THE U.S. FUSION ENABLING TECHNOLOGY PROGRAM PLAN

THE U.S. FUSION ENABLING TECHNOLOGY PROGRAM IS AN ESSENTIAL ELEMENT IN THE DEVELOPMENT OF THE KNOWLEDGE BASE FOR AN ATTRACTIVE FUSION POWER SOURCE. THE PROGRAM ADVANCES MANY ASPECTS OF MATERIALS AND ENGINEERING SCIENCE.

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EXECUTIVE SUMMARY

Harnessing the energy source of the sun and stars is a grand challenge with enormous potential payoff for future generations: an environmentally attractive energy source with essentially inexhaustible fuel with no carbon emissions. In pursuit of this vision, the mission of the Fusion Energy Sciences Program is:

> *To advance plasma science, fusion science, and fusion technology—the knowledge base needed for an economically and environmentally attractive fusion energy source.*

In support of this overall mission, the Enabling Technology Program is a full partner in the Fusion Energy Sciences Program. The Enabling Technology Program incorporates both near and long term R&D; contributes to material and engineering sciences as well as technology development; contributes to spin-off applications; and performs global systems assessments and focused design studies. The Enabling Technology research mission is:

> *To contribute to the national science and technology base by developing the enabling technology for existing and next-step experimental devices, by exploring and understanding key materials and technology feasibility issues for attractive fusion power sources, by conducting advanced design studies that integrate the wealth of our understanding to guide R&D priorities and by developing design solutions for next-step and future devices.*

The U.S. Department of Energy has established a fusion Virtual Laboratory for Technology in recognition of the evolving emphasis of technology activities, the multi-institutional nature of technology R&D, and the need for improved coordination and representation of the Enabling Technology Program. The VLT was created, in part, to assist DOE in evolving a program which is a full partner in the national program where emphasis is placed on scientific understanding and innovation. This has largely been accomplished.

The Enabling Technology Program Plan is organized around five elements:

- Plasma Technologies
- Fusion (Chamber) Technologies
- Materials
- Advanced Design
- IFE Chamber and Target Technologies

The principal technical features and five-year research objectives are described for each element.

1.0 OVERVIEW

1.1 Introduction and Background

Harnessing the energy source of the sun and stars is a grand challenge with enormous potential payoff for future generations: an environmentally attractive energy source with essentially inexhaustible fuel with no carbon emissions. The required fuels are the deuterium isotope of hydrogen and lithium, both abundantly available to all nations. In pursuit of this vision, the mission of the Fusion Energy Sciences Program is:

> *To advance plasma science, fusion science, and fusion technology—the knowledge base needed for an economically and environmentally attractive fusion energy source.*

In support of this overall mission, the Enabling Technology Program is a full partner in the Fusion Energy Sciences Program. The Enabling Technology Program incorporates both near and long term R&D; contributes to material and engineering sciences as well as technology development; contributes to spin-off applications; and performs global systems assessments and focused design studies.

As a partner in the overall national program, enabling technology R&D plays an essential role in providing the tools and capability to both produce and study high temperature fusion-relevant plasmas. Techniques for achieving high quality vacuum conditions, heating plasmas to thermonuclear temperatures and manipulating plasma properties to access advanced operating scenarios, injecting particles and extracting of "ash" of the fusion reaction, developing powerful and reliable large magnet systems, and handling of energy and particle outflow from the plasma have been developed and used in a wide variety of plasma confinement devices. This R&D has had a direct impact on the enormous progress made in the development of plasma science in general, and fusion science in particular.

Experimental advances in plasma performance and progress in theoretical understanding of plasmas places the world fusion program on the threshold of developing systems that generate substantial amounts of fusion energy. Next step devices present major challenges in terms of component performance and reliability, fuel handling systems including tritium technology, and maintenance concepts. Moreover, the choice of materials and design concepts for "in-vessel" components (e.g. divertor, first wall, blanket, shield, final optics and vacuum vessel) will more than anything else determine the safety and environmental characteristics of both magnetic and inertial fusion energy.

Advanced design activities are an important element because they help to provide the essential framework to construct the overall strategy of the U.S. Program. This element motivates the future directions of the Fusion Energy Sciences Program by examining the potential of specific Magnetic Fusion Energy (MFE) confinement and Inertial Fusion Energy (IFE) driver-target-chamber concepts as power and neutron sources, defining R&D needs to guide present experimental and theoretical studies, incorporating plasma and target physics R&D into design methods, analyzing potential pathways to fusion development, carrying out systems analysis of economic and environmental performance and designing next-step devices.

The Enabling Technology research mission may then be stated as follows:

> *To contribute to the national science and technology base by developing the enabling technology for existing and next-step experimental devices, by exploring and understanding key materials and technology feasibility issues for attractive fusion power sources, by conducting advanced design studies that integrate the wealth of our understanding to guide R&D priorities and by developing design solutions for next-step and future devices.*

This mission is fully consistent with the two principal goals for technology from the Integrated Program Planning Activity for DOE's Office of Fusion Energy Sciences (http://www.ofes.science.doe.gov/) which are to: develop enabling technologies to advance fusion science, pursue innovative technologies and materials to improve the vision for fusion energy and apply systems analysis to optimize fusion development; and to develop the science and technology of attractive rep-rated IFE power systems.

The near-term emphasis for MFE is on developing better tools and a scientific basis for the production and control of high-temperature plasmas and, thus, the further development of plasma science. For IFE, research on chamber-target technologies is focused on key feasibility issues that bear on the high-pulse-rate application of candidate drivers for IFE over the next few years.

An important technology R&D benefit in the near-term is a wide variety of spin-offs that impact our daily lives in many significant ways. Examples include development of superconducting magnet technology, microwave technology including micro-impulse radar, precision laser cutting, plasma processing and lithography of computer chips and circuits, coating of materials, waste processing, plasma electronics, new and improved materials, and biomedical applications.

The longer-term emphasis is on developing the understanding and resolving key feasibility issues for the development of fusion energy. These include extraction and utilization of heat from fusion reactions, breeding and handling of fuel (tritium) in a self-sufficient system, demonstration of reliable operation, and realization of the safety and environmental potential of fusion energy. Incorporation of improved and new materials into well-engineered systems with strong attention to safety and environmental features is the crucial element. Here the development of reduced-activation materials is particularly important.

The Enabling Technology Program depends on, and has fostered, a highly integrated approach involving broad systems assessments, design studies on a wide variety of specific concepts, materials research and development, component engineering and development and experimental validation, and safety analysis. Such an integrated approach is essential to the successful development of the knowledge base for attractive fusion energy sources because of the complex nature of fusion systems and the multi-disciplinary aspects of the underlying science and engineering. This topic is further discussed in Sec. 7.0.

Enabling technology R&D also results in increased understanding in materials and engineering sciences. Examples include fundamental understanding of radiation effects in materials, nuclear data for important nuclides, structure/property relationships in alloy design, corrosion science, liquid metal MHD phenomena, mechanics of materials, material volatilization in air and steam, radiation cooling, condensation, and re-deposition of ablation-produced plasmas, thermomechanics and thermal hydraulics.

The development of economically and environmentally attractive fusion energy sources is a tremendous challenge that requires the best intellectual and facility resources world-wide. International collaboration has been a hallmark of fusion research since its earliest days and this is particularly true of the technology activities. Essentially, all aspects of enabling technology R&D in the U.S. have a strong international component. With constrained budgets in the U.S. and larger fusion technology programs in Europe and Japan, it is essential to maintain, and even enhance, international collaboration.

The U.S. Department of Energy has established a fusion Virtual Laboratory for Technology (http://vlt.ucsd.edu) in recognition of the evolving emphasis of technology activities, the multi-institutional nature of technology R&D, and the need for improved coordination and representation of the Enabling Technology Program. A vibrant and successful Program fosters the following ideas in its governance:

- encouragement of novel and innovative solutions to the technical challenges of developing fusion science and energy;
- balance between near-term, project-type needs and long-range exploratory research;
- use of peer review to ensure the highest scientific quality;
- development of core competencies in fusion engineering sciences;
- and provision of opportunities for young, talented researchers.

The VLT was created in 1999 to, in part, assist DOE in making the transition from a program devoted primarily to ITER to one which is a full partner in the restructured national program where emphasis is placed on scientific understanding and innovation. This has largely been accomplished as indicated by the following themes and trends:

- Plasma technology activities are closely supporting ongoing plasma science experiments and are increasingly assisting alternate concepts as well as preparing for next-step, burning-plasma experiments.
- Fusion technology activities have shifted to an emphasis on scientific understanding of innovative chamber concepts in support of both MFE and IFE.
- Materials science activities now emphasize the scientific understanding of key feasibility issues through coupled theory, modeling and experiments.
- Advanced design efforts now concentrate on IFE and alternative concepts while next-step studies currently emphasize reduced-cost burning plasma options.
- IFE technology activities have been incorporated into the VLT with now several examples of synergism between MFE and IFE.
- A national VLT Program Advisory Committee (PAC) has been created to provide input on basic program balance and priorities and to enhance connections to the broader fusion science community.
- A system of peer reviews has been put into place to review the scientific quality of the ongoing activities.

Enabling technology program resources have been reduced from the ITER period by about a factor of two. Thus, it has been necessary to carefully balance a number of considerations; e.g., near-term vs. longer-term research, tokamak vs. non-tokamak support, MFE vs. IFE tasks, opportunities for additional participants vs. maintaining core competencies, etc.). All-in-all, it is generally believed (and supported by the VLT PAC) that the present balance under restrained budgets is about right and is consistent with the balance in the overall national program. This is the key planning consideration for the VLT over the next few years.

1.2 Enabling Technology Program Objectives

The five elements of the Enabling Technology Program are

- Plasma Technologies
- Fusion (Chamber) Technologies
- Materials
- Advanced Design
- IFE Chamber and Target Technologies

The principal technical features and five-year research objectives are described for each element. The following sections describe the mission, scope and plans for each element in more detail.

Plasma Technologies

Plasma technologies enable existing and near-term plasma experiments to achieve their scientific research and performance goals. They include essential plasma heating and current drive technologies that raise the plasma temperature and manipulate plasma properties to access advanced operating scenarios (e.g., reversed shear, MHD stabilization, turbulence suppression); fueling technologies, to achieve relevant plasma parameters, such as plasma density and desired operating scenarios, such as reduced transport; plasma facing components with desired characteristics, such as high heat flux and low erosion and for control of edge plasma conditions and for power and particle control; and magnets that provide the confining force for plasmas in magnetic fusion devices.

5-Year Objective: Develop enabling technologies to support the goals of the scientific program outlined above, including advanced methods for plasma heating, current drive, flow control, and fueling; develop plasma facing components; study improvements in magnet technology which could lead to significant reductions in the cost of fusion systems**.**

Fusion (Chamber) Technologies

Research on innovative plasma chamber technologies for magnetic fusion energy concepts is focused on high power density solid and flowing liquid first wall and divertor concepts. Corresponding performance limitations and necessary development programs will be identified. Implications on materials selection and testing, plasma surface interaction, components fabrication and maintenance, tritium management, chamber and divertor design, costing, licensing, safety, and waste disposal will be examined.

5-Year Objective: Demonstrate the scientific feasibility of innovative plasma chamber technologies for magnetic fusion energy; assess facilities needs for this development, including opportunities for international collaboration.

Materials

Significant progress has been made on the characterization and understanding of the properties and performance limits associated with materials processing, fabrication and joining, physical and mechanical properties, chemical compatibility, and effects of irradiation on properties of these three materials systems. Based on design studies and systems analyses, three candidate structural materials systems which offer a potential for high performance with favorable safety, radioactive waste disposal ratings, and a possibility for recycle have been identified.

5-Year Objective: Advance the materials science base for the development of innovative materials and fabrication methods that will enable improved performance, enhanced safety, and reduced overall fusion system costs so as to permit fusion to reach its full potential; assess facilities needs for this development, including opportunities for international collaboration; support materials research needs for existing and near-term devices.

Advanced Design

Detailed analyses of near-term and long-term fusion devices are carried out incorporating latest understandings from plasma physics and technology research as well as developing new models. An integrated analysis highlights interaction and trade-offs among different areas (e.g., MHD stability and current-drive, edge plasma physics and divertor heat loads) and defines R&D needs to guide present and future experimental and theoretical studies.

Advanced design studies are needed when fusion concepts reach the "proof-of-principle" stage in order to help define next step options, to focus R&D toward high-leverage areas to analyze and understand the interaction and trade-offs among various components in a fusion device, and to assist the process of concept innovation using an integrated systems approach. These studies are carried out through national teams that utilize the core expertise of the relevant parts of the fusion program. In addition to integrated design studies and assessments, this activity helps to explore and articulate the role of fusion energy in the broader context of the evolving energy marketplace and global climate concerns.

5-Year Objective: Perform a range of advanced MFE and IFE design studies to support the goals of the scientific program and identify high-leverage R&D areas; and to assess the role of fusion energy in the context of all energy systems.

IFE Chamber and Target Technologies

For IFE, research on chamber-target technologies is focused on key feasibility issues that bear on the high-pulse-rate application of candidate drivers for IFE over the next few years. These include chamber wall design, final optic protection, and target fabrication and injection.

Design of thick-liquid-wall chambers with vented jets and beam port protection requires knowing how smooth and how far free liquid jet surfaces (fixed and oscillating) can be maintained at power-plant relevant geometries and dimensionless Reynolds and Weber numbers. Also required are the vapor condensation rates, droplet clearing rates, and flow recovery rates that would limit the pulse rate of thick-liquid-wall chambers. The outcome of these issues will determine if thick liquid wall chambers are feasible and which driver and target combinations can use them. For dry-wall chambers, the reduction of thermal conductivity, swelling rates, and retention of tritium in low activation composite materials, as a function of neutron fluence, composite morphology, and operating temperature, are uncertain and need to be better determined. Validating means for protecting the first wall from x-ray and debris damage is also required. Understanding the useful lifetime for dry-wall chambers lifetime is important to the application of the direct-drive approach to IFE.

For accelerators it is necessary to determine what shielding geometries and compositions combine to provide an adequate lifetime of final focus magnets in the presence of neutron and gamma transport through shielding structures with a number of long, narrow penetrations. For lasers it is necessary to understand the fundamental mechanisms that set the threshold for laser damage of reflective and transmissive laser optics, and how those thresholds change with radiation and debris contamination.

Improved knowledge of the safety and environmental impacts of chamber design choices will guide R&D towards design combinations of targets and chambers that will increase the likelihood of public acceptance.

Understanding what practical target materials and fabrication methods can be used for IFE will provide useful guidelines on the choice of materials, geometry, and surface roughness that should be assumed in target designs. The research on materials will also affect safety, as target debris can contribute significantly to radioactive inventories in IFE.

5-Year Objectives: Evaluate feasibility of chamber concepts in the context of the response of materials to fusion pulse and radiation damage. Develop plausible designs for protecting final focusing elements for ion accelerator and laser drivers. Evaluate safety and environmental aspects of IFE power plants and modify designs such that plants can meet the no-public-evacuation safety criteria. Identify credible pathways to low-cost target fabrication, accurate injection, and target survival through experiments and analyses.

2.0 PLASMA TECHNOLOGIES

2.1 Mission, Scope and Long-Term Objectives

The dramatic progress in fusion science seen in the last few decades has been possible in part due to equally dramatic progress in plasma technologies (PT). The development of high power auxiliary heating systems for heating plasmas to fusion-relevant temperatures is an obvious example. Improved plasma performance and the achievement of advanced confinement modes have been facilitated by the application of plasma technologies on numerous confinement facilities. Examples include the H-mode (wall conditioning), record Lawson parameters (pellet fueling on Alcator-C and TFTR), and core plasma turbulence suppression and the establishment of transport barriers (such as the pellet-enhanced performance mode) through manipulation of various plasma profiles via core fueling, neutral beam, and radio frequency heating and current drive methods, and flow..

Plasma technologies enable existing and near-term plasma experiments to achieve their scientific research and performance goals. They include:

- plasma heating and current drive technologies that are essential for raising plasma temperature and manipulating plasma properties to access advanced operating scenarios (e.g. high β and high energy confinement);
- fueling technologies, to achieve relevant plasma parameters (e.g., plasma density) and to achieve desired operating scenarios (e.g., reduced transport);
- plasma facing components to generate the proper edge plasma conditions (e.g. low erosion) in a high heat flux environment and for power and particle control;
- new and improved instrumentation for plasma diagnostics and control;
- magnets for magnetic fusion devices;
- PT activities are to address issues that can significantly impact the cost of future devices.

Continued exploitation of existing and planned experiments will depend on further advances in plasma technologies, particularly those related to localized manipulation and control of the plasma and the extension to longer pulses. Within the context of the fusion program's goals to develop the knowledge base for a more attractive fusion energy source and a low-cost, next-step device, a renewed commitment from the technologists to handle higher heat loads, produce lower cost magnet designs, and develop more efficient and flexible heating, current drive, and fueling systems will be required to support the likely reduction in the size and improvement in plasma performance to accomplish these objectives. The top-level goals and objectives of the Plasma Technology program element of the VLT reflect these challenges. They are largely derived from the enabling technology needs of the fusion science community expressed in user-developer workshops, by coordinating and advisory committees of the experimental fusion facilities and through other national forums.

