organizational effort, and schedule, and (3) to discuss and prioritize key issues and planned tasks for FY99 . As for (1), Abdou urged participants to devote more time to report on technical progress and help people to evolve new ideas. As for (2) and (3), a detailed discussion was conducted during the afternoon of Tuesday on these two items. Abdou had previously sent prior to this meeting documents for review and comments to all APEX study participants on APEX deliverables in year 2000 (Appendix V), APEX Process (Appendix VI), APEX Phase I Milestones (Appendix VII), and APEX Group Organizational Chart (Appendix VIII). *More on the discussion for these items can be found in the summary of Session V (APEX Process and Organization*) of this Section. Abdou announced in this session than by the end of Phase I, an award of $5000 (1st place) and $1000 (2nd place) would be given to the individual who can come up with the best idea for high power density extraction. Likewise, similar awards will be given to those who demonstrate the best performance during the study. These awards may come from UCLA for encouragement.

Announcements of the APEX Scientific Secretary (Youssef) followed Abdou's presentation (See Appendix IV.)

Summary Session II: Analysis of Promising HPD Concepts for APEX
Session Chairmen: Neil Morley and Brad Nelson

Work was reported on the current HPD concepts being pursued by the APEX project. These concepts include: the broad class of liquid wall concepts, including both thin CLiFF (convective liquid flow first wall), thick GMD (gravity/momentum driven) and thick EMR (electromagnetically restrained) concepts; the APPLE flowing Li_2O particulate blanket; the Evaporative spray cooling FW and the pool boiling blanket; and the evolutionary He-cooled refractory metal FW/Blanket/Divertor.

It should be noted that new ideas are still encouraged from all interested people, and that comments on the development of existing concepts are most welcome at any time.

Liquid Wall Concepts

Morley (UCLA) reviewed the current status of the CLiFF concept. Points of interest included 2D hydrodynamic calculations for the surface height that match the initial 1D turbulent hydraulic calculations reported at previous meetings, and design details for more in depth power conversion considerations. Two coolant streams operating at low and high temperature may likely be required to achieve acceptable efficiency. Sze (ANL) reported that an inlet coolant temperature greater than 315 C is necessary to employ a steam cycle conversion system. Kotchenreuter (UT) advanced the idea of a backing structure for the CLiFF design that can be replaced during operation, to help avoid the inevitable DPA lifetime limit faced by thin liquid wall systems. Ulrickson (SNL) stated that 800C is required to get the tritium out of the lithium, and Mattas (ANL) thought that a separate divertor stream may be necessary for tritium inventory considerations.

Ying and Gulec (UCLA) described the latest design evolution of the thick GMD FW/Blanket utilizing discrete pockets on liquid with replaceable inserts that form the pockets. Analysis of this option was performed with the FLOW3D free surface hydrodynamic code for the Flibe case. Initial results show it may be possible to form these separately oscillating pockets. Moir (LLNL) would like to see continued effort on the all liquid options with no structure, and the UCLA group agreed to continue to investigate the possibilities along these lines.

Meade (PPPL) reported for Woolley (PPPL) about a problem formulation for investigating the EMR blanket option. A short description of the formulation was distributed and is available on the web site at UCLA. Moir suggests assuming the best case for the free surface MHD problem, and then doing the other systems calculations to see how the EMR concept compares to other liquid FW concepts.

Other issues addressed included the following. Nelson (ORNL) presented the design drawings for various liquid wall concepts and discussed what ORNL needs in order to get a consistent design. Drainage of the liquid in coordination with vacuum pumping is a concern. Mogahed (UW) discussed the possibility to form a thin film, scale-like FW using impinging jet nozzles. The group discussed concerns about the evaporation of the scales. Sze described Flibe issues, and called into question to ability of Flibe to adequately breed in the presence of small amounts of structure. He distributed a Flibe information paper that will be available on the web. Some interesting observations about Flibe were:

- corrosion caused by impurities in the Flibe,
- radiolysis should not be a problem, but electrolysis may be a problem
- Flibe costs about $2000/kg
- LiF and BeF are toxic hazards

Hadid (Boeing) and Morley talked about the need to begin developing the tools necessary to analyze the MHD problem. No new work was reported in this area although Morley, Kothe (LANL), Hadid, and Kotchenreuther (UT) all have codes they wish to modify to begin addressing subsections of the MHD problem.

With regard to the neutronics issues for liquid FW, Youssef (UCLA) presented ranges for tritium breeding ratios (TBR) and power multiplication (M) factors in the thick liquid FW as a function of Li-6 enrichment. When configuration in the Inboard (I/B) is similar to the O/B, the TBR in both the Lithium and Flibe cases decreases when Li-6 enrichment increases. Natural Li-6 gives the largest TBR. He shows that TBR in the Flibe concept is much less than in the Li concept which could impose a problem with Flibe to satisfy tritium self-sufficiency. Also, he showed that power multiplication in the Li blanket is larger than that in the Flibe blanket.

Lithium Oxide Particulate

Tillack (UCSD) presented some background work on the heat transfer in particulate flows both in the plasma chamber and the heat exchanger. He showed a divertor design using cladded falling particulate under development in Japan, and described a commercial code for doing both particle trajectory and heat transfer calculations for particulate flows. He plans to acquire this code to do some 2D calculations. Sviatoslavky (UW) describe design considerations for the APPLE concept. He stated that high elongation configurations, such as the ST are preferable applications for this concept. The design team is addressing the penetration issue by looking at diversion baffles for the FW flow. This is one of the configurations that will be examined with the particle dynamics code.

Evaporative Spray Cooled FW

Malang (FZK) presented a modified spray cooled FW designs utilizing Lithium as the working metal. In addition, he proposed a pool boiling type blanket that would remove the entire heat from the breeding zone by the evaporation of lithium and operates on the same conversion cycle as the FW. The entire blanket/FW would be almost isothermal, but operating at high temperature >1000 C. The vapor release from the pool in the presence of MHD forces was mentioned as main feasibility issue. Sze looked at the specifics of a potassium system and concluded that for this liquid metal an electric-insulating coating would be required to avoid high pressure drops in the liquid, and a higher gas pressure (2 MPa) would be required in the vapor lines.

He-Cooled Refractory Metal FW/Blanket

Wong (GA) presented a comparison of different refractory FW materials on the basis of outboard mid-plane thermal hydraulics. He concluded that the use of tungsten-alloy with a higher maximum allowable temperature of 1500 C should be adopted as the reference with a He pressure of 8 MPa. At this pressure, a CCGT efficiency of 55% can be achieved. The use of a multi-metallic loop seems mandatory, and so this needs to be investigated in the next iteration of the design. For the He/Li/V-alloy blanket design, he presented the radial distribution of volume fractions as determined also from thermal hydraulic calculations. These material volume fractions will be used for neutronics calculations for the next iteration of the He-Cooled Refractory Metal FW/Blanket design. Preliminary mechanical design of this concept was shown by Nelson. The progress on the He-cooled Plasma Facing Components (PFC) work was also reported by Nygren (SNL).

Summary Session III: Materials and Data base Evaluation
Session Char: Richard Nygren

Zinkle (ORNL) presented physical properties of proposed structural materials and coolants based on information several recent material properties handbooks (e. Fusion Material properties handbook/ITER Material Properties Handbook.) Summary of these properties were presented for 809Cr Ferritic/martensitic SS, SiC/SiC, V-4Cr-4Ti, Ta-8W-2Hf (T-111), and recrystallized Tungsten. Zinkle also discussed the radiation effects in refractory metals showing that void swelling is not anticipated to be lifetime-limiting issue and that refractory alloys are generally designed for use in stress-relieved condition in order to achieve higher strength. As for the operating temperature limits, it was shown that W, Mo (TZM) Ta-8W-2Hf, Nb-1Zr, and V-4Cr-4Ti alloys have the highest operating limits, in that order (e.g. W: 800-1400 ^{o}C.) Updated cost information of these alloys was also given per kg of material (e.g. V-4Cr-4Ti: $1000/kg-plate form, SiC/SiC: $2000/kg-CVI processing.)

Summary of physical properties of Li, Pb-17Li, and (LiF)nBeF2 coolants was also presented by Zinkle. It includes melting temperature, specific heat, thermal conductivity, electric resistivity, surface temperature, and vapor pressure. These properties can be found on the Web Site under his presentation.

