MASTER

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Preface

During the first part of FY85, the Tokamak Fusion Test Reactor (TFTR) achieved operation at full plasma current (2.5 MA) and magnetic field strength (5.2 T). In the ohmic-heating regime, high-density plasmas were fueled by pellet injection, reaching n_{Te} values up to $7 \times 10^{13} \text{ cm}^{-3}$ sec. In the neutral-beam-heating regime, 6 MW of beam power was used to produce ion temperatures up to 9 keV. Many significant new physics results were obtained, particularly in regard to the parameter dependence and radial variation of heat transport in large auxiliary-heated plasmas. The latter part of FY85 was devoted to major TFTR improvements: installation of the remaining two neutral beamlines and a large-area graphite-tile limiter, capable of sustaining the full 27-MW heating-power level.

The Princeton Large Torus (PLT) made several important advances in the development of radio-frequency techniques. In the ion-cyclotron range of frequencies (ICRF), plasma temperatures up to 5 keV were reached with good efficiency by means of minority-ion heating, and a promising new ion-Bernstein-wave heating technique was demonstrated. Lower-hybrid-frequency current drive was found to stabilize the sawtooth instability mode while raising the central electron temperature without reduction in energy confinement time.

The Princeton Beta Experiment (PBX) carried out detailed investigations of stability in high-beta L-mode and H-mode plasmas for comparison with MHD theory, and introduced pellet injection to enhance profile control. Plans for a major improvement of the PBX device (PBX-M) were completed, and the modification is scheduled to begin in early FY86.

The S-1 Spheromak project investigated

mechanisms for nonlinear relaxation to the Taylor minimum-energy state, and developed a new technique for amplifying the current and internal magnetic flux of the plasma toroid. On this basis, a program of S-1 device modifications was initiated in the last quarter of FY85. In the Advanced Concepts Torus (ACT-I) experiments, fast-wave current drive was observed for the first time, and a new program was undertaken to study tokamak current-drive techniques based on helicity injection.

The Soft X-Ray Laser Experiment produced the first demonstration of gain-enhancement by means of a soft-X-ray mirror. A picosecond KrF* laser is being installed to extend X-ray laser experiments toward shorter wavelengths. A new program of surface-plasma-interaction studies has been undertaken, aimed at explaining the "spacecraft glow" phenomenon of orbiting vehicles.

Theoretical studies in the area of MHD equilibrium and stability have played a major role in the planning of the next steps in the PBX and S-1 programs. Promising advances have been made in the theoretical explanation of tokamak transport phenomena, such as anomalous ion heat conduction and the escape of energetic-ion components. Theoretical modeling continues to give successful predictions for the radio-frequency heating and current-drive experiments.

Design studies for a next step beyond TFTR are focusing on a compact tokamak ignition device. During the first part of FY86, the Princeton Plasma Physics Laboratory will lead a national design team in the preparation of a preliminary conceptual design report for consideration by the Department of Energy.

PRINCIPAL PARAMETERS ACHIEVED IN EXPERIMENTAL DEVICES **(Fiscal Year 1985)**

Parameters	Tokamak Facilities			Alternate Concept Facilities	
	TFTR	PBX	PLT	S-1	ACT-I
R (m)	2.48	1.45	1.32	0.40	0.59
a (m)	0.85	0.45	0.42	0.25	0.1
I _p (MA)	2.5	0.6	0.7	0.35	—
B _t (T)	5.2	0.9	3.4	0.4	0.57
τ_{AUX} (sec)	0.5	0.3	0.3	—	dc
P _{AUX} (MW)					
NB	6.3, (80 keV)	6, (50 keV)	—	—	—
ICRF	—	—	5.0, (30 MHz)	—	0.002
LH	—	—	0.8, (2.45 GHz)	—	—
ECRH	—	—	0.05, (60 GHz)	—	0.002
n(0) (cm ⁻³)*	1.7×10^{14}	1.5×10^{14}	0.8×10^{14}	3×10^{14}	10^{13}
T _i (0) (keV)*	9.0	4.5	5.0	0.1	0.04
τ_E (msec)*	440	50	40	0.25	0.2

*These highest values of n, T, and τ were not achieved simultaneously.

TOKAMAK FUSION TEST REACTOR

SUMMARY

Fiscal year 1985 was an important year for the Tokamak Fusion Test Reactor (TFTR) in terms both of significant experimental results and of the extension of machine capability to new levels. Figure 1 shows the TFTR Research Plan for calendar years 1983 through 1991. As planned, the period from 1 October 1984 to 15 April 1985 was devoted to an intensive series of experimental runs with the remainder of FY85 used for major additions to the machine hardware; principally, the installation of the last two neutral beamlines and the internal armor for high-power operations.

The extraordinarily productive experimental runs included detailed studies of ohmically heated plasmas, adiabatic compression, and pellet-fueled plasmas heated with up to 6 MW of injected neutral beams. Roughly 2,500 high-power shots were made and plasma discharges were obtained for approximately 80% of them by the end of the run period. Toward the end of the run period, 2.5-MA plasmas were achieved at 5.2-T toroidal field, the full original design values for TFTR.

Summary papers covering the results were presented at the American Nuclear Society Meeting in March, 1985 and at the European Physical Society Meeting in September, 1985. Figure 2 summarizes, in a Hugill diagram, the operating ranges for the experi-

ments with large plasmas. The TFTR results extend from the high-density regime, where $n_e(0) \tau_E(a) \sim 7 \times 10^{13} \text{ cm}^{-3} \text{ sec}$ was obtained in ohmically heated plasmas, to a low-density regime, where $T_e(0) \sim 9 \text{ keV}$ was obtained with approximately 5 MW of injected neutral-beam power. A major result of this run period was that the observed scaling dependence of τ_E is in agreement with the low-mode scaling obtained on smaller tokamaks. In addition, new insights into tokamak physics (e.g., profile consistency) were gained on TFTR, especially during neutral-beam injection into pellet-injected high-density plasmas. In these cases, with surface heating, the product $n_e(0) \tau_E(a/2)$ rose to $\sim 8 \times 10^{13} \text{ cm}^{-3} \text{ sec}$ transiently.

The present status of TFTR, in terms of the progress toward reactor conditions, is shown in the Lawson diagram of Fig. 3. Further major milestones in TFTR experimental research (subject, of course, to funding limitations) are deuterium-deuterium $Q \sim 1$ in April 1987 and deuterium-tritium $Q \sim 1$ in early 1989, as indicated in Fig. 1.

In mid-April 1985, experimental operations were suspended to allow major additions to the machine. Over the next five months, two more neutral beamlines were installed to bring the total beam-power capability to 27 MW, of which 20 MW is D^0 at 120 keV. A view of the four-beamline installation is shown (from above) in Fig. 4. By the close of the fiscal year, all four beamlines

Figure 1. The TFTR Research Plan for calendar years 1983 through 1991.

Figure 2. Hugill diagram of operating ranges for experiments with large plasmas.

Figure 3. Lawson diagram of the present status of tokamak experiments in terms of progress towards reactor conditions. The TFTR is able to operate along the entire "frontline."

Figure 4. Top view of neutral-beam four-beamline installation. (85E1396)

were under vacuum, and commissioning of the power supply systems for the 11 installed ion sources was well under way.

In parallel with the neutral-beam work, the high-power bumper-limiter assembly was installed in the vacuum vessel. This assembly of graphite tiles, backed by water-cooled inconel plates, covers the small-major-radius inner wall of the vacuum vessel, extending 60° above and below the horizontal center line. Additional graphite protective plates, also water cooled, were installed on the large-major-radius interior of the vessel to handle shine-through from the two added beamlines. The remaining 28 zirconium-aluminum (ZrAl) surface-pumping panels were also mounted, complementing the eight prototype panels that had been installed the previous year. All three of these additions to the vessel interior are shown in Fig. 5. The bumper-limiter assembly is to the right, the protective plate additions are on the left, and the surface-pumping units are located symmetrically at the top.

Figure 5. The TFTR bumper-limiter assembly (to the right), protective plate additions (to the left), and surface-pumping units (at the top). (85E1057)

Extensive upgrading of many diagnostics and some diagnostic additions also took place during this period. Especially important for spatial and temporal determinations of the ion temperatures is the addition of a charge-exchange recombination spectrometer (CHERS) and an 80-keV, 22-A, modulated diagnostic neutral beam (DNB). Both are to become operational in early 1986. Figure 6 shows, on the left, the diagnostic neutral-beam installation. To the right is the repeating pellet injector built by the Oak Ridge National Laboratory (ORNL). The two substantial columns with the heavy cross member at the top are part of the multichannel far-infrared interferometer used for density measurements; five of the ten possible vertical chords became fully operational during the October-April run period.

Finally, a major upgrade of the Test Cell shielding was accomplished during the shutdown period. One-foot-thick and 25-ft-high concrete panels were installed on all inside walls and new entrance

Figure 6. The TFTR diagnostic neutral beam (on the left). (85E1507)

labyrinths were built. In addition, a pair of hinged concrete doors was added to supplement the shielding at the large retractable equipment door in the southeast corner of the Test Cell.

During this year, there has been a very marked increase in the capability of the TFTR computer system. New fast digitizers and block transfer modules greatly enhanced the data taking capability, while the addition of VAX computers provided much greater analysis power. By the end of the run period, 10-megabyte words of data were being initially processed within the eight minutes between discharges to provide waveforms in the control room, while a full transport analysis of a shot was available within twenty minutes.

Safety and environmental matters continued to require a significant fraction of TFTR engineering time in FY85 and have continued to be important considerations in the planning, testing, and operating activities of the TFTR Project.

Expanded discussions on all of the topics relating to the experimental run period and the subsequent installation period are to be found in the following detailed sections, complete with references.

EXPERIMENTAL RESEARCH

Introduction

The TFTR experimental research activities in FY85 focused on initial experiments with neutral-beam (NB) heating at modest injection power. Two neutral beam-lines, injecting a maximum of 6 MW of deuterium, were used for the two-neutral-beam run period that extended from June 5, 1984 to April 13, 1985.

The experimental effort was organized into Task Forces that carried out specific experiments on TFTR. The Task Forces for the two-neutral-beam run period were:

- Conditioning

- Plasma Optimization
- Ohmic Scaling
- Neutral-Beam Scaling
- Adiabatic Compression
- Energetic-Ion Plasma
- Pellet Injection

The following sections describe the results of these Task Forces. Summary papers were presented at the American Nuclear Society Meeting in March, 1985 and at the European Physical Society Meeting in September, 1985. The TFTR results extend from the high-density regime, where $n_e(0) \tau_E(a) \sim 7 \times 10^{13} \text{ cm}^{-3} \text{ sec}$ was obtained in ohmically heated plasmas, to a low-density regime where $T_e(0) \sim 9 \text{ keV}$ was obtained with approximately 5 MW of injection power. A major result of this run period was the extension of the low-mode scaling obtained on smaller tokamaks to larger-size, higher-current tokamak plasmas. In these cases, with surface heating, the central $n_p(0) \tau_E(a/2)$ transiently rose to $\sim 8 \times 10^{13} \text{ cm}^{-3} \text{ sec}$.

The Oak Ridge National Laboratory (ORNL) played a key role in the success of the TFTR experiments through the ORNL/TFTR collaboration, which involved the on-site participation of about 16 ORNL scientists (12 full-time equivalents) and the ORNL/TFTR pellet injector project.

Conditioning

Impurity Control, Limiters, and Getters

During this past year, a wide variety of impurity control techniques were used on TFTR to condition the limiter and to achieve clean plasmas. These techniques enabled achievement of plasmas with Z_{eff} as low as 1.3. Good power accountability was achieved by combining measurements of the radiated power from the bolometers with infrared measurements of the limiter temperature. At the beginning of this run period, a "fiducial plasma" was established in order to monitor the cleanliness of the machine during the run. At the end of the experimental run period, samples of the limiter and wall material were taken to determine the plasma modification of these surfaces.

A combination of glow-discharge cleaning (GDC), low-pressure pulse-discharge cleaning (PDC), high-pressure Taylor-discharge cleaning (TDC), and baking was used to clean the vacuum vessel and the limiter. Each of the three types of discharge cleaning was done together with baking (usually at 150°C). Typically, 50 to 100 hours of GDC is done after a major opening and for 24 hours after a minor opening. Both GDC and TDC are effective at cleaning the walls of the vessel. Pulse-discharge cleaning is very effective at cleaning the limiter and is usually the last thing done before plasma operation. Typically, 30,000 to 100,000 pulses of discharge cleaning are done to clean the machine after a major opening. The behavior

Figure 7. Behavior of residual-gas partial pressure in response to discharge cleaning.

of several residual gases, in response to discharge cleaning, is shown in Fig. 7.

The fiducial plasmas used to monitor the cleanliness of the plasma during the run period had the parameters $I_p = 1.4$ MA, $\bar{n}_e L = 4.0 \times 10^{19} \text{ m}^{-2}$ (where L is the plasma minor diameter). The radiated power from the fiducial plasmas¹ during the run period is shown in Fig. 8. The radiated power decreased substantially during the course of the run period, showing that uninterrupted running at high power also helps to clean the limiter. The increase in radiated power near the end of the run period was due to pushing the machine to high current and high density with pellet injection, both of which resulted in a higher frequency of disruptions that contaminated the limiter. The increases in radiated power early in the run were due to minor openings.

The titanium-carbide (TiC) coating on the movable limiter tiles was removed² before this run period began. The level of titanium in low-density discharges decreased by about a factor of 50 after the TiC was removed. The heat loads to the limiter were measured

Figure 8. Variation of radiated power from fiducial plasmas during the last run period.

using an infrared camera. Up to 50% of the input power was observed to flow to the limiter. The maximum total energy deposited on the limiter was 7 MJ. Surface temperatures up to 2400°C were observed at the end of neutral-beam injection (6 MW). If the power to the limiter is added to the radiated power, as measured by the bolometer array, the sum is equal to the power input to the plasma (ohmic and neutral beam). The energy deposited on the inner wall during a disruption was up to 400 J cm⁻². The resulting severe melting of the surface was violent enough to throw droplets of inconel onto the surface of the limiter tiles several meters away. This was an important source of impurities on the limiter.

The surface of the limiter tiles was examined^{3,4} after the run period was over. In the high heat flux area, a 500-Å thick layer of iron, nickel, chromium, carbon, and oxygen was found on the graphite. This is about one-fourth of the thickness of a similar layer found on the TiC-coated tiles after the previous run period. This could be due to the much higher heat fluxes during this run period, which produced much higher surface temperatures. The lower heat flux areas showed surface coatings that were similar to those observed on the TiC-coated tiles (2500 Å).

An experiment was performed⁵ to determine the difference between extra pumping speed (the prototype ZrAl pumping panels⁶) and coverage of the surface of the vessel by evaporation of chromium. An average of about 100 Å of chromium was evaporated on about 70% of the wall, but not on the limiter. The evaporation of chromium approximately doubled the overall pumping speed. The oxygen in the discharge decreased by more than ten times. The density limit increased by about 20% and at the higher densities Z_{eff} was 1.4 (the best values obtained). The effect of the gettering lasted for several days. These results indicate that coverage of oxygen on the surface may reduce the oxygen influx that typically limits the density.

Plasma Optimization

In the last year, a major achievement in TFTR operation was reaching the original design goals⁷ in

toroidal magnetic field (5.2 T at a major radius of 2.48 m) and plasma current (2.5 MA). These goals were reached through a combination of factors. First, additional power supplies were commissioned and the magnetic-field coils for the machine were qualified to higher levels. Second, the Mode-B configuration of the poloidal-field system was used, which provides increased coupling from the ohmic-heating transformer. Third, operational techniques were developed to initiate the plasma reliably with high-ohmic-heating transformer precharge flux.

As the ohmic-heating transformer precharge flux was increased to achieve higher plasma current, difficulties developed in initiating the discharge. With the available interrupter circuit, plasma currents up to 1.3 MA were being induced in the first 0.2 sec in full-bore ($R_p = 2.58$ m, $a = 0.82$ m) plasmas. Such high rates of rise of the current were usually accompanied by signs of instability, and disruptions during the start-up were unacceptably frequent. Measurements of the electron temperature and transport simulation of the start-up phase showed that hollow-temperature and hollow-current profiles existed in these discharges for up to 1 sec, due to the slow current diffusion in the large plasmas. In order to overcome these problems, the technique of growing the plasma⁸ in minor radius from the outer limiter blade was adopted. Due to the low flat-top value of the aperture safety factor q_a (as low as 2.7), q_a could not be kept constant during the plasma-growth phase, but was instead brought rapidly to a value of 3.7 and then slowly reduced to the final value. This growing technique was successful in reducing the instabilities and improving the reliability of the start-up. In addition, it was possible to ramp-up the current more rapidly to its flat-top level in growing plasmas that reduced the resistive flux consumption of the discharges. Simulation of the growing plasmas showed that hollow current profiles persisted for only the first 0.3–0.4 sec of these discharges. By growing the plasma during start-up and also shrinking the plasma during the termination phase, the energy deposition on the limiter contract area was also reduced, allowing more rapid discharge repetition. Figure 9 compares the evolution of the main discharge parameters for constant major-radius start-up and grown plasmas.

As the run period progressed, the density limit, defined by plasma disruptions, for gas-fueled plasmas increased as a result of improving limiter and wall conditions, the application of chromium gettering, and increasing the toroidal field. Near the density limit, MARFE phenomena, regions of enhanced edge radiation localized poloidally on the inner-major-radius side of the plasma, were often observed. The MARFES showed characteristic signatures on the bolometer arrays (see Fig. 10), the density interferometers, and in extreme cases, on the temperature profile and the loop voltage.

During the decay phase of the plasma current and toroidal field at the end of a discharge, when the gas feed was terminated, values of $\bar{n}_e R_p / B_T$ exceeding the normal flat-top limit were frequently observed, due to the long density-decay time in TFTR. This finding

Figure 9. Comparison of discharge parameters for constant major-radius start-up (dashed curve) and grown plasmas (solid curve).

Figure 10. Localized edge radiation measured by a bolometer array.

suggested that the deuterium-gas fueling process itself may have been partly responsible for the density limit. This hypothesis was tested by fueling discharges with helium gas and with solid deuterium pellets. With both these fueling techniques, the density limit was raised substantially. Maximum line-averaged densities of $7.5 \times 10^{19} \text{ m}^{-3}$ for helium fueling and $9.8 \times 10^{19} \text{ m}^{-3}$ for pellet fueling were obtained. Figure 2 shows a summary of the operating diagram (Hugill diagram) for large plasmas in TFTR during the run period.

Ohmic Scaling

During the past year, ohmically heated plasmas were studied near the full operating parameters ($I_p \leq 2.5 \text{ MA}$, $B_t \leq 5.2 \text{ T}$) of TFTR. After careful machine conditioning and long-term high-power operation, the effective ion charge Z_{eff} reached 1.4 for deuterium plasmas. Thus, the relative deuterium-ion content was about 0.9, the radiated power fraction was as low as 0.3 and the density limit was $\bar{n}_e \sim 4.5 \times 10^{19} \text{ m}^{-3}$. In the previous year, systematic density scans at different plasma currents ($I_p \leq 1.4 \text{ MA}$) and toroidal field ($B_t \leq 2.8 \text{ T}$) were utilized to determine the global trend of total energy confinement in TFTR. The energy confinement time⁹ was found to follow the scaling $\tau_E \propto \bar{n}_e q$. These experiments were repeated this year with higher plasma current and magnetic field. Figure 11(a) shows the deuterium density scans at $I_p = 1.8 \text{ MA}$ and 2.2 MA have the same q and the same slope. However, the 2.2-MA scan shows a saturation of confinement time near its density limit. These results indicate that $\tau_E \propto \bar{n}_e q^{0.6-1.0}$. Unfortunately, there are not enough data, at this time, to narrow down the range of the q exponent. Confinement times as long as 0.45 sec were observed.

To further study plasma confinement at high density, helium plasmas were utilized. The Z_{eff} reached 2.05 and the density scan went to $\bar{n}_e \sim 7.5 \times 10^{19} \text{ m}^{-3}$. Figure 11(a) shows a clear saturation of confinement time at the same value as in the 2.2-MA deuterium plasmas. In the saturated regime, $\tau_E \propto \bar{n}_e^{0.6}$ was observed, as in plasmas with auxiliary heating. The temperature and density profiles remain unchanged during these density scans. They are also independent of the ion species, as long as q is the same. The temperature results tend to support the principle of profile consistency.

Figure 11(b) shows the overlay of the experimental data for deuterium plasmas in the last two run periods on TFTR. They seem to obey the same scaling law until saturation of confinement time appears near the density limit. It is important to determine whether the electrons¹⁰ or ions are responsible for the saturation. Unfortunately, measurements of the electron and ion temperatures have not been accurate enough for such a determination. The electron-heat diffusivity has been studied from the heat-pulse propagation during sawtooth activities.¹¹ The result usually exceeds that determined from plasma-power-balance considerations by factors ranging from 2 to 10. Resolution of this discrepancy could shed light on the anomalous transport mechanisms in large tokamaks.

Figure 11. Variation of energy confinement time with (a) electron density and (b) $\bar{n}_e R^2 a q$ for TFTR ohmic discharges.

Neutral-Beam Scaling

During the last operating period, the deuterium neutral-beam power from the two co-beamlines¹² was increased up to 6.3 MW, with beam energies up to 90 keV. Tokamak operation up to design levels of the toroidal field ($B_t = 5.2 \text{ T}$) and plasma current ($I_p = 2.5 \text{ MA}$), together with the operation of a repeating pellet injector (RPI) provided an expanded operating range that enabled not only the evaluation of the heating efficiency and plasma confinement, but also the study of the dependence of energy confinement on the heating power profile.¹³⁻¹⁵

Parametric dependencies of heating efficiency and plasma confinement were obtained through systematic single-parameter scans over wide parameter ranges. In one such experiment, the beam-heating power was systematically varied while other parameters were held constant ($I_p = 2.2 \text{ MA}$, $B_t = 4.7 \text{ T}$, $R = 2.58 \text{ m}$, and $a = 0.82 \text{ m}$, corresponding to $q_a = 2.8$). The total D⁰ beam power (P_{in}) was varied to a maximum of 5.6 MW from two co-tangential beamlines, each with three sources operating between 70 and 90 keV (78 keV average), with a pulse duration of 0.5 sec. With injection, $\bar{n}_e$ increased substantially (by about 50% at the highest power),

consistent with the direct beam-fueling rate. In order to obtain a constant density near the end of the beam pulse ($\bar{n}_e \approx 4.6 \times 10^{19} \text{ m}^{-3}$ at $t = 3.25$ sec), the preinjection density was adjusted. The surface voltage (V_{sur}) dropped from 1.1 V to 0.7 V during injection. Although the total radiative power (P_{rad}) increased with injection, the fraction $P_{\text{rad}}/P_{\text{oh}}$ was reduced to about 20% from about 40%, typical with ohmic heating alone. Impurity concentrations generally increased with increasing power. The visible bremsstrahlung measurement (with a temperature-dependent Gaunt factor) indicated that Z_{eff} increased from 2 to 3, in good agreement with the pulse height analyzer (PHA) and the conductivity measurements using the neoclassical correction.

The variation of the central electron and central ion temperatures, as a function of absorbed power, is shown in Fig. 12 for the power scan data set. Central

Figure 12. Variation of central electron and ion temperatures as a function of absorbed beam power. The central electron temperature from Thomson scattering is shown together with the amplitude of sawtooth oscillations of $T_e(0)$ from electron cyclotron emission measurements (indicated by the bars). Variation of the global energy confinement time is shown by open bars.

electron temperatures, measured from Thomson scattering at $t = 3.25$ sec, are given by the solid triangles, while the bars indicate the variation of $T_e(0)$ during sawtooths (as measured from electron cyclotron emission) around the Thomson scattering time. The central ion temperature, shown by solid circles, was determined by the Doppler broadening of the TiXXI K_α line. The solid line corresponds to a central ion heating efficiency of $\Delta T_i(0) \bar{n}_e / P_{\text{abs}} = 1.5 \times 10^{19} \text{ keV m}^{-3} \text{ MW}^{-1}$. Plasma-stored energy (W_p), measured both kinetically and magnetically, was found to increase linearly with total heating power ($P_{\text{heat}} = P_{\text{abs}} + P_{\text{oh}} - P_{\text{cx}}$), but the rate of increase in stored energy, dW_p/dP_{heat} , is less than that expected. Nearly 100% ($\pm 15\%$) power accountability has been demonstrated in various discharges by simultaneous measurements of radiative and charge-exchange losses with bolometry and limiter power with infrared photometry (Fig. 13). Thus, the power transfer from the beams to the bulk plasma cannot be seriously affected by either beam-orbit losses or beam charge-exchange that

Figure 13. The radiative and limiter power losses have been measured simultaneously using bolometry and infrared photometry. The plot shows the accounted power loss as a function of the total input power. The line drawn represents 100% power accountability. The data show that over a wide range of ohmic and beam-heating conditions, a total power accountability (to within $\pm 15\%$) has been demonstrated. Thus, the observed confinement deterioration is not due to problems with beam-power delivery.

would not be measured by the perpendicular bolometer array. Tangential charge-exchange spectra have also been examined to investigate possible enhanced beam-ion losses. The spectra are reasonably consistent with classical expectations in D^0 injected discharges. These observations imply that the beam power is delivered to the plasma, and, thus, the less-than-expected increase in stored energy is due to confinement degradation with the auxiliary heating. The global energy confinement time, $\tau_E(a) = (W_p/P_{\text{heat}})$, fits equally well to either an off-set linear form $(\alpha + (\beta/P_{\text{heat}}))$ with an "incremental" confinement time $\alpha = 0.10$ sec, or a power law form $P_{\text{heat}}^{-\gamma}$ with $\gamma \approx 0.5$.

At constant beam power, the global energy confinement time was observed to be insensitive to the density, even with pellet injection. Furthermore, $\tau_E(a)$ increases approximately linearly with I_p (Fig. 14), as found in smaller tokamaks with injection. At the highest plasma current, $\tau_E(a)$ slightly exceeds the Goldston L-mode scaling, but this separation is within the uncertainties of the τ_E analysis and the scaling relation. The strong plasma current dependence is encouraging. At $I_p = 2.2$ MA, a $\tau_E(a)$ value of 0.22 sec was achieved at $\bar{n}_e = 4.7 \times 10^{19} \text{ m}^{-3}$ with $T_i(0) = 4.8$ keV.

In an attempt to understand the mechanisms responsible for the confinement deterioration, transport studies were carried out using the time-independent systems for nuclear auxiliary power (SNAP) code for a wide survey of experimental results and the time-dependent transport analysis (TRANSP) code for detailed studies of selected discharges. These studies were based on ion-power balance with a multiplier of the Chang-Hinton neoclassical thermal conduction adjusted to match the measured central

Figure 14. Dependence of the global energy confinement on plasma current.

ion temperature. Although the difference between $T_e(0)$ and $T_i(0)$ was not known well enough to determine precisely the multiplier for the neoclassical conductivity, a value of three was typically adequate to reproduce the experimental $T_i(0)$ and plasma-stored energy. This model then indicated that ion energy confinement time exceeds electron energy confinement time with a substantial margin for discharges in the standard (i.e., high-current, high-density) neutral-beam-heating regime. In the power scan, the electron thermal diffusivity (χ_e) in the confinement region ($r/a = 0.6-0.8$) increased with beam power, as expected from the behavior of global energy confinement. However, in the core region ($r/a \leq 0.5$) the χ_e value remained level or decreased with increasing beam power, indicating that transport in the core region may be different from that in the outer region.

