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Contents

Preface	1
1983 Principal Parameters of Experimental Devices	3
Tokamak Fusion Test Reactor	5
Princeton Large Torus	33
Poloidal Divertor Experiment	43
Princeton Beta Experiment	54
Spheromak	57
Advanced Concepts Torus-I	60
X-Ray Laser Studies	62
Theory	65
Tokamak Modeling	70
Reactor Studies	73
Spin-Polarized Fusion Program	74
Tokamak Fusion Core Experiment	75
Engineering Department	77
Planning and Resource Management	93
Quality Assurance and Reliability	94
Administrative Operations	95
Graduate Education: Plasma Physics	106
Graduate Education: Fusion Reactor Technology	109
Section Coordinators	112
Glossary of Abbreviations, Acronyms, Symbols	113

Cover: Tokamak Fusion Test Reactor (TFTR) with neutral beamline installed in position No. 3.
Photographed by John Peoples and Joseph DiBartolo

Preface

The Tokamak Fusion Test Reactor (TFTR) achieved first plasma at 3:05 a.m. on December 24, 1982. During the course of the year, the plasma current was raised to a maximum of 1 MA, and extensive confinement studies were carried out with ohmic-heated plasmas. The most important finding was that tokamak energy confinement time increases as the *cube* of the plasma size. This scaling is more optimistic than the previously assumed square-law dependence. The critical test for tokamak confinement will come during the period 1984-86 when intensive neutral-beam heating will be used to raise the TFTR parameters into the reactor plasma regime.

During FY83, the Princeton Large Torus (PLT) carried out a number of high-powered plasma-heating experiments in the ion cyclotron frequency range, and also demonstrated for the first time that a 100-kA tokamak discharge can be built up by means of rf-waves in the lower hybrid range, without any need for inductive current drive by the conventional tokamak transformer system.

The Poloidal Divertor Experiment (PDX) demonstrated that substantial improvements in plasma confinement during intense neutral-beam heating can be obtained by means of either a magnetic divertor or a mechanical scoop limiter. In both cases, the plasma impurity content can be held below $Z_{\text{eff}} = 2$. The PDX experimental program was terminated in mid-1984, to permit conversion of the machine to a new configuration, the Princeton Beta Experiment (PBX). Beginning

in early 1984, the PBX will explore the stabilizing effects of the tokamak bean-shape, which theoretically should permit substantial increases of the plasma beta value.

The S-1 spheromak experiment has come into operation, with first plasma in January 1983, and machine completion in August. The basic formation scheme works as predicted, producing spheromak plasmas with lifetimes in the 1-msec range.

The soft X-ray laser development experiment continues to make strong progress towards the demonstration of laser amplification. Thus far, a single-pass gain of 3.5 has been achieved, using the 182 Å line of CVI.

Theoretical MHD-stability studies have shed new light on the nature of the energetic-ion-driven "fishbone instability," and the utilization of the bean-shaping technique to reach higher beta values in the tokamak. Important progress is also being made in the theory of lower hybrid current ramp-up. Computer modeling studies are helping to provide insight into the experimental success of tokamak divertors and their prospects for future application.

A national program of preconceptual design studies for an ignition experiment—the Tokamak Fusion Core Experiment (TFCX)—has been initiated, with PPPL assuming responsibility for overall coordination. The objective is to lay the groundwork for the start of conceptual design activity in 1984.

1983 PRINCIPAL PARAMETERS OF EXPERIMENTAL DEVICES

Parameters	Primary Facilities			Secondary Facilities	
	PLT	PBX*	TFTR	S-1	ACT-I
R (m)	1.32	1.45	2.48	0.40	0.59
a (m)	0.4	0.45	0.85	0.25	0.1
I _p (MA)	0.7	0.6	2.5 ^{††}	0.5	—
B _T (T)	3.4	0.8	5.2 ^{††}	0.5	0.55
τ _{TF} (sec)	1.5	1.0	3.0	0.001	dc
P _{AUX} (MW)					
NB	2.0, 40 keV	8, 50 keV	27, 120 keV ^{††}	—	—
ICRF	3.1, 30 MHz	—	—	—	0.002
LH	0.7, 800 MHz	—	—	—	0.02
ECRH	—	—	—	—	0.002
τ _{AUX} (sec)	0.3	0.3	0.5	—	dc
n _{max} (cm ⁻³)	10 ¹⁴	10 ¹⁴	10 ^{14††}	3 × 10 ¹⁴	5 × 10 ¹²
T _{max} (keV)	7	1.5	20 ^{††}	0.2 ^{††}	0.04

*Under construction.

††Design parameter.

TOKAMAK FUSION TEST REACTOR

Over the lifetime of the Tokamak Fusion Test Reactor (TFTR) Project, one might project three periods of somewhat less than one year that would be expected to produce extraordinarily exciting results of worldwide impact. The events of the past year, described in some detail in the following sections, surely will qualify FY83 as one of the three. (The other two will likely be full power operation with neutral beams and the $Q \sim 1$ demonstration with tritium.)

The accomplishments of the fiscal year chronologically, and rather precisely, follow the plan outlined in detail well before the year began. The first three months (October, November, December 1982) were largely devoted to final assembly of the tokamak itself by craft laborers under the direction of the Ebasco/Grumman Industrial Subcontract team and to installation of the initial diagnostics by Princeton Plasma Physics Laboratory (PPPL) personnel. In parallel, an intensive management effort went into planning, scheduling, and implementing an Operational Readiness Review (ORR). Major review boards, chaired and staffed by international experts, closely scrutinized every aspect of the proposed operations ranging from equipment protection, personnel safety, fault-tree analysis, etc., to project management, staff organization, operating and maintenance manuals, and operations planning. A third parallel effort was directed toward implementing a comprehensive set of integrated systems tests that were codified through formal written procedures and conducted in-and-around the other ongoing preparations. These tests followed previous preoperational tests on individual subsystems, and were focused on observation and evaluation of the interactions arising from interconnecting and energizing several such systems simultaneously (e.g., power supplies, water cooling, and magnetic field coils) in the manner required for plasma operations. Throughout this period the Central Instrumentation, Control, and Data Acquisition System (CICADA) was also undergoing system testing while simultaneously supporting the integrated systems test program.

These intense parallel efforts all came into focus at 3:05 a.m., December 24, 1982, when, for the very first time, a puff of hydrogen was injected into the torus as the coil systems were energized, and a 51-kA plasma was formed that lasted for about 50 msec (Fig. 1). This first-plasma operation was followed by a month of combined plasma and systems engineering work, which demonstrated the basic ability of the TFTR device to operate according to plan and without fundamental problems. Having achieved this objective, the effort was turned to the next task, namely,

Figure 1. TFTR First Plasma. "First-plasma" pulse in TFTR at 3:05 a.m., December 24, 1982. (84X2330)

over a two-month period, to install the extensive diagnostics required for an intensive experimental run period scheduled for the months of April, May, and June. In parallel, major efforts went into additional power supply commissioning, the conversion of the CICADA system software to an advanced version, and extensive upgrades in applications programming. During this run period, results were well above expectations. Operation at pulsed, toroidal-field levels up to 27 kG, combined with closed-loop feedback control on the plasma radial position, the plasma current, and the gas feed system, allowed effective experimental work at plasma currents of up to 800 kA with flattops of more than 1 sec. In fact, a brief peak plasma current of 1 MA was achieved (Fig. 2). During the approach to these levels, glow discharge cleaning was combined with some 25,000 pulse discharge cleaning (PDC) shots to obtain adequate vacuum vessel cleanliness. The PDC shots were at plasma current levels of 100-200 kA with durations of 0.1 to 0.2 sec and typical repetition rates of 8 per minute.

These machine conditions, combined with an excellent set of diagnostics, well integrated with the CICADA system, resulted in new understandings of plasma energy confinement scaling with density as it relates to major and minor plasma radius. Figure 3 summarizes the data for TFTR which indicates that

Figure 2. TFTR Plasma Current History. Improvement in plasma current during first six months of TFTR operation.

Figure 3. TFTR Energy Confinement. Preliminary results in plasma energy confinement scaling in TFTR as compared to a compilation of data obtained from studies of ohmically heated plasmas in many earlier tokamaks in the U.S. and elsewhere.

for ohmically heated discharges the relation $\tau_E \sim n_e R^2 a$, previously demonstrated worldwide on many tokamak devices, applies as well to larger machines.

This very productive run period was followed by a two and one half month shutdown that began on schedule. The major objectives of the shutdown were the installation of the protective bellows cover plates

(Fig. 4), the high-power-capability movable limiter (Fig. 5), and additional diagnostics. In addition, eight prototype zirconium-aluminum (Zr-Al) surface pumping panels were installed, and work continued on many auxiliary components and subsystems. Of major importance was the beginning of the commissioning work on the ohmic heating interrupters,

Figure 4. Bellows Cover Plates. Bellows cover plates mounted inside the TFTR vacuum vessel. (84E0993)

Figure 5. High-Power Movable Limiter. The limiter and actuator mechanism is undergoing final assembly and checkout in preparation for installation in the tokamak vacuum vessel. (83E1111)

needed to provide adequate volt-second capability during the scheduled October, November, December 1983 experimental run. Additional power supply commissioning, preparation for vacuum vessel bakeout, and other similar tasks were also in progress. A particularly important achievement was to accelerate the completion of the mechanical assembly of the first TFTR beamline to permit its installation during this shutdown period—six months ahead of schedule. The intention was to establish, as early as possible, that no major fit-up problem existed. Fortunately none was found, thus increasing confidence that the work scheduled for the next shutdown period would proceed on schedule. All of the work inside the vessel was completed slightly ahead of schedule, and the vessel was pumped down on September 16, 1983. The final two weeks of FY83 were devoted to leak checking, vessel hi-potting, initial operation of the bakeout equipment, etc., in preparation for the fall run. A more complete discussion of the events of this exciting first year of TFTR operation is given in the following sections.

The TFTR team looks forward to a productive experimental run in early FY84 that is intended to explore more thoroughly the confinement of ohmically heated plasmas at plasma currents of 1 to 1.5 MA, and also to starting studies on plasma compression. The next shutdown is scheduled to begin on January 15, 1984, with the primary mission of completing the installation of two neutral beamlines. This shutdown will be followed by an extensive experimental run period to determine the results of neutral-beam heating at the 10-MW level. These experiments should offer the first real clues as to the ability of TFTR to reach the operating levels required for the $Q \sim 1$ demonstration with deuterium-tritium (D-T) plasmas.

SAFETY AND ENVIRONMENTAL MONITORING

Safety of personnel and property as well as possible environmental impacts continued to be important considerations for the planning, testing, and operating activities in the TFTR program. A program (initiated in CY82) of analyses to determine the concentrations of radioactive pollutants in the air and ground water at the TFTR site was continued. Analyses of nonradioactive pollutants in surface waters was performed in-house in CY83. These analyses are a part of the program to establish a reference baseline for the TFTR facility prior to significant operating activity and to carry out the continuing environmental monitoring required to comply with State and Federal regulations. The Laboratory published its first annual environmental report for CY82 in March of 1983.

Four real-time prompt gamma ionization chamber monitors were installed at the exclusion zone boundary (EZB), and eight others of lower sensitivity were placed in close proximity to the Test Cell. All monitors were active whenever the tokamak was in

operation. The interface connections to CICADA and subsequent testing are now being finalized. Passive thermoluminescent dosimeter (TLD) monitors were placed inside and outside the Test Cell to measure bremsstrahlung radiation emission levels and profiles for comparison with predicted doses during tokamak operation. The TLD data collected were found to be an important diagnostic for machine operation as well as for safety applications.

Required written procedures were prepared for all component installation, integrated systems testing, operational testing, and crane lifting activities. A primary consideration in developing these procedures was that all safety implications had been addressed and that procedures are reviewed and approved by the Project and Operational Safety Group prior to implementation. Under an upgraded safety program, Area Safety Coordinators were also assigned to cover each area of the TFTR complex in order to help in maintaining a safe working environment and a safety awareness on the part of all project staff.

CENTRAL INSTRUMENTATION, CONTROL, AND DATA ACQUISITION SYSTEM

The CICADA provided 14 console operating stations (COS) and 10 terminal operating stations (TOS) to support first-plasma operations. Half of these stations were located in the TFTR Control Room and the other half were in remote locations close to the equipment being controlled. Software and hardware were operational to collect 800 kilobytes of data for six diagnostics and to automatically display waveforms after each shot. Over one hundred interactive displays were provided to control and monitor operation of the motor generator, water, vacuum, and power conversion subsystems.

From this auspicious beginning the demands on the CICADA system grew very rapidly. By the end of the year 34 stations were operational and 23 diagnostics were taking data at the rate of 3.6 megabytes per shot. Considerable effort was put into providing the facilities and performance characteristics necessary to support the anticipated workload:

- The computer operating system was upgraded to gain necessary file and data handling capabilities.
- Three central facility computers were upgraded to SEL 32/87's to increase performance by a factor of five.
- Software that supported first plasma was overhauled to reflect new requirements, to correct problems, and to improve reliability and performance.
- Support was provided for additional devices and applications.

FACILITIES OPERATIONS

Operational Readiness Review

Organization of the first-plasma Operational Readiness Review (ORR) was carried out in the late summer of 1982, and the review itself took place in three stages during October through December of 1982. The review was organized into a "requirements tree," the top level of which included five major elements: personnel, equipment and software, safety, experimental buildings and services, and management systems and procedures. These major elements were further subdivided into more detailed, lower-level ones. Matrices were prepared in which each of the lower-level elements was listed with a set of predetermined readiness criteria. Each of these subelements was first reviewed and evaluated in terms of readiness status. Readiness of each top-level element was established when all subelements satisfied the readiness criteria. When the readiness of all five top-level elements was established, TFTR was declared to be ready for operation. Throughout the review, a major emphasis was placed upon safety of personnel and protection of equipment.

For the first-plasma Operational Readiness Review, a panel of independent authorities was assembled under the leadership of the review panel chairman, Dr. H.P.F. Conrads, of the TEXTOR project in West Germany. The panel included representatives from the Joint European Torus (JET) in England and from a number of national laboratories in the United States. The review was successfully concluded in December, 1982, and the review panel's final report, along with a request for permission to operate TFTR under first-plasma limitations, was submitted by PPPL to the Department of Energy (DOE). The DOE formally granted that permission upon completion of the required integrated systems tests on December 24.

A smaller Operational Readiness Review was held in March, 1983, prior to operation of TFTR under full ohmic heating conditions. Only those elements that had been added to TFTR since the earlier review were considered. Based upon recommendations of another independent review panel, the Department of Energy granted approval for ohmic heating operation. Further Operational Readiness Reviews will be conducted in the future, specifically prior to addition of neutral-beam heating and the use of tritium in the machine.

Tokamak Assembly

Assembly of the major machine components in the Test Cell to form the TFTR tokamak was completed in December 1982. Figure 6 shows the installation of the last major component, the umbrella structure, complete with all of the upper poloidal-field coils. This lift of approximately 100 tons was one of the most critical of the whole assembly. The lift operation proceeded smoothly and once the structure was bolted to the vertical columns (which had previously been placed in position) the vacuum vessel heating

Figure 6. Umbrella Structure. Installation of the umbrella structure, with upper poloidal-field coils attached, on the column and lintel supports—October 1982. (83E1064)

and cooling manifolds, the upper ring busbar assembly, and other auxiliary components were connected and tested. First plasma was achieved in the early morning of December 24, 1982.

During the early part of fiscal year 1983 many of the midplane horizontal vacuum cover plates were removed and replaced with specially prepared diagnostic units. The Cefilac metallic vacuum seals (Fig. 7) performed well. A procedure was developed which permits these seals to be changed and vacuum leak checked prior to the torus pump down. Two complete sections of the vertical busbar system, which had developed water leaks, were removed and replaced with new ones made in the PPPL coil shop. The vacuum vessel ground monitoring system was debugged and became fully operational.

An overhead crane of 100-ton capacity was purchased and installed in the Mock-Up area (Fig. 8). A small machine shop was set up on the north wall to serve TFTR's immediate needs. On the south wall two small diagnostic laboratories were built. Plans have been made to move the TFTR M3 Mock-Up into the center of this area, where it will be used to perfect remote handling techniques and for preassembly work on equipment to be fitted onto the tokamak in the Test Cell.

Mechanical Systems

The year marked the transition from preoperational testing to regular operation of the deionized water cooling systems for the coil and rectifier systems,

Figure 7. Cetilac Metallic Vacuum Seal. The seal is shown being prepared for installation on a large diagnostic port cover. (82E0814)

Figure 8. Mock-Up Area Crane. Installation of a bridge beam for the 100-ton Mock-Up Area crane. The first beam is shown already mounted in place on the crane rail. (83E1379)

the vacuum pump cooling system, the high volume air systems for bellows cooling and vacuum vessel heating, and also the heating, ventilating, and air conditioning (HVAC) systems for environmental control in the experimental areas.

Initial operation of the coil cooling systems indicated that the capacity of the 1100-ton chiller units

was in excess of cooling requirements during many periods of experimental operation. A high-penetrant, plate-type heat exchanger was installed between the coil cooling system (deionized water) and the component cooling system (phosphate treated water) to enable maintenance of normal system temperatures by using the 105-ton component cooling chiller except when the coil systems are powered.

Analysis of the rectifier (Field Coil Power Conversion) cooling system indicated that the 2100 gpm capacity is inadequate for the final number of power supplies (39 versus the 30 specified in the initial design) to be installed on TFTR. Plans were made (and purchase of major items initiated) to remove a number of system restrictions and to install a larger pump of 2800 gpm capacity. This will increase the system capability to meet anticipated maximum cooling requirements of the rectifier subsystems.

Initial operation of the high volume air compressor system for cooling the vacuum vessel bellows indicated satisfactory system performance. However, the vessel jacket air heating system indicated a temperature limitation of 125 °C due to excessive heat loss from the supply piping which is some 300 ft in length. The piping was insulated, and subsequent operation indicated that the system capabilities are now adequate for heating the vacuum vessel to at least 200 °C. The system was subsequently used for long-term "bakeout" of the vacuum vessel over a three-week period.

The experimental area HVAC systems were marginal during the early run period in terms of ability to maintain the dew point at levels below that required to assure no risk of surface condensation on the center-cooled, high-voltage buswork. Changes in system operating procedures were initiated and experimental area dew point temperatures are now maintained well within the required range.

Motor Generator

The General Electric Company (GE) spent most of the fiscal year attempting to balance Motor Generator (MG) Set No. 1 at its operational speed. In January the MG Set was pulse tested using the dummy load to investigate the hysteresis problems related to rotor bearing runout. Several solutions were tried, such as removing the welded blocks from the drive keys, installing air ducts to neutralize the pressure at the upper-guide bearing, reducing the bearing clearance, retorquing all of the rim studs, broaching all radial keyways and fitting new keys, adding shims to the tangential keys, and trying many different configurations of balance weights. None of these corrective actions produced a significant improvement to the vibration problem, and runout of the upper-guide bearing was typically about 18 mils. In March during pulsed operation with the TF coils as the load, an 800 MJ pulse was achieved which caused a maximum runout of 13 mils.

A meeting between PPPL and GE took place at Princeton during July to discuss the runout problem and to develop agreement on a permanent solution.

It was decided to stiffen the upper-guide bearing by fixing tubular struts from the upper-guide bearing housing to the concrete walls of the MG pit. This design was modified by PPPL, and solid bar struts have now been fitted in place (Fig. 9). It was also decided to attach strain gauges and deflection monitors on critical parts of the generator rotor (Fig. 10) to measure stresses and deflections during operation. At the same time, short radial keys were installed to tighten the rim. A trial run demonstrated that these modifications reduced the maximum bearing runout to 8 mils. As a corrective action, PPPL has asked GE to redesign the upper-guide bearing and pivot to ensure that maximum stiffness can be obtained. Acceptance tests are expected to take place early in October 1983.

Energy Conversion Systems

In December of 1982 a major effort was made to bring a minimal power system on-line for first plasma. At that time seven power supplies were operational along with all twelve capacitor bank sections. Although the equipment ran, it was not very reliable, and the control software, though functional, was neither sufficiently reliable nor "user friendly."

Early in 1983 a project organization was formed to tackle the energy conversion system problems and to expedite the commissioning of more power supplies. Since then there have been many significant

achievements. By the end of FY83 twenty-two of the full complement of 39 power supplies were fully commissioned. Most of the reliability problems were resolved, and the commissioning procedure was greatly improved. The capacitor charge/discharge equipment problems were essentially solved. The control software application programs (the "user friendly" interface) were brought into use to replace those originally intended only for testing.

By the end of the fiscal year, the toroidal-field (TF) capability was 38 kA and 6 kV. The equilibrium-field (EF) capability was 24 kA and 18 kV, and the ohmic heating system had run at 24 kA and 18 kV. Ohmic heating interrupter testing and commissioning began producing good results toward the latter part of the fiscal year. Operation at nearly full rating running into a dummy load was demonstrated.

The major goals for FY84 will be to complete the power supply and interrupter commissioning, implement the final-version power supply fault detector, operate the toroidal-field circuit with four rectifiers in parallel, and run the entire subsystem at full rating. Work will continue also on making control software enhancements.

Torus Vacuum Pumping System

The torus vacuum pumping system (TVPS) first went into operation as a complete system when the TFTR vacuum vessel was evacuated at the end of

Figure 9. Motor Generator (MG) Upper Guide Bearing Stiffeners. The stiffeners are shown (upper and lower center) mounted between the bearing support structure and MG pit walls. (83E1121)

Figure 10. Displacement Gauges Mounted on MG-Set Rotor. (83E0964)

October 1982. During the early part of that month, the TVPS, isolated from TFTR, had undergone an integrated systems test. The first month of operation consisted primarily of leak checking of the TFTR and the vacuum ducts, as well as problem solving associated with TVPS operation. The TVPS and the TFTR were vented to atmosphere at the end of November and evacuated again at the beginning of December. At that time, the first of two residual gas analyzer (RGA) systems was installed to help diagnose the conditions of the vacuum in TFTR. The three prominent impurities in a stainless steel vacuum chamber that are detrimental to the production of a fusion grade plasma are methane, water vapor, and carbon monoxide. The partial pressure of these constituents of the vacuum environment in TFTR were monitored with the RGA. During the November-December period, out of a total of eight Turbo-Molecular Pumps (TMPs), two were shut down due to concerns about vibration. In December a large leak was discovered in a stainless steel flange which is a main component of the ceramic break. The leak was due to material failure in the stainless steel which resulted in a crack through the thick cross section of metal. The leak was sealed by welding a patch on the inside of the duct.

During the month of January, plasma operation was carried out. The TVPS continued to operate with six TMPs without major incident. The first period of glow discharge cleaning (GDC) for conditioning of the vacuum vessel began in January. Tests on the vacuum system and vessel were performed during the first week of February to determine system characteristics, such as pumping speeds for various gases at different pressures, volumetric measurements, and recombination coefficients for hydrogen on the stainless steel wall of TFTR. The machine was vented to atmosphere again the second week of February, beginning a period of maintenance and diagnostic installation work. During this period, the two TMPs that had been shut down earlier were rebuilt and brought back into operation. It was discovered that the TMP isolation valves, which had polyimide gate seals, were all leaking at various rates. The leakage problem of these polyimide seals was thoroughly considered with respect to original and future design requirements, and a decision was made to rebuild all of the valves using Viton seals. The rebuilding of one valve was completed during the shutdown.

At the end of March, the torus was again evacuated and the second run period was started. Glow discharge cleaning and PDC were used to condition the vacuum vessel during the April, May, June period. During this period, significant leaks were discovered in the torus bellows sections between Bays E/F and M/N. These bellows were back filled with helium during plasma operation. The final activity during this period was bakeout of the vacuum vessel at 100 °C.

The best overall vacuum vessel leak rate obtained during FY83 operations was approximately 2×10^{-5} Torr-liter/sec for nitrogen. The lowest total pressure attained was approximately 4×10^{-8} Torr with the partial pressure of impurities reduced to the 10^{-9} -

10⁻¹⁰ Torr range. These figures are expected to improve when internal surfaces become better conditioned as the result of continued plasma operation.

In-Vessel Activities

In FY83 there were two major vacuum openings during which a considerable amount of hardware was installed inside the TFTR vacuum vessel. The first opening occurred in March, 1983. During this period, the following tasks were accomplished:

- The fixed graphite limiters were upgraded for 1-MA plasma current operation. This included the modification to strengthen the Bay-M limiter and the addition of a secondary graphite limiter in Bay-B.
- An optical survey was made to determine the "as built" positions of the approximately 300 mounting points on the internal vacuum vessel brackets. This information will be used in the construction of the protective plates and the bumper limiter.
- Approximately 150 bolt studs were mounted on the vessel shell for mounting the vessel work platform and lifting fixtures.
- Two temporary bellows cover plates were installed to investigate possible problems in the vessel.
- Ten magnetic fluctuation coils were installed.
- A calibration of the neutron detectors was performed using a radioactive source inside the vessel.
- Thomson scattering diagnostic hardware was prefitted in preparation for the next vacuum opening.
- A calibration of the magnetic diagnostics was performed using coils placed inside the vacuum vessel.

In the interval between the first and second openings, extensive work was performed inside the M3 Mock-Up of the TFTR vacuum vessel, developing the hardware and techniques necessary to install the bellows cover plates—the major activity of the second opening. Figure 11 shows an installation crew inside the TFTR vacuum vessel preparing to install one of these cover plates. The larger units weighed about 425 pounds, and a considerable amount of caution had to be exercised during installation in order to avoid damaging the vessel or the cover plates.

July 1983 Shutdown

The primary emphasis during this three-month shutdown period was directed toward upgrading the machine for operation at increased parameters. The vacuum vessel was vented to atmosphere. The vacuum vessel heating and cooling manifolds were removed for modification, hydrotesting, and installation of new electric breaks. The inboard vacuum vessel supports were modified and strengthened so

Figure 11. TFTR Bellows Cover Plate Assembly Installation. A specially designed fixture is required to handle the cover plate and bring it into final mounting position. (83E1099)

that they could withstand the increased mechanical loads to be produced during the next operating period as the result of running the machine at higher power levels.

The vacuum vessel was vented to atmosphere during the first week of July. The TVPS bellows sections were removed and the TMP isolation valves were rebuilt with Viton seals. The vacuum ducts were covered with blank flanges, and the TVPS was tested independently from the machine. The bellows sections were reinstalled at the beginning of September, and evacuation of the vacuum vessel for the third run period began in the middle of the month.

Machining was performed on support brackets inside the vacuum vessel, and 39 stainless steel diagnostic access pipes, which would interfere with the bumper limiter, were shortened. In addition, 45 vacuum vessel nut bars were removed and straightened. All of the 300 mounting points in the vessel were inspected and cleaned, and threaded inserts were replaced as necessary.

One hundred and twenty-eight bellows cover plates and eight surface pumping panels were installed during this opening. Leads for the thermocouples mounted on the cover plates and power cables for the pumping panels were also installed. Samples were removed from the EF bellows in the area of suspected leaks, after which a plate was welded over the area and leak checked.

A magnetic survey of the vacuum vessel mounting brackets was performed to determine the position of these brackets with respect to the toroidal magnetic field. This information was used in conjunction with the optical survey results to determine the position of the bellows cover plates with respect to the toroidal field, and to estimate the power loading on the plates when they are used as a bumper limiter. Mechanical measurements of the vessel mounting points were made and used in the fabrication of the initial protective plates. Other activities during this opening included:

- Installation of in-vessel support for mounting of the movable limiter.

- Installation of the Thomson scattering viewing dump, the laser dump, the baffles in the Bay-C pumping duct, and the support for the lower port cover.
- Alignment of the horizontal charge-exchange diagnostic bolometer, the Thomson scattering system, and a neutron monitor.
- Calibration of the neutron detection system using D-D and D-T neutron sources inside the vacuum vessel.
- Calibration of the magnetic diagnostic using magnetic coils installed inside the vacuum vessel.
- Connection of the leads for 19 internal magnetic fluctuation coils (mirror coils).
- Housekeeping activities such as photographing the vessel interior, inspecting the machine, and thoroughly cleaning the vessel prior to closing it.

Figure 12 is a photograph of the finished vessel interior showing the movable limiter, bellows cover plates, and surface pumping panels.

Figure 12. TFTR Vacuum Vessel Internal Hardware. The photograph shows the high-power capability limiter installed at Bay-M, with blades in the open position. Also visible are the zirconium/aluminum surface pumping arrays (upper and lower foreground at left) and the bellows cover plates. (83E1124)

Facility Fire Sealing

The continuing installation of fire seals in penetrations through fire walls and floors is on schedule. Most of the penetrations in the Test Cell, Test Cell Basement, Cable Spreading Room, and Pump Room are now sealed. A permit system was developed which allows seals to be removed and replaced during modifications while remaining under configuration control.

Training

As the assembly of TFTR neared completion in the fall of 1982, a formal training program was set up covering the operation of the various subsystems and the final assembly of the tokamak. Each instructional session lasted approximately two days, and successful candidates were awarded a certificate. Once crews became familiar with the operation of the machine, they were cross-trained in the operation of subsystems which were unfamiliar to them. These additional training sessions were typically about a week long. Lectures were held in a newly acquired training trailer with room for 15 to 20 students. Located next to the TFTR Test Cell, this site permitted easy interchange between the classroom and the practical sessions. Successful completion of each course required the passing of a final examination with a grade of 75% or better.

Since the lecturers, who were usually senior cognizant engineers or physicists, were not always available for specific training sessions, well-qualified outsiders were also invited to teach basic information in certain subjects. For example, a three-day course in vacuum technology was given by a consultant from the Lawrence Livermore National Laboratory, and another course on tritium handling and technology was presented by staff members from the Mound Facility in Ohio. Other general courses on topics in physics and mathematics were offered to project staff seeking basic background information to support their job assignments. It is fully expected that the overall training program will be expanded considerably during FY84.

TFTR Information Center

During FY83, 11,000 TFTR Project drawings were transferred onto 35-mm aperture cards. There are now 19,000 cards in the Information Center which have been indexed in a computer listing. A new reader/printer was acquired to "blow-back" hard copies of the drawings. Manuals, operations documents, and test data were also entered into the computer retrieval systems. At the end of the fiscal year the Information Center took over management of the TFTR Central Files. An inventory of the files was performed as the first step for a microfilming project. A Request for Proposal (RFP) is being prepared for a computer-assisted retrieval (CAR) microfilm system for TFTR documentation.

TFTR NEUTRAL BEAMS

The TFTR Neutral Beams Program has progressed from an effort (in FY82) primarily devoted to hardware procurement and assembly, to one of installation, commissioning, and testing (in FY83). The program is divided into five major systems: R&D, Mechanical Systems, Electrical Systems, Cryogenic Systems, and Systems Engineering. The latter encompasses instrumentation and controls, as well as the CICADA interface.

Research and Development

There was a high-level of activity in the R&D area during the latter part of FY83 in response to a general consensus that long-pulse beams should play the dominant role in any heating program for TFTR following the D-T demonstration. Active interaction was begun with the ion source development laboratories in regard to attaining the beam voltage, current, species mix, pulse length, and space envelope required to achieve the desired power capability in long-pulse (~2 sec) operation on TFTR in the 1986-87 time frame. At the same time, trade-off studies were conducted in connection with this effort by comparing the costs to upgrade beamline internal hardware versus pulse length, beam size, and beam divergence parameters in order to maximize the physics program options while minimizing upgrade costs. At this time, the consensus is that an approximately 2-sec pulse capability can be achieved with a total power in 120-keV D⁰ beams which exceeds the present short-pulse (~0.5 sec) system, matches the capability of the electrical power systems, and involves only modest internal hardware upgrades in relation to the costs of the new ion sources. The pulse-length upgrade can be achieved at the attractive cost of about \$0.4/watt of long-pulse capability.

A part of the R&D effort was also devoted to developing an in-house facility for ion source repair. Towards this end, a clean room facility was procured and installed which will house the optical alignment system and the support facilities necessary to perform in-house repairs.

Mechanical Systems

The neutral-beam test cell (NBTC) mechanical systems were completed during FY83. A checkout of the vacuum and cryogenic systems was also completed. Several tests of the dedicated 200-watt liquid helium refrigerator were made to confirm the integrity of the cryogenic system which includes the NBTC beamline, its target tank, and the cryogenic piping. These test results are discussed in detail under Cryogenic Systems.

Assembly of the first of the four beamlines planned for TFTR operation was completed in June of 1983. The system was moved to the Test Cell in July, and mechanical installation onto the tokamak was completed in August. Transfer over the approximate one mile from the assembly area to the Test Cell was

accomplished via a low-bed trailer as shown in Fig. 13, and a view of the neutral beamline connected to TFTR is shown in Fig. 14.

Assembly of the second TFTR beamline continued, with the mechanical installation onto TFTR planned for February 1984. These moves and installations are designed to achieve two beamline (six ion source) operation into TFTR by August 1984. After a reasonable shakedown period these two beamline systems should be capable of about 10 MW of H⁰ power. This should allow evaluation of the important question of energy confinement time under conditions of high-power neutral-beam heating. The last two beamline systems are to be installed in early FY85 to complete the final injected power capability.

During FY83 a large portion of the supporting water, vacuum, SF₆ and cryogenic piping systems was completed for the final four neutral beamlines.

Electrical Power Systems

Assembly of electrical hardware delivered from vendors continued throughout FY83, and at the close of the fiscal year more than 90% of the hardware was on site and assembled. This includes 12 local control centers (LCC's), 12 high-voltage enclosures (HVEs) which contain the ion source arc and filament supplies, protective equipment and telemetry, and 12 modulator/regulators, six of which are awaiting high voltage switchtube delivery from RCA. This large, manpower-intensive effort has now started to decline in favor of commissioning work.

Installation of electrical hardware progressed very well during FY83 due to a good working relationship

Figure 13. Neutral Beamline Transport. The beamline is pictured en route from assembly area (1-H building) to TFTR. Fully assembled, the beamline weighs 75 tons. (83E0934)

with the Ebasco Construction personnel who managed the craft labor pool. Installation of the following items was completed for all 12 NBPS: Surge rooms with terminating capacitors and crowbars (Fig. 15), variable voltage transformers and outdoor switch gear, decel supplies, magnet supplies, water skids (Fig. 16), power distribution centers and LCC's (Fig. 17). Ten of the main transformer/rectifiers were installed, and the final two units are expected in early November and December. Three HVEs were installed for the NBTC (Fig. 18), with six more planned for installation in the Test Cell Basement during the

Figure 14. Beamline Installed on TFTR in Position No. 3. (83E1094)

Figure 15. Surge Room Enclosures. Each room contains the terminating capacitors and crowbars for one ion source power supply. (83E0380)

Figure 16. Ion Beam Deflection Magnet Power Supplies. (83E0383)

January-April shutdown of TFTR. In addition, with the exception of the HVEs, installation of all the cable trays, cable, and terminations for the NBTC power system (N5) and the first TFTR heating system (N3) was completed. Work on the second TFTR beamline (N4) is only about six weeks behind schedule. Six

modulator/regulator units were also installed in the Neutral Beam Power Conversion Building.

Associated with the assembly and installation of the electrical hardware was the awarding of several important subcontracts. A subcontract was awarded to RPC Industries to address shortcomings in the

Figure 17. Neutral Beam Power Supply Water Skids. The units are installed in the Pump Room Basement and contain the pumps and heat exchangers for the cooling water for the modulator/regulators, decel, arc, and filament power supplies. (83E0385)

Figure 18. High-Voltage Enclosures (HVE's) for Neutral Beam Test Cell Power Supplies. Each unit contains an ion source arc and filament power supply, an arc modulator, transient voltage protection equipment, and telemetry equipment. (B3E0589)

original packaging of the modulator/regulators. In particular, the voltage hold-off capability of these units was inadequate for reliable 120-kV operation. In addition, reliability problems associated with inadequate design of other components were identified during test operation of the prototype power supply. Corrective action required an engineering redesign effort which RPC Industries was engaged in for about three quarters of the fiscal year.

The original electrical hardware did not contain arc modulators. A subcontract was awarded to Inver-power Controls, Ltd. to supply these units. A prototype unit was constructed (Fig. 19) and tested on the prototype power system at PPPL with excellent test results. The first four of twelve production units were delivered and are ready to be incorporated into the HVEs.

The Lawrence Berkeley Laboratory completed development of the flexible transmission lines which connect the HVE's to the ion sources (Fig. 20). The first three units for the NBTC are expected in November 1983.

The Prototype Power System Test Facility (Fig. 21) operated throughout the year and provided valuable information on electrical system response, most notably with regard to the modulator/regulator. As a result of these studies, most of the system's weaknesses were identified. In addition, a system performance evaluation was made which established (within voltage limitations) the full current and pulse length capability of the power system (70 A, 5 sec into a dummy load). These studies have also demonstrated that the capability of the RCA tube (at least in one case) is compatible with system design parameters. We now have a prototype system which performs the desired block (fault) function in less than 4 μ sec and which has a turn-on capability of less than 50 μ sec. The system was used for both limited

Figure 19. Prototype Arc Modulator. The unit is shown assembled on the arc deck. In the center are the divert, notch, and main series thyristor switch assemblies, and to the left are the commutation capacitors for the divert and notch functions. (B3E0807)

ion source operation (~ 50 kV, 100 msec, H^+) to evaluate a prototype ion source fault detector, and as a test bed for the initial power-system control interface with CICADA.

Cryogenic Systems

Installation of both the 200-watt liquid helium refrigerator for the NBTC and the 1000-watt liquid helium refrigerator for the four tokamak beamlines took place during late FY82 and early FY83. Also, installation of all of the cryogenic piping (except for the final jumpers to the NBLs) for both the NBTC and TFTR occurred during this period.

As part of the acceptance test, the 1000-watt refrigerator was operated in late FY82 at B-Site using one of the assembled beamlines as a load. It was subsequently moved to the TFTR site and installed in its final location early in FY83 (Fig. 22).

