APEX Reference Document
FY 2000 Technical Plan
Tasks / Performers / Level of Effort

Introduction

This document serves as a reference document for the APEX Study for FY 2000. It defines scope, approach, milestones, tasks, subtasks, and task leaders as well as individual and institutional performers for FY 2000. The level of effort is also indicated and corresponds exactly to the DOE January Fin Plan made available by Sam Berk in early December.

The technical plan contained in this document evolved from a "process" that took approximately two months. Task leaders worked with core groups in a "bottom up" approach to identify key issues and priority technical tasks and level of effort. The process expanded to include all team members and was discussed during the November 8-11 meeting. Several iterations took place.

This final plan incorporates all comments and suggestions and follows DOE guidelines. Minor revisions were made by the APEX Steering Committee on December 6^{th} and 7^{th}.

Finally, it should be noted that the tasks defined here for FY 2000 were derived from a set of 5-year goals, developed by the APEX team, for Liquid and Solid Walls. These 5-year goals are:

Liquid Walls:

1. Fundamental understanding of free surface fluid flow phenomena and plasma-liquid interactions verified by theory and experiments.

2. Operate flowing liquid walls in a major experimental physics device (e.g. NSTX).

3. Begin construction of an integrated Thermofluid Research Facility to simulate flowing liquid walls for both IFE and MFE.

4. Understand and document advantages and implications of using liquid walls in fusion energy systems.

Solid Walls:

5. Understanding of novel concepts that can extend the capabilities and attractiveness of solid walls.

APEX
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Task I: Explore options and issues for implementing a flowing liquid wall in a major experimental physics device. Characterize the technical issues and develop an R&D plan.

Task II: Explore high pay-off liquid wall options. Include: a) tokamaks and other confinement schemes, b) flibe and liquid metals (Li and Sn Li), c) concepts with physics advantages, and d) concepts with engineering advantages.

Task III: Investigate practical engineering issues associated with the design of a liquid wall in a high-power density fusion energy system (start with CLIFF-flibe because it is better understood and has more data available).

Task IV: Investigate key issues and develop a practical design for high-temperature refractory solid wall with primary focus on EVOLVE.

Task V: Other tasks.

Cross-Cutting Tasks

Task A: Plasma-Liquid Surface Interactions and Plasma Edge Modelling

Task B: Liquid Wall-Bulk Plasma Interactions

Task C: Materials

Task D: Safety and Environment

Task I: Explore options and issues for implementing a flowing liquid wall in a major experimental physics device

Task Leader **Alice Ying**

Total Effort **$450 k**

Scope

This task is for development of and agreement upon a technology-physics integrated mission to conduct flowing liquid wall tests in a major operating plasma device, performing research to identify and characterize design options and key issues of such flowing liquid walls, and development of an R&D plan.

Approach

The approach to executing this task must remain flexible and evolve over time based on updated technical results and information available. An appropriate approach to undertake this task involves the following elements:

(1) to establish close interactions with the current programs of operating plasma devices and plasma physicists
(2) to understand and convey the benefits of performing such a test
(3) to characterize the issues and assess the R&D required for conducting flowing liquid wall tests in a major operating plasma device
(4) start with NSTX as an example of an experimental physics facility

Milestones
Intermediate Milestones (Responsible Subtask No.)

An integrated technology-physics mission statement 2/00 (Task I.1 and all)

Initial projected characterizations of operating plasma devices including operating conditions and configurations 2/00 (Task I.1)

A draft R&D plan 5/00 (Task I.5)

Design review of the laboratory experiment on MHD free surface 3/00 (Task I.2 and Task I.4)

Initial assessment of technology issues 5/00 (Task I.2 and Task I.5)

FY 2000 Deliverables

1) A report of recommendations

2) Document issues concerning flowing liquid wall tests in operating plasma devices

3) A 4-year plan including required R&D

4) Construction of laboratory facility for experiments with liquid metals in magnetic field

Subtasks

Task I will consist of 5 subtasks to achieve both better coordination and effective execution.

I.1 Characterization of projected plasma operating conditions in NSTX and other facilities (PPPL-30 k/Bob Kaita – 20 k and R. Maingi – 10 k)

This subtask aims to project data required for assessing flowing liquid wall options. The data includes:

- Configuration of the machine including access, ports, and layout
- Static and transient heat loads
- Temporal and spatial distributions of magnetic fields (operational scenario and wave forms)
- Plasma operating conditions
- Off-normal conditions including disruption characteristics and frequency

I.2 Design and analysis of flowing liquid wall options in NSTX and other operating plasma devices (195 k)

The objective of this subtask is to identify and perform preliminary magnetic-hydrodynamics and heat transfer analysis as related to the flowing liquid wall options. The results will be used to guide designs of small-scale laboratory experiments for further understanding and evaluation of the proposed flowing liquid wall options in relevant plasma operating environments (e.g., 1/R toroidal field variation and surface heating). This subtask is categorized into concept explorations and analysis.

a) Configuration (ORNL 25 k/Brad Nelson, UCLA 25 k/Alice Ying)
Conceptual development on general layout with 3-D perspective, routing and divertor integration. Both LM and Flibe will be considered.

b) Divertor Integration (SNL 25 k/Richard Nygren)
Explore options for divertor integration - separate divertor or an extension of the flowing liquid walls

c) Hydrodynamics and Heat Transfer (UCLA 75 k/Neil Morley, Sergey Smolentsev/Alice Ying)
Modeling and analysis of spatial and temporal field effects on fluid flow hydrodynamics and heat transfer (also CDX-U modeling)

d) Safety (INEEL, ANL/Kathy McCarthy, Ahmed Hassanein)
- Input on liquid handling and other safety issues (INEEL, 25 k)
- Off Normal effects on liquid surface (Hassanein, 10k)
- Disruptions (Hassanein, 10 k)
- Others?