It is interesting to compare the electron-temperature profiles under different heating conditions. Using Thomson scattering data, Fig. 15, shows electron-

Figure 15. Comparison of electron-temperature profiles from Thomson scattering for a beam-heated, pellet-fueled discharge, and an ohmic-only plasma with the same limiter q_a and sawtooth phase.

temperature profiles for a beam-heated, pellet-fueled discharge and an ohmic-heating-only discharge, both cases having the same limiter q_a and sawtooth phase. The two profiles are remarkably similar for such disparate heating conditions. Using the sawtooth-averaged $T_e(r)$ from the electron cyclotron emission (ECE) measurement, the ratio of the volume-averaged electron temperature ($\langle T_e \rangle$) to the central electron temperature $T_e(0)$ was found to be a function of the inverse of the limiter safety factor ($1/q_a$) over a wide range of experimental conditions. The $q = 1$ radius (as determined by the soft-X-ray imaging system) exhibits a similar dependence. That both $\langle T_e \rangle/T_e(0)$ and $r(q = 1)/a$ are determined by $1/q_a$ over a wide range of conditions, implies that there are natural profile shapes for $T_e(r)$ and the plasma current density $j(r)$, associated with the limiter safety factor. The "profile consistency" has been noted previously in various tokamaks, and recently the constraints on current-density-profile shape imposed by the resistive kink stability requirements and its ramifications have been examined.¹⁵

One interesting consequence of the profile consistency is favorable central confinement relative to global confinement for noncentral heating profiles. This was found first by a comparison of D^0 and H^0 -injection results. Despite the shallow penetration of D^0 injection, $\tau_E(a)$ values are as large as those with more penetrating H^0 injection, indicating that the core confinement is substantially greater with D^0 injection. The D^0 injection into high-density, pellet-fueled plasmas demonstrated the same phenomenon in even more striking form, as discussed later. Similar results have been obtained in neutral-beam and electron-cyclotron-heating (ECH) experiments in other devices. In an attempt to synthesize these observations, Fig. 16 plots the fraction (F_w) of the plasma-stored energy within $r = a/3$ as a function of the fraction (F_p) of the heating power deposited within $r = a/3$. In ohmic-heated discharges, F_w increases as F_p is raised by increasing q_a . In beam-heated discharges, a change in F_p by a factor of 5 still leads to a range of F_w as narrow

Figure 16. Fractional total stored energy within $r = a/3$ versus fractional heating power deposited within $r = a/3$. The shaded areas are the areas occupied by a large number (~ 200) of ohmically heated discharges.

as the ohmic case, and F_w is a weak function ($F_w \propto q_a^{1/3}$) of q_a , independent of F_p . Since $F_w/F_p = \tau_E(a/3)/\tau_E(a)$, this indicates that the core confinement with poorly penetrating D^0 beams (in particular with pellet-fueled, beam-heated plasmas) is substantially greater than the global energy confinement time. In fact, the central energy confinement in beam-heated discharges, increases roughly linearly with density, as in low-density ohmic discharges, because F_p is inversely proportional to $\bar{n}_e$. Within the presently available data, $\chi_e(a/3)$ was found to be not much different from the International Tokamak Reactor (INTOR) type ($\chi_e = 5 \times 10^{19}/n_e$) based on ohmic-heated discharges. However, this conclusion should be taken with care, since it is not clear whether the improvement in the core confinement is due to heating-profile effects (e.g., "edge" heating by D^0 beams) or due to some property of χ_e .

The above observations point the way to the optimization of central confinement parameters in future experiments. A fusion merit factor, $n_0 \tau_0 T_0$, for the plasma core can be expressed as $\tau_E^2(a) P_{\text{heat}}(a) F_p^2/F_p$, using the shape factors. Since $\tau_E(a) \propto P_{\text{heat}}^{-0.5}$ and $F_w \propto q^{1/3} \propto I_p^{-1/3}$, as discussed above, the parameter $n_0 \tau_0 T_0$ is proportional to either $I_p^{3/5}/F_p$ or $I_p^{3/5} \bar{n}_e$. Indeed, the TFTR data fit well to these scalings. This indicates that, in order to improve the central confinement parameters, it is important to operate at high current and high density (with pellet injection), as well as to optimize the heating profile. Future neutral-beam experiments in TFTR will explore optimization in these directions.

Adiabatic Compression

The Tokamak Fusion Test Reactor (TFTR) Project was initiated to study tokamak physics near D-T (deuterium-tritium) break-even conditions ($Q = P_{\text{fusion}}/P_{\text{heat}} \approx 1$) in a two-component plasma, because the $n_0 \tau_0$ requirement for breakeven was considerably less stringent than the conventional Lawson criterion. The practical implementation of the two-component approach is through neutral-beam injection. Calculations indicate that the optimum Q is expected to occur with injection energy in the range of 150 keV to 300 keV. Since the existing neutral beams can operate only up to 120 keV, it is desirable to raise the beam energy by other means. This was recently achieved by compression.¹⁷

The experiment was performed with the following plasma parameters before compression: plasma major radius $R = 3.0$ m, minor radius $a = 0.57$ m, plasma current $I_p = 450$ kA, toroidal magnetic field $B_t = 3.3$ T at $R = 3.0$ m, central electron temperature $T_e(0) \sim 3.3$ keV, central deuterium-ion temperature $T_i(0) \sim 3.8$ keV, and line-integrated electron density $\bar{n}_e L \sim 1.5 \times 10^{19} \text{ m}^{-2}$. Deuterium neutral beams with 2.1-MW beam power and 82-keV beam energy were injected parallel to the toroidal plasma current from $t = 2.3$ to 2.5 sec. At $t = 2.5$ sec, the plasma major radius was compressed to 2.17 m by raising the vertical magnetic field.

Two charge-exchange neutral-particle analyzers were used to measure the ion-energy spectra before and after compression. One analyzer was aimed approximately along the postcompression magnetic axis, while the second analyzer was aimed for tangency at $R = 0.52$ m. The change in the ion-energy spectra due to compression is depicted in Fig. 17.

Figure 17. Comparison of charge-exchange spectra with simulation by Fokker-Planck code (dashed line). (a) Charge-exchange analyzer viewing approximately tangential to the toroidal field at $R = 2.19$ m. (b) Charge-exchange analyzer viewing at $R = 0.52$ m.

Before compression, the ion-energy distribution function showed a cutoff near the injection energy (82 keV). This cutoff energy was raised to 150 keV immediately after compression. This was expected for the compression ratio $C = 1.38$, since the energy of particles moving along magnetic field lines increases by a factor of C^2 . In order to interpret the data quantitatively, a bounce-averaged Fokker-Planck code was used to calculate the charge-exchange spectra. Figure 17 shows that the shapes of the predicted spectra are in good agreement with experimental data, providing further evidence that the energy gained by fast ions during compression is consistent with classical expectations. After compression, $dR/dt = 0$, and the decay of the fast ions is also observed to behave classically.

The fusion neutron yield was observed to increase during compression, because of the density rise and beam-ion acceleration. The measured neutron yield is compared with that calculated from the Fokker-Planck code in Fig. 18(a). The dotted line represents the

Figure 18. Fusion product measurements. (a) Neutron yield from $D(d,n)^3\text{He}$ reaction. (b) Proton count rate from $^3\text{He}(d,p)\alpha$ reaction. The dashed lines indicate the Fokker-Planck code simulations, including the detector efficiency.

calculated neutron yield rescaled to fit the experimental data, which is about half the value expected if the $Z = 1$ plasma ions are assumed to be 100% deuterium. However, the fractional increase due to compression and the decay time due to Coulomb relaxation are in good agreement with the experiment. With 4 MW of neutral-beam power, a peak neutron yield of $6 \times 10^{14} \text{ sec}^{-1}$ was observed, which is the highest value achieved in TFTR with two neutral beamlines. Since the $^3\text{He}(d,p)\alpha$ cross section is more sensitive to the energetic deuterons, a more dramatic increase in this reaction rate¹⁸ was observed, as shown in Fig. 18(b).

The co-injected neutral beams in this experiment caused the toroidal plasma to rotate about its major axis. The central rotation velocity $V_\phi(0)$ was measured by the Doppler shift of the TiXXI K_α line.¹⁹ The central rotation velocity was observed to rise during compression. Thomson scattering data indicate that although the central electron temperature does not follow the adiabatic compression law,²⁰ the total electron energy content seems to be nearly adiabatic. During compression, magnetohydrodynamic (MHD) activity was observed by Mirnov coils located near the vacuum

vessel. The poloidal mode number m correlates with the effective safety factor q at the limiter, rather than q at the "plasma surface." The effects of this MHD activity on energy transport will be investigated in future experiments.

Energetic-Ion Plasmas

An energetic-ion mode was produced by the injection of $P_b \sim 5 \text{ MW}$ into a low-density ($\bar{n}_e \sim 10^{13} \text{ cm}^{-3}$), low-current ($I_p \sim 0.8 \text{ MA}$) plasma. The density rise due to neutral-beam injection is small, which suggests a short particle confinement time ($\sim 100 \text{ msec}$). A very important characteristic of these plasmas is the high toroidal rotation produced by co-injection. Toroidal velocities increased linearly with $P_b/\bar{n}_e$ up to a maximum velocity of $\sim 6 \times 10^7 \text{ cm sec}^{-1}$ (Fig. 19). This velocity corresponds to kinetic energies of about 100 keV and 4 keV respectively for titanium-impurity ions and deuterons. At low $P_b/\bar{n}_e$, standard sawtooth oscillations are observed for these $q \sim 6-9$ discharges. However, the sawteeth disappear at high $P_b/\bar{n}_e$.

Figure 19. Evolution of toroidal rotation velocity in an energetic-ion discharge.

In the energetic-ion mode, several ion components were produced during deuterium injection into a hydrogen plasma. The uncorrected (raw) diagnostic temperature data (Fig. 20) indicate an impurity-ion temperature of 10 keV and a hydrogen charge-exchange temperature of approximately 6 keV. This difference is expected, since the injected beam ions couple preferentially to the impurities and heat the impurities above the central background plasma ion temperature. On the other hand, the hydrogen charge-exchange should indicate a temperature below the central background plasma temperature, since the cold neutral flux weights the outer part of the temperature profile. The electron temperature shows a small drop due to the density increase. If the density had been maintained constant, the electron temperature would have increased slightly. These low-density plasmas had

Figure 20. Temperature evolution, measured by various diagnostics, in an energetic-ion discharge.

impurity levels with $Z_{\text{eff}} \sim 2$, which is somewhat lower than expected for such low-density discharges.

Diagnostics were not available to measure the central background-plasma-ion temperature directly. Therefore, a computational model was used to calculate the background-ion temperature (Fig. 21). For the best cases, central ion temperatures were approximately 9 keV. The beam-ion density was about 50% of the total ion density, and the average ion energy was approximately 24 keV. Confinement time of these energetic-ion plasmas was comparable to that expected from low-mode scaling. The short particle confinement time of approximately 100 msec is comparable to the energy confinement time, thereby indicating ion convection to be the dominant loss channel.

Figure 21. Electron and ion temperatures from computer simulation.

A detailed investigation was not possible, due to diagnostic uncertainties.

The loop voltage during injection shows a large drop, and the sustaining voltage approaches zero at $P_b \sim 400$ kA. The data are consistent with a beam-driven current that is expected to be in the range of 350 kA. The disappearance of sawteeth is also consistent with broadening of the current profile by beam-current-drive effects.

The energetic-ion mode exhibits many new physical phenomena that will be studied more completely with more extensive diagnostics and heating power during future experimental run periods. This mode of operation is a promising candidate for achieving $Q = 1$ in D-T.

Pellet Injection

In March 1985, the first phase of a joint PPPL/ORNL pellet injection program was completed with the installation, over a six-week TFTR operating period, of the Repeating Pneumatic Injector—also called the Repeating Pellet Injector (RPI).²¹

The RPI can produce a continuous extrusion of solid material for several seconds, permitting the injection of single or multiple pellets. Pellets are accelerated by a pulse of high-pressure hydrogen gas through a single reciprocating gun barrel. The injector has been operated on TFTR in deuterium to produce single 4-mm diameter (2.1×10^{21} D⁰) pellets at 1300 m sec⁻¹, or multiple 2.67-mm diameter (7×10^{20} D⁰) pellets at up to 1350 m sec⁻¹. The injector is capable of producing 4-mm pellets at 1900 m sec⁻¹ in hydrogen.

During the four weeks of injector operation,²² pellets of 4-mm and 2.67-mm diameter were injected into TFTR. Results obtained with 4-mm pellets are illustrated in Fig. 22. Peaked-density profiles (peak-to-line averaged ratio of 2.25) with central densities approaching 2×10^{20} m⁻³ were achieved. Central particle replacement times can approach 2 sec. Values of $n_D(0)\tau_E(a) = 6.7 \times 10^{19}$ m⁻³ sec and $n_D(0)\tau_E(a)T_i(0) = 8.8 \times 10^{19}$ m⁻³ sec keV were achieved—the highest values of these parameters reached in TFTR to date. The Murakami parameter $\bar{n}_e R/B_T$ (10^{19} m⁻² T⁻¹) obtained with pellets was 5.6, which exceeds the value achieved by deuterium-gas fueling (3.2) and is approached only by operation in helium (5.3). In the case of helium, however, broader density profiles are observed, with a peak-to-line-averaged ratio of 1.3.

Three 2.67-mm pellets, spaced 200 msec apart and injected over a period of 400 msec, just prior to a neutral-beam-heating pulse, have been used to produce target plasmas with central electron densities of $\sim 1 \times 10^{20}$ m⁻³. Energy confinement in these plasmas has been studied in detail.

Pellet penetration in the ohmic-heating phase of these 2.2-MA discharges was approximately 45 cm ($\sim a/2$), leading to hollow density profiles immediately following pellet ablation. The resulting inverted density gradient relaxes in 20 to 100 msec, leading to a profile

Figure 22. Variation in line-integrated electron density due to injection of (a) single large pellet and (b) three smaller pellets. The insert in each figure is the electron density profile determined by Thomson scattering.

somewhat more peaked than that obtained by gas fueling.

A strong reheating of the central plasma is observed during neutral-beam injection at 5.7 MW. During the 500 msec duration of the neutral-beam pulse, the large sawtooth oscillations observed in gas-fueled discharges at this power level are not observed for the case of pellet injection. The $q = 1$ radius, as approximately determined from the sawtooth inversion radius before and after neutral injection, is not significantly perturbed. A central Z_{eff} of 1.3 was measured by X-ray pulse-height analysis. At the end of the neutral-beam pulse, neutron levels, due to Maxwellian thermal reactions, of up to 1×10^{14} neutrons sec^{-1} were observed. Central electron pressure is as great or greater than in gas-fueled discharges. These results are obtained despite the strong difference in central input power between gas and pellet cases, due to attenuation of the beam in the high-density pellet-injection case. Approximately 60% of the injected power and 50% of the total input power

is deposited outside the $q = 2$ surface. Global confinement in these discharges is between 200 and 250 msec, comparable to that obtained with gas fueling. However, a strong, transient improvement in central confinement is indicated by the observed central reheat and calculated beam penetration. This result is obtained from a time-dependent kinetic analysis of the discharge, using measured density and electron-temperature profiles. The computed radial variation of the total energy confinement time is shown in Fig. 23. The central energy confinement time improves due to reduction in electron thermal diffusivity, rather than reduction in temperature gradient. Improvement in central confinement with beam injection at high density is also seen to a lesser extent on gas-fueled TFTR discharges and has been studied on the Axially Symmetric Divertor Experiment (ASDEX).²³

Figure 23. Computed radial variations in the total energy confinement time during neutral-beam heating after pellet injection.

NEUTRAL BEAMS

Completion of assembly and installation of the final two beamlines on TFTR occurred during the summer-1985 shutdown. Upgrading the power supply system to allow 120-kV operation was nearly complete by the end of the fiscal year, when more than half of the 12 power systems had been commissioned/recommissioned. The 1070-watt helium refrigerator became operational and was used in support of Neutral-Beam Test Cell (NBTC) operation. Operations on TFTR, which began at modest power at the end of FY84, continued until the late April 1985 shutdown, at which point power levels of 6 MW had been reached with deuterium.

Operation was restricted to ≤ 80 kV because of several marginal components in the system. All of the known limitations in the high-voltage capability and

some 30-odd system improvements in reliability were addressed during the shutdown. Operations will begin again in early FY86, with the full beamline complement and eleven ion sources. One power system remains dedicated to the NBTC in order to test a prototype long-pulse ion source with the modified power system. More detailed discussions of the year's activities follow under the system headings below.

Mechanical Systems

Most visible of the year's accomplishments was the installation of the remaining two beamlines to complete the final four-beamline complement for TFTR. Of equal importance, however, was the replacement of the old pivot bellows fabricated from inconel 718 with bellows fabricated from inconel 625 (Fig. 24). The old bellows had excessive leaks and could not be repaired without successive heat-treating cycles. The new bellows are fabricated at PPPL and shipped to the Lawrence Berkeley Laboratory (LBL) for incorporation into the duct assemblies.

Figure 24. The neutral-beam torus-connecting duct pivot-point bellows. (84E1626)

All of the high-voltage isolation and pressure plate assemblies that terminate the flexible transmission lines at the high-voltage enclosures (HVE) and at the ion-source enclosure were replaced with molded-epoxy chopped-fiber composites, as the old plates of epoxy fiberglass laminate were inadequate in voltage standoff. The new pressure plates were also fabricated by LBL.

Considerable effort was spent during the year in trying to reduce the radial component of the tokamak poloidal field (arising from the large amount of magnetic material in the Test Cell floor) that existed in the vicinity of the ion sources. While the magnitude of the radial component was only about 0.5 G (the vertical and horizontal components are much smaller), it appeared to have a surprisingly strong impact on hydrogen operation of the sources in synchronism with TFTR. The additional shielding that could be fitted into the system was only moderately effective and resulted

in increased complexity. Since the field effect with deuterium operation was nil, this has been pursued no further.

Any systematic suppression of the horizontal field component would be quite expensive. A bucking coil was employed with some success, although it was not placed in the optimum position and, therefore, did not have the desired scale length. Helmholtz coils within the ion-source enclosure could be used to null the stray field, but they would probably require feedback control to compensate for variations in the time of injection and the magnitude of the TFTR poloidal fields.

Cryogenic Systems

As noted in the FY84 Annual Report, the capacity of the 225-watt helium refrigerator (for the NBTC) was inadequate to support two-beamline operation of the TFTR during the year's run period, due to fairly heavy transfer-line losses. Operations from August 1984 to April 1985 were supported by the purchase of bulk liquid helium in 1000-gal and 2000-gal dewars. Each 1000-gal dewar was capable of supplying two beamlines for a 10-12 hour operational day. The 1070-watt helium refrigerator became operational later in FY85. Bringing up the TFTR systems will begin in October 1985, and all four beamlines are expected to be in full cryogenic operation by December 1985.

Electrical Power Systems

The subcontractor, RPC Industries, was fully staffed during the year and dedicated to manufacturing, installing, and testing the upgraded hardware for the modulator/regulators, in order to achieve reliable operation of the power systems at 120 kV. Primary components involved in this upgrade task were: new filament-isolation transformers for the RCA tubes and cathode deck; new gradient-grid-resistive-divider tanks; and extensive rebuilds of the electronics on the accel decks. Almost all of the hardware was delivered, installed, and tested by the year's end, and most of the system had been commissioned to 120-kV operation.

One notable unresolved issue for FY85 was the performance of the arc modulators. Although this equipment had been built according to the prescribed specifications, operation with TFTR showed several areas of weakness, in particular, the regulation of the current in the notch and divert functions. In addition, an unacceptably high damage rate to the low-level electronics of these units from ion-source spark-downs occurred during initial operations in FY84, so that these units had to be bypassed for the remainder of the operational period. It was found that operation up to the administrative limit of 80 kV was possible without arc notching, and by the close of the operating period 95 kV was actually reached on one unit without the arc-notch capability. A new design has been developed that removes the low-level electronics from the environment of the high-voltage enclosures, and

couples them to the power components within the enclosures by means of fiber optics. Since the new production units will not arrive until the late spring of 1986, operation is likely to be limited to ≤ 95 kV until that time.

Systems Engineering

The major effort in this area was the cabling and checkout of the final control system connecting the 138-ft level of the Neutral-Beam Power Conversion (NBPC) Building to the signal isolators in the basement and to the various beamline components. At year's end, all of the installation was complete, as was the major portion of the checkout.

The CICADA interface progressed to a point where acceptable waveform display and diagnostic acquisition for performance evaluation was achieved during the spring of the 1985 operational period. Good optical-multichannel-analyzer (OMA) analysis of species mix, good thermocouple-spatial-heat profiles, and water-flow calorimetry were obtained. The next operations period will see the beginning of beamline operation from the TFTR control room with a much improved system, both from a voltage-capability and reliability standpoint.

Long-Pulse Ion Source

The substantial cost increase ($\sim 50\%$) in the long-pulse ion-source fabrication that was projected by the industrial subcontractor (RCA) for Lawrence Livermore National Laboratory (LLNL) has forced a delay from July 1986 to November 1986 in the installation of the new ion sources on TFTR. Regapping of the smaller (10 cm $\times$ 39 cm) research and development version of the new sources for 120-kV deuterium operation and subsequent testing by LBL on the Neutral-Beam Engineering Test Facility (NBETF) has resulted in good performance characteristics. The full-energy component of the ion beam is approximately 80%, and source operation up to 124 kV has been achieved. Considerably improved performance by TFTR is expected, subject to the somewhat higher power, improved species mix, and fourfold increase in pulse length that the new ion sources will permit.

Design work on the necessary upgrades to the TFTR beamlines, to permit operation with the larger beam size (12 cm $\times$ 43 cm aperture) and the increased pulse length, continued throughout the year and was about 90% complete by September 30, 1985. Fabrication of the hardware (primarily larger and better-cooled apertures) was well under way for the NBTC, which will be dedicated to operations with the second prototype unit during the spring of 1986.

Operation

Operating parameters, i.e., voltage and current, were gradually extended throughout the year. With hydrogen beams and six ion sources, 4 MW of

injected power was achieved in January 1985 at voltage levels of 60–70 kV. Voltage levels were held to ≤ 70 kV, because of the stray magnetic-field problem noted above under Mechanical Systems. The ion sources were able to operate up to 82 kV when the magnetic fields of TFTR were not present. Since the magnetic-field problem did not appear to exist with deuterium, a transition to deuterium operation occurred in February, and TFTR-synchronized operating levels were gradually increased to a mean value of about 80 kV, at which approximately 6 MW power was obtained. Individual ion sources operated between the mid-70-kV and the low-80-kV level. Because of the voltage limitations discussed under Electrical Power Systems, operation beyond the low-80-kV level was not tried until the last day, when the best system operated at 95 kV.

Reliability markedly improved when the arc modulators were removed from the system, although there continued to be an unacceptably large amount of time devoted to repair efforts. However, about 90% availability was achieved with six ion sources per plasma shot in the last month of operation. All operations were performed at the local control centers, as shown in Fig. 25.

The NBTC was reactivated in June 1985 to extend diagnostic efforts regarding species mix and to study the possible deflection-magnet configurations that would result in reduced power density on the ion dump, which would be helpful with the new longer-pulse ion sources. Operating with the highest possible magnetic field, consistent with keeping the full-energy ions on the main dump, is beneficial.

Initial species measurements were performed using five methods. Measurements were made in parallel with power-system development and ion-source integration involving four ion sources, each with different internal geometries and each with one or more gas/plasma, generator/arc-circuit configurations. Figure 26 shows the locations of the species diagnostic measurements. Significant variations in species yields were observed for some ion-source configura-

Figure 25. The local control centers for controlling the TFTR neutral-beam ion sources situated on the 138-ft floor of the Neutral-Beam Power Conversion Building. (B5E0533)

Figure 26. Schematic diagram of the Neutral-Beam Test Cell Facility showing the locations of the species diagnostic measurements.

tions and operating conditions. Radial species distributions, power-density profiles, and species-energy-spread profiles were also measured. In general, the preliminary measurements are in agreement for similar operating conditions. These results and the developed diagnostic systems will be applied to optimizing the performance of the heating systems.

DIAGNOSTICS

Fiscal year 1985 had two clearly defined phases for TFTR Diagnostics. The first was the development of plasma operation with two neutral beamlines heating the plasma. The second was a period of intense data analysis (to discover the full aspects of the plasma behavior) while, at the same time, carrying out the installation of new diagnostics on the TFTR tokamak and the refurbishment of old ones. During much of the experimental operating phase, diagnostics were being brought to their full capability and the plasma parameters moved into previously unexplored regions; thus, the study of the diagnostics themselves played a significant role in developing physics understanding.

The full scope of plasma diagnostics on TFTR is shown in Table I. There is only a brief description of the number of operational channels of each diagnostic type. Details of spatial, temporal resolution, and other specifics of the instruments can be found in the references. The table has been updated to include the diagnostics' capabilities for operation in December 1985. The superscripts indicate enhancements to the full set of diagnostics to be available for four-neutral-beamline operation in the Spring of 1986. The measurement of electron density²⁴ has been strongly enhanced by the introduction of the 119- μm wave-length multichannel interferometer, which had five of the ten channels operational.²⁵ The channels view vertically through the plasma. Experimental data of the observed density during an ohmic discharge with deuterium pellets injected into it are shown in Fig. 27.

The figure shows the Abel-inverted electron density profiles before and after injection for a case (a) with a large pellet (2.1×10^{21} atoms) injected and for a case (b) with a smaller pellet (7×10^{20} atoms) injected that does not fully penetrate the plasma. In the latter case, the hollow density profile becomes peaked in about 70 msec. The ability to follow this density behavior with time is important in transport studies. However, note that, with only five channels, the error in averaging the signals for Abel inversion is large and this gives strong encouragement for completion of the system with ten channels.

The above results on density behavior were supported by TV Thomson scattering data and additional information about the electron-temperature profiles was also obtained. Two Thomson laser scattering channels were operated, but the continuous time behavior of the electron temperature was obtained both from a fast-scanning heterodyne radiometer,²⁶ enhanced to operate up to $B_1 = 5$ T, and a Michelson Fourier-transform spectrometer.²⁷ A particularly good example of the quality of agreement of these three measurements at one time in an ohmic plasma is shown in Fig. 28(a). The dots show the Thomson scattering data while the smooth lines show the swept data from the other two instruments. A single point at the center, obtained independently by the X-ray pulse-height analysis system,²⁸ is also shown. Figure 28(b) shows the electron density profile obtained at the same time by the Thomson scattering system.

The measurement of ion temperature, at some of the most interesting beam-heated conditions, has proved particularly challenging, because of the interpretive corrections necessary to obtain true central temperatures from the raw data. Figure 20 compares the raw data for a D⁰ beam-heated high-T_i hydrogen plasma as a function of the time of T_{imp}, the temperature from the Doppler broadening of the TiXXI K α impurity line (X-ray crystal spectrometer),^{29,19} and T_i(CX), the temperature obtained from a perpendicular charge-exchange analyzer.³⁰ The arrows indicate, for

Table 1. Diagnostics Available for Four-Neutral-Beamline Operation.

Plasma Parameter Measured	Diagnostic	Location of Measurement
Electron Density	1-mm Microwave Interferometer Multichannel FIR Interferometer	Horizontal Midplane 10 Vertical Chords ^a
Electron Temperature	TV Thomson Scattering ECE Heterodyne Radiometer (75-210 GHz) X-Ray Pulse-Height Analyzer ECE Fourier-Transform Spectrometer	Radial Profile—Two Times ^b Radial Profile Horizontal Midplane, 2 Vertical Radial Profile
Ion Temperature	Charge-Exchange X-Ray Crystal Spectrometer Charge-Exchange Recombination Spectrometer Multichannel Visible Spectrometer (Diagnostic Neutral Beam)	3 Horizontal Chords, 1 Vertical Horizontal Midplane, 3 Vertical 2 Vertical Channels, 1 Tangential View 2 Horizontal Midplane (80 keV Horizontal) ^c
Impurity Concentration	Interference Filter Array (HAIFA) UV-Survey Spectrometer (SPRED) Soft X-Ray Spectrometer (SOXMOS)	18-Chord Array, 4 Toroidal Locations Horizontal Midplane Horizontal Midplane
Radiated Power	Bolometer Arrays Wide-Angle Bolometers Tangential Bolometers	19 Horizontal, 19 Vertical Chords 6 Toroidal Locations 2 Opposing Horizontal Views
Magnetic Properties	Rogowski Loops Voltage Loops B_θ/B_ϕ Loops Diamagnetic Loops	2 Toroidal Locations 6 Poloidal Locations + Saddle 2 Sets of 26 Pairs, External 2 Toroidal Locations
Wave Activity	Internal Mirnov Loops X-Ray Imaging System FIR Grating Polychrometer	19 Coils 64 Horizontal Arrays ^d 20 Channels ^e
Fusion Products	Epithermal Neutrons Proton Detectors Neutron Activation System Five-Channel Collimator Neutron Fluctuation Detector Prototype Lost-Alpha Detector	4 Toroidal Locations 4 Vertical Locations 8 Toroidal Locations 1 Toroidal Location ^f 1 Location ^g 1 Location ^h
Plasma Edge/Wall	Plasma TV/IR TV Neutral-Beam Pyrometer Probes	Periscopes at 3 Toroidal Locations 4 Toroidal Locations 2 Horizontal, 1 Vertical
Miscellaneous	Hard X-Ray Monitors Torus Pressure Gauges Residual Gas Analyzers Vacuum Vessel Illumination Laser Impurity Injector Glow-Discharge Probes	5 Wall Locations 2 Toroidal Locations 2 Toroidal Locations 3 Toroidal Locations 1 Toroidal Location 2 Mechanisms

^aFaraday-Rotation Modification in May 1986.^bEdge System in April 1986.^cOperational in January 1986.^dVertical Array in April 1986.^eOperational in April 1986.^fTen Channels in April 1986.^gFive Detectors in April 1986.^hOperational in January 1986.