Ghoniem (UCLA) presented the chemical compatibility of vanadium alloys, SiC composite, Ferritic steel, and refractory alloys (Ta, Nb, Mo, W) with coolants (Li, Li-Pb, Flibe, He). and the limits on high temperature operation of these structural materials. He showed the main mechanism (electronegativity) leading to the dissolution of metals in coolants. He presented some experimental observations of Li compatibility with refractory metal (Nb-1Zr, Tantalum alloys) given in terms of corrosion rate in µm/y. In addition, compatibility of SiC with molten salt was described. For non-metallic impurities such as H, N, andO2, compatibility of refractory metals with them was them was given based on previous investigation obtained from literature. Of compatibility) of several refractory metal He showed that most stringent control has to be on oxygen impurities at a level less than 100 wppm. Ghoniem also showed the upper temperature limits (on the basis of compatibility) for W, Mo, Ta, Nb, and V alloys with He (100 appm oxygen), Li-Be-F salt, and Li coolant. As was shown by Zinkle, W alloys show the highest temperature limit (~1400^{o}C) with He and Flibe type coolant.

Session IV: Common Design Issues in APEX and ALPS
Session Chair: Dai Kai Sze

Kathy McCarthy presented liquid metal safety issues. She covered key safety issues in liquid metal chemical reactions, then covered specifics on liquid metal - water reactions, liquid metal air reactions, liquid metal - CO2 reactions, liquid metal – concrete reactions, and the importance of contact mode in the severity of liquid metal chemical reactions. Experimental work results were briefly discussed. Calculations done for the ITER test blanket module (TBM) that are relevant to ALPS/APEX were discussed. Important considerations when designing liquid metal systems include: significant amounts of water should be kept out of the vacuum vessel; if the use of water inside the vacuum vessel is unavoidable, LiPb should be used (not lithium), and the injection contact mode between water and LiPb should be avoided; cover gas should be used with Li systems; the lithium inventory should be at low pressure, and segmented to decrease the probability of spilling the entire inventory; dump tanks are necessary when Li is used, and passive loops configurations are also desirable. More analysis of liquid metal accident frequencies is necessary for design guidance and regulatory purposes. Finally, one of the primary difficulties associated with liquid lithium designs may be convincing regulators and the public that the designs are safe given recent problems with LMFBRs (although the incidents themselves were minor and resulted in no public safety impact.)

Saurin Majumdar discussed the structural design criteria for fusion reactors. The irradiation environment in a fusion power plant in-vessel components present structural design challenges not envisioned in the development of existing structural design criteria such as ASME code. From the standpoint of design criteria, the most significant issues stem from the irradiation-induced change in material properties, specifically the reduction of ductility, strain hardening capability, and fracture toughness with neutron irradiation. The new rules for guarding against such problems was released for trial use by ITER designers. The new rules, which were derived from a simple module based on the concept of elastic follow up factor, provide primary and secondary stress limits as a function of uniform elongation and ductility. This design criterion provides a design tool for material with low ductility.

Dai-Kai Sze reviewed the various power conversion system which can be used for APEX and other fusion systems. The steam cycles have been widely used by fission and fossile power plants. The power conversion efficiency can be accurately calculated from the steam condition. An important factor is that the lower temperature for the coolant needs to be above ~ 310 ^{o}C. Any coolant with a temperature much below 300 ^{o}C will have very limited value for power conversion.

For a closed He cycle, assuming high efficiency of each individual steps can increase the conversion efficiency. There is a possibility that with 650 ^{o}C He temperature, a converting efficiency of 46% is possible. However, whether such high efficiency of each individual steps can be reached is not certain.

It has been assumed over a long period of time that a binary cycle can be designed with high thermal efficiency. This is true for an open cycle, such as using nature gas. For a closed cycle, the cycle efficiency will be always higher by using an efficient recuperates, instead of a bottom cycle.

Potassium cycle has been considered for efficient power conversion. The temperature of the potassium vapor has to be high enough so that the potassium vapor flow rate can be maintained to be modest. The potassium vapor volumetric flow rate in the condenser is a serious concern.

Summary of Session V: APEX Process and Organization
Chairmen: Mohamed Abdou and mark Tillack

This Session represented an important part of the meeting where the entire process of the APEX study during Phase I and the level of participation from each organization was discussed (refer to Appendices V-VIII). Abdou showed the miles stones of the study and the APEX process. The APEX process constitutes of: submitting innovative ideas, idea screening, design formulation and analysis with existing tools, including the identified issues to be resolved, followed by the scientific evaluation. This will lead to model development and possibility of performing small-scale experiment(s). The detailed concepts will then go through a feasibility and potential attractiveness (FAPA) evaluation after which the most promising concept(s) will be identified along with the R&D requirements. Abdou described the links between organizations and analysis groups. He announced that an interim report on the scientific bases and preliminary analyses of the concepts under consideration is due March, 1999. Therefore, adequate analyses on each concept should be completed as early as of January, 1999. He emphasized that no complete and detailed conceptual design is expected during Phase I of the study but rather, effort should be focused on ideas and scientific basis for each proposed concept.

On the organizational chart, groups, and concepts, Wong suggested eliminating the word FW from the High-T Refractory FW with He Cooling since the blanket will also include refractory materials. Malang requested changing the Spray Cooling FW concept to Evaporation Cooling FW concept. Wong raised a question on whether or not high power density is always being behind the FW. Also suggestion was made to link the safety, plasma interface, and materials to the Common Analysis Group (see Appendix VIII)

On the scientific evaluation process (scheduled March 1999) it was raised that this date is too early. We need to include people from the outside but we can not delay this evaluation towards the end of Phase I (Tillack.) Abdou said that we need at least to have good documentation of the analysis pertaining to each concept by March 1999 so we have the time to present the work in the upcoming conferences (abstracts for ISFNT-5 is due July 1999- 10 to 15 papers on APEX is expected.) Kathy indicated that the level of effort for each concept should be known and adequate from the beginning so that the concept can be more matured at the time of the evaluation. Wong suggested bringing people from physics into the evaluation group. Also, he suggested that the key issues for each concept be identified and added to the Basic Information needed for each concept (Table I, refer to previous summary.) Sawan asked when the Interim Report is due: before or after the Scientific Evaluation. Tillack suggested that the Evaluation Group include those individuals who will undertake the Scientific Evaluation (same suggestion by Wong to have the Evaluation Group judge each concept.) Abdou indicated that some people from the outside of APEX may come in and we should be prepared for that. *Abdou suggested that a community workshop could be held just after the Interim Report is issued and before the Scientific Evaluation is performed. One suggestion was to have the Interim Report out for distribution by July 1, 1999, and hold the community workshop after that date and have the Scientific Evaluation be performed by September-August, 1999.* . Kathy asked what type of information is needed before the Scientific Evaluation. Abdou indicated that the current Evaluation Group should develop the criteria for the Scientific Evaluation. *He suggested that we start developing these criteria and send them to people for comments. He specifically indicated that the Scientific Evaluation should be based on:*

(1) *Potential of the concept in (a) handling high power density, (b) having high power conversion efficiency,*
(2) *Potential of concept with regard to (a) failure rate, (b) maintainability,*
(3) *Defining the design margin for each concept,*
(4) *Defining major technical issues and uncertainties.*

Nygren asked about the required level for identify failure modes (full failure analysis?). Abdou indicated that extensive failure analysis is not needed at this point but rather qualitative guidelines to mitigate failure are needed. He suggested that INEL to help in developing these guidelines.

Tillack then gave suggestions and plans for the APEX Evaluation Group. He specified that the tasks of this group are:

(1) Specifying criteria for evaluations:
    - Idea screening
    - Scientific evaluation
    - Feasibility and performance evaluation
(2) Specifying data needs for evaluations that should be provided by concept leaders
(3) Performing concept review:
    - Convene review meetings as needed
    - Include/interface with Advisory Committee(s)

(4) Documenting recommendations.

He discussed the stages of concept development to be: (a) Concept exploration, (b) Proof-of-Principle, and (c) Proof-of-Performance and Optimization. He emphasized the similarity between these steps and those followed in the Confinement Program. The requirements to be met before an idea evolves to a concept were discussed (similar to those developed by Malang last APEX meeting.) He indicated that the requirements to be met before a concept moves to and beyond the Scientific Evaluation fall in the areas of: (a) Credibility, (b) Performance, and (R&D needs.

