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OVERVIEW OF THE U.S. MAGNETIC FUSION ENERGY PROGRAM

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Since the 1988 Symposium on Fusion Technology, steady progress has been made in the U.S. Magnetic Fusion Energy Program. The large U.S. tokamaks have reached new levels of plasma performance with associated improvements in the understanding of transport. The technology support for ongoing and future devices is similarly advancing with notable advances in magnetics, rf heating tubes, pellet injectors, plasma interactive materials, tritium handling, structural materials, and system studies. Currently, a high level DOE review of the program is underway to provide recommendations for a strategic plan.

1. INTRODUCTION

The Magnetic Fusion Energy Program of the United States Department of Energy (DOE) is currently organized around four key issues: understanding the physics of burning plasmas, development of improved confinement concepts, development of materials, and development of nuclear technology. This work involves 16 major research groups - national laboratories, universities, and industry. Steady progress has been made since SOFT-1988, and this paper reviews these advances.

2. PHYSICS RESULTS

Considerable progress in understanding plasma transport has been made at TFTR. The use of boronization, pioneered by the TEXTOR group, has reduced the time required for wall conditioning following a vacuum vent from 6 weeks to 3 weeks and has significantly reduced the time required to recover from a disruption. Carbon/carbon composite tiles installed on the high heat flux regions of the TFTR inner bumper limiter have increased its energy handling capability to 50 MJ per pulse and have eliminated the problem of carbon "blooms." Neutral beam heating of "supershots" at powers of up to 32 MW has produced D-D neutron rates of 4.1×10^{16} neutrons/second and projected Q_{D-T} values of approximately 0.5. ICRF heating experiments have reached antenna power densities of 1 kW/cm^2 and have demonstrated the capability to stabilize sawtooth oscillations and increase the electron temperature in "supershots."

The DIII-D program is a broad-based program, integrating new diagnostics with divertor geometry and heating systems of next generation devices. High beta experiments have achieved average beta values of 11% and demonstrated that the Troyon limit adequately describes the maximum beta that can be routinely obtained over a wide variety of plasma parameters. At moderate powers, H-modes of up to 10 seconds have been obtained with no impurity accumulation. Experiments with up to 1.7 MW of ECRF power have demonstrated both efficient heating, with central electron temperatures of 5 keV, and current drive, with up to 50 kA of driven current. Gas puffing in the divertor region has been shown to reduce the heat load to the divertor plates by a factor of two.

The ATF program studies concept improvement, conducts studies of fundamental plasma physics, and ultimately will investigate high-beta, steady-state operation. Recent improved performance is comparable to that of similar sized tokamaks. Gettering and proper gas programming have led to increased energy confinement times (~20 ms) with quasi-stationary conditions for 0.2 seconds (limited by the duration of the beam pulse). The bootstrap current measured during a scan of the dipole and quadrupole fields was found to agree with neoclassical theory.

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3. PLASMA TECHNOLOGIES

The Plasma Technologies Program activities include magnetic systems, plasma heating, plasma fueling and particle control, and plasma interactive materials.

3.1 Magnetic Systems

The goal of the magnet systems technology program is to establish a technical base for efficient magnet configurations for plasma shaping and confinement. This program includes research and development of superconducting magnet components/sub-systems, magnet materials, and cryogenics. The focus of the magnet program is on supporting R&D for validating the ITER magnet design assumptions.

The high field and pulsed magnet research and development activity is currently being pursued at Lawrence Livermore National Laboratory (LLNL) and Massachusetts Institute of Technology (MIT). The tasks involve the design, fabrication, and testing of various superconductors and small coils. Primary emphasis is on the development of cable in conduit superconductors for future use in pulsed high field central solenoids, shaping coils, and toroidal field magnets such as those envisioned in the designs for ITER. High field (14 T) tests are planned at LLNL as part of the development process. In addition, a pulsed superconducting coil, the U.S. Poloidal Demonstration Coil, has been designed and built under the direction of MIT and is now at the Japan Atomic Energy Research Institute (JAERI) where it will be tested later in the year.

3.2 Plasma Heating

In addition to ohmic heating, energetic neutral particle beams and high frequency electromagnetic waves have been shown to be capable of heating plasmas to thermonuclear temperatures. The many variations of techniques within each method, the complexities associated with the technology, and the physics of plasma interactions make it difficult to choose a reference at this time. Hence, component development and experimentation in both areas are systematically being pursued.

Long pulse positive ion based 80 and 120 keV neutral beam systems have been developed for current experiments. Long pulse sources have operated very reliably on TFTR and D-III. Since the efficiency of the positive ion based system falls off at higher particle energies, negative ion neutral beam systems are being developed for use up to 1 MeV and beyond. Worldwide results on the use of neutral beams for current drive have caused a resurgence of interest in developing negative ion based neutral beams for the ITER design. At Lawrence Berkeley Laboratory (LBL) an Electrostatic Quadrupole Negative Ion Source and Accelerator are under test with a 0.2 A source and voltage up to 200 kV.

