Chamber Tasks Coordination Document

June 9, 2004

1. Chamber Tasks within HAPL Program Plan

1.1 HAPL Program Plan

As illustrated in Fig. 1, the HAPL program is planned over three phases, starting off at low cost with an emphasis on research and development, and ending with a power plant-size testing facility. To advance from one phase to the next requires that specific milestones and goals be met.

Phase I (~5-6 years)- Mission Oriented R & D
- Develop required science & technology.

Phase II (~8-9 years)-Integrated Research Experiment (IRE)
- Essential reactor components operate together with required efficiency and precision.
- Includes a full-scale laser module.
- Includes more comprehensive R & D in target fabrication, materials, and power plant design.

Phase III (~10 years)- Engineering Test facility (ETF)
- Thermonuclear gain.
- Validate materials & components for a fusion system.
- Could also demonstrate fusion electrical power.

Figure 1 Three-Phase HAPL Program Plan

The chamber tasks within Phase I are focused on establishing the technology required for the chamber components. As part of this, one or more credible chamber concepts need to be identified.

During Phase II, the IRE will include a single laser module. It would not have sufficient energy to produce fusion reactions and the chamber would not require advanced materials. However, it will be used to evaluate some aspects of candidate chamber materials. The IRE will also be used to study chamber dynamics and clearing. In addition to the IRE, Phase II will also include a detailed point design for an economically and environmentally attractive laser IFE fusion power plant.

Phase III is the Engineering Test Facility (ETF) which would be the first laser IFE facility to repetitively produce significant thermonuclear burn. The ETF would test and validate the materials and components for an IFE power plant in a repetitive fusion environment. The ETF would be a modular device. Hence, it could be used to test and validate more than one chamber concept, blanket configuration, or final optics system. This is really the culmination of the chamber tasks during the earlier phases whose R&D results will be used to help develop the exact specifications of the ETF.

1.2 Chamber Tasks and ETF

The chamber tasks cover the armor, first wall, blanket and system. As summarized in the first wall battle plan [1], the chamber tasks R&D through Phase I and Phase II are essential stepping stones to help justify and make the most of testing in the Engineering Test facility (ETF).

The ETF will have operational flexibility to perform four major tasks:

I. Build and test a full size driver with sufficient energy for high gain (probably 2 MJ)
II. Optimize targets for high yield.
III. Test, develop, and optimize chamber components (including first wall and blanket, tritium breeding, tritium recovery.) This will require thermal management (125 MWth).
IV. Electricity production with potential for high availability.

The first wall/armor material for the ETF chamber must be developed and tested to provide extremely high confidence that it can at least accommodate the ETF operating conditions over the required lifetime for completion of the above Tasks II and III. These requirements translate into < 0.02 microns erosion/shot at full yield targets (approx 250 MJ) for Task II (either single shots or bursts at 5 Hz); and negligible erosion per shot at 10% yield for Task III (10^7 shots at 5 Hz).

For Task III, individual first wall/blanket test modules will be inserted about 2 m from the low yield targets with a corresponding power/energy loading on the wall comparable to a full scale system. A number of different test modules can be tested; these concepts will be selected from those with good probability of resulting in an attractive IFE power plant chamber (including the blanket and other system interfaces), based on the R&D during Phases I and II. Clearly, concepts utilizing the front runner armor and structural material options selected for the ETF chamber would figure prominently if the R&D is successful (see the next section). Depending on resources and R&D advances, concepts based on other armor and structural materials would also be tested.

2. Chamber Materials

To help focus the resources on the materials with the highest probability of success within the proposed time frame, the HAPL laser IFE community has decided to concentrate on a first wall concept based on tungsten as front runner armor material and ferritic steel as structural material.

Candidate dry chamber armor materials must have high temperature capability and good thermal properties for accommodating energy deposition and providing the required lifetime. A refractory metal, such as tungsten, is an attractive candidate in this respect. Also, there are no major trapping mechanisms of the tritium flux to the wall and tritium inventory with a tungsten armor is not of particular concern. However, lifetime is an issue that needs to be addressed. It includes: (i) the possibility of melting and whether this should be avoided; (ii) the thermo-mechanical response of the surface to the cyclic temperature gradients (which could lead to roughening or fracture); and (iii) whether the implanted He ions can be released to avoid premature armor failure due to He accumulation [2]. It is believed that these issues can be addressed through material selection (including the possibility of engineering surface for stress relief and/or He release enhancement) and a focused R&D program.

Carbon is a good armor candidate based on its high temperature capability and has been considered in previous studies [e.g. 3]. However, several mass loss processes have been identified in carbon including chemical erosion and radiation enhanced sublimation which lead to serious concerns of lifetime and tritium inventory through co-deposition in cold regions; in addition, concerns exist about the properties of carbon under high temperature and irradiation [2]. Thus, carbon would require substantially more R&D than tungsten, the front runner armor selection.

