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Section 1. Materials for fusion technology

Advances in fusion technology

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Abstract

The US fusion technology program is an essential element in the development of the knowledge base for an attractive fusion power source. The technology program incorporates both near and long term R&D, contributes to material and engineering sciences as well as technology development, ranges from hardware production to theory and modeling, contributes significantly to spin-off applications, and performs global systems assessments and focused design studies.

1. Overview

Plasma technologies have played 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, 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 had a direct impact on the enormous progress made in the development of plasma science in general, and fusion science in particular.

The near-term emphasis for magnetic fusion energy (MFE) is on developing better tools for the production and control of high-temperature plasmas and, thus, the further development of plasma science. For inertial fusion energy (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.

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 EUV lithography of computer chips and circuits, coating of materials, waste processing, plasma electronics, new and improved materials, and biomedical applications.

The longer-term emphasis in fusion technology is on resolving key feasibility issues for the development of fusion energy. These activities 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.

Design activities are an important element of the technology program because they help to motivate the future directions of the fusion energy sciences program by examining the potential of specific confinement and 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 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 safety analysis. Such an integrated approach is essential to the successful development of the knowledge base for at-

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tractive fusion energy sources because of the complex nature of fusion systems and the multi-disciplinary aspects of the underlying science and engineering.

Fusion technology R&D results in innovative concepts and 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 redeposition 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 fusion technology R&D have a strong international component. With constrained budgets in the United States and larger fusion technology programs in Europe and Japan, it is essential to maintain and even enhance international collaboration.

2. The role of technology in enabling fusion science and energy

The dramatic progress in fusion science seen in the last few decades has been possible, in part, due to equally dramatic progress in technology in general and plasma technologies in particular. These include the technologies to confine the plasma (magnet coil sets, plasma facing components) and those which are used to manipulate the plasma parameters and their spatial and temporal profiles (plasma heating and current drive, and plasma fueling systems). These essential tools have contributed to important milestones which includes the following:

- record plasma temperatures (40 keV) and fusion power (>10 MW) through neutral beam injection and tritium processing systems;
- $n\tau_E$ values exceeding the Lawson criterion through pellet injection (plasma fueling);
- the attainment of reversed shear through pellet injection and RF heating on JET and the resulting generation of internal transport barriers;
- H-mode as a result of wall conditioning techniques and PMI understanding;
- the production of low impurity containing plamas through plasma facing component (PFC) development and plasma wall conditioning techniques;
- the demonstration of non-inductive current drive by RF heating and neutral beam injection;
- stabilization of MHD modes via RF current drive techniques;
- sustained operation above the empirical density limit with pellet injection;
- disruption mitigation using fueling technologies for rapid plasma quench.

A more attractive concept of any fusion energy system concept would result from reducing the capital cost, increasing reliability, reducing in vessel component failure rates, and/or increasing the net fusion power. Reduced capital costs could be achieved with smaller fusion cores resulting from higher performance plasmas; that is, higher fusion power densities achievable through higher confining magnetic field strengths and high-plasma β. Higher field strength superconducting magnet technology, radio frequency heating and current drive systems operated in a manner to stabilize MHD activity, and PFC technology aimed at facilitating edge transport barriers would be the three principal technology program elements directly applicable to increasing the fusion power density.

The other elements of the technology portfolio also play a central role in lowering the cost and increasing the environmental acceptance of fusion energy. For example, net fusion power can be maximized not only by reducing the recirculating power fraction, which implies superconducting magnet technology and more efficient heating and non-inductive current drive systems, but also by extracting heat at higher temperature for improved thermodynamic efficiency. The latter is being addressed in the PFC, fusion technology, and materials program elements (i.e., high-temperature radiation resistant structural materials, thick flowing ‘liquid wall’ heat extraction and tritium breeding concepts).

Similarly innovative research in the fusion technology program aimed at developing thick liquid walls to absorb the bulk of the neutron energy may offer a promising solution to reduce in-vessel component and structural material failure rates (reduced component replacement costs and higher availability). Improved techniques for remote handling and maintenance are also essential for fusion power systems in general and figure heavily in increasing availability. The tritium system and fusion safety elements of the portfolio speak directly to the environmental attractiveness of fusion power in general and licensing issues of next step burning plasma devices in particular. Finally, a self-consistent integration of the technology and science program elements as embodied by reactor designs for the various confinement pathways takes place in the systems design element. This activity provides an important yardstick with which to measure the promise and potential of existing and emerging confinement approaches against the metric of an economically and environmentally attractive fusion product and steers the science and technology programs in directions that are consistent with that goal.