The mission of the VLT Plasma Technologies program element—*to provide the tools and understanding for creation, confinement and control of high-temperature plasmas*—closely mirrors the Snowmass 1999 Fusion Summer Study challenge to "develop control tools for detailed physics investigation" of the outstanding cross-cutting science issues (turbulence and transport, MHD stability and plasma boundary physics). The supporting R&D objective—*to provide the technological advances that enable existing and near-term plasma experiments to succeed in achieving their full performance goals and ultimate research potential*—addresses the science/technology partnership theme of Snowmass to improve the performance of the portfolio of MFE concepts currently in operation and those that are anticipated or planned in the near future (i.e. steady state and burning plasma devices). The detailed long-term objectives for the various task elements to be discussed later reflect the overarching Plasma Technologies element 5- Year Objective namely:

Develop enabling technologies to support the goals of the scientific program outlined above, including advanced methods for plasma heating, current drive, flow control, and fueling; develop plasma facing components; study improvements in magnet technology which could lead to significant reductions in the cost of fusion systems.

- **Major Task Elements**

This objective is carried out by the several major task elements (technologies) within the PT program element scope which currently include magnet technology, plasma heating and current drive, fueling, and plasma-facing components. The mission and corresponding long-term R&D objectives of theses sub elements are listed below.

Magnet Technology

Magnets are an essential ingredient for providing plasma confinement and high performance and are also a major contributor to the construction cost of magnetic fusion facilities. Accordingly there are three components to the magnet technology program mission that address the performance and cost issue namely:

- To reduce the size and cost of superconducting magnets by striving towards higher fields, higher current densities, reduced stress levels, and higher operating temperatures; to develop cost effective design and fabrication techniques; and by developing high critical temperature superconductors for the future.
- To develop improved normal conductors for Next Step Option (NSO) devices (e.g., FIRE) and advanced magnet concepts to achieve better physics performance.
- To develop cost effective design and fabrication techniques for IFE-Heavy Ion Fusion (HIF) quad arrays.

The long term objectives associated with this mission are:

- Improved performance, low cost magnet technology for burning plasma or long pulse experiments including advanced high field, low cost superconductor and normal conducting materials, advanced structural and conduit materials, improved conductor joints, advanced quench detection and protection systems.
- Establish technical basis for application of high-temperature superconductors (HTS) to fusion devices.
- Application of LTS and HTS to alternate concept devices including HIF quadrupole focusing magnets, LDX magnets, spherical torus magnet systems, and stellarators, etc.

Plasma Heating and Current Drive

The MFE program supports a broad range of plasma physics experiments which in general require multiple sources of auxiliary heating. The ion cyclotron heating (ICH) technology program mission is to develop ICH systems that will meet the requirements of present-day and future plasma physics experiments. ICH is a flexible enabling technology that has a crucial role in heating, current drive and flow control in innovative concepts, advanced tokamaks, spherical torus, compact stellarators, and burning plasma physics. The program strongly supports the four major MFE program goals of the Integrated Program Plan.

The long-term objectives of the ICH program are to develop reliable, advanced ion cyclotron heating and current drive systems that:

- Reduces the required port size by the development of a high power density launcher.

- Support long pulses, essentially steady-state.
- Are tolerant of rapidly varying plasma loads.
- Operate over a wide range of density and magnetic fields.
- Are compatible with a reactor environment.
- Heat either ions or electrons.
- Drive current on- and off-axis in high density discharges.
- Control plasma conditions by heating and current profile control.

The electron cyclotron heating (ECH) technology program is devoted to developing the technology of ECH heating systems that are required for heating and current drive in advanced plasma physics experiments including tokamaks, stellarators (where it is a crucial component) and alternate concept machines. ECH technology research encompasses the microwave source, power supply, output window, transmission line and antenna for carrying out ECH heating experiments. ECH is required in the experimental plasma science and fusion energy research programs both domestically and internationally

- Increase the reliability of high-power, long-pulse gyrotrons.
- Develop gyrotrons at unit power levels of up to 2 MW and at frequencies of up to 200 GHz.
- Increase the efficiency of gyrotrons from the present-day level of 30% to over 75% using multi-stage depressed collectors.
- Develop and test output windows capable of transmitting at least 3 MW of CW power.
- Develop tunable gyrotrons for use at a range of magnetic field values.
- Develop a remote, steerable launcher, with no in-vessel moving parts for use at multi-megawatt power levels, preferably cw.
- Develop mode converters that can produce nearly ideal Gaussian output beams at high efficiency.
- Develop the theoretical design tools that will allow the accurate design of new gyrotrons and transmission line components.
- Increase the efficiency of transmission lines.
- Reduce the cost of all gyrotron system components.
- Develop a low cost, solid-state gyrotron power supply system.

Fueling and Pumping

The mission of the plasma fueling and pumping element is to develop systems capable of providing a reliable, flexible particle source for controlling core plasma density so as to effect efficient fueling and plasma density gradients to affect transport and influence the fusion power density. In a related area, the technologies applicable to fuel injection will be adapted to provide systems for disruption mitigation. The long term objectives fort this program element are:

- Understand the physics and technology of high field side (vertical and inside) pellet launch.
- Exploit the observed plasma performance benefits of fueling systems on DIII-D, JET, Tore Supra and LHD.
- Develop a prototype liquid jet disruption mitigation system which could be tested on DIII-D.

- Develop compact fueling systems with flexible launch capability for initial applications on MST, NSTX and NCSX and possibly JET.
- Evaluate innovative, low inventory, DT pumping systems.

Plasma Facing Components

The mission of the Plasma Facing Component (PFC) technology program is to understand the science of plasma materials interactions and use that knowledge to create reliable plasma facing components that absorb the high heat and particle fluxes from a fusion plasma without contaminating the core plasma. Plasma facing components include divertor or limiter components that interact with the edge of the core plasma and the plasma facing portion of the remainder of the first wall that sees radiated power and charge exchanged particles.

The long-term objectives of the PFC program are:

- To provide the plasma science and materials expertise necessary to understand, ameliorate and exploit the interactions between the fusion plasma and the wall and components that surround it,
- To qualify the plasma facing materials, technology and components necessary to maintain continued progress in the tokamak program, and
- To develop the PFC technology essential to support the maturation of early-concept alternate magnetic fusion confinement concepts.

2.2 Strategic Pathway

The implementation strategy employed by each of the program elements to accomplish their respective mission and R&D objectives differ in detail but are similar in approach and philosophy. Each program element carries out both near-term and longer-term research. The former consists of research and development that addresses specific project needs and usually includes deliverables, such as working prototypes, computer codes, etc. The latter can best be characterized as a "base program" with generic, longer term or relevant basic research goals. These development program activities are carried out to serve the broader fusion energy science program including: (1) base program development, (2) project-specific development to meet the needs of next step/burning plasma devices, tokamaks and alternate/innovative confinement concepts (including IFE), and (3) international collaborations on devices and facilities that complement the US program capabilities.

An important characteristic of the relationship between the long-term and near-term R&D efforts is the constant flow of information and innovations from the base program to the science community (existing devices) and feedback from the science experiments that is incorporated into the base program R&D objectives. This feedback occurs in a formal way through various forums in which the science program needs are communicated to the developers.

- **Base R&D**

The PT base technology program represents the moderate- to long-term technology development that is carried out in parallel with shorter-term project specific development. This work, which is somewhat independent of specific experiments, allows technology development for application to a wide range of experiments. Apart from programmatic technology needs that are not presently in a project, there may also be immediate developmental requirements common to several projects or the need to sustain a critical competency for the future.

The future direction of this category of R&D that is consistent with the present fusion program strategy and the PT mission will likely include the development of plasma facing components to

handle higher heat loads with reduced erosion, low-cost, high performance magnet designs, and more efficient and flexible heating, current drive and fueling systems.

- **Project Specific R&D**

PT involvement in project specific tasks (i.e., work tied to existing or planned facilities) normally includes the developmental aspects of such activities and participation in the design, fabrication, testing and performance validation of prototypes. The deployment of suitable prototype units constructed as part of the PT R&D efforts is also appropriate in this category of work. Strategic pathways in this area of work include tokamaks, innovative and alternate confinement concepts (including IFE), and next-step devices.

Tokamaks

Tokamaks have led the confinement performance achievements in fusion worldwide, and plasma technologies have been crucial to this success. Reliable copper magnets, neutral beam heating systems, and divertor systems are common to most present-day high performance devices. The worldwide enabling technology programs have been making the transition to the technology needs of future devices with superconducting magnets, RF heating systems, compact toroid (CT) and pellet fueling, advanced heat removal concepts, and disruption control and mitigation techniques. The tokamak has been the primary "test-bed" for PT development and PT program interactions with the world wide tokamak program have been extensive. Future interactions will play an important role in the strategy to explore burning plasma physics, long-pulse issues and advanced tokamak physics. An underlying theme of much of the development program effort for tokamaks will be to demonstrate detailed control of plasma parameters from the core to the edge in order to enable and extend advanced tokamak regimes and improved performance.

Size reductions and concomitant reduction in the cost of the fusion power source is the promise of advanced tokamak operating regimes. This will place added emphasis on the development of lower cost and higher unit power density and more efficient heating and current drive (H&CD) systems. H&CD systems have an increased importance for high performance fusion devices since control of the pressure and current density profiles is one of the keys to producing "transport barriers." Major cost savings in H&CD systems can be achieved by reducing the number of systems to deliver the required power and improving the efficiency. For example, in electron cyclotron heating (ECH) systems the transmission systems can handle higher unit power than the present 1-MW gyrotrons, so development of 2- to 3-MW gyrotrons can reduce the number of systems and hence the total system cost. ICRF systems are presently limited by the voltage standoff achieved on antenna systems, so improvements could reduce the number of systems.

Disruptions are a major problem for future high performance tokamaks. Techniques for disruption avoidance and mitigation are being explored and new technology needs are envisaged. For example, massive gas injection has been shown on DIII-D to be effective at reducing halo currents and toroidal peaking factors and liquid jets are predicted to be even more effective at mitigating the effects of a disruption by controlling the current decay and forcing the thermal energy dump into radiation. High β plasmas operating at their performance limits will also require improvements in divertor heat removal technology particularly during extended pulse operation. Innovations such as tungsten brush divertor armor and high heat removal technology (swirl flow water and He gas cooling) will enable expanded advanced tokamak operation space.

Innovative/Alternate Concepts

Alternate concepts represent another important strategic interaction for the PT program and the various technologies within the PT portfolio are expected to play a prominent role in alternate concept development through their various stages of evolution (concept exploration to proof of performance). Both generic and project specific (including deployment of prototypes) development is already being performed for the stellarator, spherical tori, reversed field pinch and heavy ion beam fusion communities. The physics requirements of alternates that are relatively closely linked to the

present knowledge base (such as stellarators and spherical tori) will require a rethinking of existing technologies. Taking the ST as an example, its compact size will require the need to develop higher heat flux PFCs, and the low toroidal field will require development of high harmonic rf heating and current drive systems. The development program has responded to these challenges by developing and deploying the HHFW heating and current drive system on NSTX and deploying an exploratory free surface liquid Li limiter system on CDX-U. The ST pathway [and the Volume Neutron Source (VNS)] is expected to play a particularly important role in the further development of non-inductive current drive techniques, high heat flux PFCs, and high performance copper magnets. Compact stellarators will also require high heat flux component development and ICRF antennas that heat efficiently under conditions where the shape of the plasma edge is irregular and variable.

As the portfolio of alternates expands into emerging and new concepts that are less well linked to the present tokamak and stellarator knowledge base, it may be necessary to pursue revolutionary approaches as well as these more evolutionary changes in the technology.

Burning Plasma/ Next Step Option Devices

In the recent past, PT developmental activities in the burning plasma area were focused on development in support of the ITER device. The US PT program contributed widely across the various technologies involved in the PT area and played critical roles in the following tasks:

- fueling system design and pellet fueling development and testing,
- ICRF heating and current drive system design and prototype antenna development and testing,
- superconducting cable and Central Solenoid Model Coil (CSMC) development,
- prototype divertor cassette fabrication and associated development of PFC and high heat flux components,
- ECRH gyrotron, launcher and window development, and
- tritium handling and means to reduce the tritium inventory.

These activities have led to significant technological advances which will have a beneficial impact on any future long pulse burning plasma experiment (the Nb_3Sn CSMC, 170 GHz ECH gyrotrons, high-power density in-port ICRF antenna, and the tungsten rod high heat flux divertor targets for example). Many of these innovations have been incorporated into other burning plasma studies such as the Fusion Ignition Research Experiment (FIRE). Moreover, the traditional roles of PT (magnet technology, heating, fueling and exhaust, PFCs) in burning plasma device studies and associated developmental activities have been carried over into the FIRE project. PT development will continue to support these activities especially for those technologies that can contribute to the more immediate needs of the science program.

Non-Fusion Applications For Plasma Technology

In recent years, the PT program has proven to be an effective “bridge” to connect the fusion program to industry, other science areas, other branches of DOE, and other government agencies. These activities are usually not explicitly funded by the Enabling Technology Program. This interaction provides an important leveraging of fusion resources and benefits the fusion program in several other ways, including:

- providing the fusion program with a near-term product (spin-offs) and external visibility,
- preserving important core competencies and advancing the technology (spin-ins) ,
- contributing to important national goals such as:
  - the development of efficient high temperature superconducting (HTSC) transformers and transmission lines (DOE, industry),

- the use of radio frequency (rf) technology for plasma/materials processing (semiconductor industry),
- the application of microwave heating for efficient and environmentally acceptable processing of wood (DOE/paper industry) and carbon fibers (industry),
- high frequency gyrotrons for advanced radars,
- gyrotron systems for industrial heating, ceramic sintering, high resolution magnetic resonance imaging,
- the application of rf heating and magnet technology for medical isotope production (industry), and
- the use of rf heating and superconducting magnets for a novel plasma thruster for deep space exploration.

2.3 Recent Achievements and Contributions to Science

Progress towards meting the long-term objectives of each of the elements has been significant and several recent technological achievements have already been implemented in the form of hardware on science program facilities. The following is an abbreviated list of recent technological advances in the field and their impact on the science program mission and goals.

The magnet technology program played an instrumental role in achieving a milestone in the development of fusion technology¾the completion and successful testing of the ITER Central Solenoid Model Coil (CSMC), the world's largest (100-t, 650 MJ) and most powerful (13T) Nb_3Sn magnet. On the other end of the confinement facility spectrum the program is enabling innovative experiments like the Levitated Dipole Experiment (LDX) with equally innovative technology. The magnet technology program has recently developed the Nb_3Sn floating dipole magnet for this device and is also developing, with industry, what will be the first application of high-temperature superconductor for the levitation magnet. The development of low-cost, high current density NbTi quadrupole magnets for the HCX and IRE heavy ion fusion facilities is yet another example of how this program is addressing the near term needs of the science community.

In the heating and current drive area, the technology program is responding to the community's need for more precise spatial and temporal control of the pressure and current density profiles. Recent examples of the science/technology partnership in this area include a phased array (twelve-strap) high harmonic fast wave (HHFW) antenna developed jointly by ORNL and PPPL for NSTX and the 1 MW long pulse ECCD gyrotron developed for DIII-D. The former features real time control of the current strap phasing. These technologies are key elements in the respective facility's research program from both the operational and performance points of view. With its limited volt-second capability, NSTX will rely on non-inductive current drive to drive a large fraction of the plasma current. Recent experiments, confirmed by theoretical calculations, indicate a pronounced asymmetry in the launching of ICRF waves when the angle of the magnetic field to the launched rf field is large (in NSTX it can be > 45°). This effect is due to the anisotropy of the plasma and can have a significant effect on the current-drive loading, although preliminary calculations indicate that the current-drive efficiency should remain unaffected.

Precision current drive technologies will be required to achieve the high β equilibria of the advanced tokamak (AT) in particular. ECCD is being pursued on DIII D for precise localized current drive to affect negative central shear and to stabilize neoclassical tearing modes. This program has been enabled by the development of gyrotrons that have operated at power levels of up to 0.6 MW for 10s ¾a world record for output power at that pulse length. The 110 GHz gyrotron features several new developments including a diamond output window, a high efficiency mode converter and a diode electron gun. Further reliability, efficiency and power gains are expected from incorporation of a recently completed multi-stage depressed collector design into the next industrial prototype gyrotron.

In the past few years, the pellet fueling program has made many significant contributions to improving scientific understanding and the optimization of plasma performance. In a partnership with the science program, the technologists have developed a versatile new fueling facility for DIII-D that enables studies of low field side (LFS) and high field side (HFS) fueling physics at four different plasma locations. This system has been exploited to produce several new important results including the achievement of deep fueling (and peaked density profiles) and the spontaneous development of internal transport barriers during (HFS) launch as well as pellet induced H-modes that exhibit a power threshold reduction of more than 23 % and are not dependent on a critical edge temperature.

Fueling technology has also been utilized to explore novel disruption mitigation techniques in the AT program. Massive gas injection on DIII-D has been shown to be effective at reducing disruption forces on DIII-D by a factor of four and the initial steps have been taken to develop high speed liquid jet technology that is expected to be even more effective.