Low activation ferritic (LAF) steel was selected as structural material. Given the need to field the concept within 12-15 years, it seems to be the material with enough development maturity to minimize the risk in utilizing it while providing an acceptable operating temperature window for power plant performance (cycle efficiency). Oxide dispersion strengthened (ODS) or nano-composited steel is considered as an alternate LAF structure as it would allow for a higher temperature of operation and possibly better bonding with tungsten. However, its data base is more limited and the practical aspects of its application such as forming and bonding will require greater R&D than the conventional LAF's.

Other structural materials (such as the higher performance but higher risk SiC_f/SiC composites) could be considered for the ETF test modules if justified by future advances in R&D.

The major armor and first wall challenges to be addressed cover armor material type (e.g. W alloy and possible engineered structure), bonding to LAF, lifetime and general suitability of W/Fe in an overall fusion/nuclear system. The critical issues to be addressed through R&D can be categorized as follows:

(1) Viable First Wall
Demonstrate a material with an adherent tungsten coating which is thermally stable at IFE-relevant operating temperature.

(2) Helium and/or Hydrogen Isotope Diffusion.
Helium and hydrogen isotopes will be implanted into the armor surface in amount locally exceeding the tungsten atom concentration within about a month of operation. Helium in particular has very limited solubility in metals and the activation energy for diffusion is very high. Given that tungsten is a very high melting point material and IFE will produce significant vacancy sites for trapping, the diffusion of both helium and hydrogen is of great importance. In the absence of diffusion, Lucas [4] reports that low and high yield targets will ablate 3.6 and 6.7 cm/year, respectively. This removal rate is much higher than can be sustained by tungsten armor, and in the absence of significant diffusion eliminates this system from consideration. A combination of modeling and experiment need to demonstrate a system capable of < 0.5 mm/year exfoliation.

(3) Ablation (Ions & X-rays including surface roughening)
The armor will be subjected to cyclic bursts of about 10 J/cm^2 or more of fast burn and debris ions at intermediate and high energies. In addition to the issue of exfoliation, thermal ablation and chemical and physical sputtering need to be studied. Cyclic loading experiments will be carried out to define the removal rate of candidate materials as a function of ion energy.

In addition to the copious ion fluence incident on the armor surface, X-rays will be present with fluences of the order of 0.4-1.2 J/cm^2 in an IFE power plant. Due to the extremely high number of shots (>10^8/year) in an IFE power plant, the allowable removal rate is less than an atomic layer per shot. While previous work indicates that this level of flux is less than the ablation threshold value, high-cycle testing is required to ensure near zero material loss occurs for >10^6 cycles.

(4) Thermomechanical Fatigue and Fracture Toughness
The primary driving force for selection of armor configuration will be its thermomechanical response to cyclic loading. Determination of the fatigue performance of the armor will be quantified for candidate systems, including the tungsten/LAF bond integrity and the fatigue crack growth of LAF. This task will be well integrated and driven by modeling and design efforts.

(5) Irradiation Effects on Thermophysical Properties.
The effects of neutron and ion irradiation on base properties of chamber materials will be measured or compiled from the literature. Due to the impracticality of irradiating and thermomechanically testing IFE wall mock-ups, this element will rely heavily on modeling. Irradiation will be limited to base materials and coupons of bonded ferritic/tungsten. Data on base properties will be compiled in an IFE Materials Handbook and be made available on the HAPL website.

In addition, depending on the choice of blanket concept and coolant, there will be a number of engineering & safety issues to be addressed prior to or during the ETF phase, such as corrosion, mass transport and compatibility of coolant and structure, and various reaction and release accident scenarios for the given blanket concepts.

3. Chamber Tasks Strategy

The chamber tasks strategy is summarized schematically in Fig. 2. It includes the proposed effort in all chamber-related areas; armor, first wall, blanket, system as well as materials, and the inter-relation among the tasks in these areas. Although IFE operation is highly cyclic (as opposed to MFE which aims at steady state operation), only the armor experiences large temperature transients [2]. The structural wall (FW) and the blanket see quasi steady-state conditions. Thus, the limited laser IFE R&D resources can be focused on key IFE-specific armor issues while making the most of information from the MFE design and R&D effort on blanket and first wall.