Summary of Session VI: Key Issues and Planned Tasks for FY99
Chairmen: M. Sawan and M. Youssef

In this session, each concept's lead person presented the key issues for each concept and the pertaining tasks planned for FY99:

GMD Thick Liquid Wall Designs (Ying)

(A) Feasibility issues:

1. Hydrodynamics of geometrically complex free surface flows in the presence of magnetic field and/or turbulence.
2. Effect of evaporated materials on plasma operation

FY99 Tasks:

1. Continue to perform hydrodynamics analysis coupled with temperature evaluation using FLOW-3D for Flibe liquid pocket design and FRC.
2. Identify instability sources, which could seriously impact feasibility of this class of design.
3. Continue to perform edge plasma transport analysis to determine the maximum allowable surface temperatures.
4. Develop MHD Free Surface Codes for evaluation of Lithium flow behavior in jet and partially open pocket configurations.
5. Continue to develop heat transfer codes for wavy and turbulent free surfaces.

(B) Attractiveness Issues:

1. Design integration including penetrations, machine adaptation, and liquid distribution and collection.
2. Consistent operating temperature window for plasma operation and power conversion.
3. Thermomechanics and lifetime of fluid mechanical support structures (nozzles, reflectors) under high load conditions

FY99 Tasks:

1. Perform general design tasks including hydrodynamics, thermal-hydraulics, structural and neutronics analyses.
2. Provide data needed for an integrated design.
3. Develop an integrated design layout.

Attractiveness Issues to be addressed by tritium Group, Material Group, and Safety Group:

1. Tritium Behavior, processing, and permeation.

2. Effect of massive hydrogen guttering by lithium free surfaces.
3. Material compatibility including corrosion and operating limits.
4. Response of liquid surface to off-normal conditions.
5. Effect of spilled or condensed liquid on in-vessel systems.
6. Start up issue
7. Vacuum pumping.

Comments:
Add start-up as an issue under hydrodynamics issues. We should look into how the FW liquid responds to plasma changes and instabilities (Abdou). Vacuum pumping issues should be added (Sze). Spilling of liquid to vessel components is an issue (Morley).

Fluid Dynamics MHD Modeling (Morley)
Needs:
1. Codes able to analyze complicated 2D and 3D structure (and current flow paths)
2. Methods able to analyze phenomena resulting from complicated B fields, transients and spatial dependence and turbulence.

Development Paths:
1. Modify existing hydrodynamic free surface codes to deal with MHD forces and equations (UCLA, Boeing, LANL)
2. Modify existing plasma MHD codes to include free surface tracking and boundary layers (PPPL, UT)
3. Pay commercial companies (FLOW-3D) to develop capabilities through SBIR grants.

Li2O Particulate (APPLE) Concept (Sze)
Key Issues:
1. Tritium breeding and recovery
2. Requirements for lifetime of structure
3. Heat transfer to secondary system
4. Mechanical design (possible ways to eliminate the baffles number)
5. Penetrations cooling
6. Power conversion

FY99 Tasks:
1. Literature survey and code development of heat transfer from solid particulate to a solid wall in vacuum
2. Mechanical design of the system:
   - Particle inlet and exit system
   - Particle flow control
   - Penetration cooling and shielding
   - Divertor system
   - Start up
   - Flow stability and distribution
3. Tritium System
   - Tritium production

- Tritium recovery
- Tritium containment

4 Neutronics and Shielding
- Structure and shielding material selection
- Nuclear heating and damage
- Structure and shield lifetime
- Activation and decay heat
- Vacuum vessel and magnet shielding

5 Plasma Interface Issues
- Determine effects to plasma from Li, O, T back diffusion
- Disruption effect

6 Power conversion design
7 Safety

Names of Researchers:
ANL: D. Sze, R. .Mattas, M. Billone, A. Hassanein, S. Majumdar – 0.7 FTE
UW: M. Sawan I. Sviatoslavsky – 0.35 FTE
UCSD: M. Tillack – 0.1 FTE + student
UCLA: 0.05 FTE
Supporting Group: material, PIG, Tritium, power conversion, safety
TOTAL EFFORT: 1.2 FTE +student

Comments:
Analysis of dynamics and heat transfer properties of particulate flow in a vacuum and in heat exchangers should be emphasized (couple of pages on this is needed – Mark will get a code that deal with this issue). Try to move the baffles. How to design the inlet and exit of the particulate (this could be a week point in the design). Dust generation from particulate and distribution is an issue (Ghoniem). What is the lifetime of the baffles and who will do analysis is he Igor? (Ghoniem).

Tritium Group (Sze)
Key Issues
1..Define tritium permeation barrier requirements
2.. Develop tritium processing system
3..Identify tritium-processing issues

FY99 Tasks:
1 For each breeding material/coolant, the tritium recovery method have to be develop within concentration and pressure limits
2 If the allowable limit can not be reached, R&D programs have to be defined to relax these limits.
3 Define key impurities in tritium stream and identify steps to remove these impurities to an acceptable concentration.

Names of Researchers:
ANL: D. Sze, M. Billone – 0.2 FTE

LANL: S. Willms – 0.1 FTE
UCLA: A. Ying – 0.1 FTE
TOTAL EFFORT 0.4 FTE (50% supported by ALPS)

Flibe Group (Sze)
Key Issues:
Assess advantages and disadvantages of using Flibe as a coolant and breeding material for fusion applications

FY99 Tasks:
1 Flibe chemical state definition
2 Tritium breeding
3 MHD effects on heat transfer
4 Structural material selection
5 Tritium control
6 Beryllium issues
7 Safety

Names of Researchers:
ANL: D. Sze – 0.1 FTE + visitor
UCSD: M. Tillack – 0.05 FTE
UW: M. Sawan – 0.05 FTE
ORNL: S. Zinkle – 0.05 FTE
IEEEL: K. McCarthy - -.05 FTE
UCLA: A. Ying – 0.05 FTE
TOTAL EFFORT: 0.35 FTE + visitor

Power Conversion Group (Sze)
Key Issues:
1 Assess power conversion systems for various temperature ranges
2 Identify and review key issues for different power conversion schemes.

FY99 Tasks:
1 Evaluate various power conversion systems and assess the optimum parameter regime for each power conversion system.
2 Assist each concept group to select the most attractive power conversion system.

Names of Researchers:
ANL: S. Sze – 0.2 FTE + visitor
UCSD: M. Tillack – 0.2 FTE + student
TOTAL EFFORT: 0.4 FTE + visitor student (50% supported by ALPS)

Helium-cooled Refractory Alloys FW/Blanket HHF concept (Wong)

Tasks	Person(s)	Due date

1. Next iteration of FW/B neutronics and Thermal-hydraulics design, including FW Thickness variation	Youssef/ Wong	November 98
2. FW/B/HHF components CAD configuration	Nelson/Wong/ Nygren	November 98
3. Coolant routing transition zone concept	Wong/Nelson	November 98
4. CCGT design review and identification Of high temperature material options*	Wong	February 99
5. HHF components thermal/hydraulics*	Nygren	February 99
6. HHF refractory material test plan and analysis	Nygren	February 99
7. HHF components review and selection of reference design (e.g. porous medium versus helical tape)	Nygren/Wong	April 99
8. FW/B/HHF loops pressure drop estimate	Wong	April 99
9. Power conversion options	Sze/Wong	April 99
10. Materials compatibility & irradiated properties*	Zinkle/Ghoniem	April 99
11. FW design, 2-D and 3-D analysis*	GA	August 99
12. Identify He impurity control system*	Ulrickson	August 99
13. Tritium migration	Sze/Willms	August 99
14. Safety, decay heat, LOCA and LOFA analysis	McCarthy/Mogahed	August 99
15. Preliminary understanding and solution approach to material/coolant loop/power conversion issues*	Nygren/Wong	August 99
16. Preliminary approach on FW/plasma interaction issues*	Wong	August 99

Issues that will have to be addressed, possibly in FY2000

17. Preliminary consideration of FW/B/HHF components design and fabrication
18. Scoping 2-D, 3-D FW/B/HHF modules, thermal-hydraulics and mechanical design and analysis
19. Scoping 2-D, 3-D structural design and analysis
20. Initial reliability analysis*
21. Initial failure mode analysis*

Note:

Due dates are to be coordinated with the meeting schedule of APEX.
Progress on different tasks should be reported before and at the due date.
HHF…high heat flux components can be applied to first wall and divertor design.