I.3 Plasma-Liquid Interactions (covered under Task II)

The data from Task II should help identify issues concerning plasma-liquid wall interactions such as:

a) Surface Interactions and Edge Physics (LLNL, under C.C. Task A)
b) Bulk Plasma-Liquid (PPPL, covered under Task II)

I.4 LM-MHD initial exploratory experiments with magnetic field gradients and applied currents (UCLA-100k, PPPL-20k/Bob Woolley, SNL-25k/Richard Nygren) (also part of Task II)

The concept of using a liquid metal wall in a tokamak requires flow of the electrically conducting liquid metal across the complicated magnetic field. These fields exhibit certain characteristics such as non-uniformity like the 1/R dependence of the toroidal field on the major radius and the ripple field between adjacent coils. The feasibility of liquid metal walls in particular is very sensitive to the variation in strength and orientation of the fields. In addition, the pulsed nature of current tokamak experiments like NSTX requires exploration of inductive effects in the LM flows to demonstrate the possibility of their use in such a plasma experiment

LM-MHD experiments have traditionally been done with gap magnets that exhibit neither of these dependencies. This task aims at constructing a toroidal magnetic field facility at UCLA (with the flexibility to convert it to a straight solenoid) and studying the effects of the magnetic field gradients on LM flow characteristics. The facility will be constructed utilizing the coils donated from MIT TARA experiments and power supply from Princeton. Initial experiments will focus on the liquid metal flow on a curved backing plate in poloidal direction and pulsed toroidal field effects.

I.5 Identification of key issues and Development of an R&D plan for implementing liquid walls in NSTX and other operating plasma devices (UCLA 50 k/Alice Ying, Neil Morley, PPPL 20 k/Bob Kaita, SNL 10 k/Mike Ulrickson)

This task is to identify issues critical to successful implementation of flowing liquid walls in NSTX and other operating plasma devices and also develop an R&D plan.

Task II: Exploration of High-Payoff Liquid Wall Concepts

Task Leader: **Neil Morley**

Total Effort: **$752 k**

Scope:
This task continues the main APEX mission of exploring high payoff liquid wall concepts that increase the attractiveness of fusion energy, with emphasis on understanding the key scientific issues. The scope of this task is not limited even to any one design vision, but includes concepts for thick liquid walls utilizing both liquid metals and Flibe, and thin liquid metal walls that have the potential to improve the physics performance of plasma. Other new APEX concepts that are advanced this year will also be analyzed under this task.

Approach:
This year's subtasks (given below) pursue the continued development and application of much-needed, generic modeling tools for liquid walls and plasma interaction with liquid walls. The initiation of experiments that address fundamental LW issues identified in last year's effort that are key to the understanding of liquid wall phenomena will also be undertaken, and will undergo design review before implementation.

Major Milestones:

Subtask II.1: Exploration of thin and thick Liquid Metal wall concepts

3/00

- Complete lithium wall simulations (for tangent walls) with UEDGE (LLNL). Compare with kinetic impurity model in MCI code
- Extension of 1.5-D MHD model to the case of a 2-component magnetic field, begin analysis of cases at UCLA (toroidal+radial)
- Development of a 2-D or quasi 3-D MHD model for analyzing local flow effects and field gradients, begin analysis of cases at UCLA
- Initial results on stabilizing effects of liquid walls in simplified (straight) geometry at the Institute for Fusion Studies at the University of Texas (UT)

5/00

- Simulate discharge startup and investigate vertical stability with TSC for CDX-U and ARIES plasmas at PPPL
- Set up initial case with UEDGE for CDX-U geometry, initial scoping calculations for lithium at LLNL
- Perform resistive MHD analysis of vertical stability in highly-elongated plasmas at UT

6/00

- Report on further analysis of magnetic propulsion of intense liquid lithium streams and simple experimental tests of magnetic propulsion, PPPL and UI

7/00

- Perform ideal MHD analysis of kink modes and provide IFS with equilibrium matrix for δW code

8/00

- Perform initial fluid response assessment with vorticity equation and/or MHD resistive wall kink mode analysis at UT (8/00)

9/00

- Begin first tests for field gradients, pulsed fields, and applied fields in the MHD facility at UCLA

- Data and cost estimate of feedback systems at IFS and plan rippling mode studies in CDX-U from UT
- Concept description of "soaker hose" for liquid walls and divertors from UT

Subtask II.2: Exploration of thick Flibe blanket concepts

4/00

- Complete base construction of *Fli-Hy*, begin tests on curved wall
- Modification of the current k-ε model and the code for the developing MHD

7/00

- Flibe wall simulations in ARIES-RS geometry using UEDGE
- Perform experiments for penetration in Flibe flow in *Fli-Hy* at UCLA
- Assessment of 2 stream ideas and MHD effects in thick Flibe flow from UCLA and LLNL, propose new strategies for thick liquid Flibe wall
- Assessment of penetration hydrodynamics in thick Flibe flow from UCLA, propose new strategies for thick liquid Flibe wall
- Further improvements of the MHD k-ε model with velocity-potential correlation term to extend the model to the case of electrically conducting walls (Japanese colleagues DNS data)

10/00

- Initiate turbulence measurements using LDA on *Fli-Hy* for a fully developed flow on a plane back wall for k-ε model validation
- Benchmark non-MHD k-ε using experimental data for the layer thickness in the fully developed turbulent water flow

Subtask II.3: Exploration of liquid walls for non-tokamaks

9/00

- Document key characteristics and issues of liquid walls in FRC and RFP

Subtask II.4: Materials, safety, and nuclear analysis for high payoff Liquid walls

9/00

- Sn-Li vapor pressure and composition data obtained
- Recommendations on compatible combinations of liquids and structural materials
- Quantitative assessment and guidelines for minimizing volume and hazard of rad waste.