The 200-watt unit was initially operated into the NBTC beamline and target tank in March 1983, obtaining cryopanel temperatures of ~ 20 °K. A bearing failure on the turbo-expander terminated the run, but did identify a failure mode for this refrigerator which was subsequently corrected. A second test run was made in May 1983 which was entirely successful. Operation of the cryopanel in both the beamline and target tank at ~ 4.5 °K was achieved, as well as operation at ~ 4.1 °K using the ejector suction system. Hydrogen gas was loaded onto the panels for equilibrium vapor pressure measurements, and regeneration of the panels (boil-off of the H_2 gas) was accomplished, albeit with some lack of finesse in this "first-time" operation. Various system improvements were made in bulk gas storage and clean up. A third system test for the 200-watt unit is planned for December 1983.

Figure 20. Flexible High-Voltage Transmission Lines. The lines which carry all electrical service from the high-voltage enclosures to the ion sources are shown undergoing assembly at the Lawrence Berkeley Laboratory. (83E1059)

Systems Engineering

Hard-wired control systems using conventional relay logic and instrumentation were procured on a "build-to-print" basis for the NBTC vacuum and cryogenics systems. These systems were installed

Figure 21. Prototype Power System Test Facility. The setup is used for dummy load testing and short-pulse (≤ 100 msec) ion source testing. (83E1098)

after extensive modifications and rework to accommodate operational requirements. The controls were successfully used to support vacuum and cryogenic testing in the NBTC facility. Design of the analogous controls for the heating beams on TFTR proceeded, using a system of programmable controllers as the basis for design.

A standard, portable CICADA operating console was installed at the prototype power system test facility in order to support the CICADA/Neutral Beam development effort (Fig. 23). Operation of the prototype power supply via CICADA has demonstrated limited low-level control and data acquisition capabilities.

Thermocouple data acquisition hardware was installed in the NBTC Control Room. Two "built-up" CICADA hardware racks were installed for each of the three NBTC power system (N5) line-ups.

Mimic control panels were designed and prototyped for the vacuum, cryogenics, and beamline control functions that will be located in the local control area. A prototype sweep magnet controller was built and tested, and controls for the SF₆ reclamation system were designed and built.

Design was completed on the ion source fault detector which consists of eleven channels of fault sensors. All critical circuit designs and chassis layouts were prototyped and tested. A prototype fault-event recorder, necessary to document the "fault

Figure 22. The 1000-Watt Liquid Helium Refrigerator. The cold-box is shown undergoing final assembly and checkout at the TFTR site prior to reinstalling the vacuum shell. (83E1120)

Figure 23. Neutral-Beam Local CICADA Computer Operating Console. (83E0910)

history" as determined by the fault detector, was designed, prototyped, and tested at the Lawrence Berkeley Laboratory (LBL).

The original Transrex data links were totally inadequate with regard to signal-to-noise level. Accordingly, an all new fiber optic system based upon

a 9-bit analog-to-digital and digital-to-analog system was designed. Two prototype analog data links designed to PPPL specifications were evaluated, and a vendor was selected to supply the production quantity of 550 data link sets. Several iterations of design incorporating mutually discussed refinements have occurred, and assembly, test, and delivery of the final configuration has begun.

In-house work related to the new data links included the design of transducer circuitry, signal distribution networks, and auto calibration circuitry to accommodate power system, ion source, and user requirements. Assembly and test of these circuits has begun. Timing modules to allow stand-alone operation of the beam system were also designed and tested. The first three units were installed in the N5 test beamline local control centers. In addition, an all optical gas valve driver system, similar in concept to the data links, was designed, prototyped, and tested. Fabrication of the production units is in progress.

Present plans call for the NBTC beamline to begin operations with one ion source in January 1984, and to have the full complement of three ion sources operating in March 1984. This system is designed to demonstrate power system capability and interactions during simultaneous three source operation as well as to "condition" ion sources for future TFTR use.

A second beamline will be installed on TFTR in February 1984. As the power system commissioning is completed, these beamlines will begin operation on TFTR for plasma heating experiments. By August 1984 it is planned to have two beamlines and six ion sources in operation.

TECHNICAL SYSTEMS

The Technical Systems Division has overall responsibility for the internal components of the vacuum vessel (particularly those that provide thermal protection to the vessel wall), the thermal instrumentation for those components, the remote maintenance procedures and equipment, the radiation shielding, the provision of specialized equipment for D-T operation, and the design, fabrication, installation, and testing of the tritium systems.

The vacuum vessel armor for the ohmic heating experiments in TFTR was manufactured, assembled, and installed during the summer shutdown period. Components of the armor consist of:

- The bellows cover plates, some of which will be replaced by bumper limiters, surface pumps, or protective plates when high-power operation, aided by neutral-beam heating, begins.
- The movable limiter, consisting of three interconnected blades which are attached to three screw-driven actuators. The actuators and blades occupy Bay-M of TFTR. Since the movable limiter will operate during the high-power experiments, it is water cooled and has graphite tiles coated with titanium-carbide (TiC).

- Eight of the 36 zirconium/aluminum surface pumping units (Fig. 24) capable of pumping hydrogen at the speed of 104,000 liters/sec (as compared to 470,000 liters/sec for the full system).
- Controls and instrumentation including 350 thermocouples to monitor the temperatures of the above components.

Figure 24. Zirconium/Aluminum Surface Pumping Panel Array. One of the first eight units undergoing final checkout prior to installation. (83E0828)

First wall armor to protect the vacuum vessel during neutral-beam and D-T operation, i.e., the bumper limiters and the protective plates, had successful final design reviews. For initial heating experiments only two neutral beams will operate on TFTR and the protective plates required during that phase of the operation [called the initial protective plates (IPP)] were contracted to GA Technologies Inc. for manufacture. The bumper limiters and the protective plates required to protect against the strikes by the third and fourth neutral beams were the subject of an extensive Request for Proposal (RFP). The award of that contract was imminent as the fiscal year ended.

Work on the tritium systems in preparation for the D-T demonstration began. Engineering for the installation of the tritium handling equipment was completed, and specifications for the installation of the equipment were prepared (Fig. 25). Contracts were also awarded for neutron monitors and for the stack sampler system. Specifications for procurement of a tritium commissioning contract were prepared, and a contract for the environmental monitoring program and the construction of a new meteorological tower was awarded.

The shielding required for first-plasma operation was installed. Design for the shielding required during D-D and D-T operation continued, and successful design reviews for several of those components were conducted. Development of materials and methods for installing penetration shielding continued.

Figure 25. Tritium Storage and Delivery System. The storage and delivery glovebox is shown in position in the Test Cell Basement tritium vault awaiting final installation and commissioning tests. (82E0884)

After a cooperative agreement between the government of Canada and the U.S. was reached, Canadian support personnel joined the remote maintenance development project. A remote handling expert from the Hanford Engineering Developmental Laboratory (HEDL), Westinghouse, joined the remote handling section staff. Late in the fiscal year, a priority list of tasks was developed for work which will be carried out in FY84.

LITHIUM BLANKET MODULE PROGRAM

The Lithium Blanket Module (LBM) Program is sponsored by the Electric Power Research Institute (EPRI). Phase I of the LBM Program was formally completed in FY83, and the work accomplished to date was reported in eight volumes presently under review at EPRI. The two most important accomplishments in FY83 were (1) completion of the final design of the blanket module by GA Technologies Inc., under subcontract to PPPL, and (2) the fabrication of the Engineering Test Station (ETS). Figure 26 shows a trimetric view of the LBM, and Fig. 27 shows a photograph of the completed ETS.

Final specifications for the lithium oxide powder and the LBM pellet manufacturing procedures were developed by GA Technologies Inc. and approved by PPPL during FY83. Input to these specifications included the results of experimental tests that resolved uncertainties concerning the reproducibility of the 25,000 pellets that will be manufactured during FY84.

Neutron dosimetry qualification experiments were completed by EG&G Idaho which has responsibility for the LBM radiation measurements. EG&G also began work at PPPL on interfacing the planned dosimetry equipment to the computers that will be

Figure 26. Lithium Blanket Module (LBM)—trimetric drawing. (83P0546)

used for data analysis beginning in late 1985. Space was assigned to the LBM support laboratory in the planned new wing of the TFTR Laboratory Office Building. Work on tritium assay methods was carried out with equipment at Argonne National Laboratory. Using both small lithium metal samples and LBM-type pellets, this work demonstrated that the proposed thermal extraction method would be quite satisfactory

Figure 27. Engineering Test Station (ETS). This support platform was fabricated for the Lithium Blanket Module Test Program on TFTR. (83E1284)

for determining the minute concentrations of tritium expected in the LBM experiments. Construction was initiated on a thermal extraction and counting apparatus in a new laboratory at A-Site on the Forrestal Campus.

EBASCO/GRUMMAN

The Ebasco/Grumman industrial team provided engineering and design services, as well as installation and assembly support, to TFTR in many areas during the FY83 period. Following successful completion of the tokamak in December, the installation and assembly team began work on preparation for the installation of the neutral beams. Engineering and design support shifted to the areas of diagnostics, surface pumping, shielding, and electrical installations. Ebasco Nuclear Safety finalized the Final Safety Analysis Report (FSAR) for publication in early FY84. The following is an elaboration on the accomplishments in each of these areas.

Installation and Assembly

During the first quarter of FY83, Ebasco Grumman concentrated on the completion of the assembly phase of TFTR. With the vacuum vessel torus completely assembled, the umbrella structure and heating/cooling system components became the last major systems to be added to the machine. Columns and lintels were erected around the periphery of the vessel in early October. The umbrella structure was fabricated concurrently with the assembly of the vacuum vessel at a location within the Test Cell. Following the completion of the column and lintel assembly, the umbrella structure (containing all of the upper poloidal-field coils) was lifted over the machine and set into place atop the columns. The installation of the umbrella structure on October 26, 1982 represented the last major component to be assembled. In November, while final attachment and checkout of coil bus work was being completed, the upper heating and cooling plenum, including its associated distribution piping, was installed. System preoperational testing was accomplished concurrently with construction activities in order to save time and to expedite final system acceptance. Ebasco Services Incorporated formally turned over the completed machine to PPPL on December 10, 1982 (Fig. 28).

Following completion of tokamak assembly, installation team efforts concentrated on preparations for neutral-beam installation. This effort involved preparation of eight installation and assembly procedures, four lift procedures, and eight material staging lists. In addition, specialized equipment for lifting and handling the neutral-beam enclosure and the transition duct were designed, analyzed, and tested. Ebasco personnel provided technical direction for the installation of Neutral-Beamline No. 3, including its support system and interconnecting vacuum duct.

Figure 28. Completion of TFTR Assembly by Ebasco Services, Inc. Ceremony at which the TFTR device was formally turned over to PPPL two weeks prior to "first plasma." (B2A0348)

Electrical Systems

During FY83 two major electrical systems, the surface pumping prototype and the movable limiters, were installed in TFTR.

The surface pumping system provides for impurity removal in the vacuum vessel. Four identical prototype surface pumping systems were built and installed. There are two parallel-connected pumping panels in each system. These contain the zirconium/aluminum water modules which trap contaminants from the plasma. Each surface pumping system is powered by a 30-kVA silicon controlled rectifier (SCR) supply designed and fabricated by PPPL.

The prototype systems were successfully tested individually with the pumping panels *in situ*, i.e., inside the vacuum vessel. These tests demonstrated the impurity absorbing characteristics of the system as well as the performance of the operating logic and controls.

The TFTR movable limiter is a single poloidal limiter located within one 18° segment of the vacuum vessel. It consists of three interconnected Inconel backing plates (blades) covered with graphite tiles coated with titanium carbide. The three backing plates are positioned by three independent screw driven actuators. Limiter blade positions can be adjusted to suit any plasma size or position within the operating range of the system. The positioning actuators are driven by individually controlled dc servo motors, which are controlled locally by either servo indexers or a dedicated microprocessor, or remotely through CICAADA. The movable limiter system was installed and tested in the last months of FY83. The system has performed as designed.

In addition to the above major tasks, electrical engineering manpower was provided to support tritium systems design and the design of the neutral-beam power supply systems.

Shielding

The $Q \sim 1$ radiation shielding task was defined in January 1983. Ebasco/Grumman is responsible for design, engineering, and installation support of the auxiliary shield wall panels, the penetration shielding, and the boron coating.

The preliminary design of the auxiliary shield wall panel, site preparation for panel installation, and the panel procurement specification were all completed in FY83. Penetration shielding material was selected and underwent mechanical and mock-up testing. Installation procedures were prepared, and technical direction for installation was provided. Preliminary design of the penetration shielding for the large HVAC and basement wall penetrations was completed. Development of boron coating material including coating mixture identification, boron content analysis, and an adhesion test was carried out in FY83.

Diagnostics

Ebasco/Grumman was assigned to perform several tasks for the Diagnostics Division in FY83. Ebasco/Grumman personnel had total engineering responsibility for the vertical X-ray crystal spectrometer. In addition, mechanical engineering, design, fabrication, and installation services were provided for the B-theta (B_θ) coils, TV Thomson scattering, and the hydrogen alpha interference filter array (HAIFA) diagnostics.

Preliminary design of the vertical X-ray crystal spectrometer was started in January. The instrument utilizes curved crystals for diffracting the X-rays emitted by the plasma to detectors mounted in the basement. The instrument views the plasma through two large beryllium windows. The X-ray beam exits the vacuum vessel through these windows into a high-purity helium environment. The beam impinges on a crystal located on an adjustable crystal table directly under the Bay-Q lower port and is diffracted by the crystal to a detector located directly outboard of the crystal, approximately 30 ft from the machine centerline. The helium environment is contained within a double-walled flexible bay enclosure which extends from a vessel lower port down to the basement floor and outboard to the detector. The detectors, supplied by Brookhaven National Laboratory, are mounted on a tower which extends from the floor to the basement ceiling. Movable detector/collimator mounts permit the detectors to be translated and rotated to any position on the tower.

Preliminary design of the instrument was completed, and a Preliminary Design Review (PDR) was held at the end of March. Following the PDR the scope of the instrument was revised and final design began in May. Procurement of the beryllium windows, seals, and vessel adaptor sections was initiated by the close of FY83.

The B-theta coils are designed to give a better measure of the MHD activity in the plasma than can be achieved with the coils outside the bellows. The diagnostic consists of 20 Macor cylinders, each 1.5

inches in diameter and 4.5 inches long. The cylinders are wound with 50.5 turns of stainless steel wire set in precisely-machined helical grooves on the cylinders. The cylinders needed to be accurately located on the back sides of the bellows cover plates, evenly spaced about the vacuum vessel at azimuth 207°, to assure proper clearance to the vacuum vessel bellows. The diagnostic was delivered on schedule in July 1983.

The TV Thomson scattering diagnostic provides space-resolved electron temperatures and electron density measurements. The diagnostic consists of a fiber optics bundle terminated in an intricately-machined stainless steel box. The box can be mechanically raised and lowered 16 feet between its operating position beneath the vacuum vessel and a location near the Test Cell Basement floor where maintenance can be performed. The system was designed to accurately position the two hundred pound box beneath the vacuum vessel each time it is raised into running position. The diagnostic was delivered on schedule in September 1983.

The purpose of the HAIFA diagnostic is to measure the visible bremsstrahlung emitted by the plasma, as well as to measure the hydrogen flux around the edge of the tokamak plasma. The diagnostic consists of two aluminum arches bolted to the face of a vacuum vessel cover flange. Twenty-six telescopes are mounted within the arches. All of the telescopes are mounted on articulated supports in order to provide two degrees of adjustment to either side of a nominal setting in both the horizontal and vertical directions. Fiber optics cables are terminated on the backsides of the telescopes and routed down the outside of the arches to the Data Acquisition Room. The diagnostic was delivered on schedule in February 1983.

Safety

All Department of Energy and other review comments on the TFTR Final Safety Analysis Report (FSAR) were resolved, and approval by DOE of the

FSAR for first-plasma operations was granted. The resolutions to the comments were incorporated into the FSAR for publication of a final document in November 1983.

Safety inputs were prepared for the TFTR Operating Manuals, and an operating manual for the Radiation Safety Active Gamma Monitoring System was also developed. Ebasco Nuclear Safety participated on both the short-term and long-term task forces to review the status of the TFTR Experimental Area HVAC Systems and to recommend remedial action. Guidance was provided, as needed, on the implementation of TFTR nuclear safety criteria and on potential impacts on the project of federal and state legislation.

DIAGNOSTICS

TFTR Diagnostics made considerable progress in FY83. This is evident from the number of diagnostic instruments that were commissioned during the year (Tables I and II) and from the number of instruments being designed and built for installation in later years (Table II). Additionally, many existing diagnostics were upgraded and their performance was improved.

The year started with intense activity (Fig. 29). In the three months prior to first plasma, the Data Acquisition Room (DARM) progressed from the design stage to full operation. During this period, over 1 MW of isolated ac power capability was installed and over 15 miles of cable pulled and terminated.

The instruments that were operational for first plasma are listed in Table I. The diagnostic port covers were fabricated, insofar as possible, with the holes, windows, and shutter mechanisms for all of the instruments that would eventually be used in those ports. The port cover at Bay-S (Fig. 30) is one example of this. It shows the 1-mm microwave interferometer hardware along with a simple illumination probe mechanism, a blanking flange, and a window with shutter mechanisms to be used for future diagnostics. One of the larger diagnostics installed for first plasma was the residual gas analyzer (RGA). It is shown at the end of a pumping duct in Fig. 31. This instrument

Table I. Operational Diagnostics for TFTR First Plasma.

Diagnostic Device	Parameter Investigated
Rogowski Loops	Plasma Current
B_θ/B_p Loops, Saddle Coils	Plasma Position
Voltage Loops	Voltage Around Torus
1-mm Microwave Interferometer	Plasma Density
Hard X-Ray Monitors	Effect of Runaway Electrons
Torus Pressure Gauges	Torus Pressure
Residual Gas Analyzer	Partial Pressures
Plasma TV, Illumination	TV Pictures of Plasma
Glow Discharge Cleaning Probes	Mechanisms for Cleaning Torus
Electron Beam	Magnetic Field Quality

Table II. Operational Diagnostics for Ohmic Heating Phase of TFTR Operation.

Diagnostic Device	Parameter Investigated
Mirnov Loops	MHD Activity
Fast Scanning Heterodyne Radiometer	Electron Temperature
X-Ray Pulse Height Analyzer	Electron Temperature
Horizontal Charge Exchange	Ion Temperature
Epithermal Neutron Detectors	Ion Temperature
UV Survey Spectrometer	Impurities
Interference Filter Array	Visible Bremsstrahlung-Impurities
Infrared Plasma TV	Wall Temperatures
Bolometers	Radiation
Diamagnetic Loops	Plasma Pressure

Table III. Diagnostics Installed for TFTR Operation in FY84.

Diagnostic Device	Parameter Investigated
Thomson Scattering	Electron Temperature and Density
X-Ray Crystal Spectrometer	Ion Temperature, Impurities
X-Ray Imaging System	MHD Activity
Langmuir-Calorimeter Probes	Edge Plasma Properties
Visible Spectrometer	Impurities
Laser Impurity Injector	Controlled Impurity Studies
Neutron Fluctuation Detector	Fast Variation in Neutrons

Figure 29. Data Acquisition Room (DARM) Equipment Installation. Members of the PPPL Engineering Department installing microwave equipment and terminating cables in the TFTR Data Acquisition Room, December 1982. (82E1190)

has played an essential role in monitoring the concentration of impurities inside the tokamak vacuum vessel during cleaning operations.

As shown in Table II, additional diagnostics became operational in the spring when ohmic heating operation began and plasma currents approached 1 MA. The outputs from the microwave interferometer and the magnetic diagnostics were used in the feedback loop for plasma control. Electron temperatures were initially measured with both the first channel (75-110 GHz) of the fast scanning heterodyne radiometer and the X-ray pulse height analyzer. The latter instrument is the prototype for a multichannel system which will be fully neutron shielded and located in the Test Cell Basement. Figure 32 shows the X-ray pulse height analyzer being installed at Bay-F.

The first ion temperature measurements were made with the single radially-viewing E||B charge-exchange analyzer shown in Fig. 33. The large stand, which will ultimately support three analyzers for fast ion analysis, is necessary to support the cabling. It was designed to swing horizontally to permit regular maintenance. During operation with deuterium, the

Figure 30. The 1-mm Microwave Interferometer. The picture shows the Bay-S cover plate with the 1-mm microwave interferometer hardware, the illumination probe mechanism, and the blanked port and window with its shutter mechanism. (83E0682)

Figure 31. Residual Gas Analyzer (RGA). The equipment is shown as installed at the end of pumping duct C in December 1982. (82E1176)

Figure 32. The X-Ray Pulse Height Analyzer. The apparatus is shown during installation in the spring of 1983. The piping array in the background is for the vacuum vessel heating and cooling system. (83E0671)

neutron detectors provided an independent ion temperature measurement. These detectors were placed at selected locations and were then very carefully calibrated with a ^{252}Cf source and a D-D or D-T neutron generator, taking into account the effects of neutron scattering.

The success of the TFTR diagnostics is evident from the experimental data collected during 800-kA, 68-cm minor radius plasma operations. The magnetic diagnostics were thoroughly calibrated prior to tokamak operation, and the effects of eddy currents in the vacuum vessel shell and coil cases on the output signals were carefully analyzed. These diagnostics were vital for determination of the decay rates during plasma disruptions. For pulses which ended in a disruption, the analyses were important in studies of the plasma current, the inward movement of the plasma with the related λ , and the safety factor, q , at the plasma edge during a short interval at the end of a discharge. An example of these parameters is shown in Fig. 34. At these ohmic currents, disruptions were observed to have current decay rates of less than 1 MA/sec, which is the criterion used for design of the armor to be installed to protect the inside of the vacuum vessel. The Mirnov loops show considerable MHD activity before a disruption.

Figure 35 shows the time dependence of the electron temperature as measured by the radiometer at two different positions. The central temperature has a characteristic dip followed by clear sawteeth on the signal. The charge-exchange data for the behavior of the ion temperature as a function of time during the same discharge is shown in Fig. 36. The temperature data must be corrected for absorption effects in the plasma, using information about the electrons from other diagnostics. One corrected point is shown, and agreement with the neutron-derived temperature is excellent. For these discharges, the fraction of the input power radiated, as measured by the bolometer, is always about 60% in reasonably

Figure 33. A Single Charge-Exchange Analyzer. The apparatus is mounted on a movable stand designed to support three analyzers. (G3E0661)

Figure 34. A Disruption in an 800-kA Discharge. The time interval is 20 msec around the termination of the discharge. (a) Plasma current, (b) plasma radial position, (c) λ , and (d) safety factor q . (83X2311)

clean discharges having a $Z_{\text{eff}} \approx 3$. About 25% of the radiated power could be the result of iron impurities. Figure 37 shows a spectrum obtained using the ultraviolet survey spectrometer (SPRED) in the range between about 100 Å and 1000 Å. Using the grating selected for this discharge, the low wavelength iron lines are not fully resolved. The other principal lines are from the low-Z impurities, i.e., oxygen and carbon. For the discharge shown in the figure, a slight enhancement of these lines can be seen when it disrupted at the end of the discharge.

Throughout the operating period the plasma TV system was an invaluable tool for the operators, as it enabled them to observe directly the effects of changes they made in the plasma parameters. The infrared temperature diagnostic, also to be used for plasma monitoring during operations, was installed but not made operational. In fact, very little testing was done on this equipment since it uses the same data handling system as the plasma TV system.

In the meantime, work was proceeding on other diagnostics scheduled for operation on TFTR early in FY84. By the end of September, the X-ray imaging system, the X-ray crystal spectrometer (shown together in Fig. 38), and the Langmuir-calorimeter probes were installed. They will be final tested *in situ*. The Thomson scattering system, the visible spectrometer, and the laser impurity injector are under-

Figure 35. Electron Temperature Profile. The time dependence of the electron temperature for an 800-kA discharge as measured by the fast scanning heterodyne radiometer, (a) close to the plasma axis and (b) about 26 cm from the axis.

going final assembly and are scheduled for installation early in FY84. One major diagnostic planned for operation in 1984 is the far-infrared multichannel interferometer. Part of the main support frame is already in place in the TFTR Test Cell Basement. Figure 39 shows the box that will hold the mirror mounts for the twelve interferometer channels. One of two long probe mechanisms for use through the bottom ports of the vacuum vessel is being vacuum tested.

Numerous other devices planned for future operation on TFTR are in various stages of design and development. As an example, the electrical work on the diagnostic neutral beam has proceeded on schedule, but the mechanical work is lagging because of demands for manpower elsewhere. The far-infrared Michelson interferometer for measuring the electron temperature and the electron distribution function is shown in Fig. 40. At the end of the year, the interfaces of this equipment with the vacuum vessel and the CICADA computer system were being designed.

Figure 36. Ion Temperature Measurements. Ion temperature data from charge-exchange measurements on an 800-kA discharge as a function of time. A single point corrected for plasma absorption is shown as is the temperature derived from the neutron flux.

Figure 37. SPRED Spectral Data. Spectra obtained at 100-msec intervals using the ultraviolet survey spectrometer.

On the whole, good progress has been made on the diagnostics for TFTR. Most concepts developed for use with this large tokamak and its environment have worked well. Location and routing of cabling and other services were carefully designed to allow for placement of radiation shielding in the future. However, much more work has been necessary in this area than had been expected. The physical scale of the diagnostics and the requirement for manpower and support equipment to meet programmatic needs have necessitated careful planning. There have been further difficulties in bringing these systems on line due to the complications in check-out and start-up of the CICADA computers, the computer interfaces, and the CAMAC hardware and software concurrently with the diagnostic equipment. This has made the debugging task a complex and time consuming

Figure 38. The Large X-Ray Crystal Spectrometer and X-Ray Imaging System. The photograph shows the lead shielding being installed around the multiwire proportional counter. The mechanisms for a glow discharge probe and a Langmuir calorimeter probe are at the left in the picture, on the same port as the X-ray imaging system. (83E1247)

Figure 39. Mirror Enclosure Far-Infrared Multichannel Interferometer. The box is constructed to hold the mirrors at the bottom of the optical legs of the far-infrared multichannel interferometer. (83E0850)

Figure 40. The Michelson Interferometer. (82E1266)

process. Sophisticated diagnostic data handling and control will require much more development time and effort before becoming routinely operational.

EXPERIMENTAL RESEARCH

Overview

The TFTR Experimental Research Division consists of three branches: Physics Operations, Physics Coordination, and Experimental Computing. The primary functions of this division are to provide planning and coordination of the TFTR experimental program, and to provide project services as indicated by the titles of the branches.

This year was highlighted by the achievement of first plasma and by the first significant TFTR confinement results in ohmically heated plasmas. During this time there were two experimental run periods. The first, from December 24, 1982 to January 20, 1983, addressed first-plasma issues, and the second, from March 19, 1983 to June 21, 1983, produced approximately 300 shots with peak plasma currents up to 1 MA. Typically, experiments were run Tuesday through Saturday with one daily 10-hour shift. Experimental results were discussed and experimental plans for the coming week were developed every Monday at the Physics Coordination Meeting which involved approximately 40 physicists and engineers. During the week, a daily meeting was held at approximately 6:00 p.m. to fine-tune the experimental plans.

The schedule for FY83 is shown in some detail in Fig. 41. From October to December activities focused on final assembly of coil systems, power supplies, controls, and start-up of the vacuum system. Remarkably good vacuum was achieved early, with no serious leak problems. For plasma runs during this period a temporary limiter was used. It consisted of two large graphite rails top and bottom which provided a 136-cm vertical gap (plasma minor radius = 68 cm), and a horizontal gap of 150 cm which

Figure 41. TFTR Run Schedule for 1983.

allowed a change in plasma radius of ± 7 cm about the nominal major radius of 250 cm. In addition, another vertical, curved stainless steel plate was placed at approximately 180° toroidally from the primary limiter to protect the inner vessel wall against inward disruptions.

The historic first-plasma shot in December 1982 was achieved with very modest parameters: $I_p \sim 40$ kA, $B_T \sim 1.0$ T, $n_e \sim 5 \times 10^{12}$ cm $^{-3}$, and a pulse length of 50 msec. These values were rapidly increased during the month of January to $I_p \sim 250$ kA, $B_T = 2.7$ T, $n_e \sim 2 \times 10^{13}$ cm $^{-3}$, and a pulse length of 500 msec. During this period, the vertical field feedback system was commissioned and studies on discharge initiation were carried out. The ohmic heating (OH) start-up phase began after a vacuum vessel opening from January to March. The physics objectives for this phase were:

- Begin large plasma OH operation ($a = 68$ cm, $R = 250$ cm, $B_T = 2.5$ T, $I_p = 800$ kA for $q = 3$).
- Demonstrate plasma (R_0 , I_p) feedback controls up to 500 kA.
- Determine discharge parameter range nR/B_T versus q . Extend Murakami limit to large R .
- Determine disruption characteristics of 500 kA plasmas. Validate 1 MA/msec design criterion.

All of these objectives were achieved by the end of June. The experimental activities were organized in the form of the following physics task forces:

- Preliminary Confinement Study.
- Plasma Control.
- Discharge Cleaning.
- Disruption Characterization.
- Plasma Optimization.

Vacuum Vessel Conditioning

During the second run, glow discharge cleaning (GDC) and pulsed discharge cleaning (PDC) were used to condition the limiter and the vacuum vessel walls. At the end of the run, the vacuum vessel was baked for one day at $\sim 100^\circ\text{C}$ to test the bakeout system.

Glow discharge cleaning was accomplished by inserting into the vessel two electrodes operated at

about 400 V and running a 5 A glow discharge to the vessel wall. After each long period of work inside the vessel, the "glow" was run on an almost continuous basis for about 100 hours. Whenever possible, it was also run for periods of about eight hours each night between operational shifts. Figure 42 shows the decay rates for CO and C₂H₄ (28 amu) and CH₄ (16 amu) during the second cleaning period. H₂O (18 amu) fell to below background levels immediately. In total, over 100 equivalent monolayers of carbon and oxygen were removed in the two cleaning periods, and the resultant partial pressure of impurity gases was 1.5×10^{-8} Torr. The vacuum vessel was not heated during the glow discharge operation. This method has also helped to remove impurities from some of the appendages to the vessel, particularly the large pumping ducts which are not amenable to pulse discharge cleaning and also cannot be baked at this time.

Glow discharge cleaning could not be used to prepare the limiter adequately, and long periods of pulse discharge cleaning were necessary. A total of about 65 hours and 30,000 pulses were expended. A large fraction of the pulses were done at low hydrogen pressure, 2×10^{-5} Torr, with $I_p \sim 200$ kA for ~ 100 msec duration and $B_T \sim 0.6$ T with a repetition period of ~ 10 sec. This cleaning raised the limiter temperature ($\sim 200^\circ\text{C}$) and the vacuum vessel wall temperature and led to a significant production of CH₄, C₂H₄, and CO. A change to much higher pressure, 2×10^{-4} Torr with $I_p \sim 80$ kA for about 50 msec duration at $B_1 \sim 0.3$ T, resulted in significant production of H₂O.

The combination of low and high fill-pressure pulse discharge cleaning was effective in conditioning the wall and limiter and led to the achievement of the

Figure 42. Glow Discharge Cleaning Results. The chart shows the partial pressures of impurities obtained during the second glow discharge cleaning period (March-April 1983).

long high plasma current discharges without disruptions. However, it is clear that more cleaning is required since the impurity level in the plasma gives $Z_{\text{eff}} \sim 3$, due mostly to carbon and oxygen impurities.

Plasma Optimization

One of the principal goals during the first year of operation was to create and control high current discharges to allow effective confinement studies. Figure 43 shows the time behavior of the plasma current for some of these discharges. For the 1 MA plasma current case, q_{LIM} was 2.5, and in the highest density discharge achieved at 800 kA, the Murakami parameter ($n_e R/B_T$) was $2.3 \times 10^{19} \text{ m}^{-2} \text{ T}^{-1}$. The range of discharge conditions obtained so far in high current plasmas is shown in Fig. 44, where the inverse safety factor, $1/q$, is plotted against the Murakami parameter. The total pulse length was about 2 sec and a constant current was maintained for about 0.8 sec for 800-kA and 600-kA discharges. The time scale for current buildup was considerably longer than in previous machines operating under similar conditions. For example, the discharges begin to sawtooth at about 800 msec, compared to about 200 msec in PDX, and

Figure 43. Plasma Behavior and Feedback Control in TFTR. The figure shows the time dependence of (a) plasma current, (b) loop and surface voltage, (c) plasma major radius, and (d) line integrated density during one deuterium discharge.

Figure 44. TFTR Operating Parameters in High-Current Plasmas. The chart shows the range of operating parameters during current flattop for many discharges, both hydrogen and deuterium. The axes are the inverse safety factor and the Murakami parameter.

the sawtooth period was typically 25 msec compared to 5 msec. On the other hand, discharge initiation occurred rapidly with a typical delay of less than one msec over a wide range of parameters, despite eddy current induced fields which are especially large at breakdown.

The effectiveness of the feedback controls is demonstrated in Fig. 43. The time behavior of the plasma current, voltage, horizontal position, and electron density are shown for an 800-kA deuterium discharge in a 2.7 T toroidal field. The plasma position and current were controlled by a hybrid digital/analog system consisting of an analog processor with a dedicated SEL 32/77 CICADA digital computer to control the power supplies.

The plasma position was measured by a set of 26 B_θ and B_p position coils mounted outside one of the bellows sections of the vacuum vessel. The individual coil signals were formed into weighted sums $\langle B_\theta \cos \theta \rangle$, $\langle B_p \sin \theta \rangle$, as required to determine the position according to Shafranov's formula. Extensive measurements of the vertical and radial magnetic fields, as a function of frequency, were taken inside the vacuum vessel prior to plasma operation in order to allow compensation of the Shafranov terms for stray fields due to eddy currents. An example from these measurements is shown in Fig. 45. A loop placed inside the vacuum vessel at its center was used to determine the vertical field as a function of the frequency applied to the ohmic heating coils.

The plasma current was measured by a Rogowski loop that is also compensated for currents induced in the vacuum vessel. The plasma position and current control analog electronics compute the desired ohmic heating (OH) and equilibrium field (EF) coil voltages, which are converted by the computer into firing angles (and hence, the output voltage) of the OH and EF power supplies. Control is based on the difference between preprogrammed and mea-

Figure 45. Vertical Field Measurements Inside the TFTR Vacuum Vessel. The measured effective vertical field components at the center of the vacuum vessel are plotted as a function of the frequency of voltage applied to the ohmic heating coils.

sured I_p and $I_p R$. The system is fully programmable with time-varying gains and with extensive computer control and monitoring facilities. The power conversion computer updates the power supply firing angles at a 1-kHz rate, the power supplies being effectively 24-pulse, phase-controlled rectifiers operating off a 90-60 Hz supply.

During the initial TFTR experiments, control of quiescent discharges after start-up has been optimized to within 1% of the reference current and within a fraction of a centimeter of the reference position [Fig. 43(a) and 43(c)] without the use of feed-forward terms during the current flattop.

The vertical plasma position in TFTR is normally intrinsically stable. However, it has been found necessary to use a small preprogrammed radial field to correct minor field errors and to equalize heat loading on the upper and lower limiter blades.

Figure 43(d) shows the evolution of the line-averaged density. The density control system utilizes a CAMAC-based LSI 11/23 microcomputer as the control element. Data from fast, magnetically-shielded ion gauges mounted on the torus and from the double-pass 1-mm microwave interferometer viewing along a major radius, are digitized and processed along with preprogrammed reference waveforms to control the voltage applied to a fast piezoelectric valve. The nonlinear dependence of the flow on the voltage applied to the valve is corrected in software through use of a lookup table generated from prior calibration tests. A 500-Hz update rate is employed with simple proportional and feed-forward terms. Future enhancements to the system will include provisions for controlling multiple injection valves. At present, density feedback control is functional but limited in effectiveness by recycling and impurity influx from the walls and limiters.

Major components of TFTR have been designed to withstand the electromagnetic forces associated with major disruptions in which the plasma current falls at the rate of 1 MA/msec. Among the approx-

imately 300 well-controlled plasmas, there have been about 50 major disruptions at plasma currents ranging from 200 kA to 950 kA. Forty of these disruptions have been well-diagnosed. A histogram of the frequency of occurrence of disruptions within a band of current-fall rates is shown in Fig. 46. The fastest disruptions, one of which is shown in Fig. 47(a), has a nearly constant fall rate of 100 kA/msec. This is well below the TFTR design value but is as fast as the measured major disruptions with beam heating on PDX. In every case, the major disruptions were preceded by a period of about 200 msec of minor disruptions or increased MHD activity. The progression of $m = 4,3,2$ activity with a slowing down of the fluctuation frequency prior to the disruption has been detected by the Mirnov coils. The distribution of fall rates indicates two types of disruption. The fast ones fell uniformly and were often preceded by minor disruptions. The slow ones fell in "stairsteps." They tended to occur when the plasma was dirty, indicated by increased radiation prior to the disruption. In all cases, the plasma terminates on the inner wall. Figure 47(b) shows this movement for the fast disruption of Fig. 47(a).

Figure 46. TFTR Plasma Disruptions. A histogram depicts the number of disruptions in intervals of rate of decay of plasma current. Forty disruptions were analyzed.

Figure 47. Fast Disruption in TFTR. The chart shows (a) the time dependence of the current, and (b) the time dependence of the plasma position during the disruption.

Plasma Confinement

Although the plasma major and minor radii remained constant during this initial operational phase, some important confinement issues were studied. The large increase in major and minor radius relative to other tokamaks operating in the last few years (PLT, PDX, D-III, Alcator-C, ISX-B, TFR, T-10, FT, etc.) permit significant comparison of empirical size scaling laws for energy confinement.