A conceptually more attractive system than neutral beams for heating plasma is electromagnetic waves with frequencies ranging from low MHz to over a hundred GHz. Conventional RF sources in the low to mid MHz range of frequencies at the desired megawatt power levels are readily available from industry. These sources are used for ICRF heating. A notable recent accomplishment is the test of a Varian-EIMAC tetrode at JAERI at 1.7 MW, 131 MHz for 5.4 sec. Previous tests at 2.5 MW, 45 MHz and short pulse were conducted in the U.S.

The development efforts in ICRF heating have been primarily directed towards reliable wave launching antenna systems which can handle high power and high power density. The Radio Frequency Test Facility (RFTF) at ORNL is used to test these development antennae in a plasma environment. A compact antenna for Tore Supra has been delivered and will be installed in the near future.

Heating plasmas confined by magnetic fields up to 10 T by means of Electron Cyclotron Resonance would require high power millimeter wave sources with frequencies as high as 280 GHz. For more than a decade, the U.S. program has been supporting R&D efforts to establish an industrial base which could supply high power gyrotrons for fusion use. Currently, Varian, the major gyrotron manufacturer in the U.S., can provide steady state and pulsed 200 kW gyrotrons in the 28 to 70 GHz range as well as steady state 100 kW (and pulsed 200 kW) 140 GHz gyrotrons. Varian development of a steady state 0.5 MW 140 GHz gyrotron is in progress. Recent test results are 400 kW, 140 GHz and 0.5 sec with efforts underway to extend the pulse length to 2 or more seconds.

3.3 Plasma Fueling and Particle Control

Supplying fresh fuel to the plasma by injection of high speed solid pellets of frozen hydrogen or its isotopes has been found to improve its confinement properties. ORNL has been developing advanced pellet fueling systems that can deliver pellets with velocities up to 2 km/s using pneumatic acceleration. These injectors have been used successfully on TFTR, JET and Tore Supra. Advanced units with tritium capability are being considered for TFTR and JET. ORNL is also developing two stage injectors with pellet speeds in the 2-5 km/s range.

3.4 Plasma Interactive Materials

In the plasma interactive materials program, the main facilities are the Plasma Materials Test Facility (PMTF), the Tritium Plasma Experiment (TPX) at Sandia National Laboratories (SNL), and the Plasma Surface Interaction Research Facility (PISCES) at the University of California, Los Angeles (UCLA).

The Plasma Interactive Materials/High Heat Flux programs are coordinated national efforts providing data, materials, and components to such facilities as TEXTOR, Tore Supra, ASDEX, JET, TFTR and DIII-D.

An ongoing series of pumped limiter simulation experiments have been performed in the PISCES facility. The efficiency of plasma neutralization and pumping is being investigated for both hydrogen and helium plasmas. An active limiter program has been initiated at UCLA to study the possibility of influencing the edge plasma through electrostatic limiters.

A major collaboration with Princeton Plasma Physics Laboratory (PPPL) has been established on issues associated with D-T operation in TFTR and CIT. All plasma-facing and neutral beam materials have been tested for tritium compatibility in the TPX. Models for tritium recycling behavior have been developed, and an in-vessel tritium inventory estimate for D-T operation in TFTR has been established. Tritium inventory estimates have been made for CIT, and collaborative measurements with INEL on tritium release rates from tritiated carbon surfaces during accidental air exposures have been initiated. The properties of beryllium are being investigated in collaboration with JET, and erosion/redeposition studies are also underway in DIII-D. HHF limiter elements have been tested for Tore Supra, and the phase 3 pumped limiter will be delivered later this year.

4. FUSION TECHNOLOGIES

The Fusion Technology Program activities include fusion materials, fusion nuclear technology, and environment and safety.

4.1 Neutron Interactive Materials

The Structural Materials Program will provide material options for fusion power reactors - demo and beyond. The program produces information for nearer-term needs on the way to this goal. This has resulted in a large part of the data needed to qualify 316 SS for ITER.

A major goal is the development of low activation structural materials (shallow land burial). The approach is to develop new compositions of alloys with performance at least equal to the alloy's conventional counterparts. The major material classes under study include manganese-stabilized austenitic steels, modified ferritic steels, vanadium alloys, conventional steels of both austenitic and ferritic compositions, copper alloys, and ceramic and composite materials. The interest in ceramic composites was developed in the ARIES-I reactor design study, discussed below, which explored the use of SiC-SiC composites for the reactor structure.

The program also is obtaining a fundamental understanding of controlling mechanisms. This program element uses data on both engineering alloys and model alloy systems to test specific material performance questions and to develop predictive models.

The program is heavily weighted towards understanding the response to fusion reactor irradiation. Of necessity, this work relies mainly on fission reactor irradiations - currently using the FFTF fast reactor and the HFIR mixed spectrum thermal reactor. Other important program segments focus on compatibility and corrosion issues, physical metallurgy, mechanical properties, and fabrication and joining.