Figure 27. Abel-inverted density profiles from the five-channel interferometer following pellet injection. (a) For a large pellet (2.1×10^{21} atoms) and (b) for a smaller pellet (7×10^{20} atoms).

one instant of time, the degree of correction to the two temperatures obtained by computer modeling using other diagnostic data. Figure 29 shows a range of ion-temperature data as a function of the injected power per electron, with the extent of some of the corrections shown. The Doppler shift of the titanium K_α line has yielded a toroidal drift velocity of over $5 \times 10^5 \text{ m sec}^{-1}$. An important enhancement of this charge-exchange analyzer has been the capability to also view the plasma tangentially. An example for compressed plasmas is given in Fig. 17 in the Experimental Research Section.

There is a deficiency in the ion-temperature measurements, in that no profile data is currently available. The addition, next spring, of a diagnostic neutral beam with more charge-exchange analyzers and with the charge-exchange recombination spectrometer will make possible more comprehensive ion-temperature measurements. This beamline, with a design goal of a modulated 80-kV, 20-A hydrogen beam and the capability of perpendicular or tangential injection, was completed this fiscal year and is undergoing individual component testing at TFTR. The TFTR beamline is shown on the left of Fig. 6 in the Summary Section.

The most marked progress in spectroscopy³¹ this year was in improved data-handling methods, analysis techniques, and comparison to impurity transport codes. The major low-Z impurity is carbon and the high-Z impurity is nickel. Figure 30 shows an example

of the carbon profile obtained by analyses of the Z_{eff} profile (from the interference filter array) and the nickel profile (from the ultraviolet survey spectrometer). In the latter case, the Multi-Impurities Species Transport (MIST) code was used to project the profile back to the plasma center for the spectral lines of four nickel-ionization states in the outer region. There is a clear reduction in Z_{eff} after injection of a hydrogen-fueling pellet, but there is a large discrepancy in the calculated value near the plasma edge, as shown in Fig. 31, where different diagnostics' data was used. It is therefore essential to improve the accuracy of the measurement of the electron density and temperature near the edge for determining the radial variation of Z_{eff} .

With two 19-channel spatial arrays of bolometers and six additional bolometers with wide-viewing angles,³² it has been possible to study, both poloidally and toroidally, the variation of the total radiation. An example of a pathological MARFE case is shown in Fig. 10, where the chord-integral radiated power, seen by the top array, is shown as a function of time. The radiated power data have been coupled with the infrared measurements of the movable limiter to produce very good power accountability for the full range of TFTR plasmas.

The Mi-ID activity observed with Mirnov loops and the horizontal 64-channel X-ray imaging system^{33,34} have provided a wealth of new information on the

Figure 28. (a) Comparison of electron-temperature data at one time during an ohmic-heated plasma. Thomson scattering, fast-scanning heterodyne radiometer, and Michelson Fourier-transform spectrometer profile data are compared together with a central value derived from X-ray pulse-height analysis. (b) Electron density data from the Thomson scattering system at the same time.

Figure 29. Comparison of central ion temperatures for neutral-beam-heated plasmas measured by charge-exchange and by Doppler broadening of titanium K_α spectra. Calculated corrections made to the raw data are shown by arrows.

Figure 30. An example of calculated values of the nickel and carbon impurity levels obtained from the ultraviolet survey spectrometer and Z_{eff} measurements by the interference filter array.

many types of sawteeth fluctuations associated with $q = 1$ surfaces, heat-pulse propagation, and disruption precursors. Because of its importance, and to add to the understanding of mode shape and number at higher- β plasmas, a vertical-viewing X-ray imaging system is being designed for installation next spring.

The epithermal neutron system³⁵ has been used to study the ion temperature, where possible, and also to follow the neutral-beam plasma and the beam-beam interaction with D^0 beam heating. In addition, some new studies were possible with other fusion-product diagnostics.^{36,37} Neutron and X-ray bursts have been observed with large plastic scintillators, one close to the pellet-injection port, the other displaced toroidally

Figure 31. A comparison of calculated Z_{eff} profiles using Thomson scattering data for electron density and temperature profiles (solid curve) and the density from the multichannel interferometer with the temperature from the Michelson Fourier-transform spectrometer (dashed curve).

by 126°. When a pellet is injected into a beam-heated plasma, a rapid "spike" in neutron emission occurs (Fig. 32). An expanded time scale [Fig. 32(b)] shows that the neutron signal jumps rapidly at the time of pellet ablation (H_α trace) but rises relatively slowly at the second detector. Analysis of the data indicates that the density propagates without forming a sharp shock front with a rapid initial propagation velocity ($\geq 2 \times 10^7$ cm sec⁻¹) that subsequently decreases to around 3×10^6 cm sec⁻¹. Modeling suggests that electron thermal conduction into the pellet cloud is retarded by the steep temperature gradient. Fast measurements of the neutron emission during pellet injection also can be used to infer the fraction of the fusion yield produced by beam-target reactions in a deuterium-deuterium plasma, which is useful for accurately evaluating the equivalent Q in a deuterium-tritium plasma.³⁸

The 14-MeV neutron emission from deuterons reacting with the product tritons contained in the plasma, following the initial D(d,p)T reaction, was measured using aluminum foils in the neutron activation system.³⁹ Detailed analysis shows fairly good agreement with classical confinement calculations and suggests a triton confinement time of about 400 msec.

Figure 32. Rapid "spike" of neutrons observed when a pellet is injected (at 2.805 sec) into a beam-heated plasma. In the lower figure, the time scale is expanded and shows the neutron behavior near the pellet (solid line), the neutron behavior toroidal displaced ($\sim 90^\circ$) from the pellet (short-dashed line), and the H_α light from the pellet (long-dashed line).

Figure 33. The time displacement observed in beam-heated plasmas between the deuterium-deuterium neutron production and D- 3 He burn-up.

The burn-up of 3 He, the product particle from the D(d,n) 3 He reaction, can be studied with surface-barrier detectors at the bottom of the vacuum vessel [observing the escaping protons from the D(3 He,p) α reaction]. The present experiments are consistent with electron drag slowing the 3 He. This result can be inferred from Fig. 33 where, for a beam-heated deuterium plasma, there is a time displacement between the observed D-D neutron (and 3 He creation) rate and the D- 3 He burn-up rate. These experiments will continue to lead, eventually, to a diagnostic to study escaping alpha particles in the presence of a very high neutron background. A prototype for such a diagnostic has been built. Figure 34 is a photograph of the detector head that extends inside the vacuum vessel, but will remain behind the bellows cover plates. The head contains, behind lead shielding and a light-tight foil, a zinc sulfide scintillator coupled by fiber optics through a window to a charge-coupled device (CCD) camera.

Figure 34. The head of the prototype alpha-particle scintillator detector to be mounted on TFTR. (85E1388)

The addition of neutral beams can lead to excessive power being deposited on the outside torus wall due to a disruption removing the plasma, or due to shine-through of low-density plasmas. Some carbon-tile protection was provided but, in addition, two infrared pyrometers are now available to give inhibiting signals to terminate a beam pulse if the wall temperature rises excessively. The measurement of power depositions was extended considerably by the use of infrared cameras with the plasma TV periscopes.⁴⁰ This year the temperature rise of a wall surface was only significant for the movable limiter. Figure 35 shows the time dependence of the temperatures observed at one point on each of the ion and electron sides of this limiter, the data being extracted from two-dimensional images of much wider areas. Computer modeling of the heat load to fit the observed temperatures is also shown; by this technique (and bolometer measurements) accountability of the power has been achieved for a wide range of plasmas.

In probe measurements of the plasma-edge regions, combination probe heads with all-graphite Langmuir calorimeters and magnetic probes have been used with great care because of the high-power densities deposited on the probes at disruptions. An example of the density variation in the plasma edge is

Figure 36. The density variation in the plasma edge.

shown in Fig. 36, where an increase in edge density occurs during the neutral-beam pulse. These studies will be considerably abetted by installation of a probe that can be moved during a plasma pulse. Extremely high-reliability values of the TFTR diagnostic equipment have been achieved through many weeks of two-shift operation. The instrumentation, with its broad interfaces to the tokamak and the computer system,⁴¹ is very sophisticated, and bringing it on line has been a major experiment in itself.

TECHNICAL SYSTEMS

The Technical Systems Division provides design and fabrication of complex hardware for TFTR. In FY85, the major activities involved the internal protective components for the vacuum vessel, the radiation shielding, the pellet injectors, the tritium system, radiation monitoring, and the lithium blanket module (LBM).

Tokamak Engineering Branch

The "final" protective plates and the bumper limiters required to operate with four neutral beamlines were delivered, assembled on site, and subsequently installed on TFTR. Both the limiters and the protective plates have water-cooled inconel backing plates on which graphite tiles are mounted. The surface-pumping system, using zirconium-aluminum (ZrAl) as the pumping medium, was also delivered, prepared for assembly, and finally assembled on TFTR. Figure 37 shows these subassemblies mounted in the TFTR vacuum vessel.

The surface-pumping panels were manufactured by the Grumman Aerospace Corporation and the associated power supplies were made by the Grim Corporation. The bumper limiters and the "final" protective plates were manufactured by the McDonnell-Douglas Astronautics Company. All subcontractors delivered all components in time to have them assembled in the vacuum vessel during the 1985 shutdown. This was accomplished with close monitoring of the subcon-

Figure 35. Computer modeling of the power input to the ion and electron sides of the movable limiter to give the observed temperatures of the surfaces obtained by an infrared camera.

Figure 37. View of inside the TFTR vacuum vessel, showing the bumper limiter on the right, the protective plates on the left, and the zirconium aluminum panels near the top and bottom. (85E1156)

tractors by a team of PPPL staff members. This team was instrumental in maintaining the difficult, tight schedules and in ensuring the timely delivery of proper components. Installation on TFTR was accomplished by PPPL staff members, with assistance from Ebasco, Grumman, and McDonnell-Douglas Astronautics Company. The associated cooling systems for the bumper limiter and protective plates were designed, fabricated, and assembled at PPPL by PPPL staff. These systems distribute chilled water to all the backing plates and incorporate instrumentation to measure inlet-water and outlet-water temperatures and flow rates. Safety devices are provided to shut off the water supplies in the event that a leak develops inside the vacuum vessel.

There were 186 thermocouples installed on the bumper limiters and "final" protective plates. They will be used to monitor the heat inputs to the protective armor.

Pellet Injector

The final design and fabrication of the repeating pellet injector (RPI) continued through the first quarter of FY85. During this period, it was decided to accelerate fabrication and to install the RPI before the 1985 shutdown period. During the two-week TFTR mini-

Figure 38. The repeating pellet injector (RPI) being installed into Bay T of TFTR. The RPI is now operational. (85E0538)

shutdown period in March, the PPPL staff and the ORNL advisors accomplished the difficult task of installing the RPI and its associated control system in such a short time. The first pellet was injected into TFTR on March 15, 1985. The RPI is capable of firing a single pellet of hydrogen or deuterium at 1600–1900 m per sec or a series of pellets (more than 2 per sec) at a slightly reduced velocity. The RPI is shown installed on TFTR in Fig. 38.

Soon after the installation of the RPI, the design of the next element in the project, the deuterium pellet injector (DPI), was started. The DPI will utilize eight gun barrels instead of one. This configuration adds greater flexibility in fueling control. It will replace the RPI in the spring of 1986 and is intended for use during the deuterium-deuterium (D-D) equivalent $Q = 1$ demonstration. The original mounting stand and peripheral services (control, cryogenic, vacuum, electrical, etc.) from the RPI will remain for the DPI; the radiation sensitive control elements will be located on the new mezzanine to be designed and constructed in the Test Cell Basement. Fabrication started in the last quarter of FY85.

Final design for the tritium pellet injector (TPI) is expected to begin in FY86, after sufficient data has been obtained from RPI performance and the DPI fabrication and testing activities.

Lithium Blanket Module Program

The Lithium Blanket Module (LBM) Program continued to be sponsored by the Electric Power Research Institute (EPRI) in FY85. The most important accomplishments were the completion of fabrication of all LBM components and the assembly of the LBM on the Engineering Test Station (ETS) at PPPL, the fabrication and testing of all neutron dosimetry and counting equipment, and the initiation of an experimental neutronics program using irradiation of the LBM by a deuterium-tritium point-neutron source at the LOTUS Facility at École Polytechnique Fédérale de Lausanne (EPFL) in Lausanne, Switzerland.

More than 1,000 LBM breeder rods were manufactured and leak tested at GA Technologies, Inc.^{42,43} Approximately 500 of the 25,000 lithium oxide pellets were canned in leak-tight aluminum casings. All the LBM components were shipped to PPPL, where the LBM was assembled and installed on the ETS. Proper operation of the ETS drive mechanisms with the LBM in place was confirmed.

The specially designed, neutronically thin port cover, to be located on the TFTR vessel in front of the LBM, was successfully fabricated by McDonnell-Douglas Astronautics Company and delivered to PPPL.

Fabrication of the three wire scanners designed for radiation counting of activated LBM dosimetry wires was completed by EG&G Idaho, Inc. Scanners for the system were shipped to PPPL with their control electronics. One system consisting of a scanner, a pulse-height analyzer, and a tape drive was made operational at PPPL. Data eventually obtained with these systems will be transmitted to the National Magnetic Fusion Energy Computer Center (NMFECC) computers. There a Master Comparison Code will make three-way comparisons among the neutron dosimetry data, tritium assay data, and the predictions of the Monte Carlo Neutron and Photon (MCNP) neutronics code.⁴⁴

The investigation of tritium transport⁴⁵ in lithium oxide (Li_2O) powder was completed and the results reported in a Ph.D. thesis by P.C. Bertone, "The Kinetics that Govern the Release of Tritium from Neutron-Irradiated Lithium Oxide."

In September 1985, the LBM components were shipped to EPFL in Lausanne, Switzerland, and reassembled in the LOTUS Facility. This facility consists of a point-neutron deuterium-tritium source in a shielded room designed specifically for neutronics experiments with fusion blanket modules. The Li_2O pellets irradiated in the LBM will be assayed both at EPFL and at PPPL. During FY86, the Master Comparison Code will be tested using neutron-activation dosimetry and tritium-assay data from the LOTUS/LBM experiments.

Nuclear Engineering Branch

The TFTR Nuclear Engineering work in FY85 focused primarily on three sections:

- Tritium technology for TFTR.
- Improvements of the radiation shield of the Test Cell.
- Remote-handling technology for maintaining TFTR.

Tritium

The Statement of Work was prepared for the tritium commissioning contract. Burns & Roe, Inc. was selected as the subcontractor and work commenced on September 9, 1985.

Correction of nonconformance reports concerning the installation of tritium-handling equipment (in 1984)

and piping, as well as wiring work associated with the tritium systems delivery and storage, was initiated. Work was concentrated in the tritium vault and next year will be extended to the cleanup system.

A decision was made to use the quadrupole mass spectrometer (QMS) in the tritium analytical glove box to perform analysis of the nontritium gases being injected into TFTR. Studies were initiated for a unified control and radiation monitoring system for all nuclear components of TFTR. During 1985, significant procurements of radiation detection equipment were made.

Radiation Shielding

Installation of the $Q = 1$ deuterium-deuterium equivalent shielding was completed. This shielding consists of a concrete wall, twenty-four-feet high and one-foot thick, to be added as a liner for the existing four-foot thick Test Cell wall. Also needed were three concrete labyrinths having walls up to five-feet thick, required to shield the doorways providing access to the Test Cell. This work included the supervision of procurement of the concrete slabs required for the shield and the development of installation procedures and lifting procedures for installing the slabs and the blocks for the labyrinths. Also required were procedures for the removal and reinstallation of a large amount of electrical and other equipment that had been previously attached to the Test Cell walls. Shielding design, fabrication, and installation for more than one hundred penetrations were also completed. Most of the shielding required for the $Q = 1$ operation was installed during FY85. The design, preparations, and installation was done mainly by the Ebasco group under subcontract to PPPL.

The shielding group also installed an experimental system for measuring the total neutron fluence and also the neutron spectra in the Test Cell Basement of the TFTR. The system consisted of two NE-213 neutron spectrometers provided by subcontract from ORNL and two Bonner Sphere total neutron fluence detectors. Neutron spectra and/or total neutron fluence were measured in 36 locations in the Test Cell Basement, the safety check area, and the diagnostic data acquisition room. A report of these results was prepared.

Remote Handling

After the signature of the cost-sharing agreement between PPPL and the Canadian Fusion Fuels Technology Project (CFFTP) for the design, construction, and commissioning of a remote-handling system for maintaining TFTR, all work was focused on the conversion of TFTR (as of October 1, 1985) into a nuclear facility that could be maintained after producing large numbers of neutrons. Personnel from SPAR, CAE, DSMA, Ontario Hydro (all Canadian companies), Westinghouse-Hanford, and PPPL addressed the following key issues: first shield of TFTR; modifications to TFTR; transporters for remote-handling tools, and effectors, and tools; control systems; control station;

and waste management. This effort was stopped in January 1985 because of lack of funding from the U.S. side for FY86-87. The results obtained so far were documented.

From January on, all effort was concentrated on the design, construction, and test of a maintenance manipulator operating under ultrahigh vacuum conditions at 150°C inside the vessel of TFTR. The team was strengthened by engineers of the KFK (Germany) and CEA (France). The maintenance tasks were inspection (vision, leak detection) and replacement of tiles and surface-pumping panels. The project was subject to a conceptual design review by PPPL in May 1985. The results of this review were incorporated into further work. The preliminary design review, scheduled for September, had the goal of having almost all technical problems solved, in particular, those connected with prime movers, feed-throughs, bearings, lubrication, and cat tracks. A status report was given in September showing that all problems had been addressed and no serious gap was left open.

On September 19, 1985, CFFTP withdrew from the agreement, due to lack of funding on the Canadian side. The KFK and CEA offered to take over most the Canadian contribution and discussions were started at the end of the fiscal year.

FACILITIES OPERATIONS

On April 13, 1985, two months ahead of the scheduled milestone, TFTR operated at design-rated field strength and plasma current. Using both motor generators synchronized to deliver 4200 MJ of energy at 998-MVA peak output, a 2.5-MA plasma was produced with a 1.1-sec flat-top in a 5.2-T toroidal field. This achievement culminated an extensive series of engineering tests verifying machine protective fea-

Figure 40. Motor Generator No. 1 stator current, shot 14833, April 13, 1985.

tures, while prudently extending operating parameters. During these tests, the ohmic-heating system was operated for the first time at ± 24 kA in the Mode-B configuration. The equivalent ohmic-heating flux change is 15.4 V-sec, which exceeds the design level by 18%. Coil current waveforms for shot 14833 are shown in Fig. 39. With prior approval from the manufacturer, the motor generators were operated in excess of the design level of 950 MVA, as implied by Fig. 40.

Figure 39. Coil current waveforms, shot 14833, April 13, 1985.

Figure 41. Finite-element method (FEM) model of variable-curvature No. 1 upper stem.

Figure 42. Temperature distribution ($^{\circ}\text{F}$) in toroidal-field coil vertical cross section.

To further extend the operating envelope of TFTR, system engineering studies were initiated to reveal as-built structural, thermal, and electrical limitations. The Operations System Engineering Support (OSSES) study performed by the Engineering Analysis Division to Facilities Operations' specification includes development of detailed finite-element-method models of 18 poloidal-field coils. An example, illustrated in Fig. 41, shows the structural modeling of the lead-stem portion of the variable-curvature coil No. 1 upper stem. Operations System Engineering Support is continuing to complete the detailed models and to develop simplified algorithms approximating the detailed models to determine operating limits.

A new poloidal-field coil configuration, Mode D, was studied early in FY85 to increase ohmic-heating performance. A 10% increase in volt-seconds was calculated, if all variable-curvature coils and some horizontal-field coils were included in the ohmic-

Figure 43. Toroidal-field case stress versus $I_{TF} \times I_{EF}$.

Table II. Fiscal Year 1985 Shot Statistics for TFTR.

Attempts	2,493
No Plasma	395
Plasma Discharges	2,098
Ohmic Heating	1,504
(Ohmic Heating With Pellet Injection-98)	
Neutral Beam Heating	594
(Neutral Beam Heating With Pellet Injection-75)	
Data Sets Obtained	1,714
Discharge Cleaning	29,736

heating circuit. The bus work was redesigned to incorporate a Mode-D option, and the hardware was modified during the scheduled shutdown.

Analysis of proposed ohmic-heating overdrive operation was completed in September 1985. In order to provide additional volt-seconds, the ohmic-heating coils and power supplies were analyzed for 30-sec operation.

System studies have shown that the variation of resistivity due to the temperature distribution in critical cross sections of toroidal-field coil copper, allows increased toroidal field I_{TF} without exceeding the hot-spot temperature limit. As a result, the toroidal-field system I_{TF} limit was increased by 14% to produce the 1.1-sec flattop shown in Fig. 39. The computed temperature distribution in the toroidal-field coil copper cross section is illustrated in Fig. 42.

An extensive array of strain gauges monitored critical machine sections as machine operating levels were increased. Measured stresses are in agreement with design predictions as shown in Fig. 43.

During FY85, subsystem modifications were completed to improve efficiency, reliability, and operating controls. A toroidal-field power supply sequential control program was introduced to optimize the system power factor by operating individual supplies preferentially cut off or at full power. Power supplies are operated in the phased-back mode only when necessary to meet command requirements. Interrupted fiber-optic links and power supply firing generators were redesigned to improve performance and reliability. Small auxiliary pumps were added to the cooling-

Figure 44. The TFTR system availability.

Figure 45. The FY85 TFTR Facilities operations activities.

water system to supply standby and low-load requirements more efficiently than possible when using the main pump. A standby diesel pumping unit was installed to assure neutral-beam cooling-water flow if the main pump is lost due to interruption of facility electrical power.

In this same period, the torus vacuum pumping system (TVPS) control circuits were extensively revised to add a local control option with an explicit mimic panel. A "first-fault" detector was added to annunciate the origin of a typical sequence of fault-induced protective trips. To improve machine availability, preventive maintenance programs were introduced for the motor generator sets, the ac power distribution system and portions of the cooling-water system, and the tokamak. Reliability was also improved by installing a new nontritium gas delivery (NTGD) system with extensively modified design.

Vacuum vessel internal hardware was installed during the scheduled shutdown from April 15 to August 20, 1985, including the full complement of surface-pumping system panels, bumper limiters, and protective plates with associated water-cooling and thermocouple circuits. The bakeout heating system was expanded to include the torus-vacuum portions of 20 diagnostics and all neutral-beam ducts. Except for the surface-pumping system, the installed equipment was successfully tested.

A total of 2,098 successful experimental plasma discharges resulted from 2,493 attempts. Of these, 1,714 shots resulted in diagnostic data sets. During conditioning operations 29,736 discharge-cleaning shots were made. More detailed statistics are listed in Table II.

Results of efforts to increase machine availability are indicated in Fig. 44. The machine was available 61% of the time scheduled for experimental physics

operation, with a definite increasing trend during the year.

A summary of division activities during FY85 is shown in time-line fashion in Fig. 45.

SAFETY AND ENVIRONMENTAL MONITORING

The Laboratory was very pleased to receive the DOE Award of Excellence and the National Safety Council Award of Honor for outstanding safety performance.

Safety of personnel and property, as well as possible environmental impacts, were given high priority by the TFTR Project. A program of analyses to provide baseline data on the concentrations of radioactive pollutants in surface water, groundwater, air, soil, and vegetation was given increased emphasis. For the groundwater, a program was initiated through the U.S. Geological Service (USGS). Wells presently on the Forrestal Campus indicate tritium background levels on the order of 3.7 Bq per liter (100 pCi per liter).

The Idaho National Engineering Laboratory (INEL) reviewed the PPPL radioactive environmental program and analysis procedures and provided input to a Laboratory analysis procedures manual, which will be used as part of an Environmental Protection Agency (EPA) certification process for an on-site analyses laboratory. Analyses of nonradioactive pollutants in surface waters were accomplished by an outside vendor. Results of these analyses are reported in an annual Laboratory report⁶ on environmental monitoring results and activities.

Real-time prompt-gamma ionization-chamber monitors were in operation at the site boundary and in

close proximity to the Test Cell. Permanent neutron monitors (Bonner Spheres) were installed and operated in FY85. Surveys of the TFTR vacuum vessel were accomplished after each daily run period to measure activation levels. In general, the hot spots were less than 10 μ Sv per hour (1 millirem per hour) after a day's run scenario. Activation levels, interior to the vessel, are monitored during a vacuum vessel opening. Because of D-D operation in early 1985, the vacuum vessel was checked for the presence of tritium during the April 1985 shutdown. Tritium was detected at very low levels, giving the Health Physics Group confidence in their ultrahigh sensitivity measurement techniques.

Passive thermoluminescent dosimeters monitors were placed inside and outside the Test Cell to measure bremsstrahlung radiation emission levels and profile. Results of these measurements were reported at the 11th Fusion Engineering Symposium.⁴⁷ Permanent real-time air and particulate monitors are scheduled to be tested and installed in FY86. Off-site baseline studies for tritium and airborne particulate radiation will also commence in FY86.

Written procedures continue to be an important feature for all component installations, integrated systems testing, operational testing, and lifting activities, and these are being reviewed and approved by the Project and Operational Safety Office (P&OS) prior to implementation. The Area Safety Coordinator Program was given project support and was an important element in the reduction of the Laboratory accident performance indices.

EBASCO/GRUMMAN SUBCONTRACT

The Ebasco/Grumman industrial team provided engineering, design, and construction services, as well as installation and assembly technical support to TFTR during the FY86 period. This support was provided in the areas of neutral-beam installation, shielding, safety analysis, electrical systems, diagnostics, surface pumping, instrumentation, and construction.

Engineering, assembly support, and supervision of the craft personnel who performed the installation work, were provided for the installation of Neutral Beamlines Nos. 2 and 5. This work included the preparation of installation procedures, lift procedures, optical alignment services, and technical direction of all craft work. Additionally, the vessel attachment ducts and beamline supports for Beamlines Nos. 3 and 4 were removed and replaced.

Two major types of radiation shielding were installed on TFTR during the 1985 shutdown. One-foot-thick wall panels were installed on the four walls of the Test Cell up to an elevation of 24 ft. In addition, labyrinths with thicknesses up to five feet were installed in front of each of the three personnel access doors. Radiation shielding was installed in the majority of the 3-ft or 6-ft-deep penetrations in the Test Cell floor.

The PPPL Radioactive Waste Management Plan was prepared and formally issued by PPPL to DOE on December 17, 1984. Guidance was provided, as needed, on the implementation of TFTR safety criteria and on potential impacts on the Project of existing and proposed federal and state legislation regulations.

The electrical group provided engineering and design services on some 23 specific electrical systems during FY85, ranging from neutron detectors to neutral-beam power supply grounding procedures, and including such things as a review of tritium system drawings and various interlock systems. Assistance was also provided to the neutral-beam power supply group, as required.

Fiscal year 1985 saw the mechanical engineering, design, fabrication, and installation of two major diagnostics, the diagnostic neutral beam and the neutron activation system. For the diagnostic neutral beam, a support system was designed and installed, which allows for accurate remote positioning of the 15-ton beamline over an arc of 32°. Work on the neutron activation system involved design of the ancillary systems and design modifications for installation of a pneumatic transfer system. The pneumatic transfer system provides rapid and repeatable delivery of sample capsules to as many as eight locations at the vacuum vessel, with subsequent capsule retrieval for neutron activation analysis.

The installation and checkout of the full surface-pumping system was completed. Thirty-six pumping panels were installed in the vacuum vessel, with their associated electrical bus work. Fourteen new power supplies (30 kVA) for the surface-pumping system were added to the existing four units. Along with the supplies, additional motor control center starters and cabling were added.