*Critical issues

Evaporation Cooling Concept (ECC) (Mattas):

Key Issues

1 Thermal hydraulics (vapor/liquid separation)
2 MHD
3 Structural response and lifetime at very high temperatures

4 Tritium breeding and shielding
5 Design integration

<u>*Other Issues (Malang):*</u>
6 Will the vapor separate fast enough from the liquid metal?
7 Influence of the magnetic field
8 Will the overflow system work in the magnetic field?
9 Neutronics performance:
- Tritium breeding
- Neutron streaming
- Volumetric heat generation in second breeding zone
- Lifetime of second breeding zone

<u>*FY99 Tasks:*</u>
1 Thermal hydraulics and power conversion assessment of evaporation cooling system:
- ANL: - 0.25 FTE (power conversion, MHD, materials limit, design)
- UW: - 0.05 FTE (thermal hydraulics)
- UCSD: - 0.15 FTE (thermal hydraulics – FW 2 phase flow)
- SNL – {0.1 FTE from PFC Program }

2 General mechanical design implementation and analysis, including neutronics and activation
- ORNL – 0.1 FTE (design)
- UW – 0.15 FTE (neutronics)

<u>Comments:</u>
Name the concept “EVOLVE” (EVaporation Of Lithium and Vapor Extraction). Two phase flow in magnetic field is needed (review in literature) (Malang). MHD problem is more general issue and applied to all concepts with LM and not just the evaporation-cooling concept (Abdou). It is very difficult to do MHD analysis for vapor and another analysis for liquid. We can start at least with liquid (Ghoniem).

APEX Mechanical Design Group (Brad Nelson)
<u>*Mission:*</u>
- Assist the various concept groups with the mechanical design of their concepts, including the generation of 3-D layouts, maintenance approach, fabrication ideas, etc.
- The designs will be based on the ARIES-RS Tokamak configuration, a generic FRC design, or some other concept (to be defined).
- The group is also responsible for evaluating the availability of each concept.

<u>*FY99 Tasks*</u>
1. Develop overall concept layouts
    - 2-D schematics showing component location, size
    - 3-D illustrations showing: concept features, typical penetrations, divertor integration, piping size/routing, maintenance approach, etc.
2. Assist with improving availability:

- Maintenance approach
- Increased margins
- Develop matrix for assessment of availability

3. Assist with design of concept-specific critical features (Ongoing) (e.g. how to protect convective layer nozzles, how to integrate divertor, etc.)

FY 99 Allocation

ORNL: P Fogarty, P. Goranson, B. Nelson

0.5 FTE	Liquid Walls (Convective Liquid Wall, GMD Blanket)
0.1 FTE	Spray Cooling
0.2 FTE	Availability Analysis (all defined concepts)
0.2 FTE	General tasks and new concepts

UW: I. Sviatoslavsky

0.2 FTE	Apple concept

TOTAL EFFORT – 1.2 FTE

APEX Materials Group (Zinkle)

Key Issues:

1. *Structural material compatibility with coolants
    - max O, C, N, H levels in coolant vs. temperature
    - Convection loop corrosion tests for structural alloys in Flibe….
2. Joining/repair methods for irradiated materials
    - Can the 1 appm He limit (based on fusion welding of steel) be increased….
3. Fracture toughness data for refractory alloys
    - need experimental data vs. T (including impurity pickup effects)
4. Development of improved refractory alloys (TiC additions, etc.)
5. Critical evaluation of stress limits for structural components (c.f. ITER structural design methodology)
6. *Creep-rupture temperature limit for V-4Cr-4Ti at $\geq 650^\circ$
7. *High Temperature ($\geq 700^\circ$) radiation effects on structural materials
    - DBTT, tensile properties
    - Effect of interstitial impurities
8. Effect of transmutations on material properties (in conjunction with neutronics group)
9. T2 inventory/permeation (design specific)

- Needed for lifetime estimation.

Comments:

Add fracture toughness to the list of issues (added). Add effect of transmutation on material properties (added). The following should be acted upon:

(1) discuss where/how to include SS304 to material data bases (Mohamed/Steve/Nasr/Ralph)
(2) add property data base for a preferred W allot (Steve)
(3) look into making cost prediction based on “typical blanket” rather than $/kg
(4) Add costs of coolants to database.

Safety Group (McCarthy)
The safety issues for the ALPS and APEX programs are similar, so we do not differentiate between ALPS and APEX tasks.

FY99 Tasks
1. Provide on-call safety support to ALPS/APEX, including scoping safety assessments of design concepts to identify key safety issues
2. Non-water coolant (Li and Flibe) safety code model development
3. Liquid surface disruption safety
4. Reliability of non-water coolant systems
5. Chemical reactivity of tungsten brush material
6. No-evacuation radiological dose limits for ALPS/APEX materials
7. Tritium issues (Flibe)

Comments:
The code CHEMCOM will be used in decay heat calculations and LOCA accident (McCarthy). The code MELL will be used in thermal hydraulics (McCarthy).

FRC Activity and Issues (Moir)
1. Mechanical design – feasibility (Nelson, Moir)
2. Plasma and plant parameters (Ohnishi, Moir)
3. Hydraulics design/analysis (Gulec)
4. Galvanic corrosion of antenna design (Moir, U. Washington)
5. Edge plasma design and contamination analysis?

Spherical Tokamak: Hydraulic design, Edge-plasma design/analysis, Contamination
Spheromak: Plant design, Hydraulics design

FRC APEX/ALPS Liquid Wall Team

Moir - Fusion Tech./Plasma Physics
Ohnishi - plasma theorist
Gulec – hydraulics
Ying – thermal/hydraulics
U Wash. (Steinhauer, A. Hoffman) - antenna design, current drive
Rognlien? – Edge plasma

FRC OFES Funded Solid First Wall Team
Sanatarius, Miley, U. Wash., Ohnishi – U. Kyoto

Comments:
We need a reference FRC design. APEX will not develop a design. We have little funds to get from the FRC community a reference design (Abdou).

Note on MHD Instabilities (Mike Kotschenreuther)
Motivation:

Small-scale MHD instabilities near surface crucially affect viability of thin and thick liquid walls and some liquid divertor concepts

Example:

Rippling instability $\frac{2\Pi}{\lambda} = k \sim 2mm^{-1}$

Rayliegh Taylor $k \sim 0.5 - 1\,\text{cm}^{-1}$

CLIFF + liquid divertors $\lambda \sim 2\,\text{cm}$

Also: MHD affects FliBe

MHD damping Time T ~ $T \sim \frac{\eta P}{\beta 2} \sim 0.2\,\text{sec}$

This time is shorter than viscous damping for space scales $\leq mm\ s$

Features:

1) Time advances full resistive MHD equations
2) paralleled, runs on T3E
3) 2d (will be made 3d with minimum effort)
4) variable grid spacing
5) not free boundary (main modification effort)
6) "Semi-implicit" – time step is not limited by Courant-Fredricks-Levy numerical stability criterion for Alfven & sound waves.

Uses Harned-Schnack scheme, widely used in plasma MHD for resistive MHD stability and turbulence

Table I: Summary of Effort by Concept & Task (Morley)

(NOTE: Resources are subject to change pending on changes in funding resources and technical needs)

Concept or Task	**FTE**	**K$**
Liquid Wall Concepts (including MHD)	4.525	905
Lithium-Oxide Particulate Concept	1.25	250
Evaporative Spray Cooling Concept	0.8	160
He-Cooled Refractory FW Concept	1.1	220
Material group activities	1.1	220
Evaluation criteria group activities	0.2	40
Reference FRC for APEX Concepts	0.6	120
Plasma interface group activities	0.25	50
Safety group activities	1.0	200
Power conversion group activities	0.1	20
Mechanical design group availability	0.4	80
Analysis and general tasks		
Key areas under negotiation, subcontracts, And international collaboration	0.45	90
Total APEX Effort (Including indirect)	11.7775	2355

Table II: Summary of Effort by Organization (Morley)

(NOTE: Resources are subject to change pending on changes in funding resources and technical needs)

Organization	FTE	K$
UCLA (Including ALPS support, international Collaboration and other travel support, scientific and administrative secretarial support, management)	3.75	750
ANL	1.75	350
ORNL	1.5	300
PPPL	0.25	50
GA	0.5	100
LLNL	0.5	100
UW	0.8	160
UCSD	0.35	70
INEEL	1.0	200
LANL	0.125	250
SNL	1.25	250
Total APEX Effort (Including Indirect)	11.775	2355

III: Action Items

(1) The next APEX meeting will be held during the period November 2-4, 1998, at UCLA.