3. The technology portfolio

The following describes opportunities for technology development starting with the plasma technologies which enable existing and near-term plasma experiments to achieve their performance goals and research potential and progressing to the longer term nuclear technologies (plasma chamber technologies, fusion materials, systems design) that address issues such as power extraction, tritium breeding, radiation resistant and low activation materials, and attractive reactor designs.

3.1. Plasma heating and current drive

Heating and current drive technologies are essential for heating plasma to fusion-relevant β and temperatures and manipulating plasma properties to access advanced operating scenarios (reversed shear, MHD stabilization, turbulence suppression). Significant progress has been made in developing and deploying high-power gyrotrons in the $\sim$1 MW level at 110 GHz (see Fig. 1) and the development of 170 GHz prototype units for electron cyclotron heating/current drive as well as fast-wave antenna arrays in the >1 MW unit size for ion cyclotron heating (ICH) and current drive (via direct electron heating). With the present program emphasis on increasing plasma performance and reducing next-step option costs, the emphasis of the development of these heating and current drive technologies will concentrate on improving power density (higher voltage limits for ICH launchers), higher gyrotron unit power (2–3 MW), increased efficiency gyrotrons featuring multi-stage depressed collectors, ICH tuning and matching systems that are tolerant to rapid load changes, and steady-state gyrotrons and actively cooled ICH launchers for long-pulse/burning-plasma, next-step options.

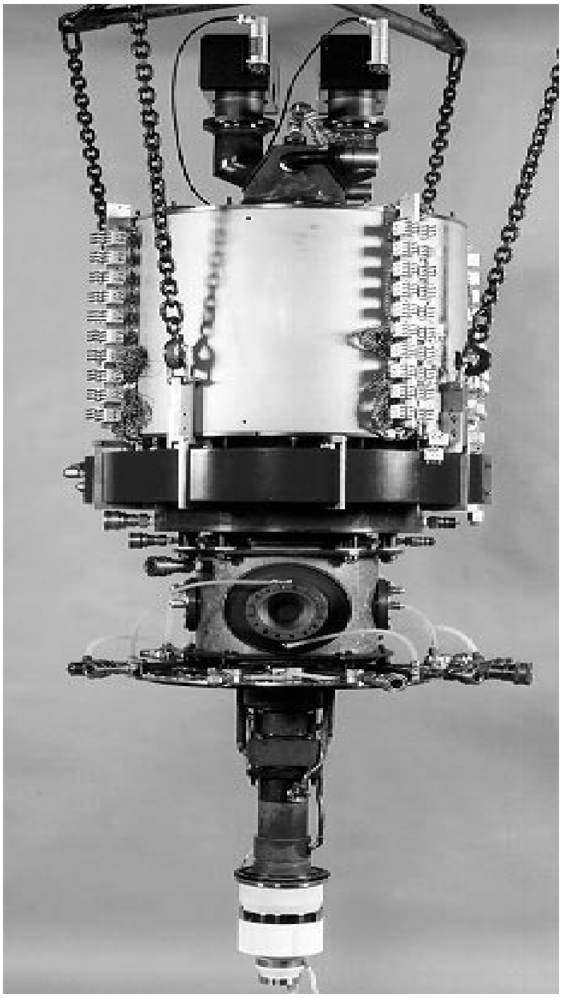

Fig. 1. Prototype 1 MW gyrotron at 110 GHz.

3.2. Fueling

Fueling is another technology that is essential for the achieving fusion-relevant plasma parameters and manipulating plasma parameters to achieve improved performance (peaking of the density profile for higher reactivity and reducing transport via turbulence suppression). Recent successes include sustained operation above the density limit on DIII-D, high-field side launch with improved density profile peaking, internal transport barrier generation, the development of steady-state pellet injectors operating in the 1.5 km/s speed range, and the demonstration of core fueling in proof-of-principal experiments using accelerated compact toroids (CTs). Pellet fueling technology has also been used recently to ameliorate the effects of major disruptions (a potentially serious off-normal event) in tokamaks by delivering massive amounts of low- and high-Z material that rapidly quench the current in vertically unstable plasmas. It has been estimated that eliminating disruptions in tokamaks in the fusion energy development class would increase the lifetime of divertor PFCs by a factor of two. Reducing the severity of disruptions could allow the advanced tokamak to operate nearer its ultimate β potential. A critical issue for fueling in next-step device plasma regimes is the degree to which profile peaking is needed (for higher density operation and improved reactivity and confinement) and the technological requirements to meet that need (pellet speed, CT density and the physics of CT deposition).