Fig. 2 HAPL Chamber Tasks Strategy

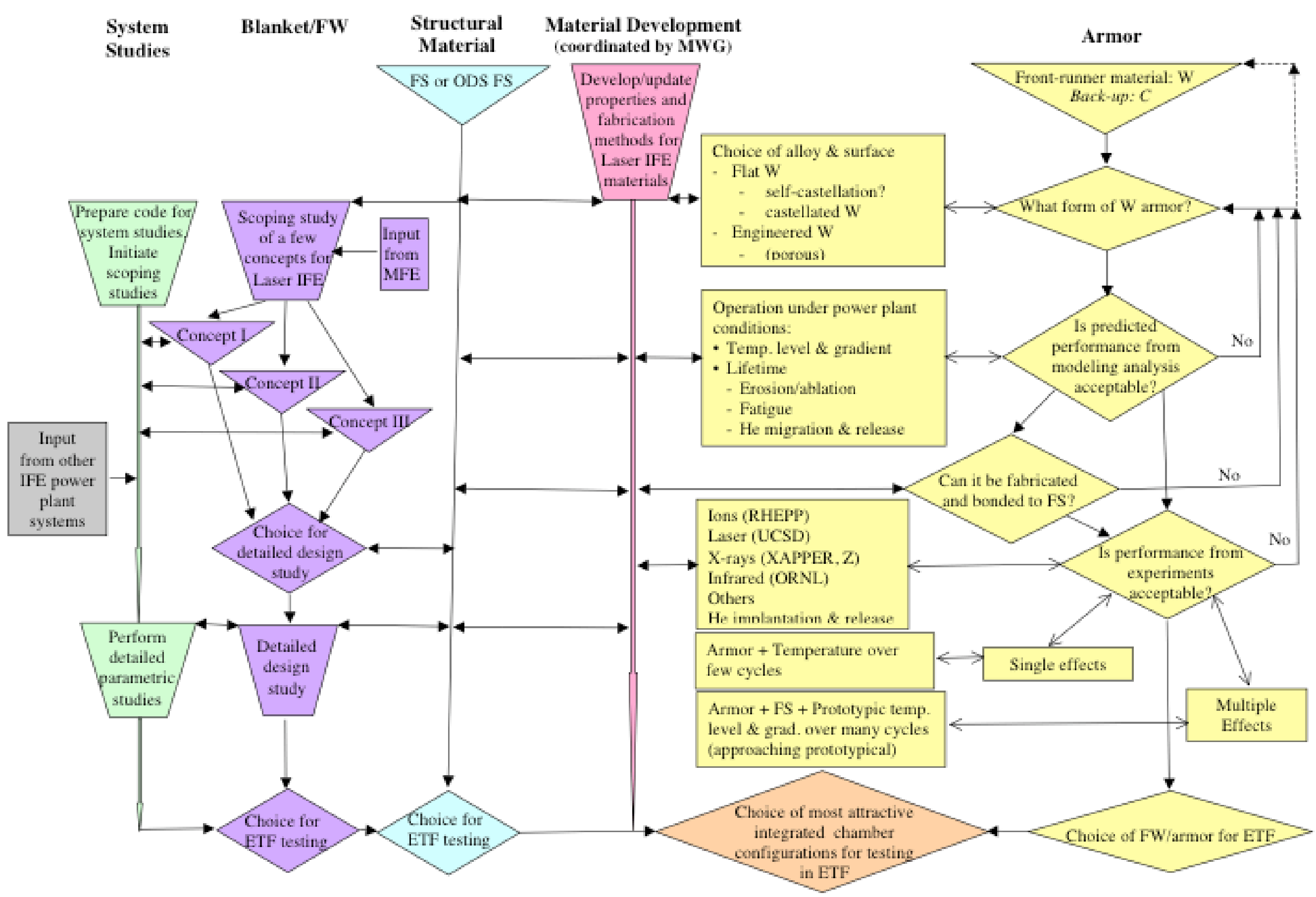

Figure 2 HAPL Chamber Tasks Strategy

3.1. Armor & First Wall

The armor and first wall tasks are focused mostly on addressing the critical issues listed in Section 2, specifically:

(1) Viable first wall
(2) Helium and/or hydrogen isotope diffusion
(3) Ablation (Ions & X-rays including surface roughening)
(4) Thermomechanical fatigue and fracture toughness
(5) Baseline and irradiation effects on thermophysical properties.

Fig. 3 HAPL FW/Armor R&D Plan (DRAFT)