The installation of 125 thermocouples for the bumper-limiter system, 65 thermocouples for the protective plates, and an additional 66 thermocouples for the surface-pumping system, was completed. All of these thermocouples are located within the TFTR vacuum vessel. Complete end-to-end testing of thermocouples was accomplished with an Ebasco/Grumman team.

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PRINCETON LARGE TORUS

During FY85, the research program on the Princeton Large Torus (PLT) has continued to make important contributions to the understanding of radio-frequency (rf) applications in tokamaks. The PLT radio-frequency program encompasses several frequencies and operating modes which, supported by past experimental successes, exhibit promising and potentially crucial improvements to tokamak operation. During FY85, the research emphasis was concentrated on ion cyclotron range of frequency (ICRF) heating and on lower-hybrid current drive (LHCD); preliminary electron-cyclotron-heating (ECH) experiments were also performed. Several important milestones were reached during this period, as high-power operation with several systems became routine. For instance, data from ICRF experiments indicated a continued favorable efficiency scaling to high-power levels corresponding to a confinement scaling somewhat more favorable than that shown by previous empirical scaling data. Moreover, LHCD experiments exhibited the ability to suppress the central MHD sawtooth activity, resulting in a significant increase in the central electron temperature. In addition, low-power ECH experiments were performed which indicate a possible new ECH frequency regime favorable for reactor-heating applications. The success of these experiments was facilitated by technological improvements, which were made possible by an ongoing parallel research program undertaken to understand the limitations of handling high radio-frequency powers in the plasma environment. Other research in support of the fusion program was carried out simultaneously with the rf experiments in such basic plasma physics areas as surface physics, impurity transport, spectroscopic line identification, and diagnostic development.

MAJOR ACTIVITIES

The experimental time was roughly equally divided between ICRF and LHCD experiments, with considerable parallel operation on other topics. Within the ICRF experiments, the emphasis was further divided between high-power heating via the fast magnetosonic wave (30 MHz) and scoping experiments with an externally launched ion-Bernstein wave (30 or 90 MHz). The LHCD work was carried out with several poloidally and toroidally distinct waveguide arrays, using two available source frequencies. During FY85, the PLT ran reliably and virtually problem free.

ICRF Heating Experiments

Experiments using the fast magnetosonic wave to heat a dilute ion component, resonant at its fundamental cyclotron frequency, in a dense background plasma, the so-called minority heating mode, were performed almost exclusively with a ^3He minority in a deuterium majority during FY85.¹ The reason for this choice was to take advantage of the favorable confinement properties of the PLT at maximum field (3.3 T) while using the total available rf source power at 30 MHz (5 MW). The full complement of source power was delivered to the plasma using an array of six one-half turn loops of the type shown in Fig. 1. Improvements in component design have led to an increase in the specific power handling capability of such an antenna; the maximum power delivered per antenna, in the presence of a plasma, is 1.4 MW. In the ^3He mode 4.3 MW, or 85% of the source power, was delivered to the plasma resulting in central ion temperatures over 5 keV at a line-averaged density of $3.7 \times 10^{13} \text{ cm}^{-3}$, as shown in Fig. 2. The neutron production rate corresponded to better than 10^{13} sec^{-1} . Evidence for the central peaking of the deposited rf power is shown by the strongly peaked ion-temperature profiles, as shown in Fig. 3. Electron heating is also observed, as shown in Fig. 4, which is found to be consistent with collisional drag on the suprathermal ^3He ion population. It is significant that the central electron temperature is dominated by the strong sawtooth activity, whose amplitude and period

Figure 1. Diagram of a half-turn loop.

Figure 2. Time evolution of the central ion temperature with 4.3-MW radio-frequency power in the ^3He minority mode.

increase with the applied rf power. The central values of the ion temperatures and the sawtooth-averaged electron temperature show linear increases with rf power, as shown in Fig. 5, with no significant degradation of the heating efficiency. In Fig. 6, the global energy confinement time is plotted as a function of the total input power (rf heating plus ohmic heating). After

Figure 3. Ion-temperature profiles as measured by Doppler broadening of impurity lines.

Figure 4. Time evolution of the electron temperature at various major radii with 4.3-MW radio-frequency power.

an initial degradation of the confinement from the ohmic-heating case, the confinement time appears to saturate at a new level.² This behavior differs from and significantly exceeds previous empirical confinement scaling laws for tokamaks at the highest rf powers. The plasma Z_{eff} is observed to increase during ICRF heating, as evidenced by an increase in radiated power, as shown in Fig. 7. However, most of this increase is found to be due to low-Z impurities radiating from the edge. The contribution to the central energy balance from radiative losses is insignificant.

Overall, these results imply a highly favorable prognosis for the use of the fast wave to heat plasmas. There is no apparent saturation in the heating efficiency at high powers, and the discharge conditions are similar to those observed at lower powers. In

Figure 5. Dependence of the central ion and sawtooth-averaged electron temperatures on applied rf power.

Figure 6. Global energy confinement scaling with total applied power.

particular, the appearance of a favorable power scaling is potentially important for proceeding along the path to an ignition device.

One of the primary approaches to the use of ICRF heating in a reactor is the proposed use of a coincident fundamental second-harmonic resonance in a two-ion plasma (D-H or $^3\text{He-T}$), whereby a transition from minority heating to second-harmonic heating takes place as the plasma beta increases. The demonstration of second-harmonic heating in a pure hydrogen plasma was done on PLT in previous experiments. Demonstration of direct deuterium heating has, up to now, been hampered by the inevitable residual hydrogen concentration. By careful conditioning on PLT, the residual hydrogen level was reduced to below 1%. At this level, second-harmonic heating of deuterium is expected, and this was indeed observed by the presence of a significant deuterium tail, as shown in

Figure 7. Total radiated power as a function of rf power. The fraction of the total power is approximately a constant.

Figure 8. Deuterium and hydrogen charge-exchange spectra corresponding to the transition between minority and second-harmonic heating.

Fig. 8.³ Deuterium tails to 70 keV with tail temperatures of 18.5 keV were observed with 1.2-MW radio-frequency power at a density of $1.5 \times 10^{13} \text{ cm}^{-3}$, accompanied by enhanced neutron production. Modeling of the charge-exchange distribution indicates that approximately 25% of the rf power was being directly deposited in the deuterium ions, indicating the onset of the transition. The conditions under which the heating transition was observed to occur indicate that the accepted theoretical model for the process is essentially correct.

Ion-Bernstein Wave-Heating Results

Low-power experiments were also carried out with loop couplers designed to launch an ion-Bernstein wave (IBW) directly at the plasma periphery.⁴ Owing to its exceedingly short wavelength deep in the plasma, this wave carries the advantage of being strongly absorbed at comparatively high ion cyclotron harmonics. This fact leads to a very narrow deposition profile coupled with an ability to produce nearly thermal heated-ion distributions. These features could lead to

Figure 9. Ion-Bernstein-wave heating at the fifth cyclotron harmonic of a deuterium minority in a hydrogen plasma.

simplification of the launching structures and facilitate temperature profile control.

Two separate experiments with externally launched ion-Bernstein waves were carried out on PLT. In the first experiment, a deuterium minority in a hydrogen plasma was heated at its fifth cyclotron harmonic; in the second experiment, a pure deuterium plasma was heated at its three-halves harmonic. The minority heating results are shown in Fig. 9. A power level of 100 kW at 90 MHz was applied to a four-element IBW antenna at a line-averaged density $n_e = 1.5 \times 10^{13} \text{ cm}^{-3}$ and a toroidal magnetic field $B_t = 27 \text{ kG}$. The power is absorbed by the perpendicular component of the deuterium distribution and then shared collisionally with the parallel deuterium component and with the hydrogen majority. The hydrogen bulk and deuterium parallel temperatures are seen to rise by approximately 350 eV. All components of the distribution function are observed to be Maxwellian. At 30 MHz and $B_t = 28 \text{ kG}$ in a pure deuterium plasma of line-averaged density $n_e = 1.5 \times 10^{13} \text{ cm}^{-3}$, an increase in the bulk deuterium temperature of approximately 450 eV is observed for an applied power of 150 kW. A limited scan of toroidal field showed peak heating when the deuterium three-halves cyclotron resonance was in the plasma center. The charge-exchange distribution was again observed to be Maxwellian. This result is significant in that it represents the first time this nonlinear damping mechanism has been shown to be a feasible means of heating a tokamak plasma.

The efficiency of IBW heating was found to be comparable to that observed for the fast wave, implying good wave penetration and sufficiently strong wave absorption rates. These initial results have been encouraging, stimulating the development of second-generation IBW launchers for testing the viability of this approach at high radio-frequency power levels.

Lower-Hybrid Current-Drive Results

Auxiliary methods of maintaining the plasma current in a tokamak in a steady state, or near steady-state fashion, stand to make a crucial improvement in the

tokamak concept, if successful. Moreover, changes in the electron distribution resulting from wave-induced electron acceleration may favorably alter the stability and, consequently, the confinement properties of the tokamak. The potential of such improvements has fostered an intense research program on PLT to explore possible LHCD applications.⁵⁻⁷

A key element in this research is the understanding of the wave propagation model, which for LHCD is based on geometric optics theory. If proven valid, ray tracing will provide an effective tool for determining the propagation, damping, and power deposition of lower-hybrid waves. The main feature of this theory is the prediction of a n_i shift as the waves propagate toward the interior of the plasma. Thus far, no unequivocal experimental proof of the validity of ray tracing in a tokamak has been carried out. During FY85, a direct proof was shown making use of two poloidally separate waveguide arrays.⁸ Since, according to ray tracing theory, couplers located at different poloidal angles should produce different n_i spectra deep in the plasma, the current-drive efficiency, which is highly sensitive to the n_i spectrum, should be measurably different for the two couplers. This is in fact the case, as seen by the current-drive results in Fig. 10 for two otherwise identical arrays of eight waveguides powered at 2.45 GHz. The conclusion is further supported by the fact that phasing the waveguides so that, according to the theory, the central wave spectra should be equal resulted in equal current-drive efficiency for each coupler. This result greatly facilitates the construction of a viable theoretical model for the current-drive process.

In another series of experiments, the feasibility of controlling the MHD activity of a standard tokamak discharge with LHCD was demonstrated. The potential benefit of this result to the tokamak concept is very great, in that the elimination of MHD activity could lead to enhanced confinement and possibly extension of

Figure 10. Current versus time for two identical waveguide arrays located at different poloidal positions. $P_H = 200 \text{ kW}$ in each coupler. $B = 31 \text{ kG}$, $n_e = 1.1 \times 10^{13} \text{ cm}^{-3}$.

Figure 11. Time evolution of the $2\Omega_{ce}$ -emission amplitude for various applied lower-hybrid powers. Suppression of the central sawtooth oscillations is observed.

the beta limit. In these experiments, up to 420 kW of lower-hybrid power was applied in equal amounts from two eight-waveguide arrays in typical discharge conditions of $n_e = 1 \times 10^{13} \text{ cm}^{-3}$, $I_p = 500 \text{ kA}$, $B_t = 29 \text{ kG}$. Under these conditions sawtooth oscillations of approximately 10% amplitude and an approximately 6-msec period occur on the central electron temperature. Figure 11 shows the suppression of these sawteeth by 400 kW of lower-hybrid wave power, as evidenced by the $2\Omega_{ce}$ -emission amplitude. At intermediate power levels, the sawtooth amplitude, as well as the incremental slope, is observed first to increase slightly, then decrease with power until the oscillations have disappeared, as shown in Fig. 12. Corresponding to this effect is a significant increase in the central electron temperature as shown in Fig. 13. Such observed central electron heating establishes a new electron-temperature profile operating regime for PLT and suggests an improvement in the central energy confinement time. The global confinement time also increases slightly with rf power and does not exhibit the degradation from the ohmic-heating case, typical of auxiliary heating methods, as shown in Fig. 14. In conjunction with these observations, a decrease in the central density fluctuations, as measured by microwave scattering techniques, was observed, as depicted in Fig. 15. The potential of suppressing MHD

Figure 12. Amplitude of the sawtooth oscillations as a function of applied LHCD power.

Figure 13. A comparison of the electron-temperature profiles with and without 500 kW of lower-hybrid power. An increase in the central electron temperature is observed accompanied by the suppression of sawtooth oscillations.

oscillations with lower-hybrid waves has received a great deal of attention worldwide as a consequence of the experimental observations made on PLT.

Motivated by these results, a vigorous research program was prepared during FY85 to further explore the possibilities of current drive. This program includes the fabrication of a sixteen-waveguide launcher which is expected to enhance current-drive efficiency by localizing in velocity space the interaction with the electrons. In addition, experiments to explore the

Figure 14. Scaling of the global confinement with applied lower-hybrid power. No degradation in the confinement is observed.

Figure 15. Amplitude of central density fluctuations as measured by microwave scattering. The scattering volume is located near the $q = 1$ surface.

feasibility of driving currents at comparatively high densities with the high-frequency version of the fast magnetosonic wave have been prepared.⁹ It is envisioned that such a wave may combine the advantage of being able to interact with fast electrons and penetrate to densities far beyond the lower-hybrid density.

Electron-Cyclotron-Heating Results

The importance of controlling the electron distribution for optimal stability and confinement has maintained a strong interest in the use of ECH techniques in tokamaks. ECH has been shown to exhibit a narrow power deposition profile and, under certain circumstances, an ability to favorably affect the plasma stability and confinement. During FY85, low-power experiments were carried out with a newly commissioned 200-kW electron-cyclotron-heating system at 60 GHz. Strong wave absorption was found and it was observed that the absorption resonance is significantly downshifted from the cyclotron resonance frequency. Recent theoretical work has shown that relativistic effects can be responsible for the downshift, and the predicted amount of the shift is consistent with the energetic-electron population found in PLT discharges. The significance of this effect is that substantially lower-frequency sources can be applied to heat electrons than that currently envisioned for a reactor, thereby greatly alleviating the requirements for the development of new high-frequency sources. Similar benefits may be derived from selective electron heating as are proposed for LHCD: namely, the control of MHD effects and optimization of the confinement. Preparations have been made during FY85 to increase the ECH system to full power and to explore the possibilities offered by joint operation with the LHCD and ICRF experiments.

Spectroscopic Studies

During the period covered by this report, a series of spectroscopic studies were undertaken for the purpose of identifying new impurity lines which may be useful for future diagnostic applications. This effort has required improvement of existing instruments as well as the addition of new types of spectrometers for improved time and spatial resolution. A specialized instrument for multiline Doppler ion-temperature measurements was designed¹⁰ and its main components constructed. In addition, a method for magnetic-field measurement utilizing Zeeman splitting was investigated.¹¹ Two new time-resolved spectrometers were installed on PLT yielding spectra of the soft X-ray and vacuum ultraviolet (VUV) regions with high resolution.

The soft X-ray region contains the $\Delta n = 0$ lines of metallic impurities and the $\Delta n = 1$ lines of light impurities. These resonance transitions, and a few forbidden lines at longer wavelengths, appear to be most promising for studying the behavior of impurities in tokamaks during auxiliary heating.^{12,13} A comparison of experiment and theory in the $2s^2 2p^k - 2s 2p^{k+1}$ transitions was performed.¹⁴ These studies help establish confidence in the theoretical basis that is used to relate the observed intensities to specific impurity densities. The higher resolution of the multichannel spectrometer (SOXMOs, 0.2 Å resolution from 10 Å to 330 Å) yields higher quality measurements than other instruments, by reducing the blending of lines from various impurity species and their ionization states and by reducing the background contribution. This instrument has been very useful in monitoring impurity behavior during ion-Bernstein wave heating and pellet injection experiments.¹⁵

A newly installed normal incidence McPherson spectrometer with a multichannel detector (0.7 Å resolution from 250 Å to 1700 Å) provided the advantage of high efficiency in the longer wavelength region. Many forbidden transitions of the intrinsic impurities (e.g., FeXXIII, 1079 Å; FeXXI, 1354.1 Å; CrXX, 1205.8 Å; etc.) were found to be strong intensity lines. The intensity of the FeXXII forbidden line at 845 Å relative to that of the allowed resonance line at 135 Å was measured during ICRF heating in PLT discharges, as shown in Fig. 16. The results indicate a noticeable effect of proton (deuteron) collisions on the intensity of the forbidden line. This diagnostic procedure is providing a new method of proton (deuteron) temperature measurement.¹⁶

The extensive spectrometric instrumentation on PLT has facilitated a large amount of line identification study for use as a high-temperature diagnostic. These studies have expanded toward heavier elements, so as to be able to follow the trend toward higher temperatures in PLT with increased levels of auxiliary heating power. These studies include the phosphorus sequence in copper to molybdenum, soft X-ray spectra, ground configuration of highly ionized silver, and soft X-ray spectra of zirconium and molybdenum. At the electron temperatures in PLT, the complex spectra of the $n = 3$ shell are important in this range of atomic charges. These spectra, for which the aluminum-like

Figure 16. Ion temperature derived from the intensity ratio of an FeXXII forbidden line to an allowed resonance line during ICRF discharges on PLT (points with error bars). This process provides a temperature measurement of the background deuterons and is compared with other ion-temperature measurement techniques.

sequence has recently been elucidated for zinc to silver¹⁷ (as shown in Fig. 17), have an additional point of interest in the fact that their simplest configuration in the neon-like sequence is a prime candidate for observing laser action in the soft X-ray regime. In the PLT tokamak, neon-like atomic states for atoms as highly charged as silver ($Z = 47$) have been observed and studied in the X-ray region. Work is in progress on the neon-like, $n = 0$ transition in iron ($Z = 26$) to molybdenum ($Z = 42$). Candidate lines from FeXXVII at 204.65 Å and 255.4 Å, already known from solar spectra, were observed during pellet-injection experiments. The availability of high-quality spectra from

Figure 17. Aluminum sequence in ZnXVIII (a) and AgXXXV (b), recently investigated in PLT discharges, provides potential diagnostic tools and may find application in X-ray laser development.

these ionization states in stable plasmas has generated an active collaboration with other laboratories.

RADIO-FREQUENCY TEST FACILITY

The Radio-Frequency Test Facility (RFTF) was used extensively in FY85 to support the ongoing radio-frequency experiments on PLT. It was also used to develop novel radio-frequency wave launchers and to improve the performance of high-power radio-frequency components intended for use on future experiments. This work resulted in the fabrication of hardware presently in use on PLT in both the ion cyclotron and lower-hybrid frequency ranges.

A novel ridged-waveguide launcher was developed and fabricated for launching fast magnetosonic waves via waveguides at frequencies far below those usable in rectangular waveguides, which are constrained by the small access available in modest-sized tokamaks. The motivation for this work lies in the continuing need to develop simple, maintainable, high-power density wave launchers for a reactor. The ridged-waveguide launcher, which is loaded with dielectric, has a cutoff frequency below 90 MHz, the resonant frequency for second-harmonic proton heating at full field magnetic field (3 T) in PLT. Following successful completion of low-power tests on the RFTF, the launcher was installed on PLT.

In the lower-hybrid frequency range, a key experimental goal is to improve the efficiency of current drive by carefully controlling the spectrum of lower-hybrid waves launched. In order to achieve this control, a new waveguide vacuum window was developed that allows a larger number of waveguides to be powered through the same small access port used in previous PLT current-drive experiments. However, in order to maximize the power-handling capability of the entire waveguide array, the window was placed near the plasma to avoid the possibility of the electron cyclo-

Figure 18. Photograph of the lower-hybrid vacuum window composed of sixteen alumina elements brazed in a titanium flange. The length of the multiple-element window is about 20 cm. (85E1516)

iron resonance layer occurring on the vacuum side of the window. Such a design required the development of a compact, multiple-element window, shown in Fig. 18, which had not previously been successfully fabricated within the fusion program. The window materials were selected carefully to minimize thermal expansion differentials during the brazing process, and the effort resulted in a sixteen-element window that is presently in use on PLT.

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PRINCETON BETA EXPERIMENT

The Princeton Beta Experiment (PBX) device is an advanced concept tokamak with a kidney-bean shaped poloidal cross section indented on the inboard side. The ultimate goal of PBX is to confine plasmas with very high pressure with respect to the magnetic pressure of the external toroidal field, that is, very high toroidal beta, β_t . The toroidal beta β_t will be referred to as a volume-averaged quantity. Attempts to increase β_t in circular cross-section tokamaks have shown that magnetohydrodynamic (MHD) instabilities limit operations to $\beta_t \leq 3\%$.¹ Magnetohydrodynamic activities can be seen as a set of barriers that have to be crossed in order to achieve high β_t , the lowest MHD barrier being the long wavelength kink mode, and the highest being the short wavelength ballooning mode. Conventional tokamaks operate in what is known as the first stability regime in which various MHD instabilities, such as the "fishbone" instability observed in the Poloidal Divertor Experiment (PDX),² are excited at the maximum operational β_t . Recent theoretical studies^{3,4} have shown that the bean configuration has strong stability properties against both the ballooning mode and the internal kink mode. The stabilizing properties of this plasma shaping are provided by the large magnetic shear and strong magnetic well produced by the outward radial shift of the magnetic axis with respect to the geometrical center of the configuration. Furthermore, a bean-shaped plasma indented beyond a critical point, and with the appropriate pressure and current profiles, is expected to pass beyond the first stability regime and provide access to a very high-pressure regime, namely, the second stability regime for the internal kink and ballooning modes. Values in the 10 to 20% range for β_t are predicted to be achievable, even with large aspect ratio. This is very attractive from the viewpoint of reactor design. However, this bean-shaped plasma configuration is not effective for all modes. For example, the external kink mode (a long wavelength perturbation on the plasma surface), is unaffected by the bean shape and may be strongly excited depending upon the plasma edge and boundary conditions. This will be discussed later.

The modification of PDX (Poloidal Divertor Experiment) hardware to build PBX was reported in the FY83 Annual Report.⁵ The initial experimental results were presented in the FY84 Report.⁶ Fiscal year 1985 was a year of consolidation of previous results, with the main goal being the full documentation of the various operating modes and the high-pressure phenomena. Major results and studies are: (1) the establishment of a reliable operating scheme to achieve high β_t , the so-called "long-sawtooth mode," (2) studies of MHD activities to identify the possible causes of the "high- β_t

disruption" (β_t limit in the first stability regime), (3) an interesting observation of "beta collapse" during neutral-beam heating with low and steady plasma current, (4) detailed studies of the high-confinement regime (H-mode) in search of the better operating modes, (5) studies of impurity transport, (6) utilization of hydrogen pellet injection for achieving high β_t , and (7) a design study for the modification of PBX to PBX-M. Each of these subjects will be discussed later in separate sections.

An example of the bean-shaped configuration with $\beta_t = 5\%$ is shown in Fig. 1. The plasma shape geometry is characterized by the indentation parameter i_n and the elongation κ . The indentation parameter is defined as the ratio $d/(d + 2a_{mid})$ where d is the depth of indentation and a_{mid} is half of the plasma width on the midplane. The elongation is the ratio of the height of the plasma to the width on the midplane. The plasma edge is defined by the flux surface enclosing 95% of the poloidal flux within either the separatrix or the nearest limiter, whichever is smaller.

The overall PBX performance with respect to beta is summarized in Fig. 2, where the β_t values experimentally obtained are plotted against the Troyon-Gruber⁷ parameter $\beta_c = \mu_0 i_p / a_{mid} B_z$. Here, B_z is the value of the vacuum toroidal field strength at the magnetic axis. Figure 2 is a revised version of a similar plot shown in the previous annual report⁶ and now includes more than 800 experimental points. Data point entry has been made for all PBX modes of operation including the L-mode (low-confinement mode), H-mode, pellet injection, and also modes of operation specific to PBX, such as the long sawtooth mode and the beta-collapse discharges. Furthermore, the determination of β_t limit was improved with the installation of a diamagnetic loop early in the year.

The ratio of β_t to β_c , designated β_n , can be used as a figure of merit to evaluate experimental conditions relative to the β_t limit in the first stability regime. Here, the boundary $\beta_t = 2.5\beta_c$, shown in Fig. 2, corresponds approximately to the first stability regime limit of the external kink mode as given by Troyon *et al.*⁸ The high-beta shots are located at the right side of the plot at high- β_c values. Plasmas with $\beta_c \geq 1.9$ were obtained by means of a high plasma current ramp-up rate and, consequently, high i_p . This mode of operation will be discussed in the next section. These discharges are always terminated by a disruption. The MHD activities related to its occurrence are reviewed in the MHD section. The success of PBX to date in producing high β_t , up to 5.3%, is attributable to its ability to achieve high β_c (up to 2.7).

Data points with $\beta_c \leq 1.9$ correspond to discharges

Figure 1. The PBX poloidal cross section showing major components and typical flux contours. P1, P2, and P3 are the passive stabilizers; 1 to 4 are the shaping coils; 5 to 7 are the vertical-field coils, and 8 is the horizontal-field coil.

with lower- I_p and more peaked current profiles. The current was either ramped up slowly or not at all. Slow current-ramp-up discharges tend to excite a stronger MHD activity than fast current-ramp-up discharges, but have a lower probability of disrupting. The data of the beta collapse belong to this category. All the data points fall below the Troyon-Gruber limit, indicating

Figure 2. Princeton Beta Experiment β_t scaling. Volume-averaged toroidal beta β_t is shown as a function of the Troyon-Gruber parameter β_c . Open circles are nondisruptive plasmas during neutral-beam heating. "Xs" are with plasma disruption. The Troyon-Gruber limit for the external kink is shown as solid lines for β_t values of 2.5 and 3.0, the lower value being the better for PBX data.

that these experimental results are in the first stability regime.

HIGH- β_t , FAST CURRENT-RAMP-UP OPERATION: LONG-SAWTOOTH MODE

Two very important aspects of the PBX for FY85 were the study of the physics of high- β_t plasmas and the evaluation of experimental β_t limit within the present hardware capability. Such investigations would not be possible without, first of all, establishing a reproducible operational procedure to achieve high- β_t plasmas. A successful approach was found to be the use of a fast current ramp-up (from 1.5 to 2.0 MA per sec) and appropriate gas fueling rate (30 to 50 Torr-liter per second) during the neutral-beam-heating phase. Such a current ramp-up tends to minimize the occurrence of disruptions as q_{ψ} passes through integral values (e.g., 5, 4, 3) during the discharge evolution, where q_{ψ} is the safety factor q evaluated at the edge. It was also found that the large current ramp-up suppresses the sawtooth oscillation as well as the fishbone instability for a period of up to 140 msec. Figure 3 shows a time history of such a high- β_t discharge, where β_t reaches over 5%. The high current ramp-up is applied from $t = 440$ msec (about half way into the staggered neutral-beam injection phase) to $t \approx 570$ msec. As shown by the signals of the soft X-ray detector and the Mirnov probe, MHD activity was significantly reduced after the last sawtooth crash at $t = 470$ msec. Derived parameters shown here, such as β_t and l_i , were calculated by the analysis code SURFAS⁶ using as input data the magnetic flux measurement, diamagnetic signal, coil currents, and plasma current.

During the current ramp-up the internal inductance, l_i , decreased to 0.5–0.45. This seemingly low value, $l_i = 0.5$, is not only due to the broadness of the plasma current density profile, but also due to the plasma elongation. A full MHD analysis confirmed that the current profile is still slightly peaked with large current ramp-up.

Detailed measurements of the plasma parameters were carried out using this type of discharge but with a lower β_t ($\approx 4.5\%$), to maintain reproducibility, at $I_p \approx 550$ kA and $B_t = 0.92$ T. The indentation was 0.2 and $q_{\psi} \approx 3.0$. The quiescent period begins at $t \approx 490$ msec, just after the last sawtooth crash. Figure 4(a) shows the time evolution of the $T_e(r)$ and $n_e(r)$ profiles measured by a multipoint Thomson scattering diagnostic system (TVTS). The electron temperature $T_e(0)$ increased monotonically in time to a value of ≈ 1.8 keV, with the $T_e(r)$ profile maintaining a triangular shape. The $n_e(r)$ profile became flatter and a sharp gradient appeared at the plasma edge. The maximum central density, $n_e(0)$, reached $6.0 \times 10^{13} \text{ cm}^{-3}$ just before the high- β_t disruption. The ion-temperature profiles were measured by using charge-exchange

Figure 3. Time evolution of a long sawtooth discharge. (a) Plasma current I_p , injected and absorbed neutral-beam powers, P_{inj} and P_{abs} , respectively, volume-averaged toroidal beta β . (b) Plasma normalized inductance L_i . Time expansion of soft X-ray detector (c) and Mirnov probe (d) signals.