Dramatic progress has been made recently in improving the heat removal capability and reliability of plasma facing components, featuring both water and helium cooling. Actively-cooled composite structures have survived 3000 thermal cycles at 10 MW/m^2 with Be/Cu and over 20 MW/m^2 with W/Cu. Steady state heat removal of over 35 MW/m^2 has been demonstrated over small areas with helium cooling. A near term goal of this program that addresses the need for improved power and power handling expected in the future high performance plasma configurations is to develop PFC's with significant improvements in both heat flux and erosion lifetime. The ALPS free surface liquid divertor project has been initiated to study the potential of liquid surfaces for active heat removal without concerns for plasma-facing component erosion-limited lifetimes.

2.4 Relationship to Other Elements of the U.S. Program

Plasma technologies have extensive ties to virtually all elements of the U. S. program. Within the VLT itself, essentially all of the PT R&D elements directly support the burning plasma experiment , or Next Step Option (NSO), studies and provide the latest technological innovations to the fusion power plant design studies carried out within the Advanced Design element. Interconnects within the VLT also occur in the Fusion Technologies (liquid divertor), Materials (PFC), and IFE Technologies (HIB magnets) elements of the VLT. Plasma Technologies are primary contributors to the FESAC Program Goals 4 and 6.

Extensive connections also exist to the experimental plasma science program, both domestic and international, as typified by the examples presented in section 2.3 and elsewhere in this document. In this respect the element is a primary contributor to FESAC Program Goal 3:

> *advance understanding and innovation in high-performance plasmas, optimizing for projected power-plant requirements: and participate in a burning plasma experiment.*

PT is also a secondary contributor to Program Goals 1 and 2.

2.5 Role of International Collaboration

- **<u>Technology Applications on Confinement Facilities</u>**

Plasma technologies have long enjoyed a rich tradition of pioneering international collaborations that have advanced the science and technology objectives of the US fusion program. In many instances, PT participation through development of unique hardware and subsequent application of that hardware on foreign facilities has provided the broader scientific community with access to unique facilities that complement US capabilities. For example, science collaborations on Tore Supra and JET followed the deployment on those devices of PT hardware including pellet injectors, radio frequency heating antennas and actively cooled plasma limiters. These interactions have resulted in a

significant leveraging of program resources with the following benefits to the scientific and developer community:

- Collaborations provide access to facilities that complement US capabilities.
- The combination of unique technology and unique facility capabilities often leads to science advances (e.g., the PEP mode or enhanced shear reversal on JET).
- Costs and knowledge are shared through joint systems development thereby leveraging technology resources (rf breakdown studies and detection systems on JET and ASDEX-U, ECH transmission lines and mode converters on LHD).
- Developers are provided with access to unique or advanced physical plants (e.g., ICRF heating system on JET).
- Collaboration partners provide dedicated operations for testing and validation of US developed hardware and concepts (e.g., combine antenna testing on JFT-2M).
- Involvement in collaborations sharpens critical expertise and maintains core competencies.

The involvement of PT in these types of collaborations is widespread and spans the breadth and depth of the confinement device portfolio from concept exploration to proof-of-performance and burning plasma phases of tokamaks and innovative confinement concepts. Recent contributions of PT include R&D on a wide spectrum of devices including JET (pellet fueling and rf heating), LHD (ECH, pellet fueling, ICRF heating and PFCs), Tore Supra (pump limiter, pellet fueling, ICRF heating), START/MAST (neutral beamlines), TJ-II (neutral beamlines), JFT2-M (ICRF antenna testing), KSTAR (design of magnets, heating and current drive systems and PFCs), and GAMMA 10 (pellet fueling). Many of these collaborations have received direct funding for US participation from the parent institution.

The importance and future contribution of PT in this area is recognized in the OFES Strategic Plan for International Collaborations in Fusion Science and Technology Research. The stated focus of the Department's strategy with regard to PT is to "deploy US technologies to access test conditions unavailable domestically, particularly on scientific issues related to long pulse/steady-state operation, high-power densities, and reliability." Of particular importance to the US plasma science program are collaborations in the areas of (1) burning plasma and tokamak performance (including long pulse), and (2) innovative confinement concepts. PT is well positioned to take advantage of opportunities in several foreign facilities.

- **Joint International Development**

In addition to collaborative programs involving applications of the technologies on foreign confinement devices, the PT program is involved at all levels in joint R&D that supports the generic development program objectives. Strategic partnerships with international development activities can be used to supplement areas which cannot be adequately addressed given the limited US funding. These activities generally involve the use of test stands and other facilities within the US and abroad and effectively capitalize on the extensive US investment in its own development facilities such as the Radio Frequency Test Facility (RFTF), and numerous test facilities for materials and component testing (PISCES, PMTF, and TPE). Recent or current examples of collaborative interactions include:

- Inside launch pellet fueling technology (JET and LHD)
- High power ECH window and gyrotron development (JAERI, RF),
- Development and testing of actively cooled divertor concepts (Russia, Japan, and Europe)
- CS model coil and other magnet test facilities [Pulse Test Facility (PTF), TOSKA, SULTAN],

- ICRF high-power density antenna and fast matching system development (JET, ASDEX-U),
- Studies of the fundamental science of erosion/redeposition and tritium retention/removal (Japanese and Europe).

2.6 Five-year Objectives and Implementation Approaches

Listed below are the implementation approaches which represent measures of performance towards the respective five-year objectives of the technologies listed in section 2.1.

Plasma Facing Components

The main issues for plasma facing components are to understand, ameliorate, and exploit the interactions between the plasma and the wall and components that surround it and to develop power removal systems that are consistent with high heat flux, high temperature, low erosion and plasma compatibility.

- A critical milestone in the program's long-term science and technology priorities will be reached. The test of the first theoretical code which couples a core plasma to the first wall while integrating all of the known major plasma/first wall interactions will be completed. This milestone will not only provide a more complete theoretical understanding of wall interactions with the core plasma, but will allow for significant improvements in the design of more accurate alternate concept proofs-of-principle and new machines.
- By 2005, the program will provide the next generation of reliable solid state sensors ("smart tiles") required for the understanding of plasma/materials interactions in tokamak and alternate concept plasmas. A demonstration of new conditioning techniques compatible with high magnetic fields will also be performed.
- The advent of smaller alternate concept devices means that development of more efficient and reliable heat and impurity removal techniques will be required. In 2005 the program will complete the fabrication and demonstration of an innovative plasma/facing component which will have both a 50% increase in critical heat flux, as well as a 50% increase in erosion lifetime. Plans for deployment of such a component on a fusion device will be developed.

▪ Plasma Fueling

The main issues for fueling technologies are to understand and exploit advanced fueling physics (such as high field side launch) and demonstrate the performance (i.e., pellet speeds, density of compact toroids and repetition rates) required to effect adequate control of the density profile shape and high fueling efficiency.

- Demonstrate one or more technologies to provide density and density profile control (i.e., flexibility) for ongoing plasma science programs, at home, and abroad. The technical objectives would include:
  - long pulse,
  - variable fueling location (high vs. low field, vertical fueling),
  - variable throughput, and
  - tunable speed (pellet injectors).

- Fueling systems will have progressed to the point of delivering hydrogenic and nonhydrogenic (for disruption mitigation and plasma radiation control) pellets repetitively at speeds required for control of core parameters of burning plasmas.
- High speed cryogenic liquid jet technology will be developed for rapid plasma quench and disruption mitigation.
- The development of the DT fueling system for a burning plasma experiment will resume.
- The program will have developed the tools and data/analysis to understand the physical principles and scaling of high field side pellet launch physics.
- Experiments will be performed to understand the fueling properties and effects on plasma transport of compact toroid fueling of a tokamak/stellarator where the CT length is a small fraction of the minor radius.
- The issue of whether deep (central) or shallow fueling will be required for profile control will be resolved experimentally and scenarios will be developed to deliver fuel inside internal transport barriers.

ICRF Heating and Current Drive

The main issues for ICRF heating and current drive are the development of higher power density launchers, improved reliability and efficiency of delivering power to the plasma, and real time control of heating and current density profiles.

By 2005 the program should have advanced to the point where:

- High-power density launchers that deliver high power to the plasma under modest loading conditions will be tested and validated.
- A fast, automated control system will be developed that detects arcs in the rf components and protects the system from their effects, delivers a large fraction of available rf power to the plasma during rapid changes in plasma loading, and allows real-time control of current drive directivity while maintaining high heating power to the plasma.
- The capability to sustain long-pulse, fully noninductive discharges using fast-wave and/or mode-conversion current drive to maintain current and/or current profile control will be demonstrated.
- The interaction between the plasma edge and high-amplitude rf waves near the antenna, both for fast-wave and ion Bernstein wave launch will be studied.

ECH Technology

By 2005 the ECH technology development program will develop the key components needed by the domestic and international plasma physics and fusion program. Major advances that are required include:

- Increase the reliability of gyrotrons at 110 GHz for General Atomics.
- Qualify the CVD diamond window for reliable, CW operation at 1 to 2 MW power levels.
- Develop higher power gyrotrons at 110 GHz for upgrading the DIII-D ECH system.
- Increase gyrotron efficiency using a multi-stage depressed collector.
- Increase the efficiency of mode converters and transmission lines.

- Develop a remotely steerable ECH launcher and a reliable, rotatable launcher mirror suitable for long pulse / CW operation.

Magnet Technology

The main issues for magnet development are achieving higher fields, higher current density and higher critical temperatures, while striving to reduce size and cost.

- Improved performance, lower cost magnet technology developed for a Burning Plasma Experiment or long-pulse experiment by means of
  - development of advanced high field, low ac loss superconductor materials,
  - advanced radiation resistant insulating materials,
  - development of advanced conductor conduit and magnet structural materials,
  - low-resistance, low-loss, high-stability conductor joints, and
  - development of high T_c internal stabilizer coils.
- Scientific and technical basis established for application of high T_c superconductors to fusion devices.
- Application of improved superconductor (both low and high temperature) and magnet materials and technology to alternate concept devices including superconducting coils for HIF drivers, a comparison of copper with superconducting coils for a near-term Integrated Research Experiment, and upgrade of an LDX superconducting ring.
- Development and upgrade of superconductor, magnet, and cryogenic system design codes.
- Magnet technology development for copper machines (water or LN_2 cooled, joint technology, electromagnetic design, structural design).

2.7 Key Decision Points

There are several key decision points before the broader fusion community (domestic and world wide) that can dramatically impact the direction of this area of research within the next five years. First, if a decision to proceed with a burning plasma experiment internationally is made in 2003, the PT element will be a logical area for a major U. S. participation owing to its extensive previous involvement in the ITER program (divertor cassette, ICRF and ECH heating and current drive, pellet fueling, CS Model Coil). If a decision is made to proceed with a U. S. burning plasma device such as FIRE, the PT area involvement will similarly increase in all areas (magnet technology will shift emphasis to copper coil development). Opportunities may also exist for near–term expanded collaborations on international facilities such as JET (AT physics and burning plasma physics issues) and KSTAR (long-pulse AT physics). The JET collaboration in particular would offer an opportunity to leverage the European program in developing the next high power density ICRF launcher. The KSTAR facility with its 300 s pulse or longer capability offers a unique test bed for the PT element to focus its long pulse and AT profile control development efforts.

On the domestic front, there are numerous developmental needs expressed by the science facilities that are currently unmet. These include, for example, higher power, long pulse gyrotrons and ECH components for DIII-D, a possible medium scale test of free liquid Li surface limiter on NSTX, HFS launch pellet injection on NSTX, and improved delivery of lower hybrid and ICRF power on Alcator-C Mod. The innovative confinement concept community will similarly need increased involvement in the next few years from the plasma technology program to progress beyond the concept exploration stage.

3.0 FUSION TECHNOLOGIES

3.1 Mission, Scope and Long Term Objectives

Fusion Technologies include the Chamber Technology and Safety program elements which are described in this section.

The mission of Chamber Technology is to:

> *Extend the engineering science knowledge base, explore innovative concepts, and resolve key feasibility issues for Chamber Technologies that in the near-term enable better capabilities in plasma experiments, and in the long-term improve the economics, safety, and environmental attractiveness of fusion energy systems;*

Chamber Technology is concerned with the regions enclosing the plasma which fulfill three essential functions in a fusion system: providing the vacuum, heat and particle removal, and other conditions necessary for stable plasma operation; providing self-sufficient internal generation of tritium fuel for DT plasmas; and providing a product useful to mankind (e.g. power, synthetic fuel) through safe, efficient, reliable, and economical utilization of a fusion plasma. Chamber Technology embodies many of the fusion issues related to feasibility, economics, safety, and environmental impact.

Chamber Technology research is important now because: 1) it is a critical element in the joint undertaking between physics and technology to develop a vision for an attractive fusion product; 2) it can help lower the cost and reduce the technological constraints of future plasma experiments and fusion R&D facilities; and 3) it makes it possible to exploit advances in plasma physics, for example by providing high power density handling capability.

The restructured US Fusion Energy Sciences Program provides the opportunity to explore innovative, possibly revolutionary, concepts for Chamber Technology that can substantially improve our vision of an attractive fusion energy system. New initiatives such as APEX were started in FY 1998 to explore such concepts. APEX has already identified a number of promising innovative concepts that may greatly improve the capabilities of plasma devices and the potential economic and safety attractiveness of fusion energy systems. These novel concepts fall into two categories. The first category, called “liquid walls,” seeks to eliminate the solid “bare” first wall. This category of liquid walls is “concept rich” with many variations. The second category of ideas focuses on extending the capabilities, particularly the power density and temperature limits of solid first walls.
A key part of the Chamber Technology research involves advancing the engineering sciences necessary for conceptualization, design, analysis, and development of the chamber components. These engineering sciences include: fluid mechanics, magnetohydrodynamics, heat transfer, neutron and tritium transport, nuclear physics, mechanics of materials, thermomechanics, surface sciences, and chemistry. The multi-field environment of the fusion system (vacuum, magnetic field, neutrons, intense surface heat loads, tritium, etc.) results in new and challenging phenomena whose understanding requires advancing the underlying engineering sciences.

The long-term objectives of the Chamber Technology program are to:

- Advance the underlying engineering sciences and develop predictive capabilities necessary for understanding new phenomena and predicting the behavior of the chamber in the complex plasma and fusion environment.

- Identify and explore novel concepts that can enable plasma experiments to more fully achieve their potential, improve the potential attractiveness of fusion energy systems, and contribute toward achieving a more affordable and cost-effective research and development pathway toward the practical, economical, and safe utilization of fusion energy.

- Resolve the key feasibility issues and develop a practical and attractive Chamber Technology.

The mission and long-term objectives of the Fusion Safety and Tritium Technology program are to:

- Understand the major sources of radioactive (activation products, dust/debris) and toxic materials (Be, V, Li, Flibe) in fusion facilities.

- Understand how the energy sources in the facility (plasma, magnets, decay heat, chemical reactions) can mobilize radioactive and toxic materials.

- Develop state of the art integrated safety codes and models to demonstrate the safety and environmental potential of fusion.

- Assess/evaluate safety and environmental issues for new and emerging concepts such as those in ARIES, ALPS, APEX, FIRE and IFE.

3.2 Strategic Pathway

The Chamber Technology Research Program consists of two elements: Innovative Concepts and Evolutionary Concepts.

The strategy for allocation of resources and efforts between these two elements is as follows:

- Focus the greater part of the resources on the Innovative Concepts element to enhance creativity and innovation in exploring new, possibly revolutionary, concepts that have high pay-off potential to: enhance the capabilities of plasma devices, improve the vision for an attractive fusion energy system, and lower the cost and shorten the time of the research and development pathway.

- Provide a smaller part of the resources to international cooperation on selected R&D areas for Evolutionary Concepts, i.e. first wall/blanket/divertor concepts now being pursued by Europe, Japan, and Russia. Although these concepts may have limited attractiveness potential (e.g. they may be limited to relatively low power density, high failure rate, and complex maintainability), their data base is considerably larger than that of the innovative concepts. U.S. participation in selected R&D areas for evolutionary concepts will allow the U.S. to: gain access to data and R&D results from the larger European and Japanese programs, and learn the actual technological limits, which is essential to our endeavor to extend these limits.

The approach to executing the above two elements of the strategy must remain flexible and evolve with time based on future technical results. Key elements of the approach are:

- Utilize, for the most part, a multidisciplinary, multi-institution integrated team approach to foster collaboration, pool talents, and expand expert and specialty input. Chamber Technology is complex and encompasses many technical disciplines. In a limited budget, limited man-power situation, the team approach is most effective.

- Establish close coupling with the plasma confinement community because developing a vision for an attractive product must be a joint undertaking between physics and technology. Mechanisms include involving physicists as part of the Chamber Technology team and holding periodic joint workshops.

- Address Chamber Technology needs for innovative confinement concepts as well as advanced tokamaks. A substantially improved vision for an attractive fusion system will

most likely emerge from a combination of advances in confinement configuration and innovative technology concepts.

- Make effective utilization of international cooperation. In the near-term, this involves supporting other countries in selected areas of R&D for evolutionary concepts and encouraging other countries to participate in U.S. initiatives such as APEX for innovative concepts.

- Continue to ensure close coupling and integration of the Material and Chamber Technology efforts.

As we depart from current concepts and explore more innovative approaches, the design constraints on materials will change and the list of candidate materials will need to be broadened. There will be a need for basic material property data and evaluation of materials issues, interactions, and performance in the design environment of innovative concepts. Direct participation of material scientists in studies such as APEX is an example of an effective mechanism that is currently in place and should continue.