FY 2000 SubTasks and Work-Breakdown-Structure

II.1 Exploration of thin and thick Liquid Metal wall concepts ($332k)

a) Bulk Plasma-Liquid metal wall interactions including (130k) – **Kaita and Kotschenreuther**
   - Eddy currents and fluid motion during plasma startup studies with Tokamak Simulation Code (TSC) (PPPL- $30k: Jardin, Kessel, and Pomphrey)
   - Considerations regarding plasma elongation - new equilibrium with higher triangularity for toroidal limiter (PPPL - $20k: Jardin, Kessel, and Pomphrey)
   - Resistive MHD analysis of vertical stability in highly-elongated plasmas and assess feedback stabilization (UT - $20k: Kotschenreuther)
   - Stabilizing effects of liquid walls on free-boundary plasma modes. Perform MHD analysis of kink modes and determine equilibrium matrix for dW code to complete investigation of stabilizing effects of liquid walls in simplified (straight) geometry (PPPL - $30k: Manickam and Zakharov; UT – $30k: Kotschenreuther and Rappaport)

b) Plasma-liquid surface interactions with lithium (covered under ALPS/APEX PLSI) – **Rognlien**
- Provide 2-D hydrogen edge-plasma profiles from ARIES for use in near-surface test-particle codes and core systems codes (LLNL: Rognlien, Resnick and Evans)
- Determine first-wall temperature limits based on Lithium impurity influx in ARIES with optimal assumptions. (LLNL: Rognlien and Resnick)
- Brief assessment of advantages of different device geometries and plasma-engineering intervention techniques such as auxiliary heating for impurity wall influx. (LLNL: Rognlien and Resnick)
- Work with CDX-U people to get initial UEDGE edge-plasma and impurity influx model in place (minimal calculations) and other ALP/APEX related tasks. (LLNL: Rognlien and Resnick)

c) LM-MHD numerical tool development and analysis of potential LM wall designs (192k) **- Smolentsev**
- Effect of temporal and spatial field gradients on free surface flow. Upgrade of 1.5D "shallow water" codes to allow developing electric currents and field gradients. Development of 2D "full solution" codes assuming axi-symmetric conditions in 3rd dimension for analyzing 3-component time-varying fields and eddy currents {work with II.a}. Ground work fro 3D Reduced Navier-Stokes-Maxwell implementation (UCLA-150k: Smolentsev, Morley, and student)
- Analysis of submerged walls for poloidal flow and applied electric currents (UCLA-above: Smolentsev, Morley, and student, PPPL – 10k: Zakharov)
- Other flow configurations for better performance during startup (UCLA-above: Smolentsev, Morley, and student; UT-32k: Kotschenreuther)

d) LM-MHD experiments (10k plus Task I) **- Morley**
- Coil setup and initial exploratory experiments with flow on inclined plane and inverted curved surface with and without field gradients and applied currents. (covered under Task I)
- Simple experimental tests of magnetic propulsion (PPPL – 10k: Ruzic@UI)

II.2 Exploration of thick Flibe blanket concepts ($280k)

a) Identification and analysis of potential thick Flibe concepts (130k) – **Ying and Gulec**
- Conception and analysis of two-streams and other concepts for enhanced heat transfer and reduced flowrate using existing 3D hydrodynamic modeling tools (UCLA-50k: Gulec, Smolentsev, Ying, and student; LLNL-30k: Moir)
- Evaluation of MHD drag forces and heat transfer degradation using modeling tools adapted from II.1 and the MHD k-ε model (UCLA-25k: Smolentsev, Gulec)
- Analysis of penetration shapes for moderate and thick Flibe flows (UCLA-25k: Gulec and student) –

b) Plasma-Liquid Surface Interactions (covered under ALPS/APEX PLSI) **- Rognlien**
- Determine first-wall temperature limits based on Flibe impurity influx in ARIES with optimal assumptions. (LLNL: Rognlien and Resnick)
- Other general tasks listed under II.1 (LLNL)

c) Flibe simulant experiments in basic poloidal flow LW geometries ($130k) **- Gulec**
- Facility assembly and operation, basic test section construction for flow on curved plate with and without penetrations (UCLA-100k: Gulec, Sketchley, Ying, and Morley, ORNL-10k: Nelson)
- Design and manufacture of test nozzles (ORNL-20k: Nelson and Fogarty)

d) Mechanical configuration issues and drawings (ORNL-25k) **- Nelson**

II.3 Exploration of Liquid Walls for non-tokamak confinement schemes ($50k)

a) Continuation of FRC work (LLNL-25k) **- Moir**

b) RFP, Stellarator (LLNL-25k) **- Moir**
- Work with Daniel Hartog (UW) on definition of a general configuration and parameters for an RFP (e.g. magnetic field, heat fluxes, etc.)
- Definition of potential flow schemes for RFP and preliminary hydrodynamic analysis (some small effort by UCLA for hydrodynamic, heat transfer, and nuclear analysis will be covered under subtasks II.1, II.2, and II.4)