Figure 4. Kinetic documentation of long sawtooth mode. (a) Time evolution of electron-temperature and density profiles; composite picture based on many shots. Note last sawtooth crash at $t = 490$ msec. (b) Central ion temperature versus time measurement by charge-exchange recombination spectroscopy. Neutral beams are staircased at $t = 350, 400, 450$ and 500 msec. Note, in this case, the sawtooth crash at $t = 510$ msec.

recombination spectroscopy of fully stripped impurity ions. As shown in Fig. 4(b), $T_i(0)$ dropped by as much as 1.0 to 1.5 keV at the last sawtooth crash, and then increased sharply to the maximum value of $T_i(0) = 4.5$ keV.

MHD ACTIVITY NEAR HIGH- β_t DISRUPTION

The precise character of a high- β_t disruption varies from one shot to another making it very difficult to describe the disruptions in a simple manner. But a systematic study has shown that disruptions can be characterized in terms of β_c and q_ψ . One must keep in mind that, for PBX operation, both quantities are intrinsically coupled to the current ramp-up rate. A fast

Figure 5. Time evolution of plasma parameters and MHD signals for (a) medium q_ψ (low β_t) discharge, and (b) long-sawtooth mode discharge at low q_ψ (high β_t). The long-sawtooth mode plasma is much more quiescent, as can be seen by the soft X-ray wave detector and Mirnov probe signals.

Figure 6. Time evolution of MHD signals close to high- β_t disruption. The upper trace is the soft X-ray signal and the lower trace corresponds to a Mirnov probe at an outer midplane location.

Figure 7. (Continued on next page).

Figure 7. Vertical profiles of the normalized peak-to-peak X-ray signal amplitude $\bar{S}/S$ and phase for three discharges. (a) A large central $m/n = 1/1$ oscillation, consistent with a sawtooth precursor, (b) an intermediate case, and (c) no obvious mode structure.

ramp-up rate results in high plasma current (with low q_ψ and high β_c , long-sawtooth mode) with a broad current profile, while a slow ramp-up rate produces lower plasma current (with high q_ψ and low β_c) with a peaked current profile. These differences are reflected in the MHD behavior, as can be seen for the two cases shown in Fig. 5. The long-sawtooth-mode discharge has a much more quiescent MHD behavior.

An analysis of the occurrence of high- β_i disruptions in relation to the q_ψ value showed that most of the disruptions happen when q_ψ reaches 3.0, and that only 10% of the discharges survive to lower- q_ψ values, disrupting later at $2.0 \leq q_\psi \leq 3.0$. The observed instabilities can be grouped, for the most part, into two types. In the first type, the precursor growth leads directly to a plasma disruption. In the second type, the precursor growth leads to an internal disruption which is followed by a plasma disruption after a time delay (t_{delay}) varying from 0 to 10 msec. An example of such a disruption is shown in Fig. 6. At the Mirnov probe observation point, approximately 40 cm from the plasma surface, the perturbation is of the order of 0.3%. When extrapolated to the plasma edge these oscillations can lead to a relative amplitude of approxi-

mately 1%, which is indicative of substantial MHD activity at the plasma boundary. For all the discharges that have been analyzed so far, the toroidal number of the MHD fluctuation is $n = 1$.

Analysis of the soft X-ray detector data reveals the nature of the precursor to be a complex subject. In some of the cases where $t_{\text{delay}} > 0$, the large internal disruption is similar to a sawtooth exhibiting an $m = 1$ precursor. An example is shown in Fig. 7(a), where a plot of the vertical profile of normalized precursor amplitudes of soft X-ray signals, $\bar{S}/S$, is shown. The dominant central mode is odd as indicated by the approximately 180° phase shift across the center, which is consistent with an $m/n = 1/1$ internal mode. Similar large internal $m/n = 1/1$ modes were observed in medium q_ψ discharges.⁹

Figures 7(b) and 7(c) show other types of MHD behavior with zero t_{delay} . In Fig. 7(b), there is a smaller central mode and other structure outside of the center. Figure 7(c) is another example. In spite of this large variety of disruption behaviors, the oscillation frequency is linked to the plasma toroidal rotation frequency as can be seen in Fig. 8. In this figure, the mode frequency is compared with the rotation velocity

v_ϕ measured at the center of the plasma by the charge-exchange recombination light of fully stripped impurity ions. For the discharges shown in Fig. 8 the mode frequency of shot 95886 ($t_{\text{delay}} > 0$) is larger than that of shot 95888 ($t_{\text{delay}} = 0$), but both discharges have similar ratio to the rotation frequency, namely $0.60 \leq t/t_\phi \leq 0.75$.

The low value of the toroidal number, $n = 1$, rules out the ballooning mode as the agent responsible for disruption in these discharges. The remaining candidates are the ideal external kink, the internal kink, and the tearing modes. The data analysis indicates that the purely ideal external kink is too fast and the resistive tearing mode is too slow to explain the bulk of the observations.

Theoretical studies were carried out to identify the possible causes of high- β_i disruption. Magnetohydrodynamic stability calculations on a high- β_i PBX discharge have shown that the external kink can produce a significant $m = 1$ central component, as shown in Fig. 9. The appearance of an $m = 1$ component is consistent with the experimental results shown in Fig. 7(a). One approach to evaluate the experimental condition for MHD stability is to compare the experimental observations of MHD activity with theoretical predictions. A comparison between the Mirnov signals measured at different poloidal and toroidal locations and PEST-simulated signals shows good agreement in amplitude. However, to obtain agreement in both amplitude and phase it is necessary to modify the plasma boundary treatment by introducing resistive effects. Details of the analysis are presented in the Theoretical Section of the present Annual Report. The MHD instability structure is sensitive to details of equilibrium. Cases representative of the MHD behavior shown in Figs. 7(b) and 7(c) are under study.

A PEST analysis was also carried out to find the maximum achievable β_i as limited by the external kink mode or the ballooning mode in the first stability regime. The results are summarized in Fig. 10 where the beta limits are plotted against the central q value.

Figure 8. Time evolution of precursor mode frequency, the toroidal rotation velocity v_ϕ , and the ratio t/t_ϕ , where $t_\phi = v_\phi/2\pi R$. Open symbols are for shot #95888 and solid symbols are for shot #95886.

Figure 9. Displacement pattern (a) and mode amplitude (b) obtained in a PEST calculation of an external kink mode for a high- β_i discharge (corresponding to Fig. 1 configuration). Mode amplitude ξ_ψ is plotted against normalized poloidal flux, ζ .

The ballooning limit at approximately 9% is well over the experimentally observed β_i limit. The effect of an outboard conducting wall located at a minor radius b_w was investigated, and the external kink calculations show that by setting $b_w = 2a_{\text{mid}}$, good agreement with the experimental limit is obtained. Although the experiment does not have a conducting shell at that position, it is not unrealistic to assume that the existing interior structure is equivalent to having a wall located at twice the midplane radius.

The above analyses are not sufficient to unequivocally

Figure 10. The PEST code calculations of the onset condition for the external kink mode as a function of $q(0)$, for a conducting wall at infinity and at $b_w = 2a_{mid}$. The ballooning mode and experimental limits are also shown.

cally identify the mode responsible for the β_t limit, if indeed one single mode is responsible, but the evidence favors an ideal external kink with growth rate reduced by a finite radius of the wall position and/or a conducting plasma sheath. Other modes (particularly the tearing mode) cannot be excluded from participating in some cases.

BETA COLLAPSE

In order to investigate high- β_t behavior near the β_t limit free from the extra complications arising from low- q_e disruptions and from conditions caused by fast plasma current ramp-ups, steady I_p discharges were investigated at various neutral-beam injection powers. Since no I_p ramp-up was used, the plasma current for these discharges was typically smaller than for the long sawtooth mode and, consequently, resulted in lower β_c (higher q_e). In some discharges of these regimes, the β_t value was observed to rise with time and, subsequently, to decrease markedly while the beam heating was still being applied. This phenomenon will be referred to as "beta collapse." Figure 11

Figure 11. Time evolution of β_t and I_e for two discharges with the same plasma current. (a) A four-neutral-beam discharge with a peak power of 5 MW and experiencing beta collapse at $t = 610$ msec; (b) A three-neutral-beam (3.75 MW) discharge.

shows the time evolution for two macroscopically similar discharges, one heated with three neutral-beam injectors, the other with four. Each injector was operated at a power level of approximately 1.25 MW. The β_t traces show that only the four-neutral-beam discharge experienced a beta collapse (starting around 610 msec). For this case the instantaneous stored energy loss rate was close to 2 MW, in spite of the input heating power of 5 MW. The beta collapse seems to occur above a threshold value in either heating power or β_t value. It is interesting to note that the β_t value fell below the level reached by the three-neutral-beam discharge. At the time of collapse, the I_e trace for the four-neutral-beam discharge showed an upward jump by 10 to 20% during the beta collapse, indicating sudden shrinking of the current density profile.

The beta collapse phenomenon is characteristic of steady or nearly steady I_p discharges and has not, so far, been observed in fast current-ramp-up discharges. At higher β_c values, the rate of collapse becomes faster than that in the example shown in Fig. 11(a). The beta collapse is different from the well-known thermal collapse of the central region of the plasma due to excessive energy loss by radiation. Spectroscopic and bolometric observations show that, while some impurity accumulation and peaking of the Z_{eff} profile are evident, they do not reach a catastrophic level at the time of the collapse. The beta collapse has been observed in both L-mode and H-mode discharges.

In corroboration of the diamagnetic beta measurements, kinetic diagnostics also show a severe energy loss, as illustrated in Fig. 12, by the two sets of electron-temperature and density profiles, taken before and after the beta collapse. The electron pressure loss is evident as both the temperature and the density profiles shrink after the beta collapse. Figure 13(a) shows the temporal evolution of the ion temperature at the center. The timing marker indicated in this graph corresponds to the time midway through the beta drop. It is clear that the ion temperature

Figure 12. Electron-temperature and density profiles before and after beta collapse. A shrinking of the two profiles is observed after the beta collapse.

decreases significantly during the beta collapse. Simultaneously, the toroidal rotation drops to a value very close to zero at the beta collapse. The soft X-ray signal shows more varied behavior: in some cases the central signal continues to rise during the collapse, in others, abrupt shrinking of the soft X-ray profile occurs.

What also distinguishes the beta collapse from more usual disruptions, is that the total current can be maintained largely intact with the feedback system, although it shows a "bumpy" behavior. Another striking feature of the beta collapse is that this process occurs relatively slowly (taking anywhere from a few

Figure 13. Time evolution, including beta collapse, of (a) ion temperature and (b) toroidal rotation velocity at the plasma center.

milliseconds to several tens of milliseconds). The MHD fluctuations, observed with a Mirnov probe, begin to grow tens of milliseconds before the onset of the collapse and become large at the occurrence of the collapse. An example is shown in Fig. 14. The fluctuation frequency is of the order of 10 kHz at this point, but decreases almost to zero as the collapse proceeds, while leaving the amplitude unchanged. Note that the trace shown in the figure is a time-integrated Mirnov signal and is directly proportional to the amplitude of the fluctuating magnetic field. The poloidal mode number m , measured at the plasma edge, seems to be as high as $m \geq 6$, but uncertain. Note that these discharges have relatively high- q_p values (>4).

Charge-exchange analyzer measurements also showed oscillations during the period leading to and during the beta collapse. Associated fast-ion bursts

Figure 14. Slowdown of MHD mode during beta collapse. (a) Displaced toroidal flux (diamagnetic signal) versus time shows beta collapse beginning at $t = 610$ msec. (b) Contour plot of frequency spectrum of Mirnov probe signal versus time. (c) Integrated Mirnov signal against time. The signal is directly proportional to amplitude of the magnetic field.

were observed. These measurements are reminiscent of the fishbone instability, in that the oscillation slows down and mostly the perpendicular fast ions are affected. There are, however, significant differences: in the usual fishbones, the oscillations "whistle down" within each burst, repeating the same process in a succession of bursts, while in the beta collapse the oscillations usually whistle down continuously throughout the process. A decrease in the neutron emission rate is also observed during the beta collapse.

H-MODE

As mentioned in the previous Annual Report,⁶ PBX can be operated in the high-confinement (H-mode) regime when the plasma is limited by a free separatrix. The H-mode discharges in PBX are especially interesting for future devices since, unlike PDX and ASDEX (Axially Symmetric Divertor Experiment), PBX has "open" divertor geometry where no mechanical baffles are used to contain the recycling neutral particles. This H-mode is similar to those observed in other machines in that it is characterized by a spontaneous drop of the H_α signal accompanied by a substantial rise of the electron density without any increase in gas puffing. While increased particle confinement always occurred with the H-mode, the achievement of a significant and lasting improvement in energy confinement time τ_E depended sensitively on the conditions of operation of the machine. It was found that τ_E would usually show a transient jump of 50% or more at the time of the H-mode transition, but often the confinement time would decay back to values comparable to the L-mode phase over a time of 50–100 msec. In an effort to find an operation regime where the steady-state confinement did not deteriorate back to near L-mode levels, parametric studies were carried out with various discharges. They showed that improved steady-state H-mode confinement was more readily obtained at high toroidal field strength. For example, the steady-state energy confinement time increased by 10% in the H-mode regime compared to L-mode regime at $B_t = 1.1$ T, while this increase was typically 50% at $B_t = 1.9$ T. The increase of confinement time in the steady-state H-mode regime as a function of toroidal field is shown in Fig. 15. At the highest fields,

Figure 15. H-mode energy confinement time versus toroidal field strength for discharges of indicated operation parameters.

the confinement quality factor $\tau_E / (I_p a^{1/2})$ reached values of ~ 0.11 , which is comparable to the better H-mode discharges obtained in the PDX experiments. In addition, it was found that the ratio of hydrogen recycling light H_α from the divertor region to that from the plasma midplane also increased with B_t , suggesting that improved confinement is related to localization of recycling in the divertor region. This relationship between the improved confinement and increased localization of plasma recycling in the divertor region was first noted in earlier PDX closed-divertor studies.¹⁰ It is also worthwhile to note that in the best cases, this "open" divertor configuration showed edge pedestals in the electron temperature, as was also observed in PDX for the closed-divertor H-mode.¹⁰

IMPURITY STUDIES IN PBX

Under some conditions, PBX plasmas have a strong tendency to accumulate impurities in the center of the discharge. This behavior is especially prevalent in discharges which show a transition to the H-mode regime. Strong central accumulation of metallic impurities often leads to excessive radiation from the plasma center, which in turn results in a thermal collapse of the core of the plasma. Indeed, experiments on other tokamaks have indicated that a strong and usually disastrous accumulation of metallic impurities is a side effect of improved particle confinement in the H-mode regime.¹¹ In efforts both to document this accumulation and possibly learn enough to remedy this problem, a series of measurements of intrinsic impurity behavior in PBX were made during the past year. The aims were to study (1) the impurity transport properties which lead to strong accumulation and (2) the operational aspects of impurity accumulation in both the L-mode and H-mode.

The diverse diagnostics on PBX allowed a relatively complete characterization of all impurity species in a given discharge, which is crucial for the evaluation of the transport properties and for comparison with the theoretical models. The degree of central impurity accumulation was found to be strongly dependent on Z , the charge of the impurity ion. This can be seen quite strikingly in Fig. 16, which shows a composite of several measurements of impurities in a relatively steady-state H-mode plasma. It is seen in Fig. 16(b) that the metallic impurities have a much more peaked radial profile than the lower- Z , O^{8+} profile. Likewise, the radiated power profile in Fig. 16(d), which is due almost exclusively to the presence of high- Z impurities in the hot plasma core, is much more peaked than the Z_{eff} profile in Fig. 16(c) which reflects the distribution of mostly the low- Z impurities (i.e., C^{6+} and O^{8+}) in the plasma core. The dashed and solid curves in the figures represent simulations of the impurity measurements based on an impurity radial transport code for various values of a profile peaking factor, C_l or C_h (l = low Z , h = high Z), which represents the ratio of the convective to diffusive transport in the model. Since the choice of $C_l = 4$ and $C_h = 20$ provides a consistent picture of the experimental results, the

Figure 16. Impurity and plasma parameters profiles for a sawtooth-free case with strong impurity accumulation. (a) Plasma electron temperature and density profiles; (b) Relative density profiles of O^{8+} and several metallic species along with calculated profiles for various impurity peaking parameter C_l and C_h ; (c) Radial profile of Z_{eff} from visible bremsstrahlung along with model Z_{eff} profiles calculated with the impurity transport code; (d) Radial profile of radiated power with three results from the impurity modeling code: $C_l = 4$ and $C_h = 20$.

metallic impurities are seen to peak in the center about five times more strongly than the low-Z impurities.

This strong dependence on Z for the degree of accumulation is similar to that expected from simple neoclassical theory, and it was, thus, of great interest to compare the absolute values of the model transport coefficients for these impurities with the theory. This was accomplished by analyzing the time-evolving redistribution of impurities in the plasma associated with large sawteeth. The time dependents of the impurity radial profiles was then simulated with the transport code which yielded values of the diffusion coefficient (D) and the inward convective velocities for low- Z and high- Z impurities (v_l and v_h , respectively) in the plasma core.

Assuming a cylindrical plasma of radius r_c , reasonable fits to the experimental data were obtained with $D = 1000 \text{ cm}^2 \text{ per sec}$, $v_l = 2.2 \times 10^3 (r/r_c) \text{ cm per sec}$ and $v_h = 1.1 \times 10^3 (r/r_c) \text{ cm per sec}$. These model results are in good agreement with simple Pfirsch-Schlüter estimates of transport coefficients in the plasma core. Although significantly more work is needed in both data analysis and in applying correct neoclassical transport theory to the model, these results indicate that, at least in the case where the impurity concentration is relatively high, transport inside the $q = 1$ surface appears to be close to neoclassical.

Since the theoretical results indicated that the accumulation itself was due mainly to impurity-impurity collisions,¹² it appears that catastrophic accumulation may be avoidable by reducing the impurity influx and, hence, the overall impurity level. In fact, a series of experiments in PBX have shown that the central

Figure 17. Time evolution of the central electron density, the proton density estimated from $Z_{eff}(0)$, the electron temperature, and the nickel concentration (measured by pulse-height analysis, PHA) without (a) and with (b) gas puffing after 400 msec. The two discharges shown experienced a H-mode transition.

impurity accumulation can be suppressed to a tolerable level by carefully tailoring the gas puffing which fuels the discharge. For example, Fig. 17 shows the central electron and proton densities for two H-mode discharges. In Fig. 17(a), a discharge with little or no gas puffing during the neutral-beam phase is shown. A strong accumulation of both low- Z and high- Z impurities leads to significant dilution of the plasma ion density. In contrast, as shown in Fig. 17(b), a mild gas feed of ≈ 10 Torr liter per sec produced substantially cleaner discharges with much less dilution of the central plasma ion density.

PELLET INJECTION

In an effort to provide additional means of controlling the plasma density profile and, consequently, the pressure profile, the PDX pellet injector (condensing type with three barrels) was reinstalled on PBX. Since it was often found that bean-shaped configurations with a free separatrix were hard to fuel efficiently with standard gas puffing, the injection of pellets provides an attractive alternative means of fueling discharges. Initial experiments were concentrated on relatively small, separatrix-limited discharges with a well-defined open-divertor configuration. In order to optimize central fueling with these relatively slow pellets (0.6–0.9 km per sec), all three pellets were injected during the one-beam-heating phase ($\approx 1.2 \text{ MW}$) with short separation intervals ($\approx 20 \text{ msec}$) between them, resulting in an increase of the central plasma density from $n_e(0) = 3.5 \times 10^{13} \text{ cm}^{-3}$ to $6 \times 10^{13} \text{ cm}^{-3}$. Subsequently, three additional beams ($\approx 4 \text{ MW}$ total beam power) were injected. In general, the final value of β_t was increased by raising the plasma density with pellet injection, while the electron-temperature profile, after recovering from the transient drops at the time of injection, was less affected. This procedure allowed production of plasmas with $\beta_t \geq 4.5\%$ at $B_t = 1.1 \text{ T}$, better than all but the very best β_t results obtained with gas puffing at lower toroidal field.

With pellet injection, two distinctive modes of dis-

charge evolution were observed. The first type of discharge produced relatively peaked profiles with $n_e(0) = 1.1 \times 10^{14} \text{ cm}^{-3}$, while the second had $n_e(0) = 6 \times 10^{13} \text{ cm}^{-3}$ with a flat density profile. The latter type of discharge was more conducive to achieving higher- β_i values. While further study is needed to understand the physical causes of these two types of discharge evolution, it appears to be related to slight variations in the target plasma and to the timing of the pellets with respect to neutral-beam injection, both of which influence the penetration of the pellet into the plasma core.

PBX-MODIFICATION

In PBX, bean configurations have been successfully formed with a simple arrangement of passive stabilizers and two sets of poloidal coils, one for the equilibrium and one for the shaping field. Indentations of up to 0.2–0.22 have been achieved, but higher values require a more flexible external field pattern as well as better stabilization of the vertical instability associated with high indentation. When the separatrix bounds the plasma, H-mode operation has been readily achievable.

However, most high- β_i discharges terminate with a high- β_i disruption in which the external kink mode is implicated. It is, therefore, essential to stabilize these high- β_i disruptions, if operation in the second stability region for ballooning modes is to be achieved. One well-known remedy against the external kink is the presence of a conducting shell close to the plasma

surface, and such a shell is the core of the next planned modification of PBX, or PBX-M.

Theoretical studies have shown that it is possible to meet the conflicting requirements of sufficient shell structure for stability and adequate open area for neutral-beam injection and various diagnostics on the midplane. Figure 18 shows the magnetic configuration and hardware arrangement for PBX-M based on these calculations. The PBX-M has been designed not only to remedy the high- β_i disruption, but also to allow high indentation, $i_n \geq 0.3$, and a better divertor arrangement for H-mode optimization. Five new coils will be constructed inside the vacuum vessel, and seven separate sets of poloidal coils will be energized with independent rectifier power supplies to control the magnetic axis, plasma shape, and separatrix.

The operating parameters of PBX-M are expected to be similar to those in the present PBX except for an increase of the major radius from 1.45 m to 1.65 m and of the indentation from 0.2 to 0.3. The maximum plasma current for $B_t = 0.8 \text{ T}$ and $q_0 = 3$ is expected to be over 600 kA. The ultimate goal of PBX-M remains the achievement of the second stability regime for the ballooning mode and, consequently, high- β_i plasma. The operation of PBX-M, which will commence in April of 1987, should provide new insights into the understanding of toroidal confinement devices.

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Figure 18. Hardware and magnetic configuration of PBX-M. Passive stabilizers are closer to the plasma than for PBX. Indentation parameter i_n is 0.3.

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S-1 SPHEROMAK

A spheromak is a toroidal magnetic confinement configuration for plasmas of the "compact toroid" type. The toroidal field in the plasma is sustained entirely by poloidal plasma currents, eliminating the need for coils that link the plasma. This topology allows for a simply connected first wall and blanket and also allows for translation so that the plasma can be created in one place and then moved to a separate burn region. In addition, adiabatic compression can be conveniently applied to the spheromak. The very low aspect ratio of the spheromak permits a small volume for a given characteristic confinement scale length, which makes possible a small-sized reactor core. The objectives of the S-1 experiment¹⁻⁴ are to investigate the formation, equilibrium, stability, confinement characteristics, scaling of confinement quality with various parameters, and the physics of sustainment of spheromak plasmas.

The main features distinguishing the S-1 from other spheromak schemes are (1) the plasma formation technique, which is based on an inductive transfer of

toroidal and poloidal magnetic flux from a toroidal "flux core" to the plasma, and (2) stabilization of the plasma against dangerous rigid-body tilt and shift instabilities by use of loose-fitting conductors and coils. The S-1 Spheromak device⁵ (Fig. 1) was completed and started full operation in September 1983.

Spheromak plasmas produced in the S-1 device have major radii in the range 0.4 to 0.65 m and minor radii of 0.25 to 0.45 m. Toroidal plasma currents up to 350 kA are obtained at power levels of 50% of the design value. Peak plasma electron densities n_e range from 2×10^{13} to 1×10^{14} cm⁻³ for hydrogen discharges; shot-averaged electron temperatures T_e range from 25 to 70 eV with measured temperatures ranging from 10 to 110 eV. The volume-averaged beta is 5–10%.

The first half of FY85 was devoted to a detailed study of the equilibrium and stability of, and relaxation phenomena in, S-1 Spheromak plasmas. These studies included:

- Comparison of the experimental equilibrium with the Taylor state, the state of minimum magnetic energy subject only to the single constraint that the global magnetic helicity is conserved (see below).
- Identification of high n -number toroidal modes ($2 \leq n \leq 8$) during formation, their possible origin, and their relation to the relaxation of the plasma towards the Taylor state.
- Scaling of T_e with plasma current.
- Sustainment of spheromak plasmas by inductive techniques.

These studies were made possible by the improved stability, against rigid-body $n = 1$ modes, gained by installation of a passive figure-8 coil system.^{6,7}

The S-1 device has now reached two of the most important milestones established when the S-1 Project was proposed in 1979: attainment of hot (100 eV) plasmas with stable lifetimes of 1 msec or more.

The second half of the year was devoted to a two-part upgrade of the S-1 device for increasing the plasma current capability:

- Design and fabrication of an improved flux core.
- Design of a poloidal flux transformer for additional inductive current drive. Operation with this transformer would constitute a large-scale test of the plasma's tendency to relax toward the Taylor state.

Figure 1. Cross section of S-1 device showing vacuum vessel, equilibrium-field (EF) coils, flux core, passive figure-8 coil stabilization system, and the n -mode diagnostic. The experimentally obtained poloidal flux contours of a spheromak configuration toward the end of the formation phase are also shown.

VERIFICATION OF THE TAYLOR STATE—AFTER PLASMA FORMATION

Of fundamental importance to understanding the physics of spheromak plasmas is the concept of the Taylor minimum-energy state. Taylor proposed that a plasma in which the resistivity is small but finite will relax with the aid of some type of turbulence to a minimum-energy state through reconnection of magnetic field lines. He further suggested that the only important constraint for determining the final state was the conservation of global magnetic helicity defined as $\int dV \mathbf{A} \cdot \mathbf{B}$, where the integration is over the whole plasma volume. (Helicity can be thought of as the linkage of magnetic flux tubes.) The Taylor principle predicts the final state to be the force-free equilibrium $\mathbf{j} = (\mu/\mu_0)\mathbf{B}$ for which μ is a constant in space. μ_0 is the permittivity of free space, $\mathbf{j}$ is current density, and $\mathbf{B}$ is magnetic field strength.

The most direct way to discover how close the S-1 plasma was to the Taylor state was to experimentally determine the μ profile. The μ profile in S-1 was measured as follows. The magnetic configuration was measured as a function of space and time with a movable multicoil magnetic probe inserted into the plasma. The time evolution of a magnetic field profile in major radius R was obtained during a single discharge for fixed z (distance along device axis) and ϕ (toroidal angle). A two-dimensional cross section in a chosen R - z plane was then obtained by scanning this probe in the z direction between discharges and interpolating between spatial grid points. From this data set, $\mu = \mu_0 \mathbf{j} \cdot \mathbf{B} / B^2$ was calculated.

Experimental measurement of the two-dimensional μ -profile⁸ after formation showed that μ was constant over the plasma volume and all spatial gradients of μ were confined to the plasma edge (Fig. 2), indicating good agreement with the Taylor hypothesis. That is, the measured magnetic structure of the S-1 Spheromak plasma after its formation was close to the Taylor minimum-energy state, with the deviations from the Taylor state occurring near the edge of the plasma.

GLOBAL MAGNETIC FLUCTUATIONS AND RELAXATION DURING FORMATION

During formation, currents from the toroidal- and poloidal-field capacitor banks induce poloidal and toroidal simultaneously so that, in principle, the magnetic configuration could be guided toward the Taylor state. A very important experimental result from S-1 (and other recent spheromak research) is the observation that the plasma tends to relax toward a stable spheromak plasma configuration by itself,^{9,10} independent of the initial conditions or the details of the formation process, and the final state is near the Taylor state as described above.