- Continue to ensure close coupling with advanced design and system studies groups (e.g. ARIES Team) for advanced tokamaks and innovative confinement approaches.

- Emphasize understanding the important scientific phenomena and advancing the engineering sciences essential to Chamber Technology. Chamber Technology involves many complex scientific and engineering phenomena and issues whose understanding and analysis involve many engineering sciences such as fluid mechanics, magnetohydrodynamics, thermal engineering sciences, solid mechanics, nuclear physics, and particle transport. Building a core competency in these engineering sciences is important to providing opportunities for new discoveries and innovative solutions to fusion technology problems through better understanding, and to providing capabilities to draw upon and interact with the external community in other fields.

- Enhance interactions with external engineering science communities. This is very important in order to effectively utilize advances in other fields (e.g. computational fluid mechanics, structural mechanics, and nuclear physics). Advances within fusion technology should also be communicated to other communities. Several mechanisms for achieving such interactions will be pursued. Examples include jointly sponsored technical sessions in topical conferences for other communities, inviting scholars from other fields for state-of-the-art presentations, and publishing scholarly fusion technology papers in scholarly journals of external communities.

3.3 Recent Achievements and Contribution to Science

The Chamber Technology Program has made very substantial progress during the past three years, particularly through APEX, a study being conducted by an integrated team that involves 12 US organizations and significant international participation. This progress includes:

- Identifying and exploring a number of new novel concepts for the Chamber that offer promise for fundamental improvements in the vision of an attractive fusion energy system; these novel concepts include innovative designs for a range of “liquid wall” ideas as well as promising approaches for extending the capabilities of “solid wall” concepts.

- Significant contributions to identifying solutions of important problems in present magnetic confinement devices and contributing to practical plans for testing these solutions.

- Better understanding of the challenging scientific issues of “free- surface flows”, including turbulence modification, surface renewal, MHD interactions, for low conductivity , high Prandtl Number fluids as well as high conductivity, low Prandtl Number liquid metals.

- Joint initiatives with the broader scientific community outside fusion, (e.g. with environmental groups working on “global warming”, the “turbulence” community, the “fluid flow control and drag reduction” community) to develop advanced phenomenological and computational models to further understand and predict fluid flow and mass and heat transfer in free surface flows.

- Design and construction of two free-surface laboratory experimental facilities.

- Improved understanding and models for plasma–liquid interactions including “surface” and “bulk” interactions.

These achievements have been documented in several major reports (including the 600-page APEX Interim Report) and published in a number of papers in scholarly journals. APEX has been conducting research in a number of areas, called Tasks, with each Task involving an integrated team of plasma physicists, scientists, and engineers with expertise in the multiplicity of technical disciplines involved. Below, we briefly summarize these achievements.

Liquid Surfaces in Plasma Devices

As a key part of the APEX mission to develop innovative chamber technologies for future fusion reactors, the APEX effort has made significant contributions to solutions of important problems in present magnetic confinement devices. For the National Spherical Torus Experiment (NSTX), for example, neutral beam heating, and pellet fueling are strong particle sources. Particle control is thus a critical scientific and technical issue. Research on liquid surfaces for fusion applications has shown that flowing surfaces offer the possibility for both power and particle removal from fusion devices.

To provide a means for particle control for NSTX, the APEX and ALPS programs have developed a preliminary design for a limiter or divertor module that will provide the ability to remove hydrogen and deuterium particles from the edge plasma region and alter edge conditions for the core plasma. The module will be capable of exhausting the total particle content of the plasma well within the typical discharge. It can also demonstrate the power handling capability of liquid surfaces in contact with a fusion plasma. The scientific and technical understanding this effort provides is particularly valuable because of the way it integrates actual data from an operating magnetic confinement device with detailed engineering analysis.

Theoretical models for the stabilization of magnetohydrodynamic (MHD) modes have been applied to explore “high-payoff” liquid wall concepts. Analysis of the stabilizing effects of liquid walls in simplified (straight) geometry has been completed. The requirements for conducting walls to stabilize toroidal configurations at high elongations have been established. New schemes for driving liquid metals that take advantage of magnetic field gradients in toroidal magnetic confinement devices (“magnetic pumping”) have been developed and experimentally verified. By focusing on reactor concepts, this work has provided significant insight into MHD effects involving thermonuclear discharges, the plasma facing walls, and the interactions between them.

Edge-plasma science

The impact of low-recycling surfaces on edge-plasma properties have been characterized. In particular, the resulting high temperature at the core/edge boundary may help explain the improved core confinement in TFTR supershots where low-recycling lithium was evaporated on the material surfaces; the higher edge temperatures are believed to yield lower turbulent core losses.

A multi-species simulation model has been extended to analyze the self-consistent shielding of the core plasma from a dense impurity plasma, following the intermixing of pre-dominantly hydrogen plasma at the core edge or a dominantly impurity plasma near a distributed impurity source. This tool has been used to evaluate the acceptability of different liquid first-wall materials with regard to core impurity contamination for various MFE device configurations.

Divertor plasma properties have been provided to analyze sputtering, redeposition, and neutral transport near divertor plate surfaces. The impurity source from such calculations has been used to evaluate impurity influx to the core from divertor sources.

Modelling and Experiments for Liquid Walls

Before the APEX effort there was a fundamental lack of modeling tools capable of analyzing the MHD flow phenomena present in free surface liquid flows as they apply to liquid walls for magnetic confinement fusion. APEX specifically created a task to fill this void. The task is a significant one, and the approach used is a combination of near-term and long-term development focused on the dominant features of liquid metal (high thermal and electrical conductivity) and molten salt (low thermal and electrical conductivity) flow.

Liquid Metals are assumed to be largely "laminarized" by the strong magnetic field. While this is not strictly true, especially for free surface flows, the near-term development of LM-MHD models has used this assumption, as well as geometric simplification of axisymmetry and Hartmann averaging along the toroidal field to reduce the complex Navier-Stokes / Maxwells Equations system to various 1.5, 2, and 2.5 D numerical models. These tools have been used to explore flow phenomena in APEX designs and provide some basis for continued quantitative development of these designs.

Results of particular scientific interest for these LM flows include:

- Quantification of strong drag forces arising from strictly toroidal and strictly surface normal magnetic fields in toroidally segmented and toroidally-axisymmetric poloidal flow, (windows for thin film poloidal flow designs have been identified for APEX).

- Identification of various instability modes that arise from the interaction of magnetic field gradients and multiple component magnetic fields for both poloidal flows and toroidal flow concepts.

- Numerical demonstration of the effectiveness of "magnetic propulsion" and other active EM control ideas where external currents are applied to the liquid wall flow.

- Quantification of surface temperature rise for wavy, laminar LM flows in a radiant plasma heat flux.

Long-term development for liquid metal modeling is attempting to assemble a more complete solution including all magnetic field, electric current and velocity components simultaneously. The increase in computer power and available resources has made this task possible. The effort is proceeding in cooperation with an SBIR to attempt to address the two main difficulties that have plagued the full MHD solution in past. Specifically, an implicit scheme is required to ease the extremely small time step restrictions of high Hartmann number MHD flow, and unstructured/adaptive gridding will be used to resolve boundary layers and geometric complexities while keeping total mesh numbers in a range solvable in a highly-paralleled computational environment. This full solution will allow us to explore a much wider range of realistic problems and phenomena for liquid walls and many other applications in and out of fusion (non-exhaustively) including:

- 2D or helical turbulence and its effect on surface heat transfer.

- complex geometry flows around penetrations, jet streams emerging from nozzles, etc.

- full coupled temporal and spatially varying fields.

For the molten salt flow turbulence is not suppressed. In fact, it is necessary for promoting interfacial heat transfer at free and solid boundaries. Neglect of this turbulence would lead to predictions of surface temperatures of liquid walls that are very high and not at all physical. The turbulence process however is a complex (but interesting) one, and inclusion of MHD only makes the problem more intractable. APEX has again adopted a near and long-term approach to analyzing this phenomena. Near term efforts have focused on the development of two-equation turbulence models (the so-called k-ε model) to include terms describing the effect of the magnetic field on turbulence production, transport and dissipation. These models work in conjunction with the base flow models developed for the liquid metal flows to include the effects of turbulence in an integral way. The most significant findings from a scientific standpoint include:

- Quantification of heat transfer degradation in the near free surface region due to free surface effects on turbulence and MHD effects on turbulence.

- Prediction of effective friction factors for poloidal flows, especially at large thickness when MHD effects again can dominate the flow drag.

The long-term approach is the development of models that can directly simulate the turbulence development and dissipation under free surface and MHD conditions. This work is proceeding in collaboration with Japanese scientists interested in global warming and other environmental applications, as well as fusion application. This work, even if unable to reach the Re number of fusion flows, will provide key data for benchmarking and tuning the two-equations turbulence models for accurate prediction of surface heat and mass transfer rates. Initial results of this work are already being used in such a manner.

In conjunction with both of these model development efforts, we also recognize the need for experimental data for verification of the numerical predictions as well as testing of prototypes for in-reactor plasma experiments. We have already planned, designed and constructed two flexible free surface flow experimental test stands for investigation of critical issues for liquid wall flow control and heat transfer identified from modeling:

- M-TOR facility for LM-MHD flows in complex geometry and complex multi-component magnetic fields.

- FLIHY facility for molten salt turbulent flow simulation and surface heat and mass transfer measurements (which will also be used as part of the JUPITER-II collaboration with Japan).

Very soon, both of these facilities will begin their first free surface flow experiments and we look forward to a multitude of data from them.

Engineering Issues and Designs for Liquid Walls

Significant progress has been made in identifying, analyzing, and resolving some of the key engineering issues associated with thin liquid wall designs. A significant increase in magnetic fusion energy reactor wall loading may be possible based on the results of studies performed by the APEX team. Previous reactor designs were limited to relatively low wall loading by the thermal stresses in the plasma facing walls. In order to accommodate higher heat fluxes, the walls would need to be too thin for a practical design. In the new configuration, a thin layer of flowing liquid metal or salt is

used to intercept the direct heat flux from the plasma, almost eliminating the thermal stress problem. The liquid also helps reduce or eliminate erosion problems as well. A primary issue with the liquid is finding an operating temperature window that maximizes the thermal efficiency but avoids excessive evaporation of the liquid into the plasma. One of the key innovations in this area was the investigation of a SnLi mixture that combines the low vapor pressure benefits of Sn with the tritium breeding benefits of lithium. This idea led to the investigation of pure Sn, which seems to offer a very high operating temperature window. When combined with a blanket of LiPb, an attractive high efficiency system with high power density can be envisioned.

High Temperature Solid Wall Concepts

APEX has made substantial progress in exploring ideas for extending the capabilities, particularly the power density and temperature limits, of "solid first wall" concepts. A promising example is the use of high temperature refractory alloys (e.g. tungsten) in the first wall together with an innovative heat transfer and transport scheme based on vaporization of lithium; the concept is called EVOLVE.

APEX has made significant progress in the understanding of the application of refractory W-alloy for the first wall and blanket design in order to achieve the very high thermal efficiency of 57%. The evaluation of EVOLVE shows that this innovative concept can minimize the burden on the relatively ductile W-alloy with a low operating Li-vapor pressure of less than 0.5 atmosphere. Even though W-alloys will produce relatively high afterheat, with the addition of passive cooling loops, the concept has a strong possibility of achieving the safety requirement of not needing a public evacuation plan under the loss of power accident conditions. Similarly, the irradiated W-alloy could have projected problems in embrittlement, yet with the relative low system pressure of the design, detail analysis showed that the first wall can withstand a large number of cracks without the detrimental impact to plasma operation in terms of fuel dilution. The planning of experiments to address the key issues of the two-phase flow issues have been initiated. The fundamental issues of W-alloy properties under high neutron fluence irradiation and the technique of components fabrication will need to be addressed in the future. Preliminary investigations of W-alloy fabrication and heat flux removal through SBIR programs have begun and the initial results are encouraging.

Pebble Bed Thermomechanics

Substantial progress has been made in advancing the engineering science knowledge base necessary to understand the thermomechanical performance and material interactions of the ceramic breeder and beryllium material systems for fusion tritium production and heat generation. This research activity, conducted through an IEA collaboration, has allowed the US to contribute and gain access to data from the larger international community. Significant progress has been made in understanding and predicting the mechanisms that control ceramic breeder/beryllium pebble bed thermomechanical interactions. Recent achievements include: completion of a 3-D discrete numerical model for pebble bed thermal and mechanical properties prediction and thermomechanics characterization, and initiation of US-JA JUIPTER-II collaboration on the SiC material system thermomechanics study. Present numerical simulations have provided a detailed stress profile at the particle and particle contact points, and thus the integrity of the particle under prototypical operating conditions. Pebble bed thermomechanics (or more generally particulate material mechanics) is a topic of importance for diverse applications including ceramic processing, soil mechanics, and powder metallurgy. Because of the complex environmental conditions (high temperature, low stress, and irradiation) fusion relevant pebble bed thermomechanics denotes a unique branch of the field. Its accuracy requirement, as an important performance measure, urges model advancement for the field.

▪ Fusion Safety and Tritium Technology Program

The safety program's most important achievements have been the development of the US DOE Fusion Safety Standard and demonstrating that a D-T burning plasma device, at power plant scale (ITER-EDA), could meet all of the safety and environmental criteria. The most important of these criteria was having no need for a public evacuation plan for any foreseeable accident event. The

R&D activities in the fusion safety program have made fundamental contributions to a number of fields of engineering science as listed below.

Materials Science and Chemistry

- Behavior of materials at high temperature oxidizing conditions (e.g., Be, W, C, 316SS, Nb, Cu chemical reactivity).
- Volatilization of materials during oxidation (W, 316 SS, FS, Nb, V, Cu, Be).
- Fundamental chemistry and materials modeling of processes (e.g., Be chemical reactivity, activation product mobilization).
- Volatilization and mobilization from fusion liquids (Flibe, SnLi).

Aerosol/Particulate Science

- Fusion dust characterization (DIII-D, C-MOD, TFTR, Tore Supra, LHD, NOVA).
- Disruption-induced aerosol generation (North Carolina State SIRENS plasma gun experiments).
- Dust mobilization and transport models (e.g., impaction in ducts, mobilization in vacuum).
- Tokamak dust formation modeling (erosion and disruption induced).

Surface Science

- Tritium implantation and mobilization in PFC's (W, Be, Cu, C/Be, C/W etc.).
- Tritium content in TFTR dust.

Fluid Mechanics, Heat Transfer and Mass Transfer

- Transient thermofluid modeling (e.g., blowdown in vacuum, jet impingement).
- Cryogenic fluid behavior.
- Integrated systems modeling for safety analysis (leveraging INEEL fission safety expertise).
- Liquid/Liquid interactions and vapor explosions (U-Wisconsin) (e.g., LiPb/water, Ga/water, Li/organic, Li/water, Li/air and cryogen/water).

Plasma Science and Magnetics

- Metal-vapor plasma behavior (NCSU SIRENS facility).
- Plasma disruption modeling (DSTAR/TSC) .
- Coupled 3-D magnetic/thermal analysis of arcing magnets.
-

3.4 Relationship to Other Elements of the U.S. Programs

The MFE Chamber Technology and Safety Programs interact with the plasma science programs, as well as with other parts of the enabling technology program. The interactions with the physics community involves several aspects, such as joint undertakings to define attractive fusion concepts, evaluation and testing of novel chamber concepts (e.g. liquid surfaces) in plasma devices and providing safety analysis and support to existing and planned plasma and next-step devices. The MFE Chamber Technology and Safety Programs have strong interactions with the IFE Chamber Technology, Materials, PFC, and system studies elements of Enabling Technology R&D. These interactions involve joint research on key common issues and development of models and codes. The safety program performs R&D and safety assessments for MFE and IFE Chamber Technology.

3.5 Role of International Collaboration

The Chamber Technology Program has established important and strong bilateral and multilateral international collaboration activities, such as:

- IEA task agreements on liquid metals, ceramic breeder systems and neutronics.

- US-Monbusho collaboration on thermofluids and pebble bed thermomechanics (part of JUPITER II), where Japanese Universities are providing resources for collaborative research activities on US facilities.

- US-Japan collaboration on High Power Density Systems.

These international collaborations are important because the EU and Japan have much larger programs than the US, particularly on R&D for evolutionary concepts. Such international collaborations enable the US to gain access to the R&D results from these larger programs on evolutionary concepts. It also provides the US with an effective mechanism to encourage Europe and Japan toward exploration of innovative concepts.

The safety program has a strong and important international collaboration under the International Energy Agency Environment, Safety and Economic (IEA-ESE) agreement. Under this agreement we perform collaborative R&D with Europe, Japan and Russia in the following six tasks:

- Task 1: Tritium Safety and Environmental Effects
- Task 2: Transient Thermofluid Modeling and Validation Tests
- Task 3: Activation Products Safety and Environmental Effects
- Task 4: Safety System Study Methodology
- Task 5: Failure-Rate Database
- Task 6: Fusion Radioactive Waste Management

Each task meets periodically to discuss progress and plans for the upcoming 12 to 18 months. This collaboration helps us leverage the important work going on internationally and thus meet our longer term goals.