3.3. Plasma facing components and plasma materials interactions

The successful development of high-performance (high-heat flux, low erosion) PFCs and the understanding of plasma materials interaction is central to the development of fusion energy. The understanding and the control of the interaction of the plasma material surfaces is important in creating edge plasma conditions that are conducive to developing an edge transport barrier (H-mode) and the development of low erosion PFCs will have a strong impact on component lifetimes and hence the cost of fusion power. Significant progress has been made recently in the understanding of net divertor erosion pointing to refractory high atomic number materials, mixed materials and co-deposited carbon–tritium films, the development of innovative wall conditioning techniques, and water cooled PFCs (Be/Cu and W/Cu) with steady-state heat removal rates at the 10–30 MW/m^2 level. A free surface liquid divertor project (ALPS) has recently been initiated to investigate the potential of active heat removal without concern for PFC lifetime limits (see Fig. 2). Critical issues that need to be addressed in this are the development of even higher surface heat flux PFCs (50 MW/m^2 goal) that do not require periodic maintenance to renew the plasma-facing material (i.e., liquid surfaces or helium-cooled non-sputtering refractory metals). In concert with tokamak experiments, investigations are underway to distribute the heat flux more evenly via radiation without confinement degradation.

3.4. Magnet technology

Superconducting magnet systems which provide the confining magnetic fields represent a major cost element for long-pulse or burning-plasma next-step MFE options. Dramatic progress has been made recently in development of large-scale DC and pulsed Nb_3Sn magnets for ITER at a field strength of up to 13 T (see Fig. 3). Further reductions in cost for superconducting magnets could be realized by development of higher performance (higher current density and increased quench protection capability) superconductor strand, higher strength structural materials and higher radiation resistant magnet insulators (which presently limit the life cycle of magnet systems). Dramatic progress has been made with the development of high-temperature superconductors which can be applied to certain fusion problems (e.g., leads for magnets). Quadrupole focusing magnets for heavy ion beam fusion are also a major contributor to the cost of the heavy ion driver. The development of large, warm bore qaudrupole arrays has been identified as a key element in developing an affordable next-step heavy ion fusion system.

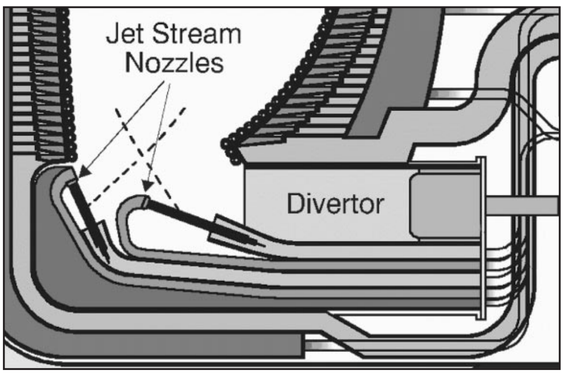

Fig. 2. ALPS – Advanced limiter-divertor plasma-facing systems.

3.5. Tritium processing and fusion safety

The safe handling of tritium fuel and tritiated exhaust streams, the minimization of tritium holdup and inventory in in-vessel components, and the understanding (and mitigation) of tritium and activation product mobilization and release are critical to the goal of demonstrating fusion power with attractive safety and environmental characteristics. Significant progress has been made in the development of cryogenic distillation systems for isotope separation and the demonstration of a novel once through exhaust gas cleanup system (palladium membrane reactor) that efficiently processes tritiated water and has the potential to eliminate tritiated water altogether in fuel processing systems.

From data generated on the mechanisms for mobilization and migration of radiologically hazardous materials such as dusts (see Fig. 4) and the development of state-of-the-art safety analysis tools, ITER was designed with the confidence that public evacuation would not be required under worst case accident scenarios. Critical/development issues in this area are the minimization or elimination of waste streams (such as tritiated water from fuel cleanup systems) and demonstration of the feasibility of recycle and reuse of fusion materials, minimization (and removal and processing) of tritium in first-wall materials and co-deposited layers and understanding the interaction between energy sources and the mobilization of tritium and other radiological hazards, and safety R&D and development of techniques for removal of tritium from advanced coolants (i.e., liquid walls) now being considered for future MFE and IFE reactor-class devices.