(2) No complete and detailed conceptual design is expected during Phase I of the APEX study but rather, effort should be focused on ideas and scientific basis for each proposed concept.

(3) The key issues for each concept be identified and added to the Basic Information needed for each concept

(4) The interim report on the scientific bases and preliminary analyses of the concepts under consideration is due March, 1999. Adequate analyses on each concept should be completed as early as of January, 1999. The Scientific Evaluation process is also scheduled March 1999.) It was raised that this date is too early. It was also suggested that the Evaluation Group include those individuals who will undertake the Scientific Evaluation. . *Abdou suggested that a community workshop could be held just after the Interim Report is issued and before the Scientific Evaluation is performed. One suggestion was to have the Interim Report out for distribution by July 1, 1999, and hold the community workshop after that date and have the Scientific Evaluation be performed by September-August, 1999. This is under discussion and will be finalized before or on the next APEX meeting.*

(5) People should be prepared to submit abstracts to the upcoming ISFNT-5 Symposium (headline July, 1999).

(6) Changing the Spray Cooling FW concept to Evaporation Cooling FW concept. This concept is now termed Name the concept “EVOLVE” (EVaporation Of Lithium and Vapor Extraction).,

(7) Abdou indicated that the current Evaluation Group should develop the criteria for the Scientific Evaluation. *He suggested that we start developing these criteria and send them to*

people for comments. He specifically indicated that the Scientific Evaluation should be based on:

(a) Potential of the concept in

- *handling high power density,*
- *having high power conversion efficiency*

(b) Potential of concept with regard to (a) failure rate, (b) maintainability,

(c) Defining the design margin for each concept,

(d) Defining major technical issues and uncertainties.

(8) Extensive failure analysis is not needed at this point but rather a qualitative guideline to mitigate failure is needed. Abdou suggested that INEL to help in developing these guidelines.

(9) Add start-up as an issue under hydrodynamics issues

(10) We should look into how the FW liquid responds to plasma changes and instabilities.

(11) Analysis of dynamics and heat transfer properties of particulate flow in a vacuum and in heat exchangers should be emphasized in the Li2O particulate concept (couple of pages on this is needed – Mark will get a code that deal with this issue).

(12) Dust generation from particulate and distribution is an issue that should be added to the Li2O particulate concept.

(13) For the Materials Group, the following was decided:

(a) Add fracture toughness to the list of issues

(b) Add effect of transmutation on material properties

(c) Include SS304 to material data bases

(d) Add property data base for a preferred W allot

(e) Look into making cost prediction based on "typical blanket" rather than $/kg

(f) Add costs of coolants to database.

(14) We need a reference FRC design. APEX will not develop a design. We have little funds to get from the FRC community a reference design (Abdou).

(15) The level of effort and task distribution by organization shown in Table I and II (see also Appendix IX) received acceptance from the APEX study participants. However, it was emphasized that some changes in tasks/resources may take place subjected to the final funding level to the APEX study.

Appendix I
Agenda for APEX Study Meeting
Sandia National Laboratory
Building 6585, Auditorium
July 27-28, 1998

Monday, July 27

8:30 a.m.	Coffee/Donuts	
8:55 a.m.	SANDIA Welcome	

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

9:00 a.m.	Introductory Remarks	Berk
9:15 a.m.	Status and Direction	Abdou
9:50 a.m.	Secretary's Announcements	Youssef

Session II Analysis of Selected HPD Concepts for APEX (Chairs: Neil Morley and Brad Nelson)

Liquid Wall Concepts

10:00 a.m.	Convective Liquid Flow First Wall (CLiFF)	Morley
10:30 a.m.	Coffee Break	
10:45 a.m.	Thick Liquid Gravity/Momentum Driven (GMD) Concept	Ying/Gulec/ Uchimoto
11:45 a.m.	Mechanical Design for Liquid Concepts	Nelson
12:30 p.m.	Lunch	
1:30 p.m.	CFD Tools: TELLURIDE and MHD Codes	Morley/Kothe/ Hadid
2:00 p.m.	FliBe Issues	Sze
2:30 p.m.	Nozzles to Maintain Thin Liquid	Mogahed
2:45 p.m.	Power Multiplication/Tritium Breeding	Youssef
3:00 p.m.	Group Discussion on Liquid Walls	
3:45 p.m.	Coffee Break	

Flowing Li2O Particulate Blanket Concept (APPLE)

4:00 p.m.	• Heat Transfer Issues	Tillack
	• APPLE Configuration	Igor

Evaporation Spray Cooling Concept (ESCC)

4:45 p.m.	Issues of Evaporation Spray Cooling Concept (ESCC)	Malang/Mattas

He-Cooled Refractory Metal FW/Blanket/Divertor Concept

5:15 p.m.	• He-Cooled Refractory Alloys FW/Blanket Concept: Issues and Design	Wong
	• Mechanical Design and Configuration	Nelson
	• Progress on He-cooled PFC	Nygren
6:00 p.m.	Group Discussions	
6:15 p.m.	Adjourn	

Tuesday, July 28

8:00 a.m.	Coffee/Donuts	
8:30 a.m.	Magnetically Restrained LM Flow in Tokamaks	Woolley

Session III: Materials and Data Base Evaluation (Chair: Richard Nygren)

8:45 a.m.	Properties of High Temperature Refractory Metals: - Physical and Mechanical Properties - Temperature Limits - Cost	Zinkle/El-Azab/Ghoniem

	Compatibility of High Temperature Refractory Metals with Coolants: - Physical Properties of Coolants - Temperature Limits of F/M Steels, V Alloys, SiC/SiC, Ta, Nb, Mo, W, Austenitic SS in Contact with Li, FliBe, Pb	Ghoniem/Sze/ Zinkle

Session IV (Special Session) Common Design Issues in APEX and ALPS (Chair: Dai Kai Sze)

9:30 a.m.	Safety Issues related to Liquid Metals	McCarthy
10:00 a.m.	Tritium Permeation and Power Conversion Issues	Sze
10:30 a.m.	Coffee Break	

Session V: APEX Process and Organization (Chairs: Mohamed Abdou and Mark Tillack)

10:45 a.m.	Suggestions on APEX Process, Organization, and Schedule	Abdou
11:00 a.m.	Suggestions and Plans for Evaluation Criteria on APEX	Tillack
11:30 a.m.	Group Discussion on: 1. Stimulating Ideas from Within and Outside 2. Organization 3. Steering Committee/Advisory Committee 4. Process and Criteria 5. Schedule and Reports 6. Peer Review and Open Competition 7. Frequency of Meetings and Conference Calls 8. Reporting and papers	
12:30 p.m.	Lunch	

1:30 p.m. Session VI: Key Issues and Planned Tasks for FY 99
(Chairs: M. Sawan and M. Youssef)

(Each Speaker: Please Plan for 15 minutes or less. Your talk should concisely: *1) state key issues and priorities, 2) work plan and schedule tasks for FY99, and 3) indicate names of researchers who will perform the tasks. Use the funding guidance provided by DOE and agreed to with APEX management.)*

	Convective Liquid Wall and Liquid GMD	Ying
	EM Lithium Blanket	Woolley
	Fluid Dynamic MHD Modeling	Morley
	Li2O Particulate	Sze
	He-Cooled Refractory FW	Wong/Nygren
	Spray Cooling FW	Mattas/Malang
	Mechanical Design	Nelson
	Materials	Zinkle
	Safety	McCarthy
	Tritium, FliBe, Power Conversion	Sze
	Other ANL Tasks (Disruption, etc.)	Mattas
	LLNL Tasks	Moir
5:00 p.m.	Group Discussion on Tasks and Plans	
6:15 p.m.	Adjourn	

(Please Note that Wednesday, July 29, 1998, is a joint day with ALPS on Plasma Interface, including plasma edge modeling and innovative confinement concepts. Please plan on attending Wednesday's meeting because it is critical for APEX