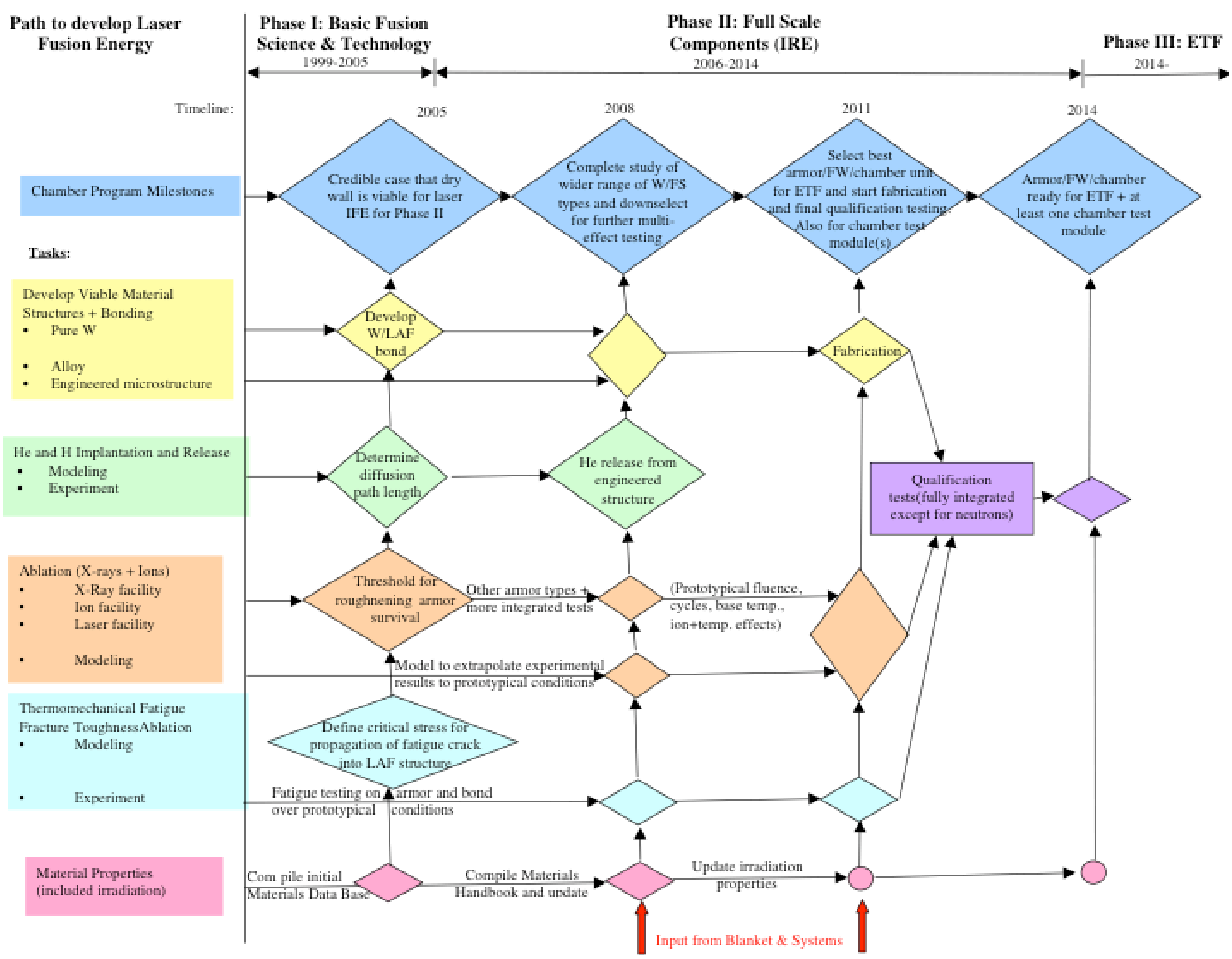

Figure 3 HAPL FW/Armor R&D Plan

These challenges must be overcome to demonstrate the feasibility of a dry wall design based on W and FS within the overall goals and schedule of the proposed path to develop laser fusion energy. The FW/armor R&D has been developed to that end, as illustrated by the FW/armor R&D plan schematically shown in Fig. 3. Also shown in the figure are the overall chamber program milestones to be met in order to achieve the overall program objectives and schedule. The tasks are divided among a number of institutions in coordination with the Materials Working Group.

The top level goals, major deliverables and task descriptions for addressing each critical issue are summarized below. A near-term schedule associated with each deliverable is also shown (as from April 1, 2004).

(1) Viable First Wall

Top-Level Goal: Develop a W/LAF structure with good bond integrity and thermal stability

Deliverables

(1.i)	Complete initial screening through bend testing and thermo-mechanical testing.	~ 6 months
(1.ii)	Down select to ~3 material combinations that look the best.	~ 1year
(1.iii)	Assess and select most promising engineered structure(s) (including pre-testing in RHEPP, XAPPER, DRAGONFIRE Lab, He-testing).	~1 year
(1.iv)	Complete bonding and similar pre-screening and testing for engineered structure.	~2-3 years

Tasks

(1-a) Develop vacuum plasma spray, diffusion bonded, and transient melt processed LAF/tungsten structures (ORNL, MWG)

(1-b) Determine long-term thermal stability of LAF/tungsten systems (heat in a furnace and check thermal stability). (ORNL, MWG)

(1-c) Identify "engineered materials" and work with developers (PPI, Ultramet, others) to try to get most promising configurations for testing as part of (3) below. (UCLA, UCSD)

(1-d) Materials development of advanced-concepts including ODS LAF's and engineered tungsten.(UCLA, UCSD, ORNL,MWG)

(2) Helium and/or Hydrogen Isotope Diffusion.