II.4 Materials, safety, and nuclear analysis for high payoff Liquid walls ($85k)

a) Identifying compatible liquid-structure combinations and temperature and other operating limits for a variety of applications: flexible vs. rigid, hermetic vs. non-hermetic, etc. (ORNL-10k: Zinkle; UCLA-5k: Ghoniem) **- Zinkle**

b) Preliminary assessment of erosion rates for various coolant/material combinations as a function of temperature and coolant velocity (focus on key areas such as nozzles and potential non-structural insulators or semiconductors like SiC) (ORNL-10k: Zinkle; UCLA-5k: Ghoniem) **- Ghoniem**

c) Analysis of safety issues for liquid walls ($25k) **- McCarthy**
- Perform scoping safety assessment of rough designs including CHEMCON thermal calculations when needed, and potential off-site doses during accidents (INEEL – 15k: McCarthy)
- Participate in optimized shield redesign for ARIES with LW (INEEL – 10k: McCarthy)

d) Sn-Li and Flibe vapor and composition (INEEL-Planned Under Safety Program) **- McCarthy**

e) Nuclear analysis and activation {some overlap with Task III nuclear work} ($30k) **- Youssef**
- Assessment of heating rate and penetration depth of X-rays in LWs from a more realistic X-rays spectrum that accounts for radiation from impurities and line radiation and recombination (UCLA – 5k: Youssef)
- Estimation of nuclear heating and damage data rates for back wall, inlet/outlet nozzles and near penetrations of various shapes with assumptions about LM flow depths and geometry (UCLA – 5k: Youssef)
- Assessment of hazard and waste volume of LW concepts with optimized shield and comparison to solid wall concepts with optimized shield (UCLA – 10k: Youssef; UW – 10k: Sawan)

Task III: Practical Engineering Issues Associated with the Design of a Liquid Wall

Task Leaders: **Dai-Kai Sze and Brad Nelson**

Total Effort: **$660 k**

Scope: This task focuses on investigating the practical engineering issues associated with the design of a liquid wall in a high power density fusion energy system. Examples of these issues are: 1)inlet and exit nozzles, 2) hydrodynamic configuration including flow around penetrations, 3) integration of divertor functions with flowing liquid walls, 4) particle exhaust, 5) liquid pumping, 6)liquid temperature profiles and tradeoffs, 7) tritium fueling, inventory and extraction, 8) He trapping and pumping, and 9) other engineering issues. This task will also provide valuable input to Task I and II.

Approach: This task will start with CLIFF Flibe. The initial reference reactor configuration will be ARIES-RS, but with adjusted power level to obtain higher wall loading. For the CLIFF flibe concept, the focus is on the flowing 2-cm Flibe on the plasma side of the first wall. For the configuration, a reference blanket will have to be identified, but the blanket design is not a focus of this study. This reference blanket will be decided upon by the task leaders.

For the Task III.2, it was agreed that it would be important to assess the issues associated with a low re-cycle material such as lithium on the wall and in the divertor. It will be assumed that all the tritium will be removed by the divertor stream, and He will either be trapped in the divertor stream, or be pumped away by a pump yet to be designed.

Milestones

Feb. 2000

- Establish parameter regimes for the divertor exhaust system.
- Determine optimum temperature window of the flibe first wall coolant.
- With the selection of a blanket, determine the first wall/blanket/divertor configuration options.

May 2000

- Assess the tritium pumping, fueling, He trapping and pumping issues and develop possible solutions.
- Develop methods to enlarge the temperature window.
- Optimize the configuration of the design, with the addition of the penetrations, including plasma heating and fueling systems.
- Identify feasibilty issues on each sub-task.

June 2000

- Develop possible solutions for the feasibility issues.
- Incorporate those possible solutions into the design.

Aug. 2000

- Prepare a report.
- Identify the R/D issues.

FY 2000 Tasks:

III.0 Task Coordination (Sze 30K)

III.1 Mechanical Design, Maintenance, Integration (Nelson/Fogarty)

a) Document requirements and system parameters (ORNL ~10k)
b) Develop and update configuration layout and CAD models based on input from other subtasks, including pumping, divertor, inlet and exit nozzles, piping, maintenance approach, etc.(ORNL ~60k)
c) Define penetrations for heating, fueling, etc. (ORNL ~10k)
d) Conducting shell and other liquid-bulk plasma considerations (PPPL-Kaita et al, 10k, UCSD-ARIES)

III.2 Pumping and Divertor Function Integration (Nygren)

a) Design for divertor functions (SNL – 100k, 20K – Mattas – ANL)
b) Hydrodynamics and heat transfer (UCLA, Gulec, Smolentsev – 40k)
c) Particle pumping (30k for Rognlien and 20K for SNL)

III.3 Liquid Wall Fluid Flow Configuration and Design

a) Definition of penetration requirements for plasma heating and flexibility (ORNL-10k)
b) Hydrodynamics and Heat Transfer for inlet, main flow, penetrations, and exit (UCLA, Gulec, Smolentsev - 30k)
c) Liquid-bulk plasma interactions (PPPL – 10k – D. Stotler)
d) Plasma-liquid surface interactions (Rognlien-covered under C.C. Task A)
e) Design considerations and coupling to plasma edge constraints (LLNL-Moir-20k)
f) Structural design (ANL-Majumdar-20k)