Appendix II

APEX
Study Participants

Mohamed Abdou (UCLA)
Charles Baker* (UCSD)
Sam Berk (Monitor, OFES)
Lee Berry* (ORNL)
Don Clemens (RIC)
Mohamad Dagher* (UCLA)
Anter El-Azab* (UCLA)
Paul Fogarty* (ORNL)
Alexander Gaizer (UCLA)*
Nasr Ghoniem (UCLA)
Karani Gulec (UCLA)
Dong-Hong Guo (UCLA)*
Ali Hadid (Boeing)
John Haines* (ORNL)
Ahmed Hassanein* (ANL)
Hesham Khater* (U.WIS)
Askar Konkachbaev (UCLA)*
Mike Kotschenreuther (U.TXS)
Siegfried Malang (FZK)
Rich Mattas (ANL)
Kathy McCarthy (INEL)

Dale Meade (PPPL)
Ralph Moir (LLNL)
Neil Morley (UCLA)
Brad Nelson (ORNL)
Richard Nygren (SNL)
John Santarius (U.WIS)
Mohamed Sawan (U.WIS)

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 Youssef (UCLA)
Jim Yuen* (RIC)
Steve Zinkle (ORNL)

* *Did not attend this meeting*

Other Attendees:

Peter Mioduszewski (ORNL)
Saurin Majumdar (ANL)
Stephen Birdsell (LANL)
Todd Evans (GA)
Elsayed A. Mogahed (UW)
Igor Sviatoslavsky (UW)
Brent Freeze (UCLA)

Appendix III

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Appendix IV
Secretary's Announcement

ANNOUNCEMENTS

SUMMARY OF LAST MEETING

- Distributed to participants. Thanks for Sessions Chairs who provided summaries. Action Items developed are attached for reference.

ACTION ITEMS FROM LAST MEETING

- Items requested by Abdou for each concept and proposed effort from each organization participating in APEX were sent to UCLA. These items included:

  - Crucial issues,
  - New models/experiments needed, if any
  - Required resources

- A list of APEX research tasks and level of effort was prepared (Morley) for FY99 based on input from several individuals/organizations. Direct and indirect funding was outlined consistent with DOE anticipated funding level. (More detailed discussion on the topic reserved for this meeting.

- Four charts were e-mailed to participants for reviewing on APEX deliverables (Year 2000), Process, Schedule and milestones for Phase I, and APEX study organizations/groups.

- As agreed, systems other than steady state operation in Tokamaks will be considered as an alternative confinement system (FRCs). (Proposed funding to support this action item is reflected in the.distributed proposed effort list). This will be further discussed Wednesday in the physics issues common to APEX and ALPS study

-. Brad Nelson and Paul Fogarty (ORNL) spent several days at UCLA during the week of July 20. Further details of their cooperative work with UCLA on design will be discussed this meeting.

APEX WEB SITE:

Full operational. Please visit frequently for updates.
(http://www.fusion.ucla.edu)

E-MAILING ATTACHMENTS AMONG ORGANIZATIONS (COMPATIBILITY OF FILE TRANSFER)

- There is a current problem in reading files sent by participants among organizations. *<u>WE SHOULD AGREE ON THE FORMATTING OF FILES (TEXT FILES, GRAPHING FILES, etc) TO BE EXCHANGED (Word97?, Word6.0/95?, Word5.1 for Mac?, Power Point?, Kaleidograph?, McDraw?, Adobe?, etc</u>*)

APEX Secretary
M. Youssef, July 27, 1998

Action Items from May 6-8, 1998 APEX Meeting

The following action items were agreed upon during the workshop:

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

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

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

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

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

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

Other items are:

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

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

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

(10) From the Materials Session, the values used for costs of several of the materials presented by Ghoniem appeared to be inaccurate and much too high (several). He will check these data. Other data to be checked are: Nb-1Zr in range of 700-1000°C (Ghoniem), Al2O3 coating on Ta (suggested by Wong), using 304SS with flibe (suggested by Moir). Sze suggested raising the operating temperature limit of interest for from 650°C max. to 1000°C. This action was accepted.

Appendix V

APEX
PHASE I DELIVERABLES
(Year 2000)

1. Understanding of Technological Limits and How to Extend Them

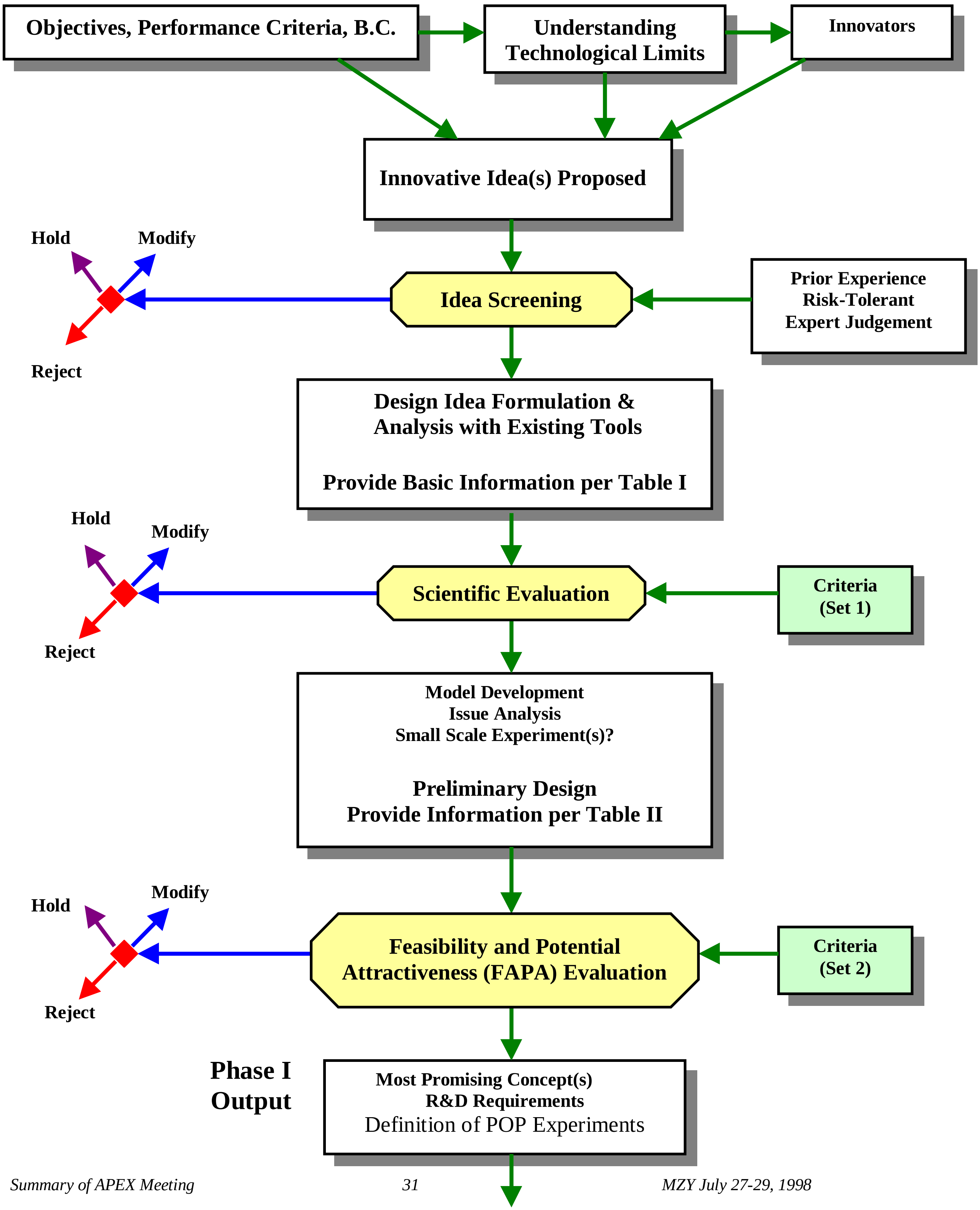
2. Identification and Preliminary Design of the Most Promising Innovative Concept(s)