Top-Level Goal: Demonstrate zero armor exfoliation

Deliverables

Complete:

(2.i)	Model development (refinement) for He behavior in tungsten	~6 months
(2.ii)	Monoenergetic He testing	~1 year
(2.iii)	Spectrum testing (with foils)	~1 year
(2.iv)	Synergetic effect (He+H)	~1 year
(2.v)	Implantation/anneal to prototypic FS/W structure	~ 2 years
(2.vi)	Similar testing as (2.ii) to (2.v) for engineered W	~ 2-3 years

Tasks

(2-a) For IFE relevant ion energy and implantation temperature, determine critical fluence for exfoliation in single crystal and powder-processed forms of tungsten. (ORNL, UW)

(2-b) Determine effect of annealing to IFE-relevant temperature on the helium and hydrogen retention of pure tungsten (monoenergetic He first, then foils to obtain spectrum, then mix of He and H). Combination of (2-a) and (2-b) to yield diffusion coefficients required for helium transport modeling. (ORNL, UCLA)

(2-c) Develop and apply automated implantation/anneal system to determine effect fluence-packet size and annealing temperature on retention and microstructure of single crystal and powder-processed tungsten. Determine role of grain boundaries as compared to bulk in helium diffusion in tungsten. (ORNL)

(2-d) Develop/refine model(s) of helium transport in tungsten to help understand rate-limiting steps (UCLA, ORNL).

(2-e) Use model and experimental results to better understand helium transport in tungsten under prototypic conditions, to identify rate limiting steps and guide evolution of armor microstructure to enhance helium release, including: (i) damage (exfoliation) delaying effect of He ion spectrum in spreading He implantation through W; and (ii) benefit of using porous engineered material with small microstructure compared to characteristic He migration distance. (UCLA)

(2-f) Implantation/anneal system applied to prototype LAF/W structure. Prototypical IFE temperature, > 10^6 anneal cycles, total fluence helium >10^{25} ion/cm^2. (ORNL)

(3) Ablation (Ions & X-rays including surface roughening)

Top-Level Goal: Demonstrate that armor should have acceptable lifetime of about 3 years (end of life armor characteristics (thickness))

Deliverables

Complete:

(3.i) Engineering modeling (including validation) in support of short-term experimental results ~6 months

(3.ii) Development of long term predictive capability (understanding mechanisms such as roughening ~ 2 years

(3.iii)Demonstration testing (RHEPP, DRAGONFIRE, XAPPER)

- Cook and look experiments (scoping) ~6 months
- Model validation experiments ~ 1 year
- Full range of testing to enable prototypical evaluation (in conjunction with modeling) ~ 2 years
- Same range of tests for engineered materials ~2-3 years

Tasks

Modeling

(3-a) Develop/refine model for the thermo-mechanical response of W, for example to help better understand the roughening process initially observed with RHEPP experiments and assess whether it saturates. (UW, MWG, Others)

(3-b) Perform modeling of engineered material to determine damage threshold (UCLA, UCSD)

Experiments in RHEPP

(3-c) Determine threshold fluence for a) surface roughening and, b) ablation for IFE relevant ion species, ion energies, ion fluence, and irradiation temperature for single crystal, CVD, and powder-processed tungsten. (SNL)

(3-d) Determine if the thresholds measured in a) vary with number of pulsed exposures, and specifically determine if roughening varies with number of exposures, and if there is a saturation behavior to this roughening, as a function of exposure number.(SNL)

(3-e) Develop He beam capability on RHEPP for repetitive exposure at IFE relevant dose-packets, i.e. 2000 pulses or more, to see if effects attributable to He bubble formation or embrittlement can be seen. Compare with He implantation database. (SNL, MWG)

(3-f) Determine if the parameters measured in (b) and (c) vary with the form and thickness of W, i.e. if “engineered” or 3-dimensional structures, or flat structures with thin or thick-film W produce different parameters. (SNL, HAPL team)

(3-g) Determine if a composite form of W on structural material produces differing parameter results from those seen in a) and b) above. Examples are W/F82H, W/SiC. (SNL, HAPL Team)

(3-h) Repeat experiments above as deemed appropriate for W-25%Re alloy in place of pure W. (SNL)

(3-i) Perform exposure experiments on other materials or forms as deemed appropriate by the HAPL community in coordination with Materials Working Group.(SNL)

Experiments in XAPPER

(3-j) Determine threshold fluences for surface roughening and ablation as a function of the number of pulses (up to 10^6 for leading candidates), irradiation temperature, and type of tungsten (single crystal, CVD, and power-processed) (LLNL)

(3-k) Evaluate option for higher energy (250-300 eV versus 90-130 eV) X-ray production with an argon plasma. If attractive due to deeper deposition length scales, implement on XAPPER and determine effects upon thresholds measured in (3-j). (LLNL)

(3-l) Determine if threshold fluences vary for tungsten-ferritic composite armors. (LLNL)

(3-m) Determine thresholds for roughening and ablation for tungsten-rhenium alloys, as appropriate. (LLNL)

(3-n) Evaluate performance of "engineered" armor structures and/or materials, such as foams and fibers. (LLNL)