3.6. Remote handling and maintenance

In eventual MFE and IFE fusion reactors, all in-vessel maintenance will need to be performed remotely because of activation of materials in the intense radia-

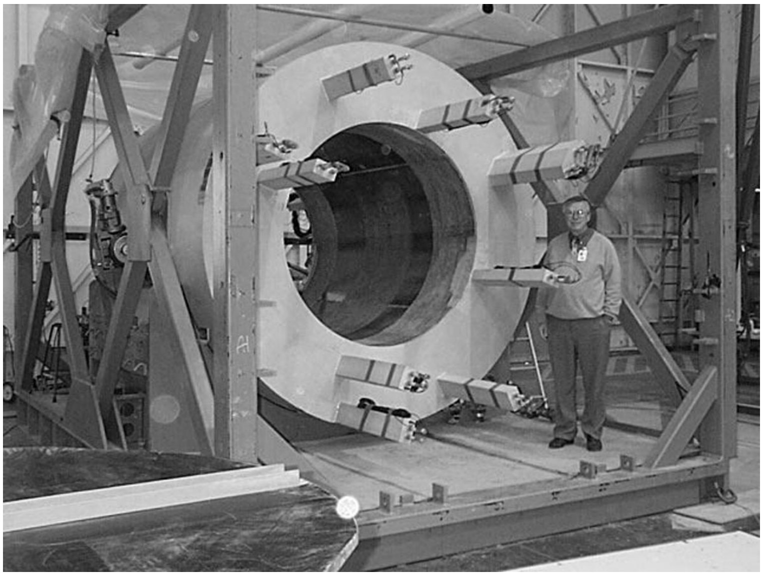

Fig. 3. Inner module of the superconducting central solenoid model coil built for ITER project.

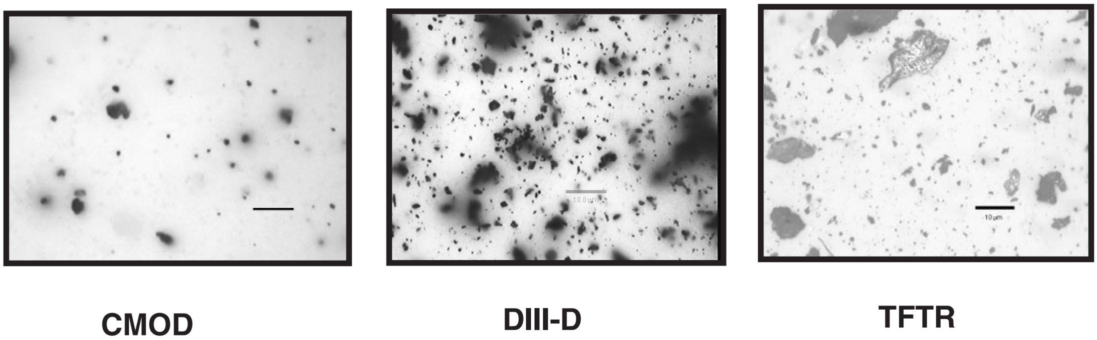

Fig. 4. Characterization of hazard associated with tokamak dust.

tion environment. Rapid in situ repair operations are important from the perspective of achieving adequate power plant availability levels. Recent successes include the development of precision in vessel metrology systems. Significant additional development will be required to reduce costs, improve reliability and human interfaces, develop dexterous servo manipulation of heavy payloads, and techniques for remote welding and refurbishment of in-vessel components.

3.7. Plasma chamber technologies

The goal of plasma chamber technology research is to extend the engineering science knowledge base, provide innovative concepts, and resolve key feasibility issues for the practical, economic and safe utilization of fusion energy. This effort will identify and explore novel concepts for the in-vessel components that can substantially improve the vision for an attractive fusion energy system. The R&D will focus on concepts that can have high-power density, high-power conversion efficiency, low failure rates, faster maintenance, and simpler technological and material requirements. R&D will be carried out to establish the knowledge base necessary to evaluate the most promising innovative concepts. This R&D includes theory, modeling, experiments, and analysis in key areas of engineering sciences (e.g., fluid mechanics, MHD, heat transfer, thermomechanics, plasma-material interaction, nuclear physics, and particle transport) and materials science, safety and other technical disciplines.