3.6 Five Year Objectives and Implementation Approaches

3.6.1 Chamber Technology

The overall five-year objective for the Chamber Technology is to "demonstrate the scientific feasibility of innovative plasma chamber technologies for magnetic fusion energy; assess facility needs for this development, including opportunities for international collaboration."

Research on innovative plasma chamber technologies for MFE is focused on high performance, high power density liquid and advanced solid wall concepts with simpler technological and material requirements and constraints. A smaller part of the chamber research is devoted to thermal-mechanical interactions of non-structural materials such as ceramic pebble bed breeders and beryllium. The specific five-year objectives for liquid walls, advanced solid walls, and non-structured material systems are:

Liquid Walls

- Fundamental understanding of free surface fluid flow phenomena and plasma-liquid interactions verified by theory and experiments.
- Operate flowing liquid walls in a major experimental physics device (e.g. NSTX).
- Begin construction of an integrated Thermofluid Research Facility to simulate flowing liquid walls for both IFE and MFE.
- Understand and document advantages and implications of using liquid walls in fusion energy systems.

Solid Walls

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

Non-Structural Material System Interactions

- Understand scientific phenomena and develop models for predicting the thermal-mechanical interactions of ceramic pebble bed breeders and beryllium with structural materials.

Progress will be measured in the chamber area by assessing the compatibility of proposed schemes with plasma performance constraints and projections for achieving high power density handling, high power conversion efficiency, low failure rates, faster maintenance, and simpler technological and material constraints.

The main issues for chamber research are: 1) determining limits on the amount of material allowed to evaporate and sputter from solid and liquid surfaces based on sophisticated edge modelling coupled to experimental results, 2) establishing phenomenological and computational models for predicting the behavior and performance of free-surface fluid flows under the effects of various forces and MHD interactions in complex geometrical configurations, including penetrations and magnetic filed gradients, 3) developing heat and mass transfer models for free surface flows, including surface renewal mechanisms, turbulence structure, and MHD effects, 4) exploring various liquid formation schemes in different MFE confinement configurations, 5) identifying promising high-temperature structural materials, 6) understanding and predicting the thermal-mechanical interactions of ceramic breeders and structural materials, and 7) evaluating the performance of promising solid and liquid wall concepts.

Implementation Approaches

- Identify the most promising chamber concepts with respect to different MFE configurations. Identify the key scientific and engineering issues for these concepts.

- Advance models for predicting: impurity transport from liquid wall surfaces into the plasma, and possible improvements in plasma stability and performance in the presence of flowing liquid metals. Verify model predictions for the maximum allowable evaporation rate and effects on plasma stability and confinement through tests in magnetic confinement devices.

- Develop phenomenological and computational models for understanding and predicting free-surface fluid flow characteristics under the effect of various forces (gravitational, electromagnetic, surface tension, etc.) in complex configurations, including penetrations and magnetic filed gradients and heat and mass transfer for free-surface flows under intense surface and bulk heating including turbulence and MHD interactions.

- Perform laboratory experiments for free-surface fluid flow and heat and mass transfer for liquid metals and low-conductivity fluids.

- Identify practical heat transfer enhancement schemes necessary for minimizing liquid-wall surface temperatures and improving solid-wall concepts.

- Develop models and perform laboratory experiments to predict the effective thermal conductivity for pebble bed ceramic breeders and beryllium, as well as the interface thermal conductance, and the thermal-mechanical interactions with various structural materials.

- Evaluate requirements for proof-of-principle tests for liquid and solid wall concepts in plasma confinement devices and laboratory experiments.

- Evaluate the performance and attractiveness of advanced solid and liquid wall concepts and assess facility needs for research and development.

3.6.2 Fusion Safety and Tritium Technology

The key five-year objectives for the fusion safety and tritium program are:

- Continue safety R&D on fusion dust/debris and solid plasma facing components to understand and quantify safety margins associated with these materials relative to tritium inventory and mobilization, chemical reactivity and radiotoxicity.

- Continue safety R&D on how energy sources in fusion can mobilize radioactive materials under accident conditions focusing on chemical reactivity of materials with air and steam, magnetic arcing and plasma disruptions.

- Begin safety R&D on new and advanced fusion materials and coolants being considered in the program with the aim of quantifying experimentally the chemical and radiotoxicity, and chemical reactivity of these materials.

- Develop criteria for the recycling and reuse of fusion materials to be used in fusion conceptual design studies.

- Upgrade safety computer codes to deal with liquid surface concepts being considered for some fusion designs.

- Assess safety and environmental issues associated with high power density fusion designs, inertial fusion energy systems and other alternate confinement concepts.

- Integrate safety lessons learned form ITER into all future fusion conceptual systems studies.

- Continue international safety and environmental collaborations.

Implementation of these objectives will be accomplished by means of both experimental data and analytical tools/computer models to improve the quality of the safety assessments needed for future fusion facilities. Tasks include the following:

- Experiments to evaluate the chemical reactivity hazard of solid PFC's.

- Characterization of dust/debris from existing fusion facilities.

- Measurement of the chemical reactivity of fusion dust/debris.

- Measurement of the dust/debris mobilization in a fusion chamber.

- Measurement of the mobilization of Flibe and SnLi resulting from the interaction with air and steam.

- Measurement of the tritium inventory and mobilization in solid PFC's for next step devices.

- Development of dust/debris formation model for both MFE and IFE.
- Improvement in safety computer codes to model advanced power plant systems being considered for both MFE and IFE.
- Validation of computer models using international benchmarking and thermofluid simulation experiments.

4.0 MATERIALS SCIENCE

4.1 Mission, Scope and Long-Term Objectives

Advance the materials science base for the development of innovative materials and fabrication methods that will establish the technological viability of fusion energy and enable improved performance, enhanced safety, and reduced overall fusion system costs so as to permit fusion to reach its full potential; assess facilities needs for this development, including opportunities for international collaboration; support materials research needs for existing and near-term devices.

One of the primary challenges to the establishment of fusion as a viable energy source is the development of materials for the in-vessel systems that will provide acceptably high performance and reliability and exhibit favorable safety and environmental features. The Materials Sciences research program is focussed on structural materials because the characteristics and properties of the structural material largely determine the economics, safety, and environmental attractiveness, and thus the feasibility of fusion energy. Structural materials must operate at elevated temperatures for extended lifetimes under severe conditions characteristic of a fusion power system, including high fluxes of high energy (14 MeV) neutrons, x-ray, ionic debris, high surface heat fluxes, and high temperature coolants and breeding materials. Based on design studies and systems analyses, three candidate structural materials systems have been identified which offer a potential for high performance with favorable safety, radioactive waste disposal ratings, and a possibility for recycle. These materials systems, which are the focus of the current materials research program, are (1) Fe-Cr-WV ferritic steels, (2) V-Cr-Ti alloys, and (3) SiC/SiC composites. Copper alloys are also considered for special heat sink applications, and work on ceramic insulators and other functional materials that are vital for establishing the technological feasibility of fusion energy is being conducted. In order to test the robustness and accuracy of theory and models developed by fusion materials scientists, experiments and analysis on a broad range of materials are needed (ranging from pure metals to complex multi-phase materials).

The current mission of the Materials Science program is to develop fundamental understanding of the scientific underpinnings of materials for fusion. The Materials Sciences program will utilize and expand on revolutionary advances in computational and experimental methods(e.g., nanoscience) for fusion materials design. In addition to the long-term mission focussed on materials for enabling the development of a technologically viable and economic-, safety- and environmentally-attractive fusion energy source, the Materials Science program also has a secondary mission to support the materials research and development needs for near-term plasma and IFE experiments. The current long-term objective of the Materials Science program is to produce a suite of experimentally-validated models and materials synthesis techniques that can be used to establish the viability of using materials in the demanding fusion environment. It is anticipated that these materials will have to be specifically designed for their particular application; materials developed for non-fusion applications will not be suitable.

4.2 Strategic Pathway

The principal product of the Materials Science program is establishment of the fundamental knowledge, theory and models needed to resolve materials-related feasibility issues for fusion energy. The national research program is planned by integrated teams of materials scientists that are organized into task groups. The major national Materials Science task groups include structural alloys (encompassing FCC and BCC alloy systems such as vanadium alloys, ferritic/martensitic and oxide dispersion strengthened steels), ceramic composites, and a cross-cutting theory & experiment coordination task group (to ensure that experiments are designed to guide and validate theory and modeling). The R&D approach places a large emphasis on addressing crosscutting issues (broad applicability of the research to a wide range of materials systems). The Materials Science program will continue to utilize research roadmaps (which have been indispensable in numerous other

materials science efforts, e.g., semiconductors) to guide the research program. Progress will be measured in part by assessments of the performance limits of the various materials systems relative to projected operating conditions of high energy neutron fluxes, high surface heat fluxes, chemical compatibility in the fusion environment, and potential operating lifetime.

Significant progress has been made on the characterization and understanding of the properties and performance limits associated with materials processing, fabrication and joining, physical and mechanical properties, chemical compatibility, and effects of irradiation on properties of the key fusion materials systems. These advances are being accomplished through a science-based program of theory, experiment and modeling that (1) provides an understanding of the behavior of candidate material systems in the fusion environment and identifies limiting properties and approaches to improve performance, (2) undertakes the development of alloys and ceramics with acceptable properties for service in the fusion environment through the control of composition and microstructure, and (3) provides the materials technology required for production, fabrication, and power system design. In the past year, there has been a concerted effort to enhance the emphasis on theory and modeling, and to further promote research activities on cross-cutting materials phenomena that broadly impact a wide range of materials systems, i.e., deformation and fracture mechanisms, microstructural stability, corrosion and compatibility phenomena, fabrication and joining science, and other physical and mechanical properties.

Implementation of a modest effort in support of near term materials issues for plasma and IFE studies is expected to be launched in FY02. Requests for expressions of interest in utilizing the expertise of the Materials Science program will be distributed to institutions involved in fusion research. After prioritization, work will be initiated on the highest priority tasks.

4.3 Recent Achievements and Contributions to Science

The Materials Science program continues to have a strong record of technical achievements that are directly relevant for fusion, many of which are also of significant interest to the broader materials science community. The prominent stature of the scientists involved in the Fusion Materials Science program is reflected in their strong involvement as organizers and invited speakers at national and international materials science meetings (both fusion and non-fusion). Examples of some recent (within the past two years) achievements and contributions to the broader field of materials science are summarized below.

Microstructural Stability

Continued molecular dynamics (MD) investigations of the production and evolution of defects in atomic collision cascades has provided several new insights. For the metals of interest for fusion applications, it is now firmly established that the subcascades produced in 14 MeV fusion neutron collision events are very similar to the cascades/subcascades produced in fission neutron events. Several intriguing phenomena have been uncovered in the MD studies. For example, there is now extensive evidence that small clusters of interstitial atoms in both FCC and BCC pure metals migrate one-dimensionally rather than via three-dimensional random walk. This can have a profound impact on the theoretical analysis of defect accumulation in irradiated metals. Kinetic Monte Carlo and rate theory analyses are being used to track the microstructural evolution induced by irradiation, using defect migration and binding energies obtained from MD simulations or experimental studies.

Experimental evidence for localized melting in displacement cascades (validation of the thermal spike model) has been obtained in a recent study of hafnon, zircon and thorite ceramics. Examination of the flux and temperature dependence of amorphization in SiC has provided fundamental information on the migration energy of interstitial atoms in SiC, E_{im}~0.85 eV, as well as information on the density change and property changes (elastic modulus, hardness, etc.) associated with the crystal to amorphous transition. Analysis of the loop denuded zones adjacent to defect sinks in ion irradiated Al_2O_3 and $MgAl_2O_4$ has provided similar pioneering experimental estimates of interstitial migration energies in ceramic insulators.

Deformation and Fracture Mechanisms

Impressive advances in the understanding of the detailed interaction between dislocations and defect clusters are being obtained from molecular dynamics and 3-D dislocation dynamics modeling efforts. The physical mechanisms responsible for flow localization in metals irradiated at low temperatures (dislocation channeling, twinning, etc.) are being investigated by a combination of experimental and theoretical studies. The understanding obtained from these studies may lead to the development of materials which are resistant to these radiation-induced flow localization processes, and the information being obtained has broad applicability to the important materials science subfield of deformation of materials.

A comprehensive investigation of mechanical deformation mechanisms in unirradiated and irradiated vanadium alloys is in progress. Experimental deformation studies performed at temperatures from 80 to 1123 K and over 8 decades of strain rate are nearly complete, and the data are being analyzed to obtain the constitutive equations for deformation. These results will help to establish the operating limits (stress, temperature) for V alloys, and will also provide significant insights into the dominant creep mechanisms in refractory metals. Similar experimental thermal creep studies on nanocomposited (oxide dispersion strengthened) ferritic steels are also nearing completion, and the data will be analyzed to determine the dominant creep mechanisms.

Development of a sound understanding of the effects of intrinsic (e.g., matrix strength) and extrinsic (e.g., notch acuity, strain rate and specimen constraint) factors on the ductile to brittle transition temperature in BCC alloys is of high importance for fusion as well as numerous other structural applications. The fusion materials science program has made major contributions to the advancement of the knowledge of fracture mechanics in structural alloys. Significant progress has been made toward establishing a fracture mechanics master curve for unirradiated V alloys and ferritic steels, which incorporates the key intrinsic and extrinsic parameters.

Work is continuing on investigation of the thermal creep mechanisms in SiC/SiC composites and fiber-bridging by propagating cracks. A science-based program has led to the development of SiC/SiC composites with improved resistance to radiation-induced mechanical property degradation. These improved ceramic composites utilize the latest generation of SiC-based fibers (which have a better elastic modulus match to the SiC matrix and therefore can more effectively partition stresses during loading) and tailored interphase regions between the fibers and matrix (in particular, SiC multilayer interphases). The improved fibers and interphase respond to irradiation in a manner similar to the SiC matrix (all having relatively good structural and mechanical stability in response to irradiation at temperatures 150-1000˚C) , and therefore minimize the mechanical property degradation in the irradiated composite.

Other Physical and Mechanical Properties

Investigation of the thermal conductivity of unirradiated and irradiated SiC composites and other ceramics (from the DOE/Monbusho HFIR TRIST-TC1 and other experiments) is producing a wealth of information. In addition to providing important guidance to designers on the lower operating temperature limit of ~600˚C for SiC/SiC composites in first wall structures (due to radiation-induced reductions in the thermal conductivity), analysis of the thermal conductivity data in irradiated SiC/SiC and other ceramics is producing significant advances in the understanding of phonon transport and scattering in materials. For example, the fluence-dependent phonon scattering from radiation-induced defects is being correlated with the density and size of defects. These correlations will allow a critical analysis of the quantitative accuracy of existing phonon scattering (thermal conductivity degradation) models to be performed.

Corrosion and Compatibility Phenomena

Recent corrosion and compatibility studies within the fusion materials sciences program have been focussed on three areas: V alloy oxidation kinetics, MHD insulator compatibility with Li, and mechanical behavior of SiC/SiC composites in oxidizing environments. A multi-institutional experimental program on oxygen pickup by vanadium alloys has determined that the rate of oxygen pickup exhibits parabolic kinetics at temperatures up to at least 500˚C. A higher rate of oxygen pickup (approaching linear rates) is observed at higher temperatures for low oxygen partial pressures. It appears that oxygen partial pressures of less than 10-10 torr may be required to prevent oxygen embrittlement of V alloys during long-term operation at temperatures above 600˚C. Scoping compatibility experiments for CaO and AlN insulators have determined their upper use temperatures (due to the onset of rapid corrosion) in pure Li. Work is underway to determine the feasibility of increasing these upper use temperatures by doping the Li with suitable concentrations of Ca, O, Al or N solute.

Fabrication and Joining Sciences

A fundamental study of the composition of small clusters present in nanocomposited (oxide dispersion strengthened) ferritic steel has determined that the initially pure Y2O3 particles can incorporate significant amounts of Ti during ball milling. These nanoscale clusters have high thermal stability, and produce outstanding thermal creep resistance in the steel (6 orders of magnitude improvement over existing ferritic/martensitic steels).

Several different techniques have been evaluated for the initial deposition and subsequent in-situ redeposition of CaO or AlN films (candidate MHD insulators) on V alloys. Encouraging results have been obtained for the initial deposition of the MHD insulator films, but further work is needed to establish the viability of self-healing (in-situ redeposition of the coating from a Li-rich liquid).

A concerted multi-institutional effort has resulted in the successful development of techniques to produce a high-quality, high-ductility joint in V alloys by either gas tungsten arc (GTA), electron beam, or laser welding. Successful welding requires careful control of the surrounding atmosphere, particularly for the case of GTA welds. Further work is needed to identify the best technique for field welding of V alloys. In a recently initiated parallel project, it has been determined that high tensile ductility can be achieved in GTA welded Mo alloys by controlled (ppm level) additions of certain solutes to the base metal. These solutes inhibit the migration of oxygen impurity atoms to the grain boundaries, which is a major cause of embrittlement in the Group VI refractory alloys.

4.4 Relationship to Other Elements in the U.S. Program

The Advanced Materials program relies on input from the Fusion Technologies (Safety and Chamber Technologies) and Advanced Design communities for assessing the attractiveness of various candidate blanket systems.