Experiments in UCSD Laser Facility (DRAGONFIRE Lab)

(3-o) Develop thermometer for in-situ surface temperature measurement (UCSD)

(3-p) Provide and install thermometer on other facilities as requested (UCSD)

(3-q) Determine threshold fluences for surface roughening and ablation as a function of the number of pulses (up to 10^6 for leading candidates), irradiation temperature, and type of tungsten (single crystal, CVD, and powder-processed). (UCSD)

(3-r) Determine thresholds for roughening and ablation for tungsten-rhenium alloys, as appropriate. (UCSD)

(3-s) Evaluate performance of "engineered" armor structures and/or materials, such as foams and fibers. (UCSD)

(4) <u>Thermomechanical Fatigue and Fracture Toughness</u>

<u>Top-Level Goal</u>: Demonstrate that for a nominal stress level fatigue-induced cracks will not propagate in the underlying structure and delamination will not occur

<u>Deliverables</u>

Complete:

(4.i) Modeling of temporal stress state of W/FS interface
- Fully dense material ~ 6 months
- Engineered material ~ 1 year

(4.ii) Thermomechanical fatigue testing of bond and fatigue crack growth
- Fully dense material ~ 1.5 years
- Engineered material (depending on availability) ~ 2 years

(4.iii) IR thermal-fatigue of selected coupons >2 years
(Prototypical conditions) 10^6 pulses

<u>Tasks</u>

(4-a) Modeling temporal stress state of W/FS interface (bond) (UW, UCLA, MWG)

(4-b) Determine effect of thermomechanical fatigue on bond integrity in the diffusion bonded and vacuum plasma sprayed LAF/W system. (ORNL, UW)

(4-c) Determine fatigue crack growth for the diffusion bonded and vacuum plasma sprayed LAF/W system.(ORNL, UW)

(4-d) Carry out fatigue and fatigue crack growth of engineered LAF/W systems for IFE relevant temperature and stress conditions. IR thermal-fatigue facility at $>10^6$ pulses, >5 Hz.(ORNL, UW)

(5) <u>Baseline and irradiation effects on thermophysical properties</u>. (HAPL team)

Top-Level Goal: Compile baseline property data base (including irradiation effects)

Deliverables

Complete:

(5.i)	Compilation of relevant MFE material properties	~6 months
(5.ii)	Identification of data need	~6 months
(5.iii)	Development of plan to measure missing properties if possible (including irradiation effects)	~1 year
(5.iv)	Compilation of Materials Handbook	~1 year

Tasks

(5-a) Mine the literature for relevant baseline and irradiation effects data on IFE relevant materials.

(5-b) Assemble baseline property data-base.

(5-c) Carry out ion and neutron irradiation program on base materials to determine design-relevant thermophysical properties (including for engineered materials)

(5-d) Carry out low-dose neutron irradiation of bonded structure to determine effect of swelling and embrittlement on interfacial integrity.

(5-e) Compile Materials Handbook.

3.2 Blanket (UCSD, UW, Others as needed)

At least one credible blanket concept must be developed, compatible with the choice of armor (W) and structural material (FS). The chamber configuration needs then be considered in an integrated system context (including power cycle and other related power plant components) to show that this can lead to a credible and attractive laser IFE power plant.

As mentioned earlier, the blanket sees quasi steady-state operation and much information from the MFE blanket design and R&D effort can be utilized. A 2-phase strategy is envisioned: a scoping phase and a detailed design analysis phase (each covering about a year). During the first phase (lasting about a year), a number of blanket concepts (2-4) will be developed to the point where we can intelligently evaluate then in terms of key issues: performance, reliability, simplicity, safety and perception from the outside. This assessment would allow us to converge ideally on a single (or perhaps on two) design concept(s) which should then be analyzed more thoroughly during the second phase to cover all the key aspects: fabrication, operation, maintenance and integration, and to end up with a strongly-credible and attractive integrated design. The work will be carried out in coordination with the first wall/armor effort and in consultation with the Materials Working Group (as needed).

The choice of possible blanket materials concerns essentially the breeder and coolant since the front runner structural (FS) and armor (W) materials have already been selected. Most recent MFE blanket designs have diverged away from using water as coolant for different reasons including low performance and compatibility problems with different materials (structural, breeding and/or coolant). Potentially attractive blanket concepts for IFE would then include:

1. Self-cooled Li
2. He-cooled ceramic-breeder
3. He-cooled or dual cooled Pb-17Li
4. Dual cooled molten salt (with He as FW coolant)

Fully self-cooled Pb-17Li and/or molten salt (flibe) blankets could also be considered but their rather poor heat transfer performances (for flibe even more than for Pb-17Li) make it very difficult to provide accommodation of the heat fluxes and material constraints with reasonable performance (cycle efficiency) and power densities. In addition the rather low compatibility temperature limit for Pb-17Li /FS could be overly constraining.