R&D will also be done to understand and extend the technological limits of those concepts that are currently employed in system studies primarily through international collaboration. Also, an assessment will be made of the need for a plasma-based neutron-producing facility for testing and demonstrating engineering feasibility of advanced technology concepts (testing of heat extraction technology at high-power density, data on failure rate, data on maintainability).

The near-term effort on innovative concepts will identify, analyze and evaluate novel, high performance advanced technology concepts within the APEX program (emphasis on high-power density heat removal technology) (see Fig. 5). This will consider all magnetic confinement concepts (not limited to tokamak) and will involve a close interaction and coordination with the plasma science community. Examples of near-term activities include the following:

- experimental study of free laminar and turbulent jets under the effect of magnetic field and external heating;
- stability of laminar and turbulent fluid layers flowing on concave surfaces;
- feasibility of forming void penetrations in liquids;

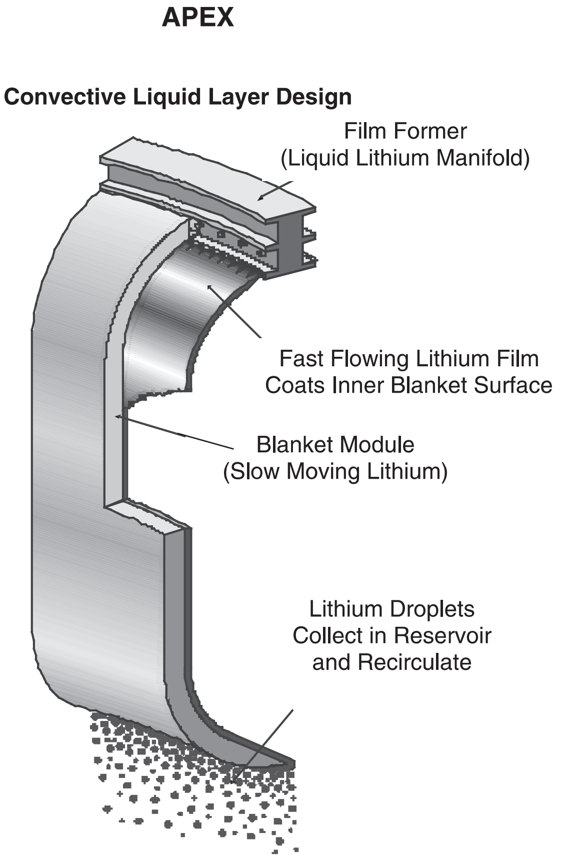

Fig. 5. Example of a flowing liquid wall concept being studied in the APEX program.

- feasibility of insulator coating in liquid metal flows;
- sputtering and basic surface properties of candidate plasma-facing liquids;
- helium cooled refractory metal fusion power core components.

3.8. Fusion materials

The long-term goal of the fusion materials program is to develop structural materials that will permit fusion to be developed as a safe, environmentally acceptable, and economically competitive energy source. This will be accomplished through a science based program of theory, experiments and modeling that provides an understanding of the behavior of candidate material systems in the fusion environment and identifies limiting properties and approaches to improve performance, undertakes the development of alloys and ceramics with acceptable properties for service in the fusion environment through the control of composition and microstructure, and provides the materials technology required for production, fabrication, and power system design.

Selection of material systems for development as a fusion power system blanket structural material is based upon key performance targets. The determination of which material systems have potential to meet these performance targets is made through an interaction between the systems design studies and fusion materials program tasks. Three material systems have been judged to have potential for being developed as fusion power system structural materials: SiC composites, V-based alloys and advanced ferritic steels. High temperature refractory alloys have been recently added to conceptual design evaluation. Copper alloys, because of their excellent thermal and electrical conductivity, are critically important in near term applications and will most likely find special applications in fusion power systems including normal conducting coil options. Opportunities for consideration of new material systems may arise in the future as a result of advances within the broad field of materials science, or new design concepts that permit additional choices of materials systems that have potential to meet performance goals.

Fusion materials for MFE and IFE must operate in a very demanding environment which includes various combinations of high temperatures, chemical interactions, time-dependent thermal and mechanical loads, and intense neutron fluxes. One of the major materials issues to be faced in developing attractive fusion power is the effect of the intense neutron fluxes. The first-wall neutron spectrum from a DT reacting plasma contains a large 14 MeV component. This not only results in high-displacement rates ($\sim$20 dpa/yr at a neutron wall loading of 2 MW/m^2) but also causes higher transmutation rates than are experienced in fission reactors.