Globally coherent $m = 1$ modes were observed^{11,12} during formation (Fig. 3) in S-1. These low n -number modes occur during flux conversion and plasma relaxation, suggesting that these modes provide a means for relaxation. The n and m integer numbers are defined by the functional dependence $\exp i(n\phi + m\theta)$ of the fluctuations on toroidal angle ϕ and poloidal

Figure 2. Two-dimensional contour plots, during (0.2 msec) and after (0.5 msec) formation, of (a) poloidal flux (in increments of 10 mWb) and (b) $\mu = \mu_0 \mathbf{j} \cdot \mathbf{B} / B^2$. The shaded areas are within $\pm 15\%$ of the nominal value for μ of 5.5 m^{-1} .

Figure 3. Toroidal mode amplitude versus time. This discharge shows a clear sequential time evolution of the ($n=3, 2$) modes. Formation is completed at 0.4 msec and discharge terminates at 0.75 msec. Toroidal dependence of B_θ is shown with respect to the $n=0$ component (circles) at various times in the discharge.

angle θ . In Fig. 4, the poloidal flux (a) captured by the spheromak drops suddenly (relative to the formation time) during the same period that there is a large increase in the toroidal flux (b) in the plasma. Mode activity is high during this relaxation period. Formation is complete, in this case, at 0.4 msec, which is also when the external circuits are no longer driving the discharge.

A significant finding is the temporal progression of these modes through an $n=5, 4, 3, 2$ sequence (Fig. 3) as q rises through rational fractions m/n . Comparison of the observed modes and the sequence of occurrence with theory suggests that these modes are due to resistive MHD instabilities.

The n -modes are resolved by Fourier-analysis of poloidal field measurements from 16 magnetic pick-up coils distributed toroidally. The poloidal mode number is determined to be $m=1$ from emissivity measurements, using a 19-channel array of silicon surface-barrier detectors sensitive to ultrasoft (≥ 10 eV) X-ray radiation, which show a dominant $m=1$ structure which rotates. Theoretical analysis predicts that the $m=1$ modes are most unstable.

The tendency of the spheromak to relax towards a more stable minimum-energy state has led to proposals for techniques using dc or low-frequency ac for sustaining the configuration (see below).

ELECTRON-TEMPERATURE AND SCALING STUDIES

Peak electron temperatures were increased from approximately 50 eV to just over approximately 100 eV after several improvements: Toroidal plasma currents for stable discharges were increased from 200

Figure 4. Time evolution of (a) maximum poloidal flux Ψ_{max} , (b) toroidal flux Φ included in the poloidal flux contour at a distance $[\Psi - \Psi_{max}] = 0.06$ Vsec from Ψ_{max} and (c) q on the magnetic axis. There is a precipitous drop in Ψ_{max} and a concurrent sudden and large increase in Φ during the period of strong magnetic mode activity.

kA to over 300 kA. Stabilization of rigid-body instabilities increased the plasma lifetime (allowing for further heating) and decreased plasma-wall interaction (reducing impurity radiation). Improved vacuum conditions, using auxiliary pumping, resulted in lower levels of oxygen and carbon impurities.

An important observation in preliminary scaling studies is that the electron temperature increases with plasma current¹³ (Fig. 5), generally faster than linearly, in rough agreement with the commonly quoted RFP scaling where beta is constant. This trend is significant since it indicates that the electron temperature is not limited by impurity radiation losses. This result emphasizes the need to study higher-current operation.

Figure 5. Electron temperature measured in the S-1 device versus bank voltage ($I_p \propto V_{bank}$). The electron temperature T_e increases in proportion to $I_p^{0.5-1.0}$ with $\alpha \approx 0.5-1.0$. Average electron density $\bar{n}_e \approx \text{const.}$

Preliminary examination of particle and energy confinement in S-1 has recently begun.¹⁴⁻¹⁶

INDUCTIVE SUSTAINMENT EXPERIMENTS

Increased understanding of the relaxation phenomena in S-1 has provided the capability and motivation to use inductive current drive¹⁷ to achieve significantly higher plasma currents in the future, thus allowing confinement studies of hotter spheromak plasmas. One scheme for inductive sustainment is the use of a poloidal flux transformer along the major axis. This technique does not compromise two important advantages of a spheromak configuration: translation and compression. The transformer is similar to the ohmic-heating (OH) transformer in a tokamak, but it is inserted from only one end of the device. This method of sustainment relies heavily on plasma relaxation.

A prototype S-1 device was used to test this technique. This experiment was successful in demonstrating that not only the toroidal plasma current but also the toroidal magnetic flux in the plasma could be

Equilibrium Field Pulsed (EFP) Coils

SPHEROMAK S-1-U

Figure 6. Schematic of how a poloidal flux transformer installed along the axis of the S-1 device might look.

increased and prolonged while maintaining a spheromak configuration.

The operation of this type of transformer in S-1 has been simulated¹⁸ using a two-dimensional computer code model with a term in the mean-field Ohms law which describes three-dimensional relaxation effects and flux conversion. This simulation has successfully demonstrated that the toroidal current can be increased from an initial level of 0.5 MA to the 1.0 MA level, while maintaining a relaxed spheromak plasma configuration, for a poloidal flux swing of approximately 1 Vsec. A schematic of how a poloidal flux transformer might be installed in S-1 is shown in Fig. 6.

UPGRADE

S-1 operations were temporarily shut down in July, 1985 to concentrate efforts and funds on a two-part program for upgrading the plasma current capability of the S-1 device. The first part was the design and

fabrication of an improved flux core for reliable operation at current levels higher ($I_0 \rightarrow 600$ kA) than previous design and fabrication allowed. Major changes from the old design included:

- Use of solid conductors (with cooling channel) in the flux core in place of stranded cable.
- Redesign of the feedthroughs that carry the pulsed power from outside the vacuum vessel to inside the flux core for added strength and added ease of leak checking.
- Use of alternate methods of forming the flux core liner. Most importantly, the liner is now explosion formed instead of spun, eliminating significant irregularities in its thickness. To reduce its thickness, chemical milling of the liner is still performed, but the operation is much simpler since the liner, after explosion forming, is now much more uniform. Also, fiberglass backing now strengthens the thin (0.010 mil) liner.

Otherwise, the spatial dimensions of the core have remained the same. Operation with the upgraded flux core is expected to commence in April 1986.

The second part of the upgrade involved the design of a poloidal flux transformer based on the experimental and theoretical work mentioned above. Fabrication and installation of this transformer is expected to proceed during the coming year.

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ADVANCED CONCEPTS TORUS-I

The Advanced Concepts Torus-I (ACT-I) is a steady-state 5-kG toroidal device with minor and major radii of 10 cm and 59 cm, respectively. The main research effort in the ACT-I experimental program during FY85 was directed towards fast-wave propagation and current drive,^{1,2} and, in these experiments, fast-wave current drive was successfully observed for the first time. In FY85, the ACT-I group also developed new concepts for current drive including viscous current drive,³ dc helicity injection via an electron beam, and ac helicity injection with a pusher coil. In FY86, the ACT-I project will be redirected towards this new initiative, the Current Drive Experiment,⁴ which is designed to test these new ideas and to investigate the physical processes relevant to efficient current drive and to the current-profile control based on nonclassical diffusion of radial current.

FAST-WAVE CURRENT DRIVE

The maintenance of steady-state plasma current is one of the most important objectives of tokamak fusion research, and in recent years lower-hybrid current drive (LHCD) has produced impressive results. For tokamak reactor operation, however, there still remain problems such as the density limit, scattering by density fluctuations, parametric instabilities, etc., which might be overcome by using other types of radio-frequency (rf) waves. In particular, the use of the fast wave for current drive has received attention in recent years because of its relatively favorable wave accessibility properties in reactor regimes.

The fast-wave current-drive (FWCD) experiment on ACT-I was conducted in an electron-beam-produced helium plasma with density $\bar{n}_e \approx 3 \times 10^{12} \text{ cm}^{-3}$. The electron beam also provided a unidirectional fast-electron population to facilitate efficient unidirectional absorption of the fast wave.⁵ To excite the wave, a Faraday-shielded single half-turn loop antenna was used, of the same type as those commonly employed for fast-wave ion cyclotron heating in tokamaks. Through a number of rf diagnostics (magnetic loop probes, Langmuir probes, and far-infrared laser scattering), the fast wave was identified and it was confirmed that this mode indeed can permeate the entire torus.

Monitoring the signal from a Rogowski loop, fast-wave current drive was observed as the rf power was pulsed on. From an initial value of 30 A, the circulating current doubled when 1 kW of rf power was coupled into the plasma, as shown in Fig. 1(a). The amount of

Figure 1. Fast-wave current drive (FWCD). (a) Evolution with time of the circulating current. The 1-kW 18-MHz radio-frequency power was enabled for 5 msec. Plasma parameters were $B_0 = 4.7 \text{ kG}$, $\bar{n}_e = 2.0 \times 10^{12} \text{ cm}^{-3}$, $T_i(\text{center}) = 5 \text{ eV}$, and $T_e(\text{center}) = 17 \text{ eV}$, with approximately 1% unidirectional superthermal electrons having a mean energy of 500 eV. (b) Fast-wave cutoff densities (open triangles) and current-drive threshold densities (solid points) for various excitation frequencies. (86X3063)

driven current was similar to that observed in previous LHCD experiments in ACT-I, but here the current was driven at much higher density. The critical density factor ω_{pe}^2/ω^2 was about 100 in this experiment, well exceeding the limit of unity found for the lower-hybrid-wave experiments.

A low-density limit below which the current drive disappears was observed. The scaling of this threshold density with excitation frequency was experimentally determined: for a given frequency, the plasma density was gradually lowered while holding all other parameters constant until the rf-driven current began to vanish [solid points in Fig. 1(b)]. The fast wave propagates in the plasma only above a certain density; the scaling of this cutoff with frequency was measured using magnetic probes inserted into the plasma [open triangular points in Fig. 1(b)]. Reasonable correlation is observed between the current-drive threshold density and the wave propagation density cutoff, supporting the conclusion that the current is, in fact, driven by the fast waves.

EXCITATION OF LOWER-HYBRID WAVE BY A FAST-WAVE ANTENNA

Parasitic excitation of lower-hybrid waves by a fast-wave antenna can result in reduced fast-wave current-drive efficiency. In an earlier experiment⁶ on ACT-I, parasitic excitation of the ion-Bernstein wave [in the ion cyclotron range of frequencies (ICRF)] by a fast-wave ICRF antenna had been investigated. Now, in the ACT-I fast-wave current-drive work just described, the density of the plasma was chosen so that only the fast wave could propagate in the plasma, thus avoiding parasitic excitation in this experiment. In order to investigate parasitic phenomena, the density of the ACT-I plasma was lowered so that the lower-hybrid wave could propagate in the plasma. In this regime, lower-hybrid wave excitation was seen even though the antenna was covered with a Faraday shield to suppress direct electrostatic coupling. The observed excitation was comparable to that from an electrostatic antenna that is known to be an efficient lower-hybrid wave exciter.¹ This parasitic excitation mechanism, which arises due to the $\vec{E} \times \vec{B}$ plasma response in the density gradient region,⁶ presents a potentially serious complication for the planned fast-wave current-drive experiments in tokamak plasmas.

CURRENT-DRIVE EXPERIMENT

Fiscal year 1985 witnessed a transition from the rf-wave oriented ACT-I research to the resistive-MHD oriented current-drive experiment (CDX) research.⁴ The major objective of the CDX is to investigate nonclassical plasma current diffusion mechanisms which may lead to more efficient methods for driving

steady-state current and for controlling the current profile, both crucial for economic tokamak reactors.

In order to drive plasma current, it is necessary to inject "helicity" into the plasma (helicity is a quantity closely related to the amount of current in the plasma). Inductive ohmic drive and noninductive rf current drive are the two main methods now used for helicity injection into tokamak plasmas. However, the former

Figure 2. The CDX Experimental Setup. (a) A sketch of the configuration for dc helicity injection; the electron beam flows from cathode to anode. Calculated poloidal flux contours are shown for a discharge with $I_p = 2.0$ kA. (b) A schematic of ac helicity injection with a pusher coil. Alternating current in the pusher coil drives nearby plasma in and out. That velocity, interacting with an oscillating portion of the poloidal field, produces a net current according to $\vec{v} \times \vec{B} = \eta \vec{J}$. (86X3061)

method is not inherently steady-state and the efficiency of the latter may not be high enough for reactor application. Recently, other types of helicity injection have been proposed that are generally called "dc" and "ac" helicity injection. In the CDX, dc helicity injection will utilize a nonrelativistic electron beam to introduce the helicity. Figure 2(a) shows the proposed setup: the electron beam is injected from a diverted region into the main plasma region and as the beam circulates around the main current-carrying plasma, the beam's helicity is transferred to the main plasma. In the second approach, ac helicity injection, currents in a pusher coil and in an ohmic-heating transformer coil are modulated with proper phase relations, Fig. 2(b). The resulting $\vec{v} \times \vec{B}$ field drives steady-state current in the outer region of the plasma. For both dc and ac helicity injection, the current is generated near the plasma edge and diffuses into the inner region of the plasma to offset the resistive current decay. The process requires a nonclassical mechanism for current diffusion such as a current-profile-dependent instability. For example, a strong edge current triggers the double-tearing instability provided its direction of flow is parallel to that of the interior current. Magnetic turbulence associated with the instability then facilitates the rapid radial penetration of the edge current. This penetration can be modeled by adding to Ohm's law a new term—one which represents the mean-field behavior of the instability-driven turbulence as an anomalous shear viscosity for parallel electron flow.³ In fact, the strongly asymmetric character of the current-penetration condition gives rise to an interesting current-drive concept called "viscous current drive (VCD)".³ One implementation of this concept calls for repeated pulses of the primary circuit of the ohmic-heating transformer. Due to the unidirectional nature of the current diffusion, the plasma itself rectifies the transformer-induced alternating current resulting in a net steady-state current.

During FY85, much of the preparatory work for CDX

was carried out by the ACT-I group. A sophisticated data acquisition system will record CDX data and will also control a two-dimensional scanning probe. Fast time-resolved images of the plasma will be obtained with a newly developed technique dubbed "box-car photography" that makes use of a state-of-the-art electronically controlled polarizer. Plasma density and fluctuation measurements will be made with a dual-beam far-infrared laser system, now being constructed. One of the most important additions for CDX is the new internal coil system consisting of a four-turn pusher coil and two sets of diverter coils, shown in Fig. 2(a). These coils will facilitate electron-beam injection and will be used for the ac helicity injection experiments, as well as for plasma shaping and positioning. Finally, rapid data acquisition, particularly useful for two-dimensional mapping of the plasma, will be possible by pulsing the CDX discharge several times per second.

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X-RAY LASER STUDIES

During FY85, much progress was made in the area of X-Ray Laser Studies at the Princeton Plasma Physics Laboratory. Work continued on the primary experiment (Experiment 1) which involves focusing an approximately 1-kJ CO₂ laser onto a carbon disc.¹ The resulting carbon plasma is confined radially by a strong ($B = 90$ kG) solenoidal magnetic field. The plasma is, however, free to expand axially and a relatively long plasma column ($L \sim 1$ cm) is produced. The plasma cools rapidly, primarily by radiation losses, resulting in strong recombination. The higher-energy levels are populated first and, in this way, a population inversion is created between levels $n = 3$ and $n = 2$ in the hydrogen-like carbon VI ion. This allows for amplified stimulated emission at the transition wavelength of 182 Å which is in the soft X-ray regime. Experimentally, stimulated emission has been observed at intensity levels of 100 times that of spontaneous emission, which compares well with previously measured values reported in the FY84 Annual Report.² Experiments using a soft X-ray mirror, with an effective reflectivity of approximately 12%, showed significant increases ($\sim 120\%$) in the X-ray emission providing further evidence of stimulated emission. The main advances in this experiment, during FY85, included: use of multichannel systems, improved target design, improved methods for extreme ultraviolet (XUV) mirror alignment and initial divergence measurements.

Along with the experimental work, many new theoretical and numerical code results were produced during FY85. In particular, a one-dimensional (1-D) hydrodynamic/atomic physics code was developed.³ The code predicted spatial and temporal characteristics of the gain, for the 182 Å, $n = 3$ to $n = 2$ transition in hydrogen-like carbon, which was in good agreement with the experimental observations. Studies were also made of the effect of oxygen, which is present in the plasma, on the cooling rates.^{4,5} Methods to enhance the radiative cooling rates of the expanding plasma by including high-Z materials in the carbon target were also investigated.⁶

Much of the effort in FY85 was directed towards a new two-laser approach to produce an X-ray laser at shorter wavelengths. A collaborative study⁷ to examine the possibility of using multiphoton processes to achieve X-ray lasing action was undertaken. This resulted in a proposal to develop a system which uses a powerful picosecond KrF* laser (248 nm) to produce a population inversion in krypton-like or argon-like ions to obtain gain at X-ray wavelengths (Experiment 2). The laser medium (the krypton- or argon-like ions) would be produced by the irradiation of a target

by a 1.5-kJ CO₂ laser. A 100-kG magnetic field would confine this plasma which would then be irradiated by the picosecond KrF* laser pulse. Work to develop the major subsystems involved in the project was started in FY85. This included experimental design, construction of a new laboratory, optical design and ordering of components for the picosecond laser, and design and preparation of the target area including the magnet and diagnostics. The entire system should be completed in the upcoming year.

The X-Ray Laser Group was expanded during FY85. The research has also attracted much collaborative work with physicists both within Princeton University and from other institutes. In FY85, the first doctoral degree was awarded for work in X-Ray Laser Studies at Princeton University. There are, currently, four graduate students involved in all experimental and theoretical aspects of the project.

EXPERIMENTAL SETUP—EXPERIMENT 1

Figure 1 shows the basic approach followed in Experiment 1. Details of the setup have been provided in previous reports¹ and only a brief description is included here.

The CO₂ laser beam is approximately 25 cm in diameter and is focused by an f/10 Cassegrain arrangement to an approximately $200 \times 400 \mu\text{m}$ elliptical focal spot. The pulse energy is variable from 0.1–1.0 kJ and the pulse width is approximately 80 nsec full width at half maximum (FWHM). The maximum power density on target is $\sim 2 \times 10^{13}$ W/cm². The target chamber is situated along the axis of a 1-m

Figure 1. Experimental arrangement of the Soft X-Ray Laser Experiment—Experiment 1.

long solenoidal magnet, normally operated below 100 kG.

The magnetic field radially confines the plasma but allows free axial expansion. The large-aspect-ratio (axial length $\gg$ radius) plasma thereby formed is desirable in that a relatively uniform axial gain path is produced while the sharp radial gradients allow effective cooling by escaping line radiation.

A linear array of optical fibers is fed into a streak camera to provide an overall view of the spatial and temporal development of the plasma. The primary diagnostic is performed with two XUV spectroscopic instruments monitoring, simultaneously, the radiation in the axial and transverse directions.

Several improvements were introduced to the instrumentation during FY85. Multichannel systems were added to both the transverse (SOXMO5) and the axial (Minuteman) XUV instruments. This greatly simplified data acquisition and improved the system calibration by providing a wide range of spectroscopic

data on a single shot. Examples of the multichannel output are given Fig. 2. The primary measurement made with this data is the enhancement (amplification) level.

Enhancement (amplification), E , is defined by,

$$E = [I(182 \text{ \AA})_{\text{axial}} / I(182 \text{ \AA})_{\text{transverse}}] \times R,$$

where $I(182 \text{ \AA})$ is the intensity of the 182- $\text{\AA}$ line and R is the relative instrument sensitivity. The one-pass gain, G , is related to the enhancement by,

$$E = [\exp(G) - 1] / G.$$

For the data shown in Fig. 2, the measured gain was $G \sim 6-7$.

The axial instrument was further modified by the inclusion of a translation system. A bent, grazing-incidence focusing mirror was used to bring the signal to the spectrometer, which could then be translated from shot-to-shot in the horizontal plane. In Fig. 3, the line intensities from several shots taken at different horizontal positions, including those shown in Fig. 2 (corresponding to a position of 250 μm), are presented. In order to observe the nonlasing lines, the

Figure 2. The XUV Spectrometer multichannel output showing transverse and axial line intensities in the 145-190 $\text{\AA}$ region. Measured gain for C VI 182- $\text{\AA}$ line is approximately 6-7.

Figure 3. Relative divergence measurements of lasing line C VI 182 $\text{\AA}$ and nonlasing lines O VI 173 $\text{\AA}$ and C V 186 $\text{\AA}$ from Experiment 1.

sensitivity of the axial instrument was increased resulting in saturation of the detector in the 150–200 μm horizontal range. The data in this region were determined by comparing the intensities at the FWHM. Initial results indicate that the relative divergence of the lasing line CVI 182 $\text{\AA}$ is much less than the nonlasing lines CVI 173 $\text{\AA}$ and CV 186 $\text{\AA}$ (see Fig. 3).

Theoretical considerations (discussed below) suggest that maximum gain would be expected in the outer regions of the plasma column due to increased recombination in the cooler, higher-density plasma which is present there. As was reported in the FY84 Annual Report,² by masking a carbon disc target (see Fig. 1) so that the axial and transverse spectrometers observe only the off-axis region of the plasma, maximum enhancements of $E \sim 100$ ($G \sim 6.5$) were observed. During FY85, the target design, which had included a single thin carbon blade, was modified by improving masking techniques and including up to four blades. This provided better reproducibility of the high-gain medium.

In order to find the radial region of the plasma column with the maximum one-pass gain G , the CO_2 laser was focused on the target at different radial positions. The results of these measurements and comparison with theory (discussed below) are shown in Fig. 4. These data were taken under nonoptimal conditions corresponding to a laser energy of approximately 450 J and a magnetic field strength $B = 90$ kG. From Fig. 4(b), one can see that the enhancement rapidly rises off the central axis at a radial position near $r \sim 1.5$ mm.

Initial results showing a 120% increase in the intensity of the stimulated emission by using an XUV mirror (with 12% reflectivity) on axis, were reported in the FY84 Annual Report. The mirror had a radius of curvature $r = 200$ cm and alignment of the mirror with the high-gain region (a thin cylindrical shell) of the plasma was difficult. Mirrors with radii of curvature 100 cm and 85 cm were obtained and a remote three-axis rotator was introduced to allow greater precision in alignment of the mirrors. Unfortunately, these mirrors had to be placed too near the plasma and were damaged after just a few shots. The main direction for improvement with the XUV mirrors lies with alignment techniques and cavity development. With the development of an X-ray laser cavity, the device will become more efficient.⁹

An X-ray laser will find numerous applications in medicine, biology, and semiconductor manufacture. An X-ray source which can be focused and which is monoenergetic would provide a much more precise tool for use in medical diagnosis. Techniques in X-ray microscopy and microholography may be developed and provide a detailed look at living cells which would be of great importance in many areas, including cancer research. The laser could also be used to provide a simpler and less expensive method for imaging biological molecules which would have a tremendous impact in molecular biology and biotechnology (a rapidly growing industry). The miniaturization of large-scale integrated circuits through X-ray laser lithography would have obvious application to semi-

Figure 4. (a) Gain and temperature profiles as a function of radial position using one-dimensional MHD/atomic physics numerical code. Profiles correspond to time of maximum gain. (b) Enhancement of CVI 182- $\text{\AA}$ line measured at different distances from the center of the plasma column (corresponding to different distances of the CO_2 laser focus from the horizontal slot). In this experiment, conditions were not optimized for maximum gain.

conductor manufacturing and, consequently, a significant impact in many industries. It is safe to say that many other applications of the X-ray laser will be discovered in the future.

THEORY AND NUMERICAL MODELING

Rapid three-body recombination (TBR), by virtue of a sudden drop in electron temperature, leads naturally to population inversion in the recombined ion since TBR principally populates upper atomic levels. As mentioned, this effect has led to observation of an amplification (enhancement) of approximately 100 for stimulated emission at 182 $\text{\AA}$ in a laser-produced, hydrogen-like carbon plasma.

A one-dimensional hydrodynamics plus atomic physics code has been developed⁹ to aid in understanding these results. Because the laser pulse length is much longer than the compressional Alfvén radial transit time, radial pressure balance is quickly established and persists, to a good approximation, both during and after the laser pulse. The centrally peaked temperature profiles associated with strongest heating at the laser focus lead to a density minimum on the cylindrical axis of symmetry. It is found that radiative cooling of the electrons, principally by resonance radiation from hydrogen-like and helium-like carbon, effectively produces much of the required temperature decrease from initial temperatures of approximately 200 eV established at the peak of the laser pulse. However, this cooling rate decreases to a negligibly small value at temperatures of approximately 45–50 eV, whereas significant gain is observed only for rapid temperature drop to somewhat lower temperatures, approximately 20 eV. One possible explanation for the observed gain is that the ion species, distinguished by ionization state, diffuse relative to each other and to the electrons, which are strongly tied to the magnetic field, with the radial temperature gradient then being seen as time varying by the outwardly diffusing, fully stripped carbon ions. Inclusion of classical, collisional, ion-ion diffusion provides too small an effect. However, artificial enhancement of the diffusion rate by about an order of magnitude yields time and space variation for the gain profiles in good agreement with experiment. Figure 4(a) shows a theoretical radial profile which can be compared directly with experimental data given in Fig. 4(b). One can see that in both cases the gain rises rapidly off the central axis, near the position $r \sim 1.5$ mm. Under more optimal experimental conditions the maximum enhancement was observed in a thin cylindrical shell of radius $r \sim 1.3$ –1.5 mm, in good agreement with theory. Present effort in this area concentrates on an examination of possible hydrodynamic modes which could produce this anomalous ion diffusion.

A detailed computational study of the cooling rate of oxygen in a high-density time-dependent plasma was completed.⁴ This gave insight into the additional cooling which oxygen can provide in the experiments

with carbon plasmas. A simpler two-level model was also devised as a guide for the selection of the most efficient coolant species.⁵

Studies have also been made of the effects of inclusion of relatively high atomic number material mixed with the active target material in order to enhance the radiative cooling rate in a freely expanding, laser-produced plasma.⁶ Results of computations (Fig. 5) for a mixture of carbon (C) and selenium (Se), in which hydrogen-like carbon is the gain medium and selenium is the cooling medium indicate that optimal gains of several per centimeter are achievable at 182 Å for a freely expanding, initially solid, C/Se plasma in which the carbon and selenium fractions are comparable. Computations lend theoretical support to experimental results obtained with such targets at the University of Rochester Laboratory for Laser Energetics on the OMEGA neodymium glass laser operating at 0.35 micron wavelength.

X-RAY LASING ACTION USING MULTIPHOTON PROCESSES—EXPERIMENT 2

It has been demonstrated^{9,10} that multiphoton absorption can lead to multi-ionization and excitation of an atom. Studies have been undertaken to determine the possibility of using high-order multiphoton absorption to provide high gain and lasing action at much higher energies (shorter wavelengths).^{7,11}

Unlike other experiments which have used a powerful, short-pulse laser to both ionize and excite a cold target, the basic idea in this scheme is to use a high-energy CO₂ laser to produce a plasma medium and use a powerful, picosecond laser (PP-laser) to produce a population inversion in the medium. This simplifies the role of the PP-laser and, more importantly, provides access to higher-energy transitions and the possibility of X-ray lasing action.¹¹

Present experiments¹ have already demonstrated that the conditions for population inversion and gain at 182 Å exist in a laser-produced, hydrogen-like carbon plasma even without the interaction of a picosecond laser pulse. The additional multiphoton processes are expected to significantly increase the population inversion and lead to yet higher gain in the spectral region below 100 Å.

A collaborative study⁷ was undertaken to determine the feasibility of exciting either one subvalence electron or two valence electrons of an ionized atom through multiphoton processes. The study dealt specifically with the excitation of ions in the krypton isoelectronic sequence (up to Cd¹²⁺) with a powerful picosecond KrF* laser (248 nm). It was found that excitation of two valence electrons (the 4s²4p⁴5s² state) was especially attractive for the development of an X-ray laser because of the faster progression to shorter wavelength (higher energy) with increasing atomic Z number. The minimum wavelength obtained was 89 Å in Cd¹²⁺. It was also found that the best chance for successfully populating the excited states

Figure 5. Temporal profiles of gain, temperature, and level populations for CVI 182 Å for carbon cooling by selenium.

As a result of these studies, an experimental program has been proposed. This will consist of three stages: (1) the design and construction of a powerful, picosecond KrF* laser, (2) experimentation with the goal of increasing the population inversion and gain in CVI at 182 Å by the interaction of the PP-laser with the confined plasma column, and (3) studies of the interaction of the PP-laser with multi-electron high-Z ions in a recombining plasma.