The above four concepts cover a good range of performance and potential risk (e.g. in terms of issues required additional R&D). For example, the self-cooled Li blanket can be viewed as a high performance concept in terms of operating temperature and cycle efficiency but use of liquid Li carries some safety drawbacks (real and perceived) and there are some concerns with the compatibility of Li and FS. A He-cooled ceramic breeder would be a lower performance concept but possibly with better acceptability criteria.

Through a scoping study of some (or all) of the above concepts, the first phase effort will also help to better understand the trade-off between different blanket characteristics as applied to IFE, such as:

- high performance v. lower performance options (based on thermal to electric conversion efficiency);
- self-cooled (i.e. breeder is also the coolant) v. separately cooled options;
- liquid breeder v. solid breeder options;
- use of lithium v. use of Be, which may be required as a neutron multiplier to provide adequate tritium breeding (and other safety or public perception issues for both concepts)
- Brayton cycle v. Rankine cycle

This assessment during the first phase will allow us to converge on a single design which should then be analyzed more thoroughly during the second phase, as mentioned before.

Top-Level Goal: Develop at least one credible blanket concept compatible with the choice of armor (W) and structural material (FS).

Deliverables

Complete:

(B1.i) Scoping study and down selection of blanket concepts (choose 1-2 concepts for detailed study) ~1-1.5 years

(B1.ii) Detailed design study of selected blanket concept(s) ~2-3 years

Tasks

(B1-a) Perform scoping study of a number of blanket concepts for a laser IFE power plant (UCSD, UW, others)

(B1-b) Down-select to 1-2 most attractive concepts and perform a detailed blanket design study (UCSD, UW, others)

3.3 System Studies (LLNL, UCSD, UW)

The system study effort is also envisaged in two phases. During the first phase, the system code will be developed including input from the blanket/FW/armor effort on operating parameters as well as modeling of other subsystems. During this phase scoping studies will be performed to guide the overall design (including the chamber components). The second phase will involve more detailed and complete parametric design studies for the chosen blanket configuration and will help to provide a good basis for a credible and attractive integrated design of a laser IFE power plant.

Top-Level Goal: Develop an integrated systems code that can be used to investigate a variety of laser-IFE design options and configurations

Deliverables

Complete:

(S1.i) Integrated chamber/blanket/power cycle model for 2-3 blanket options, including cost estimates ~6 months

(S1.ii) Development and inclusion of performance and costing models for KrF and DPSSL drivers ~2 years

(S1.iii) Inclusion of cost scaling models for remaining power plant systems ~3 years

Tasks

(S1-a) Develop an integrated systems code that can be used to investigate a variety of laser-IFE design options and configurations. (LLNL)

4. Baseline Assumptions for Design and Analysis

It is important in such a chamber study where development on one chamber component could affect the design and operating parameters of another component that a common set of baseline assumptions for design and analysis be used to make sure that the analysis and R&D on the different components are consistent. These assumptions are part of a living document which can change as we progress with the study or as new data become available.

This set of baseline assumptions include a list of parameters to be used in scoping studies in the absence of detailed system parameters and complete R&D data. For example, much of the scoping design and analysis of the armor and first wall is being done without the benefit of a full system analyses to provide the exact parameters on power density (dependent on yield, repetition rate and chamber size). In this case, baseline values are recommended for consistency in the initial analysis. However, once the actual parameters are established (from system studies, R&D or otherwise), they should be used for more detailed analysis.

4.1 Power

The energy distribution from the target is assumed similar to the154 MJ NRL direct-drive target: (see http://aries.ucsd.edu/ARIES/WDOCS/ARIES-IFE/SPECTRA/accounting.shtml, courtesy of J. Perkins' LASNEX results), i.e:

- X-rays: 1%
- Neutrons: 70.5%
- Gammas: 0.006%
- Burn product fast ions: 12.5%
- Debris ions kinetic energy: 16%

For initial scoping calculations, the following power parameters are recommended (unless or until precise values are available). It is recommended that sensitivity analysis be carried out to understand the impact of variation in this initial set of parameters.

- Armor should be designed at least to accommodate a nominal 150 MJ yield target spectra in chamber of radius ≈8 m with no protective gas (the presence of a protective gas would reduce the chamber size).