The transmutation products He and H are of particular concern, but other impurities can also be important. The influence of transmutations on property changes has been very well established, the most well-known example being the role of He in swelling behavior. Thus neutron irradiation is a particularly important issue, due to both its effects on physical and mechanical properties, as well as the production of radioactive materials, and is the most difficult to investigate with currently available facilities.

At present, fission reactors are the primary means to investigate the effects of irradiation on fusion materials. However, the response of materials to a fission radiation field can be significantly different from that due to a fusion neutron spectrum. Various techniques have been used to more nearly reproduce the fusion environment, but an intense source of 14 MeV neutrons will ultimately be needed to develop and qualify fusion materials. The international community has proposed a point neutron source, an accelerator facility based on the D–Li interaction to fill this role. A key programmatic issue which remains to be resolved is the role of such a point neutron source vis-à-vis a 'Volume Neutron Source' which could provide an experience database with a fusion system at moderate availability, as well as component testing and some materials testing capability.

3.9. Advanced design

Advanced design activities guide fusion research and development toward an attractive and achievable end product, and provide necessary technical information for major program decision points. This is achieved through detailed analysis of scientific issues, design of fusion facilities, development of visions of attractive fusion products, and strategic planning and forecasting.

Conceptual design of commercial fusion facilities is essential in guiding fusion R&D and providing a focus for the fusion program – namely development of useful products. Conceptual design studies ensure that all physics and technology aspects can be integrated within constraints imposed by physics, materials, and technologies to produce a system that is economically and environmentally attractive and technologically feasible. Through investigation of the interactions among physics and technology constraints, optimum goals are set and high-leverage areas identified which in turn guide the R&D effort. These studies also provide a forum for roll-back planning.

Design of fusion test facilities such as burning plasma experiments and technology and material testing facilities provide data to support program decisions. This program element provides for ongoing analysis of critical issues, maintenance of necessary physics and technology databases and identification of their limitations, development of engineering and physics design analysis capability, and assessment of systems issues arising from physics-technology interfaces. This program element links broad national and international interests in fusion development and explores options with substantial variation in performance, cost and technology requirements. These studies also provide a forum for 'roll-forward' planning and help to identify the appropriate balance between near scientific investigation and the necessary technology development.

Development of fusion as a commercial product is a great challenge, in part for technical reasons, in part due to limited resources, and in part due to competition from other options. Strategic planning and forecasting studies help in developing the 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, as highlighted in the Rio and Kyoto agreements. Studies of fusion non-electric applications (or co-generation) help develop new clients and new products for fusion. The systems design activity also contributes to the search for development paths for fusion with test-facility requirements that minimize the cost and risk of fusion development and compress the schedule.

Fig. 6 shows a schematic of the ARIES-RS power plant design producing a net 1000 MW of electric power. The ARIES-RS plasma is optimized to achieve a high-plasma pressure and a high-bootstrap current fraction (90%) which is very well aligned with the required equilibrium current-density profile. The current-drive analysis showed that about 80 MW of current-drive power is necessary for steady-state operation. This design utilizes a lithium-cooled blanket with a vanadium structure which achieves a high-thermal conversion efficiency of 46% (using 610°C coolant outlet temperature and a Rankine steam cycle). Use of vanadium in the high-temperature zones provides sufficiently low levels of afterheat that worst-case loss-of-coolant accidents can be shown to result in a small release of radionuclides (below 1 rem at site boundary), well below the values specified by standards and regulations. The blanket is made of sectors, and rapid removal of full sectors is provided through large horizontal ports followed by disassembly in the hot cells during plant operation. The simple blanket design with a small number of cooling channels and low mechanical stresses in the structure provides a good basis for high reliability.