Initial operation of TFTR produced ohmically heated plasmas with $\bar{n}_e \sim 1.25 \times 10^{13} \text{ cm}^{-3}$, $T_e(0) \sim 0.9 - 1.4 \text{ keV}$, $B_T \sim 2.7 \text{ T}$ and $I_p \sim 500\text{--}800 \text{ kA}$ with a current flattop lasting about one sec. Both hydrogen and deuterium plasmas were studied in detail. The characteristics of the one deuterium discharge, shown in Fig. 43, will be reviewed in detail. During the current flattop, the plasma voltage gradually approached 1 V, and both the line-integrated density and the central electron temperature [cf. Fig. 35(a)] exhibited sawtooth-like fluctuations. The time evolution of the electron temperature 28 cm from the center at $R = 220 \text{ cm}$ [cf. Fig. 35(b)] indicated a continuous broadening of the electron temperature profile during the plasma current flattop. This increase in electron stored energy and simultaneous decreases in loop voltage resulted in an increase of the electron energy confinement time, which reached a maximum at about 1.4 sec into the discharge. The electron temperature profile was parabolic squared in shape with a peak temperature $\sim 1.5 \text{ keV}$. This temperature profile, measured by a calibrated fast scanning radiometer, was corroborated by the peak temperature measured by soft X-ray pulse height analysis. The spectrum of the X-ray bremsstrahlung continuum is shown in Fig. 48. The slope corresponds to a temperature of 1.64 keV. Impurity K_α spectral lines of chlorine, iron, nickel, and chromium are also apparent, and their intensity can be used to estimate the heavy-ion contribution to Z_{eff} . The total Z_{eff} can be determined from the continuum intensity both in the X-ray and visible spectral regions. In this case, the total Z_{eff} is estimated to be 3.6 which is in the range 3-4, typical of this operation.

The ion temperature was obtained by charge-exchange measurement. Referring back to Fig. 36, the data for the ion temperature is shown as a function of time without including corrections of the data for opacity of the plasma. The ion temperature at the center of the plasma was 1.4 keV—200 eV higher than the uncorrected data, as indicated by the one corrected point. In this deuterium discharge, the temperature was also obtained from the neutron flux measured by a moderated He^3 proportional counter. The time evolution of the count rate is shown in Fig. 49. Assuming $Z_{\text{eff}} = 3$ to estimate the deuterium density, the temperature was calculated for a single time and is shown to be in good agreement with the charge-exchange result (Fig 36).

Total power efflux measured by the wide-angle bolometer during this discharge was about 60% of the input power; for the whole period of operation it ranged from 50 to 75% of the ohmic power. The

Figure 48. The X-Ray Bremsstrahlung Spectrum. The soft X-ray pulse height analysis spectrum shows impurity K_α lines, with the bremsstrahlung giving a temperature of 1.64 keV.

Figure 49. Neutron Flux Measurements. Time dependence of the neutron flux measured by a moderated He^3 proportional counter.

assumption of a parabolic density profile used in the analyses of the energy confinement time was confirmed from the unfolding of the visible bremsstrahlung emission from six radial chords, assuming constant Z_{eff} profile, and making use of the line-integrated density and electron temperature profile.

Confinement analyses were completed using TRANSP, the time dependent transport code. This code calculates tokamak transport by analyzing the experimental data in terms of the one-dimensional magnetic field diffusion equation, evaluating the neutral density profile, and using particle and energy conservation equations. The total energy confinement time for this discharge was calculated to be $\tau_E \sim 170 \text{ msec}$. The uncertainty in τ_E is estimated to be $\pm 20\%$ based upon the accuracy of the density in ungettered carbon limited discharges. The confinement time in PLT is between 25 and 50 msec.

The total energy confinement times were calculated near the end of the current flattop ($t \sim 1.4 \text{ sec}$) where

those times have reached their maximum values. In Fig. 50(a) the range of TFTR confinement time is included on the same plot of $\tau_E/\bar{n}$ versus $R^{2.04}a^{1.04}$ utilized to infer the Alcator-C confinement scaling law from the published confinement times of many tokamaks.¹ On this plot, the TFTR confinement times agree with the extrapolation of the Alcator-C scaling law. This R^2a dependence in confinement time scaling is similar to that proposed originally by Pfeiffer and Waltz.² Figure 50(b) is a linear plot of the TFTR total energy confinement times versus $\bar{n}$. These discharges vary in density over a range of $\bar{n}_e = 0.9 - 2.5 \times 10^{13} \text{ cm}^{-3}$. In addition, the predictions of the INTOR, Alcator-A,³ and Alcator-C scaling laws are

plotted. The TFTR confinement times clearly agree with the predictions of the Alcator-C scaling of $\tau_E = 0.192 \bar{n} R^{2.04} a^{1.04}$ (MKS units).

A total energy confinement time of 190 msec represents the best TFTR results to date. Note that the density range of comparison is only $\bar{n} = 0.9 - 2.5 \times 10^{13} \text{ cm}^{-3}$, a range insufficient to observe the saturation of confinement with density observed on many tokamaks. Furthermore, the present limitation of a fixed limiter position prevents direct observation of any size scaling at this time. Experiments with variable limiter size and plasma position will commence in the first quarter of FY84 to determine size scaling in TFTR.

Figure 50. TFTR Energy Confinement. (a) TFTR confinement data superimposed on previously published data prepared by the Alcator Group for ohmically heated plasmas in many tokamaks. (b) The total energy confinement time as a function of average density for well-documented TFTR discharges. The predictions from three proposed scaling laws are also shown.

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PRINCETON LARGE TORUS

The research program conducted on the Princeton Large Torus (PLT) tokamak in FY83 was directed toward two main objectives: to evaluate radio-frequency (rf) heating and current drive methods of potential benefit to larger fusion devices, and to extend PLT operation to plasma conditions as close as possible to those contemplated for these larger devices. In support of the first objective, the program emphasis was placed on understanding the wave physics and heating and current drive effects. To achieve the second objective there was a continuing effort to maximize power input per source through launcher system development and to control the plasma edge condition including provision for high thermal loading on limiter and launchers.

The rf experiments on PLT were divided into two main categories: ion cyclotron range of frequency (ICRF) heating and lower hybrid current drive (LHCD).

The ICRF experiments in the past have demonstrated efficient heating in the minority and second harmonic heating experiments.^{1,2} During FY83, experiments concentrated on the details of the wave propagation, impurity generation and influx, and fast particle behavior during the heating process. The LHCD experiments focused on measuring the efficiency of current start-up and ramp-up with and without ohmic heating.

In addition to these main-line experiments, other continuing studies of X-ray spectroscopy, fusion particle production, impurity transport and line identification, and neutral efflux took place.

MAJOR ACTIVITIES

Each five day "run" week was divided between ICRF, LHCD, and other experiments. This division resulted in 50% of the PLT discharges being used for ICRF experiments, 45.5% for LHCD experiments, and 4.5% for ohmic heating experiments. Neutral-beam injection was used in conjunction with the ICRF experiments to study both transport and wave physics. The auxiliary experiments were generally performed in the same discharge as the main experiments in a "piggyback" mode.

ICRF Heating Experiments on PLT

During FY82 ICRF heating experiments demonstrated good heating results in both the fundamental minority and majority second harmonic heating regime for powers up to 3 MW. Notably, deuterium

ion temperatures of $T_d \sim 3$ keV in both the ^3He minority regime at an electron density of $\bar{n}_e \sim 3 \times 10^{13} \text{ cm}^{-3}$ and in the H minority regime in conjunction with deuterium neutral-beam heating at $\bar{n}_e \sim 6 \times 10^{13} \text{ cm}^{-3}$ were achieved. Hydrogen average ion densities up to $\langle E_d \rangle \sim 4$ keV have been achieved in the second harmonic regime at $\bar{n}_e \sim 4 \times 10^{13} \text{ cm}^{-3}$.

In order to enhance confidence in the scaling of these results to the reactor regime, the experiments in FY83 concentrated on the details of the plasma effects occurring during the ICRF heating, the physics of the wave launched into the plasma, and the appropriateness of the modeling used in the extrapolation. Particular emphasis was placed on studies during ICRF heating of energetic ions, impurity influx, and recycling for wave excitation with several couplers.

Since heating for both minority and second harmonic regimes involves the production of an energetic ion tail, measurements of this tail have always formed an important part of the ICRF experiments. Measurements with the horizontal scanning charge-exchange analyzer FIDE (Fast Ion Detector Experiment) during hydrogen minority heating have shown a difference between co-going and counter-going energetic ions.³ As expected, the energetic hydrogen flux for counter-going ions was observed to increase toward the near-perpendicular viewing angle. Co-going ions, on the other hand, were observed to give a peak flux at an angle intermediate between perpendicular and parallel (Fig. 51). During FY83 further measurements of this effect were made,

Figure 51. Fast neutral flux versus $V_{||} / V$ derived from the detector tangency radius at three energies during ICRF heating ($I_p = 450$ kA, $B_\phi = 29$ kG, $f = 42$ MHz).

and modeling analysis of the phase space ion distribution using a bounce-averaged Fokker-Planck code, which includes a modified Kennel-Engelmann quasilinear operator, has shown qualitative agreement between the observed fluxes and the standard heating model. The maximum in the flux is interpreted as corresponding to banana trapped ions whose banana tips lie in the resonance layer.

In conjunction with the fast ion measurements, bolometric probes⁴ have shown a fast ion component at the outside midplane in both hydrogen minority and second harmonic heating experiments. If this flux is poloidally symmetric it could account for up to 15% of the input rf power. Measurements with two identical probes, one inserted from the top and the other from the outside midplane, have shown an absence of signal on the top probe even when it is inserted 0.8 cm inside the top limiter. This lack of signal is in agreement with the interpretation of the fast ion data.

Even though the evidence of poloidal asymmetry indicates a much smaller fraction of rf power is lost than was at first thought, the loss of these ions to the limiters is a major concern with regard to localized heating and material sputtering. A recent analysis of the graphite probe cap used for these studies indicates that there may be a synergistic carbon erosion effect between the fast ions and the bulk plasma.⁵ The heavily eroded, blackened zone seen in Fig. 52 at 50°-60° from the aperture was caused by the impact of fast ions. This erosion is much larger than the level expected for either thermal plasma bombardment or fast ion bombardment. It appears that a small flux of fast ions increase the sputtering rate of the D⁺ bulk plasma ions by a factor of approximately 30-50.

Fast ion losses in the case of ³He minority heating of deuterium have not been detected with the bolometer probes in either the midplane or top locations. It is clear from the 14.7 MeV proton spectrum that very energetic ³He ions are present in the plasma core. This suggests that either the diffusion of these ions to the surface or the production

Figure 52. Two views of the graphite probe cap eroded at the fast ion impact location.

of trapped ions near the surface is much reduced over that for the case of hydrogen minority heating. This result, coupled with the higher heating efficiencies, has led to the choice of 30 MHz ³He minority heating as the major experiment to be emphasized during FY84.

Even though high-Z impurities do not play a dominant role in the central energy balance of ICRF heated discharges in PLT, it is desirable to understand their origin to ensure that they do not become a problem in the future. A series of experiments was performed using different Faraday shield material on the half-turn (standard) coils and then comparing the impurity levels between launching with half-turn and quarter-turn coils⁶ (Fig. 53). It is clear that the metal surfaces closest to the plasma contribute the most metal impurities (Faraday shield material as opposed to materials on the wall), but that both the shield and the wall related impurity levels in the plasma core increase to a higher level during the heating pulse, apparently independent of the type of coupler used (Fig. 54).

In addition to measurements of coil loading and magnetic probe measurements of surface fields in FY83, measurements of the rf wave fields were extended by making direct microwave scattering measurements of the ion-Bernstein waves inside the plasma. The purpose of these measurements was to obtain more quantitative understanding of the fate of the coupled rf power. With a 2-mm heterodyne microwave scattering system, the existence of the mode conversion of fast magnetosonic waves into ion-Bernstein waves at the ion-ion hybrid layer have been clearly identified. The scattering geometry was chosen to make a well-localized measurement for relatively well-selected k values.

Figure 53. Comparison of impurity levels with different Faraday shield materials.

Figure 54. Comparison of impurity levels with quarter-turn and half-turn ICRF coils.

The identification of the detected density fluctuations as ion-Bernstein waves is based on the dependence of this amplitude on minority concentration and toroidal magnetic field, and on the direction of their phase velocity. Figure 55 shows that for a maximum scattered signal, the theoretical dispersion curve intersects the detection region. Additional confirmation of the dependence on minority concentration was found by modulating the concentration with neutral-beam injection.

In addition to the measurements made in two ion species plasmas, scattering measurements during second harmonic heating of a pure hydrogen plasma have shown the existence of an analogous density fluctuation (Fig. 56). This is very important since previous second harmonic heating experiments showed stronger damping than was expected from

Figure 55. The WKB kinetic dispersion curve with $n_{\parallel} = 10$, $T_e(0) = 750 \text{ eV}$, $n_e(0) = 3 \times 10^{13} \text{ cm}^{-3}$, $n_{3\text{He}}/n_e = 15\%$.

Figure 56. Microwave scattering amplitude for $k = 7.5 \text{ cm}^{-1}$ in a hydrogen plasma during second-harmonic heating versus the applied frequency normalized by the local ion cyclotron frequency ($f = 90 \text{ MHz}$, $P_H \sim 100 \text{ kW}$, $n_e = 2 \times 10^{13} \text{ cm}^{-3}$).

the simple models. This stronger damping was theoretically predicted to be due to the existence of these fluctuations.⁷

Plans for FY84 are to concentrate once again on extending the parameters of high power ICRF heating. The rf sources are all being modified to operate at 30 MHz in order to achieve 6 MW source capability. In addition, improvements to the coaxial vacuum feedthroughs are expected to allow this power to be coupled to the PLT plasma. The effects of this large increase in power on the discharge (energy confinement, surface interaction, limiter loading, etc.) will form the main thrust of the experiments in the next year.

Lower Hybrid Current Drive Experiments on PLT

Lower hybrid current drive has proved to be the most successful method for maintaining plasma

current in long pulse tokamak discharges. Its most promising role in the near future is to assist the ohmic heating transformer to achieve high current during the initial low temperature stage of discharges in large tokamaks, such as TFTR. High currents appear to result in good ion confinement in beam-heated tokamaks.

Accordingly, experiments on the PLT tokamak during the past year have focused on measuring the efficiency of current start-up⁸ and ramp-up using the 800 MHz lower hybrid system. In the start-up studies, lower hybrid waves have been used to create the target plasma and then to generate the current-carrying electron tail. In the ramp-up work lower hybrid waves, operating alone or in tandem with the transformer, were used to increase the plasma current in discharges initiated by conventional induction.

Start-up experiments were carried out at 800 MHz using one of two different couplers: one was a narrow, 2-cm, six-element waveguide grill ($N_{||} = CK_{||}/\omega \sim 3.5$ at 30°) and the other was a broad, 3.55-cm grill ($N_{||} \sim 2$). In each case the background gas, deuterium at a pressure of $(1-2) \times 10^{-5}$ Torr, was broken down by the rf fields, and a plasma of line-averaged density 10^{12} cm^{-3} was formed. The phase angle between the waveguides during this 10-30 msec initial stage was set to 0° to minimize reflection.

Following the breakdown stage, the waveguide phase was switched to 90° or 135° so that the waves would propagate toroidally in one direction and drive an electron current. With the narrow grill, it was then possible to initiate and raise the plasma current with the lower hybrid waves. Simultaneously, the vertical field was raised by the normal PLT feedback control. With the broad coupler, however, careful programming of the vertical field proved necessary. As shown in Fig. 57, the rf power was turned on with the vertical

Figure 57. Behavior of basic plasma parameters during start-up experiments with only lower hybrid current drive.

field biased at ~ 30 G, a level somewhat higher than that estimated to cancel the stray fields from the toroidal field. The vertical field was slowly decreased towards zero and then ramped up sharply over 20 msec. Following the application of rf power the plasma current rose quickly at a rate of 200 kA/sec to 30 kA followed by a 2 sec rise at 35 kA/sec to 100 kA. Approximately 4% (20 kJ) of the total rf energy input to PLT was converted into poloidal field energy.

Hard X-ray measurements at 90° to the magnetic field show a rising level of X-rays during the discharge and the development of a second tail at intermediate times. The 40-keV X-ray tail "temperature" is good evidence that the current is carried by a fast electron tail similar to that observed in earlier experiments. Soft X-ray emission (10-30 keV) shows that the fast electrons are centered on axis and are spread out over a minor radius of 12 cm (Fig. 58). Very soft emission (< 10 keV) from the main body electrons shows a slow rise in the central electron temperature from 300 to 400 eV. Spectroscopic measurements of Doppler broadening of carbon V shows that the carbon ion temperature is 100 eV at $r = 10$ cm.

Figure 58. Soft X-ray spectra and profile during start-up experiments.

The intensity of microwave radiation near the electron plasma and cyclotron frequencies rises gradually with the current until $t = 0.6-0.8$ sec, when strong oscillations begin (Fig. 59). In past work on PLT this behavior has been associated with velocity space instabilities driven by the electron tail.

Figure 59. Intensity of plasma radiation near (a) the electron plasma frequency and (b) the electron cyclotron frequency during LHCD start-up experiments.

This work represents the first creation of a tokamak discharge by lower hybrid waves alone, and it provides tokamak designers with new options for current drive in their efforts to achieve a more efficient and practical reactor design.

In the ramp-up experiments, the current was raised above 200 kA by the rf fields following a normal PLT ohmic heating (OH) transformer start-up. The results, given in Fig. 60, show that the ramp-up rates up to 130 kA/sec can be achieved at power levels of 200-300 kW. During the later stages of the high power ramp-up, the current saturated as the plasma density rose to $5 \times 10^{12} \text{ cm}^{-3}$. Examination of the limiter by photography showed that the uncontrolled density rise was associated with the appearance of small hot spots on the leading edge of the limiters. It is likely that the hot spots are created in regions where the hot electron cloud touches the carbon limiters. A rotating limiter designed to smear out the hot spots and reduce the limiter outgassing was installed on PLT and will be tested this coming year.

The determination of the conversion efficiency, i.e., the fraction of the rf energy that is converted into poloidal-field energy, is of great importance for future experiments on large tokamaks. As shown in Fig. 61, our measured efficiency is ~25%. The top of the bars in Fig. 61 give the efficiency after subtraction of the

Figure 60. Behavior of plasma current during LHCD ramp-up experiments.

Figure 61. Efficiency of converting rf energy to poloidal-field energy during LHCD current ramp-up.

residual transformer flux. The height of the bar is the estimated contribution from the vertical field. The theoretical value of the conversion efficiency depends on the magnitude of the back current, which depends, in turn, on the plasma resistance. The data are consistent with a plasma resistance of 2-3 $\mu\Omega$, which is the approximate resistance of the background plasma. Theoretically, one would expect the resistance to be determined by the hot electron tail and the efficiency to be $<10\%$. At this time, it is not clear whether the discrepancy is caused by the presence of an unidentified power source, or whether there is an unknown impediment to the flow of the back current.

A new 2.45 GHz, 500 kW source for lower hybrid heating and current drive was constructed and will be tested in PLT during the coming year.

During lower hybrid current drive, a fast current-carrying electron tail is created by the unidirectional rf waves. Therefore, one of the PLT lower hybrid experiments was to determine the velocity distribution of this tail using the bremsstrahlung produced by those electrons. The hard X-ray emission, as a function of energy and angle, was measured with a tangentially scanning hard X-ray detector.⁹ A 3" $\times$ 3" NaI (thallium) detector views the plasma along a

line-of-sight which intersects the magnetic axis of the plasma at an angle defined as θ_d . The symbols in Fig. 62 show photon counts at four different photon energies and fourteen different viewing angles. The data has been weighted to account for the different lengths of the line-of-sight through the plasma at each viewing angle. These weighting factors are computed from radial profiles determined by Abel inversion of 14-keV radial chord X-ray measurements which are made separately with a Si (lithium) detector. In order to interpret these data, calculations were performed on the X-ray emission from the model distribution function using relativistic electron-ion and electron-electron bremsstrahlung.

Two models of the tail electron distribution function were mainly used. The first is a simple, three temperature exponential form given by

$$f(p) = C_N \exp \left(-\frac{p_{\perp}^2}{2T_{\perp}} - \frac{p_{\parallel}^2}{2T_{\parallel F}} \right) \quad \text{for } p_{\parallel} \geq 0,$$

$$= C_N \exp \left(-\frac{p_{\perp}^2}{2T_{\perp}} - \frac{p_{\parallel}^2}{2T_{\parallel B}} \right) \quad \text{for } p_{\parallel} < 0,$$

$$= 0 \quad \text{for } p_{\parallel}, p_{\perp} > P_{O}^*.$$

The second model uses results by Karney and Fisch, who solved the two-dimensional Fokker-Planck equation with quasilinear wave diffusion, both numerically and analytically. The adjustable parameters are the minimum and maximum extent of the rf wave spectrum (W_1 and W_2), the strength of the rf diffusion coefficient $D_H(W)$, and the Z_{eff} of the plasma.

As a first approximation it was assumed that the tail distribution (i.e., $T_{\parallel}$ and $T_{\perp}$) was homogeneous throughout the plasma. Figure 62(b) shows a fit to the data as a solid line for photon energies of 100, 200, 300, and 400 keV assuming a three-temperature distribution function with the parameters $T_{\parallel F} = 750$ keV, $T_{\perp} = 150$ keV, $T_{\parallel B} = 150$ keV, and $E^* = 600$ keV. The model distribution exhibits a plateau which extends out to 600 keV. These parameters give a mean percent difference of 35% between the calculated and measured photon counts. A contour plot of the model electron distribution is shown in Fig. 62(a). The bremsstrahlung spectrum calculated from the model duplicates the two main features of the data: (1) the general peaking of the emission for forward viewing angles ($\theta_d \sim 90^\circ$) and (2) the relative spacing between lines with 100 keV increments in photon energy (i.e., the slope of the X-ray spectrum at each viewing angle). A major feature of the data that the simple homogeneous, three-temperature model does not duplicate is the relatively narrow peak in the emission at $\theta_d \approx 45^\circ$ and the subsequent fall off as θ_d approaches 28° . This peak was always present during the time when the rf was on in the four major scans which were done on PLT. The peak at $\theta_d \sim 45^\circ$ always disappeared after the rf turnoff. This suggests that during current drive the distribution is more complicated than assumed. More refined models are being investigated, such as allowing $f(p)$ to vary with radius.

Figure 62. Angular distribution of photon intensity for four different energies during LHCD.

Among the many important observations made with the tangential hard X-ray system the following are listed: (1) A significantly more energetic X-ray spectrum was observed for 60° phasing ($n_{\parallel 0} \sim 1.5$) of the waveguides than for 90° phasing ($n_{\parallel 0} \sim 2.25$). (2) The electron distribution was observed to run away after rf turnoff. (3) An increase with time of the backward ($\theta_d = 152^\circ$) X-ray emission was observed during rf ramp-up, presumably due to the induced $-Li_p$ voltage.¹⁰

A further important observation was the transfer of parallel energy into perpendicular energy during the Parail-Pogutse instability. Measurement of the total hard X-ray emission parallel (28°) and perpendicular (90°) to the magnetic field is shown in Fig. 63(a-d). The instability occurs in normal current drive discharges when the rf power is switched off, and then $I(28^\circ)$ decreases whereas $I(90^\circ)$ increases [Fig. 63(a) and (b) at time $t = 400$ msec]. Whenever a electric field is left in the plasma, i.e., at low rf power [Fig. 63(c)] or near the high density limit of the current drive [Fig. 63(d)], a very energetic electron tail is observed that becomes subject to the Parail-Pogutse instability.

Figure 63. Measurements of total hard X-ray intensity showing conversion of perpendicular energy to parallel energy at low power during LHCD.

Other Experiments

X-Ray Spectroscopy

An X-ray crystal spectrometer was used to study the ionization equilibrium and transport of titanium impurity ions in discharges with ion cyclotron heating. The spectrometer consisted of a bent 1120 quartz crystal with a radius of curvature of 526.5 cm and a multiwire proportional counter in the Johann configuration. This made it possible to obtain simultaneous spectra of the 1s-2p radiation from the carbon-like up to the hydrogen-like charge states of titanium with a spectral resolution of $\lambda/\Delta\lambda = 5000$. Figure 64 shows 16 titanium spectra which were recorded from discharges with 2 MW rf heating during consecutive time intervals of 60 msec. Helium-like titanium, TiXXI, is evidently the dominant state of ionization in these discharges. A small concentration of hydrogen-like titanium, TiXXII, is produced during the period of rf heating when the central electron temperature exceeds 2 keV. The spectra of TiXXII were analyzed previously using a crystal spectrometer of very high resolution.¹¹ The lower titanium charge

Figure 64. Titanium spectra versus time during ICRF heating using the X-ray crystal spectrometer.

states, TiXVII-TiXX, occur in appreciable fractional abundances at the beginning and the end of the discharge pulse when the central electron temperature is below 1 keV.

Neutral Particle Measurements

In 1983, PLT became the first tokamak used as a neutral particle source for an atom scattering experiment.¹² Total scattering cross sections were measured in the energy spectrum of approximately 30 eV to 1400 eV for H⁰ on helium, D⁰ on helium, neon, argon, and krypton; and He⁰ on helium, argon, and krypton. The total scattering cross sections for neutral-neutral collisions are very important for understanding edge effects in fusion devices.¹³ Designing and modeling structures, such as divertors and pumped limiters,¹⁴ for future large-scale fusion devices will require knowledge of these cross sections since neutral-neutral collisions will influence the neutral density distribution near these structures. Codes which calculate the neutral density profiles in the plasma should also include the effects of neutral-neutral collisions. The total scattering cross sections have not previously been measured in the energy range of 2 eV to 400 eV for many pairs of atoms.

The cross sections were determined by using the charge-exchange efflux from PLT as the source of H⁰, D⁰, and He⁰. These neutrals passed through a gas-filled scattering cell and were detected by a time-of-flight spectrometer. The cross section, $\bar{S}_{sc}$, for scattering greater than the effective angle of the apparatus was found by measuring the energy-dependent attenuation of H⁰, D⁰, or He⁰ as a function of scattering gas pressure in the cell. The advantage of using a broad-energy-band neutral-particle source such as a tokamak in conjunction with a time-of-flight spectrometer is that the entire energy distribution is measured at once. The scattering cross sections for D⁰ incident on rare gases are shown in Fig. 65. The effective scattering angle ranged from 1.1° to 1.4°.

Figure 65. $\bar{S}_{sc}$ for deuterium incident on helium, neon, argon, and krypton. Each smooth curve is the result of an interpolation between about 100 data points. The error bars for neon and argon at a given energy are the same size as the ones shown for helium at that energy, while those for krypton are about 50% larger.

Fusion Product Measurement

During ICRF heating in PLT, ^3He minority ions with energies of ~ 200 keV produce 15-MeV protons through $(^3\text{He}, p)\alpha$ fusion reactions with the majority deuterium species.¹⁵ In previous measurements of the energy spectrum of the 15 MeV protons produced during ICRF,¹⁵ the highest proton energies were cut off by the finite depth of the surface barrier detector. When the full energy of all the protons is measured, the asymmetric, downward-shifted spectrum reported previously becomes a spectrum with two peaks separated by about 2 MeV (Fig. 66). Analysis of this spectrum in terms of a model two-component distribution function that has one component purely perpendicular and the other purely isotropic in velocity space indicates that $\sim 90\%$ of the high energy ^3He ions created by the waves have velocities perpendicular to the tokamak toroidal field.¹⁶

Line Identifications

A number of spectrum lines within the ground configurations of the $n = 3$ shell have been identified and their wavelengths measured for elements between copper and molybdenum.¹⁷ Also, some progress has been made in correlating the emissivities of the lines and the corresponding ion densities for molybdenum, as a representative case of this group. These lines are emitted in the electron temperature range of 1-3 keV; thus they are useful for localized diagnostics in PLT, as well as for serving as a starting point of the diagnostics of the (hopefully) 5-10 keV plasmas of TFTR, where the lines of the $n = 2$ configurations of these elements may be expected.

Figure 66. Fusion proton energy spectrum during (a) ICRF and (b) NBI.

Advances in Spectroscopic Diagnostics on PLT

Significant advances were achieved in spectroscopic diagnostics on PLT: (1) the identification of emission lines from $\Delta n = 1$ of high- n quantum number levels (with air wavelengths) from charge-exchange recombination of C and O and their application to measuring central ion temperatures¹⁸ during ICRF heating, and (2) the first direct observation of charge-exchange recombination of medium-Z elements (Al, Sc).¹⁹

Emission at air wavelengths due to charge-exchange recombination of C and O was identified for the first time. The emission lines are OVIII 2976 Å (8 7), CVI 3434 Å (7 6), and CVI 5291 Å (8 7). These lines are from high- n transitions and have an advantage over earlier work with H α 6563 Å in that they are not significantly excited by electron collisions. The emission is confined to the region of the plasma intersected by the neutral beam and, in the present geometry, comes from the plasma center (minor radius 0-5 cm). Figure 67 shows a fast spectral scan of the OVIII 2976 Å line during neutral-beam

Figure 67. Intensity of O VIII neutral doping enhanced emission as measured by fast rotating mirror spectrometer.

injection and also a gaussian fit to the spectral line profile. The signal-to-noise ratio is excellent, and the measured ion temperature is in agreement with measurements based on neutron radiation and neutral hydrogen charge-exchange spectra. These lines are now used routinely as a convenient and direct diagnostic of the central ion temperature during ICRF heating.

Charge-exchange recombination has an important role in impurity radiation losses. Particularly important is charge-exchange of medium-Z elements which radiate in the central region of the plasma. The first direct observation of charge-exchange recombination of medium-Z elements (Al, Sc) injected into a PLT discharge by the laser blow-off technique were made. The emission lines were Al XI 154.7 Å ($4f \rightarrow 3d$), Al XI 3209 Å ($10 \rightarrow 9$) and Sc 112.1 Å ($5g \rightarrow 4f$). One of the lines, Al XI 3209 Å, is in the convenient air region of the spectrum. This is a significant advantage as it permits the use of lenses, mirrors, and optical fibers for fast spectral and spatial scanning. Figure 68 shows a repetitive radial scan of the Al XI 3209 Å line and the volume emission profile

Figure 68. Measurement of charge-exchange recombination light from medium-Z elements injected into the PLT discharge.

calculated by Abel inversion. The emission is confined to the region of the plasma intersected by the neutral beam, and it indicates a surprisingly narrow neutral-beam profile, much smaller than that measured on the neutral-beam test stand with a scanning calorimeter. The central ion temperature was also measured by a spectral scan over the Doppler broadened line profile.

The long (air) wavelength of the Al, C, and O lines will become especially significant in the future as tokamaks progress to D-T burning mode; the emission can be easily transferred via optical fibers to remotely located spectrometers without activation and neutron damage problems to the detector.

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POLOIDAL DIVERTOR EXPERIMENT

The time from October 1982 to June 1983 marked the final operating period of the Poloidal Divertor Experiment (PDX) before its shutdown. The research program on PDX during that time emphasized studies of a regime of enhanced confinement during neutral-beam heating. This "H-mode" (for high-confinement mode) operation was obtained only in a modified divertor geometry. After obtaining the H-mode operation, the PDX effort concentrated on detailed diagnostic measurements of this type of plasma in order to gain some insight into H-mode plasma properties. Confinement times of up to or greater than 50 msec with high-power injection ($P_{INJ} = 2.5$ MW) were obtained in these H-mode plasmas, while only about half that value was obtained in earlier studies on PDX with rail-limited plasmas. These studies have led to a new awareness of the importance of edge conditions and particle fueling and recycling in improving energy confinement times.

The second major effort on PDX in FY83 involved installation and tests of electron cyclotron heating (ECH) which heats the plasma electrons instead of ions as an alternative heating method. A 200 kW ECH pulse lasting 40 msec was available. Major physics results with these ECH tests included a demonstration of efficient central electron heating, identification of the trapped electron population with ECH, and modification of MHD activity via ECH. With $n_e = 1 \times 10^{13} \text{ cm}^{-3}$ and $P_{ECH} = 80$ kW, the central temperature rose from less than 1.5 keV to 2.5 keV and above.

Tests of plasma operation when limited by a large particle scoop limiter were also performed on PDX. This advanced limiter concept was tested as a possible alternative to the more complex and expensive magnetic divertor design for the purpose of particle control. Successful operation with P_{INJ} up to 5 MW of neutral injection power was obtained in a relatively short run time (a total of 7 days with neutral injection). In addition to detailed studies of the edge plasma in the region of the scoop limiter, the general confinement properties of a plasma with this limiter were studied, and the results indicate that H-mode-like confinement levels may be achievable in nondiverted plasmas with careful limiter design.

Investigations of MHD instabilities at high beta were continued on PDX during FY83, and new fluctuation phenomena associated only with H-mode confinement were identified and examined in detail. Plasma fueling with injection of solid hydrogen pellets resulted in ohmic plasmas with $n_e(0) = 3 \times 10^{14} \text{ cm}^{-3}$ at moderate magnetic field strengths, while several experiments were performed to examine pellet penetration and fueling efficiency in the

presence of high power neutral injection. Diagnostic development for present and future devices continued on PDX, as did studies of particle fueling and impurity control.

HIGH CONFINEMENT REGIME IN DIVERTED PLASMAS

Modifications to a Closed Divertor Geometry

In its first three years of operation, the divertor system in PDX was usually operated in an open divertor configuration, wherein recombined neutrals in the divertor region could return unimpeded by plasma to the main plasma chamber via open channels near the outer divertor coils [Fig. 69(a)]. Due to theoretical advancements in the understanding of high-density divertor operation and to experimental results from other tokamaks showing favorable energy confinement and power handling characteristics of closed divertor geometries, the PDX hardware was modified in late 1982 in order to close off most of the open conductance paths for neutral gas between the divertor and main plasma chambers [Fig. 69(b)]. In addition to closing the divertor geometry, the outer divertor coils were taken out of the magnetic circuit to reduce the field gradients in the outer region and thus allow for easier plasma start-up. This allowed routine operation with diverted discharges with $I_p = 500$ kA. Also, titanium gathering in the upper divertor chamber was eliminated to allow high neutral gas buildup and to reduce earlier difficulties with metallic bursting.

Figure 69. Flux plots for the open (a) and closed (b) PDX divertor geometry.

With these modifications came substantially altered plasma behavior in diverted discharges, even with only ohmic heating. The compression ratio of neutral gas pressures between the divertor and main plasma chambers increased from unity in the open divertor case to up to ~30 in the closed geometry.¹ In addition, only about 10-15% of the total input energy was deposited on the divertor neutralizer plates in the closed divertor geometry, whereas up to 60% of the input energy was deposited there in the older open geometry.² Figure 70 shows an example of power balance measurements for ohmically heated diverted discharges with the closed divertor geometry. In addition, electrostatic probe measurements³ in the divertor region showed plasma temperatures of 20 eV or less, indicating an approach to the high recycling low-temperature divertor regime of interest.

Figure 70. (a) Variation in measured terms in the overall energy balance with density for ohmically heated discharges in the PDX closed divertor configuration. P_{NP} : time-averaged neutralizer plate power; P_{MCB} : main chamber bolometer power; P_{DB} : divertor bolometer power. (b) The solid curve is the sum of the three individual terms in (a). The dashed curve includes a contribution from radiation from the asymmetric peak in the main chamber radiation, and a doubled value of the P_{DB} term to account for possible radiation from the inner separatrix region.

Confinement Experiments with Neutral-Beam Heating

It is with the onset of high-power neutral-beam heating that the largest changes in plasma behavior in the closed divertor geometry were most evident. At low injected powers (<1.5 MW), the energy confinement time τ_E dropped from the values obtained with ohmic heating only, just as observed in earlier PDX experiments with rail-limited discharges.^{4,5} Above a threshold in absorbed power, however, a spontaneous rise in τ_E , τ_p (the particle confinement time) and $\bar{n}_e$ occurred as the discharge evolved from a low-confinement (L) phase to a high-confinement (H) phase.^{6,7} The power threshold for this transition to occur was found to depend on n_e , B_T , and I_p . Figure 71 shows the change in various central and edge plasma properties which are typical of the H-mode transition. Sometime during neutral injection, a spontaneous rise in the plasma density occurs without an increase in the ionization particle source at the plasma edge as monitored by D_α emissions [cf. Fig. 71(a), (c), and (d)]. At the same time, a large jump in the electron temperature occurs near the plasma edge [Fig. 71(b)]. This rise in n_e and T_e and the drop in the particle source all indicate improved particle and energy confinement at the H-mode transition.

The striking rise in T_e at a few centimeters inside the plasma separatrix ($R_{sep} = 180 \text{ cm}$) often follows a sawtooth oscillation of the main plasma, suggesting that the heat pulse propagating out of the plasma center to the edge aids in triggering the H-mode onset. Transitions to the H-mode were also observed without sawtooth activity. Electron density and temperature profiles during an H-mode discharge were studied with the Thomson scattering system, and it was found that the density profiles broaden just after the transition and remain relatively broad as n_e rises.

Figure 71. Variations in edge plasma parameters during an H-mode discharge. (a) Line-averaged electron density in the plasma midplane. (b) $T_e(t)$ at a position ~4 cm inside the separatrix in the plasma midplane, as measured via second harmonic electron cyclotron emission. (c) D_α emission in the plasma midplane. (d) D_α emission from the divertor region. The H-mode transition is at $t = 530 \text{ msec}$.