- Blanket, first wall and system should be designed with the goal of accommodating the following loads:
  - Fusion power: 1.8 GW (e.g. 150 MJ target and 12 Hz rep rate)
  - Chamber radius: 6.5 m for 150 MJ yield
  - First wall time-averaged heat flux ≈ 1 MW/m^2
  - Time-averaged neutron wall loading ≈ 2.4 MW/m^2
  - Blanket multiplication factor ≈ 1.1 or more (depending on blanket concept)
  - Total thermal power ≈ 2 GW

4.2 Armor Parameters

- 1-mm W thickness recommended for scoping analysis pending fabrication/adhesion confirmation tests (or as the specific case requires to accommodate lifetime requirements and/or limits on maximum W and/or FS temperature levels and gradients)
- Operating window for tungsten is based on consideration of both temperature level and gradient and include considerations of a number of processes, such as vaporization, melting, roughening, fatigue, surface cracks, crack growth and blistering. Our modeling and experimental R&D will help determine this. In the mean time for scoping calculations, it is recommended to maintain W < ~2400°C (roughly based on early roughening results from RHEPP)

4.3 First Wall Parameters

- It is desirable to maintain the temperature swing at the W/FS bond at a minimum level to provide more room in accommodating the W maximum temperature limit of the W armor as well as to minimize any effect of cyclic temperature gradient at the bond. Again, the exact value will vary from design to design based on detailed analysis of the integrated component. For the scoping analysis, it is recommended to maintain this temperature swing < ~20° C.
- To make the most of potential thermal-to-electric conversion performance, design for maximum FS temperature limit in FW.

4.4 Blanket and Cycle Parameters

- Optimize coolant inlet and outlet temperatures to maximize power cycle efficiency for given material constraints.
- Aim at design simplicity as a measure of reliability
  - Minimize number of coolant channels and structural joints
  - Minimize welds in FW area
  - Moderate coolant system pressure if possible
- Provide adequate tritium breeding
  - TBR~1.1 or more
  - Active means of adjusting TBR during operation (if possible)

4.5 Power Cycle :

- Choose power cycle provided highest efficiency for expected coolant temperatures (Brayton cycle v. Rankine cycle)
- Brayton Cycle

- Turbine Efficiency = 0.93
- Compressor Efficiency = 0.89
- Recuperator Effectiveness = 0.95
- Out of Vessel Cycle Fractional Pressure Drop ~ 0.07

- Rankine Cycle
  - Turbine Isentropic Efficiency = 0.9
  - Compressor Isentropic Efficiency = 0.8
  - Other Parameters: TBD

5. Materials Data Base

As we progress with the design, modeling analysis and experiments on the chamber armor, FW and blanket, we should try to be consistent and use a common database for material properties. Properties from the database shown on the ARIES & APEX web sites are suggested as starting points and can be found at:

http://aries.ucsd.edu/HAPL/DOCS/database.html

As more accurate properties become available (per the MWG), the database will be updated. As different armor samples are used in the experiments, the actual properties of the samples should be used (if available) and added to the database.

6. Comparison of Experimental Facilities

The experimental facilities proposed to carry out the chamber FW/armor testing R&D include:

- XAPPER (LLNL)
- Laser Lab (UCSD)
- RHEPP (SNL)
- Z (SNL)
- Infrared facility (ORNL)
- IEC facility (UW)

The capabilities of these facilities are summarized in Tables 1 (a) and (b). UCSD Laser facility, XAPPER, Z, and RHEPP can all simulate surface thermostructural effects. Those which can provide an initial temperature of around 500 °C will do better. The proposed list of data to be taken per run is shown in Table 2.

Table 1 Summary of capabilities of experimental facilities for chamber tasks

Experiment	Type	Energy (keV)	Maximum Fluence per Pulse (J/cm^2) or Heat Flux (W/cm^2)	Approximate Depth of Energy Deposition (microns)	Maximum Starting Temperature of Sample (C)	Maximum Sample Size (cm)	Max. Spot Size (cm)	Flat Top Pulse Width (ns)	Rise Time (ns)	Maximum Rep Rate (Hz)	Maximum Number of Cycles	Is Sample Actively Cooled?
RHEPP (SNL)	Ions	750	7	1-10	600+			100				NO
Z (SNL)	X-Rays	0.8-1.2	3000	1-2	1000			6				NO
XAPPER (LLNL)	X-Rays	0.1-0.4	7	1-2	RT+	2.5 diameter	0.07-0.2	30-50 (FWHM)		10	10^6	NO
Laser Lab (UCSD)	Laser		0.7	0	1000	1 cm x 1 cm		8		10	$3x10^5$	NO
Electra (NRL)	electrons	500	2	100		30 cm x 100 cm		100	40	5	10^4/d	YES
Infrared (ORNL)	Infrared		q=10 MW/m^2	0				>10 ms				YES
IEC (UW)	Ions	100	Flux=$5x10^{19}$ $/m^2$-s	1								NO

Table 2 Proposed List of Data from Experiments

Experiment Name Energy Form Energy Spectrum Energy Deposition Profile Spot Size and Uniformity Over Spot Size Number of Cycles Pulse Width Dwell Time Heat Flux History Fluence per Pulse	Target Material(s) Material Identifier (Code) Thermal conductivity Heat Capacity Density Target Thickness Target Surface Finish Target Dimensions Chamber Environment Mass Loss	Materials Characterization before and after Exposure (surface and in-depth) Initial Target Temperature Is the Target cooled? How? Estimated Temperature History Measured Temperature History

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