A new laboratory which will house the picosecond laser and the target and diagnostics area was constructed. Major elements such as construction of the rf-shielded control room, design of the gas handling and ventilation system and the electrical cable layout, installation of cable trays and the data acquisition system, ordering of the computer system and optical layout (described below), and ordering of components for the picosecond laser have been completed.

spectrometers and design of the various support structures for the diagnostic has begun.

The dye amplifier is pumped with YAG pulses taken from the same source as those used to pump the main dye oscillator. By using the same source to pump both the main oscillator and the dye amplifier it is hoped that difficulties associated with pulse synchronization will be reduced. The energy output from the dye amplifier is expected to be a few millijoules.

The next stage of the laser design involves the use of nonlinear crystals to produce the 248-nm wavelength characteristic of the KrF* laser. This is a two-stage process involving frequency doubling of the dye pulse followed by mixing with a 1064-nm signal from the YAG laser. The laser intensity in these nonlinear crystals will be approximately 2–3 GW/cm², which should provide high conversion efficiency. The output from this stage will be a 1-psec pulse of 248-nm radiation with energy of a few hundred microjoules.

The final stage of the system uses two KrF* amplifiers designed to increase the pulse energy to the joule level. The first of these amplifiers will be a

commercial unit, while the other will be fabricated at PPPL. The initial design work and ordering of some long-lead items for this final amplifier have been completed.

The entire picosecond laser system should be completed and available for experimental work in the upcoming year.

GRADUATE STUDIES

To date, five graduate students have been involved in the X-ray laser program at the Princeton Plasma Physics Laboratory. H. Milchberg completed his doctorate^{12,13} in FY85. C. Keane is nearing completion of his studies and is currently writing his thesis.¹⁴ Chang Hee Nam has performed detailed calculations of cooling rates associated with the inclusion of relatively high-Z materials in the targets and has begun experimental work associated with the PP-laser. Dong Eon Kim has begun initial experimental work dealing with XUV mirror calibration and alignment techniques, and Youngjoo Chung is involved with construction and calibration of the spectroscopic instruments to be used in the detection system for Experiment 2.

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THEORETICAL DIVISION

The work of the Theoretical Division includes the development of new theoretical concepts and computational techniques to ensure that future theoretical work will be well grounded and will be on the forefront of what is possible, the application of the presently available understanding and tools to the interpretation of experiments, and the development of new ideas for experiments and the application of computational resources to the conception and design of device upgrades. These purposes are all involved in each of the Division's research projects. For example, the development of large MHD codes has enabled the Division to address the important physics issues relative to the nature of internal kinks and sawtooth oscillations and to contribute to the investigation of profile control. At the same time, these tools have been instrumental for the interpretation of experimental data and the design of new experiments, including the determination of the eddy currents in the walls of the PBX Upgrade and the design of axisymmetric stability control for tokamaks and spheromaks. The earlier work on internal kink modes and fishbone instabilities has been extended to include the effect of alpha particles in ignition experiments. The understanding of transport properties of toroidal devices has been extended through improved understanding of ion-temperature gradient instabilities by the application of a gyrokinetic formalism, the development of transport models which are consistent with the most expected kinetic instabilities, a new ripple bounce-averaged Fokker-Planck computer code for investigation of the lowest collisionality regimes in stellarators, and a careful analytical treatment of electron transport in three-dimensional systems. Progress has continued in the application of radio-frequency theory including good agreement between theoretical predictions of the energy and angular dependence of bremsstrahlung emission and the experimental measurements. Significant advances have been made this year in basic plasma physics, with an improved understanding of clump theory as it contributes to the formulation of turbulence models. In addition to its central role as a fusion theory group, the Division maintains a small program in space plasma physics to foster interaction with plasma physicists in different areas and has initiated an effort on the X-ray laser to support the activity in the Experimental Division.

ION TEMPERATURE GRADIENT INSTABILITIES AND ANOMALOUS TRANSPORT

Theoretical models of the electron diffusivity, which were developed during the last fiscal year, have been

augmented by a model of the anomalous ion transport due to the so-called η_i mode, where $\eta_i = (d \ln T_i / dr) / (d \ln n / dr)$. The nonlinear behavior of the η_i mode has been studied extensively using the gyrokinetic code.

During the 1985 fiscal year, theoretical models for the anomalous electron thermal diffusivity were developed. These models are consistent with reasonable global constraints on the current and electron-temperature profiles, as well as with the key properties of the kinetic instabilities most likely to be present, and they are in good agreement with experimentally observed scaling trends in low to moderate density ohmic discharges, Fig. 1.¹ For studying high-density ohmic

Figure 1. Comparison of theoretical and experimental electron thermal diffusivity in PBX.

discharges with flat density profiles, these models have been augmented during this fiscal year for the effect of toroidal ion-temperature-gradient-type (η_i) mode excitation.² A two-fluid steady-state transport code incorporating such effects was developed³ and has yielded results consistent with the observed trends. Application to results from the Alcator and Doublet-III experiments shows that, for the flatter density profiles corresponding to large η_i , density saturation occurs well below the neoclassical limit, and for more peaked density profiles (smaller values of η_i), density saturation moves closer to the neoclassical prediction.

The recent development of gyrokinetic simulation techniques where one can use large time steps, of the order of the shear-Alfvén transit time, and large grid

spacings, of the order of the ion gyroradius measured at the electron temperature, while keeping all the relevant kinetic and finite-Larmor radius effects intact, has resulted in meaningful investigations of anomalous transport problems associated with steady-state microturbulence.⁴ A variety of instabilities have been studied using a two-dimensional gyrokinetic code, providing considerable insight concerning the mechanisms responsible for the saturation of the instability as well as those giving rise to the ensuing anomalous transport. Of particular interest are the ion-temperature gradient-driven instabilities (η_i -modes).⁵

A typical time evolution of the electrostatic potential $e\Phi/T_e$ due to the instability in a system in which only a few nearly coherent unstable modes are dominant is shown in Fig. 2. Here $\eta_i = 4$ and $k_{\perp}\rho = 0.4$. The mode

Figure 2. Time evolution of the unstable η_i mode.

frequency ω_k and growth rate γ_k agree well with linear predictions based on a model using fluid ions and adiabatic electrons. A prediction of the saturation of the instability at $|e\Phi/T_e| \approx |\omega_k + i\gamma_k|/\omega_{ci}(k_{\perp}\rho)^2$, made with a nonlinear analysis of this model, compares favorably with the simulation results as well. The corresponding quasilinear ion thermal diffusivity $\chi_i \approx \gamma_k/k_{\perp}^2$ also agrees with the measured values, as shown in Fig. 3. However, the theoretical model predicts that χ_i should vanish in the steady state after saturation, since the phase difference between the potential and the pressure perturbations should vanish because there is no dissipation in the system. This disagrees with the simulation results of Fig. 3, which indicate that there is a rather prolonged relaxation period before χ_i settles to a small but nonvanishing value. The implication is that velocity-space nonlinearities, $(\partial\Phi/\partial x_{\parallel})(\partial f/\partial v_{\parallel})$, play an important role in controlling steady-state transport. This can be verified by inserting a small amount of electron-ion collisions into the simulation model. This shows a negligible effect on the linear stability and nonlinear saturation, but the resistivity provides a substantial increase in the steady-state ion thermal diffusivity. Thus, the param-

Figure 3. Time evolution of energy flux.

ter dependence of the final transport coefficient can differ markedly from that deduced from linear theory, bringing into question the adequacy of using quasilinear estimates for transport analyses. Similar calculations for systems demonstrating strong turbulence show no increase in χ_i .

RIPPLE-INDUCED TRANSPORT IN TOKAMAKS AND STELLARATORS

The theory of ripple-induced transport in both the banana-drift and ripple-plateau regimes has been generalized substantially⁶ to allow for a low-toroidal and nonzero poloidal mode number, to treat time variation of the ripple perturbation, and to account for bounce resonances. This makes the theory applicable to magnetic perturbations, which arise in tokamaks due to low- n MHD modes and design imperfections, and which can produce as much or more transport than that produced by the moderate- n ripple associated with the finite number of toroidal-field coils. Application of this theory to rotational equilibria with neutral-beam injection shows that, in contrast to previous belief, both the low- n and moderate- n mechanisms may explain the experimentally observed rotational damping times and steady-state rotation speeds.

A computer code (FPSTEL) which solves the ripple bounce-averaged Fokker-Planck equation numerically has been developed in its first applications made,⁷ Fig. 4. The code is much faster than the bounce-averaged Monte-Carlo codes which had been the fastest available approach. It makes possible the study of transport in the lowest collisionality regimes and provides a detailed picture of the distribution function as well as the more standard gross transport results, making possible a deeper and more direct comparison with analysis than before.

Figure 4. Comparison of different analytical numerical calculations of the diffusion coefficient. The solid lines are from analytical theory. The solid dots are from the Fokker-Planck code with $E_p > 0$, and the open circles with $E_p < 0$.

IDEAL MHD INSTABILITY STUDIES

The ideal MHD stability codes have been used to investigate the generality of the Troyon-Sykes beta limit, to compare the observed PBX magnetohydrodynamic activity with the theoretical predictions, and to study the stabilization of $n = 1$ modes by various wall configurations.

In an effort to understand the empirical scaling law, $\beta_{\max} \sim cI/aB$, the role of the current profile in determining the β limit has been examined. Several equilibria were chosen with the same dee-shape geometry and parabolic pressure profile, fixing the safety-factor q at the axis and at the plasma edge but adjusting its shape by changing α_1 where $q(\Psi) = q_{\text{axis}} + (q_{\text{edge}} - q_{\text{axis}})\Psi^{\alpha_1}$ with Ψ varying from zero on axis to unity at the plasma boundary. Contrary to expectation, there is a fairly strong dependence on the shape of the current profile. Flux-conserving equilibrium sequences with fixed values of α_1 and increasing values of β were generated and analyzed to determine the critical betas above which the $n = 1$ external kink mode and the ballooning mode become unstable, Fig. 5. A systematic dependence was observed, with the kink mode having the largest beta threshold at large values of α_1 , corresponding to a peaked current profile, while the ballooning mode threshold is highest at the small values. The kink mode is primarily driven by the current and can be stabilized by the magnetic shear. However, since the shear stabilization is limited, the pressure couples the different Fourier modes and drives internal modes which set the beta limit. The ballooning mode is driven by a combination of the pressure

Figure 5. Critical β dependence on current profile for kink and ballooning modes. The system is stable to the respective mode below the line and unstable above.

gradients and magnetic curvature. When α_1 is small, the local shear is more readily modified, leading to increased stability. The pressure profile plays an important role so that broad, flat profiles are needed to get higher-beta limits. These ideas have been exploited to access the second region of stability to ballooning modes in a dee-shaped plasma, as well as to demonstrate the existence of a second region of stability to kink modes in a bean-shaped plasma.⁸ These studies lead to the suggestion that the Troyon-Sykes scaling law is empirical, represents the limits set by the present operational constraints, and is essentially an accessibility limit. Better profile control may open the door to substantially increased β values. Besides profile control, plasma shaping can provide many benefits.⁹

The magnetic field at selected points in the vacuum region external to the plasma have been calculated from the stability analysis and compared to the results with actual loop measurements in PBX.¹⁰ The results are given in Fig. 6 for a typical high- β shot (#83724). Here the left-hand curves are the signals on the different Mirnov loops on a fine time scale starting at 574.9 msec, soon after the onset of the mode. The right-hand side is the $n = 1$ perturbed magnetic field obtained from the stability analysis at each magnetic loop, with the plasma given an arbitrary toroidal velocity to generate the time behavior. The relative amplitudes of the signals from the coils and the relative phases of the signals in loops 1 through 4, 7, 9, 12, 14, and 16 agree quite well with theory. Disagreement is found for loops 6, 8, 13, and 15 which are on the inner side of the plasma. No data was available from loops 5, 10, 11. Although the majority of the loop signals agree quite well with the measurement, the crucial in-out pairs, i.e., (7, 8), (13, 14), and (15, 16), have opposite parity when compared with the experimental data. Another discrepancy in the comparison is the time scale. The rise time of the loop signal is judged from the data to be approximately 120 μsec . While this

Figure 6. Experimental Mirnov probe signals (left) and theoretical calculations (right) for PBX shot #83724.

is faster than the time scale of typical resistive mode theory, it is much slower than the ideal growth time calculated with the wall at infinity. Improvements of the model to better represent the outer region and the conducting shell have been suggested which could remove these discrepancies. Thus, these models can be expected to provide insight into future magnetic measurements.

Suppression of the external kink mode could be an important ingredient for extending the high-beta limits in the PBX Upgrade.¹⁰ Extensive theoretical analysis of the stabilization of the $n = 1$ mode by various wall configurations has been carried out. The eddy current distribution, which arises on an external conducting shell due to the plasma boundary perturbations, and the perturbed magnetic field at several positions in the vacuum region, including the locations of the Mirnov coils, have been calculated. A typical theoretical case is shown in Fig. 7, where the growth rate of the $n = 1$ kink mode is given for a system with $\langle \beta \rangle = 8.8\%$, $1.03 \leq q \leq 4.2$, $R/a = 4.0$, $b/a = 1.4$, and $d/2a = 0.304$. Here R/a is the aspect ratio, b/a is the ellipticity, and $d/2a$ is the indentation of the plasma surface. These parameters were adjusted to get into the second region of stability to ballooning modes. The shape of the outer stabilizing plate is shown for the different points by the cartoons inserted into the figure. The

Figure 7. Kink instability growth rates for PBX-Upgrade model for different wall positions and shapes.

solid curve gives the growth rate as a function of the angle covered by the wall with $D/a = 0.3$, while the other points are plotted as functions of the wall distance D . Stabilization of this plasma, which is in the second region of ballooning stability, is possible if $D/a \sim 0.25$. Calculations taking into account the gap that must be present for the introduction of neutral beams show that stability can be obtained in the PBX Upgrade.

AXISYMMETRIC STUDIES OF NONCIRCULAR TOKAMAKS AND SPHEROMAKS

The tokamak simulation code TSC, developed to model axisymmetric transport time scale evolution and the positional stability and control properties of noncircular cross-section tokamaks, has been validated against both analytic test problems and against experimental data obtained from several controlled shots in PBX.¹¹ The results of modeling a controlled vertical instability in PBX¹² are shown in Figs. 8 and 9. In the experiment, the plasma was held in a bean-shaped configuration 0.5 cm above the $z = 0$ midplane by adding an offset term to the radial-field active feedback system. The radial-field system is short circuited at time $t = 0.4$ sec after plasma initiation, and the plasma displaces vertically off the midplane with an instability growth time characteristic of the resistive time of the passive aluminum plates. The experiment is

Figure 8. Magnetic flux contours for vertical stability test at (a) time of feedback shutoff, $t = 0.50$ sec, and (b) $t = 0.475$ sec.

modeled by running the code in a predictive mode, but using the values of the actual experimental currents in the vertical-field and shaping-field systems. Active feedback in the radial-field system is included with the computation feedback system offset to match the offset currents in the experiment. The plasma evolves into a resistive steady state in which the magnetic measures at the eight flux-loop locations agree with the experimental values. The active feedback system in the code is shut off at $t = 0.4$ sec, as it is done experimentally. The magnetic flux surfaces at the time of shutoff and at $t = 0.75$ msec after shutoff are shown in Fig. 8. The time history of the difference of the flux in loops 1 and 2, which is a measure of the vertical displacement, is shown in Fig. 9, together with the experimental results. The agreement for the time period before the experimental detector saturates is quite good. Another simulation with the horizontal conducting plates moved 4 cm closer to the plasma, both on the top and on the bottom, was performed as a sensitivity test. The flux difference plot for this run, also shown in Fig. 9, differs substantially from the original simulation and the experimental curves. This indicates that the simulation program can resolve this difference between plate locations adequately. The code has been applied to model the evolution to high beta of a PBX discharge and to show that a small inward radial shift of the plasma, caused by either a sudden thermal loss or by a decrease of the plasma internal inductance, can cause the system to lose ideal MHD time scale stability so that the plasma is lost. This result is in good agreement with the experimental description of disruptive PBX discharges. A typical unstable sequence is shown in Fig. 10, where a high- β plasma equilibrium (a) changes to a smaller major radius due to a disruptive thermal quench (b), and then displaces exponentially off the midplane due to the lack of ideal MHD time scale stability (c).

The code has been used to model other experiments and proposals, including the Tokamak Condition Variable (TCV),¹³ TFTR and its possible magnetic configuration,¹⁴ the Ignition Studies Project (ISP), and the PBX Upgrade.¹⁰ It has also been used to predict the consequences of adding an inductive current transformer to the S-1 Spheromak experiment.¹⁵ Axisymmetric modeling with only classical dissipation shows an increase of toroidal current and a shrinking and hollowing of the current channel, conserving

Figure 9. Comparison of simulation (theory) and experimental values of flux between two loops labeled 1 and 2. The upper curve is for a calculation with the top and bottom plates moved 4 cm closer to the plasma.

Figure 10. Disruption sequence for a PBX discharge.

toroidal flux. These unstable profiles will undergo helical reconnection, conserving helicity $K = \int \mathbf{A} \cdot \mathbf{B} \, dr$ while increasing the toroidal flux and decreasing the poloidal flux so that the plasma relaxes toward the Taylor state. This flux rearrangement is modeled by a new current-viscosity term in the mean-field Ohm's law which conserves helicity and dissipates energy.

THREE-DIMENSIONAL CODES

With renewed interest in stellarators and the recognition that three-dimensional effects are important in two-dimensional configurations such as tokamaks, work has continued on MHD codes for three-dimensional systems. Comparison of stability results from the stellarator expansion equilibrium and stability code STEP with the helically invariant code HERA and the fully three-dimensional code BETA showed remarkable agreement, demonstrating the efficacy of using asymptotic codes for modeling devices.¹⁶

A basic obstacle in obtaining three-dimensional equilibria numerically is the existence of islands and stochastic regions. This problem can be circumvented with an initial value code that uses time-dependent resistive and viscous relaxation to find ohmic steady states.¹⁷ The HBS code uses a fixed spatial grid and makes no assumptions about flux surfaces. It contains a fictitious velocity that provides rapid convergence to make the pressure constant in stochastic regions as the condition $\mathbf{E} \cdot \nabla p = 0$ implies. This has been used to solve a set of reduced equations that are applicable to high-beta, long-wavelength heliacs and stellarators. Heliac equilibria with magnetic islands and stochastic regions have been found. Toroidal curvature produces a large displacement of the magnetic axis. For ellipticity (major/minor axis ratio) $\lambda < 3$ and rotational transform $t < 0.4$, the toroidal shift limits beta to much lower values than in the straight helical case, of the order of 10% for typical parameters. Higher beta is possible in principle, since the equilibrium beta limit scales as $\beta \sim \epsilon N^2$, where ϵ is the inverse-aspect-ratio and N is the number of helical wavelengths.

A straightforward iteration approach, using natural coordinates associated with either the vacuum field or the field at any stage of the iteration and directly solving the equation $\nabla \times \mathbf{B}_{k+1} = \mathbf{j}_k$ for $\mathbf{B}_{k+1}$, is also being implemented as another way to circumvent the island problem. The necessary computational routines have been developed and the code has been written.¹⁸

RESISTIVE MODES, MAGNETIC ISLANDS, AND ENERGETIC PARTICLE EFFECTS

Resistive instability theory has included the study of kinetic stabilization of tearing modes, the control of magnetic island development by using localized current drive or heating, and the effect of resistivity on the "fishbone" instability.

Ordinary slab model resistive MHD theory of tearing modes is applicable only if the growth rate is faster than the drift frequency, $\omega^* = kv_D$, and if the inner layer thickness is larger than the ion gyroradius. These conditions are violated in hot plasmas, and it is necessary to include kinetic effects in both the electron and the ion physics of the mode. Then the mode develops a real frequency of order ω^* . This, in turn, implies that the ion-polarization currents are quite

large and that their divergence demands correspondingly large currents along the magnetic field lines. The mode frequency must develop a large negative imaginary part to cancel these currents, so that the tearing mode is stable in the slab approximation in the kinetic limit. The detailed proof of this stability has been demonstrated by obtaining the analytical solution of the integral equation governing the kinetic mode.¹⁹ This result can be reconciled with the experimental observation of tearing modes in high-temperature plasmas in two possible ways. First, the tearing layer is often in the cool outer regions where resistive MHD may apply. Second, the theoretical tearing layer may be thinner than equilibrium islands that exist so that the slab model does not apply. Then, a rough calculation shows that the already existing islands can evolve exponentially into a tearing mode if the condition for the resistive MHD tearing mode to be unstable is satisfied.

Resistive instabilities are responsible for much of the global behavior and the determination of the possible domains of operation of tokamaks. Their successful control could have definite advantages, preventing disruptions and making available new regimes of operation. Elimination of sawtoothing might allow operation with higher currents and more peaked current profiles, with q on axis well below unity. Simple analytic models and simulations show that local current drive or heating in the interior of a magnetic island is stabilizing. Although control of modes with $m \geq 2$ by this means is fairly straightforward, the control of the $m = 1$ mode is more difficult because of its proximity to ideal instability. This makes the necessary feedback amplitude scale unfavorably with temperature. Nevertheless, control of the $m = 1$ mode in its nonlinear regime is a distinct possibility.²⁰

The effects of finite resistivity on the energetic trapped-particle-induced $m = 1$ internal kink mode (the "fishbone" instability) have been analyzed.²¹ Due to the instability having a real frequency and the associated Alfvén resonance absorption at the singular layer, there exists a threshold hot-particle β value. Thus, finite resistivity provides a stabilizing effect by enhancing the absorption rate. In particular, the instability is predicted to be completely stabilized in large tokamaks such as the Joint European Torus (JET) where the hot-particle precessional frequency is smaller than that of the resistive internal kink scale, $\omega_A S^{-1/3}$.

RADIO-FREQUENCY CURRENT DRIVE

An important diagnostic of the lower-hybrid current-drive experiments conducted on PLT was the measurement of bremsstrahlung emission as a function of energy and angle. This can provide detailed information on the electron-distribution function. In order to compare the standard quasilinear theory with the experimental measurements, the bremsstrahlung was computed for the electron distribution determined from the Fokker-Planck code. Good agreement was

found, indicating that the quasilinear model is adequate to describe the wave-particle interaction in radio-frequency current drive.²²

NONFUSION PROGRAMS

Although the main emphasis of the group has been focused on fusion-related problems, effort has continued on problems such as the double sheath which interest the larger astrophysical community. With the emergence of a major experiment on the development of the X-ray laser, a theory effort to develop and apply a one-dimensional hydrodynamics plus atomic physics computer code has been initiated to aid in understanding the results. Results of this work are incorporated in the X-Ray Laser Studies section of this report.

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TOKAMAK MODELING

The Tokamak Modeling Group is engaged in modeling the plasma, impurity, and neutral gas transport in both existing and future tokamak experiments. Most of the modeling is of the predictive nature, but many applications are in the areas of interpretation of experiments and determination of the theoretically unknown model parameters. Model development, in general, requires a constant interaction with experiments, and the modeling is used both as a substitute and as an integral part of the experiments. Several computer codes have been developed by the Group for this purpose. The most general of these codes is BALDUR, a multispecies plasma transport code which incorporates a variety of models for sources, sinks, diffusion, and convection of the plasma energy and particles.¹ This code considers radial transport averaged over the magnetic flux surfaces. The scrape-off region created by divertors and limiters, where transport along the field lines often dominates, is studied with the PLANET code. This code is designed to run in conjunction with the neutral gas transport code DEGAS. The latter can be used with any of the codes where the interaction of the plasma and the neutral gas is important, and it is also used alone to study pumping and other gas transport problems. Finally, the MIST code follows impurity species through various stages of ionization, charge-exchange, radiation, and transport within the plasma. The DEGAS and MIST codes involve very detailed models for the numerous atomic processes and for the plasma and neutral interactions with the walls. Apart from predicting and interpreting the behavior of present experiments, the codes have the important role of predicting the performance of the designs for future tokamaks now in the planning stage.

PLASMA TRANSPORT

There have been a number of important model developments in the area of plasma transport. In order to simulate plasma confinement in tokamaks with noncircular cross sections, a new 1-1/2 dimensional version of the BALDUR transport code was developed. It solves the flux-surface-averaged transport equations together with an equilibrium force balance equation to determine the shape of magnetic surfaces within the plasma. The shape of the magnetic surfaces affects the area through which the plasma is diffusing or convecting, the differential volume within which particles and energy are deposited or removed, and the depth of neutral-particle penetration. Changing the shape of the magnetic surfaces as a function of time

can be used to compress or expand the plasma volume or induce electric fields which affect the plasma current. The shape of the magnetic surfaces also has a strong effect on large-scale instabilities and alters the physics of plasma transport.

Improvements of the one-dimensional BALDUR code include the extension of the code's ability to model transport coefficients dependent on a wide variety of plasma parameters and an improvement of the neutral impurity influx model. The new 1-1/2 dimensional BALDUR code was used to study compact ignition tokamaks (Fig. 1), the transition from

Figure 1. Left: Cross section of magnetic flux surfaces (closed contours) for a compact ignition tokamak with 1.23 m major radius, 0.45 m halfwidth, 10.5 T toroidal field, and 10 MA toroidal current. Right: Ion temperature (vertical axis) as a function of minor radius (horizontal axis) and time (receding axis) with 20 MW of auxiliary heating and beta-limited confinement.

circular to bean-shaped plasma cross sections, and strong adiabatic compression.²⁻⁴ The one-dimensional version of BALDUR was used to evaluate transport models (proposed for use in modeling compact ignition tokamaks) by simulating ohmic and neutral-beam-heating experiments in TFTR. The neo-Alcator transport model reproduced the observed $q(a)$ dependence of τ_E , as well as the density dependence of τ_E in the unsaturated regime. It (surprisingly) also reproduced most of the τ_E degradation with power in high-density, deuterium neutral-beam-heated plasmas. The model failed to produce the experimentally observed high-density saturation in τ_E or the beam power dependence of τ_E at moderate densities.

A predictive study of TFTR deuterium-tritium (D-T) plasmas with more realistically, centrally peaked plasma density profiles produced $Q = 1$ (breakeven)

plasmas with a 30% lower τ_E than previously thought necessary. Theoretical transport models were also tested. The Tang⁵ microinstability drift-wave electron-energy transport model, applicable to ohmically heated plasmas, predicted temperature profiles and loop voltages in agreement with experiment (Fig. 2) for the high-density cases simulated.

Figure 2. Comparison of TV Thomson scattering electron-temperature profile and BALDUR simulation results for TFTR ohmic shot # 14618 with Tang microinstability transport model. (86T1011)

IMPURITY TRANSPORT

Though impurity transport is taken into account in BALDUR, using a coronal equilibrium model, a much more realistic treatment is provided in MIST, a one-dimensional multispecies impurity transport code. The development and application of MIST has been in two principal directions during the past year, both motivated by needs of the experimental groups.

A principal effort was directed towards providing, on a more routine basis, the detailed modeling capabilities of the MIST code for the analysis of spectroscopic and other impurity data. The code now has direct access to plasma profile data from the TFTR shot data base. This feature, together with parameterized empirical transport model, automatic access to spectroscopic line excitation data, and other developments, has allowed MIST to be used directly by the experimentalists as a principal tool for the analysis of all TFTR impurity data.

Recent spectroscopic, X-ray, and visible bremsstrahlung data from the PBX tokamak has indicated a variety of interesting impurity phenomena, including strong on-axis accumulation of the impurity density. Interpretation of this data was based on MIST code simulations, and in particular, development of a model for the impurity transport during sawteeth so that these effects could be included in the analysis.

In a related direction, work was started on a new and flexible atomic physics data base software system specifically directed towards the needs of fusion plasma modeling. This system, when fully developed, should facilitate the manipulation of needed atomic data for plasma models, and it will also, hopefully, provide an improved vehicle for communication of

recent atomic physics results to the fusion community.

PLASMA TRANSPORT IN THE SCRAPE-OFF REGION

In the scrape-off region the magnetic field lines are open in the sense that they intersect a solid object (limiter, or wall) which completely changes the nature of transport compared to the closed magnetic field lines region of the main plasma. In particular, the very high parallel heat conductivity transports the heat very quickly down the field lines, accounting for the very rapid temperature fall-off with the (minor) radius. Another scrape-off feature is the often very strong interaction (ionization) of the surrounding neutral gas with the plasma, which leads to plasma recycling at the places of contact with solid objects. Plasma recycling greatly increases the number of energy carriers, which dramatically lowers the scrape-off plasma temperature. The two-dimensional transport code PLANET predicts the scrape-off plasma behavior, which includes the plasma temperature, density, and the mass flow patterns important for impurity transport. The PLANET predictions for a cool, high-density scrape-off, with no impurity generation at divertor plates has been confirmed by experiments. While the qualitative agreement with experiments has been very good, quantitative comparisons require accurate representation of the actual experimental geometry.