3.10. IFE chamber and target technology R&D

Many concepts for chamber components have been advanced in design studies during the past 20 yr. These include chambers with neutronically-thick layers of liquid or granules which protect the structural wall from

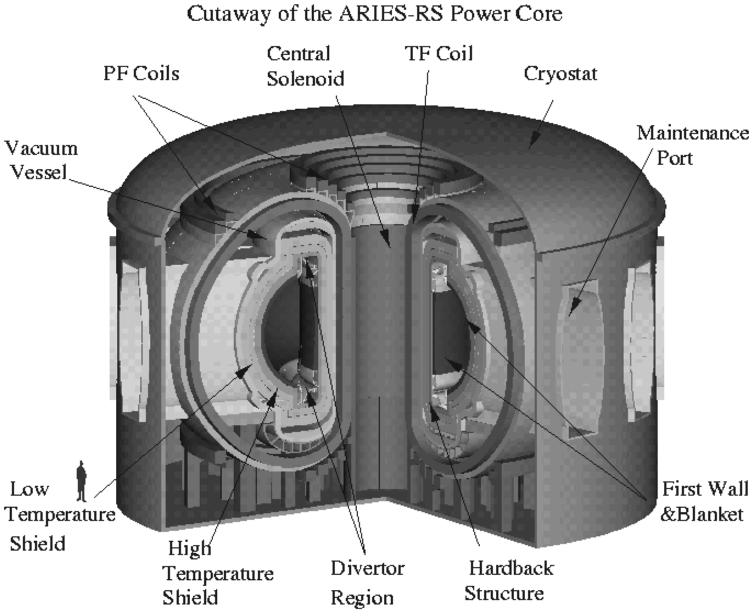

Fig. 6. Schematic of the fusion power core of the ARIES-RS advanced tokamak.

neutrons, X-rays, and target debris. There have also been chamber designs with first walls that are protected from X-rays and target debris by a thin liquid layer, and dry wall chambers which are gas filled to protect the first wall from X-rays and target debris. The last two types, the wetted wall and dry wall chambers, have structural first walls that must withstand the neutron flux. The currently favored approaches are: (1) heavy ion drivers with indirect-drive targets and neutronically-thick liquid chambers and (2) laser drivers with direct-drive targets and gas-protected, dry-wall chambers.

Generic issues include: (a) wall protection, which involves hydraulics and flow control for liquids and includes ablation damage and lifetime for solids; (b) chamber dynamics and achievable clearing rate following capsule ignition and burn; (c) injection of targets into the chamber environment; (d) propagation of beams to the target; (e) final-focus shielding and magnet/optics thermal and neutron response; (f) coolant chemistry, corrosion, wetting, and tritium recovery; (g) neutron damage to solid materials; (h) safety and environmental impacts of first wall, hohlraum, and coolant choices.

An IFE chamber requires 1×10^8–2×10^8 cryogenic targets each year at a rate of up to 10 Hz injected into the center of a target chamber operating at a temperature of 500–1500°C, possibly with liquid walls. The targets must be injected into the target chamber at high speed, optically tracked, and then hit on the fly with the driver beams. Preliminary design studies of cryogenic target handling, injection, and tracking for both direct-drive and indirect-drive IFE power plants were done as part of all major IFE design studies.

The heart of an inertial fusion target is the spherical capsule that contains the D–T fuel. ICF capsules are currently made using a process which may not extrapolate well to IFE. The microencapsulation process previously used for ICF appears well-suited to IFE target production if sphericity and uniformity can be improved and capsule size increased. Microencapsulation is also well-suited to production of foam shells which may be needed for several IFE target designs. ICF hohlraums are currently made by electroplating the hohlraum material onto a mandrel which is dissolved, leaving the empty hohlraum shell. This technique does not extrapolate to mass production. Stamping, die-casting, and injection molding, however, do hold promise for IFE hohlraum production.

4. Virtual laboratory for technology (VLT)

The mission of the VLT is to provide leadership and coordination for US community participation in the enabling technology program, including consensus recommendations on enabling technology priorities and resources. The VLT will also facilitate interconnection of people and facilities through strong and effective communication linkages, data and hardware sharing, and cross-institutional teaming to integrate fully tasks conducted at many performing institutions.

As a mechanism for organizing and integrating the performing institutions that will carry out the enabling technology program's diverse, interrelated activities, the VLT will provide the vehicle for coordinating program elements and for obtaining community participation in program planning.

The VLT concept gives recognition to the fact that fusion enabling technology programs are a collection of diverse, but interrelated, activities that have lacked clearly defined community leadership for advocacy and representation among fusion program leaders. In addition, greater uniformity has been needed in processes for planning and technical review of program activities.

The VLT is intended to provide benefits with regard to advocacy for enabling technology programs, community participation in program planning and prioritization, communications with internal and external customers and stakeholders, program coordination and integration, consensus-building and program review. The 'virtual' quality of the VLT is meant to acknowledge the achievements of the stated objectives through the use of electronic interconnection of existing, distributed facilities.

Acknowledgements

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