While the electron temperature profile sometimes broadens, it almost always appears to gain a pedestal, or constant addition, of 200-300 eV across the profile. Like the n_e profile, ion temperature and toroidal rotation velocity profiles also broaden after an H-mode transition.⁸

The energy transport of H-mode plasmas was analyzed with the time-dependent transport analysis code TRANSP. Analysis of several cases indicates that the dominant energy loss mechanism can be attributed to anomalously high electron thermal conduction, just as in L-mode plasmas. Sample results from such a transport analysis (Fig. 72) indicate that the thermal energy confinement time rises sharply at the transition to the H-mode, and part of the rise can be attributed to a drop in the electron thermal conductivity at the time of the transition. The rise in τ_E is also due to the increased stored energy in the plasma as evidenced by the development of the pedestal in the T_e profile.

A sensitive single-point Thomson-scattering diagnostic was installed to study the edge of H-mode discharges. Measurements with this system revealed very sharp gradients in the plasma edge during the H-mode phase. These gradients, shown in Fig. 73, appear to fall inside the location of the plasma separatrix, in contradiction to theories about the H-mode mechanism which invoke thermal barriers along open field lines.

The H-mode work on PDX revealed that one of the crucial features in the improvement of confinement appeared to be the localization of the plasma fueling source to the region around the divertor. This

Figure 72. Kinetic transport analysis results for an H-mode discharge. (a) Total thermal confinement time as a function of time. (b) Comparison of the electron thermal diffusivity for the pretransition (L-mode) and H-mode phases of the discharge.

Figure 73. Electron temperature and density profiles at the outer edge of the plasma for a high-confinement discharge. The shaded region indicates the estimated location of the separatrix as determined from an MHD equilibrium code.

was found by noting a degradation in confinement with intense gas puffing even though some signatures of the H-mode transition remains. Likewise, a reexamination of earlier open divertor data showed the characteristic drop in H_{α} , D_{α} emission of H-mode plasmas, but without significant improvement of confinement. A common feature of these low-confinement cases was the presence of neutral particles and recycling in the plasma main chamber, while improved confinement was found to depend monotonically on decreasing neutral particle pressure in the plasma main chamber. A comparison of measurements of the contours of equal D_{α} emission (proportional to particle source rate) is shown in Fig. 74 for a good H-mode discharge and a similar plasma with the density rise forced by intense gas puffing. These results have indicated that, while divertor plasmas can always show the characteristic transition above some threshold power whether the divertor is open or closed, improved confinement appears to depend on the control and localization of the neutral particles and plasma fueling source.

In general, it was found that τ_E depended primarily on the total plasma current, I_p , for both H- and L-mode plasmas. Thus a discharge quality factor, τ_E/I_p , is used to remove this I_p dependence in comparing

Figure 74. H_{α} , D_{α} emission contours (in relative units) in a poloidal cross section for (a) a standard high-confinement H-mode plasma, and (b) an H-mode plasma with a forced density rise induced by intense gas puffing in the divertor region. The separatrix is noted by the dashed line.

confinement under different conditions. The behavior of ϵ/l_p as a function of total input power, Fig. 75, shows that significantly improved confinement was achieved at modest values of P_{TOTAL} in PDX. The shaded region in Fig. 75 shows the range of ϵ/l_p achieved for $D^0 \rightarrow H^+$ discharges formed on a carbon rail limiter. No reasonably high confinement discharges were obtained for $P_{TOTAL} > 3$ MW, and the residual improvement above the limiter cases for high P_{TOTAL} may be due to an isotope effect. At least two processes were identified to contribute to the degradation in H-mode confinement at high input powers. First, it was necessary to substantially increase the gas fueling rate in the divertor dome to avoid disruptions at high P_{TOTAL} and, as mentioned above, intense gas puffing invariably led to reduced confinement. Second, the edge relaxation phenomena (ERP), a new H-mode related instability at the plasma edge which is described in more detail below, are known to cause a large decrease in stored energy on the outer half of the plasma, and these instabilities become more intense and frequent as the input power increases. Indeed, the best confinement was achieved in a narrow range of injected power where enough power was available to induce the H-mode transition, but it was not enough to cause serious ERP's.

Figure 75. Normalized total energy confinement time as a function of total input power ($P_{INJ} + P_{OH}$) for H-mode discharges. The shaded region denotes the range of τ_E / l_p for L-mode discharges obtained with a graphite limiter.

MHD Activity and Fluctuations in H-Mode Plasmas

Two types of MHD and fluctuation activity were uniquely associated with the H-mode phase of a discharge. The first was a quasi-coherent density oscillation in the 50-100 kHz range which was observed by both CO_2 laser scattering and microwave scattering experiments. The amplitude was zero outside the separatrix but rose sharply inside the separatrix.³ This localized mode at the plasma edge occurred in bursts of $\sim 300 \mu\text{sec}$, and it persisted throughout the H-mode phase of the discharge.

The second instability associated with H-mode plasmas is the previously mentioned edge relaxation phenomenon (ERP), which is characterized by a sharp spike in the edge $H_{\alpha}D_{\alpha}$ signal. Seen on all edge signals, such as $H_{\alpha}D_{\alpha}$ emissions, soft X-ray emissions at large radii, and divertor density measurements, these oscillations are sawtooth-like relaxation modes on the outer half of the plasma with an inversion radius at the plasma edge, as seen in Fig. 76. The presence of these bursts is correlated with decreases in n_e , τ_p , τ_E , and $\langle \beta \rangle$, along with an increase in the parallel power flow outside the separatrix. During an ERP, the $H_{\alpha}D_{\alpha}$ emission increased around the entire plasma in the main chamber, and the angular distribution of the fast neutral flux from the plasma was consistent with an increase in the background neutral density in the main plasma. The ERP's appear to affect the thermal plasma rather than the slowing-down fast ions. The presence of this mode results in an abrupt loss of stored energy from the plasma, and this instability clamps the rise in average τ_E achievable in H-mode discharges. When these bursts disappeared in the course of an H-mode discharge, the $\langle \beta \rangle n_e$ and τ_E subsequently were observed to rise.

Figure 76. (a) Soft X-ray emissions as a function of chordal height in the plasma during the H-mode phase of a discharge. (b) Divertor $H_{\alpha}D_{\alpha}$ signal for the case shown in (a).

The relative amplitude of the $D_{\alpha}(\text{rms})/D_{\alpha}$ increase with increasing I_p and $\partial I_p/\partial t$, and it is noted that H-mode plasma profiles, with their relatively broad T_e and current density profiles, are calculated to be more unstable to surface kink modes than L-mode plasmas. Indeed, a poloidal array of Mirnov coils often shows a possible surface kink precursor oscillation with $(m,n) = (3,0)$ or $(3,1)$ which appears strongest at the X-point region near the divertor throat. Simultaneous observations at different toroidal locations show the ERP's to have a helical nature, propagating toroidally in the ion diamagnetic direction.

ELECTRON CYCLOTRON HEATING EXPERIMENT

The unique properties of electron cyclotron heating (ECH)—almost optical propagation of the waves, localized absorption of wave power, direct electron heating, and the possibility of selective interaction in velocity space—make ECH attractive for a number of objectives in tokamak research. These include providing bulk plasma heating, depositing the appropriate wave momentum to start and maintain a current in the tokamak, and controlling plasma profiles (e.g., temperature, pressure, and current) to optimize plasma stability and possibly improve tokamak confinement. Experiments addressing several of these issues were initiated during FY83 with the installation and operation of a 200 kW, 100 msec ECH system on PDX.^{10,11} Because of shortage in operating time, these experiments are more illustrative than definitive.

The PDX-ECH experiment utilized two Varian pulse-type gyrotrons (60 GHz, 200 kW, 100 msec). Waveguide components were designed and constructed specifically for transmitting power from the gyrotrons to the tokamak over a distance of >100 ft. About 70-85% of the power at the gyrotron window was transmitted into the PDX vacuum vessel. Figure 77 shows the two ECH launchers on PDX, one from the larger major radius side (or the outside) and the other from the smaller major radius side (or inside). The outside launch was aimed at a "washboard" reflector in order to convert the polarization of the incoming wave from that of the ordinary mode into that of the extraordinary mode. Most experiments were done on diverted plasmas with $R_{pl} = 135$ cm, $a = 40$ cm, $B_T = 21$ kG, $I_p < 300$ kA, $\bar{n}_e \approx 0.15 - 2.5 \times 10^{13}$ cm⁻³, and $T_e(0) = 1 - 1.5$ keV before ECH. Both ohmic and neutral-beam heated target plasmas were used.

A major advantage of ECH is the localized electron heating, with its localization controlled mainly by the toroidal field. Most central heating data on PDX was obtained with 80 kW of O-mode launched from the outside. Central electron heating has been observed in both ohmically and neutral-beam heated target plasmas. Density depletion was observed but the percentage decrease in line average density becomes insignificant as n_e increases. Three regimes of heating, defined in terms of n_e , were identified for central heating operation. At intermediate densities

Figure 77. Schematic diagram showing the inside and outside ECH launchers in a poloidal projection of PDX.

$[n_e(0) = 0.7 - 2.0 \times 10^{13}$ cm⁻³], a well defined peak in the T_e profile and centrally localized density depletion were observed during ECH, as shown in Fig. 78. In this region, $\Delta T_e(0) \sim 1$ keV for 80 kW of O-mode heating, and the single pass absorption of ECH power is >80%. The increase in $T_e(0)$ lasts longer than the average electron energy confinement, which is consistent with the central plasma region having better confinement properties than the total plasma column. Similar results were obtained for neutral-beam heated target plasmas. For densities approaching the O-mode cutoff density (i.e., $n_e(0) > 2 \times 10^{13}$ cm⁻³), the change in $T_e(0)$ due to ECH was roughly inversely proportional to the central density. This decreased central heating is consistent with refraction and the resultant divergence of wave energy which prevents the concentration of ECH power in the small central plasma volume.

At very low densities [$n_e(0) < 0.7 \times 10^{13}$ cm⁻³], the single pass absorption of the O-mode wave is ~50% or less, so that substantial power is connected to the X-mode by the inside wall reflector. This X-mode wave provides fast electron heating in the direction perpendicular to the magnetic field, thereby creating a class of collisionless trapped electrons. The existence of an additional trapped-electron population after ECH is indicated by asymmetric peaks observed on the outside of both the electron

Figure 78. Thomson scattering profiles at different times during a discharge with 80 kW of ECH applied from 400 to 440 msec. The horizontal axis indicates both time (when read at the profile center location) and major radius. Each horizontal division denotes 40 cm in radial displacement. The resonance is placed within 2 cm of the plasma center.

temperature and density profiles, as shown in Fig. 79. Results with the inside launcher added to the outside launcher demonstrate even greater asymmetry.

The behavior of MHD activity during ECH is different from that observed in plasmas without ECH. While sawtooth activity was generated during ECH as $T_e(0)$ increased, the sawtooth oscillation carries a large and persistent $m = 1$ oscillation, in contrast to the case with other types of heating where $m = 1$ oscillations occur only before the internal disruption. The excitation of sawtooth activity was very sensitive to the location of the electron cyclotron resonance layer, and it could be completely avoided by off-peak heating.

Finally, plasma production using ECH without any ohmic induction field was obtained with the outside launch of the O-mode wave. Figure 80 shows an example of the results of plasma production with ECH only. Whether the presence of the special mode-converting reflector on the inside wall is essential for plasma production is not definite. Further experiments on this and other questions about ECH will be pursued at PPPL in the future on the PLT tokamak, to which the existing ECH system was connected after the shutdown of PDX.

Figure 79. Electron density and temperature profiles for low density ($n_e = 0.35 \times 10^{13} \text{ cm}^{-3}$) showing trapped-particle population on the outboard side of the plasma. $P_{ECH} = 70 \text{ kW}$ from the outside launch.

Figure 80. Plasma start-up with ECH without the ohmic heating field. The right figure shows the radial distribution of plasma light detected by the Thomson scattering diagnostic.

PARTICLE SCOOP LIMITER EXPERIMENTS

Limiters equipped with various means for particle removal have been proposed as alternatives to magnetic divertors for control of recycling, reduction of impurities, and removal of helium ash in fusion reactors. A specially designed pump limiter, called a scoop limiter, was installed in PDX in late 1982 to investigate such properties of a pump limiter.¹² This PDX scoop limiter [Figs. 81(a) and (b)] consisted of a box, with an internal volume of 50 liters, rigidly mounted on the outer vacuum vessel wall. The side facing the plasma consisted of graphite blades shaped to form a saddle surface. Open channels behind these blades allow plasma to flow along the field lines and to hit vanadium-coated copper neutralizer plates, with the resulting neutral particles either remaining in the volume or exiting back to the plasma edge.

Figure 81. (a) Plan view of the PDX Scoop Limiter showing the channels, neutralizer plates, and diagnostics. (b) Elevation view of limiter blades and the side entrance channel.

Plasma discharges limited by the scoop were run on a total of 13 days from December 1982 to June 1983. Due to lack of conditioning, the plasmas were often disruptive during the first few days of operation. A lack of run time prevented tests of the particle pumping characteristics of this limiter, and all results were obtained with the scoop volume unpumped. Nevertheless, some intriguing results concerning neutral particle behavior and energy confinement during neutral-beam heating were obtained.^{7,12}

Neutral gas pressures of $>10^{-3}$ Torr were obtained in the scoop volume during neutral-beam injection while the pressure outside the scoop in the main plasma chamber was $\sim 10^{-5}$ Torr, indicating a very large neutral gas compression ratio. Probe measurements inside the scoop channel showed $n_e < 5 \times$

10^{12} cm^{-3} and $T_e \sim 10 \text{ eV}$ for the edge plasma. In general, there was not strong recycling of the plasma in the scoop channel region, indicating that a strongly plugged scoop limiter was not attained except perhaps at the highest plasma densities achieved, $n_e \sim 6-8 \times 10^{13} \text{ cm}^{-3}$. Plasma densities in the scoop channel were asymmetric, with the ion drift side being larger than the electron drift side. This asymmetry could be explained partly by the pitch of the magnetic field lines and possibly by a residual amount of plasma rotation at the edge.

The power handling characteristics of the scoop limiter were relatively favorable, in that up to 5 MW of injected power could be handled without disruption after only a few days of running. The peak surface temperature of $\sim 1400^\circ \text{C}$ and power fluxes of ~ 3

kW/cm² for $P_{inj} > 3$ MW were comparable to that observed on rail limiters, but the scoop, with its larger front surface area, absorbs 25-50% of the total input power, while rail limiters usually absorb 10-20% of P_{TOTAL} . In spite of this higher input power, high density plasmas with $Z_{eff} \sim 2$ were readily obtained with $P_{inj} > 4$ MW.

The H-mode results in diverted plasmas emphasized the importance of controlling the fueling and neutral particles in the discharge. If this is the salient feature for attaining improved confinement with auxiliary heating, there is a possibility that high confinement may be achieved without an expensive magnetic divertor system. Intriguingly, scoop limiter discharges, with their high neutral pressures localized in the scoop volume, did display some characteristics of improved confinement over rail limited discharges. It is clear from measurements of H_α emissions far from the scoop and from fast neutral charge-exchange flux measurements that long particle confinement times were the norm for these discharges. The scoop thus had a significant effect on the particle confinement and/or recycling in these discharges. While no transition to a higher confinement regime was obvious during these discharges, the confinement quality factor τ_E/I_p was similar to that observed for the diverted H-mode plasmas, as shown in Fig. 82. Although sparse, the data indicates a regime, at least for $P_{TOTAL} < 3$ MW, wherein the confinement is improved above those obtained with a rail limiter. Obviously further investigation is needed to explore this possibility of achieving high confinement in a nondiverted discharge.

Figure 82. Confinement quality factor as a function of total input power for $D^0 \rightarrow D^+$ scoop limiter plasmas.

ADDITIONAL ACTIVITIES

In addition to the main efforts already mentioned, a wide variety of activities were carried out on PDX in FY83. Many of these activities are closely related to the future needs and efforts of both PPPL and the fusion program in general.

Studies of the "fishbone" (internal kink) instability and its effects on beam ion loss at high values of β_{Tq} continued on PDX during FY83. High beta

experiments on PDX had indicated that an additional degradation in the global energy confinement time during high-power injection with $\beta_{Tq} > 4.5$ was due mainly to a rapid expulsion of fast ions from the plasma.^{4,13} Two experiments were performed to study the details of this process and to compare the observations to the mode-particle pumping model developed by PPPL theorists. The first involved observations of charge-exchange particle losses from the inner and outer major radial regions of the plasma.¹⁴ The results indicate that the particles escape the plasma primarily in the direction of increasing major radius. The instability is found to cause the ejection of beam ions in a toroidally rotating beacon with toroidal mode number $n = 1$, in agreement with theory. The data also suggest the presence of an additional (as yet unexplained) mechanism for accelerating particles to energies higher than the injection energy. The second series of measurements included a D^+ detector to measure directly the fast ion flux out the edge of the plasma, instead of inferring such a flux from charge-exchange measurements.¹⁵ In addition, rf probe measurements in the 10 to 400 MHz range suggest that a non- μ conserving mechanism may also be involved in fishbone dynamics. Further studies of fishbone instabilities and fast ion losses will be a prime focus of experiments on the Princeton Beta Experiment (PBX) device.

Gas fueling studies on PDX continued to include the closed divertor plasmas,¹ and they showed measurements of high neutral gas pressures in the divertor chamber along with inferences of low divertor plasma temperatures at high main chamber densities. A preliminary comparison of gas fueling requirements of neutral-beam heated plasmas¹⁶ showed that the open divertor required the largest gas flow to achieve a given value of $\bar{n}_0$ in the main chamber, while the rail limiter plasmas required the next largest amount, with the closed divertor and scoop limiter plasmas following in that order.

An alternative fueling mechanism is the injection of solid hydrogen pellets at high speed (600-900 m/sec) into the plasma. The earlier studies of pellet injection on PDX¹⁷ were extended to the case of neutral-beam heated diverted discharges.¹⁶ A four-pellet injector was modified to inject three large ($\sim 1.5 \times 10^{20}$ atoms/pellet) pellets with arbitrary differences in the injection time for each pellet. In discharges with neutral injection, the pellet penetration is substantially reduced since the ablation rate is increased due to both the higher electron temperatures in beam-heated plasmas and the additional ablation due to fast beam ions. It appears that a significant perturbation in the plasma density profile occurs only when the pellets penetrate the plasma to near the $q = 1$ surface. A single pellet from the existing injector is incapable of such penetration into a beam-heated discharge, but the use of several pellets spaced closely in time effectively increases the pellet mass and results in particle deposition inside the $q = 1$ surface for low beam power. This is shown qualitatively in Fig. 83, which shows the change in the central chord visible continuum

radiation for beam-heated discharges with pellet injection. Since the continuum emission rate is proportional to $n_e^2 / T_e^{1/2}$, the incremental change at the time of injection gives a qualitative measure of the overall density increase due to the pellets. As the power increases the penetration decreases, but it can be improved somewhat by stacking all three large pellets closely in time.

Impurity transport studies concentrated on the behavior of low-Z impurities in PDX. Detailed radial profiles of the poloidal asymmetries in the distribution of ionization states of carbon¹⁸ show that low charge

states (e.g., CII to CIV) are located near the shadow of the limiter and are subject to edge processes such as recycling, and, therefore, vary with plasma conditions. A higher charge state such as CV is less sensitive to edge conditions since it lies several centimeters inside the plasma edge. It was found that a quasi-fluid neoclassical model of impurity transport reproduced the observed asymmetries of CV if the main plasma ions were assumed to lie in the banana regime.

In anticipation of substantial densities of alpha particles (i.e., He⁺⁺ ions) in D-T operation on TFTR, detailed measurements of He⁺⁺ injected into PDX via gas puffing were performed using the newly developed charge-exchange recombination spectroscopy techniques.¹⁹ By studying the transport of He⁺⁺ instead of the more conventional heavier metallic impurities, several of the uncertainties in deriving particle transport coefficients due to atomic physics uncertainties were avoided. Temporal and spatial evolutions of He⁺⁺ puffed into the PDX plasma were directly measured for the first time, demonstrating this technique for use in reacting plasmas. The He⁺⁺ radial transport was found to be in disagreement with neoclassical transport theory, but it could be described by a simple convective/diffusive transport model with transport coefficients $D = (2.1 \pm 0.9) \text{ m}^2/\text{sec}$ and $v(r)/D = (0.8 \pm 0.03) \partial(\ln n_e)/\partial r$.

Power handling and impurity level studies in PDX continued during FY83. The temperature profiles on the inner wall toroidal limiter system²⁰ were studied with infrared TV cameras, and the results were shown to be consistent with previous measurements of scrape-off lengths in the plasma edge.²¹ The conditioning and power-handling of the rail limiter in PDX was also considered in some detail,²² and a comparison of plasma purity levels revealed that relatively clean plasmas were obtained with high-power neutral-beam injection for both diverted and limited plasmas.¹⁶ For example, values of Z_{eff} vs injected power for several different operating conditions are shown in Fig. 84. These results indicate

Figure 83. Central chord visible continuum signals for pellet injection into discharges with different P_{inj} and varying timing of the three pellets. The change in signal at the pellet injection time gives a qualitative measure of the change in plasma density due to the pellets. The last pellet penetrates to $r = 13, 16, 25$, and 11 cm for cases (a), (b), (c), and (d) respectively.

Figure 84. Line-averaged Z_{eff} after at least 150 msec of neutral injection for several operating configurations in PDX.

that the supposed advantage of divertors in power handling and impurity control is not evident in PDX-scale machines and data is needed from larger, longer pulse experiments.

Finally, diagnostic development for use on future fusion experiments continued on PDX. A fiber-optically coupled Fabry-Perot spectrometer allowed detailed line shape measurements of H_α emission in the plasma edge,²³ which in turn provided an estimate of molecular influx and H_2 particle lifetimes. Extensive development of the charge-exchange recombination spectroscopic diagnostics for a variety of plasma parameter measurements was continued. In addition to the He^{++} transport measurements mentioned above, ion temperature and toroidal rotation velocity measurements using radiation induced by the heating neutral beams were made during H-mode studies on PDX (cf. Fig. 85). These measurements were all made with simple fiber-optically coupled spectrometers, and this technique^{24,25} has been adopted since then on several other tokamaks around the world. Novel use of the Thomson scattering optics allowed two-dimensional distributions of H_α emission to be measured in a poloidal cross section of the plasma.^{7,23} The development of a ten-channel grating polychromator for electron cyclotron temperature diagnostics was carried out by the University of Maryland and installed on PDX for H-mode, pellet injection, and ECH studies.²⁶ The SPRED multichannel vacuum ultraviolet (VUV) spectrometer system²⁷ was further refined on PDX, and its successful use led to its adoption as a primary impurity diagnostic tool on the larger TFTR and JET tokamaks.

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Figure 85. Radial profiles of ion temperature for $H\alpha \rightarrow D^+$ H-mode plasma at three times during the discharge. Closed circles: charge exchange recombination spectroscopy measurements ($HeII$ 4686Å emission) using technique developed on PDX; open circles: conventional passive charge-exchange results. Beam injection from $t = 400$ –700 msec; transition to the H-mode occurred between 520 and 550 msec for all shots used here.

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PRINCETON BETA EXPERIMENT

When the PDX experimental program was completed in June 1983, work began immediately on the machine conversion to the Princeton Beta Experiment (PBX). The scheduled "first plasma" date is January 1984 and the estimated cost (with contingency) is \$1.2 M. The purpose of the PBX is to go beyond the 2-4.5% beta values already achieved in various tokamak devices (e.g., PDX, D-III, ISX-B, JFT-2) by exploiting the theoretically predicted stability of indented (bean-shaped) plasmas against both the ballooning mode and the $n = 1$ internal kink mode. The economic attractiveness of a tokamak reactor depends strongly on the beta value at which it can be operated. The preliminary documentation of PBX will be carried out in early 1984 and the present hardware will be evaluated in late 1984.

THEORETICAL BACKGROUND

Recent theoretical studies¹⁻⁵ have demonstrated that a bean-shaped tokamak plasma has strong MHD stability properties against high- β , pressure-driven, ideal MHD modes, such as the ballooning and internal kink modes. Particularly, the β -limit of the ballooning mode should increase significantly with sufficient indentation. Indeed, when the indentation exceeds a critical value [which depends on the pressure and safety factor (q) profiles], the second stability regime of the mode can be accessed (Fig. 86). This is the first attempt to access the second stability regime in a controllable quasi-static manner in tokamak devices and hence achieve high β , although betas of about 20% have been achieved dynamically with belt-pinch type devices.

Theoretical study also shows that strong indentation imparts triangularity on the inner magnetic surfaces around where $q = 1$, and increases the minimum- B properties against the internal kink mode. This mode is, at present, considered a potential candidate responsible for the fast ion loss observed in PDX (the fishbone instability).⁶

IMPLEMENTATION

The major experimental objectives of PBX are (1) the controlled formation of bean-shaped tokamak plasmas, (2) the study of the stabilizing effects of bean shaping on the fishbone instability, (3) the achievement of beta values higher than those achieved in present-day tokamaks (3.0-4.5%), and (4) the study of the transport properties in highly noncircular plasmas. In order to minimize the persistence of the fishbone instability, two neutral beamlines will be

Figure 86. Stability boundary to infinite n -ballooning modes as a function of indentation and β , showing complete stability beyond $d/2a \sim 0.3$ and accessibility to the second stability regime at lower indentations.

reoriented to inject tangentially, while two others will be left in their present, near-perpendicular orientation.

A noncircular tokamak plasma is susceptible to the MHD axisymmetric ($n = 0$) modes, and an extensive theoretical design study⁷ was carried out to ensure the stabilization of this global mode. This is accomplished by using a combination of passive and active feedback coils, with the constraint that the active feedback coil requirements do not exceed the capacity of the PDX amplifier.

Figure 87 shows the post-conversion arrangement of the PBX internal machine hardware: IF denotes the indentation field-shaping coils, EF the radial

position control external field coils, PP the passive plate coils for stabilizing the vertical ($n = 0$) motion, and FB the active feedback coils. The main coil that produces the indentation field, the "pusher coil," lies on the inner midplane: It was a divertor coil in PDX located at $Z = +0.55$ cm. The other IF coils are suitably placed in order to fine-tune the plasma shape and to provide zero net turns coupling to the ohmic heating coils. The plasma radial position is controlled by the original PDX equilibrium-field coils but with the inner solenoid coils removed to improve the shaping in the lobe area. Thus, all the poloidal coils for bean-shaping are original PDX poloidal coils, with some relocated vertically in the vacuum vessel either to create the indentation or to provide a larger plasma volume. The upper and lower passive plates and inner wall cylinders (2.54 cm thick nickel-plated aluminum) are connected in parallel to form three sets of passive coils with a resistive decay time constant of 70-100 msec. The active feedback (FB) coil for the vertical positioning of the plasma is excited by error signals induced in a pair of flux loops near the pusher coil.

Figure 87. Identification of PBX coils and passive conducting plate. Passive conducting plates (PP) are shown by shaded areas. The coils for the active feedback system are indicated FB.

A typical plasma configuration in PBX is shown in Fig. 88 with the parameters tabulated in Table IV. The machine parameters chosen are based on the maximum available beam power (7 MW) and the empirical scaling law for the confinement time observed in PDX, i.e., $\tau \propto I_p/c$ with $c = 15-20$, where I_p is the plasma current. Other less-indented plasma shapes can be produced by shifting the magnetic axis outward or by simply lowering the indentation field. With a suitable choice of magnetic axis and indentation field the separatrix can be located inside the limiter and can be used for the study of an

expanded boundary divertor configuration. (Note that in Fig. 88 the separatrix is seen just outside the passive plate.) The bean-shaped PBX plasma will be created through gentle deformation and major radius contraction after a circular plasma is formed (Fig. 89). This process will eliminate the delicate field balance required during plasma initiation so that the formation will be reproducible.

Figure 88. Typical configuration with an indentation of $d/2a = 0.26$. A full list of parameters is given in Table IV.

Figure 89. Formation of bean-shaped plasma.

Table IV. Typical PBX Parameters.

R_{geo}	1.40 m
R_{mag}	1.425 m
$\langle\beta\rangle$	10%
β_p	0.97
$\langle a \rangle$	0.44 m
a_{edge}	0.32 m
$d/2a$	0.26
b/a	1.44
q_0	0.8
q_ψ	3.0
I_p	600 kA
I_{IF}	15 kA
I_{EF}	8.2 kA
$\int pdV$	150 kJ
B_t	0.8 T
n_{mag}	-1.5

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SPHEROMAK

The S-1 Spheromak device¹ was completed in August 1983, and engineering tests were carried out at the design limits of all systems. The construction was accomplished on schedule and within budget, with the exception of preparation of a spare pair of flux core liner halves. These were originally planned for completion in September 1983 but did not meet this schedule.

The primary objective of the S-1 experiment is to study the confinement features and MHD stability properties of the spheromak configuration with loose-fitting conducting walls. The formation scheme,² which does not require electrodes, is based on an inductive transfer of toroidal and poloidal magnetic flux into a plasma from a flux core. This formation scheme, earlier proved in the Proto S-1 devices, has now been verified in S-1.

The S-1 Spheromak was intermittently operated under limited conditions for several months prior to completion of device fabrication. The equilibrium field was operated primarily in Mode D (index of curvature $n = 0.354$); Modes A ($n = -0.033$) and C ($n = 0.124$) were tried with equal success. Spheromaks were formed on time scales of 0.1, 0.2, and 1.0 msec. Stabilization coil systems had not been installed. Bank voltages were usually kept below 14 kV (20 kV max). Two modes of operation were studied: the "detached" mode, in which the spheromak is completely pinched-off from the flux core, and the "linked" mode, wherein the plasma is not completely detached from the core, and there is some poloidal flux shared by both the plasma and the core.

Plasma major and minor radii were 0.4-0.6 m and 0.25-0.4 m, respectively. Midplane radial profiles of poloidal and toroidal fields as a function of time for a discharge lasting over 0.7 msec are shown in Fig. 90. These data were obtained from one shot using magnetic pickup coils inside the plasma. Toroidal plasma currents of up to 350 kA have been measured at intermediate power levels. Toroidal plasma current versus bank voltage shows a linear trend (Fig. 91) toward 0.5-MA operation, the design value. The solid data points denote the detached mode. This mode utilizes the full flux swing capability of the poloidal field circuit, thus allowing for higher currents to be achieved. Open points are for various linked modes. Currents and fluxes were measured directly with Rogowski coils and flux loops external to the plasma.

Stable spheromak lifetimes over 1.0 msec, the target value, have been achieved. The detached mode is unstable to shifting and tilting without a stabilizing conductor system nearby, resulting in lifetimes on the order of 0.2 msec. Plasmas shift randomly at

Figure 90. Time evolution of poloidal and toroidal fields in midplane of the S-1 device.

speeds over 10^6 cm/sec on a shot-to-shot basis. The linked mode is an order of magnitude more stable, with shift speeds less than 10^5 cm/sec, and the longest lifetimes have been achieved with this mode (Fig. 92). Lifetimes for various linked modes increase roughly linearly with bank voltage.

The electron temperature and density have been measured with a single-point Thomson scattering system capable of scanning the major radius on a shot-to-shot basis. Operating conditions for these measurements have been limited to bank voltages of 14 kV or below, of toroidal plasma currents equal to or less than 200 kA, fill pressures above 1 mTorr for hydrogen or helium, and relatively unconditioned vacuum wall surfaces. Measured electron densities

Figure 91. Toroidal plasma current versus bank voltage of poloidal- and toroidal-field coils. Solid points are for the detached mode. Open points are for various linked modes. The lower currents for the linked modes are due to the smaller poloidal flux swings associated with operation in these modes.

Figure 92. Spheromak configuration lifetime versus bank voltage of poloidal- and toroidal-field coils. Solid points are for the detached mode. Open points are for various linked modes.

are between 0.6 and $6.0 \times 10^{14} \text{ cm}^{-3}$ for fill pressures of 1 - 10 mTorr. Peak electron temperatures up to 60 eV have been observed (Fig. 93). There is a definite trend toward higher temperatures as the fill pressure is decreased below 2 mTorr.

Figure 93. Electron temperature as a function of H_2 fill pressure. Electron density is roughly $0.6 \times 10^{14} \text{ cm}^{-3}/\text{mTorr}$. Toroidal plasma currents for these data are equal to or less than 200 kA.

One of the most significant results to date is the observation⁹ of flux conversion between toroidal and poloidal fields of the plasma. The conversion is a manifestation of relaxation to a minimum-energy state. Relaxation is a strong mechanism in S-1 Spheromak plasmas. The plasma seeks a state such that the ratio of the plasma toroidal current to flux, I/Φ , is constant, independent of initial conditions. It is evident from the discharge (Fig. 94) how similar I and Φ are in time behavior. I/Φ remains nearly constant even though I and Φ are individually changing dramatically. This typical, long-lived discharge is linked. The I/Φ ratio is a global λ measurement, where λ is defined by $j = B$ and therefore is related to the pinch parameter Θ through a geometric factor involving the size of the plasma. Measured I/Φ values agree with theoretical estimates.

Figure 94. Toroidal plasma current I and flux Φ of the S-1 Spheromak with respect to time. The constancy of I/Φ is consistent with the plasma's maintenance of a minimum-energy state.

Relaxation is achieved by either quiet, continuous flux conversion during formation, or by abrupt flux conversion during equilibrium and decay. The toroidal flux in the plasma is as much as 40% greater than that in the flux core for the discharge shown in Fig. 94. Conversions of poloidal-to-toroidal and toroidal-to-poloidal magnetic fluxes have been identified in S-1 Spheromak plasmas. Flux conversion and the favorable operation in the linked mode can be combined to achieve steady-state inductive maintenance of the S-1 Spheromak, analogous to F- Θ Pumping⁴ in an RFP (Reversed-Field Pinch).

In the near future, higher current operation will be employed to seek higher electron temperatures and longer configuration lifetimes. A stabilizing conductor system, such as a figure-8 coil system, will be installed to obtain gross MHD stability of well-detached spheromaks.

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ADVANCED CONCEPTS TORUS-I

ACT-I (Advanced Concepts Torus-I) is a steady-state, 5-kG toroidal device with minor radius of 10 cm and major radius of 59 cm. Research on ACT-I is currently devoted to the investigation of wave physics in the lower hybrid and ion cyclotron range of frequencies (ICRF). Particular emphasis is being placed on advanced concepts in radio-frequency (rf) heating, current drive, and plasma diagnostics relevant to fusion reactors.

ION-BERNSTEIN WAVE HEATING

Ion-Bernstein wave heating^{1,2} was proved successful in ACT-I, and a joint Princeton Nagoya experiment was carried out under the U.S.-Japan Exchange Program in Nagoya in 1983. In principle, the ion-Bernstein wave can be launched by waveguides for tokamak reactors and is a very attractive method to heat the plasma to ignition temperature.

The JIPPT-II-U tokamak plasma has $\bar{n}_0 = 1.5 \times 10^{13} \text{ cm}^{-3}$, $T_{e0} \approx 700 \text{ eV}$, and $T_{i0} = 300 \text{ eV}$ for $P_{rf} \leq 100 \text{ kW}$. The wave is launched by inductive loops with the rf current flowing in the toroidal direction. In a two-ion-species helium-hydrogen plasma, the heating takes place at the third harmonic of helium minority cyclotron resonance. Figure 95 shows that the background hydrogen ion temperature monitored by charge exchange has a significant rise, $\Delta T_i \leq 600 \text{ eV}$, when the helium harmonic resonance layer is placed near the center of the plasma. The typical observed hydrogen ion heating quality factor, $\Delta T_i / (P_{rf}/n_0)$, is approximately $10 \text{ eV/kW}/10^{13} \text{ cm}^{-3}$. The heating efficiency is relatively insensitive to the ion concentration; however, it is strongly optimized when the resonance layer is placed near the center of the plasma. The observations are generally consistent with theory and with previous results from ACT-I. The result is also in good agreement with theoretical modeling calculations shown by the solid curve in Fig. 95(b). This heating technique is now being implemented in PLT with the hope that it will eventually lead to reactor application.

PARAMETRIC DECAY OF ICRF FAST WAVES

A fast wave induction loop antenna in the ion cyclotron frequency range ($\omega_0 \sim 2\Omega_i - 4\Omega_i$) is observed to excite ion-Bernstein waves and ion quasimodes via a parametric decay process. The daughter waves are identified by measurements of wavelengths and

frequencies. Onset of this decay process occurs at a low-threshold electric field in a warm ion hydrogen plasma over a wide range of parameters. Since the ion-Bernstein wave propagates for $\omega < \omega_{pi}$, the decay process is allowed in high density regions. This process may have an important effect on the deposition of rf energy during second harmonic fast wave heating where the waves are launched from the low field side with $\omega_0 > 2\Omega_i$.

LOWER HYBRID WAVE ECHO

Lower hybrid waves at two different frequencies, f_1 and f_2 , are launched simultaneously from two localized antennae, and a third wave is observed to arise near the plasma edge at the frequency $f = f_2 - f_1$. The experiment was performed in ACT-I with the following parameters: magnetic field on axis $\approx 2.8 \text{ kG}$, neutral pressure $\leq 10^{-5} \text{ Torr}$ (gauge), plasma density varying from $3 \times 10^8 \text{ cm}^{-3}$ to 10^{10} cm^{-3} , and electron temperature $\sim 1-2 \text{ eV}$. Figure 96(a) is a schematic drawing of the experimental setup. The excited lower hybrid waves propagate along spatially localized resonance cones, as shown in Fig. 96(b). In addition to the excited waves at frequencies f_1 and f_2 , the probe picks up a signal at the beat frequency $f = f_2 - f_1$ near the plasma edge when $f_2 > f_1$. When the two oscillators are switched, the signal disappears as shown in Fig. 95(c). This interesting asymmetry can be explained by the echo effect³ near the plasma surface. In fact, the maximum signal amplitude is observed at the location predicted by the echo theory. This process is not an important source of inefficiency in low-power experiments because the fraction of rf power in the echo wave is very small. However, to assess the importance of this loss in lower hybrid wave heating or current drive for fusion reactors, it will be necessary to determine the degree of energy transfer to the echoes at high-power levels.