III.4 Tritium Recovery and Control (Sze)

a) Tritium recovery, control, and inventory (Sze-40k)
b) Flibe-specific experience (ORNL-Toth, additional funds requested, but not allocated)
c) Tritium Processing (LANL-20k)

III.5 Nuclear Analysis

a) Neutronics (UCLA-Youssef-30k)
b) Activation (UW- Khater 15k)

III.6 Material Analysis (Zinkle)

a) Choice of structure for compatibility, temperature and other operating limits (ORNL-Zinkle-20k, UCLA-Ghoniem-10k)
b) Material issues including erosion for nozzles (ORNL-Zinkle-10k, UCLA-Ghoniem- 10k)

III.7 Safety (McCarthy)

a) Safety analysis (INELL-McCarthy-25k)
b) Flibe movement after disruption (ANL-Hassanein-20k)

III.8 Primary Loop Design and Power Conversion (ANL-Sze-20k)

III.9 Flibe Chemistry (ANL-Sze-20k)

Task IV: High-Temperature Refractory Solid Wall

Task Leader **Clement Wong**

Total Effort **$430 k**

Scope

This task will investigate the fundamental issues and develop a practical design based on analysis for the high-temperature refractory solid first wall and blanket design. For FY2000 our primary focus will be on the EVOLVE concept (vaporization cooling of the first wall and boiling heat removal from the blanket, with lithium as the coolant and breeder, and W-alloy as the structural material) operating in a tokamak environment. In addition, we will evaluate the possible advantage of the low system pressure approach of the EVOLVE concept and develop an R&D plan.

Approach

The approach for this task is to identify and analyze the fundamental issues in order to establish the necessary scientific and engineering understanding on the possible performance and R&D needs for the use of high-temperature solid first wall and blanket design. For FY2000, our approach to take advantage of the low system pressure EVOLVE will involve the following elements:

(1) to scope a conceptual design that can take advantage of the low pressure liquid metal vaporization approach while using W-alloy as the structural material,
(2) to establish the analytical capability and scientific understanding on the effect of liquid metal vaporization cooling of the first wall and the boiling heat transfer in the blanket while operating in the magnetic field configuration of a tokamak reactor,
(3) to further establish the necessary scientific irradiated material and engineering data base for the use of refractory structural material and the necessary design code and method for the use of irradiated and relatively low ductility structural material in a tokamak environment,
(4) to continue the fundamental study of irradiation resistant refractory material,
(5) to establish the basic performance and safety implications of the EVOLVE concept,
(6) to identify necessary test plan to address essential R&D items.

Milestones

Complete the scoping MHD analysis of the first wall design options and select the reference design. 2/00

Based on the MHD analytical models developed for the reference first wall and blanket design, complete the first iteration of the analysis and design. 5/00

Based on more complete MHD analytical models, complete the second iteration of the analysis of the reference first wall and blanket design. 8/00

Complete a draft R&D plan 9/00

FY 2000 Deliverables

(1) Provide an annual report including identification of un-resolved critical issues.

(2) Provide a draft R&D plan with identification of testing facilities.

Subtasks

IV.0. Coordination (GA-30k/C. Wong, FZK-10k/S. Malang)

IV.1 Material

IV.1.a Continue to update and project the properties, needed development and costing of low activation W-alloy. (ORNL-40k/S. Zinkles)

IV.1.b Evaluate fabrication and testing, and support first wall thermal analysis (SNL-40k/R. Nygren)

IV.1.c Generate testing plans and perform testing (SNL-20k/R. Nygren)

IV.1.d Perform fundamental modeling on innovation W-alloy like the TiC doped option and project radiated properties. (UCLA-10k/N. Ghoniem)

IV.2 Thermal hydraulics analysis including MHD effects

IV.2.a Frist wall: (UW-60k/M. Corradini, ANL-20k/R. Mattas)

IV.2.a.1 Perform scoping MHD analysis for the spray and capillary cooling concepts, select one for more detail analysis.

IV.2.a.2 Develop the MHD thermal-hydraulics analytical model to study the effect of liquid metal vaporization heat transfer at the first wall with the goal of understanding the underlying science influencing the performance of the selected design. Early analytical results will form the basis for the 1st design iteration.

IV.2.a.3 Continue the development of the MHD thermal-hydraulics analytical model in concert with the mechanical design to enhance the scientific understanding of the basic effects of liquid metal vaporization heat transfer. Results from this work will support the 2nd iteration design and will be used to identify future R&D requirements.

IV.2.b Blanket design (GA-40k/C. Wong, Barleon-25k)

IV.2.b.1 Develop the MHD thermal-hydraulics analytical model to study the effect of liquid metal boiling heat transfer, with the design goal of maintaining constant heat removal and temperature distribution in the poloidal blanket module. We will focus on achieving the understanding of the fundamental science that would impact the satisfaction of the design requirements. Preliminary results from this modeling effort will form the input to the 1st design iteration.

IV.2.b.2 Continue the development of the MHD thermal-hydraulics analytical model in concert with the mechanical design of the blanket to enhance the scientific understanding of the basic effects of boiling liquid metal heat transfer. Results from this work will support the 2nd design iteration and will be used to identify future R&D requirements.

IV.3 First wall and blanket mechanical and structural design (UW-30k/I. Sviatoslavsky, GA-20k/E. Reis)

IV.3.a First wall: Consider the structural and thermal properties of the selected W-alloy, and the projected MHD effect on the boiling heat transfer, generate mechanical design for the spraying first wall and capillary first wall concepts for scooping design. Perform the 1st iteration design on the selected concept. Perform the 2nd iteration of the selected first wall design and identify and analyze critical structural locations. The design will have to satisfy all material design requirements.