3. Recommendation on R&D Requirements, Proof-of-Principle Experiments, and Further Design Conceptualization Effort

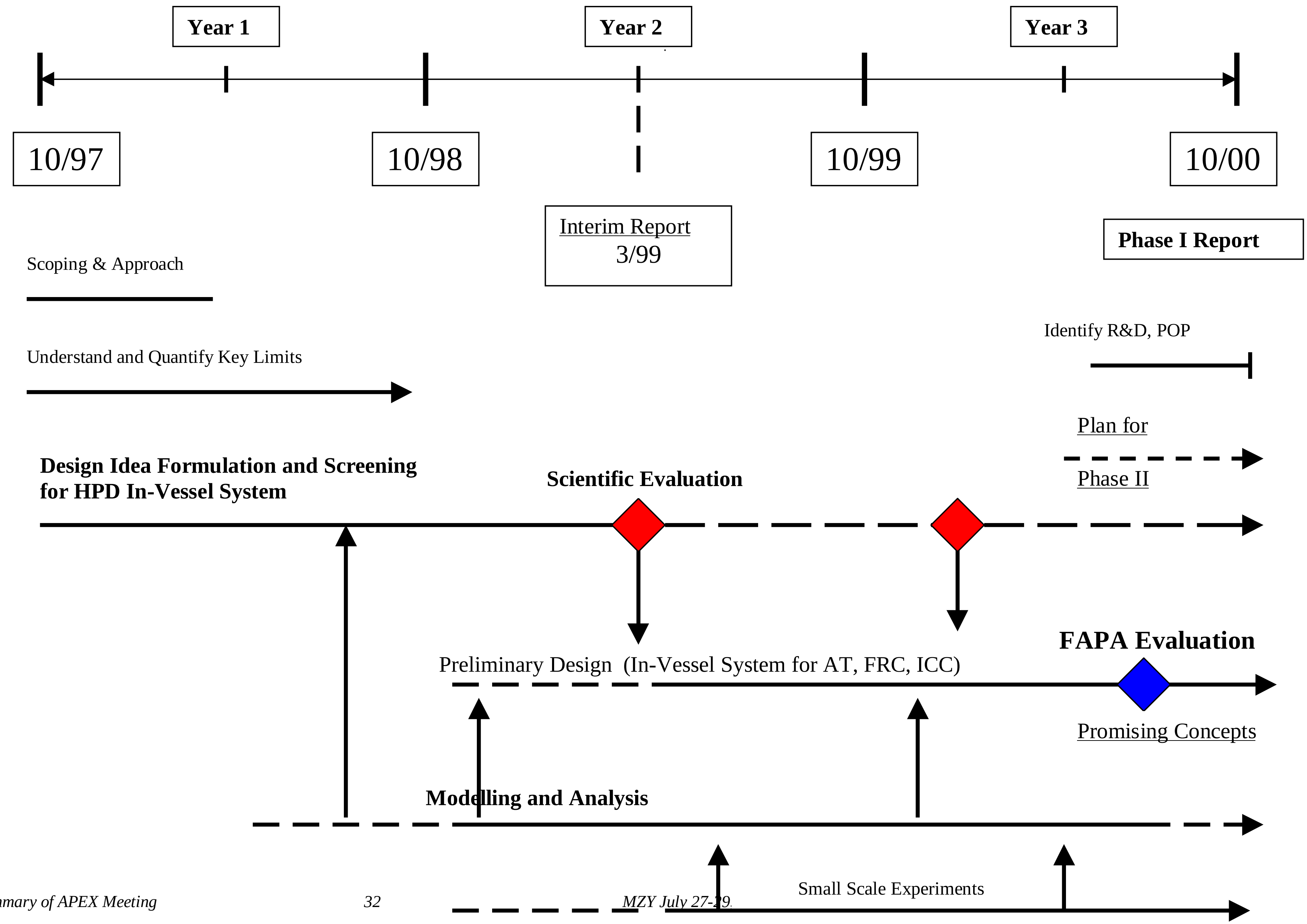
4. New Models and Data for Advanced Fusion Technology (and Advances in Engineering Science)

Appendix VI

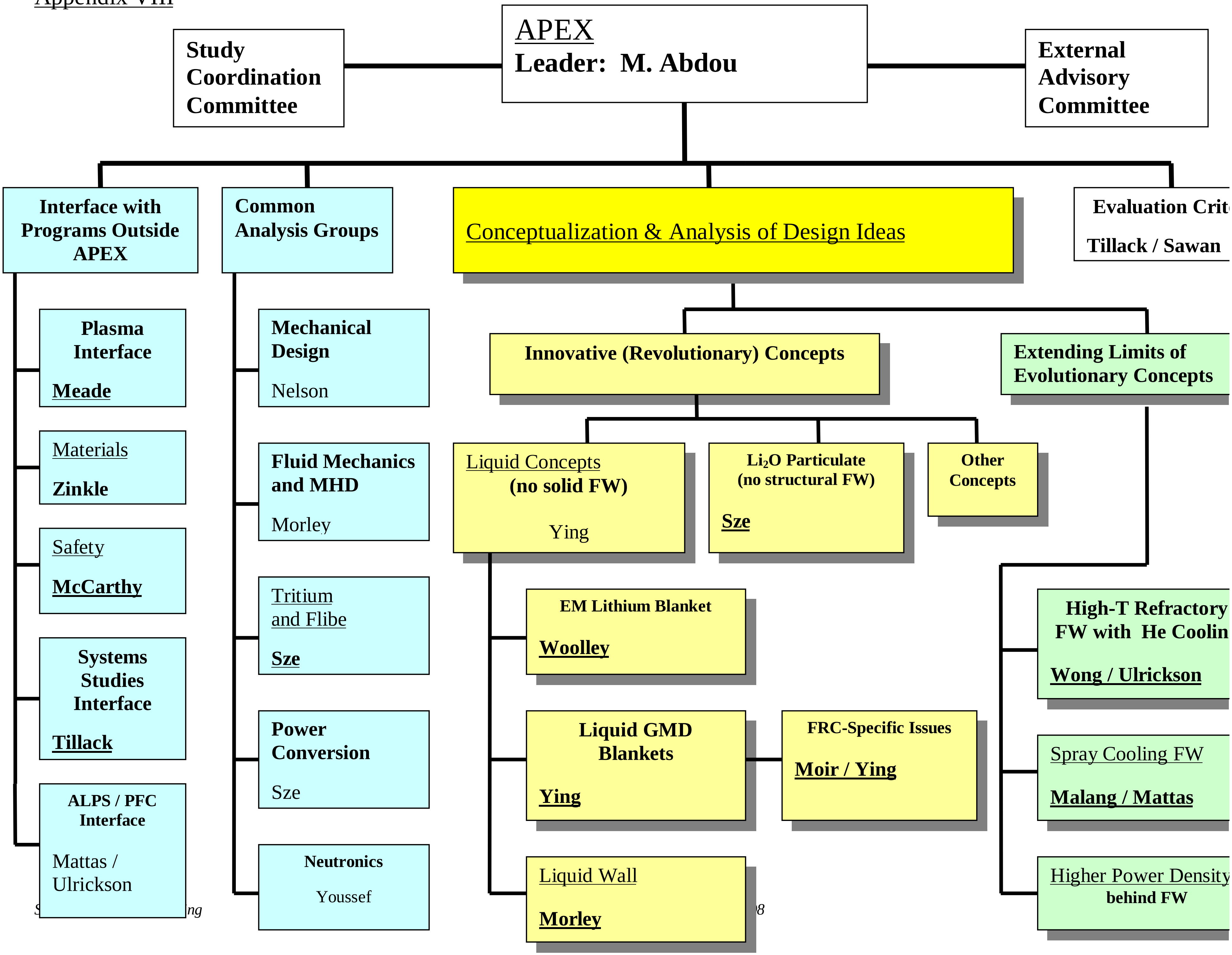
APEX PROCESS



APEX Schedule and Milestones for Phase I



Appendix VIII



Appendix IX

Organizational Tasks and Anticipated Funding for FY99

(A) Breakdown by Concept and Task

Liquid Wall Concepts, LWC
Including:

- Electromagneticially Restrained, EMR
- Gravity and Momentum Driven, GMD
- Convective Liquid Flow Firstwall, CLIFF

{Green} indicates indirect funding from other programs, not included in APEX totals

1. Plasma edge modeling of the ionization and transport of evaporated material from liquid first walls. Determination of acceptable evaporation flux levels based on transport calculations.

   Key responsibility of ALPS program, {> 1 FTE}
   LLNL, 0.1 FTE (work with UCLA on UEDGE)
   UCLA, 0.1 FTE {0.1 FTE match by Japanese Collaboration}

2. Development and benchmarking of turbulent free-surface hydrodynamic and heat transfer modeling tools and experiments. (MHD development is also required, but UCLA work will support ALPS effort.)

   UCLA, 1 FTE (all facets, including exp. development)
   PPPL, 0.2 FTE (application to EMR concept)
   SNL, {0.25 FTE from PFC Program} (exp. development)

3. Evaluation and preliminary analysis of effects of transient plasma conditions, complicated magnetic fields, and inverted cylendrical geometries on free surface flows for tokamaks and FRCs (a variety of stability problems exist and need to be investigated in some approximate way).