ION DAMPING ON LOWER HYBRID WAVES

Theoretical investigation of the ion cyclotron harmonic damping effects on slow and fast waves in the lower hybrid frequency range were carried out for tokamak reactor parameters. Inclusion of the higher-order terms in the hot plasma dielectric tensor introduces ion cyclotron harmonic damping; these terms also contribute to the real part of the dispersion relation and affect the wave trajectories.^{4,5} However, wave absorption by 15-keV deuterium and tritium ions

Figure 95. Ion-Bernstein wave heating data from the JIPPT-II-U Experiment. (a) Radio-Frequency power loaded. (b) Ion temperature time evolution with and without rf. (c) Charge-exchange raw signal before and during rf. $B_0 = 1.8T$, $I_p \approx 110$ kA, $\bar{n}_0 = 1.5 \times 10^{13} \text{ cm}^{-3}$, and 40% He.

can be avoided by choosing the slow-wave frequency above the lower hybrid frequency and the fast-wave frequency below the lower hybrid frequency. Preliminary estimates show that energetic alpha particles tend to absorb both the slow and the fast waves. This absorption may become a serious obstacle for fusion-reactor current drive in the lower hybrid frequency range.

DIAGNOSTICS

In addition to the above physics achievements, several important diagnostics were installed on ACT-I in 1983. These include a far-infrared (FIR) laser scattering system, an 8-mm microwave interferometer with radial scanning capability, a scanning optical Fabry-Perot interferometer, and a microwave detection system for electron cyclotron emission measurements. These diagnostics enable experiments to be performed in high density, high temperature plasmas.

Figure 96. Observation of lower hybrid wave echo. (a) Schematic drawing of experimental setup. (b) Amplitude profile of the excited resonance cones detected by probe #1 ($f_1 = 50 \text{ MHz}$, $f_2 = 95 \text{ MHz}$). (c) Echo signal appears at probe #1 only when $f_2 > f_1$.

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X-RAY LASER STUDIES

In 1983 the soft X-ray laser development experiment progressed to time and space-resolved measurement of level populations and, hence, the measurement of population inversions and gain. Recent experimental results include the time-resolved measurement of axial enhancement of the CVI 182 Å emission, corresponding to a one pass gain, $k \times \ell \approx 3.5$, in both carbon disc (C-disc) and carbon fiber (C-fiber) targets and the time-resolved measurements of population inversions in OVI and NeVIII.

The CO₂ laser focusing optic was changed from a NaCl lens to a spherical copper mirror. This enabled the focal spot size to be decreased significantly from 1 mm in diameter to an ellipse of 0.2 × 0.4 mm. In this way the laser beam intensity at the focus was increased by an order of magnitude to about 10¹³ W/cm². With the new optics, the emission spectra of a carbon disc measured in the axial direction using photographic plates showed that the ratio of the intensity of CVI 182 Å to CVI 33.7 Å and OVI 173 Å lines increased by a factor of 2-3 in comparison with earlier data.¹⁻²

Most of the experimental work in 1983, however, was performed using time-resolved spectroscopic instruments. The XUV (extreme vacuum ultraviolet) grazing incidence duochromator viewing transverse to the plasma column was equipped with two-channel electron multipliers, and a 16-stage electron multiplier was installed in the axial XUV monochromator. Both instruments were calibrated for absolute intensity at 150 Å and 88 Å by the branching ratio method. The relative sensitivity of the axial and the transverse instruments was obtained for both the CVI 182 Å and CVI 33.7 Å lines by viewing simultaneously with both instruments the plasma created by the CO₂ laser interaction with a vertical carbon fiber.

A larger variety of targets was used than in the past.² In addition to gas targets (CO₂, O₂, Ne), experiments were performed with solid targets (C-disc, C-disc with Al-blades, C-blade, C-fiber, teflon disc, quartz disc). All the disc targets listed here had a 1-mm or 1.5-mm hole in the center, and the laser beam was focused on the edge of the hole. Attention to the solid targets was motivated by experimental conditions; with solid targets it was expected to attain more easily an electron density close to the critical density for the CO₂ laser wavelength of 10 μ [n_e(cr) = 10¹⁹ cm⁻³] than for gas targets.

In some experiments the CO₂ laser was focused onto a carbon disc. The time evolution of the CVI 182 Å and CVI 135 Å (4-2 transition) line intensities, measured in both the axial and transverse directions for two consecutive discharges, are presented in Fig.

97. In the upper part of the figure, the laser intensities obtained with a photon drag detector are shown as a function of time. The laser power was similar for both shots, with the laser energy in the range of ~500 J. The plasma column was created in a solenoidal magnetic field, B = 90 kG, by focusing the laser beam onto the edge of the 1.5-mm hole in the center of the carbon disc. One channel of the transverse XUV duochromator recorded the CVI 33.7 Å line and showed very good reproducibility of CVI radiation. Both the second channel of the XUV duochromator and the axial XUV monochromator simultaneously measured the intensities of the CVI 182 Å line for the first shot (first row in Fig. 97) and CVI 135 Å line for the second shot (second row in Fig. 97). The relative intensity of the CVI 135 Å line in the transverse direction was obtained by subtracting the known contribution of the fourth order of the 33.7 Å line, which was less than 30% of the total intensity at 135 Å. (For the axial instrument this contribution was negligibly small due to the different angle of the blaze of the grating.) It was found that the ratio of axial to transverse intensity of the CVI 182 Å line exceeded the same ratio of the CVI 135 Å line by a factor larger than 10. Such enhancement of axial intensity of the CVI 182 Å line corresponds to a one pass gain, $k \times \ell \approx 3.5$.

Figure 97. Time evolution of CVI 182 Å and CVI 135 Å line intensities measured in the axial and transverse directions, and indicating a gain-length product $k \times \ell \approx 3.5$, the time of the peak axial intensity of the 182 Å line (marked by the arrows).

Some initial experiments were performed with long, narrow graphite fibers suspended along the axis of the magnet bore and illuminated end-on with the CO₂ laser. The most interesting result in this set of runs was observed in the case of a 75 $\mu \times 4$ mm fiber (Fig. 98) that was completely in view of both the axial and transverse XUV instruments.³ The 182 Å line intensities were then compared using the measured axial-transverse relative instrumental sensitivity. In addition to an enhancement of 182 Å radiation of 5.3 ($k \times \ell \approx 2.8$), the sharp time history of the axial 182 Å emission is suggestive of stimulated emission. The rise time of the axial instrument is not better than 20 nsec so that a possible faster time behavior has not been recorded.

The spatial distribution of the XUV line emission from the various targets was measured also.⁴ A scanning slit assembly limited the field of view of the duochromator to a region 4 mm $\times$ 0.16 mm, the long dimension being parallel to the laser beam. By scanning the slit, the transverse distributions of the line intensities were obtained on a shot-by-shot basis. Between runs the target and laser focus were moved to different axial locations; hence, a complete spatial picture of the plasma was constructed.

The most interesting spatial scan was obtained with a carbon blade target. The target, a 0.3-mm thick carbon blade, was placed horizontally in the target chamber, and the CO₂ laser was focused on the corner of the blade. The idea here is that the low intensity wings in the laser focal spot do not interact with the target and, hence, the transverse profiles in the vertical direction are narrower than in the case of the carbon disc. This is confirmed by the data of Fig. 99. The width at half maximum for C VI 182 Å is 0.4 mm. Surprisingly, for the B = 0 kG case the width is even narrower, being limited by the instrumental resolution for this data of 0.3 mm. This is encouraging, both for carbon blade plasmas and also, by implication, for the carbon fiber plasmas. In the horizontal direction the plasma thickness is estimated to be in the range 0.2-0.8 mm. In Fig. 99, the maximum population, n_n , of level $n = 3$ of C VI

Figure 98. Axial and transverse C VI 182.17 Å (3-2) line intensities. Vertical scales have been adjusted with relative calibration data, initiating a gain-length product $k \times \ell \approx 2.8$.

Figure 99. Vertical distribution of C VI 182 Å and 33 Å line emissions with B = 0 and 50 kG and showing very narrow profiles at B = 0 kG. The laser energy used here was 120 J.

is $5 \times 10^{13} \text{ cm}^{-3}$ for the $B = 50 \text{ kG}$ case, and $2 \times 10^{14} \text{ cm}^{-3}$ for the $B = 0 \text{ kG}$ case with a plasma thickness of 0.2 mm and for a relatively low laser energy of $\sim 120 \text{ J}$. Initial results with 600-J laser energy show an order of magnitude higher column density at $B = 50 \text{ kG}$. These numbers are encouraging and are approaching that which is required for lasing action.

Our earlier works on population inversions in lithium-like CIV, OVI, FVIII, and NeVIII ions were continued in experiments with time resolution. In Fig. 100 are shown changes in the population inversions of the 4d and 3d levels of NeVIII as a function of initial neon (Ne) pressure.

Neon gas was puffed into the target chamber a few milliseconds before the laser pulse and was limited by mechanical apertures to a region 5 cm long. The initial Ne pressure was controlled by varying the delay of the laser pulse with respect to the gas valve opening. The populations of the 4d and 3d levels were obtained from the intensities of the NeVIII $73.5 \text{ \AA}$ (4d-2p transition) and NeVIII $98.2 \text{ \AA}$ (3d-2p transition) lines measured in the transverse direction with the XUV duochromator. Column density populations were deduced from the absolute intensity. Since these lines are close in wavelength, corrections for the variation of instrument sensitivity as a function of wavelength is small and therefore was neglected. Hence, the relative population of the 4d and 3d levels can be much more accurately determined than the absolute populations, which depend on the reliability of the absolute intensity of calibration. It can be seen that the 4d population exceeds the 3d population for higher pressure with the maximum population inversion at a gas pressure $p = 12\text{-}15 \text{ Torr}$. Since the 4d and 4f levels are expected to be closely coupled by collisions, this leads to gain on the 4f-3d transition at $292 \text{ \AA}$. The effect of optical trapping on the observed $73 \text{ \AA}/98 \text{ \AA}$ ratio was checked by measuring the ratio of the intensity of the fine structure components of the $98 \text{ \AA}$ line; this was close to the theoretical value for an optically thin plasma. The NeVIII $292 \text{ \AA}$ line emission was also observed in the axial direction, but a significant increase at high neon pressures were not seen, possibly because of absorption in the neutral gas boundary. Further target development should eliminate this problem.

In the future, it is planned to optimize experimental conditions in order to further increase the gain on carbon and aluminum coated carbon fibers, and to develop neon gas targets for the correlation of the NeVIII 4d/3d population inversions with emission on the 4f-3d potential lasing transition. A comparatively small increase in gain from the present values should lead to a dramatic enhancement in the axial emission.

Figure 100. Population inversion of the 4d and 3d levels of NeVIII as a function of initial neon pressure.

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THEORY

Theoretical research at the Princeton Plasma Physics Laboratory (PPPL) is concerned with problems immediately related to the design of experiments and the interpretation of experimental results, as well as with problems of a more fundamental and long-term nature. This distinction is often blurred as problems initiated with long-term goals in mind unexpectedly assume immediate importance, or the solution of a short-term problem leads to a fruitful long-term research effort. Often large efficient numerical codes, designed to increase general understanding in a particular area of research, unexpectedly lead to important and immediately relevant insights. The examples provided below attest to the healthy cross-fertilization of long-term research efforts and immediate laboratory needs.

HIGH-BETA CONFIGURATIONS

The attainment of high plasma temperature and density using as small a magnetic field as possible is an important part of obtaining an economical fusion reactor. Recent theoretical work has shown that a bean-shaped tokamak configuration can attain high values of plasma β , the ratio of plasma pressure to magnetic field pressure.

Different basic theoretical efforts combined to provide detailed assistance in the design of the bean-shaped tokamak configuration, the Princeton Beta Experiment (PBX). The PEST code was used to study stability properties of equilibria to ballooning and interchange modes. Indentation (a measure of the degree to which poloidal field coils push in the small major radius side of the plasma) has a dramatic effect on the stability boundary for ideal MHD ballooning modes. With modest aspect ratio and typical q profiles, indentation lowers the value of β corresponding to the second stability regime. In addition there is a critical indentation beyond which no ideal ballooning modes exist. Figure 101 illustrates how the instability region depends on indentation (i) for several aspect ratios (R/a). Extensive study has been made of the details of the accessibility of the second stability domain as a function of aspect ratio, elongation, current distribution, and pressure profile.

The inclusion of finite gyroradius effects further enlarges the stability domain since the high-mode number ballooning modes tend to be most unstable. This result was obtained by an examination of the lowest-order ballooning mode equation including ion diamagnetic drifts. The finite gyroradius contribution from the drifts acts directly against the interchange driving mechanism and becomes significant when

$k_{\perp}^2 \rho_i^2$ is comparable to L_p/L_k ; ρ_i is the ion gyroradius and L_p, L_k are pressure and field line curvature scale lengths, respectively. This effect shifts the right-hand edge of the instability regions shown in Fig. 101 to the left typically by 25%.

The internal $n = 1$ kink mode is completely stabilized by modest indentation. However, the internal $n = 2, 3$ modes remain unstable at any β for $q_0 < 1/n$ and above a critical β_p for central q values in the range $1/n < q_0 < 1$. Since these modes have broad eigenfunctions and exhibit a β threshold, they may be candidates for driving beam injection instabilities similar to the fishbone mode discussed in the next section.

Indenting the cross section generally causes the free boundary $n = 0$ mode to be unstable, and passive stabilizing conductors near the tips of the bean are necessary for stabilization. An active feedback system is required to stabilize this mode longer than the resistive L/R time of the passive conductors.

A free boundary axisymmetric resistive MHD code STARTUP, has been developed to aid in the design and interpretation of the PBX experiment. In this code, the poloidal-field coils are explicitly represented, and the inertial terms are retained in the momentum equation, but with enhanced mass to slow down the Alfvén waves. Axisymmetric magnetics, as represented by the STARTUP code, is a rapidly advancing subject. With supporting data from the PBX experiment, the design of larger advanced tokamaks for burning plasma experiments can be made with high confidence.

Figure 101. The stability boundary for ballooning modes in a bean-shaped plasma, in the plane of indentation and beta, for various aspect ratios. The central region is the instability domain.

TRAPPED-PARTICLE DESTABILIZATION OF MHD MODES

The understanding and prediction of plasma instabilities occurring in tokamaks is an important part of the theoretical effort. Recently a new, large amplitude instability was discovered experimentally on PDX (Poloidal Divertor Experiment). It ejected beam ions and thus inhibited plasma heating. Theoretical understanding of this so called "fishbone" instability was obtained this year.

It was shown that high-energy trapped ions have a destabilizing effect on near marginally stable ideal MHD modes. The resulting mode has a growth rate and a real frequency given by the trapped-ion toroidal precession frequency. The trapped-particle beta sufficient to cause destabilization is typically a fraction of a percent, provided that the overall plasma beta is near marginal stability for the ideal MHD mode. Shown in Fig. 102 is the growth rate of the internal

Figure 102. The growth rate of the two branches of the internal kink mode in the presence of trapped-beam particles, as a function of the trapped-particle beta. The MHD branch (M) is stabilized by the particles. The trapped-particle branch (T) has a real frequency equal to the trapped-particle precession frequency. Parameters used correspond to PDX beam-injection experiments.

kink mode, destabilized by trapped beam ions, as a function of trapped ion beta. The plasma parameters used are those typical for PDX. The regular MHD branch of the mode (M) is stabilized by the beam particles, but the trapped-particle branch (T) has a growth rate and frequency which agree with PDX fishbone results.

This theory of the mode destabilization, coupled with a mechanism for beam particle loss induced by the mode, has made possible a simulation of the full fishbone cycle. In Fig. 103 are shown typical simulation results, which are in good agreement with those observed on PDX. An understanding of this mode indicates methods for its avoidance, including less perpendicular beam injection and plasma shaping.

Figure 103. Fishbone mode simulation results, showing trapped-particle beta and MHD signal as a function of time.

The close correlation between theory and experiment on the fishbones serves as an important check on both the resistive MHD codes and an understanding of several particle drift effects.

CONFINEMENT AND TRANSPORT

The effect of plasma turbulence on confinement, and the modified growth and saturation of modes in the presence of turbulence, is an important step in understanding the scaling of confinement times with device parameters. The theory of general nonlinear dynamical systems has advanced significantly in the last few years, but fundamental properties such as the decay of correlations are still not understood. One of the physically intuitive approaches to the understanding of turbulent plasmas is resonance broadening theory (RBT). One of the predictions of RBT is the decay rate of the two-time force correlation function. This prediction is being tested by using a spectrum of ion-acoustic modes in a numerical simulation which follows particle trajectories for statistically long times. Preliminary results are in violation of the predictions of RBT, but they support certain modern ideas of nonlinear dynamics. This result is significant, since a large number of very complex calculations based on the fundamental

premises of FBT have been made. It is likely that many of the details of such calculations, which predict spectra and transport coefficients, are in error. It would appear that a satisfactory theory of plasma transport will require further development in the understanding of the nonlinear dynamics of plasmas.

RESISTIVE MHD

Resistive instabilities are of great importance in tokamak discharges; they govern many of the main features of a pulse, including current penetration, sawtooth oscillations, Mirnov oscillations, and disruptions.

The examination of domains of linear instability in general equilibria was carried out using a resistive version of PEST. The treatment of multiple rational surfaces in toroidal geometry for small values of resistivity is complicated by singular behavior at the rational surfaces. A Frobenius analysis at the rational surfaces showed that it was necessary to retain singular solutions with both even and odd parity. To resolve the singular behavior at marginal stability, special finite elements were used with appropriate asymptotic behavior. In the cylindrical pressureless pinch the usual Δ' criterion can be generalized to multiple rational surfaces. In toroidal geometry the existence of a similar Δ' criterion does not seem to exist except at zero pressure. In this case toroidal effects and noncircular shaping of the cross section can be quite stabilizing.

There are many aspects of resistive instabilities that can be studied with resistive PEST. Present work is concentrating on the study of finite pressure equilibria with multiple rational surfaces. Two possible approaches present themselves. The calculation of growth rates for small amplitude modes requires the analysis of additional physics inside the boundary layer, such as viscosity, finite Larmor radius, other kinetic effects, and assumptions about the plasma pressure. The behavior of the pressure in the resistive layer, in turn, requires some assumptions concerning thermal transport in the resistive layer. Alternatively, the calculation could be restricted to resistive MHD without kinetic effects. This could be accomplished by restricting the analysis to magnetic islands of width large compared to the resistive layer, so that the physics of the interior region becomes significantly simpler. This approach should lead to insights into the nature of three dimensional, nonaxisymmetric equilibria, a topic of fundamental importance for the understanding of anomalous transport in tokamaks.

In addition to linear stability analysis, a large effort is devoted to analysis of the experiments using nonlinear initial value resistive MHD codes. These codes were used routinely for the identification and analysis of MHD phenomena observed on PDX, including the fishbone oscillations. In addition, they are used to investigate fundamental properties of magnetic reconnection. It had long been assumed, on the basis of approximate analytical models, that a rapid reconnection rate (the Petschek reconnection) would form in appropriate geometry. Numerical

simulations fail to find any domain in which this type of reconnection occurs.

Numerical simulation of magnetic reconnection in toroidal geometry uses a set of reduced equations, obtained through an expansion in the inverse aspect ratio. This expansion is particularly useful since the short time scale magnetosonic waves occur only if high order terms are retained, and thus a truncation of the equations results in much more rapid numerical codes. However some interesting physics is also discarded by the lowest order truncation, in particular the internal kink mode. This year the expansion was carried out to higher order and, in fact, to optimum order. This means that the truncation is stopped one order short of retaining the magnetosonic waves. These optimal reduced equations have been coded into a nonlinear initial value code which can follow internal kink and ballooning modes in low- or high-beta equilibria.

GYROKINETIC APPROACH IN PARTICLE SIMULATION

Nonlinear microinstabilities are believed to play a major role in determining confinement in tokamaks. The simulation of these modes involves a self-consistent treatment of particles and their associated fields. Unfortunately, such plasma systems possess modes with characteristic frequencies several orders of magnitude larger than frequencies of interest, making it very difficult to simulate microinstabilities with a numerical code which follows all of the particle dynamics. The gyrokinetic ordering, which assumes that frequencies are small compared to gyrofrequencies and that parallel wavelengths are large compared to gyroradii, allows the implicit treatment of the high-frequency motion. A Hamiltonian formalism has been used to derive nonlinear gyrokinetic equations which are in a form suitable for efficient numerical analysis. To date only electrostatic fluctuations in slab geometry have been considered, but there is a straightforward generalization to arbitrary field geometry and electromagnetic perturbations. The simulations carried out thus far have shown the importance of nonlinear electron dynamics in the saturation of collisionless drift instabilities. The nonlinear $E \times B$ advection of nearly resonant electrons leads to oscillations of the perturbation amplitude around a finite saturation level.

THE STELLARATOR EXPANSION

Alternate concepts for the attainment of a fusion reactor must be pursued as part of the goal of economical fusion power. In addition to keeping the laboratory at the forefront of this innovative field, this effort provides a source of ideas and techniques applicable to tokamak research. One of the major alternatives is the stellarator, which is now showing confinement properties comparable to those observed in tokamaks. Analysis of stellarator

equilibria provides important insights and develops techniques for handling the tokamak three dimensional (nonaxisymmetric) states, which are important for the understanding of transport.

The PEST equilibrium and stability codes have been modified to incorporate the stellarator expansion. This allows analytical treatment of the multipolar fields and reduces the numerical computation to a two-dimensional one. Both codes have been applied to two existing devices, Heliotron-E and Wendelstein VII-A, and to several proposed configurations. The codes are also capable of investigating basic physics questions such as a study of the destabilizing effect of Pfirsch-Schlüter currents.

A typical application is the treatment of the ATF-1 device, for which stability with respect to free boundary modes has been investigated for various pressure profiles with average β of up to 2.5%.

CURRENT DRIVE AND ICRF HEATING

The use of lower hybrid waves to provide the initial ramp-up of current in future tokamaks such as TFCX (Tokamak Fusion Core Device) is being investigated. The large currents required, ~10 MA, and relatively short ramp-up times requested, ≤ 100 sec, place constraints on the initial discharge parameters. The ramp-up situation is modeled using a lower hybrid code which calculates the electron and ion distribution self-consistently in one dimension with the quasilinear damping of the lower hybrid waves by the electrons and ions. The induction electric field is calculated self-consistently from the evolving poloidal flux. The model calculations show that satisfactory results can be obtained if both the density and temperature are kept low. Densities of order a few 10^{13} cm $^{-3}$ or less are required to assure accessibility of the lower hybrid waves. The initial low density poses no problem for operation since the density can be easily increased once the current has been established. Temperature of a few keV are required to avoid edge absorption and to maintain sufficient resistance to allow a reasonable ramp-up time. To assure these low temperatures, during the injection of the radio-frequency power needed for ramp up, short energy confinement times of the order of tens of milliseconds are required. This requirement is the result of ray tracing and deposition codes which trace the energy flow from the antenna to its local modification of the particle distribution function.

By oscillating plasma parameters, such as density or resistivity, in synchronism with external current drive power, a nearly steady-state current can be generated with less power than would be required to simply drive steady-state current. The basis for this scheme lies in the fact that ohmic and nonohmic current carriers are impeded in different ways. In a reactor-sized tokamak, current can be driven in this manner with a peak power requirement of 30% and a circulating power requirement of 0.5% of the power needed for the steady-state case.

MURAKAMI DENSITY LIMIT

Some properties of fusion devices are first discovered as phenomenological descriptions of experimental data. Often a theoretical analysis, which succeeds in deriving the phenomenological law, leads to a more far-reaching understanding of related behavior. The Murakami density limit is an example of a previously poorly understood phenomenological law.

A theoretical upper limit for the density in an ohmically heated tokamak discharge follows from the requirement that the ohmic heating power deposited in the central current-carrying channel exceed the impurity radiative cooling in this critical region. A compact summary of results gives this limit n_M for the central density as $n_M = [Z_e/(Z_e - 1)]^{1/2} n_{eo} (B_T/R)$ where B_T is in Tesla, R is in meters, and n_{eo} depends strongly on the impurity species and is remarkably independent of the central electron temperature $T_e(0)$. Representative values are given in Table V. The results agree quantitatively with Murakami's original observations. A similar density limit, known as the $1/N$ limit, exists for reversed-field pinch devices and this limit has been evaluated also for a variety of impurity species.

Table V. Murakami Density Limit.

Impurity Species	Electron Density Parameter n_{eo} (in 10^{13} cm $^{-3}$)
Beryllium	15
Carbon	9
Oxygen	5
Titanium	1.5
Iron	1.0
Tungsten	0.5

SPACE PLASMA PHYSICS

Magnetic fusion and space plasma research share many basic physics problems, so that their solution by physicists working in either discipline often enriches both fields. The National Science Foundation supported effort in space physics at PPPL contributes to the space physics effort and provides, for use in magnetic confinement research, a source of techniques, codes, and methods developed with space physics problems in mind.

It is now well-known that there are two kinds of double layers: strong double layers and weak double layers. A strong double layer is characterized by a potential jump larger than the thermal energy, while for a weak double layer, the potential jump is comparable to the electron thermal energy. It was

shown that a weak double layer as a result of current-driven ion acoustic instabilities, may be produced in a sufficiently long system of several hundred Debye lengths. The potential jump associated with a double layer is characterized by the presence of a negative potential spike at the upstream side. While the electron acceleration due to a single double layer is small, numerical simulations with several thousand Debye lengths show the generation of several double layers in a series separated by a distance of about one thousand Debye lengths. The total potential jump integrated over the system length increases with the system length, and the acceleration of electrons thereby increases with the system length. A strikingly similar structure of multiple double layers has been observed recently on auroral field lines by the S3-3 satellite, suggesting the possibility that a series of small double layers may be responsible for generating auroral electrons instead of the single strong double layer commonly assumed.

MAGNETIC COORDINATES

Magnetic coordinates clarify the relation between magnetic fields and Hamiltonian mechanics, and can be used to quickly define the quality of the magnetic surfaces in a given field. An arbitrary magnetic field can be written in the form

$$\vec{B} = \vec{\nabla} \psi \times \vec{\nabla} \theta + \vec{\nabla} \phi \times \vec{\nabla} \Psi_p (\psi, \theta, \phi),$$

with θ and ϕ any poloidal and toroidal angles, $2\pi\psi$ the toroidal flux inside a constant ψ surface, and $2\pi\Psi_p$ the poloidal flux outside a constant Ψ_p surface. This expression immediately leads to Hamilton's equations for the field lines

$$\frac{d\psi}{d\phi} = -\frac{\partial \Psi_p}{\partial \theta} \quad \text{and} \quad \frac{d\theta}{d\phi} = \frac{\partial \Psi_p}{\partial \psi}.$$

To study the quality of magnetic surfaces in a given field a few field lines are integrated in R, ϕ, Z cylindrical coordinates with R the major radius and ϕ the toroidal angle. Along each line, which approximately lies on a toroidal surface, one can Fourier decompose $R(\theta, \phi)$ and $Z(\theta, \phi)$ with the poloidal angle defined so $\theta = \pm \phi$ along a line. The transform $\pm$ is a constant along a line. Retaining only a few Fourier components and letting $\vec{x} = R\vec{R} + Z\vec{Z}$, one can find the Fourier decomposition of the magnetic Hamiltonian using

$$\frac{\partial \Psi_p}{\partial \theta} = -\frac{\vec{B} \cdot \vec{\nabla} \psi}{(\vec{\nabla} \psi \times \vec{\nabla} \theta) \cdot \vec{\nabla} \phi} = \vec{B} \cdot \left(\frac{\partial \vec{x}}{\partial \phi} \times \frac{\partial \vec{x}}{\partial \theta} \right).$$

The part of Ψ_p , which depends only on ψ , is defined by $\pm$. As an illustration, Fig. 104 gives the Poincaré plot of a 5-period, $\ell = 2$ stellarator field which has an island for $\pm = 5/6$. The poloidal Fourier components of Ψ_p are shown in Fig. 105 for $n = 5$. The resonant term, $\Psi_{5,6}$, has been found to give an island width in agreement with the Poincaré plot. With the use of this method one can study high-order islands which are difficult to find by Poincaré plot methods, and can define how the quality of the magnetic surface changes as the field is changed. Magnetic coordinates and the magnetic Hamiltonian can also be used to define efficient Hamiltonian drift orbit following techniques (as used in the fishbone studies), and to generalize the energy principle to tearing modes.

Figure 104. The Poincaré plot of a 5-period, $\ell = 2$ stellarator field.

Figure 105. The Hamiltonian $\Psi_{5,m}$ for the magnetic field of Fig. 104 is plotted against the poloidal mode number m . The transform $\pm$ here is $\approx 5/6$.

TOKAMAK MODELING

Tokamak modeling typically involves the development and application of computer codes such as the BALDUR one-dimensional tokamak transport code which models energy and particle transport in tokamak plasmas. Recent work has included development of computer models specifically addressed to understanding the complex physics of the plasma edge and scrape-off region. Tokamak modeling codes are based on tokamak confinement physics, atomic physics, surface physics, and other areas of study, and their applications often involve extensive collaborative efforts both within and outside PPPL. They are used to help interpret current experimental data and test theory, in addition to providing a predictive capability for the design of future devices and diagnostics.

IMPURITY TRANSPORT

Computer modeling of impurity behavior in tokamak plasmas continues to be an area with diverse applications. In collaboration with the Theoretical Division, a model based on the radiative cooling-ohmic heating power balance in the critical current-carrying core region of a plasma was formulated that yields a straightforward upper limit to the density achievable in ohmically heated tokamak plasmas.¹ Collaboration with the Experimental Division in the interpretation of impurity observations and effects in PDX, PLT, TFTR, and S-1 continued. On PLT, these efforts included modeling impurity behavior during both beam-heated² and ICRF-heated³ discharges. A close collaboration with the experimental effort on the PDX tokamak resulted in the first application of the new technique of charge-exchange recombination spectroscopy to the detailed, quantitative study of low-Z particle transport in tokamaks.⁴ Figure 106 shows modeling results parameterized by the particle diffusion coefficient D (cm^2/sec) in comparison with experimental data for the time-evolving He^{++} density at $r = 7$ cm following a helium gas puff. Other parameters of the model include a convective term in the particle flux derived by using the measured equilibrium radial profile of the He^{++} ions. The transport results obtained from this data are relevant to an understanding of helium ash confinement in reacting plasmas. The quantitative demonstration of this diagnostic technique on PDX represents an important step in the timely development of similar alpha-particle and impurity diagnostics for TFTR.

Figure 106. Time evolution of $r = 7$ cm He^{++} density and central chord He^+ 304 Å radiation after a short helium puff. The solid line is the estimated best fit to the data using a diffusive/convective particle transport model, and the dashed curves show the sensitivity of the model to variation of the diffusion coefficient.

NEUTRAL-PARTICLE TRANSPORT

The DEGAS computer code has been extended to model neutral-particle transport in three-dimensional limiter and divertor geometries. Detailed treatments of neutral-plasma reactions and neutral-wall interactions are included. The DEGAS code can be linked to one- and two-dimensional fluid treatments of a flowing hydrogen plasma, and also it can be used in combination with the radial transport code BALDUR. DEGAS is being used extensively outside PPPL, including research for the Doublet-III tokamak, the ISX tokamak pumped limiter, the MARS (Mirror

Advanced Reactor Study) mirror experiment at the Lawrence Livermore National Laboratory, the ASDEX (Axially Symmetric Divertor Experiment) poloidal divertor, the ASDEX Upgrade design, and the DITE (Divertor and Injection Tokamak Experiment) bundle divertor. At PPPL, recycling in the PDX divertor has been modeled in order to compute the evolution of particle refueling during H-mode discharges. Figure 107 shows a sample calculation of the D_α line radiation in a detailed model of the PDX divertor geometry. The performance of the zirconium-aluminum (Zr-Al) getter experiment on PDX was analyzed and applied to the TFTR Zr-Al getter design. Recycling in TFTR from both the movable and bumper limiters was modeled to determine the wall fluxes and tritium inventories in the TFTR components. Finally, modeling of the Princeton Plasma Physics Laboratory scoop-limiter experiments on PLT and PDX, and of the ALT limiter experiment on TEXTOR, continues in order to provide the data base necessary for the design of the Tokamak Fusion Core Experiment (TFCX) impurity control system.

Figure 107. Calculated D_α emission contours in the vicinity of the PDX divertor neutralizer plate.

DIVERTOR/SCRAPE-OFF FLUID MODELS

Hydrogen recycling at the neutralizer plate has been shown to be the single most important factor determining scrape-off plasma properties. Treating this recycling as a free parameter and using the PPPL divertor models with much simplified representations of the experimental geometry, excellent agreement was achieved with D-III experimental results.⁵

Accurate geometry is required for the *a priori* computation of recycling. Methods have, therefore, been developed which use flux surfaces computed

by an equilibrium code as a starting point to generate the orthogonal meshes needed to solve the plasma fluid equations. This has made it possible to create a realistic model for the outer PDX divertor and to reduce the number of free parameters in the model to only the input particle flux. This resulted in very good overall agreement with the PDX experimental data and gives credibility to predictions for other experiments. In particular, a start has been made in modeling the International Tokamak Reactor (INTOR) divertor geometry. Early results are encouraging in that it should be possible to reduce the plasma temperature at the neutralizer plate to about 20 eV in a divertor with an open geometry, with a consequent drastic reduction in plate erosion.

An independent two-chamber model of the scrape-off divertor region was developed for application in the BALDUR tokamak radial transport code in order to model particle and heat loss terms at the edge of a tokamak plasma. The solutions are constructed by integrating the dominant terms in the fluid equations, including sources along open field lines, and neglecting radial flows. The solutions for the PDX divertor parameters characterized four observed operating conditions for beam-heated divertor plasmas: L-mode, H-mode, blowthrough, and blow-back. Figure 108 shows the midplane Mach number as a function of density for various pumping fractions in the divertor. It is readily seen that the flow stagnates at high density, a result of increased neutral recycling (i.e., a large-source term) in the divertor, leading to reduced radial particle flow in this regime.

Figure 108. Parallel flow Mach number in a scrape-off region as a function of the density and the pumping fraction.

ATOMIC PROCESSES

A systematic survey was made of all atomic and molecular processes involving hydrogen in the cool edge region of a tokamak plasma. A relatively complete characterization of each process was completed, including cross sections, reaction rate coefficients, and energy loss/gain per collision, together with appropriate numerical fits. This work was applied to calculating the roles of excited states of hydrogen and of molecular dissociation in the energy balance of edge plasmas.⁶ In the latter example, it was found that the dissociation of molecular hydrogen could dissipate a considerable fraction (up to 80%) of the power going into a divertor.

This loss may explain PDX diverted plasmas which show less than 20-30% of the heating power measured as lost via fast neutrals, radiation, or heat flux to the neutralizer plate.

The usual model for the penetration of neutral heating beams into plasmas assumes the neutral hydrogen atoms to be in their ground states before ionization by electron impact, ion impact, and charge exchange in the background plasma. Since charge-exchange and ionization cross sections increase rapidly for atoms in excited states, the effective stopping cross section for neutral beam atoms can be increased by multistep processes in which the ground atom is first excited before the ultimate ionization or charge-exchange collision occurs. A detailed calculation of this effect, including collisions with impurity atoms, yielded significant cross-section enhancements.⁷ Defining $\delta = (\sigma - \sigma_0)/\sigma_0$ where σ is the stopping cross section including multistep processes and σ_0 is the stopping cross section for ground state atoms, δ was found to be as large as 25-50% for TFTR and JET injection energies (Fig. 109), and as large as a factor of two at very high beam energies.

Figure 109. Enhancement of the beam stopping cross section due to excitations, calculated as a function of beam energy for four electron densities. The electron temperature is taken as $E/10$ for $E < 100$ keV and as 10 keV for $E > 100$ keV. The solid curves are for $Z_{eff} = 1$ and the dashed curves are for $Z_{eff} = 3$ produced by carbon, oxygen, and iron in the ion density ratio 10:10:1.

TOKAMAK TRANSPORT AND REACTOR MODELING

A previously developed optimization procedure for beam-driven steady-state reactors was used to estimate the effect on reactor performance of using very high energy tritium neutral beams to drive the plasma current in tokamak reactors.⁸ If significant improvements (~10%) in cost or power efficiency can be realized, raising the beam energy from 1-2 MeV to 5-10 MeV would be desirable. Estimates of the

neutral-beam-driven current obtainable in TFTR were made to support studies of a long-pulse TFTR upgrade, high-current (>3 MA) TFTR operation, and an experimental demonstration of neutral-beam driven current.⁹

Experimental results from the initial ohmic heating confinement studies on TFTR were simulated with the BALDUR code, with the preliminary conclusion that an electron diffusivity with neo-Alcator scaling was consistent with TFTR results. BALDUR was also used to support planning for neutral-beam operations and pellet injection experiments in TFTR. From work with the PLT experimentalists, it was concluded that the electron thermal diffusivity in low-density, lower-hybrid current-drive experiments in PLT is similar to that found in comparable ohmically heated plasmas.

The BALDUR code was also improved in several ways. A sawtooth model was implemented, along with a general formulation for specifying transport coefficients which allows scaling with local values of the plasma parameters and their gradients. A semiempirical transport model was developed¹⁰ based on the global ohmic heating and L-mode neutral-beam heating experiments reported on at the Ninth International Conference on Plasma Physics and Controlled Nuclear Fusion. This model was then extended for studies of H-mode neutral-beam heated plasmas in PDX and ASDEX.

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REACTOR STUDIES

Recent theoretical work has demonstrated that bean-shaped tokamak plasmas can be stable at very high "beta" (the ratio of spatially averaged plasma pressure to magnetic field pressure). The reactor studies effort in FY83 focused on the potential application of such plasmas to ITRs (ignition test reactors) and DEMOs (demonstration power reactors). Illustrative machine configurations for ITR and DEMO applications were worked out with extensions to full-scale power reactors.