IV.3.b Blanket: Consider the structural and thermal properties of the selected W-alloy, and the projected MHD effect on the boiling heat transfer, generate a mechanical design that could fulfill the requirement of maximizing blanket shielding with uniform temperature distribution in the blanket, while satisfying all material design requirements.

IV.4 Design criteria and support: Provide suitable design criteria for W-alloy at high temperature and high neutron fluence and provide structural analysis support. (ANL-20k/S. Majumdar)

IV.5 Nuclear analysis (UW 20k/M. Sawan)

Perform nuclear heating, afterheat and induced radioactivity nuclear analysis in concert with the designs being evaluated. When time allow perform TBR analysis.

IV.6 Configuration (ORNL-10k/B. Nelson)

In concert with the first wall and blanket design, generate 3-D perspectives with focus on coolant routing and module support.

IV.7 Safety design and analysis (INEEL-25k/K. McCathy)

In concert with the blanket design analysis and the proposed passively safe design approach and with afterheat input from the nuclear analysis task perform LOFA and LOCA safety analysis.

IV.8 Power management (GA- 0k/R. Schliecher)

Perform optimization of power conversion system including the scoping evaluation of Li-MHD power conversion and high performance CCGT systems.

IV.9 Tritium management (ANL-10k/D. K. Sze)

Investigate and evaluate means to extract tritium from Li by taking advantage of the available high temperature of Li at 1200 C. Evaluate the issues of tritium control during routine operation and accident conditions.

Task V: Other Tasks

V.1 APEX Scientific Secretary (M. Youssef – UCLA – 30k)

- Coordinate reports.
- Coordinate meetings, including agenda and summary.
- Maintain and update website.
- Other assignments by the Study Leader.

V.2 Special Assignments (M. Sawan – UW – 15k)

- Coordinate schedule for conference calls.
- Prepare and post minutes for Steering Committee.
- Monitor progress and performance in each task, as well as coordination among tasks. Report problems/suggestions to study and task leaders.
- Other tasks to assist study leader.

Common Task A: Plasma-Liquid Surface Interactions and Plasma Edge Modeling

Task Leader: **Tom Rognlien**

Total Effort: **Funds from ALPS, plus $30 k from APEX under Task III**

Scope:

This task area focuses on predicting the influence on the core plasma of the impurity ions generated from the liquid vapor and the effect of core energy exhaust on the liquid temperature. The edge plasma provides the interface between the hot core plasma and the liquid first-walls and divertor plates. The liquid surfaces can impact the edge and core plasmas by releasing impurities through sputtering, recycling, and evaporation. Such impurities degrade fusion core performance through enhanced radiation loss and fuel dilution. In addition, the recycling properties of the liquid surface and the impurity ions from the vapor itself can modify the density and temperature of the hydrogenic edge-plasma which, in turn, affects the core-plasma stability and confinement characteristics. The conductivity and proximity of the liquid material to the core plasma also impacts core MHD stability. This work is being carried out within the Plasma-Edge Modeling Group which provides support for both ALPS and APEX; here we focus on the liquid first-wall modeling, but there is a close connection between that and the liquid divertor work done for ALPS.

Approach:

There are numerous issues to be understood in this area, and the approach is to use a set of existing modeling codes to determine the effects for each area. It is also important to obtain integrated descriptions of the difference issues and thus part of the effort is going toward increased coupling of the various codes. The edge plasma is modeled by the 2-D UEDGE fluid transport code which includes particle, momentum, and energy balance equations for multispecies ions and electrons from the liquid surface to a region somewhat inside the magnetic separatrix for the core plasma. This provides the basic hydrogenic plasma profiles in the edge region and also the distribution of the impurities from the liquid walls. An important issue is the kinetic transport corrections to such impurity transport in the whole edge region, and here we use the MCI Monte Carlo core. Interactions close to the liquid surfaces (walls or divertor plates) is provided by the WBC and BPHI Monte Carlo codes; these provide a detailed description of the plasma sheath and near-surface profiles where prompt redeposition of the impurities can take place. Work is being performed to more closely couple the whole-edge UEDGE modeling with the near-surface WBC model. Transient, large-energy plasma-wall interactions from ELMs and disruptions are modeled using the HEIGHTS package which includes effects like vapor shielding and splashing of the liquid. The ONETWO core transport core is being used to model the response of the core to the changing edge conditions. Benchmarking of the various models with experimental data for impurity behavior in plasma devices in a very important aspect of this work.