4.5 Role of International Collaboration

International collaborations have been the hallmark of the Materials Science Program AMP for two decades. Formal bilateral collaborations that involve joint planning, funding, testing and data analysis, and reporting of materials research and development have been in existence with JAERI and Monbusho in Japan (now known as MEXT) for over 15 years, and have yielded numerous advances in the fusion materials sciences knowledge base. An important bilateral collaboration exists with the Russian Federation that provides access to the RF fast reactor BOR-60 and other facilities for radiation effects research. The international fusion materials research and development effort is coordinated through the IEA Implementing Agreement on a Programme of Research and Development on Fusion Materials. Japan, the European Union, Switzerland, the Peoples Republic of China, the Russian Federation, and the United States are active participants. Fusion materials research activities coordinated through the IEA include SiC composites, vanadium alloys, advanced

ferritic steels, beryllium technology, ceramic insulators, conceptual design of IFMIF, test specimen miniaturization technology, and irradiation damage theory and modeling.

For the next five years, the DOE-JAERI fusion materials collaboration will provide important experimental data on the flow and fracture behavior of irradiated model alloys (including intermetallic and refractory alloys), ferritic/martensitic and oxide dispersion-strengthened steels. Definitive irradiation experiments on the effect of helium on low-temperature embrittlement will be performed. The DOE-MEXT JUPITER-II collaboration will allow a significant enhancement of US research on MHD insulators for Li-cooled systems, mechanical deformation and fracture behavior of irradiated BCC alloys and weld joints (with emphasis on V alloys), and investigation of a wide range of feasibility issues for SiC/SiC composites (gas-cooled solid breeder blanket concepts).

4.6 Five-year Objectives and Implementation Approaches

The overall five-year objective is to perform targeted research in several key materials science areas which will help establish the feasibility of developing fusion energy as a commercial energy source. The research program will make extensive use of international collaborations and will leverage research being performed by other funding agencies in order to achieve the maximum cost-effectiveness. State-of-the-art materials science theory and modeling analyses (coupled with appropriate focussed experiments on model systems) will be applied to key cross-cutting feasibility issues such as radiation-induced mechanical property degradation, interactions between dislocations and defect clusters, development of coatings, etc. The overall research program will be guided by task groups on structural alloys (in charge of R&D for vanadium alloys, ferritic/martensitic and oxide dispersion strengthened steels, refractory alloys, etc.) and ceramic composites, and a cross-cutting theory & experiment coordination task group. The current version of the Materials Sciences roadmap will be reviewed and revised where appropriate by the task groups in order to provide an optimized prioritization of the research program, with well-defined milestones and decision points.

4.6.1. Structural Materials.

The majority of the effort within the Materials Sciences program will continue to be placed on the three material systems judged to have the highest potential of being developed as attractive fusion power system structural materials: Vanadium-based alloys, advanced ferritic steels (including oxide dispersion strengthened steels) and SiC composites. However, an increased emphasis will be given to the investigation (experimental and modeling studies) of other model alloy systems which can contribute to the knowledge base in the materials science subject areas of interest (microstructural stability, deformation and fracture behavior, other physical and mechanical properties, corrosion and compatibility phenomena, and fabrication and joining sciences). Research will also continue to be performed on copper alloys and high-temperature refractory alloys.

Due to the different degrees of technologically maturity in the three main classes of reduced-activation structural materials, the prioritized lists of feasibility issues are not identical. However, there are several common feasibility issues (particularly for the V alloys and ferritic steels) which are ideal candidates for a cross-cutting research program. In the following, the focus of research objectives for the next five years are summarized for each of the three main classes of structural materials. Research topics which are common or complementary are highlighted in the following paragraph.

Cross-cutting research activities which are of high importance for most structural metals include 1) determination of the constitutive equations for deformation over a wide range of temperatures and strain rates, 2) development of a fracture mechanics master curve (including investigations of the effect of irradiation on the shape of the master curve), 3) and investigation of defect cluster-dislocation interactions (responsible for the observed loss of tensile ductility in metals irradiated at low temperatures)

The Advanced Ferritic Steels utilize the well-developed ferritic steel technology for nuclear, fossil,

and other applications; the fusion Materials Science program has developed low activation versions of these commercially deployed materials with equivalent or superior properties. These materials are resistant to radiation-induced swelling and helium embrittlement and are compatible with a range of aqueous, gaseous, and liquid metal coolants. Four key feasibility issues have been identified: 1) Verify ferromagnetic structures are acceptable for MFE; 2) Expand lower temperature operating limit; 3) Expand high-temperature and dose limits; and 4) Resolve system-specific compatibility issues (e.g., T permeation barriers). The fusion Materials Sciences is monitoring developments in Europe and Japan on issues 1 and 4 via the IEA workshops. Current research is focused on issues 2 and 3: (a) collaborative irradiation experiments with Europe and Japan (DOE/Monbusho Jupiter-I and DOE/JAERI collaborations) and associated modeling to understand the micromechanics of fracture processes (low temperature embrittlement, including He effects), (b) development of methodologies to account for the effects of radiation-induced changes in properties on component integrity, and (c) approaches to improve creep performance and thus improve high temperature capability. Research has recently been expanded on dispersion strengthened (DS) ferritic steels, which are attractive candidates for high-temperature operation. Planned near-term R&D on DS ferritics includes measurement of thermal creep, identify suitable joining techniques, and measure fracture toughness before and after low-dose irradiation.

Because of their favorable combination of physical properties, compatibility with pure lithium, and relatively high creep strength, Vanadium Alloys based on the V-Cr-Ti system are an attractive option for high-temperature liquid lithium-cooled blanket systems. The four key feasibility issues identified in the fusion Materials Sciences roadmap are 1) development of self-healing MHD insulator coatings for Li-cooled systems (discussed in the functional materials section 4.6.2), 2) development of welding methods, 3) establish design window (including effects of neutron damage, high helium concentrations and chemical compatibility), and 4) determine effects of impurities on mechanical behavior and radiation response (including pickup from the operating environment). Successful full-penetration welds (DBTT below -50˚C) have recently been achieved, and further improvements are being investigated along with alternative joining techniques for field repairs such as friction stir welding (issue 2). Progress on issues 3 and 4 is being achieved by effective leveraging of the DOE/MEXT JUPITER-II collaboration. Work is in progress to understand the micromechanics of fracture in the brittle-ductile transition regime and to develop methodologies to account for these radiation-induced property changes in assessing component performance. Thermal creep studies in representative environments (issue 3) are in progress to establish the upper operating temperature limits for V-Cr-Ti alloys.

The development of SiC/SiC Composite Materials presents the most difficult challenges of the three material systems. However, there are potentially high payoffs in terms of very low radioactivity and after heat and high operating temperatures. The primary feasibility issues involved in the development of SiC/SiC composite materials are: 1) determine the fundamental mechanisms which control properties such as high-temperature fracture strength, creep and thermal conductivity, 2) develop fusion-relevant joining technologies, 3) improve composite hermeticity and quantify permeability of gases, 4) identify major compatibility issues with coolants and breeders and thereby develop compatibility temperature limits, 5) understand the effects of neutron irradiation (with and without H, He gaseous transmutation products) on the behavior of SiC fiber/interphase/SiC matrix structures, and develop improved radiation-resistant composites, 6) quantify and overcome the adverse impact of low thermal conductivity of current generation SiC/SiC (unirradiated and irradiated), 7) develop structural design methodology for ceramic matrix composites, and 8) demonstrate techniques for production of large components. Due to their long-term nature, and engineering (as opposed to science) emphasis, the fusion Materials Sciences program is not currently addressing issues 7 and 8. A small effort is being devoted to issue 3. The current program is aggressively addressing issues 2, 5 and 6 in concert with researchers in Europe (informal collaborations) and Japan (DOE/MEXT Jupiter-II and DOE/JAERI collaborations). The fusion Materials Sciences program research on issues 1, 2 and 5 is utilizing heavy leveraging of other DOE and other R&D programs in order to minimize costs. A modest effort on issue 4 (SiC/Pb-Li compatibility) is being initiated in FY01. Based upon our current knowledge and understanding of

radiation effects, advanced composite materials with improved properties are being fabricated and evaluated in conjunction with private industry partners through the SBIR program (issues 1, 5, 6).

4.6.2 Functional Materials

One of the major functional materials research activities for the coming years will be to determine the feasibility of developing a self-healing, insulator coating to mitigate magneto-hydrodynamic (MHD) effects in lithium-cooled systems. The research is currently focussed on the formation, properties, and long-term stability (including chemical compatibility) of CaO and AlN insulator coatings in the Valloy/Li system.

4.6.3 Materials Science Support for Plasma and IFE Studies

It is anticipated that this program subelement will be initiated in FY02. The specific materials topics to be investigated will be determined from the expressions of interest received from the plasma and IFE communitiesy.

4.7 Key Decision Points

FY01 (summer): Evaluation of the feasibility and cost-benefit analysis of performing a new dynamic helium charging experiment on vanadium alloys (in order to investigate the effect of fusion-relevant He/dpa levels on the microstructural evolution and properties of BCC alloys)

FY02: DOE/MEXT Jupiter-II program evaluation of the viability of CaO and AlN as MHD insulators (favorable evaluation would lead to initiation of tests in a flowing loop system; negative evaluation would suspend R&D on these materials and switch resources to other candidate MHD insulators)

FY03-FY04: Evaluation of the effects of helium on the low-temperature embrittlement of BCC alloys (with emphasis on ferritic/martensitic steels, as part of the DOE/JAERI program). Analysis and modeling of an experiment currently in the planning stages should provide definitive information on this controversial subject.

FY04: Comprehensive evaluation of the general applicability of the Master Curve model for predicting and quantifying embrittlement in BCC alloys (similarities and differences between different alloy systems; effect of irradiation on the shape of the Master Curve, etc.).

5.0 ADVANCED DESIGN

5.1 Mission, Scope and Long-Term Objectives

Fusion Energy Sciences is a very complex area involving intricate combinations of physics, technology, and engineering. There are also many subtle variations of the main plasma confinement configuration. Integration of advanced technologies and materials, experimental techniques, and sophisticated engineering are required to realize effective experiments. Extensive systems studies are needed to identify not just the most effective experiments for the moment, but also the most cost-effective routes to the evolution of the experimental, scientific and technological program. These studies of future devices are performed under the advanced design activities and they encompass 1) studies of reference fusion power plants, and 2) studies of next-step options (NSO). In addition, Advance Design includes a modestly funded activity of Socio-Economic studies of the long term role of fusion.

5.1.1. Studies of Reference Fusion Power Plants

The realization of fusion energy is a beacon that lights the way for advancing the Fusion Energy Sciences Program. It is the most demanding of the program goals, and it provides the toughest standard to judge the usefulness of program elements. Advanced design studies of reference fusion power plants have been and remain an essential tool in guiding the program, illuminating the development paths in the roadmap. Increased performance is not simply an aspect of power plant development. It is also a measure of general scientific capability – wider range of dimensionless and dimensional physics parameters, more demanding technology, greater control and flexibility – that has importance to the broader program.

Advanced design studies of reference power plants are needed when fusion concepts reach the "proof-of-principle" stage in order to help define next-step options, to focus R&D toward high-leverage areas, to analyze and understand the interaction and trade-offs among various components, and to assist the process of concept innovation using an integrated systems approach. These studies are mainly carried out through national teams that utilize the core expertise of the relevant parts of the fusion program. Smaller studies of novel concepts are also performed to assess new ideas and concepts. In addition to integrated design studies and assessments, this activity helps to explore and articulate the role of fusion energy in the broader context of the evolving energy marketplace and global climate concerns.

5.1.2. Studies of Next-Stop Options

There are a number of unresolved physics issues that can only be fully addressed in next-step burning plasma experiments. They include burn control, fast-particle driven instabilities, transport barrier dynamics at large scale with dominant self-heating, particle fueling and ash control, power handling, and plasma physics at fusion parameters (β, υ^*, ρ^*).

The physics basis of the tokamak concept is largely sufficient to proceed with a next-step experiment to evaluate burning plasma physics. The physics basis of the conventional tokamak is sufficient to form the basis of a conservative design, whereas the physics basis for more advanced modes (with profile control, transport barriers, and feedback stabilization of MHD modes) is not yet ready to form the basis for a design, but is sufficient to identify the flexibility needed to accommodate more advanced scenarios and to predict enhanced performance possibilities.

Several design options are being pursued, both domestically and internationally. One of the long-range goals of fusion energy sciences program is to participate in an international collaboration to construct a high-gain burning plasma experiment. As such, continued conceptual design work and trade-off studies for next step devices are carried out to best understand key issues that need to be

addressed, and to be ready to move forward with participation in a next step burning plasma experiment.

5.2 Strategic Pathway

5.2.1. Studies of Reference Fusion Power Plants

Advanced design studies of reference power plants are needed when fusion concepts reach the "proof-of-principle" stage in order to help define next-step options, to focus R&D toward high-leverage areas, to analyze and understand the interaction and trade-offs among various components, and to assist the process of concept innovation using an integrated systems approach. This objective is accomplished by detailed analysis of fusion devices; incorporating the latest understanding from plasma physics and fusion technology research as well as the latest accomplishments in other fields outside Fusion Energy Sciences program. An integrated analysis highlights interaction and trade-offs among different areas (*e.g.*, MHD stability, current-drive, edge-plasma physics and power and particle control and handling) and defines R&D needs to guide present and future experimental and theoretical studies.

These studies are carried out through national teams that utilize the core expertise of the relevant parts of the fusion program. For each study, a small core group of scientists (to allow for continuity of work) is augmented by part-time experts from the national program to make up the research team. This approach leads to a scientifically credible research of the highest quality. The use of team members who are only involved in the national teams on a part-time basis, and spend the remainder of their time in other fusion or technical activities, is a highly effective way to leverage against expertise developed as part of other activities in the fusion program. This structure of largely part-time participants also broadens the communication base of the ARIES program with the fusion community. It ensures that the latest understanding from plasma physics and fusion technology research are incorporated and the research results are effectively and readily distributed to the national program.

Strategic planning and forecasting studies help develop criteria describing what fusion must do to be successful in the market place. Socioeconomic studies of fusion's role in a sustainable global energy strategy address the potential of fusion to resolve global energy issues such as greenhouse gases and sustainable economic development. Studies of fusion non-electric applications (or co-generation) help develop new clients, new products, and new research directions for fusion.

5.2.2. Next-Step Options

Research in burning plasma physics is fundamental to the development of fusion energy. These high-performance plasmas provide a research tool for extending our understanding of fusion plasmas. There is a large degree of scientific excitement for burning plasma experiments as they allow for investigating and integrating frontier physics in many areas, including energetic particles, transport, stability and plasma control, in a dominantly self-heating regime. Since only the tokamak concept has the technical basis today to move forward with a high gain burning plasma experiment, most of the research in near term is focused on tokamaks.

One of the long-range goals of fusion energy sciences program is to participate in an international collaboration to construct a high-gain burning plasma experiment. Conceptual design work and trade-off studies for next step devices are necessary to understand the trade-offs and address key unresolved issue for next-step devices. This research ensures that the US fusion program is ready to move forward with participation in a next step burning plasma experiment. A team with broad community participation performs the next-step research.

5.3 Recent Achievements and Contributions to Science

5.3.1. Studies of Reference Fusion Power Plants

The U.S. is pre-eminent in the world in such integrating studies, and they have contributed substantially to the continued vitality and viability of the program. Original physics contributions include identification of specific physics paradigms for approaches to a fusion power system (*e.g.* ARIES-I, a high field, first-stability regime tokamak; ARIES II/IV, a second-stability regime tokamak; ARIES-RS, a reversed shear tokamak). The self-consistent integration of a detailed physics model of the plasma configuration with the technical embodiment of the power plant design makes the ARIES power plant studies extremely valuable in assessing the potential for specific approaches to fusion power systems. In addition, the ARIES power plant studies have identified and provided a quantitative analysis of 'high-leverage' issues in plant design including the trade-off between high beta and high bootstrap fraction, extreme shaping and engineering constraints, as well as technical limitations in pulsed designs, and relative costs of non-inductive current drive.

From the technology perspective this includes: pioneering work in the use of silicon carbide composites as major structural elements in the power plant; adaptation of innovative manufacturing techniques to greatly reduce the cost of major systems; development of innovative assembly/disassembly techniques; high-temperature thermodynamic cycles; advanced manufacturing; self cooled lithium-lead blankets; and low activation designs.

A set of socio-economic studies have focused on a long term vision of the deployment of fusion energy. These studies have illustrated the beneficial aspects of implementing fusion. In addition, the studies have quantified the resource needs and waste production to demonstrate that these are manageable issues.

5.3.2. Studies of Next-Stop Options

A design study of a Next Step Option based on a compact high field tokamak (FIRE) is underway in the U.S. The overall goal is to provide a steppingstone between the capabilities of existing fusion experiments and an attractive Engineering Test Reactor. The physics objective is to explore and understand the strong non-linear coupling among confinement, MHD stability, edge physics and wave-particle interactions that is fundamental to fusion-dominated plasma behavior. This will require plasmas dominated by alpha heating ($Q \geq 5$) that are sustained for a duration comparable to characteristic plasma time scales ($\geq 10\ \tau_E$, $\sim \tau_{skin}$). The programmatic plan is to access the alpha-dominated regimes with confidence using the present tokamak data base while maintaining the flexibility for accessing and exploring advanced tokamak modes (e.g., ARIES-RS -like modes) at lower fusion power for longer duration in later stages of the experimental program.