Resistive toroidal-field (TF) coils were used in these studies because of the smaller shielding thickness required, the possible inclusion of demountable joints for access to in-bore poloidal-field (PF) coils, and the fact that they give physically smaller machines (cheaper and faster to build). For a DEMO reactor using a plasma with $\beta > 20\%$, the resistive power loss in the TF coils is less than 200 MW. All copper magnets are assumed to use SPINEL (magnesium aluminate) insulation with a radiation dose limit of about 10^{13} rads. Inductive current drive is used during the burn with start-up of the plasma current in the DEMO cases assisted by radio-frequency waves.

The design of these tokamaks is significantly influenced by the requirement that the high-current "pusher coil," needed to produce the bean indentation of the plasma cross section, be located on the midplane as close as possible to the innermost edge of the plasma. But the in-bore location of the pusher coil makes its maintenance almost impossible and also prevents modularization of the reactor. Thus, consideration was given to the option of an outwardly arched inboard leg of the TF coils. In this case the pusher coil would be located outside the TF coil bore, but still adequately close to the plasma in the case of an ITR or in the case of a DEMO with minimum inboard shield thickness. Modularization of the tokamak would then be possible.

With the objective of minimizing the inboard blanket/shield thickness, a Monte Carlo neutronics investigation was performed of the total tritium breeding ratio (TBR) that can be obtained in tokamaks with no breeding on the inboard side of the plasma. Maximization of the neutron albedo of the inboard shield is achieved with 20 cm of lead or beryllium backed by water-cooled stainless steel or copper. Global TBR achieving unity is obtained readily when a breeding blanket consisting of 80% lithium and 20% beryllium covers the outboard region, as well as 3/4 of the top and bottom of the vessel, taking into account structural materials and essential penetrations. In the case of DEMO and power reactors, the in-bore pusher coils could be located immediately behind the 20-cm region of high-albedo material.

Stable high-beta bean plasmas can be attained in both the so-called "first and second regions" of stability, although the latter allows much higher betas. The first region was found to be appropriate for an ITR, with $R/a \sim 2$, $q_a \approx 2$ and indentation $d/2a \sim 0.1$ giving $\beta = 12-15\%$. A DEMO requires a larger central solenoid to maintain the plasma current during a long pulse and also a larger inboard shield thickness because of the high lifetime neutron fluence. The second region was found to be suitable for a DEMO reactor, with $R/a > 3$, $q_a \sim 4$ and $d/2a \approx 0.18$ giving $\beta \geq 20\%$, a neutron wall load of about 3 MW/m^2 and fusion power $\sim 1000 \text{ MW}$.

The use of high beta in an ITR could provide insurance against low τ_E by allowing much higher density. In the case of demonstration and commercial power reactors, use of very high beta can lead to reduced TF coil costs and/or smaller machines, although the practical limit to beta will occur when higher PF coil costs outweigh the TF cost coil savings.

SPIN-POLARIZED FUSION PROGRAM

Experimental testing of the polarized fusion concept in a reactor requires the development of a source capable of producing about 10^{21} particles/sec. Existing polarized hydrogen sources fail to produce this particle current by six orders of magnitude. Furthermore, the techniques utilized by these sources are incapable of being scaled sufficiently. During FY83, an experimental program was started to investigate the use of the optical pumping technique to produce spin-polarized hydrogen atoms. Optical pumping converts the angular momentum of a circularly polarized laser into hydrogen spin. Since it is inconvenient to pump hydrogen directly with Lyman alpha light, an alkali such as rubidium is first polarized and then the spin is transferred to the hydrogen via spin-exchange collisions. Owing to the hyperfine interaction, both the hydrogen electron and the nuclear spins become polarized. A one-watt commercial laser will polarize about 10^{18} particles/sec. Suitable lasers have been developed at the Lawrence Livermore National Laboratory for producing 1 kW of output which would be sufficient for a polarized hydrogen source for a reactor. Figure 110 shows a conceptual design for an optical pumping spin-polarized hydrogen source for a tokamak reactor.

Figure 110. A conceptual design for an optical pumping spin-polarized hydrogen source for a tokamak reactor.

Initial funding for the laboratory experiments was obtained through a private consortium of utilities: Public Service Electric and Gas, Pennsylvania Power and Light, Southern California Edison, and Duke Power and Light. Pending subsequent Department of Energy funding, this funding allowed procurement of the necessary lasers and other equipment to begin laboratory investigation of optical pumping. The first experiments (Figs. 111 and 112) have been concerned with the fundamental physics and technology of optical pumping production of spin-polarized

hydrogen in small closed cells. Eventually, a flowing system will be constructed for a tokamak experimental test of polarized fusion.

Figure 111. A schematic diagram of the experiment. The closed pyrex cell containing rubidium and hydrogen is pumped with either a resonance lamp or dye laser. A radio-frequency discharge is pulsed to create atomic hydrogen. These initial experiments have used bare pyrex cells which requires the use of high hydrogen pressures (10 Torr) to act as a buffer gas by impeding wall relaxations. At these high pressures, an atomic hydrogen density of 10^{12} cm^{-3} was produced in a 10^2 cm^3 cell using a 100 W source.

Figure 112. The observed hydrogen signal including Zeeman structure obtained with the conventional rubidium resonance lamp (few microwatts). Analysis of this data yields a hydrogen polarization of about 1%. Future experiments are being performed to increase the hydrogen density and polarization by using the ring dye laser (one watt) and coating the cells.

TOKAMAK FUSION CORE EXPERIMENT

Early in 1983 the Magnetic Fusion Advisory Committee (MFAC) recommended that a project definition study be initiated for the Tokamak Fusion Core Experiment—TFCX. (At the time, the device was being called the Tokamak Fusion Core Device—TFCD.) The TFCX would be a next-generation tokamak beyond TFTR and the fusion device preceding an Experimental Test Reactor (ETR). The TFCX is intended to be a fully ignited, equilibrium burn experiment with pulses of the order of 300 sec.

In July 1983 the Office of Fusion Energy (OFE) of the DOE requested that the Princeton Plasma Physics Laboratory (PPPL) produce a definitive planning and budget document for further development of TFCX in FY84 and FY85. Complying with that request, PPPL delivered to OFE on August 29, 1983, the TFCX Proposal.

Following evaluation of the proposal, DOE requested PPPL to establish the organization at PPPL

to pursue planning and preconceptual design of TFCX. Figure 113 shows the organization for this effort. The plan outlined in the proposal incorporated the engineering and physics resources at PPPL, the Fusion Engineering Design Center (FEDC), and the other U.S. national fusion laboratories. The organizational plan includes the development of the TFCX team at PPPL, where the bulk of the design effort will be carried out. Other U.S. toroidal fusion laboratory groups will have strong representation at PPPL, although some design work will be carried out at their home institutions. These studies will be used to determine a reference concept for the TFCX.

To provide guidance for the TFCX project, a Technical Advisory Committee (TAC) was established. The Committee is chaired by the PPPL Associate Director for Program and is advisory to the PPPL Director. Membership consists of representatives from U.S. toroidal fusion laboratories, as well as from

Figure 113. TFCX Project organization at PPPL. (84X2307)

the broader fusion community. Meetings are held to consider the engineering and physics bases for TFCX. The TAC developed a TFCX Mission Statement that was reviewed and redefined in discussions with the DOE. The Mission Statement reads as follows: "The essential objective of the TFCX is to achieve ignition and long-pulse equilibrium burn. To the extent that resources permit, the TFCX project should also serve as a focus for the development of future fusion technologies." The physics objectives that need to be met to fulfill the TFCX project mission are as follows:

- Attainment of reactor-level betas and confinement times required to achieve the $n\tau$ for ignited operation.
- Development and demonstration of the radio-frequency (rf) heating physics required for heating to ignition in a reactor.
- Development of the physics of impurity control required for energy and particle removal for equilibrium burn in a tokamak reactor.
- Development of the physics of ignited burn control required for maintaining equilibrium burn conditions.
- Development and demonstration of the physics of ignited plasma current profile evolution required for maintaining equilibrium burn conditions.

The technology objectives for the TFCX project are derived from the technology required to fulfill the project mission. To meet the ignited, long-pulse requirement, while serving as a focus for development of future fusion technologies to the extent that resources permit, the following technology objectives need to be met:

- Development of a poloidal-field coil system to maintain the discharge for an ignited plasma during equilibrium burn.
- Development of the ion cyclotron range of frequencies (ICRF) generation and coupling system necessary for a tokamak reactor to heat to ignition.

- Development of the lower hybrid range of frequencies (LHRF) generation and coupling system necessary for the rf current ramp-up in a tokamak reactor.
- Development of the technology of energy and particle removal for impurity control for a tokamak reactor during equilibrium burn.
- Development of the technology for remote maintenance to maintain an active TFCX.

The basic features of TFCX are summarized in Fig. 114. The TFCX will be ignited with a projected ignition margin of 1.5. The pulse length will be in the 300-600 sec range. Attaining this pulse length will be facilitated by using rf current ramp-up to relieve the ohmic heating start-up requirements. Radio-frequency heating will be used to heat the vertically elongated plasma to ignition. Both limiters and divertors are being considered for energy and particle control. High fluence nuclear testing is not a design objective; however, at the fluences being considered the device will become highly activated and will require remote handling. Both copper and superconducting coil options are being considered.

- Ignited ($\frac{P_{\text{ALPHA}}}{P_{\text{LOSS}}} \sim 1.5$)
- Long Pulse ($150 < T < 500$ sec.)
- RF Current Rampup
- RF Heating to Ignition
- Vertically Elongated ($\frac{b}{a} = 1.6$)
- Limiters or Divertors
- No High Fluence Nuclear Testing $0.004 < T < 0.3 \text{ MWyr/m}^2$
- Full Remote Handling
- Nuclear Facilities
- Copper or Superconducting Coils

Figure 114. Basic features of the TFCX. (84X2309)

ENGINEERING DEPARTMENT

The Engineering Department was formally organized during fiscal year 1983. In that formalization, the three previous engineering divisions (Advanced Project Design and Analysis, Engineering, and Fabrication, Operations and Maintenance) were reorganized, renamed, and joined as a Department reporting to the Deputy Director for Technical Operations. The three became the Engineering Analysis Division, the Electronic and Electrical Engineering Division, and the Mechanical Engineering Division. Personnel trained and functioning in the disciplines defined in the division names were transferred accordingly.

A matrix interaction between the Engineering Department and all Technical Operations projects was formally defined and put into operation. By this system, the Engineering Department provides services directly to a project by the transfer of personnel. In addition, a job system in the several engineering divisions continues to perform defined work for programs outside the Technical Operations' project structure.

Midway through the fiscal year a fourth division, the Computer Division, was added to the Engineering Department. This division does all technical computing for PPPL, and is responsible for the procurement of hardware and the creation or acquisition of software to accomplish this mission.

During FY83, the Engineering Department had roughly 585 people on board. A breakdown of this number is: 200 Engineers and Scientists, 100 Senior Lab and Shop Staff, 250 Technicians, 25 Office and Clerical Support Staff, and 10 Administrative Staff.

A detailed description of the work performed by the four divisions is given below.

ENGINEERING ANALYSIS DIVISION

The role of the Engineering Analysis Division (EAD) is to support the Laboratory's physics programs and the national fusion effort by providing planning and evaluation of new and upgraded experiments, conceptual and preliminary engineering design services, and systems engineering services. The EAD also develops and maintains computer programs for design and analysis, and performs engineering and scientific analyses in specialized areas of technology such as radiation, solid and fluid mechanics, heat transfer, vacuum and cryogenics, superconductivity, electromagnetics, and field design. The EAD consists of the Division Office and four technical units. They

are the Electromagnetics Branch, the Thermomechanical Branch, the Radiation Analysis Group, and the Systems Group.

Electromagnetics Branch

The Electromagnetic Branch carries out design and analysis activities related to magnetic field systems and their interaction with the associated electrical and mechanical systems. The branch employs a staff of broad-based talents which range from power to plasma engineering.

The staff has extensive experience in optimizing magnetic configuration and analyzing transient eddy currents and their related magnetodynamic effects. A comprehensive library of magnetic field design computer codes has been developed over the years by the branch. These codes are continuously supplemented and revised to meet the latest requirements in fusion engineering. The branch also provides capabilities in plasma equilibrium calculations, as well as the planning and design of power supply systems.

The following is a breakdown of the branch's efforts this past year on a machine-by-machine basis.

TFTR

The TFTR Magnetics Handbook was completed. This includes information on all phases of the machine's magnetic parameters. As a part of this effort, eddy current studies were completed which incorporated dynamic effects of the overall structure of TFTR. A series of vacuum vessel models were developed, and with the rest of the structure in the simulation, the calculations were compared with experimental measurements of field penetration. Very good agreement between one of the simulations and experimental results provided a methodology for the computation of field penetration in future tokamak devices.¹ A code for the determination of maximum dynamic forces on the poloidal-field (PF) coils was developed.

Following the "first-plasma" experiment, the TFTR power supply and conversion system continued to expand. All components underwent preoperational checks and operational tests. The test procedures were worked out for the safe and efficient utilization of the equipment.

On commissioning the final version of the ohmic-heating (OH) system, transient analyses were performed to check the safe functioning of the equipment. The code used was an expanded version

of the "SPICE" code and it allowed for the simulation, in great detail, of the OH coils and power supplies. Parasitic oscillations were accounted for, and means were devised to reduce their amplitude.

S-1 Spheromak

The S-1 Spheromak project entered its concluding phase of operational testing in which test procedures were developed and implemented.

Heliac

Statistical methods were used to optimize $N=3$ and $N=4$ heliacs, where N is the toroidal node number. A statistical program was designed which will allow greatly improved efficiency in the optimization phase. An upgraded version of the Heliac simulation program was designed and partially implemented. This program uses magnetic coordinates to increase both speed and accuracy in determining the magnetic surfaces and related parameters.

PBX

A magnetic design check of background fields for the PBX experiments, as well as force and field calculations of the passive plates, was completed.

TFCX

A code called TSCALE was created to scale plasma equilibrium parameters over a wide range of R (major radius) and A (aspect ratio). The vacuum magnetic flux was fitted by using expressions for toroidal multipoles.² Scaling equations can now be evaluated for any (A,R) in the design space.

The shaping field coils were optimized for each of the overall Tokamak Fusion Core Experiment (TFCX) design changes; this is a continuing effort.

The copper toroidal-field (TF) alternative of the TFCX was investigated. This version may require over 400 MW of power for a pulse duration of more than 5 minutes. The cost efficient source of the supply is the utility grid. The magnitude and length of the pulse is unprecedented, and investigations to prove its feasibility in generic (i.e., site independent) application are continuing. The results thus far are very encouraging. Public utilities are participating in the study because they appreciate the potential for large pulse power applications.

SPARK Code

In TFTR and other fusion devices, both the normal operation of the coil systems and the plasma disruptions can induce large electrical eddy currents in the surrounding metallic components. The eddy currents create undesirable secondary magnetic fields and also interact with the primary field to produce significant mechanical forces.

A highly automated, general geometry computer code called SPARK was developed at PPPL to calculate transient eddy currents and the resulting

fields. In addition, the SPARK code analyzes mechanical loads in a form compatible with existing structural analysis codes such as NASTRAN.

SPARK is now operational at PPPL and will be available on the National Magnetic Fusion Energy Computer Center (NMFEECC) Cray Computer System in 1984. A reference and user's manual will also be available.

Figure 115 illustrates a typical SPARK streamline plot of eddy currents. The figure shows the top half of the TFTR vacuum vessel at a selected time during a transient response due to a plasma disruption. The vacuum vessel contains nine symmetrically located high-resistance bellows sections. These bellows cause the streamlines to have a distinct jog.

Figure 115. A typical SPARK streamline plot of eddy currents.

Thermomechanical Branch

The Thermomechanical Branch provides a broad spectrum of capabilities in engineering mechanics, finite element analysis, thermal analysis and mechanical design. The primary activities of the Branch included engineering analysis and design support for the TFTR and the S-1 Spheromak projects, as well as for new programs such as TFCX.

During the year, two members of the Branch continued in responsible assignments to project organizations: one as Manager of the TFTR Neutral-Beam Mechanical Systems, the other as Mechanical Subsystem Coordinator for the S-1 Spheromak. Branch engineers were engaged in performing design and analysis tasks and in monitoring and guiding engineering efforts for TFTR Diagnostics, TFTR Neutral Beams, TFTR Operations, and for TFTR/TFM. Others participated in the TFCX preconceptual design studies.

Spheromak Mechanical Systems

The mechanical systems activities were completed in support of the S-1 Spheromak first-plasma milestone and subsequent operations phase. Engineering studies for improved flux core liner designs were performed.

TFTR Diagnostics

Engineering support for TFTR Diagnostics was provided in several areas. The design of the impurity injector system was completed and the fabrication was started. Engineers supervised subcontractor's fabrication of several diagnostics items, including the Thomson scattering viewing dump and the MIRI support structure. Numerous short-term design and installation tasks in the category of general engineering support were completed.

TFTR/TFM

The finite element analyses of the transient responses of the TFTR protective plates and of the bumper limiters were completed in support of the final design of these components. The dynamic analysis of the TFTR vacuum vessel was continued, using updated models and plasma disruption excitations to confirm the operating capabilities of vessel support upgrade modifications. Thermal analyses and thermal stress analyses were performed to establish safe envelopes for temperature differences between the vacuum vessel bellows and the adjacent stiffening ring during bakeout.

In the course of the bumper limiter design studies it was discovered that an important coupling exists between the mechanical dynamics and the electrical dynamics of the bumper limiter.³ The motion of the vibrating bumper limiter in a strong magnetic field produces important new eddy currents which simultaneously provide a strong effective mechanical damping and an increased effective stiffness. These effects are referred to as magnetic damping and inductive mechanical stiffness. Calculations predict that significant reductions in mechanical stresses and deflections will result from including these effects. It is expected that these phenomena will be significant for other components as well in the high-field environments of TFTR and similar tokamaks. A joint experiment will be conducted by PPPL and the Argonne National Laboratory (ANL) using the FELIX device to quantify the basics of these phenomena.

TFTR Neutral-Beam Upgrade

The preliminary investigation of various thermal and heat transfer concepts for beam dump designs aimed at long-pulse upgrade capabilities was completed, and an engineering development program for FY84 was defined.

TFCX Preconceptual Design Studies

Several members of the Branch were involved in the design studies for the various TFCX concepts. They performed finite element analyses for the TF coil and support designs, thermal analyses for first wall and shield components; and they participated in the evaluation and assessment of the mechanical and structural design approaches for the various TFCX concepts.

Radiation Analysis Group

The Radiation Analysis group provides radiological and radiation related analyses, and evaluations and assessments for the design, operation, and instrumentation of the fusion devices at PPPL. In late FY83, the manpower level of the group was increased 50% to cope with the increasing demand on services.

The major projects carried out during the year were the reference field and the perturbation analyses for the TFTR Q = 1 demonstration configuration and the neutronic analyses for the TFTR diagnostics designs. The Radiation Analysis Group also participated in the preconceptual design effort for TFCX.

TFTR Radiation Analysis

A two-dimensional model of the entire Test Cell was developed which is consistent with the projected facility configuration for the Q = 1 demonstration program. Analysis based on this model established the reference radiation field characteristics.⁴ Iso-dose and iso-fluence contours as well as the flux spectra were compiled; an illustration is given in Fig. 116.

Figure 116. A close-up view of the fluence contours near the TFTR tokamak. The source normalization is 1.0×10^{18} neutrons.

The data served as the basis for the assessment of the shielding adequacy, both in terms of meeting the design objectives and in terms of establishing the allowable perturbation limit due to shielding irregularities.

The perturbation studies included the streaming through doorway labyrinths, the effect of I-beams in substructure concrete, the rectangular slot penetrations in the Test Cell floor, and the effect of filling penetrations with different materials.

For the doorway labyrinth analysis, an Albedo Monte Carlo calculational capability was established. The analysis showed that improvement of the existing design is needed to meet the design criteria when the neutron output is increased beyond the present level. A new design effort was initiated.⁵

The interest in studying fast neutron flux perturbation due to the I-beams in concrete arises because the existence of antiresonance cross sections in the beam material provides easier passageways for the neutrons to leak through the concrete shield. The study indicated that such perturbation appeared to be small for TFTR, but it may be important for other devices where the neutron spectrum incident on the beam-concrete assembly is much softer than that of the TFTR device.⁶

In the area of slot penetrations through the Test Cell floor, the analysis for the 14-MeV incident neutron case was completed. Coupled with the cylindrical penetration results, which were compiled last year, the data constitutes part of the Radiation Handbook for TFTR Operation and is useful in realizing local perturbation problems.

The penetration filler study is an effort to shield as many penetrations as possible by finding mechanically and neutronically compatible materials to minimize the radiation levels in the diagnostic areas. A variant of silicone gel was shown to be a reasonably good choice, and the water hose penetrations were filled with such materials.

TFTR Diagnostics

The primary work for diagnostics was the analysis for the fission detector assembly. The fission detector system is one of the major diagnostics for the fusion neutron yield measurement, and it provides indirect measurement for the ion temperatures in the ohmically-heated plasmas. An analytic efficiency study of the detector-moderator assembly was carried out, and the effect of scattered neutrons on the detector calibration was investigated.⁷

Other diagnostic work included a cross-talk study for the good geometry scatterer in the multichannel collimator system and the shielding requirement study for the X-ray imaging system and the multichannel collimator system.

Other Activities

In addition to the analyses for TFTR, the Radiation Analysis Group also participated in the preconceptual

design effort for TFCX. The nuclear analyses provided essential input to the inboard and outboard shielding requirement, the nuclear heating profiles, the neutron wall-loading characteristics, and the radiological safety assessments (such as the tritium and radioactive effluent releases and dispersions).

In FY84, a comprehensive documentation of the PPPL radiation analysis software package will be made. In collaboration with the NMFECC, this effort will lead to an activity that will contribute to the establishment of a fusion neutronics software library for the fusion community.

Systems Group

The Systems Group provides overall systems support for large experiments, from the preconceptual design stage to the start of operation. Major areas of responsibility for the Systems Group in FY83 included support of TFTR's operational start-up, as well as systems engineering and preconceptual design studies for TFCX.

TFTR

Heading the TFTR First-Plasma Operation Readiness Review Task Force was a major task of one member of the systems group. Another member of the group was responsible for the final design of the Safety Lockout Device, an essential element of the personnel-access-control system. Two electrical engineers from EAD served as integrated systems test cognizant engineers. Specific areas of responsibility included TF and PF power system checkout into dummy loads, mapping the fault protection systems level and response time, and powering the integrated coil systems. This last responsibility included developing a detailed integrated systems test plan, which defined and coordinated prerequisite tests, and running the step-by-step test on both dummy loads and the TF and PF systems in place. These staff members contributed significantly toward the success of the TFTR first plasma in December 1982.

TFCX

Systems engineering services were provided for TFCX during its preconceptual design. This support included assuring clear interfaces between all subsystem groups, providing for appropriate information flow between subsystems and between various design teams, developing the cost specification and format of the subsystems and the Work Breakdown Structure.

The TFCX, in its preconceptual design stage, was defined by extensive design studies. A design code that uses tens of selected options as input was developed to size and evaluate a new fusion device concept in one run. This code should prove to be invaluable for future generations of fusion devices.

ELECTRONIC AND ELECTRICAL ENGINEERING DIVISION

An Electronic and Electrical Engineering Division was created near the beginning of FY83 from the diagnostic and radio-frequency elements of the former Engineering Division, and from the energy systems elements of the former Fabrication, Operations, and Maintenance Division. The Division is organized into three major branches, eleven engineering sections, three technical service centers, a drafting group, an administrative office, and a computer-aided drafting and design program. The three major branches of the Division are the Diagnostics Branch, the Power Branch, and the Radio-Frequency Branch. The Division consists of a permanent staff of slightly over 200 engineers and technicians and in FY83 included a peak of about 100 temporary subcontract personnel.

Computer-Aided Drafting and Design

During FY83, the procurement of a computer automated design and drafting system for the five major U.S. fusion laboratories was redirected to solicit competitive bids. A new national committee was formed consisting of representatives from each major laboratory and the National Magnetic Fusion Energy Computer Center (NMFECC). Princeton was assigned the coordination responsibility for the project. The major accomplishments included preparation of the Department of Energy implementation plan, the technical specification for the Request for Proposal, the evaluation criteria for evaluating vendor bids, and the performance tests to evaluate actual vendor capability. A contract was expected which would result in delivery of the first system to PPPL in mid FY84.

Funding was obtained and a plan developed to construct a computer facility in the Guggenheim building. This site, centrally located to the mechanical and electrical engineering staffs, was expected to be connected to the NMFECC computing facilities in Livermore, California, through an existing satellite network. The combination of local and remote resources was projected to provide PPPL with local computerized drafting and design capability, analysis on large computational facilities at the NMFECC, and interchange of information with other fusion laboratories engaged in similar activities.

Analog Engineering

During FY83, two receivers along with controls and waveguide systems for the TFTR fast scanning radiometer were designed, built, tested, installed, and operated. The radiometer has been used to measure TFTR plasma electron temperature profiles with central temperatures of 1 to 2.5 keV, and to provide resolution of temperature sawteeth with periods in the 10 to 100 msec range.

The two receivers operated in FY83 are swept in frequency from 75-110 GHz (Band I) and 110-170 GHz (Band II), respectively, in 2 msec every 4 msec to measure the plasma electron temperature versus major radius profile and its time evolution during a shot. This is achieved by repeatedly measuring ordinary-mode blackbody microwave emission near the fundamental electron-cyclotron frequency. This radiation, when viewed with a microwave horn antenna, is proportional to the local electron temperature at the midplane of the cyclotron emission layer. The Band I receiver is shown in Fig. 117.

Across the diameter of the TFTR plasma, the range of frequencies for this blackbody emission is 75-210 GHz for 32-50 kG tokamak operation. The radiometer is actually three separate receiver systems, using a common antenna and waveguide, which scan the entire frequency range of electron-cyclotron emission. Each receiver is frequency-scanned by a swept local oscillator. Two receivers were in operation during FY83. A third receiver with a frequency of 170-210 GHz is scheduled for operation in FY84 for tokamak operation at magnetic fields above 40 kG.

Input frequency selection is done by sweeping each receiver's local oscillator (LO) frequency across its band. The LO's are backward wave oscillators that are swept by varying their delay-line-to-cathode voltage. Received emission is measured when the cathode voltage reaches particular values corresponding to preselected cyclotron emission frequencies.

Figure 117. Fast scanning microwave radiometer (75-100 GHz). (83E0729)

Receiver operation is monitored and subjected to analysis by CICADA. This analysis consists of converting the individual receiver's output voltages, mixer bias currents, and cathode voltages into time evolution of the electron temperature profile. CICADA performs table searches to match measured cathode voltage to the corresponding receiver's frequency, verifies the proper level of LO mixer input power, calculates radial position of the emitted radiation from the toroidal-field value and receiver frequency and, finally, converts the receiver's voltage output to plasma temperature by means of a table search of calibration values.

Controls Engineering

The first half of FY83 saw significant effort devoted to the final preparations for the S-1 Spheromak first plasma, which was achieved on January 31, 1983. This effort included:

- PF/TF timer system software and hardware completed.
- Central grounding system installed and tested.
- Ignitron firing system installed and tested.
- S-1 mimic panel installed and tested.
- Final version of the scan routine completed.
- Water flow and temperature monitors tested and calibrated.
- I₂t and instantaneous protective relay panel installed and calibrated.

A thorough safety review was conducted which exercised all aspects of the personnel and machine safety systems, including watchdog timers, hardwire fail-safe circuitry, emergency shutdown, and door and key interlocks.

During the first months of operation, the control system^a (Fig. 118) performed extremely well. Minor changes in hardware and software were made as operating experience increased. Some early problems were corrected:

- Premature firing of PF/TF ignitrons was greatly improved with proper ignitron conditioning and the replacement of "sensitive" tubes.
- Electrical noise in the machine area crate was reduced by the addition of a time delay relay in the TF capacitor bank charge/discharge sequencing. Additional noise on the power line was noted using a recording line monitor. The addition of an rf line filter further reduced noise problems.
- Failure of the MG CAMAC crate power supply led to a loss of equilibrium-field (EF) current control during an operating run. This was caused by a blown fuse in a CAMAC digital-to-analog converter. After replacement of the crate, operation was allowed to continue with the EF instantaneous overcurrent relay set to an artificially low value of 10 kA. Closed loop current control and air conditioning for this MG

Figure 118. S-1 Spheromak operator's console. (83E1364)

crate are planned for future higher current operation.

Another major activity during this fiscal year was the design and construction of a central control room for the radio-frequency test facility (RFTF). Although on a smaller scale than existing PLT, PDX, and S-1 control rooms, this room will provide all essential control functions for RFTF, using a Texas Instruments 530 distributed programmable controller. These functions include a master safety system with hardwire backup, door and key interlock, a master safety lockout switch, emergency shutdown stations, I₂t and instantaneous overcurrent protection, MG controls, a master timing system, watchdog timer, and operator console and mimic panel.

Other jobs were also started on PLT using the Texas Instruments programmable controller system. Notable among these was the lower hybrid current drive to PLT control interface. At the end of the fiscal year, specification and design reviews were completed, delivery of the programmable controller components was 80% complete, and the drawing package was completed. Initial wiring in the control room and rf enclosure was started.

The TFTR glow discharge cleaning system was well advanced from its initial operating mode. Interlocks were installed and tested. Motor drive

circuits were designed and built, and remote operation of the probe stepper-motors was achieved. The temperature sensors and trip circuits were designed and installed. The drawing package for this system was 50% completed.

Electronics Engineering

Most FY83 electronics engineering was devoted to designing and building diagnostic and control systems for TFTR. Two major projects that were completed are the TFTR Langmuir-calorimeter probe electronics system and the TFTR window shutter control system. Projects started in FY83 for the TFTR neutral beam and scheduled for completion in FY84 include the fault detector system, the water instrumentation system,⁹ the sequence timer system, and the gas valve driver system. Two additional continuing major projects are described below.

Operation of neutral-beam sources requires safe and accurate transmission of analog signals originating from points at high voltage with respect to control and monitoring equipment located at ground potential. A high performance fiber-optic coupled data telemetry system was developed for use with TFTR neutral beams.¹⁰ The analog links have a zero to 1 MHz bandpass, with a very stable gain and low drift. The links are designed to operate over a 20 °C to 55 °C temperature range and to have a mean time before failure of 100,000 hours. To satisfy all the above requirements, the link was designed using an analog-to-digital converter, a high-speed digital serial link, and a digital-to-analog converter. Data is sampled at 4 million samples per second to 9 bits of resolution using a high-speed flash converter. Three synchronizing bits are added, and the data is transmitted serially over a fiber-optic link at 48 MHz. The transmitter is shown in Fig. 119. The receiver reformats the digital data and applies it to a digital-to-analog converter where the original analog signal is reconstructed.

Diagnostics which must be connected to the TFTR vacuum vessel are required to do so through a torus interface valve. A system was developed for TFTR to monitor and control the interface between the vacuum vessel and associated diagnostics.¹¹ The system is designed to be as fail-safe as possible. It is intended to prevent damage to probes which could be caused by attempts to insert a probe through a closed valve or to close a valve which has a probe inserted through it. The system attempts to preserve the integrity of the vacuum in both the TFTR torus and the diagnostic by permitting the interface valve to be opened only when the pressures on both sides of the valve are equal.

Instrumentation Engineering

The first of several charge-exchange neutral analyzers was installed on TFTR during the summer of 1983. Figure 120 shows the first of six such analyzers scheduled to be installed over the next several years.

Figure 119. Transmitter for high-performance dc to 1 MHz analog fiber-optic telemetry. (83E1469)

The charge-exchange neutral analyzer for TFTR will simultaneously measure singly charged ions of atomic mass 1, 2, and 3 with 75 energy channels per mass. The analyzer is an E1B device utilizing a 225-element, chevron type, micro-channel plate (MCP) detector array.¹² Ion temperatures in the 1.5-keV range were measured during FY83 operation. These measured temperatures were in very close agreement with the neutron emission ion temperature diagnostic and the X-ray Doppler broadening diagnostic.

The detector was characterized, and then the necessary electronic equipment was designed, built, tested, and installed. This equipment processes the detector signal, controls and monitors the MCP detector power supplies, and controls and monitors the supplies used to establish the E1B fields of the analyzer.

The 225-element detector array has each of its outputs processed by an in-vacuum buffer. This buffer converts the 0.032 pC (pico Coulomb) detector signal to a voltage pulse, and it provides modest line driving capabilities to feed the low-level signal over an eight-foot cable to the amplifier/discriminator module. The amplifier/discriminator module was designed to provide 40 dB of voltage gain, voltage level discrimination, and pulse shaping. The processed outputs are connected to 12 bit, 10 MHz scalars with local memory. The scalars are CAMAC modules which are read by CICADA after each tokamak pulse.

Electro-Optics Engineering

The second of three periscopes for viewing the TFTR plasma and vacuum vessel interior was installed along with an infrared (IR) sensitive television camera. The IR camera is designed to make quantitative measurements in a 0.9 micron band centered at 1.7 microns. Using this data the temperature of the wall and other elements within the vacuum vessel can be calculated in the range from 220 to 2300 °C.

Figure 120. Horizontal charge-exchange analyzer on TFTR. (83E0661)

A neutral-beam pyrometer interlock system is under development to make real-time temperature measurements of the wall where shine-through of the neutral beams can occur. This system employs silicon photodiodes and electronic signal processing that can handle a 107 dynamic range, corresponding to a temperature range from 500 °C to about 2000 °C.

A 20-channel bolometer array and a wide angle bolometer were designed and installed on TFTR with excellent results. There is considerable interest from other members of the fusion community in these bolometers because of their radiation-hard platinum detectors and their real-time power measuring electronics.

AC Power Engineering

The AC Power Engineering Section continued to provide support to TFTR from installation through operation, including contributing significant support for the first-plasma effort.¹³ The installation phase included field wiring for the diagnostic, surface pumping, vacuum vessel instrumentation, and strain gauge systems. In addition, preparatory work was completed for the upcoming installation of MG No. 2. Synchronizing capability was added to the TFTR diesel generator, increasing its overall usefulness to the Laboratory.

Commissioning activities included preoperational tests of the ac power systems supplying the TF-1, OH, and NB systems. Operations support was focused on the hardware control system and the safety disconnect system.

More traditional ac power activities included completing the design and engineering for the addition of a second 138-kV circuit breaker, completion of a second battery room for C-Site, and completion of power and control checkout for the TFTR helium refrigerator. In addition, emergency diesel generator power was made available for most of A, B, and C-Sites.

Neutral Beam Power Engineering

The Neutral Beam Power Engineering Section continued to provide operational and maintenance support for the PLT and PDX neutral-beam systems. This included several heating beams as well as a diagnostic beam for each of the tokamaks.

The component equipment for the TFTR diagnostic neutral beam was put into the procurement cycle. A change in requirements for the arc/filament supplies from dc to rf excitation necessitated engineering changes. Some difficulty was encountered in finding a supplier for the accel supply shunt regulator. At year's end it appeared that this might

be resolved by allowing a cost-type contract for the shunt regulator. It is anticipated that all of the electrical apparatus will be delivered and installed during FY84.

The section participated in assembly, installation, and test of 12 power supply systems for TFTR neutral-beam heating. During the first six months of the year, efforts were concentrated on assembly and preparation of installation instructions for the construction subcontractor Ebasco. One of the highlights of this effort was the completion of the high-voltage enclosure (HVE) design, including the incorporation of the arc/modulator source protection system,¹⁴ and the interface with the source cable system.¹⁵ Three HVE's were assembled, tested, and installed in position for the three-source test. This installation, circa March 1983, is shown in Fig. 121.

Preliminary operational testing of TFTR supplies, primarily checkout of switchyard apparatus, was started in the spring of 1983. As Ebasco finished wiring the first three systems (those designated to be used in the three-source test), full scale power start-up and testing began (July).

At the end of the fiscal year, installation engineering was complete for all major apparatus components. Assembly of major components was about 90% complete. Testing of the first three power supply systems had progressed through start-up of the primary power subsystems (production of 175 kV raw dc).

Motor-Generator Engineering

Many new and varied projects were accomplished in this area during FY83. Most of the new projects were in support of the TFTR effort, although normal responsibilities continued with support for the S-1 Spheromak, PLT, RFTF, and PDX efforts.

A project to prepare preliminary maintenance manuals for all of the TFTR systems was successfully completed. The required maintenance manuals were prepared in time for the TFTR Operational Readiness Review.

Figure 121. Three high-voltage enclosures installed for the neutral-beam three-source test. (83E0589)

Computer simulations were done for the C-Site motor-generator parameters for all of the operating modes of the S-1 Spheromak, and the power tests for the S-1 Spheromak were conducted successfully. In addition, a computer simulation was done early in FY83 to prove the feasibility of the C-Site motor-generators supplying enough energy to the TFTR TF coil to achieve first plasma, in the event that the D-Site motor-generator and/or energy conversion systems were not available.

Statements of work were completed that allowed outside subcontractors to perform preventive maintenance on the C and D-Site motor-generator systems. Generator breaker main contacts at C-Site were refurbished by a subcontractor. The returned parts were outside of acceptable tolerance and, to expedite rejuvenation of the subject breakers, the contacts were finish-machined to tolerance at the Princeton University Machine Shop.

The first undercutting in several years of the commutators of the C-Site large dc generators was completed in December 1983. The undercutting was preceded by several minor commutator flashovers.

The scope of the RFTF Project was quickly expanded when computer studies showed the need for using two large dc generators operating in series to supply sufficient voltage for the RFTF research load. Power tests for this load were successfully completed. In addition, motor-generator computer simulations were also done for the PBX Upgrade.