Milestones:

12/99 Generate mesh and hydrogen edge-plasma for ARIES-RS

2/00 Lithium evaporation limits for ARIES-RS

3/00 Kinetic corrections for lithium intrusion in ARIES-RS

4/00 Initial assessment of geometry and edge heating on temperature limit

5/00 Edge plasma for CDX-U; initial scoping of lithium effect

6/00 Flibe evaporation limits for ARIES-RS; also coupled UEDGE/WBC

7/00 Initial assessment of non-tangent B-field at walls

9/00 Assess helium pumping with liquid wall and divertor together

<u>Subtasks and Work Breakdown Structure:</u>

A.1a Obtain mesh and basic hydrogen plasma for ARIES-RS configuration. Complete lithium and Flibe wall simulations for tangent walls; uses UEDGE with Rognlien and Rensink ($50K), LLNL. (also task II.1b and II.2b)

A.2a Compare with kinetic impurity model in MCI code; uses MCI with Evans ($10K?) GA; UEDGE with Rognlien ($5K), LLNL. (also task II.1b)

A.3a Survey effect of geometry and edge heating using simple adjustable slab model; uses UEDGE with Rensink and Rognlien, LLNL ($15K). (also task II.1b)

A.4a Couple UEDGE and WBC; uses UEDGE with Rognlien and Rensink ($30K) and WBC with Brooks, ANL ($?) - mostly ALPS related

A.5a Set up initial case with UEDGE for CDX-U geometry, initial scoping calculations for lithium; uses UEDGE with Rensink and Rognlien, LLNL ($15K); Maingi, ORNL ($15K?). (also task I.3a)

A.1b Assess non-tangent side wall effects; uses UEDGE with Rognlien and Rensink, LLNL ($10K)

A.3b Helium pumping in presence of liquid walls and divertors; uses UEDGE with Rognlien and Rensink, LLNL ($30K) (also task III.2a)

A.4b Combined with A.5a ($10K added to A.5a)

A.5b Inserted as A.2a ($5K added to A.2a)

A.6b (added) Disruption effects on Flibe; uses HEIGHTS code with Hassaein, ANL ($20)

Common Task B: Liquid Wall-Bulk Plasma Interactions

Task Leader: **Robert Kaita**

Total Effort: **$272 k included in Tasks I – IV**

FY 2000 Tasks:

Task I. Explore options and issues for implementing a flowing liquid wall in NSTX

Scope:

I.1 Characterization of NSTX operating conditions

I.4 LM experimental facility set up and initial exploratory experiments with and without a magnetic field gradients and applied currents

I.5 Identification of key issues and development of an R&D plan for implementing liquid walls in NSTX

Approach:

I.1 Provide information on the following for NSTX:

- Configuration of the machine including access, ports, and layout
- Static and transient heat loads
- Projected temporal and spatial distributions of magnetic fields (operational scenario and wave forms)
- Plasma operating conditions
- Off-normal conditions including disruption characteristics and frequency

I.4 Contribute to design of LM experimental facility set up and initial exploratory experiments with and without a magnetic field gradients and applied currents.

I.5 Set up working group to identify key issues and assist in development of an R&D plan for implementing liquid walls in NSTX.

Milestones:

I.1 Provide information on NSTX operating conditions (1/00)

I.4 Contribute to LM experimental facility set up and initial exploratory experiments with and without a magnetic field gradients and applied currents (2/00)

I.5 Report on key issues for implementing liquid walls in NSTX identified by NSTX Working Group (3/00)

Subtasks:

I.1 Characterization of NSTX operating conditions (PPPL - $20k, Oak Ridge National Laboratories - $10k)

- R. Kaita and R. Maingi (Oak Ridge National Laboratories) to feed into Task I intermediate milestone:
  Initial projected characterizations of operating plasma devices including operating conditions and configurations 2/00 (Task I.1)

I.4 LM experimental facility set up and initial exploratory experiments with and without a magnetic field gradients and applied currents (PPPL - $20k)

- R. Woolley to feed into Task I intermediate milestone:

Design review of the magnetic testing facility 3/00 (Task I.2 and Task I.4)

I.5 Identification of key issues and development of an R&D plan for implementing liquid walls in NSTX (PPPL - $20k)

- R. Kaita to provide recommendations from NSTX Working Group to feed into Task I intermediate milestone:
  Initial assessment of technology issues 5/00 (Task I.2 and Task I.5)

Task II. Exploration of High-Payoff Liquid Wall Concepts

Scope:

II.1 Exploration of thin and thick LM wall concepts

- Effects of liquid lithium walls on discharge evolution, including startup, fueling and transport phases and potential beneficial effects of H gettering and low recycling
- Effect of liquid metal walls on plasma stability, including potentially beneficial effects of conducting shell and the associated engineering and design requirements on liquid walls

II.1.c Other flow conditions for better performance during startup

Approach:

II.1 Exploration of thin and thick LM wall concepts

1. Fluid motion during plasma startup studies with Tokamak Simulation Code (TSC)
   - Induced eddy currents and resultant fluid motion
   - Requirements on startup voltages

2. Considerations regarding plasma elongation
   - Effect of vertical feedback system on liquid wall
   - Limits on plasma elongation
   - Investigate vertical stability and estimate cost of feedback systems

3. Stabilizing effects of liquid walls on free-boundary plasma modes
   - Develop dispersion relation in simplified (straight) geometry
   - Quantify dependence of thickness and flow rate of liquid layer
   - Begin formulation of toroidal problem building on PEST, DCON, or NOVA
   - Investigate rippling mode in CDX-U

4. New concepts for liquid walls
   - Further analysis of magnetic propulsion of intense liquid lithium streams
   - Perform simple experimental tests of magnetic propulsion

II.1.c Other flow conditions for better performance during startup

- Develop “soaker hose” concept for liquid walls and divertors

Milestones:

II.1 Exploration of thin and thick LM wall concepts

1) Investigate stabilizing effects of liquid walls in simplified (straight) geometry at the Institute for Fusion Studies (IFS) at the University of Texas (3/00)

2) Simulate discharge startup and investigate vertical stability with TSC for CDX-U and ARIES plasmas at the Princeton Plasma Physics Laboratory (PPPL) (5/00)