Two major international collaborations with Japan use HFIR and FFTF. Collaboration with the USSR is limited to exchange of information and experimental work on manganese stabilized austenitic stainless steels. Collaborations with the EC include ties with KfA, KfK, Riso, and Ispra.

4.2 Blanket Technology

Blanket technology efforts are focused on critical feasibility issues for promising blanket concepts. The Argonne Liquid Metal Experiment (ALEX) studies magnetohydrodynamic effects on pressures and flows of liquid metal transport through magnetic fields. Data from ALEX guides the development of models and computer codes for predicting the performance of self-cooled liquid breeder blankets. Experiments have been completed on circular and rectangular cross-section flow channels as well as a more complex "flow-tailoring" module in collaboration with KfK. Blanket collaboration is continuing in the IEA BEATRIX programs to develop solid breeder materials and study their performance in fission reactors. Data is accumulating on a wide range of candidate solid breeder materials tested in both open and closed capsules. BEATRIX-II is providing high-fluence, in-situ tritium recovery data in the FFTF reactor during its 1990 testing period.

4.3 Nuclear Analysis Activities

Efforts continue on development and dissemination of computational methods and data bases that support design and analysis of fusion devices. A major element is the U.S.-Japan collaboration on blanket integral neutronics experiments in Japan's Fusion Neutron Source facility. These experiments establish a data base for the tritium breeding performance of Li_2O blankets. Experiments on simple blanket models and on more advanced prototypical models have been completed, and experiments simulating a line source of neutrons began in late 1989.

4.4 Tritium Processing Technology

Experiments on tritium processing and handling are carried out on the Tritium Systems Test Assembly (TSTA) at LANL. Since June 1987, TSTA has been funded jointly by DOE and JAERI. The facility tests the technology required to control, separate, and purify deuterium and tritium from the plasma exhaust. TSTA, which contains a full tritium processing loop, became operational in 1984 and has operated with up to 105 grams of tritium. Studies are presently underway to consider expanding the TSTA to demonstrate the technology for processing different blanket concepts. Outside of the processing system, LANL is conducting a number of tests, including a pellet injector with tritium and testing candidate tritium storage bed materials. LANL has completed testing two JAERI designed "process-ready" components, a palladium diffuser and a ceramic electrolysis cell. These components are part of JAERI's newly designed and built fuel cleanup unit that was installed at TSTA in early 1990.

4.5 Environment and Safety

The environment and safety program is responsible for assessing and evaluating issues related to the operation of fusion reactors and for developing appropriate technology for public and operator safety. The fusion safety research program is centered at the Idaho National Engineering Laboratory (INEL). INEL has completed the environmental assessment for siting the CIT at Princeton and is developing codes and models which can demonstrate the operational and safety aspects of fusion systems. Demonstration of safety features, particularly passive safety, will help ensure public and operator safety as well as public acceptance of fusion devices.

Two major experimental efforts over the past year have been tritium and activation product behavior. INEL is continuing its experiments on tritium implantation/permeation in plasma facing materials to determine the extent of tritium build-up and release mechanisms in the material. Activation product behavior tests involve release of activation products by heating potential materials to high temperatures and measurement of volatized elements. Both activities have recently emphasized tests on copper and tungsten.

5. FUSION DESIGN STUDIES

Near-term experimental device studies include the CIT and ITER. The U.S. continues involvement as a full partner in the ITER conceptual design activities, including associated research programs. Discussions among the parties are continuing regarding the design and supporting research of the ITER-EDA.

The long-term study of commercial reactors is the Advanced Reactor Innovations Evaluation Study (ARIES) which began in January 1988. It will explore several "visions" of attractive tokamak power reactors given the physics and technology advances that have been made since the STARFIRE study 10 years ago. Many methods have been considered for improving the tokamak concept, including high beta (>20%), direct conversion, very low activation materials, advanced fuels, and high aspect ratio (~6). The ARIES-I design, based on near-term physics and advanced technologies, was completed in early 1990. ARIES-II, which is based on high beta and other advanced physics but more conventional technology, and ARIES-III, based on the D-^{3}He advanced fuel, will be completed in 1991.

6. REVIEW OF FUSION PROGRAM

The Fusion Policy Advisory Committee (FPAC) was established by the Secretary of Energy in March 1990 to advise the Secretary on the optimal way to structure the U.S. Fusion Program. An interim report of the committee in July 1990 recommended, among other things, that the U.S. commit to a fusion energy program, participate in the ITER Engineering Design Activity, and pursue an engineering demo operating by the year 2025 and a power plant by 2040. The committee is scheduled to submit its final report to the Secretary in September. Subsequently, the Department of Energy will establish a strategic plan for fusion as part of the National Energy Strategy which is due to the President in December 1990.