The design and fabrication of the dc power motorized disconnects for the S-1 Spheromak EF coil were finished (Fig. 122). The scope of this project was broadened to allow four complete motorized disconnects to be mounted along the top of the dc generator breakers (Fig. 123).

Figure 122. Motorized disconnect switch for S-1 Spheromak equilibrium-field coils. (83E0352)

Figure 123. Two S-1 Spheromak equilibrium-field disconnect switches in position over generator breakers. (83E0351)

Rectifier Power Engineering

The Rectifier Power Engineering Section continued to supply support for the power supplies of the PLT/PDX machines. Construction and testing of the power system for the S-1 Spheromak was completed. The shaping field (SF), OH, and Ling (bipolar transistorized wideband audio amplifier) power supplies were upgraded to meet the requirements of the PBX machine. This increased the current level of the SF supply from 7.2 kA to 8.5 kA, operated the OH at the full rated 20-kA level, and increased the output of the Ling supply from 1 kA to 2 kA.

Surface pumping power supplies for TFTR were designed. Four of these units were constructed, tested, and went into satisfactory operation. The documentation was completed so that bids could be solicited for fabricating the remaining 14 units.

Fault detectors for the TFTR rectifiers were redesigned, and 40 of these units were completed and tested.

The cycloconverter for TFTR MG No. 2 was tested, and a pickup or noise problem due to the circuit breaker closure was corrected. Other misfire problems were corrected after being traced to pickup, noise, or feedback to the SCR gate circuits. The No. 2 exciter was tested and was readied for operation, awaiting MG No. 2 availability.

An energy transfer system was devised for transferring stored energy at C-Site to D-Site and for lowering the MVA requirement on the TFTR MG sets by correcting the power factor required from these machines.¹⁶ A model of this stepped waveform, forced commutated, pulse-width-modulated inverter was constructed and demonstrated. This type of inverter, along with batteries having a stored energy of as much as 300 GJ, was proposed as one alternative for the power supply for TFCX.

High-Frequency Radio-Frequency Engineering

The 1.2-MW, 800-MHz rf source used for lower hybrid heating and current drive on the PLT tokamak was upgraded in FY83. Improvements included a filter in the canal water line, protective shields around the vac-ion connections, high-power circulators, additional solid-state amplifiers in the klystron cabinets, and acquisition of spare parts needed to minimize downtime. A program to increase reliability of this system by replacing marginal components was started, with completion expected in FY84. A work statement and specification were written for a dielectric-loaded coupler to be used in 800-MHz fast-wave coupling experiments.

Significant progress was made toward installation and checkout of a 1.5-MW, 2.45-GHz rf source¹⁷ to be used for high-density current drive on the PLT tokamak. Integration of the high-voltage controls with the ECRH system was completed, the control console was completed and installed, one klystron cabinet was completed and partially checked out, and the other two klystron cabinets were 50% completed. All cooling systems were completed except for the power divider cooling manifolds on the PLT floor. In July 1983, the transmission line vendor encountered problems with the material for the circular waveguide. As a result of vigorous PPPL expediting and vendor effort, the proper material was obtained, and the first circular waveguide was accepted at the vendor's plant in September 1983. At FY83 end, this major program was on schedule. Figure 124 shows some of the waveguide components¹⁸ used in one of the three 500-kW, 2.45-GHz channels.

Debugging and operation of a recently installed 400-kW, 60-GHz rf source required significant effort in FY83. This source was used in heating and profile control experiments on the PDX tokamak. This system was supplied by a vendor (except for the rectifier), and essentially all of the problems encountered were in the vendor-supplied system. Many minor problems, especially in fault-sensing and control circuits, prevented operation until late in November, although the equipment was received in August. After the fault circuit and control problems were overcome in November, problems in the vendor-supplied crowbar and capacitor bank further delayed the checkout so that full system operation was not possible until the May-June period. During that time, both channels operated at high power and full pulse width into PDX until the PDX shutdown on June 11. This operation yielded major new ECRH experimental results.¹⁹

Figure 124. E-Plane taper for one channel of the 2.45-GHz source. (83E1266)

Low-Frequency Radio-Frequency Engineering

Modifications were started on one of the three ICRF 2-MW amplifiers in order to shift the operating frequency from 42 MHz to 30 MHz. A major redesign of the amplifier cavities, based on preliminary tests of the modified amplifiers, was started. A second ICRF high-power amplifier continued to be used at 42 MHz for experimental operations on PLT and to support tests on the radio-frequency test facility (RFTF). Upon completion of the 42 MHz tests, all three systems were scheduled to be converted to 30 MHz to provide a combined power of six megawatts in FY84.

A 90-MHz amplifier²⁰ was nearing completion at the end of FY83 and was scheduled to be tested early in FY84. This system is intended for harmonic heating experiments on PLT and for evaluating loaded waveguide coupling techniques.

A 10-MHz, 100-kW rf source for impurity control experiments on PLT was designed, and construction was started.

Several programs to develop high-power rf feed-thru bushings were started. One program, to develop improved six-inch diameter bushings for PLT, was completed, and six assemblies were tested successfully to voltage levels adequate to feed 6 MW into PLT.

MECHANICAL ENGINEERING DIVISION

The Mechanical Engineering Division (MED) provides engineering and technical services to the many projects and programs at the Laboratory. The Division consists of three branches: the Mechanical Technology Branch, the Vacuum and Cryogenic Branch, and the Coil Systems Branch. In addition to the branches there is a Special Projects Group and an independent Engineering Services Group. The Division's major efforts and activities during FY83 were for TFTR, with the needs of the remaining research programs being met as required.

The Special Projects Group is available to the MED and others for technical support. Major efforts this past year concerned studies of the problems facing the TFTR Project. A study of the MG No. 1 rotor runout problem, and suggestions for solving the problem, was one of the major contributions of this group. Another major task, which will continue into FY84, is the program to provide mechanical supports for the poloidal-field leads.

The Engineering Services Group, which reports directly to the Division Head, provides skilled technicians to work for the various MED branches and for other organizational groups at PPPL.

Mechanical Technology Branch

During FY83, the major effort of the Mechanical Technology Branch was in support of the TFTR Project. These activities can be grouped into several categories: the fabrication, installation, and preoperational testing of auxiliary systems; the design and fabrication of neutral-beam subsystems, and the installation of the beamlines; the design, procurement, and installation of internal components for the vacuum vessel; and the instrumentation, testing, and analysis of major mechanical systems. In addition to the TFTR effort, the branch continued to provide mechanical engineering services to the other experimental projects and programs of the Laboratory.

The Mechanical Technology Branch was responsible for the fabrication and installation of a number of auxiliary systems in the TFTR Test Cell and the Test Cell basement. This work included the installation of the vacuum vessel heating and cooling system piping, the bellows cooling system piping, the vacuum system foreline and exhaust piping, and the low and high pressure nitrogen distribution systems. Concurrent with these activities, the branch assumed operational responsibility for the TFTR pump room equipment which consists of the various chilled water systems, the vacuum vessel heating and cooling equipment, and the heating, ventilating, and air conditioning system for the experimental area. Preoperational testing was conducted for each of these systems, as well as for the experimental area fire protection system.

The design and fabrication of the TFTR neutral-beam subsystems, and the installation of the neutral beamlines continued as major activities for the branch during FY83. Early in the fiscal year a neutral beamline was installed in the Neutral-Beam Test Cell, and this was followed in the summer by the installation of a neutral beamline to the TFTR device. This installation work involved the supervision by branch engineers of up to 60 subcontract personnel and 25 PPPL technicians. In addition to these activities, mechanical design services were provided for the SF₆ system, the ion source assembly, the various work platforms, and for several material handling systems. Extensive design and fabrication services were provided for the neutral-beam water systems. Work on various neutral-beam projects for TFTR will continue into FY84.

The Mechanical Engineering Branch continued to be involved in the design, procurement, and installation of TFTR vacuum vessel internal components and their associated cooling systems. A preliminary limiter, required because the bellows cover plates would not be available for first plasma, was fabricated and installed in the vacuum vessel in October, 1982. After the fabricated components for the bellows cover plates were received and assembled in the Coil Shop, the final installation of the assemblies inside the TFTR vacuum vessel was completed during the summer of 1983. The movable limiter was also received, assembled, and installed during FY83. The actuators for the movable limiter required considerable modification and testing prior to their installation. The assembly of the movable limiter to the TFTR vacuum vessel is shown in Fig. 125.

The Materials Testing Section of the branch is responsible for the instrumentation, testing, and analysis of major mechanical systems. During FY83, this section performed a total 126 tasks, of which 85% were for the TFTR Project. As in previous years, there was a wide range in both the complexity and duration of these tasks. Major accomplishments during this period included support for the TFTR Motor Generator No. 1 (MG No. 1) Task Force. This work involved the instrumentation of the MG No. 1 bearings, and the development of a data acquisition system for use on MG No. 1. Other tasks performed by the Materials Testing Section included the proof testing of various lifting fixtures, and the development

Figure 125. Installation of the TFTR movable limiter in the vacuum vessel. (83E1117)

of the instrumentation and the procedures to be used for the calibration of the TFTR toroidal-field coil water system. The Materials Testing Section was moved into larger quarters during FY83. This relocation should enable the section to provide a more extensive range of services in the future.

In FY83, the PPPL Model Shop fabricated models for the Heliac, Tokatron, and Spheromak devices. Small components for the TFTR neutral beamlines and the radio-frequency windows for PLT were also fabricated in the Model Shop.

Vacuum and Cryogenic Branch

The Vacuum and Cryogenic Branch supported a variety of project needs for TFTR, PLT, PBX, and the S-1 Spheromak.

Vacuum lines were installed on TFTR neutral beam boxes 3 and 4 and on the neutral-beam test stand, and the liquid nitrogen manifolds for these boxes were manufactured. In addition, a number of modifications and repairs were made on the neutral-beam systems. Eight Al-Zr getter pumping arrays and three gas injection assemblies were fabricated, and assistance was provided for their installation on TFTR. Forty-five scraper assemblies and other parts were vacuum brazed for the TFTR neutral-beam group, and a number of vacuum-brazed ceramic breaks ranging in size from 3/4-inch to 12-1/2 inches were also fabricated. Figure 126 shows the vacuum brazed ceramic rf windows and assemblies for the 2.45 GHz system on PLT, and Fig. 127 shows the micro-brazed coupler for this system. Vacuum components for PLT, PDX, and TFTR were vacuum baked prior to installation. Assistance was also provided for the conversion of PDX to PBX and for the S-1 Spheromak.

The 1000-watt liquid helium refrigerator temporarily installed in the 1-H Building for acceptance testing was disassembled and shipped to the TFTR site. During the period June through September, the individual units, two compressor skids, the helium purification skid, the cold box, the 1500-gallon dewar, and three control panels were mechanically installed.

Figure 126. Ceramic rf window assembly for PLT's 2.45-GHz system. (83E1085)

Figure 127. The micro-brazed coupler for the PLT 2.45-GHz system. (83E1604)

Figure 128 shows the cold box without the vacuum jacket, and Fig. 129 shows the compressors for the 1000-watt liquid helium refrigerator. During September, the ambient helium lines from the compressor room to the cold box area were installed and vacuum tested, and most of the cold box area cryogenic transfer lines were installed.

Diagnostics Section

The major portion of the Diagnostics Section's effort was directed to the commissioning of TFTR. Twelve of the TFTR port covers were modified for diagnostic flanges, and remote-controlled protective shutters were installed where required. Magnetic instrumentation was fabricated and installed for various diagnostics, including the Diamagnetic Loops, the Rogowski Coils, and the B_θ Coils. Platforms for various pieces of equipment were also fabricated and installed. A number of vendor-designed and vendor-fabricated probes were installed on TFTR. These included the electronic gun and target pair (used for initial magnetic field alignment), the glow-discharge conditioning probe positioning mechanisms, and the langmuir and calorimeter probe positioning mechanisms.

Other TFTR diagnostics that the section worked on during this period included the neutron detectors

Figure 128. Installation of the 1070-watt liquid helium refrigerator cryostat. (83E1120)

and the array and wide angle bolometers. A telescope and structural support for the HAIFA (Hydrogen Alpha Interference Filter Array) diagnostic device were fabricated and installed. The first channel of the horizontal charge-exchange diagnostic (Fig. 130) was installed, and fabrication efforts continued on the vertical charge-exchange system. The first X-ray pulse height analyzer and the first X-ray imaging system were also installed successfully on TFTR. Design and construction continued on the TV Thomson scattering system and the multichannel for the infrared interferometer.

Figure 129. Compressors for the 1070-watt liquid helium refrigerator. (83E0769)

Figure 130. Horizontal Charge-Exchange diagnostic.
(84E0320)

Concurrent efforts on other PPPL devices included work on parts for the ERCH power system on PDX and work on the positioning mechanisms on PLT. The optics support structure and the periscope system for the radial-scanning Thomson scattering diagnostic on the S-1 Spheromak were completed. A supplementary use of the optics structure to support a portion of the CO₂ infrared interferometer diagnostic verified its predicted stability. Other efforts included the continuing maintenance and modification of existing diagnostics.

Coil Systems Branch

During FY83, the major activities of the Coil Systems Branch included the conversion of PDX to PBX (Princeton Beta Experiment), the completion and installation of the S-1 Spheromak generator filter coils, operational support to TFTR, PLT, and S-1, and participation in the TFCX (Tokamak Fusion Core Experiment) preconceptual design proposal.

Figure 131 shows the interior of PBX during the final phases of the conversion process. The Coil Systems Branch was responsible for the engineering design and fabrication of the passive coil system, the reconfiguration of the internal poloidal-field coils to provide a "pusher" coil at the midplane and shaping coils around the plasma periphery, and for the modification of the bussing arrangements of the PF coils to provide the proper field topology for the "bean-shaped" plasma. The various components are identified in Fig. 132. The passive coil system consists of three pairs of nickel-plated aluminum single-turn coils, each connected electrically to its match so as

Figure 131. Interior of PBX vacuum vessel during conversion. (83E1262)

Figure 132. PBX interior components. (83E1467)

to provide a restoring force during gross movements of the plasma. These were fabricated in segments and assembled in the vacuum vessel. A "pusher" coil was provided by relocating one of the divertor coils to the midplane and by installing a new lead and modifying the coil vacuum liner.

To operate the S-1 Spheromak with the generator-powered EF coil located in the flux core, an L-C filter to protect the generator from the induced voltage spike is required. This filter consists of inductors and capacitors. The Coil Shop fabricated the inductor by winding water-cooled copper coils and supporting them in concrete blocks. The assembly was completed and tested in early FY83. In addition, figure-8 shaped passive stabilizer coils were also designed and fabricated to help stabilize the S-1 plasma against undesirable motions.

The Coil Systems Branch also participated in the configurational design of the coil systems for the TFCX device. A proposal was prepared in August, 1983, and further work is currently underway on both the copper and superconducting TF coil version of the device.

Engineering Services Group

This section provides skilled tradesmen for all branches of the Mechanical Engineering Division and for any other PPPL group requesting support. Tradesmen available include carpenters, electricians, metal smiths, plumbers, welders, millwrights, and general technicians. As in the previous year, the majority of Engineering Services work was on the TFTR Project; however, low-level support of Research Department projects continued.

COMPUTER DIVISION

Fiscal year 1983 was characterized by rapid growth and expansion in the services and facilities provided by the Computer Division. The data processing requirements for the Laboratory increased in all areas. Data acquisition levels continued to grow on the real time systems, and the number of users increased markedly for all three computer centers.

The new diagnostics and equipment added to TFTR after first plasma resulted in a sizable workload for the Computer Division. On the Data Acquisition System (DAS) new diagnostics were added at the rate of two per month, and for the first time it became necessary to run two experimental machines (PLT and S-1 Spheromak) simultaneously.

At the beginning of the fiscal year, nearly one-third of the 600 offices at C-site were wired to the PPL computer network. This number was doubled by the end of the year, and the demand for additional ports continues to grow.

TFTR Support

Initially all effort was directed toward the support of TFTR first plasma. There were 14 Console Operating Stations and 10 Terminal Stations on line for first plasma. Six diagnostics and over a hundred

subsystem applications were operational, and 800 kilobytes of data were acquired from each shot. By the end of the year, the number of stations increased by 40%. There were 23 diagnostics taking data with 3.6 megabytes of data collected per shot.

Considerable effort was put into improving the performance and reliability of the Central Instrumentation, Control, and Data Acquisition (CICADA) system. The computer operating system was upgraded to MPX 2.1 to gain much needed file handling capabilities and to support dual-ported disc storage. Three Central Facility Computers were upgraded to SEL 32/87's to increase performance by a factor of five or more. Software that was pressed into service to support TFTR first plasma was overhauled to reflect new and revised requirements, corrections to problems, and reliability and performance enhancements.

DAS (PLT, PDX, S-1 Support)

It became clear in FY83 that the DAS computer system had run out of computer power. A detailed study was conducted to determine the practical throughput limit for the DAS configuration. The study showed that although enhancements could be made to relieve the situation somewhat, the growing requirements dictated that supplemental processing would be necessary. It was decided to gain the necessary throughput by adding a VAX computer to the DAS system. Procurement was initiated for FY84 operation. Short-term enhancements included adding memory, modifying software scheduling, and tuning the operating system. Data acquisition increased to over two million bytes per shot on a regular basis.

User Service Center

The processing requirements for the User Service Center (USC) continued to increase. In April, 1983, the print station was made operational to significantly improve the rate of graphic output available to NMFEE users. In August, 512 kilobytes of Ampex memory was added to improve overall performance and throughput.

HL/DAS

The VAX 11/780 was upgraded in preparation for its increasing role in TFTR support. Plans were made for a data link to the online CICADA system. Initially a low-speed RS232 link would be provided for early FY84 operation. A high-speed link would be procured for April 1984 service.

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PLANNING AND RESOURCE MANAGEMENT

The Planning and Resource Management Office has three distinct organizational units for carrying out its responsibilities. These three units are the Planning Office, the Project and Operational Safety Office, and the Project Management Systems Group.

PLANNING OFFICE

In FY83, the Planning Office developed a PPPL Technology Transfer Program Plan and prepared PPPL's FY82 Technology Transfer Report. These actions enabled PPPL to comply with Department of Energy Order DOE 5800.1 which implements Public Law 96-480 (The Stevenson-Wydler Technology Innovation Act of 1980). This Act requires government-funded research and development laboratories to establish a formal technology transfer program.

The Planning Office also served as a single point of contact for the Department of Energy concerning PPPL computer matters. A long-range automated data processing (ADP) plan was prepared, which outlined PPPL's FY84 to FY89 computing needs and proposed methods for satisfying those needs. A short-range plan, which addressed FY83 ADP procurements, was also prepared. All ADP equipment and software purchases were reviewed by this office to assure that they were consistent with PPPL's ADP plans.

Also in FY83, the Planning Office analyzed the anticipated workload on the technical labor force by reviewing the budget and personnel data bases. The analysis compared the projected FY83, FY84, and FY85 workloads with the current staff. Recommendations were then made concerning adjustments to the workload and/or staff so that a balance between the two could be achieved.

PROJECT AND OPERATIONAL SAFETY OFFICE

This office worked closely with TFTR and other PPPL projects, and a heavy emphasis was placed on day-to-day interactions and on close support of project personnel. In April, PPPL's first "Annual Environmental Report" was published. This document reported on PPPL's environmental monitoring program and reviewed PPPL's compliance with government regulations.

Work was completed on a Safety Assessment Document (SAD) for the S-1 Spheromak. SAD's were initiated for the PBX and RFTF experiments.

Requirements for written procedures increased in FY83, and Project and Operational Safety Office input, review, and sign-off became a requirement for projects. Because facility reviews have become more extensive, a standard construction specification was proposed and adopted to reduce the turnaround time of reviews. Other standardization procedures were proposed and are being worked on to further streamline this process.

In-house radioactive analysis capabilities were expanded with the intent of doing the program fully in-house in CY84. In addition, plans were begun for a CY84 review of all in-house environmental monitoring procedures and methods associated with PPPL operations.

PROJECT MANAGEMENT SYSTEMS

Work efforts intensified during the year toward implementing a laboratory earned value performance measurement system (PMS). Major emphasis was placed on developing three areas: staffing, computer systems, and procedures. A full-time dedicated staff was assembled, to develop and coordinate implementation of PMS.

The second area of emphasis was the development of functional computer software which, when linked with the PPPL accounting system, enabled the generation of various cost and schedule reports.

The third area of emphasis resulted in the development of initial procedures and instructions that enabled PPPL to create and maintain an integrated cost and schedule data base. Preparation of a PMS operator's manual was started which instructed users in the basic implementation and operation of PMS.

By year's end, PPPL had in place an initial integrated cost and schedule data base, which will be used during FY84 to monitor cost and schedule performance. This data base consisted of approximately 860 job estimates for TFTR, TFCX, Experimental Projects, and miscellaneous technical center work planned for FY84. It is based upon integrated activity schedules, manpower estimates, and cost estimates for both operating and equipment funds.

QUALITY ASSURANCE AND RELIABILITY

In May 1983 the Laboratory Director issued a policy directive establishing a Laboratory-wide Quality Assurance program compliant with ANSI/ASME NQA-1 (1983). The directive placed responsibility for implementation upon the Deputy Director for Technical Operations. It further provided for an organizational entity, Quality Assurance and Reliability (QA/R), reporting to the Deputy Director. This functional group was charged with setting QA policy, developing a uniform quality assurance program to meet the Laboratory's objectives, and structuring and staffing the organization with the skills and scope necessary to support the broad spectrum of Laboratory technical and scientific activity. During the latter six months of 1983, existing, but organizationally isolated, QA personnel were brought together into the central QA/R organization. Staff skill levels were enhanced by training and the acquisition of needed skills, and substantial strides were made toward the initiation of a NQA-1 baseline program. This program was designed to have appropriate flexibility to permit

tailoring of requirements to special situations involving trade-off of cost, schedule, and technical risks. In the process, care was taken to assure the retention (and expansion where indicated) of existing quality systems that were established by individual Laboratory functional groups during preceeding years. The QA/R organization, while not fully staffed by year end, was structured as shown in Fig. 133.

Figure 133. Quality Assurance and Reliability Group organization structure at PPPL.

ADMINISTRATIVE OPERATIONS

During FY83, the administrative and financial functions of the Laboratory were reorganized under a Deputy Director for Administrative Operations with a Controller's Office and an Administration Department reporting to him. The organizational change was designed to consolidate financial activities under a Controller, to coordinate more effectively administrative and financial operations, and to improve support to research and technical operations of the Laboratory.

In FY83, the total Laboratory staff increased from 1237 to 1257 employees. The composition was as follows at year end:

Faculty	2
Physicists	118
Engineers	284
Technicians	560
Other	<u>313</u>
Total	1257

ADMINISTRATION DEPARTMENT

Plant Maintenance and Engineering

The Plant Maintenance and Engineering (PM&E) Division is a technical and administrative support organization. Its function and purpose is to support the Laboratory's research programs by operating, repairing, constructing, and modifying physical plant facilities, systems, and equipment at A, C, and D-Sites and at several buildings at B-Site.

The Division's workload has increased significantly over the past five years with the construction of the Tokamak Fusion Test Reactor (TFTR) and the addition of numerous support facilities. During this time, organizational restructuring throughout the Laboratory has resulted in approximately 130 office moves. With many of these moves renovation and facility upgrading were incorporated to enhance the working and safety environment.

A brief summary of major fiscal year accomplishments follows.

TFTR Preliminary Test Runs

Preparation for first plasma, which occurred on Christmas Eve of 1982, increased substantially involvement between PM&E and other areas of the Laboratory. Since then, preliminary test runs of TFTR

have increased short-notice demands for facility changes and new operational procedures, off-shift maintenance requirements, and equipment modifications. In addition, a computerized preventive maintenance system for all of the TFTR facilities was initiated in January, 1983. This support was provided while operating within a stringent budget and with strict workforce constraints. The TFTR project was fully supported while responsiveness to the rest of the Laboratory was improved.

A key factor in this improved responsiveness was the creation of a Manager of Maintenance Control position within the PM&E organization. This position allowed for greater professional attention to the planning of plant maintenance repairs and minor plant alterations. The Manager was responsible for the implementation of a computer-controlled work order system which is capable of handling the increased demand for proper planning and scheduling of the mounting workload. The new system, which was operational as of October 1, 1983, also provides instant project tracking for other departments at PPPL. Management information and reports are now being used for accurate manpower forecasting, budget control, work history analysis, and instant job status appraisal.

Fire Detection and Alarm System

The fire warning system at C-Site is 25 years old. A mandated upgrading of the entire C-Site fire warning system was initiated in FY83. During upgrading, it was necessary to make changes to the existing system without interrupting its operational capability. This project is being completed on schedule and without any system interruptions. The total project is scheduled to be completed by June 30, 1984.

Training

In-house training continued to receive strong support in FY83. Ten PM&E employees attended in-house classes for two hours, twice weekly for an eight-month period. This was the sixth year that these vendor (Technical Publishing Company) designed courses were given. Safety training continued to receive strong emphasis, with all PM&E mechanics attending monthly training sessions on various safety-related subjects. Additionally, the need for special instruction on specific equipment was recognized, with training provided for pyrotronics and for various types of air conditioning systems peculiar to the TFTR facility.

A newly developed general apprentice program, with emphasis on training minorities, was planned by a group of PM&E managers, supervisors, and technicians, and was initiated in October, 1982. The program is specifically designed to produce well-rounded general maintenance mechanics, and it may be the first of its kind in New Jersey to receive State and Federal certification.

Energy Conservation

In order to maximize the Laboratory's energy resources, conservation efforts were concentrated in four areas: (1) improvements in the operation and maintenance of the major energy systems, (2) implementation of retrofit and modification programs, (3) continuation of central plant improvements, and (4) continuation of employee awareness and related energy conservation programs. These efforts included: field testing and replacement of steam traps; close surveillance and inspection programs for chilled water treatment; clearing of apparatus coils and tubes; improvement of chilled water and steamline insulation; computerization of the maintenance and auxiliaries equipment "tune-up" program; initiation of start-up procedures for large horsepower equipment; initiation of the central plant boiler tune-up and trim program; retrofit and modifications to the fresh air intake systems; installation of a central plant economizer oxygen trim system on #2 boiler; installation of boiler blow-down heat exchangers on boilers #1, 2, and 3; and cleaning of the soot blower tubes on boilers #1 and 3.

The Laboratory also sponsored an Employee Ride Sharing Program, with 45 participants, and a Drivers Energy Conservation Awareness Training (DECAT) Program, which trained 35 drivers in FY83. Energy Awareness Week was observed in conjunction with the State of New Jersey with a display of posters and exhibits throughout the Laboratory.

Library

The past year was devoted to improved financial management and improved productivity. By eliminating external distribution of monthly Acquisition Publications, more time became available to other areas of Library operations. By training the Library staff on the use of the MAG 1 typewriter, 40% more catalog cards were produced. This allowed for the addition of report subject headings to the catalog cards, a practice which had been discontinued during the past two years.

In order to provide additional drawer space, a systematic program to eliminate obsolete catalog cards was undertaken. Approximately 3000 cards were withdrawn, providing enough drawer space until the arrival of sixty new drawers. In the future, with the aid of a Laboratory-appointed committee, the possibility of establishing a computerized cataloging system will be studied. One issue to be explored will be compatibility with the existing Firestone Library cataloging systems.

During FY83, the NASA/RECON computerized literature searching data base was added to the Library's searching capabilities. This system provides increased searching capabilities in the areas of metallurgy, mechanical engineering, and astrophysics. Information in this data base usually cannot be located in any other search systems, and its low cost makes it especially attractive. Overall, computer subject searches increased by 20% in FY83.

In keeping with cost awareness, an evaluation of translated Russian journals was made to determine their relevancy to the fusion program. A few journals that had previously been considered very useful were found to be of marginal applicability, and a recommendation was made for their discontinuance.

Many times during the past fifteen years, the Library has been called upon for assistance in establishing a library in newly formed plasma physics/fusion centers. In response to these requests, a bibliography on reference sources of information was developed. The purpose of this thirty page, annotated bibliography is to provide information on reference books and agencies that assist in providing answers to Laboratory staff reference questions. Accompanying the bibliography is a complete listing of PPPL journal holdings, including journals to which PPPL currently subscribes and journals to which PPPL no longer subscribes. An expanded and revised listing of subject headings used in cataloging reports and journal articles was completed during the past year. With these aids, better assistance can now be provided to fledgling plasma physics libraries.

The Librarian designed and PPPL Plant Maintenance built a new circulation desk for the PPPL Library. The addition of this functional unit greatly increased the ease with which the many library functions are performed.

At the end of FY83, the Library had approximately 10,000 bound volumes, 18,000 technical reports, and about 29,000 microfiche. There was a slight increase of 7% in Library circulation.

Telecommunications

The role of the Telecommunications Office is to provide the Laboratory voice communication services that are both cost-effective and efficient. With this as its goal, the Telecommunications Office completed the following work:

- Processed over 3300 requests for moves, installation, and changes in telephone service.
- Ordered sixty new pocket pagers, bringing the total number of pagers to two hundred and seventeen.
- Initiated extensive studies with DOE consultants in order to upgrade and improve radio communications within all areas of the Laboratory. Results will be available in FY84.
- Provided telephone service to the TFTR complex.

- Processed monthly charges for all telephone service.
- Initiated studies to determine the cost effectiveness of retaining the Federal Telecommunications System (FTS). Conclusive tests will be conducted during FY84.
- Installed a teleconferencing office with an electronic blackboard that links the Lawrence Livermore National Laboratory, the Oak Ridge National Laboratory, and PPPL (This will enable project teams to meet electronically and to exchange information.)
- Worked in conjunction with the Chicago Operations Office (COO) to develop the specifications for a digital telephone system to replace the obsolete Centrex II System currently in operation. The proposed telephone system will be installed during FY85.

Increases were levied on communication charges despite strong efforts to control costs. New Jersey Bell was granted a rate increase that escalated costs by 10.5%, and substantial increases have been forecast for FY84. The cost of telecommunication services remains a significant factor in the PPPL budget.

Information Services

The Information Services Branch of the Administration Department includes all Laboratory services supporting the preparation and dissemination of information pertaining to PPPL's program. Service areas include photography, graphics arts and technical illustration, word processing, printing, technical information, and public and employee information. Various administrative services—specifically, reception, mail, travel, and food services—are also provided.

Public and Employee Information

Fiscal year 1983 was one of the busiest on record for public information activities, primarily because of the start-up of TFTR operations.

On Saturday October 9, 1982, Family Day was held for employees, spouses, and children. This was the first such event since 1976; families were able to witness the substantial Laboratory expansions that had occurred since that time. Guests were provided an opportunity to see PLT, PDX, and TFTR, as well as smaller machines and fabrication shops. Approximately 800 people attended and were provided refreshments and mementos in the form of tee shirts and helium-filled balloons.

Also in October, 1982, PPPL was host to a national meeting of public information specialists representing industries, universities, and national laboratories conducting fusion energy research. The purpose of the meeting was to improve communication among public information officers, especially relating to the achievement of program milestones at the various laboratories.

Preparations for TFTR first plasma occupied much of the public information staff time during November and December. Media relations activities were very heavy during this period. The office received frequent calls from major national and local press representatives requesting the latest schedule for TFTR first plasma. Plans were made for a first-plasma news conference to be called shortly after the achievement. A subcontractor was hired to capture on film and video tape the excitement of the activities in the main TFTR control room and the temporary control room set up in the Mock-Up Building.

A news conference was held on Tuesday December 28, the second working day following the Christmas Eve achievement of first plasma. Representatives of major media including *The New York Times*, *The Philadelphia Inquirer*, *Time Magazine*, *Business Week*, NBC, CBS, and a host of other prominent national and local print and broadcast media attended. Broadcast journalists were provided copies of video tapes made at the time of first plasma. The footage greatly enhanced the visual impact of their news reports.

Virtually all of the resources of the Information Services Branch were marshalled during the first four months of 1983 in preparation for the TFTR Dedication Ceremony and Celebration, scheduled for May 5. Extensive planning was required, as was the identification and procurement of services from numerous subcontractors. Major procurements included contracts for facility preparation (platforms, chairs, drapery in the TFTR Mock-Up Building and Test Cell), video recording of the ceremony and playback of selected portions at the celebration in Jadwin Gymnasium, printing of invitations, credentials, and programs, and food services.

The TFTR Dedication Ceremony (Fig. 134) was attended by approximately 450 people representing the national laboratories, government, and industry.

Figure 134. With a snip of a scissors, United States Secretary of Energy Donald P. Hodel (left) officially dedicated the Tokamak Fusion Test Reactor (TFTR) during ceremonies held Thursday, May 5, 1983. Looking on is Laboratory Director Dr. Harold P. Furth.

Speakers included Secretary of Energy Donald P. Hodel, Science Adviser to the President George A. Keyworth, II, and Director, Office of Energy Research, U.S. Department of Energy Alvin W. Trivelpiece (Figs. 135 and 136). Following the ceremony, a celebration was held for PPPL employees and their guests. Over 2,000 people attended.

Coinciding with the start-up of TFTR was the implementation of PPPL's Community Outreach Program. A committee, established in FY82 and chaired by PPPL Deputy Director for Administrative Operations, made recommendations to University and PPPL management in early FY83. The goal of the program is to foster a broad base of local public understanding of the work at PPPL and to forge closer communication links with local government, industry, and educational groups.

The first activities under the Community Outreach Program included the establishment of monthly Open Houses for the nearby public. This program proved popular, with an average of approximately 100 people in attendance each month throughout FY83. Also beginning in January 1983 was a series of luncheon

meetings for representatives of local businesses and government. During FY83, officials of the five closest townships visited the Laboratory and were provided an overview of PPPL's fusion program followed by a tour of TFTR. Several business groups, such as the residents of the Princeton Forrestal Center, attended similar programs throughout the year.

In the summer of 1983, PPPL participated in the Scientist-Science Teachers Interaction Project. A physics teacher from a nearby high school spent one week at the Laboratory interviewing a variety of technical specialists. On the basis of his experience, the teacher developed a series of lesson plans on fusion energy for use in the classroom. Plans were developed to expand this program to include several teachers during the summer of 1984.

All of these Community Outreach activities were in addition to PPPL's continuing visitor and speakers program. During CY83, 303 tours (7,000 visitors) were arranged by the Public and Employee Information Section, an increase of 20% over 1982 and 600% over 1975. Twenty-three speaking engagements were arranged during CY83.

Figure 135. Following the ribbon-cutting ceremony, PPPL Director Harold P. Furth and Princeton University President William Bowen receive the congratulations of the distinguished speakers. Pictured left to right are George A. Keyworth, II, Science Adviser to the President, U.S. Secretary of Energy Donald P. Hodel, Dr. Bowen, Dr. Furth, and Alvin W. Trivelpiece, Director, Office of Energy Research, U.S. Department of Energy. (83A0299)

Figure 136. Princeton Plasma Physics Laboratory Director Harold P. Furth listens as Secretary of Energy Donald P. Hodel reads a congratulatory message from President Ronald W. Reagan during the TFTR Dedication Ceremony. (83A0298)

Patent Awareness Program

During FY83 there were thirty Invention Disclosures submitted to DOE. Based on previously submitted PPPL Invention Disclosures, DOE prepared ten patent applications, which were executed by the PPPL inventors and then filed with the U.S. Patent and Trademark Office. Three patents were issued to DOE for PPPL inventions during this time period.

As part of the Patent Awareness Program initiated in 1981, the Committee on Inventions awarded 55 PPPL inventors with cash and certificates and honored the inventors at an Annual Awards Banquet. The invention disclosure titles and inventors for FY83 are listed in Table VI.

Word Processing

Word processing activities increased dramatically throughout FY83. An NBI OASys 64 with 60 Mb of storage and 16 ports for peripherals was installed in November 1982 in the C-Site Word Processing Center. This centralized the word processing operations of the Word Processing Center, the Theory Division, and TFTR Operations, and provided for additional linking of remote workstations and printers. In early spring, a system backup option was installed and procedures implemented to protect against potential damage caused by software or hardware crashes, vandalism, or facility fire. In early summer, the OASys 64 central processing unit was upgraded from 16 to 24 ports, 512K to 768K of memory, and 60 Mb to 120 Mb of storage. By the end of FY83, a second OASys with 60 Mb of storage, 768K of memory, and 24 ports was installed and interlinked with the first OASys 64. The interlink centralized the network in the C-Site Word Processing Center and provided centralized storage, processing, and backup for nearly 46 peripherals. This enabled the Director's Office, Applied Physics, Plant Maintenance,

and various sections from the Experimental and Research Departments to be brought on-line.

A third OASys 64 with 60 Mb of storage, 768K of memory, and 24 ports was installed in the Procurement area at A-Site and was linked, as needed, to the C-Site NBI network via telecommunications. An additional half dozen NBI System 4000S standalone units for remote locations were also installed. These are compatible with those on the network so that they can be linked to a network in the future and so that storage media are standard. Standardizing on the NBI word processing system also enables trained operators to work on any NBI terminal around the Laboratory, which is beneficial for backup, temporary assignments, transfers, etc.

In-house training was provided on NBI equipment at no cost to PPPL. Approximately 30 operators were trained in both basic word processing functions and advanced features including equations, records sort, statistical math, spelling verification, and communications. Mini-sessions for principals were offered on a trial basis to facilitate a basic understanding of accessing, editing, and printing. These sessions were found to be informative and instructive to participants, and will be offered in the future.

During the extensive installations and training activities of this period, production continued to increase. Total production reported for the year for NBI word processing was 52,400 pages. Production in the Word Processing Center was 27,800 pages, approximately 53% of the total.

Plans provide for the full expansion of the A- and C-Site NBI networks, with communications used to link the two sites and to access the PPPL computer systems. Equipment upgrades, training, continuous operation, and further office integration will be the directions word processing operations will be taking.