3) Perform resistive MHD analysis of vertical stability in highly-elongated plasmas (IFS) (5/00)

4) Report on further analysis of magnetic propulsion of intense liquid lithium streams and simple experimental tests of magnetic propulsion (6/00)

5) Perform ideal MHD analysis of kink modes and provide IFS with equilibrium matrix for δW code (7/00)

6) Perform initial fluid response assessment with vorticity equation and/or MHD resistive wall kink mode analysis at IFS (8/00)

7) Investigate and estimate cost of feedback systems at IFS and plan rippling mode studies in CDX-U (9/00)

II.1.c Other flow conditions for better performance during startup

1) Develop "soaker hose" concept for liquid walls and divertors (9/00)

Subtasks:

II.1 Exploration of thin and thick LM wall concepts

1. Fluid motion during plasma startup studies with Tokamak Simulation Code (TSC) (PPPL- $30k)
   - S. Jardin, C. Kessel, and N. Pomphrey to simulate with TSC for CDX-U and ARIES plasmas

2. Considerations regarding plasma elongation (PPPL - $20k, IFS - $20k)
   - S. Jardin, C. Kessel, and N. Pomphrey to investigate with TSC for CDX-U (new equilibrium with higher triangularity for toroidal limiter) and ARIES plasmas
   - M. Kotschenreuther to perform resistive MHD analysis of vertical stability in highly-elongated plasmas and assess feedback stabilization

3. Stabilizing effects of liquid walls on free-boundary plasma modes (PPPL - $30k, IFS – $30k)
   - J. Manickam and L. Zakharov to perform MHD analysis of kink modes and provide IFS with equilibrium matrix for δW code
   - M. Kotschenreuther and H. Rappaport to complete investigation of stabilizing effects of liquid walls in simplified (straight) geometry
   - M. Kotschenreuther to perform initial fluid response assessment with vorticity equation and/or MHD resistive wall kink mode analysis
   - M. Kostchenreuther to investigate inducing rippling mode in CDX-U

4. New concepts for liquid walls (PPPL - $20k, University of Illinois - $10k)
   - L. Zakharov to perform and report on further analysis of magnetic propulsion of intense liquid lithium streams
   - D. Ruzic (University of Illinois) to perform simple experimental tests of magnetic propulsion

II.1.c Other flow conditions for better performance during startup (IFS - $32k)
- Develop "soaker hose" concept for liquid walls and divertors

Task III. Practical Engineering Issues Associated with the Design of a Liquid Wall

Scope:

III.1 Mechanical Design, Maintenance, Integration
- d) Conducting shell and other liquid-bulk plasma considerations (combine with PPPL effort for Task II.1)

III.3 Liquid Wall Fluid Flow Configuration and Design

- c) Liquid-bulk plasma interactions

Approach:

III.3 Liquid Wall Fluid Flow Configuration and Design

- c) Liquid-bulk plasma interactions - refine DEGAS 2 neutral transport code with further measurements from plasma surface interaction experiments

Milestones:

III.3 Liquid Wall Fluid Flow Configuration and Design

- c) Liquid-bulk plasma interactions – report on DEGAS 2 neutral transport code refinements based on further measurements from plasma surface interaction experiments (7/00)

Subtasks:

III.3 Liquid Wall Fluid Flow Configuration and Design (PPPL - $10k)

- c) Liquid-bulk plasma interactions D. Stotler to refine DEGAS 2 neutral transport code with further measurements from plasma surface interaction experiments

Common Task C: Materials

Task Leader: **Steve Zinkle**

Total Effort: **$130 k included in Tasks I – IV**

Scope:

Provide material data and analysis to support Tasks I – IV.

Milestones:

03/00 Recommendations based on assessment of compatible combinations of structural materials and liquid coolants/breeders.

06/00 Preliminary estimates of erosion and corrosion rates in high velocity components (e.g. nozzles).

09/00 Report on structure/liquid compatible combinations, erosion, tungsten alloys, and design impact.

FY 2000 Tasks:

C.1 Identifying compatible liquid-structure combinations and temperature and other operating limits. Material analysis to support tasks I – IV (liquid and high-temperature refractory alloy design concepts. (Zinkle, Ghoniem)

C.2 Preliminary assessment of erosion rates for various coolant/material combinations as a function of temperature and coolant velocity (focus on key areas such as nozzles) (Zinkle, Ghoniem)

C.3 Mechanical properties of dispersion – strengthened W-TiC and tungsten heavy metals (W-Fe-Ni) before and after irradiation (Zinkle et al.)

C.4 Sn-Li vapor pressure and composition (planned under the INEEL Safety Program)

Common Task D: Safety and Environmental Analysis

<u>Task Leader:</u> **Kathy McCarthy**

<u>Total Funding:</u> **100 k included in Tasks I – IV**

<u>FY 2000 Tasks:</u>

1) Safety Support to liquid wall tasks I-III including liquid wall experiments in physics devices and exploration of liquid walls for fusion energy systems
   - Specific Subtasks: TBD

2) Safety support to high-temperature refractory (W) two-phase lithium flow (EVOLVE)
   a) Decay Heat Issue
   b) Other Specific Subtasks: TBD

<u>Note</u>:
Other tasks funded under INEEL Safety Program that are relevant to APEX include:

- Measure SnLi and Flibe vapor pressure using a Hertz Knudsen Mass Spectrometer
- Measure mobilization of unirradiated Flibe in air and steam and get used to handling of Flibe etc.
- Update MELCOR and ATHENA to be able to handle Flibe and LiSn