Recent analyses has focused on the evaluation of a compact, high-field, highly-shaped tokamak with the parameters: $R_o = 2.14$m, $a = 0.595$m, $\kappa_{95} \approx 1.8$, $\delta_{95} \approx 0.4$, $q_{95} > 3$, double-null-divertor, $B_t(R_o) = 10$T, and $I_p = 7.7$ MA with flat top time ~ 20s ($25\ \tau_E$ and $\geq 1\ \tau_{skin}$). These requirements can be satisfied with BeCu/OFHC toroidal field coils and OFHC poloidal coils that are pre-cooled to 77K prior to the pulse. The initial studies indicate a cost of about $300M for the tokamak with a total construction cost of $1.2B at a "green field" site.

5.4 Relationship to Other Elements of the U.S. Program

Advanced design studies help shape the direction of the fusion energy sciences program by examining the technical, safety, and economic potential of specific concepts. These activities provide an insight to behavior of fusion plasmas and fusion devices with conditions that are not yet available in any experimental devices. These simulations and analyses studies are the most cost-effective method to identify key critical issues that will be encountered in future devices and help

define and shape present R&D to prepare for these future challenges. As such, these activities of these activities provide critical guidance to the activities being pursued for all other program Goals. The Integrated Program Plan document identifies the advanced design activities to have a primary relationship to four of six program goals and have a secondary relationship to the remaining two program goals.

Mote than half of the research on advanced design studies of reference fusion power plants are performed in the universities. This program also provides valuable training for many fusion energy science researchers.

5.5 Role of International Collaboration

5.5.1. Studies of Reference Fusion Power Plants

Other nations also vigorously pursue advanced design studies of reference fusion power plants. The US effort in this area, while much smaller, is unique in the world in assembling a national team of experts who work on the full scientific and technical integration of a power plant vision. The structure of US effort has attracted a large number of international participants and collaborators in this area. US study teams usually include one or more international participants who are on a long-term assignment to US. This use of international collaboration has been a valuable link to other power plant studies groups in Europe and Japan.

5.5.2. Studies of Next Step Options

There is an active international program to develop Next Step Options for magnetic fusion. The International Thermonuclear Experimental Reactor (ITER), currently a collaboration among Japan, Europe and the Russian Federation, is the largest effort. The goal of ITER is to demonstrate the scientific and technological feasibility of fusion for peaceful purposes. The ITER activity has developed an optimized design, ITER-FEAT, that is presently being considered for construction. A medium-scale long-pulse advanced tokamak, KSTAR, is under construction in South Korea, and is expected to operate in about 2004. Other international design efforts underway include IGNITOR and JT-60 SC. IGNITOR is a small low cost burning plasma experiment with a limited mission funded by Italy. JT-60 SC is a design effort in Japan for a superconducting long pulse tokamak on the scale of JT-60.

5.6 Five-year Objectives and Implementation Approaches

5-year objective: The research thrust areas are optimization of the tokamak concept, the evaluation of alternative approaches, including magnetic and inertial fusion concepts, the evaluation of socioeconomic factors on fusion development and the identification of attractive next-step facilities.

Implementation Approach

- Carryout engineering design work and system optimization studies for next-step burning plasma device. Identify and understand key issues that need to be addressed, resolve technical issues and be ready to move forward with participation in a next step burning plasma experiment.

- Study inertial fusion energy concepts with particular emphasis on chambers and chamber interfaces with target and driver systems.

- Study advanced magnetic fusion energy concepts (proof-of-principle and beyond), such as compact stellarator and reversed-field pinch, to evaluate and improve the attractiveness of these concepts for energy applications.

- Perform socioeconomic studies in order to better understand the possible roles of fusion in the global energy marketplace and to better represent fusion energy in long-range energy policy and planning.

5.7 Key Decisions Points

Progress in studies of reference fusion power plants is measured by the creation of state-of-the-art integrated design concepts for both MFE and IFE, by the definition of significant new R&D directions, by the degree of innovation and evolution of fusion concepts toward attractive and practical end-products, and by the incorporation of fusion energy in the long-range energy policy and planning.

Progress in Studies of Next-Stop Option is measured by understanding the trade-offs and the resolution of key technical issues and by the degree of readiness to move forward with participation in a next step burning plasma experiment.

6.0 IFE CHAMBER AND TARGET TECHNOLOGIES

6.1 Mission, Scope and Long-Term Objectives

The mission of the IFE Chamber and Target Technologies (C&TT) element of the VLT is to:

> *Address and resolve the critical issues for high-rep-rate chamber concepts, target fabrication and injection for heavy ion and laser drivers through assessment studies, experiments and numerical simulations.*

The scope of the C&TT R&D includes the following:

- R&D planning – collaborating with accelerator and laser scientists and target physicists to define development paths and facilities.
- Chamber design – focusing on requirements for high rep-rate operation and protection of chamber structures.
- Driver/chamber interface – developing approaches for protection of final focus magnets and laser optics.
- Safety and environmental – conducting assessments and making design improvements to create attractive power plants.
- System integration – fitting all the pieces together, assuring that chamber and target technologies are compatible with target designs and drivers and making sure that the final product is attractive.
- Target fabrication and injection – developing accurate, low-cost, high-pulse-rate systems. Target fabrication and injection R&D is funded by the Research Division of OFES and is included here for completeness.

Long-Term Objective

The long-term objective for this area is given in FESAC Goal-2 for IFE:

> *Develop the science and technology of attractive rep-rated IFE power systems.*

To meet this objective, IFE C&TT R&D will need to benefit from research in key areas such as materials science, fluid mechanics and dynamics, radiation science, chemistry and computational science.

As currently envisioned, the development path for IFE will proceed through a series of facilities including one or more Integrated Research Experiments (IRE), the Engineering Test Facility (ETF) and a Demonstration Power Plant (DEMO). The near-term R&D program for IFE, only a part of which is described here, focuses on resolving key issues in preparation for the decision to proceed with an IRE.

6.2 Strategic Pathway

The strategic pathway for IFE C&TT is an R&D program that focuses on critical issues for chambers and targets for IFE power plants. Previous IFE power plant conceptual design studies identified many different driver/chamber/target options and the critical technical issues associated with them. At this time, R&D in the U.S. is primarily focused on two promising options. One is the renewable thick-liquid-wall chamber (e.g., HYLIFE-II with indirect-drive targets and a heavy ion driver; and the other is the gas-protected, dry-wall chamber (e.g., Sombrero with direct-drive targets and a laser driver (KrF or diode-pumped, solid-sate laser (DPSSL)). The top-level critical issues for these two

approaches and supporting technologies are summarized below. Work on other chamber concepts (e.g., wetted-walls and fiber-coated first walls) is also beginning as part of the ARIES-IFE study.

Thick-Liquid-Wall Chambers

Design of thick-liquid-wall chambers with vented jets and beam port protection requires knowing how smooth and how far free liquid jet surfaces (fixed and oscillating) can be maintained at power-plant relevant geometries and dimensionless Reynolds and Weber numbers. Also required are the vapor condensation rates, droplet clearing rates, and flow recovery rates that would limit the pulse rate of thick-liquid wall chambers. The outcome of these issues will determine if thick liquid wall chambers are feasible and which driver and target combinations can use them. The success of thick-liquid-wall chambers will require significant advances in fluid dynamics (theoretical, experimental and computational) and chemistry and corrosion control of high-velocity liquids.

Dry-Wall Chambers

Understanding the useful lifetime for dry-wall chambers is key to the application of the direct-drive approach to IFE. Validating means for protecting the first wall from x-ray and debris damage (e.g. by using a buffer gas) is also required. First wall protection depends on the target output spectrum and must be compatible with target survival. The reduction of thermal conductivity, swelling rates, and retention of tritium in low activation composite materials as a function of neutron fluence, composite morphology, and operating temperature, are uncertain and need to be better determined. The success of dry-wall chambers will require significant advances in the materials sciences. Materials developed for dry-wall IFE chambers are likely to find wide application in other fields such as space and defense sciences.

Driver / Chamber Interface

For accelerators it is necessary to determine what shielding geometries and compositions combine to provide an adequate lifetime for final focus magnets in the presence of neutron and gamma transport through shielding structures with a number of long, narrow penetrations. For lasers it is necessary to understand the fundamental mechanisms that set the threshold for laser damage of reflective and transmissive laser optics, and how those thresholds change with radiation damage and debris contamination. Understanding the driver-chamber interface issues will be key to the choice of the optimal number of laser or ion beams needed for each driver; this will be an important input on symmetry to target design and target fabrication and will affect neutron leakage and safety. Radiation resistant materials such as long lifetime insulators are being developed and will advance the state-of-the-art in materials science.

Safety and Environment

Improved understanding of radionuclide release fractions from various solid and liquid fusion materials, and of the potential for end-of-life processing of those materials, can have an important effect on public acceptance of future experiments and fusion power plants. Improved knowledge of the safety and environmental impacts of chamber design choices will guide R&D towards design combinations of targets and chambers that will increase the likelihood of public acceptance. An increased understanding of the behavior (e.g., spalling, oxidation, surface oxide formation, etc.) of materials under accident-relevant conditions (e.g., under irradiation, high temperatures, etc.) will improve capabilities for materials science and material processing technologies.

To minimize tritium inventory within the target factory, it is necessary to identify capsule materials and target designs that allow fast tritium fill and can tolerate transient heating and acceleration during injection, while preserving ablator smoothness and geometrical precision required for high gain implosions. To minimize activated material volumes, it is necessary to identify high-Z hohlraum materials and mixtures that can be mass manufactured at low cost, can be readily recycled from chamber debris outflow, and retain high wall x-ray albedos for good coupling efficiency.

Target Fabrication and Injection

Understanding what practical target materials and fabrication methods can be used for IFE will provide useful guidelines on the choice of materials, geometry, and surface roughness that should be assumed in target designs. The research on materials will also affect safety, as target debris, particularly for indirect drive targets, has the potential to make a significant contribution to radioactive inventories and accident doses. Some presently available target designs call for exotic materials such as ultra low-density foams and strong, yet permeable plastics that can withstand exposure to relatively high temperatures. The need for such materials will likely lead to materials science breakthroughs, and the materials that are developed are likely to find a wide range of applications in others fields of research such as thermal insulation, space sciences, and within the automotive industry.

The ability to inject, track and intercept targets with the required illumination geometry at high rep-rate is essential to the feasibility of IFE. Injection/tracking/triggering systems with high accuracy, repeatability and reliability must be developed. Targets must survive the mechanical and thermal loads due to acceleration in the injector and transit to the center of the chamber.

6.3 Recent Achievements and Contributions to Science

Thick-Liquid-Wall Chambers

The major issues for thick-liquid-wall (TLW) chambers involve complex fluid mechanics including establishment of liquid jet configurations for the pocket and beam ports, rapid recovery of the flow after disruption, and condensation of vaporized flibe between pulses to a level acceptable for beam propagation and target injection. Progress in understanding key phenomena related to these issues has been made through modeling and small-scale university experiments. Recent achievements include:

- Demonstration of oscillating jets needed to form the vented pocket around the target. This flow region provides the bulk of the shielding needed to reduce neutron damage and activation to the wall. It is this feature of TLW chambers that leads to attractive power plant designs with long-lived structures.
- Demonstration of very high quality (low surface ripple) cylindrical jets needed to form the crossed-jet shielding for beam port entry. This flow region is important for shielding final focus magnets of heavy ion drivers with 10's to 100's of beams. The large number of beams is needed by recent target designs and also leads to reduced driver cost.
- Construction of new experiments that will be used to demonstrate re-establishment of multi-jet flow after disruption by a sequence of simulated fusion pulses, and to study condensation dynamics of flibe, which is the preferred liquid for the TLW. These experiments address key issues of high rep-rate systems that IFE requires.

In terms of more general contributions to science understanding, the mechanisms that control surface roughness evolution on high-velocity liquid jets is a topic of importance to diverse applications from jet cutting operations to fuel atomization. Other contributions include creating nozzle designs with very small contraction ratios for extremely smooth cylindrical liquid jets, developing a novel method using laser-induced dye fluorescence to measure surface topologies of high velocity jets, and validating models for oscillating liquid jet motion with experiments.

Dry-Wall Chambers

Key issues for dry-wall chambers are protection of the first wall surface from intense heat loads of x-rays and debris and estimation of lifetime of structural materials due to neutron damage. The Sombrero design uses a carbon-carbon composite first wall and blanket, but other low activation materials (e.g., armor coated SiC or fiber-type materials) are also being considered. Significant

progress has been made in the understanding of these issues for various candidate materials. Achievements supporting dry-wall designs include:

- Calculations on the effectiveness of gas protection with a new target spectrum have recently been completed and show that the gas pressure can be reduced (and possibly eliminated), at least for low yield (150 MJ) direct-drive targets in a 6.5 m radius chamber. This is important since reducing the gas pressure reduces the heat load on injected targets.
- Comparison of shock characteristics from experiments and simulations shows excellent agreement. These dynamic effects are important to understanding cyclic loading and stress on first walls and possibly on final optics.
- Assessment of existing data indicates that the reduction of graphite thermal conductivity due to neutron irradiation is less severe when operated at high temperature, such as in Sombrero. High thermal conductivity is important since the first wall of a high rep-rate IFE chamber must deal with ~ 30% of the power. Without adequate thermal conductivity, the wall would reach unacceptably high temperatures following a pulse and erosion would occur.
- Experiments on x-ray ablation of materials have been planned and will begin in FY01. Results will help benchmark the chamber dynamics codes used to predict dry-wall dynamics and survival.

Driver / Chamber Interface

The interface of the drivers with chamber concepts requires a multidisciplinary effort and continual design trade-offs. Progress has been made in defining and resolving issues, and improvements in the ability to model and analyze the interface issues have been made. Achievements include:

- Detailed 3-D neutronics calculations for realistic magnet shielding configurations for ion drivers with large numbers of beam lines, showing long magnet lifetimes, and identifying the effects of major shielding configuration parameters were completed. A magnet shielding design was developed to provide adequate protection to magnets such that they last for the lifetime of the power plant (30 full-power-years). R&D of radiation-resistant insulators is ongoing and expected to have application to a wide variety of fields.

- CAD drawings for the HYLIFE-II chamber and final focus system were completed and used to resolve many geometry issues involved in delivering 100's of ion beams to the center of the thick liquid wall chamber.

- A laser damage test facility was completed at one of the participating universities in FY00. Metal mirrors, which would be used in the grazing incidence metal mirror concept, were fabricated and tested. A companion theoretical modeling effort on laser damage has recently started to complement the experimental work.

- Understanding heating and compressible response of grazing incidence liquid metal mirrors requires sophisticated modeling of the near surface region of the liquid film. A detailed analysis of hydrodynamic response and nucleation processes was completed in order to determine the likelihood of spallation of a liquid layer. Preliminary experiments have also shown that induced surface waves can indeed be large, but may damp out relatively quickly compared to the repetition rate of the laser pulses.

Safety and Environment

Reducing radioactive waste and assuring safe operation are essential for attractive IFE power plants. The knowledge base and tools for such assessments have improved significantly. Recent achievements include:

- Development of a new methodology for IFE safety assessment, adopting and adapting a set of state-of-the-art safety codes for IFE accident analysis. Loss of coolant/loss of vacuum analyses were completed for the HYLIFE-II and Sombrero designs. The analyses show that, with some design modifications, both designs should be able to meet the no evacuation requirement, an important goal for all fusion designs.

- Candidate target materials were surveyed to identify those with the best characteristics for safety, waste disposal and recycling capability. This information is important help guide target design and manufacturing R&D.

- Computationally efficient methods for the calculation of neutron activation under pulsed irradiation have been developed. Dose conversion factor libraries that include an expanded list of radionuclides, which are important for fusion systems, were created for a variety of weather and release conditions. Both of these have application to a broader scientific community.

- Experiments to measure materials properties important to safety assessments have been designed and experiments are planned to begin in FY01. Results of these experiments will be used in safety assessments and will help refine predictive capability.

Target Fabrication

For IFE, it will be essential to fabricate high quality, cryogenic targets at high production rates (corresponding to the chamber pulse rate or higher for multi-unit plants) and at low cost. The R&D program to develop the capability for IFE target fabrication includes a good deal of basic materials science. Recent achievements include:

- The initial feasibility of fabricating low-density metallic foams for indirect drive targets by doping organic foams was demonstrated. These materials are a key component of the close-coupled target design, which produces high gain performance.

- A fluidized bed was used to coat 3 μm GDP layers onto spherical mandrels. Initial layer quality was encouraging for this potential mass-production coating method.

- Concepts for mass-production target layering in the hohlraum have been proposed, and thermal analyses are underway to support system design. This manufacture step is key not only to target performance (fuel layer quality) but also strongly impacts the target factory tritium inventory, which must be accounted for in the safety assessments.

- Target Fabrication Facility tritium inventories have been estimated for various target supply process flows. Concepts to minimize the tritium inventory are being evaluated.

Target Injection

Another key issue for IFE is the feasibility of accurate, reliable target injection without damage to the target and precision tracking. Significant design and modeling and analyses effort have advanced our understanding of the requirements and challenges in this area. Recent achievements include:

- The capabilities of a wide variety of injector and accelerator technologies, ranging from gas guns to advanced high temperature superconductor systems, were evaluated. A gas gun was selected as an effective design for the next set of demonstration experiments and a conceptual design was completed.