   UCLA, 0.25
   ANL, 0.25 (disruption analysis)

4. Tritium issues, flibe issues and LM insulator coatings for free liquid (there is some overlap with ALPS effort).

   ANL, 0.1 FTE
   UCLA, 0.1 FTE
   LANL {0.075 FTE from Tritium Program}

5. General design tasks for LWCs, including hydrodynamics, thermalhydraulics, and neutronics analysis; also material evaluation, drawings and layouts, safety, power conversion, *etc.*

UCLA, 1.1 FTE (hydrodynamics, thermalhydraulics, neutronics, design)
ORNL, 0.5 FTE (mechanical design)
UW, 0.1 FTE (activation)
ANL {included under power conversion group activities}
INEEL {included under safety group activities}

APPLE: Flowing Li_2O Particulate Concept

6. Design and analysis for Li_2O particulate blanket including: elimination of baffles, neutronics and thermalhydraulics calculations, and packed and loose particulate bed flow.

   ANL, 0.3 FTE (all facets)
   UCSD, 0.1 FTE (particle dynamics and thermalhydraulics)
   UCLA, 0.05 FTE (particle dynamics)
   UW, 0.35 FTE (mechanical design, neutronics and activation)

7. Tritium implantation, breeding and recovery, and diffusion in Li_2O particulate.

   ANL, 0.2 FTE
   LANL, {0.05 FTE, from Tritium Program}

8. Li_2O particulate properties: sputtering characteristics, particulate attrition, and heat transfer to solid surfaces.

   ANL, 0.2 FTE

Evaporative Spray Cooling Concept (ESCC)

9. Thermal hydraulics and power conversion assessment of spray cooling concepts.

   ANL, 0.25 FTE
   UW, 0.05 FTE (thermalhydraulics)
   UCSD, 0.15 FTE (thermalhydraulics)
   SNL, {0.1 FTE from PFC Program}

10. General mechanical design implementation and analysis, including neutronics and activation

   ORNL, 0.1 FTE (design)
   UW, 0.15 FTE (neutronics)

He-Cooled Refractory Metal FW

11. Conceptual design activities including neutronics analysis, thermalhydraulics, mechanical configuration, and power conversion

GA, 0.4 FTE (all facets)
UCLA, 0.1 FTE (neutronics)
SNL, {0.25 FTE from PFC Program}

12. Refractory alloy issues including joining, fabrication, compatibility with He coolant, tritium, and impurities

    SNL, {0.25 FTE from PFC Program}
    ORNL/UCLA {included under material's group effort}

13. Analysis of reliability and safety of system including crack detection and growth in FW and joints

    SNL, {0.1 FTE from PFC Program}
    INEEL {included under safety group activities}

General Tasks (not classifiable by concept)

14. Materials exploration and data evaluation including refractory metals, flibe, porous metals, ceramics, *etc.*

    ANL, 0.15 FTE
    UCLA, 0.25 FTE
    ORNL, 0.25 FTE {0.25 FTE matched by Materials Program}
    SNL, {0.2 from PFC Program}

15. Determination of evaluation criteria

    UCLA, 0.05 FTE
    UW, 0.05 FTE
    UCSD, 0.05 FTE
    ANL, 0.05 FTE

16. Design and integration of reference FRC concept

    LLNL, 0.4 FTE
    UW, 0.1 FTE
    UCLA, 0.1 FTE

17. Plasma Interface Group Activities

    PPPL, 0.05 FTE
    GA, 0.1 FTE
    SNL, {0.1 FTE from PFC Program}

18. Safety Group Activities: All Concepts

INEEL, {1 FTE from Safety Program}

19. Power Conversion Group Activities, All Concepts

    ANL, 0.15 FTE
    UCSD, 0.05 FTE

20. Mechanical Design Group Activities (parentheses indicate resources have already been included in *breakdown-by-concept*)

    ORNL, 0.2 FTE Availability Analysis for All Concepts
    0.2 FTE General Tasks/New Concepts,
    (0.5 FTE) Liquid Walls/Blankets for AT and FRC
    (0.1 FTE) Spray Cooling
    UW, (0.2 FTE) APPLE concept

- MHD Modeling (common to ALPS and APEX)

    UCLA, 0.5 FTE

- Other key areas under negotiation

    0.25 FTE (subcontracts from UCLA, including international collaborations)

(B) Breakdown by Organization*

UCLA (3.75 FTE)

- Plasma edge modeling for LWCs, 0.1 FTE {0.1 FTE matched from Japanese Collaboration}
- Development of turbulent free-surface hydrodynamics and heat transfer modeling tools and experiments for all liquid wall concepts (LWCs), 1 FTE
- LWC stability analysis in reactor environment, 0.25 FTE
- Tritium issues, flibe issues, and insulator coatings for LWCs, 0.1 FTE
- Hydrodynamics, thermalhydraulics, and neutronics analysis and design for LWCs, 1 FTE
- Particle dynamics for APPLE concept, 0.05 FTE
- Neutronics for He-cooled refractory metal concept, 0.1 FTE
- Evaluation criteria, 0.05 FTE
- Materials issues (*e.g.* foams, flibe), 0.25 FTE
- Development of reference FRC designs, 0.1 FTE
- (MHD modeling with free surfaces for ALPS and APEX, 0.5 FTE)
- (Subcontracts including international collaborations, 0.25 FTE)

{Green} indicates indirect funding from other programs, not included in totals

ANL (1.75 FTE)

- Li_2O particulate FW and Blanket (APPLE) design and analysis, 0.3 FTE
- Tritium issues in Li_2O particulate, 0.2 FTE
- Sputtering and heat transfer in Li_2O particulate, 0.2 FTE
- Evaluation criteria, 0.05 FTE
- Design and evaluation of spray cooling concepts, 0.25 FTE
- General materials issues, 0.15 FTE
- Tritium issues, flibe issues, and insulator coatings for LWCs, 0.1 FTE
- Disruption and transient analysis of LWC, 0.25 FTE
- Power conversion for LWCs and other concepts, 0.15 FTE
- ALPS effort on edge plasma modeling for LWCs, {>1 FTE}
- Other ANL contributions??, 0.1 FTE

ORNL (1.25 FTE)

- Mechanical design for all concepts (except APPLE), 0.6 FTE
- Availability Analysis for all concepts, 0.2 FTE
- General tasks and new concepts, 0.2 FTE
- Materials tasks, 0.25 FTE {an additional 0.25 FTE from the Materials Program}

PPPL (0.25 FTE)

- MHD modeling for EM restrained lithium blanket concept, 0.2 FTE
- General physics interface group tasks, 0.05 FTE

GA (0.5 FTE)

- Design and analysis of He-cooled refractory FW/Blanket concept, 0.4 FTE
- General physics interface group tasks, 0.1 FTE

UW (0.8 FTE)

- Activation analysis for LWCs, 0.1 FTE
- Mechanical design, neutronics and activation analysis of APPLE concept, 0.35 FTE
- Thermalhydraulics for evaporative spray cooling concept (ESCC), 0.05 FTE
- Neutronics and activation for ESCC, 0.15 FTE
- Evaluation criteria, 0.05 FTE
- Reference FRC design, 0.1 FTE

LLNL (0.5 FTE)

- Adaptation of LWC to FRC, 0.4 FTE
- Plasma edge transport modeling of evaporated impurities from LWCs, 0.1 FTE

UCSD (0.35 FTE)

- Thermalhydraulics for Li_2O particulate design, 0.1 FTE
- Thermalhydraulics of evaporative spray cooling concepts, 0.15 FTE
- Evaluation criteria, 0.05 FTE
- General power conversion activities, 0.05 FTE

SNL {1.25 FTE, from PFC Program}

- Development of He cooled refractory FW design, {0.6 FTE}
- Experimental development for LWCs, {0.25 FTE}
- Evaporative spray coolant concept development, {0.1 FTE}
- General materials group tasks, {0.2 FTE}
- General physics interface group tasks, {0.1 FTE}

INEEL {1 FTE, from Safety Program}

- Safety analysis for all concepts, {1 FTE}

LANL {0.125 FTE, from Tritium Program}

- Tritium issues for LWCs, {0.075 FTE}
- Tritium issues for APPLE concept, {0.05 FTE}