Administrative Services

During FY83 DOE's Pilot Project Electronic Mail System was implemented to provide fusion laboratory Directors, secondary offices, and DOE Headquarters with communications capability through terminal access. Survey results of the Pilot Project will be used as a means for determining feasibility of a long-term system capable of providing terminal-access communications among an unlimited number of users.

Staff of the Administrative Services section were heavily involved in TFTR first-plasma and dedication activities. A reception was arranged in January 1983 for all PPPL employees in recognition of their first-plasma efforts. An estimated 2,000 employees were guests for refreshments, an address by the PPPL Director, and a TV viewing of first-plasma news reports.

Administrative Services staff provided essential support before and during the dedication by handling invitation mailings, responses, credentials, and arrangements for food service.

Table VI. PPPL Invention Disclosures for FY83.

Title	Inventors
Plasma Ion Temperature Diagnostic Using Radiation Produced by Charge Exchange Collisions	R. Fonck R. Goldston
Process of Creating a High-Beta Tokamak with a Second Stability Regime	R. Kulsrud S. Yoshikawa
The EST (Elmo Snaky Torus)	H. Furth A. Boozer
Prompt Radial Profile Species Diagnostic for Intense Neutral Beams	H. Kugel R. Kaita
Non-Interlocked Planar Coil Stellarators with a Magnetic Well	A. Boozer A. Reiman
A Nuclear Diagnostic for Fast Alpha Particles	L. Grisham D. Post J. Dawson
Resonant-Cavity Antenna for Plasma Heating	F. Perkins S.-C. Chiu P. Parks J. Rawls
Getter and Limiter System for Controlling Hydrogenic Density and Impurities in a Magnetic Fusion Device	J. Cecchi R. Knize H. Dylla J. Sredniawski
The Quasi-Isobaric Reactor	R. Mills
Method of Winding High-Field Double-Pancake Superconducting Coils	P. Materna
Gaseous Diverter	F. Tenney W.L. Hsu M. Yamada
High Rejection Ratio Differential Amplifier	S. Yoshikawa
Hexagon Tap Driver Neutron Band-Pass Filter for Fusion Diagnostics	R. Silvester T. Elevant L. Samuelson
Current Generation by Phased Injection of Pellets	N. Fisch
TFTR Ion Source Protection Equipment	R.C. Segers
Calculation Method and Computer Program for Determination of Inductance of Multiconductor Transmission Lines	A. Nudelman N. Fromm
Technique for Coupling Electrical Energy Sources	F. Lawn D. Huttar

**Table VI. PPPL Invention Disclosures for FY83.
(Continued)**

Title	Inventors
Parabolic Tapers in Overmoded Waveguide	J. Doane
Bends in Overmoded Waveguide With Hyperbolic Secant Curvature Variation	J. Doane
High Voltage DC Break for High Power Overmoded Waveguide	J. Doane M. Goldman
Tokamak Plasma Current Disruption Infrared Control System	H. Kugel M. Ulrickson
High Speed Crowbar	G. Grotz
High Speed High Current Spark Gap	G. Grotz
Stabilizing Center Cylinder for Spheromak	A. Janos M. Yamada
Tokamak Current Drive by Asymmetric rf-Induced Stochasticity	T. Stix
Disruption Configured Limiter	J.G. Murray
Spoolless Pieces for Connecting Ultra High Vacuum Components with Facing Blind Tapped Flanges	J. Timberlake S. Cohen
Spring Loaded Thermocouple Module	T. McKelvey J. Guarnieri
Arched Toroidal-Field Coil for Tokamaks	D. Jassby M. Okabayashi L. Bromberg D. Cohn J. Williams

Personnel

The major programs and activities of the Personnel Division during FY83 were the following:

- A revised Health Care Plan was implemented which emphasized cost containment as a principal objective, and the bi-weekly personnel were made eligible for the University Long-Term Disability Plan. Also, three Health Maintenance Organizations (HMOs) in addition to the Mercer Medi Group were offered to all employees.
- The Compensation Section concluded a major study of the Laboratory's existing Wage and Salary Practices and is currently in the process of modifying several techniques and procedures essential for measuring market competitiveness.
- The Laboratory made a commitment to intensify its Training and Development activities, and during the past fiscal year the Personnel

Division conducted two supervisory training programs: the Initial Blessing-White Self-Development Program and a one-day Stress Seminar. In conjunction with Plant Maintenance and Engineering, a general Maintenance Apprenticeship Program was initiated to develop individuals as general mechanics and to continue to enhance the Laboratory's Affirmative Action objectives. In addition, a Procurement Intern Program was developed to enable the Procurement Division to train and promote the growth of entry-level professionals as Buyers or Subcontract Administrators.

- A new section, Human Resource Information Systems, was created with the primary mission to computerize personnel data in a timely and accurate fashion.
- The Personnel Division published several new policies covering Exempt Overtime, Relocation, and Maximum Working Hours.

Occupational Medicine and Safety

An occupational medicine program was inaugurated with the addition to staff of a physician certified in that specialty. Interim dispensary facilities were constructed by modifying existing office space in Building 1-0. The staff was expanded to include a physician, two occupational health nurses, and a medical secretary. This allowed for a more complete preventative medicine program to be started. The program consists of preplacement, periodic, and termination health evaluations, as well as treatment for most occupational injuries. More serious injuries are referred to specialists at the Princeton Medical Center.

Later in the year, a new organization, the Occupational Medicine and Safety Office, was created by combining the preexisting Health and Safety Branch with the Medical Office. This has allowed closer coordination between the medical, safety, and industrial hygiene professionals and has been a factor in the marked reduction of PPPL's lost-time injury rate in the second half of the fiscal year.

The Laboratory embarked on a program to implement a more formalized and documented safety program. Based on an independent, in-depth audit, the Administration Operations' safety program was evaluated and given an overall good rating. The evaluation was based on interviews of personnel at various staff levels in order to examine their knowledge and understanding of the goals of the safety program, on reviews of safety training records, and on inspections of work areas. The appraisal was prepared using the DOE Safety Assurance System summary criteria in accordance with Health and Safety Directive (HSD) 5031 and will serve as a benchmark for future appraisals.

The system of assigning Safety Managers and Area Safety Coordinators to specific areas of operation was started last year in Administrative Operations and proved to have a beneficial effect on overall accident experience. Plans were made to introduce this accident control technique into Technical Operations in FY84. This system involves the active participation of all levels of management, including the Deputy Directors, in the inspection of work areas, in safety meetings, and in the investigation of accidents requiring more than first aid.

Emergency Services

In order to provide the Laboratory with round-the-clock, weekend, and holiday fire protection, the Emergency Services Unit (ESU) became a full-time, permanent work force this year. Five captains and 16 safety technicians are responsible for providing fire safety and protection for the entire facility, as well as inspecting fire detection and suppression systems and testing emergency equipment. In addition, the ESU formed a Hazardous Materials Response Team that responds to all calls of a hazardous nature.

As part of its program to train employees to handle emergencies, the ESU has instructed over 200 employees in Cardiopulmonary Resuscitation. The ESU also has a continuing program that provides employee training in fire safety, the use of fire extinguishers, and the use of self-contained breathing apparatus. A program to be implemented in FY84 will provide the first responder-type, basic first-aid course to employees.

The Emergency Preparedness Planning Committee appointed an *ad hoc* committee to revise, edit, and update the Emergency Preparedness Plan and its 27 supplements. The revised plan will be ready for distribution in mid-FY84.

During this fiscal year, the ESU responded to 85 calls. Of these, 56 were calls for the First Aid Squad.

Procurement

During the second quarter of FY83, the Procurement Division underwent a Contractor Procurement System Review (CPSR). As a result of this review, the Laboratory's authority for entering competitive fixed-price procurements was increased from \$100,000 to \$250,000. All other previously approved authorization levels were unchanged.

During the year, 12,867 procurement actions totalling \$47,082,066 were placed. This represents an increase of 31% in procurement actions and a 25% increase in dollar value over FY82.

Late in the last quarter of FY83, the Procurement Division converted to word processing equipment for the secretarial staff. Full implementation of this equipment will continue into FY84.

Materiel Control Office

In 1983, the primary objective of Materiel Control was to improve the Laboratory's property control for capital and sensitive equipment. Congress, the General Accounting Office (GAO), the DOE, and Laboratory management continued to emphasize the necessity for controlling government-owned property and preventing waste, fraud, and abuse. Toward this end, new Laboratory procedures were implemented for custodian control of equipment, for security and loss reporting, and for the use of property being transported from Laboratory property. These procedures, coupled with our new computerized Equipment Tracking and Control System (ETACS), provided a solid foundation for the control and accountability of property.

Stockroom activity reached an all-time high in FY83 with \$1.8 million in sales and over 130,000 withdrawals being made by users. To meet the increased demands, improved productivity was realized through the installation of modular cabinets, reorganization of stock, and new procedures for the requisition and distribution of stockroom assets. Stockroom hours were also increased, and the stockroom provided service daily until 9:30 p.m. and on Saturdays from 8:00 a.m. till noon. Storage space for stockroom assets continues to be a problem, and plans were

formalized for the addition of storage sheds at both the B- and C-Site stockroom locations.

In the Warehouse, over 18,000 receipts, deliveries, and shipments were made in support of Laboratory requirements. Storage space needs for equipment and supplies being held for projects continued to grow, and a new mezzanine was installed in Receiving 3 that provides an additional 1,200 sq ft of storage space. The Spares Parts Section, consisting of process, device, and maintenance spares, processed \$4.1 million in withdrawals, \$900 thousand in receipts, and had a combined inventory value of \$9.7 million with over 11,000 line items.

Walk-thru inspections were conducted within the Laboratory and off-site storage facilities to identify and dispose of excess property. During the year, over \$900,000 in material and property were excessed to other labs or retired. The Excess Property Section brought in (for the cost of transportation only) almost 4,000 items valued at \$1.3 million to apply against Laboratory requirements. The Hazardous Material Section disposed of 1,100 PCB capacitors, 5 PCB transformers, and other types of hazardous material, while making 25 shipments to approved disposal facilities. The department continued to work closely with Health and Safety in arranging for the safe disposal of hazardous material.

CONTROLLER'S OFFICE

In 1983 during a reorganization of the Laboratory, the Controller's Office was formed in an effort to integrate financial management procedures and to pursue a systematic approach to data management. This reorganization involved the offices of Accounting and Financial Control, Budget, and Information Resource Management. Also, during the year, the final coordination of the Budget and Accounting Systems was completed, and the necessary controls were established to ensure their operation in unison. All existing data management systems (and their software) in the Procurement, Materiel Control, Personnel, Facilities, and Occupational Medicine and Safety Offices were organized so as to provide timely information.

Accounting and Financial Control Division

The Payroll Cost Distribution System was designed during FY82 and installed during FY83. The system was further enhanced to include the time of subcontract and industrial subcontractor employees.

Design of the new Accounts Payable System, which permits direct computer transmission of accounting information from the PPPL System to the Main Campus System, was completed. Implementation began in October 1983. The first draft of the Accounting and Financial Control Manual was completed. Reporting of equipment was expanded to include items purchased with operating funds, and procedures that automate the transfer of information from the Budget System into the Financial Accounting System were designed and installed.

A new system which allocates the budgets, commitments, and costs of all indirect expenses was designed and installed. The Chart of Accounts was revised and is completely integrated in both the Budgeting and Accounting Systems. This new system speeds the daily processing of data by substantially reducing the number of calculations and transactions. It also permits daily updating of the budget file. The new program is run overnight just prior to printing reports. As a result, the reports contain the latest budgets and allocation of budgeted and actual indirect costs. It is no longer necessary to run special programs or wait for month-end to make the allocations. Whenever revisions are necessary, they can be accomplished with a simple change of the rate tables that are a part of the program.

Table VII is a financial summary of the Laboratory for the last five years.

Information Resource Management

The activities of the Budget Office ADP (Automated Data Processing) and the Administration Department ADP were merged, and the office of Management Information Systems was renamed Information Resource Management (IRM). This merger helped to streamline data processing activities at the Laboratory and aided in the integration of the Budget and Accounting Systems. Major new systems that have been developed during this year are discussed below.

The Procurement Automated Data System (PADS) was expanded to include the addition of new files, thereby eliminating the storage of paper records. New programming enhancements for generating purchase orders eliminated redundant information. Formerly, the practice had been to enter data on the system and then type the same data on a purchase order. By using an IBM CICS screen, users can now retrieve purchase orders in their entirety as they were issued to the vendors. This results in cost savings and reduces the effort and time required to produce purchase orders.

An Accounts Payable Transfer System was developed to electronically transmit payment transactions to the Princeton University Accounting System. The new system both transmits and receives information. When the University issues payments to vendors, the system's files are updated to provide fully reconciled records and, through CICS screens, quick inquiry on vendor payments. The system has reduced the payment cycle from 10 days to 4-1/2 days and provides records to enhance the reconciliation process.

The Conversational and Interactive Project Evaluation and Control (CIPREC) System, an IBM project management software package, was studied. It provides for multiple project work breakdown structures, organizational breakdown structures, functional tables, and flexible network processing. It has undergone demonstration and testing and is being assessed for PPPL applications.

The Equipment Tracking and Control System (ETACS) was completed and is fully operational.

**TABLE VII. PPPL Financial Summary
(Thousands of Dollars)**

	FY79	FY80	FY81	FY82	FY83
OPERATING (Actual Costs)					
Department of Energy					
TFTR Res. & Develop. Operations	\$12,230	\$ 4,744	\$ 2,314	\$ 2,945	—
TFTR Facility Operations	1,578	5,587	11,832	10,424	18,029
TFTR Tokamak Flexibility Mod.	1,535	4,885	13,951	13,033	17,725
TFTR CICADA	493	1,184	2,437	4,044	8,588
TFTR Neutral Beams	—	—	1,870	6,253	24,410
TFTR Experimental Research	975	1,768	2,081	2,835	5,682
TFTR Diagnostics	2,595	5,832	7,706	8,973	14,143
TFTR Remote Handling	—	—	—	—	65
TFTR Tritium Systems	—	—	—	—	301
PLT/PDX	23,105	21,050	23,271	18,893	17,846
RF Development	—	—	—	—	742
ACT-I	666	398	438	443	458
S-1	141	1,569	3,223	3,254	3,703
Theory	2,459	2,437	2,643	2,488	2,808
Applied Physics	358	396	807	1,280	1,352
Other Research	419	290	364	495	418
Fusion Engineering Device	—	—	125	412	—
Inventories	5,519	2,305	1,922	(237)	(3,169)
X-Ray Laser Development	—	160	251	266	313
Energy Management Studies	—	—	170	197	47
SRSA	37	1	—	—	—
Department of Defense	88	88	280	297	77
Other Contracts	48	491	563	565	893
Total Operating	\$52,246	\$53,185	\$76,248	\$76,860	\$114,431
EQUIPMENT (Budget Authorization)					
Capital Equipment not Related to Construction	\$ 4,295	\$ 6,974	\$ 8,237	\$ 9,272	\$10,285
CONSTRUCTION (Budget Authorization)					
TFTR	\$35,778	\$19,361	\$25,000	\$31,600	\$1,800
PDX Neutral Beams	—	1,100	—	—	—
General Plant Projects	1,250	1,000	610	1,400	1,000
Energy Management Projects	60	558	115	—	499
Total Construction	\$37,088	\$22,019	\$25,725	\$33,000	\$3,299

ETACS is a database system for tracking major, minor, sensitive, and nonsensitive equipment by location and responsible person. It also provides reports formatted by type of equipment, cost, responsible person, location, and surplus equipment.

The Payroll and Labor Cost Distribution System was rewritten to allow interactive time-sharing access and linkage to the Laboratory Personnel System. This has a two-fold effect. First, payrolls are processed and corrected on an interactive rather than a batch basis, increasing the testing facilities and decreasing the turnaround time. Second, its linkage to the Personnel System allows payroll to receive the most current personnel information while reducing data entry to a minimum.

The Laboratory Budget System structure was modified to match the Personnel System to allow

comparison of budget to staff. With the modifications made to payroll, budgets and costs can be matched and compared to staff. In addition, the Laboratory Budget and Personnel Systems were modified to be menu-driven and transferred to a public access area. This is the first step towards making all Laboratory financial systems accessible on-line for use by the Laboratory managers.

During FY83, the Information Resource Management Division revised and drafted both its Short-Range Automated Data Processing Equipment (ADPE) Plan and the Automatic Data Processing Implementation Plan for Administrative Computing. These plans, to be published in FY84, identify the intended evolution from central batch data processing on the Princeton University computer to remote or local applications processing on an IBM 4300

computer. The long-range objective is to increase the use of dedicated PPPL administrative computer facilities and eventually use the University computer for processing only very large applications, as a back-up facility, and as a data files repository.

The current administrative computer network is comprised of the University IBM 3081 computer connected by telecommunications with local com-

munication subnetworks. The administrative Laboratory computers provide information for Laboratory budgets, accounting, purchasing, materiel control, plant and personnel management, projects planning, and status reporting.

The ADPE Plans are focused toward more local processing, such as replacing older, less versatile terminals with new, less expensive units.

GRADUATE EDUCATION: PLASMA PHYSICS

With its close physical proximity to the main campus of Princeton University, the Princeton Plasma Physics Laboratory (PPPL) provides an ideal location for a program of graduate study in plasma physics. Shortly after the declassification of the fusion energy research effort in 1959, the plasma physics program was first offered at Princeton in the Department of Astrophysical Sciences; to this day, the program is one of a few offering training in plasma physics.

Graduate students entering the plasma physics program at Princeton spend the first two years in classroom study, laying a firm foundation in the many disciplines which make up plasma physics: classical and quantum mechanics, electricity and magnetism, fluid dynamics, hydrodynamics, atomic physics, applied mathematics, statistical mechanics, and kinetic theory. Table VIII lists the Departmental courses offered this past academic year. Many of these courses are taught by the members of PPPL's research staff who also comprise the seventeen member plasma physics faculty (see Table IX). The curriculum is supplemented by courses offered in other departments of the University and by a student-run seminar series in which PPPL physicists share

their expertise with the graduate students. In addition, during FY83 a student-organized course on plasma diagnostics was held.

Most students hold Assistantships in Research at PPPL through which they participate in the continuing experimental and theoretical research programs. In addition to formal class work, first and second-year graduate students work side by side with the research staff and learn first-hand the job of a research physicist. First-year students assist in experimental research areas, including TFTR diagnostics development, PLT, PDX, ACT-I, Proto S-1, and the X-Ray Laser Project. In a similar fashion, second-year students assist members of the Theoretical and Applied Physics Divisions. Often the results of this work are documented by the students and published in professional journals. Following the two years of class work, students concentrate on the research and writing of a Ph.D. thesis. This research is under the guidance of a member of the PPPL staff, although thesis students bear greater responsibility for the content of their projects than do first and second-year students. Of the forty-two graduate students in residence this past year, twenty-seven were engaged

Table VIII. Plasma Physics Courses Offered and Instructors.

Course Number	Course Title	Instructor
Fall 1982		
AS 551	General Plasma Physics I	T. H. Stix and S. E. von Goeler
AS 553	Plasma Waves and Instabilities	L. Chen
AS 557	Advanced Mathematical Methods in Astrophysical Sciences	M. D. Kruskal
AS 558	Seminar in Plasma Physics	C. R. Oberman
AS 560	Advanced Magnetohydrodynamics	R. C. Grimm
Spring 1983		
AS 552	General Plasma Physics II	R. M. Kulsrud and W. M. Tang
AS 554	Irreversible Processes in Plasma	C. F. F. Karney
AS 558	Seminar in Plasma Physics	C. R. Oberman
AS 559	Nonlinear Interactions in Plasma	P. K. Kaw and J. A. Krommes

Table IX. Astrophysical Sciences/Plasma Physics Faculty.

Faculty Members	Title
Thomas H. Stix	Associate Chairman, Department of Astrophysical Sciences, and Associate Director, PPPL, for Academic Affairs
Liu Chen	Principal Research Physicist and Lecturer with rank of Professor
Harold P. Furth	Professor of Astrophysical Sciences
Raymond C. Grimm	Principal Research Physicist and Lecturer with rank of Professor
Charles F. F. Karney	Research Physicist and Lecturer with rank of Associate Professor
Predhiman K. Kaw	Visiting Lecturer
John A. Krommes	Research Physicist and Lecturer with rank of Associate Professor
Martin D. Kruskal	Professor of Mathematics and Astrophysical Sciences
Russell M. Kulsrud	Principal Research Physicist and Lecturer with rank of Professor
Carl R. Oberman	Principal Research Physicist and Lecturer with rank of Professor
Hideo Okuda	Principal Research Physicist and Lecturer with rank of Professor
Francis W. Perkins, Jr.	Principal Research Physicist and Lecturer with rank of Professor
Gregory Rewoldt	Research Physicist and Lecturer in Astrophysical Sciences
Paul H. Rutherford	Principal Research Physicist and Lecturer with rank of Professor
William M. Tang	Principal Research Physicist and Lecturer with rank of Professor
Schweickhard E. von Goeler	Principal Research Physicist and Lecturer with rank of Professor
Shoichi Yoshikawa	Principal Research Physicist and Lecturer with rank of Professor

in thesis projects—fourteen on theoretical topics and thirteen on experimental topics. Table X lists the doctoral thesis projects completed this fiscal year under the plasma physics program.

Outside support for the graduate program came, in part, from the Westinghouse Educational Foundation. A grant from this Foundation has permitted the Department of Astrophysical Sciences to offer prizes (which supplement the research assistantships) to outstanding applicants to the plasma physics program. In addition, some students were awarded fellowships by the National Science Foundation, the Fannie and John Hertz Foundation, the State of New Jersey Department of Higher Education, and the

National Sciences and Engineering Research Council of Canada. In most cases these fellowships are supplemented by partial research assistantships.

Overall, the plasma physics graduate studies program in Princeton's Department of Astrophysical Sciences has had significant impact on the field of plasma physics: More than 100 physicists have now received doctoral degrees in this field. Many of them have become leaders in plasma research and technology in academic, industrial, and government institutions. Even now the process goes on. The Laboratory continues to train the next generation of scientists, preparing them to take on the challenging problems of the future.

Table X. Recipients of Ph.D. Degrees.

Giorgio Anania	
Thesis:	Equilibrium and Stability of Stellarators, December 1982
Advisor:	John L. Johnson
Employment:	Booz, Allen, and Hamilton, Inc.
Philip L. Andrews	
Thesis:	Scattering of Lower-Hybrid Waves by Density Fluctuations, November 1982
Advisor:	Francis W. Perkins, Jr.
Employment:	GA Technologies Inc.
Kevin Brau	
Thesis:	Impurity Poloidal Asymmetries and Plasma Rotation in the PDX Tokamak, May 1983
Advisor:	Szymon Suckewer
Employment:	Centre d'Etudes Nucleaires de Fontenay-aux-Roses
James DeLucia	
Thesis:	Linear and 2D Nonlinear Studies of Resistive Instabilities in the Cylindrical Spheromak, June 1983
Advisor:	Stephen C. Jardin
Employment:	Columbia University
Gerald B. Elder	
Thesis:	Electron Cyclotron Emissions from an Electron Cyclotron Heated Discharge, March 1983
Advisor:	Hulbert C. S. Hsuan
Employment:	Western Electric Research Center
Michael T. Kotschenreuther	
Thesis:	The Effect of Small-Scale Fluctuations on Several Plasma Processes, December 1982
Advisors:	John A. Krommes, Carl R. Oberman
Employment:	Institute for Fusion Studies, University of Texas, Austin
Carter P. Munson	
Thesis:	Experimental Identification and Control of Spheromak Tiltng Instabilities, August 1983
Advisor:	Masaaki Yamada
Employment:	Los Alamos National Laboratory
Chang-Mo Ryu	
Thesis:	A Numerical Study of Resistive MHD Eigenmodes in Cylindrical Geometry, December 1982
Advisor:	Raymond C. Grimm
Employment:	Los Alamos National Laboratory

GRADUATE EDUCATION: FUSION REACTOR TECHNOLOGY

PROGRAMS

The Fusion Reactor Technology Program, initiated 12 years ago as a cooperative effort between the Department of Chemical Engineering in Princeton University's School of Engineering and Applied Science (SEAS) and the Princeton Plasma Physics Laboratory, enjoyed the best period in its history during the past fiscal year.

Three notable achievements made this possible:

1. The new Chemical Engineering Laboratory, located on the Forrestal Campus adjacent to PPPL's neutron generator facility, was completed. This laboratory was installed for the study of neutron-induced effects such as tritium bred in lithium and is used currently by two graduate students in the program. The laboratory's tritium assay apparatus is shown in Fig. 137.
2. The first two mid-career engineers qualified in the Industrial Training Program in Fusion Reactor Technology, also a joint SEAS/PPPL undertaking. They received certificates from Dean Robert G. Jahn and Director Harold P. Furth during a luncheon ceremony at Prospect. A third Industrial Fellow is in residence.
3. The number and quality of resident graduate students increased. Three students were admitted to the Fusion Reactor Technology Program, and all three matriculated. Two of them have Magnetic Fusion Energy Technology Fellowships, bringing to four the total number of these prestigious DOE-sponsored Fellowships now at Princeton.

Figure 137. Tritium assay apparatus located in the Chemical Engineering Laboratory on the Forrestal Campus.

Although scheduled for termination in 1983, the cooperative research program between the Department of Civil Engineering and PPPL's Tokamak Fusion Test Reactor Flexibility Modification (TFM) Project was extended for one year. This will permit a former graduate student, who wrote his doctoral dissertation on the work completed during this program, to assist the PPPL Engineering Department in solving actual thermoelastic problems associated with current and future experimental machines.

SEAS/PPPL COOPERATIVE EFFORT

During the fiscal year a concerted effort was mounted by PPPL and by the School of Engineering and Applied Science to identify new areas appropriate for cooperation. The prime mode sought was thesis topics appropriate for graduate students that would be related to a need of the Laboratory and would therefore justify support of the student with Laboratory funds. This, of course, implies a topic of interest to a professor. Thus three criteria must be met: scholarly interest to a faculty member, relevance to a Laboratory activity, and availability of a graduate student. By the end of this reporting period, several likely tasks had been identified. Conversations among faculty of all four SEAS departments and members of the research and engineering staffs of PPPL were being initiated.

DEPARTMENT CURRICULUM

In addition to the graduate education program, the Chemical Engineering Department offers a strong undergraduate curriculum to stimulate interest in fusion. A minicourse on fusion is included in Chemical Engineering 101. It is designed primarily for A.B. students to satisfy their science requirement, but it is frequently elected by entering freshman engineering students. Junior and Senior independent work in fusion is also sponsored in keeping with Princeton's tradition of undergraduate thesis work. The undergraduate course, Introduction to Fusion Power (Ch.E. 417), is suitable for both undergraduate and graduate students, and has been elected by graduate students of four different departments.

Each year Chemical Engineering 417 welcomes as auditors a few members of the professional engineering staff of the Laboratory. These people are specialists seeking a broader understanding of aspects of the Laboratory work that differ from their professional specialty. Since FY79 this arrangement

has provided a unique opportunity for students to associate with working professionals in the topic of the course. To reinforce this opportunity, a key feature of the course is a machine design project. The class is divided into two teams for a competition. The professional staff members are divided into three groups, two sets of consultants for the teams and a selection board to evaluate the final designs. Oral

presentations before the board are a fairly realistic preview of the "real world's" contract selection procedures.

Chemical Engineering courses relating to the Fusion Technology Program, the Chemical Engineering Faculty, and the graduate students in the Fusion Reactor Technology Program are given in Tables XI, XII and XIII.

**Table XI. Chemical Engineering Courses
Relating to the Fusion Technol-
ogy Program and Instructors**

Course Number	Course Title	Instructor
CHE 351,352	Junior Independent Work	Staff
CHE 451,452	Senior Independent Work	Staff
CHE 417	Introduction to Fusion Power	R.G. Mills
CHE 418	Nuclear Engineering	R.C. Axtmann
CHE 50	Fusion Reactor Technology	R.C. Axtmann R.G. Mills

Table XII. Chemical Engineering Faculty

Faculty Members	Title
Robert C. Axtmann	Professor of Chemical Engineering
Ernest F. Johnson	Professor of Chemical Engineering
Robert G. Mills	Associate Head for Academic Affairs, Engineering Department, PPPL, and Lecturer with Rank of Professor.

Table XIII. Graduate Students in The Fusion Reactor Technology Program

H.H. Tseng	
Thesis Topic:	The Practicability of Molten Fluorides in First Generation Fusion Power Reactor Blankets
Advisor:	E.F. Johnson
Status:	Ph.D. to be awarded 1984
P.C. Bertone*	
Thesis Topic:	Tritium Recovery from Li ₂ O Blanket
Advisor:	R.G. Mills and D.L. Jassby
Status:	Ph.D. expected 1984
T.M. Kasturirangan	
Thesis Topic:	Li ₂ O Slurry Blankets
Advisor:	R.C. Axtmann
Status:	Ph.D. expected 1984
J.A. Isaacson*	
Thesis Topic:	Calibrations for Neutron Flux Measurements in TFTR
Advisor:	R.G. Mills and H.W. Hendel
Status:	M.S.E. expected 1984
K.W. Goossen*	
Thesis Topic:	Undecided
Advisor:	R.G. Mills
Status:	First Year Student
J.V. Foley*	
Thesis Topic:	Undecided
Advisor:	R.G. Mills
Status:	First Year Student

*Has a Magnetic Fusion Energy Technology Fellowship.

SECTION COORDINATORS

Tokamak Fusion Test Reactor
H. Allen

Princeton Large Torus
R. Wilson

Poloidal Divertor Experiment
R. Fonck

Princeton Beta Experiment
M. Okabayashi

Spheromak
R. Ellis, Jr.

Advanced Concepts Torus-I
K.L. Wong

X-Ray Laser Studies
S. Suckewer

Theory
R. White

Tokamak Modeling
R. Hulse

Reactor Studies
D. Jassby

Spin-Polarized Fusion Program
J. Cecchi

Tokamak Fusion Core Experiment
M. Machalek

Engineering Department

Engineering Analysis Division
M. DeCamillis

Electronic and Electrical Engineering Division
F. Bennett

Mechanical Engineering Division
G. Martin

Computer Division
T. Snyder

Planning and Resource Management
A. Upperco

Quality Assurance and Reliability
H. Howard

Administrative Operations
O. Bennett
K. Haney

Graduate Education: Plasma Physics
T. Stix

Graduate Education: Fusion Reactor Technology
R. Mills

GLOSSARY OF ABBREVIATIONS, ACRONYMS, SYMBOLS

A	Amperes
ac	Alternating Current
ACT-I	Advanced Concepts Torus-I at PPPL
ADP	Automated Data Processing
ADPE	Automated Data Processing Equipment
Alcator	Family of tokamak devices being developed and built at the Massachusetts Institute of Technology
ALT	Advanced Limiter Test on TEXTOR (Jülich, West Germany)
amu	Atomic Mass Unit
ANL	Argonne National Laboratory
ASDEX	Axially Symmetric Divertor Experiment (Max-Planck Institute für Plasmaphysik, Garching, West Germany)
ATF-1	Advance Toroidal Facility-1 (a stellarator at Oak Ridge National Laboratory)
BALDUR	PPPL one-dimensional tokamak transport code
CAMAC	Computer-Automated Monitor and Control (System)
CAR	Computer-Assisted Retrieval
CAR	Cost Analysis Report
CGS	Centimeter Gram Second (a system of units)
CICADA	Central Instrumentation, Control, and Data Acquisition System
CIPREC	Conversational and Interactive Project Evaluation and Control System
COO	Chicago Operations Office
COS	Console Operating Station
CPSR	Contractor Procurement System Review
CTR	Controlled Thermonuclear Research
D-T	Deuterium-Tritium
DARM	Data Acquisition Room
DAS	Data Acquisition System
dc	Direct Current
DECAT	Drivers Energy Conservation Awareness Training
DEGAS	A PPPL computer code for studying the behavior of neutrals in plasma
DEMO	Demonstration Power Reactor
DITE	Divertor and Injection Tokamak Experiment (Culham Laboratory, United Kingdom)
DOE	Department of Energy
Doublet-III	Tokamak located at GA Technologies Inc.
EAD	Engineering Analysis Division
ECH	Electron Cyclotron Heating
ECRF	Electron Cyclotron Range of Frequencies
ECRH	Electron Cyclotron Resonance Heating
EF	Equilibrium Field
EPRI	Electric Power Research Institute
ERP	Edge Relaxation Phenomena
ESU	Emergency Services Unit
ETACS	Equipment Tracking and Control System
ETR	Engineering Test Reactor
ETS	Engineering Test Station
EZB	Exclusion Zone Boundary
FCPC	Field Coil Power Conversion
FEDC	Fusion Engineering Design Center (Oak Ridge National Laboratory)
FELIX	An experimental test facility under construction at the Argonne National Laboratory
FIDE	Fast Ion Detector Experiment
FIR	Far Infrared
FSAR	Final Safety Analysis Report
FTS	Federal Telecommunications System

FY	Fiscal Year (October 1 to September 30)
G	Gauss
GAO	General Accounting Office
GDC	Glow Discharge Cleaning
GE	General Electric Company
GHz	Gigahertz
GJ	Gigajoule
gpm	Gallons Per Minute
H	High-Confinement Mode
HAIFA	Hydrogen Alpha Interference Filter Array
HLDAS	High-Level Data Analysis System
HVAC	Heating, Ventilating, and Air Conditioning
HVE	High-Voltage Enclosures
ICH	Ion Cyclotron Heating
ICRF	Ion Cyclotron Range of Frequencies
ICRH	Ion Cyclotron Resonance Heating
INTOR	International Tokamak Reactor
I_p	Plasma Current
IPP	Initial Protective Plates
IPP	Institute für Plasmaphysik at Garching, West Germany
IR	Infrared
IRM	Information Resources Management
ISX	Impurity Study Experiment (Oak Ridge National Laboratory)
ITR	Ignition Test Reactor
JET	Joint European Torus
kA	Kiloamperes
kG	Kilogauss
kJ	Kilojoule
kV	Kilovolt
kVA	Kilovolt Ampere
L	Low-Confinement Mode
L-C	Inductor/Capacitor
LBL	Lawrence Berkeley Laboratory
LBM	Lithium Blanket Module
LCCs	Local Control Centers
LH	Lower Hybrid
LHCD	Lower Hybrid Current Drive
LHRF	Lower Hybrid Range of Frequencies
LHRH	Lower Hybrid Resonance Heating
LLNL	Lawrence Livermore National Laboratory
LO	Local Oscillator
LOB	Laboratory Office Building
MARS	Mirror Advanced Reactor Study (Lawrence Livermore National Laboratory)
Mb	Megabyte
MCP	Microchannel Plate
MED	Mechanical Engineering Division
MeV	Mega-Electron Volt
MFAC	Magnetic Fusion Advisory Committee
MG	Motor Generator
MHD	Magnetohydrodynamics
MHz	Megahertz
MIT	Massachusetts Institute of Technology
MJ	Megajoules
mm	Millimeter
msec	Millisecond
MVA	Megavolt Ampere
MW	Megawatt
n	density
NASTRAN	A structural analysis code
NB	Neutral Beam
NBI	Neutral Beam Injection
NBLs	Neutral Beamlines
NBPS	Neutral Beam Power Supply
NBTC	Neutral Beam Test Cell

NMFECC	National Magnetic Fusion Energy Computer Center
OFE	Office of Fusion Energy
OH	Ohmic Heating
ORNL	Oak Ridge National Laboratory
ORR	Operational Readiness Review
PADS	Procurement Automated Data Processing System
PBX	Princeton Beta Experiment
pC	Pico Coulomb
PDC	Pulse Discharge Cleaning
PDR	Preliminary Design Review
PDX	Poloidal Divertor Experiment
PEST	Princeton Equilibrium, Stability, and Transport Code
PLT	Princeton Large Torus
PM&E	Plant Maintenance and Engineering
PMS	Performance Measurement System
PP&L	Pennsylvania Power and Light
PPPL	Princeton Plasma Physics Laboratory
QA	Quality Assurance
QA/R	Quality Assurance and Reliability
RBT	Resonance Broadening Theory
rf	Radio Frequency
RFP	Request for Proposal
RFP	Reversed-Field Pinch
RFTE	Radio-Frequency Test Facility
RG	Residual Gas Analyzer
rms	Root Mean Square
rpm	Revolutions Per Minute
SAD	Safety Assessment Document
SCR	Silicon Controlled Rectifier
SEAS	School of Engineering and Applied Science
sec	Second
SF	Shaping Field, equivalent to EF
SPARK	A highly automated, general geometry computer code that calculates transient eddy currents and the resulting fields
SPICE	A general purpose circuit simulation code
SPRED	Survey, Power Resolution, Extended Domain Code
τ_E	Confinement time for energy
T	Temperature
T_e	Electron Temperature
T_i	Ion Temperature
TAC	Technical Advisory Committee
TBR	Tritium Breeding Ratio
TEXTOR	Tokamak Experiment for Technologically Oriented Research (Jülich, West Germany)
TF	Toroidal Field
TFCD	Tokamak Fusion Core Device
TFCX	Tokamak Fusion Core Experiment
TFM	TFTR Flexibility Modification
TFTR	Tokamak Fusion Test Reactor
TLD	Thermoluminescent Dosimeters
TMPs	Turbo Molecular Pumps
TOS	Terminal Operating Station
TRANSP	Time-dependent transport analysis code
TSCALE	A computer code that scales plasma equilibrium parameters over a wide range of major radius and aspect ratio
TVPS	Torus Vacuum Pumping System
TVTS	TV Thomson Scattering
USC	User Service Center
UV	Ultraviolet
VUV	Vacuum Ultraviolet
W	Watt
WKB	Wentzel, Kramers, Brillouin. A method for analyzing wave behavior if propagation characteristics depend on position
XUV	Extreme Ultraviolet
Zr-Al	Zirconium-Aluminum