- Prototype target protection sabots were built. Gas leakage rates into the sabot met requirements and preliminary sabot separation experimental results are encouraging. A sabot will be needed to protect the target from damage during acceleration and possibly during transit through a portion of the chamber itself.

- Direct Simulation Monte-Carlo modeling of the interactions between cryogenic targets and high-temperature chamber fill-gas was performed to evaluate target survivability during injection. The reference Sombrero chamber conditions (0.5 torr of Xe gas and ~1500C first wall) were found to be too severe for direct-drive target survival and alternatives (e.g. lower gas pressure) are being evaluated.

- Thin gold film samples were prepared simulating the surface of an NRL direct drive radiation preheat target. The optical properties measured imply reflectivity of approximately 98% for a gold thickness of 570 Å down to 2-μm wavelength. This gold layer reduces thermal radiation load from the hot chamber wall to the target.

- Preliminary feasibility calculations were performed for using shutters and a small helium gas flow into the reaction chamber to keep vapor out of the target injection area for thick-liquid-wall chamber design.

6.4 Relationship to Other Elements of the U.S. Program

The principal areas of interaction with other elements of the U.S. fusion program are in the area of chambers, safety and environment, and systems integration. In the area of chambers, there is some degree of synergy on liquid protected chambers and materials issues. Liquid hydraulic modeling used for APEX has also been applied to IFE chambers. There have been good interactions with the fusion safety program, and codes developed for MFE have been adapted and applied to IFE chambers. The ARIES team, responsible for many recent MFE power plant design studies, has recently turned its attention to IFE.

6.5 Role of International Collaboration

International collaboration on IFE is limited but growing. There is an ongoing series of US/Japan workshops on Laser IFE and another similar US/Japan workshop series on Heavy Ion Fusion. While the focus of these workshops has been on the drivers, chamber, target technologies and systems studies work has been included. On an institutional level, there is a continuing collaboration between LLNL and DENIM in Madrid, Spain primarily in the area of neutron activation and safety. In late 1999, the IFE community proposed that three groups of the IEA (the Environment, Safety, and Economics group, the Chamber Technology Group, and the Fusion Materials Group) expand their activities to include conditions and materials of relevance to IFE. This proposal was supported by our IFE colleagues in Japan and Spain. Thus far, however, we have been unsuccessful in obtaining this expansion. Recently (Dec. 2000), the IAEA started its first Cooperative Research Agreement on "The Elements of IFE Power Plants." This will include participants from the US, Japan, Spain, Germany and other developed and developing countries yet to be identified.

6.6 Five-Year Objectives and Implementation Approaches

Five-Year Objectives

- Demonstrate the feasibility of chamber clearing for thick-liquid-wall chambers.

- Develop dry-wall chamber concepts that are resistant to radiation and debris from the target.

- Develop plausible designs for protecting final focusing elements for ion accelerator and laser drivers.

- Evaluate safety and environmental aspects of IFE power plants and modify designs so that plants can meet the no-public-evacuation safety criteria.

- Identify credible pathways to low-cost target fabrication, accurate injection, and target survival through experiments and analyses.

Implementation Approaches

Liquid Wall Chambers

The proof of principle (PoP) liquid chamber experiments should take advantage of the modularity of liquid-jet pockets by performing experiments with single scaled jets and clusters of a few jets, allowing extrapolation to the much larger flow and power levels that will be required in later Performance Extension experiments. PoP experiments should also take advantage of the large differences in time scales of groups of phenomena, separating studies of slow liquid hydraulic response from studies of rapid ablation and venting phenomena. Required tasks include:

- Liquid jet hydraulics experiments to study free jet formation and other potentially important flows (e.g., vortices and wetted walls).

- Liquid response experiments to study effect of shocks on liquid jets and droplet clearing between pulses.

- Plasma/vapor condensation work to study superheated vapor condensation.

- Design, modeling and system studies to integrate chamber designs with driver and target technologies.

- Additional studies are needed in the areas of flibe chemistry (structure corrosion and erosion, tritium and hohlraum materials recovery) and heavy ion target x-ray/debris spectrum quantification. Pulsed x-ray ablation of candidate liquid coolants may be studied on existing z-pinch x-ray sources.

Dry-Wall Chambers

Dry wall chamber research deals mostly with structural materials that are low activation (e.g., carbon and silicon carbide composites) and intended to operate at low pressures and stresses, and at much higher temperatures (1500 degrees Centigrade) than usually considered for MFE blankets. First wall response to pulsed soft x-rays and debris, and final optics protection from target radiation/debris are key areas. Required tasks include

- First wall/blanket R&D on materials development, radiation damage, flowing granular beds, and tritium implantation/retention.
- Chamber dynamics modeling and experiments to study fireballs in gas filled chambers and resultant threat to the first wall. Pulsed x-ray irradiation of carbon composite dry-wall materials may be studied on existing z-pinch x-ray sources.
- Design, modeling and system studies to integrate chamber designs with driver and target technologies.

Driver / Chamber Interface

As expected, the tasks required for addressing driver/chamber interface issues are quite different for heavy ion and laser drivers. For heavy-ion driven IFE final focus magnets the essential task is

- Use 3-D radiation transport codes, working in partnership with the heavy-ion driver physics design for final focus ion optics and the heavy-ion target designs, to seek a self-consistent design for final-focus magnets consistent with heavy ion target requirements and the standoff of thick-liquid-wall chamber designs.

For laser-driven IFE final optics, the tasks are:

- Perform experiments and simulations on laser, neutron, x-ray and possibly ion damage to grazing-incidence metal mirrors, fused silica and other candidate optical materials.
- Explore alternative final optic protection methods (e.g., liquid metal film mirrors).

Safety and Environment

The S&E work includes the development of tools applicable to both laser and heavy-ion fusion, experiments to produce data needed for better simulations, and analyses specifically tailored to the different chamber concepts and their issues. Tasks include:

- Experiments to gather data on the mobilization, diffusion, and transport of radionuclides in various candidate materials (coolants and structures) at elevated temperatures.

- Measurement of tritium retention and migration in structural materials (including effects of radiation damage and temperature).

- Updated safety analyses using state-of-the-art models for simulation of accident scenarios and new data from the experimental programs.

- Studies of ways to minimize waste disposal volumes (such as maximum use of recycling and/or clearance).

- Validation of dust/aerosol transport models.

- Identification of methods to control and remove tritium and coolant impurities (target-debris and corrosion products) for liquid-wall chambers.

- Safety analyses for both direct and indirect-drive target fabrication facilities.

Target Fabrication

Methods of low cost manufacture and rapid injection need to be identified, and candidate prototype targets tested for compatibility with IFE injection into representative IFE chamber environments. Promising candidate IFE target designs need to be tested both on a target injector test stand that can simulate IFE chamber environments, as well as on existing laser facilities to determine both the achievable and required target tolerances, precision and injection compatibility for IFE. A coordinated design effort is required of both IFE target fabrication and IFE target physics design groups working in partnership.

Fabrication tasks to develop the required knowledge include:

- Development and testing of foam materials, barrier layers, and high-z coating processes.
- Evaluation and recommendations for scalable manufacturing techniques for direct and indirect drive targets.
- Experiments on fuel layering inside overfilled foam shells.
- Evaluation of material properties at cryogenic temperatures (DT and other target components).

- Study on permeation filling vs. cryogenic injection filling.
- Fill facility concept and required tritium inventory for each target design.
- Radiation damage data for membranes and foams.
- Demonstration of filling and layering of target concepts.

Target Injection

Target injection tasks to develop the required knowledge include:

- Design and construction of a high speed, high accuracy injection and tracking system.
- Demonstration of ability of cryogenic hohlraums to withstand accelerations.
- Measurements of DT ice strength and predictions of acceleration effects on targets.
- Measurement of thermal radiation effects on DT filled and layered cryogenic targets.
- Modeling of target chamber gas effects on target injection.
- Demonstration of hitting an indirect drive target on the fly.
- Demonstration of injection and tracking of direct drive targets.
- Examine effects of rapid warm up (< 20 ms) on DT ice layer.

6.7 Key Decision Points

The Chamber and Target Technology R&D is one part of the overall plan to develop the science and technology needed for IFE. Currently, work is proceeding in parallel on various driver technologies (heavy ion, DPSSL, and KrF laser) as well as target physics. The next major decision point in the development of IFE is one of readiness to proceed with one or more Integrated Research Experiments (IREs). A green light for an IRE will require continued success on all fronts (target physics, drivers, and chamber and target fabrication and injection) and a vision of a sufficiently attractive end-product. Thus for C&TT, the IRE decision will require that the key feasibility issues for chamber and target technology have either been resolved or sufficient progress has been made that a pathway to an acceptable solution is likely. By structuring the planned R&D to address the key issues, we assure that progress toward this goal is made. Estimates for the time of the IRE decision vary depending on available funding, but it could be in 5 years or less.

7.0 INTEGRATION OF VLT PROGRAM ELEMENTS

7.1 Introduction

The goal of technology integration is to foster collaboration and exchange among individual technology programs, with the larger U.S. fusion community, and with our international partners in order to make optimum use of technology personnel and resources in advancing fusion science.

There are several anticipated benefits from enhanced program integration:

- Close collaboration between enabling technology and plasma science can lead to improved performance of present and near term plasma devices as well as improved understanding of plasma science.

- Close collaboration among technology personnel can lead to improved visions of attractive fusion energy sources. Enhanced exchange of information between technology areas fosters innovation and cross-fertilization of ideas. Such an integrated approach is essential due to the broad base of disciplines involved in fusion development.

- Program integration assists in making maximum use of personnel expertise, facilities, and resources.

- There is greater potential for new spin-off applications.

- Enhanced program integration gives technology better flexibility to adjust to changes in program direction as advances in understanding.

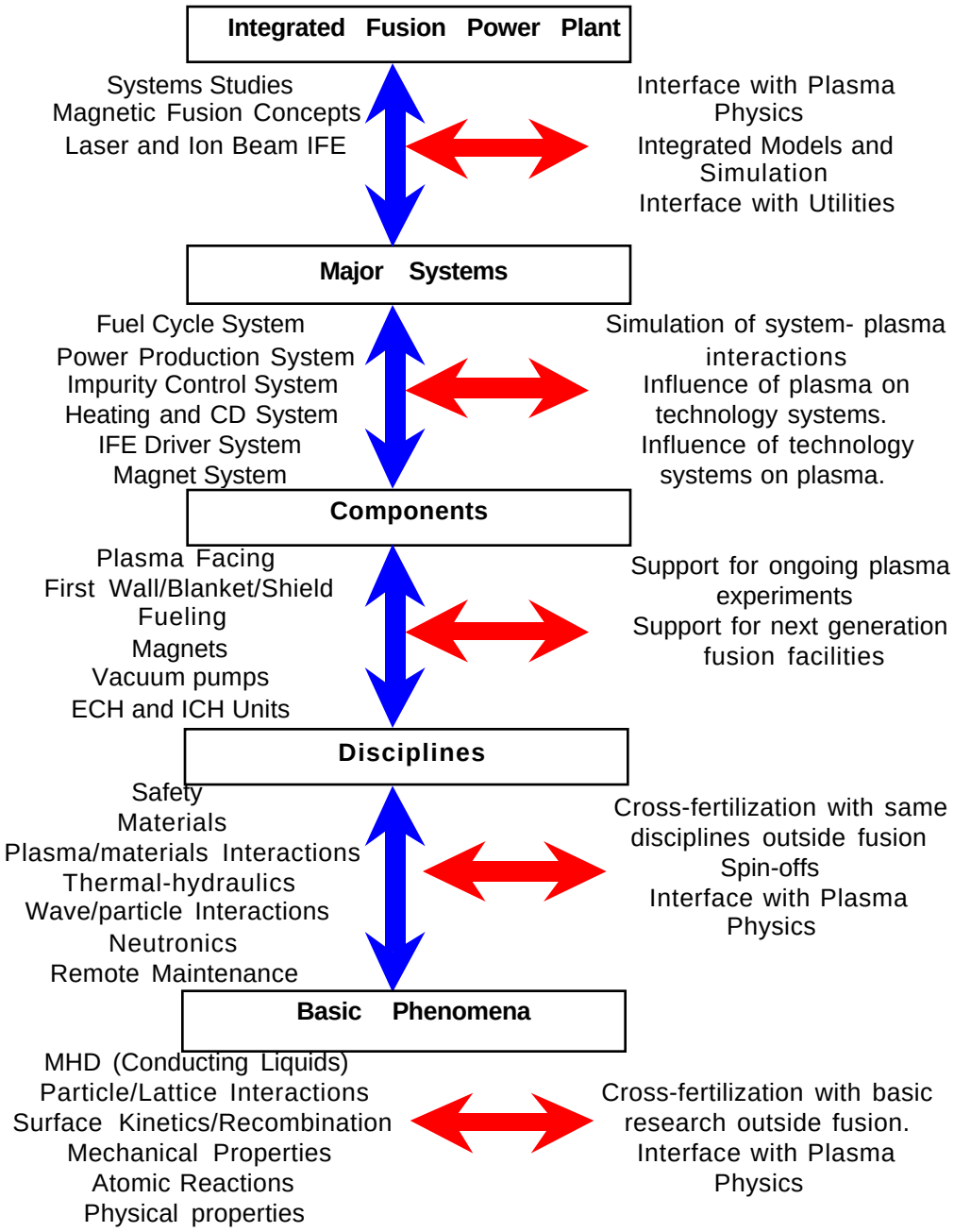
An important role of the VLT has been to promote integration of all of enabling technology. This section reviews key linkages between technology areas and the suggested methods for fostering collaboration between disciplines.

7.2 Linkages Between VLT Areas

Figure 1 illustrates the hierarchal levels associated with technology. The effort in enabling technology spans the range from fundamental science to development of applied technology for specific applications in fusion test devices. Enabling technology is also responsible for creating attractive visions for fusion power plants that help guide development of advanced performance systems. At each level, technology interacts with the plasma science community and well as organizations outside of fusion.

At the fundamental level, the work emphasizes an understanding of underlying phenomena, and there is a strong connection to the basic science community. The types of problems addressed make use of first principles models as well as experiments aimed at obtaining data on the fundamental nature of matter and energy. At the discipline level, the work emphasizes basic understanding in performance regimes of greatest interest to fusion. Spin-offs are likely to and from other areas where advanced performance is required. At the component level, there is a close connection to the plasma science community, and components are developed that enhance the performance and understanding of plasmas in present and near term devices. Major systems integration emphasizes advanced technology that will be required for attractive fusion power applications. This area addresses the need for very high performance in terms of power density, high temperatures, and extended lifetimes. Integrated fusion power plant studies examine all areas of technology and plasma science.

Figure 1 -Hierarchy for Enabling Technology



7.3 Implementing Technology Integration

An essential part of program integration is providing people with easy access to their colleagues and to relevant information. Since VLT researchers are distributed throughout the U.S., this is a task that requires deliberate effort.

The VLT has made good use of electronic technologies for enabling the rapid exchange of ideas. There is a VLT newsletter and website, and many programs within the VLT have their own websites that provide up-to-date reports and presentations for anyone who is interested. Regular VLT conference calls with electronic presentations that review recent progress also keep people informed. This technology is rapidly improving, and the VLT should take advantage of new capabilities as they arise. Some possible ways of enhancing long distance information exchange, making it more interactive and dynamic, are:

- Electronic bulletin boards where people can pose a particular question or need for their program to the rest of the VLT.
- Electronic forums on a particular topic. Topical technical questions can be discussed and debated over the Internet, and the text can then be saved and used as a reference in the future.
- On-line databases, e.g., materials properties, that can be searched for key pieces of information.
- On-line experimental notebooks where raw data and notes can be viewed by collaborators from other institutions.
- On-line experiments, in real time. It is possible to view tests results or even to control experiments remotely.

There will, no doubt, be a trial and error process in implementing new means of information exchange. It is important the there is active participation and feedback, positive or negative, so that the most useful technology can be adopted.

7.4 Integration of MFE and IFE Technology

While this section has focused on MFE, there are several areas where substantial overlaps occur in technology between MFE and IFE. This is particularly true for chamber technology, with shared interests in safety, materials, and first wall/blanket. Over the last couple years, the safety codes developed for MFE have been adopted and adapted to perform safety analyses for various accident scenarios for IFE power plant designs. MFE and IFE colleagues have worked closely on this, and the result has been improved modeling capability for both. Flibe has been considered as a possible liquid for thick and thin liquid-wall concepts for both IFE and MFE. Information exchange on material properties and plans for safety related studies of flibe benefit both communities. The interest in thick liquid walls for MFE chamber is a good example of cross-fertilization, since this has been a favored approach in IFE for many years, and several individuals are currently working on applications for both MFE and IFE. Another area of growing integration is in power plant studies. In FY00, the ARIES team began looking at IFE power plants. Although many of the existing ARIES members already had some experience in various aspects of IFE technology, this study is providing broader involvement by some traditionally MFE groups. Another example of technology integration is in magnet technology, where MFE expertise is being applied to magnet design and testing for the quadrupole magnets used in heavy ion driver. In summary, steps have been taken and will continue to ensure that the expertise built up over the years is made available to both MFE and IFE.