The emphasis during the year has been on generating computational grids from the given realistic equilibrium solutions. Subsidiary codes now exist for this purpose, and realistic geometries have been generated for the International Tokamak Reactor (INTOR), D-III-D, PBX, and compact ignition tokamak (CIT) experiments. The PLANET code has also been speeded up by an order of magnitude and made more robust. Preliminary results have already been obtained for INTOR and D-III-D in the new realistic geometry. These results show a very effective confinement of the neutral gas to the divertor plate region, believed to be important for good confinement in the H-mode of tokamak operation. This past year's model development work was in preparation for applications work during the coming year, though further developments, important for the impurity transport, will also be required. The PLANET code solves fluid plasma equations with sources which represent the plasma interaction with the neutral gas. These sources are computed in the DEGAS neutral transport code using the plasma parameters provided by PLANET. The DEGAS code and its other uses are described in the next section.

NEUTRAL-PARTICLE TRANSPORT

The emphasis during the past year has been on applying the DEGAS neutral transport code⁶ to analyze

experimentally obtained data. Most of this work involved TFTR. Based on this experience, the performances of various proposals for designs of a pump limiter for TFTR were estimated. Older results from the Poloidal Divertor Experiment (PDX) were also reexamined. A number of collaborations with groups outside of PPPL were also maintained, notably with those at the University of California at Los Angeles (UCLA), the Lawrence Livermore National Laboratory (LLNL), the Japan Atomic Energy Research Institute (JAERI), the Culham Laboratory, United Kingdom, and the Institut für Plasmaphysik at Garching, West Germany (IPP Garching).

TFTR Recycling

Knowledge of the density and temperature of atoms and neutral molecules in TFTR is necessary for the interpretation of measurements of limiter heating, charge-exchange emission spectra, hydrogen-line radiation, residual gas analyzers, and estimation of getter pumping. It is also important for the modeling of the bulk plasma transport and energetic-ion behavior, the generation and transport of impurities, and in determining the overall particle and power balances.

The calculated atomic density from a sample three-dimensional calculation is shown in Fig. 3. This illus-

Figure 3. Contributions to the poloidally averaged-D⁺ density in TFTR from three sources and the total D⁺ density.

trates a high degree of localization of the neutral-particle population near the movable limiter. The effect of the asymmetric limiter source is apparent near the limiter where the density of atomic D was a factor of 100 times greater than anywhere else.

Other quantities dependent on neutral populations also showed asymmetries, with the D_α emission and the particle and energy sources due to ionizing neutrals being localized near the limiter.

Neutral particle flux averaged $\sim 10^{14} \text{ cm}^{-2} \text{ sec}^{-1}$ over most of the vessel, but peaked at approximately $10^{16} \text{ cm}^{-2} \text{ sec}^{-1}$ in the region immediately in back and to the sides of the limiter. Thus, with getter panels covering 9% of the vacuum vessel inner wall, an upper bound for their pumping capacity would be on the order of 0.1% of the flow into the scrape-off.

Highly rotating plasmas can be created through neutral-beam heating. A study of the effect of plasma rotation on neutral kinetics was made. The effect of the plasma flow is dramatic, with the atomic density increasing in the rotating plasma over that for the stationary plasma at all radii up to 100 degrees toroidally on the downstream side.

In order to study in detail the time evolution of recycling off the TFTR movable limiter, DEGAS has been used to compute particle implantation rates in the limiter, providing a particle source for the DIFFUSE code⁷ which calculates the one-dimensional diffusion and trapping of atoms in a wall. A number of issues were addressed, such as the level of hydrogen saturation in the limiter and the overall wall pumping during a discharge, the degassing rates between discharges, the rate of isotope exchange over a series of discharges, and the expected size of the wall tritium inventory.

The TFTR movable limiter geometry used in the calculation is shown in Fig. 4. The overall limiter particle desorption rates and the diffusing populations in the limiter, over five discharges, are shown in Fig. 5. The limiter absorbs particles during the first half second of the flattop in an ohmic discharge before becoming saturated. The overall diffusing population continues to rise during the cycle of discharges, indicating a continuing particle build-up in the limiter. Verification of these results with experimentally measured particle balances and hydrogen limiter inventories is presently underway.

Figure 4. Computer model of TFTR movable limiter geometry.

Figure 5. Total computed particle release rate (a) and diffusing particle population in the movable limiter (b). A 3-sec ohmic discharge is modeled followed by a 3-sec ramp-down, with 300 sec between discharges.

It is also important to understand the mechanism for the introduction of carbon and oxygen into the TFTR plasma.⁶ The DEGAS code is presently being modified to include neutral methane, and its important dissociation process, in order to construct a more complete picture of how carbon initially enters the plasma.

TFTR Pump-Limiter Design Work

A pumped limiter system is being studied for TFTR. The planned system would consist of two toroidal belt limiters located at large major radii above and below the midplane, positioned over the existing zirconium-aluminum (ZrAl) getter panels.

The DEGAS code has been used to study the pumping efficiency of various designs for the limiter/getter system. Calculations show that by using the belt limiters as primary limiters, over 30% of the particles

striking the neutralizer plates would be trapped by the getters. This results in an order-of-magnitude improvement in particle collection over the present bumper-limiter/getter systems and should provide enough density control for pellet injection and for the hot-ion mode of operation.

EXTERNAL COLLABORATION

The DEGAS code is presently used by a number of fusion laboratories around the world, independently, and in collaboration with the PPPL Tokamak Modeling Branch. During 1985, the Group collaborated with the IPP-Garching Surface Physics Division (Drs. W. Eckstein and R. Behrisch) on the construction of a data set for the distributions of the particle and energy reflection coefficients, resulting in a realistic reflection model used in plasma edge calculations. Collaboration with UCLA (Prof. R. Conn and R. Schaeffer) and KFA, Jülich was on the ALT-II pump limiter design. Dr. Reiter from KFA spent six months working at Princeton.

The DEGAS code was used with our assistance by LLNL and the Sandia National Laboratory (SNL) for TMX modeling and MFTF-B design work. It was used at JAERI for the Fusion Experimental Reactor (FER) design work, for which purpose Dr. Hitoki visited the Group for one month. Dr. Harrison's group at Culham Laboratory used DEGAS for DITE (Divertor and Injection Tokamak Experiment) data analysis and NET (Next European Torus) design work.

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SPIN-POLARIZED FUSION PROGRAM

The goal of the spin-polarized fusion program is the development of an intense source (10^{21} sec^{-1}) of spin-polarized hydrogen for eventual test in a fusion reactor. Some of the advantages of using spin-polarized fuel include an increased fusion reactivity and control of the directivity of the products. The first stage of this program is initiation of laboratory experiments to study the physics and technology of optical pumping production of spin-polarized hydrogen in small cells. Eventually, a large flowing polarized hydrogen source would be constructed.

Optical pumping converts the angular momentum of circularly polarized laser light into net hydrogen spin. Rubidium is initially pumped by the laser and the hydrogen atoms are polarized by subsequent spin-exchange collisions with the rubidium atoms. Atomic hydrogen is produced by a pulsed radio-frequency discharge. The degree of hydrogen polarization will depend on the rubidium polarization and density and the hydrogen relaxation rate. The first two variables are functions of the laser power, the rubidium relaxation rate and the cell temperature. The hydrogen relaxation rate will depend on the interaction of the polarized hydrogen with the cell walls. One method to decrease the hydrogen relaxation rate is to use a high-pressure background gas to act as a buffer to impede diffusion to the walls. Figure 1 shows the

Figure 1. Hydrogen signal for pumping with σ^+ light. The two observed signals correspond to the different $F = 1$, $m_F = 1 \rightarrow 0$, and $m_F = 0 \rightarrow -1$ transitions. Analysis of these data yield a hydrogen polarization of 64%.

hydrogen signal obtained in a 40 Torr cell being pumped by 150 mW of laser light. Analysis of the difference in the strengths of the $F = 1$, $m_F = 1 \rightarrow 0$ and $m_F = 0 \rightarrow -1$ signals yields a hydrogen polariza-

tion of 64%. The atomic hydrogen density was determined to be 10^{12} cm^{-3} and the hydrogen relaxation rate was about 100 sec^{-1} in this cell.

These initial experiments showed that it is possible to achieve a large hydrogen polarization at a moderate hydrogen density. To increase the hydrogen polarization, the relaxation rate must be reduced, while to increase the atomic hydrogen density, the discharge must be operated at a lower pressure. Fortunately, it is possible to use wall coatings such as a paraffin to reduce the relaxation rates by several orders of magnitudes in low-pressure cells (<1 Torr) where

Figure 2. Rubidium relaxation rate as a function of rubidium density. The increased relaxation rate with density shows the contribution due to rubidium-rubidium collisions. The observed relaxation rate for the next lighter alkali, potassium, are an order of magnitude smaller. These results indicate that hydrogen-hydrogen collisions will not be an important limitation for hydrogen densities less than 10^{18} cm^{-3} .

efficient discharges are possible. Initial experiments with coated cells showed that it is possible to achieve a rubidium relaxation rate of 1 sec^{-1} without a buffer gas. Experiments are in progress to measure the hydrogen relaxation rate in these coated cells and to achieve large hydrogen polarization.

In addition to wall collisions, collisions between polarized atoms can contribute to the hydrogen relaxation rate. These collisions will eventually limit the hydrogen density that can be highly polarized with a fixed laser power. Experiments were performed to

measure these depolarization rates for the alkalis cesium, rubidium, and potassium. Figure 2 shows the observed relaxation rate for rubidium-rubidium collisions as a function of temperature. Empirically, it was found that the relaxation rate decreases an order of magnitude for the next lighter alkali. Since hydrogen is closely related to the alkalis, the estimated relaxation rate from hydrogen-hydrogen collisions should not be deleterious for hydrogen densities of less than about 10^{18} cm^{-3} . Further work is in progress to understand the origin of these depolarization collisions.

SPACECRAFT GLOW EXPERIMENT

In FY85, the Princeton Plasma Physics Laboratory received a research grant from the National Aeronautics and Space Administration (NASA) to develop a ground-based facility to study spacecraft glow phenomena.¹ Spacecraft glow is a surface illumination on the ram side of orbiting spacecraft such as the Space Shuttles and Atmospheric Explorer Satellites.² This glow has visible, infrared, and ultraviolet components that usually extend to 20 cm on the ram side of the craft, and in some places as much as a few meters. It has been theorized that the glow can be explained by aeronomic chemistry in which energetic neutral molecules colliding with the surface interact to produce excited radiating species. The orbital speed of the spacecraft is approximately 8 km sec^{-1} , and corresponds to a relative kinetic energy with atmospheric gases (primarily nitrogen and oxygen at densities ranging from 10^8 to 10^{11} cm^{-3}) of 4 to 10 eV. The conversion of this energy into excitation of atoms and molecules by collisions with surfaces, followed by emission, could explain the spacecraft glow.

To study spacecraft glow on the ground it is necessary to produce a beam of low-energy (2–10 eV) neutral atoms and molecules with sufficient flux ($\geq 10^{14} \text{ cm}^{-2} \text{ sec}^{-1}$) at the target to simulate spacecraft conditions. A novel scheme has been proposed whereby low-energy neutral beams can be produced by reflecting light ions, from a beam or plasma source, off surfaces. Using the ACT-1 as a source, beam currents of 1 A have been produced by using an electrically biased limiter to intercept, accelerate, and neutralized plasma ions from a discharge. The reflected neutrals enter an 80-cm-long drift tube and produce a beam with a flux of approximately a few times $10^{14} \text{ cm}^{-2} \text{ sec}^{-1}$ on a target located 1 m away from the limiter. A sketch of the experimental facility for studying the glow is shown in Fig. 1.

A number of targets are exposed to nitrogen beams at various values of the limiter bias voltage. The presence of the target resulted in an enhancement of the photon flux in the viewing volume, which is characterized as a surface-induced glow. Figure 2 shows the results for a target coated with Z-302 paint using limiter bias voltages of 25 and 7.5 V corresponding to average beam energies of about 10 eV and 4 eV, respectively. The light intensity decreases over a distance of 10 cm with a scale length of approximately 2 cm. From preliminary spectral studies using broadband filters, variations of the spectra as a function of energy are found. It is too early to know the origin of these changes without higher spectral resolution. The spectra and scale length of the glow may be different from the spacecraft glow because of the absence of

Figure 1. Sketch of the experimental facility used to study spacecraft glow phenomena. A cross section of the toroidal ACT-1 plasma and the drift tube containing the diagnostics and gas cylinders is shown.

Figure 2. The relative photon flux as a function of distance from the target (the target is on the left and the beam arrives from the right). The target surface is Z-302 paint, the plasma in ACT-1 is nitrogen, and two different bias voltages are shown. The relative intensity ΔI , which is the surface glow divided by the limiter current, is plotted in order to correct for slight changes in plasma current and, therefore, beam flux that occurs during the course of the experiment.

oxygen in these studies. However, nitrogen interactions have been proposed as a source of glow on spacecraft.²

A volume glow due to beam particles of nitrogen and nitrogen-oxygen mixtures interacting with a variety of target gases in the drift tube were also observed. The intensity of the volume glow is such that it could contribute to the spacecraft glow. Volume glow in the

spacecraft environment would be due to pressure build-up on the ram surface of the craft. This glow component scales with the square of atmospheric density since both the incoming beam flux and ram pressure enhancement scale with density. Recent studies of the glow on the Atmospheric Explorer Satellite³ indicate that the glow has two components; one of which scales with the nitrogen density squared. This variation is precisely that predicted by the studies of the volume glow and is consistent with conclusions based on the laboratory studies.

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IGNITION STUDIES PROJECT

INTRODUCTION

Since the start of the Tokamak Fusion Test Reactor (TFTR) fabrication in 1976, a portion of the U.S. magnetic fusion community has been studying the options for the next step beyond the achievements of TFTR. All of the studies have had one central goal: the achievement of substantial nuclear self-heating—ideally, enough so that a deuterium-tritium (D-T) plasma will ignite and continue to burn in the absence of any external power input. There have also been other important goals, such as technological advancement, particularly in the areas of superconductivity and nuclear engineering, and the study of the long-term dynamics of a burning plasma.

The most recent cycle of these studies (the Tokamak Fusion Core Experiment—TFCX) was concluded in 1984 with the realization that the simultaneous achievement of the goals of ignition and technology development would cost in the range of \$1.0–\$1.5 B—considerably in excess of the resources likely to be made available in the near term to advanced projects in fusion research. The fusion community then began to study the option of achieving a burning plasma in a minimum-cost device, while economizing on the other aspects that will be desirable for the long-term development of fusion power.

The adoption in 1984 of ignition at minimum cost as a central near-term goal for the U.S. fusion effort led to the consideration of a range of parameters similar to those already studied by Professor Bruno Coppi (Massachusetts Institute of Technology) and embodied in a device named "IGNITOR" (Ignited Torus). An important feature of the IGNITOR studies is the goal of igniting a plasma with ohmic heating. A device with small major radius (1 m) and high magnetic field (14 T) would be suitable for the pursuit of this objective, consistent with low cost.

The first activity of the Ignition Studies Project (ISP) was to review the IGNITOR design studies and report on the findings. This task was completed in October 1984. (See "A Review of the IGNITOR Studies" by The Ignition Studies Group, Princeton Plasma Physics Laboratory, October 1984.)

The Ignition Studies Project [including a major design effort at the Fusion Energy Design Center (FEDC), the Massachusetts Institute of Technology (MIT), and GA Technologies, Inc.] then proceeded to develop and analyze new designs for a compact ignition tokamak. This work was presented at a three-day conference on ignition studies in Boston in June of 1985. Cost estimates, prepared in conjunction

with the FEDC, totaled just under \$300 M, if the TFTR site and some equipment at other laboratories could be used. At that conference, a panel of fusion scientists from the U.S., Europe, and Japan endorsed proceeding with a compact ignition project, provided that experimental operation could begin relatively early, 1992–93.

In the period July–September 1985, it was agreed that the Princeton Plasma Physics Laboratory (PPPL), MIT, and the FEDC would work in concert towards the selection of a single concept in January 1986, and from then to May 1986 on the preparation of a reference design. The reference design would be the basis for seeking DOE approval to proceed with an ignition project.

Late in FY85, three external advisory bodies were formed. They are the Ignition Technical Oversight Committee (ITOC, H. Furth, PPPL, Chairman), the Ignition Physics Study Group (IPSG, J. Sheffield, Oak Ridge National Laboratory, Chairman), and Panel XIV (D. Meade, PPPL, Chairman) of the Magnetic Fusion Advisory Committee. The functions of these three groups are divided roughly as follows: ITOC provides guidance to design teams for performance objectives and scientific design criteria; IPSG gives technical advice to ITOC, on the basis of broad community discussion of scientific issues; Panel XIV studies the overall programmatic justification of a compact ignition device.

IGNITOR ASSESSMENT

In October 1984, the Ignition Studies Project published for DOE "A Review of the IGNITOR Studies." One valuable aspect of the review was to catalogue relevant documents since May 1981 and to summarize the IGNITOR parameters as the studies have evolved. Table I gives a simplified summary of parameters.

The conclusions of the study can be summarized as follows: IGNITOR has the capability to ignite, with more margin against uncertainties in plasma physics than TFCX; the focus on ohmic heating to ignition should be broadened to allow radio-frequency heating, which will guarantee a test of beta limits and full utilization of the device; there are mechanical problems with the close tolerances required to put loads in desired places and with the integrity of the insulation; handling disruptive loads and heat removal have received insufficient design attention. This study showed that the IGNITOR is a valid preconceptual design point, even though serious engineering problems can be seen and the

Table I. Ignited Torus (IGNITOR) Parameters.

Parameters	IGNITOR-1982		Advanced Burning Core Experiment—1984
	Precompression	Compressed	
R (m)	1.09	0.75	1.00
B (T)	10.20	15.00	12.70
a (m)	0.30	0.25	0.43
b (m)*	0.40	0.33	0.67
I_p (MA)	3.00	4.50	10.50

*b = $a\kappa$ where κ is elongation

lack of a significant radio-frequency heating capability limits scientific flexibility.

The next step for the ISP was to develop a preconceptual design point between TFCX and IGNITOR. This was done at PPPL and included PPPL engineering design efforts (not just review) and PPPL scientific input.

TRANSITION FROM TFCX TO ISP

The parameters for the FY85 Ignition Studies Project (ISP) device are nominally R = 1.6 m, a = 0.5 m, B = 9 T, and I_p = 8 MA. Previous TFCX studies at PPPL had R = 3.2 m, a = 1.3 m, B = 4 T, and I_p = 11

MA. Table II gives a more complete comparison of the parameters and features of TFCX and the ISP compact ignition machine. The changes in design philosophy that allow reducing the size of the machine to this extent are important. Figure 1 can help explain this process. Plotted is a family of curves of major radius R versus magnetic field B for roughly constant ignition and engineering margins in a given design concept. The top curve represents a TFCX design point with ohmic-heating start-up. To get to the ISP device range, one must increase allowable stresses, restrict clearances, and reduce pulse length. Of these effects, reducing the pulse length is most important in programmatic impact, and increasing allowable stresses is most important to the engineering of the machine.

As the machine decreases in size, the magnetic

Table II. Comparison of Parameters and Features of TFCX (FY83-84) and ISP (FY85).

Parameters	TFCX	ISP
R (m)	3.2	1.6
a (m)	1.3	0.53
κ (elongation)	1.6	1.6
B (T)	4	8.9
I_p (MA)	11	7.8
β (%)	6	5
Burn Time (sec)	300	5
Fusion Power (MW)	300	300
Radio-Frequency Power (MW)	30	30
Features		
Field	Moderate	High
Plasma Current	High	High
Coils	Copper or Superconducting	Copper
Pulse Length	Long	Short
Current Drive	Radio-Frequency	Ohmic
Heating	Radio-Frequency	Radio-Frequency
Elongation	1.6	1.8
Neutron Wall Load	Moderate	High
Neutron Fluence	Low	Very Low

Figure 1. Parameter changes from TFCX (FY83-84) to ISP (FY85).

field must rise to maintain current and other parameters that are believed to be necessary for the device to achieve ignition. The increased magnetic field increases the stress on the coils and/or the structure to restrain the coils. For example, the vertical separating force associated with $B = 10$ T, $R = 1.6$ m, $a = 0.5$ m is approximately 800×10^6 newton $\approx 80,000$ tonnes, the displacement of a large naval vessel. A large fraction of this force appears on the inner leg, which is in a high-field region. Given the fundamental size constraints, the stress in the inner leg can be estimated at 400 MPa, or around 60 ksi, a value considerably more than the normal stress allowed for high-conductivity copper.

ISP DESIGN WORK

Once it was decided to study a compact, short-pulse-length machine, the engineering design issues centered on materials to maximize allowable stresses and on configurations to minimize predicted stresses. A committee to examine the question of allowable stress was formed. (Table III lists the Committee members.) This group agreed, after several meetings, to adopt the following rule for allowable stresses: use 70% of ultimate stress or 85% of yield stress for supported magnet coils, and 60% ultimate stress or 67% yield stress for self-supporting coils. That is, in a given machine design, the maximum stress must be smaller than the smallest number given by the rule. Implicit in the derivation of this rule (which is about a factor of two more permissive than standard pressure-vessel criteria) is the decision that only 3,000 full-stress (full power) pulses will be required for the experimental program.

Two concepts were studied by the ISP Group for removing much of the vertical separating force from

Table III. Committee on Alloys and Allowable Stresses for the Ignition Study Project.

H. Becker (MIT), Chairman
P. Bonanos (PPPL)
C. Bushnell (PPPL)
P. Heitzenroeder (PPPL)
F. Puhn (GA Technologies, Inc.)
E. Dalder (LLNL)^a
W. Reed (NBS)^b
W. Wiffen (ORNL)^c

^aLawrence Livermore National Laboratory

^bNational Bureau of Standards

^cOak Ridge National Laboratory

the interior of the toroidal field magnet. The first concept uses a bow-shaped coil and coil case to put stress on the outer strong-back and can even put compression on the inner leg. Vertical compression could conceivably combine with the toroidal and radial compression from centering forces, so that the inner leg of the toroidal-field coils could approach hydrostatic equilibrium, in which the allowable stress rises without limit. The second concept uses a sliding joint in the copper coil, so that most of the vertical separating force is transferred to an external "C" clamp, which is constrained from opening by a toroidal ring.

The bow-shaped coil concept, shown in Fig. 2, can be thought of as a linkage in which outward motion on the horizontal midplane is coupled to a vertically collapsing motion, with high mechanical advantage. As a result, tension in the inner leg is reduced, even below zero, in favor of tension in the outer strong-back. Unfortunately, the coil must be tall to gain sufficient mechanical advantage, so the size, weight, cost, power, and energy associated with using the bow-shaped coil are quite large. Also, bending at the corners of the coil is a problem for which no completely satisfactory solution has emerged.

Figure 3 shows an example of the sliding-joint concept and surrounding structure. In this design, the problem of dealing with the vertical separating force has been reduced to the problem of building a reliable joint. There is experience in the electric utility industry with the use of sliding joints in bus work, where thermal cycling causes repetitive motion.

A program was initiated at PPPL to test several sliding-joint contacts under simulated conditions, including operation at liquid-nitrogen temperature. The best success so far has been achieved with contacts in use by the Westinghouse Electric Company in its own equipment. Figure 4 shows a drawing of the sliding-joint contacts as employed in a coil, and also a drawing of the test apparatus. Test results as of the end of FY85 showed that there is a wide variation in the temperature rise of individual contacts, but that failures occur at current densities much greater than the required current density. This behavior suggests

BOW COIL EXTERNAL
OH/EF SYSTEM

Figure 2. The bow-shaped coil concept.

that more should be learned about the sliding-joint concept. Beyond this, there is widespread intuitive concern about using a configuration with many inaccessible moving pieces at high current and stress levels.

While the conceptual design of the toroidal field magnet coils and supporting structure received more attention in FY85 than other components, there was considerable activity related to the vacuum vessel and internal hardware, facilities, electrical power, and radio-frequency heating. A summary of these studies follows.

The primary consideration for the vacuum vessel design is energy removal. The basis for this is the fact that ignition means up to 60 MW of alpha-particle power being generated inside the plasma, which eventually is to be deposited inside the vacuum chamber. The conceptual method for absorbing most of this energy is an axisymmetric toroidal inner limiter (small

WEDGE DESIGN-INTERNAL
OH/EF SYSTEM

Figure 3. Toroidal-field coil configuration based on the sliding-joint concept and an external "C" clamp.

major radius), much like the bumper limiter of TFTR. Refractory tiles approximately 10-cm square made of graphite or similar material would be attached to a substrate with good thermal contact to the vessel, but with no active cooling. In addition, the nonlimiter portion of the vessel appears to need tile protection from runaway currents and disruptions, so tiles would appear everywhere except at ports.

Key issues to planning for the facility are the inventory of tritium and the usage of liquid-nitrogen coolant. The tritium inventory requirement is 100-200 kCi (10-20 grams) for the ignition machine, about three times that needed for TFTR and one third that needed in TFCX. The operating plan calls for six pulses per day, which will require three truckloads per day of liquid nitrogen. For initial cool down at the beginning of an operating period, fifteen truckloads will be necessary.

Location and design of the new facility were stud-

Figure 4. (a) Details of sliding joint and the current-carrying contacts. (b) Drawing of PPPL apparatus for testing sliding contacts.

ied, with particular attention to the TFTR site. While the new machine should seek to make the best use of existing systems (power, tritium, cooling), reusing the TFTR Test Cell was considered to be impractical during the period following successful completion of the TFTR D-T program. After reviewing several options, the area to the west of the TFTR Test Cell was chosen. Figure 5(a) shows the proposed layout and the relationship of the new machine to TFTR.

In the design study, the test cell is small (about one-fourth the floor area of the TFTR Test Cell). The concrete shielding wall is circular and 2.8-m thick. Inside, there will be movable shielding close to the machine to provide for diagnostics that must be shielded. Outside the test cell there will be a tritium-sealed area for a pellet injector and diagnostics. A hatch in the test cell floor provides for the movement of components to a "warm" cell in the basement, or a "hot" cell at grade level [see Fig. 5(b)]. The warm cell will be used for limited hands-on maintenance, and the hot cell will provide for complete remote operation.

The present design provides for a polar crane and a rotating concrete shield above the torus. This shield

Figure 5. (a) Plan view of the ignition facility, showing geographical relationship to TFTR. (b) Elevation view, showing new test cell, hot cells, and polar crane with rotating shielding.

serves as a tritium seal when it is stationary, and it shields the crane from neutrons, preventing activation of the crane and permitting hands-on service of the crane when it is not operating. Through a slot that can be opened in the shield, the crane can reach almost the entire test cell area.

The electrical power design is dominated by the toroidal field, which requires 2.6 GJ (energy) and 450 MW (power). However, the radio-frequency and the poloidal-field systems need 60 MW and 35 MW, respectively, at the ac input, so these are also substantial electrical systems. Total energy for all systems, including allowance for losses and conversion, will be 3.3 GJ. Maximum energy system demand is on the order of 800 MVA. These requirements are well within the capability of the TFTR Motor Generator/Flywheel Facility, which is rated at 4.5 GJ and 950 MVA. Liquid nitrogen cooling of the copper coils plays a key role in minimizing the power and energy requirements.

The radio-frequency design considerations have focused on a loop coupler (as opposed to a waveguide) recessed in a cavity to gain protection from the high average heat and particle fluxes expected. The mode chosen is fast-wave ion-cyclotron heating of minority hydrogen or second-harmonic deuterium, yielding 135 MHz as the source frequency. A significant factor in the cost of the device is the use of 14 existing power supply units made available by the cancellation of an earlier DOE program. These supplies are believed to be capable of 1.5 MW each, if the EIMAC developmental power tetrode X2242 becomes available and is installed, yielding 21 MW from 14 supplies. An additional 9 MW, to make a total of 30 MW radio-frequency power at the source, would be added with new equipment.

PHYSICS OF IGNITION

The object of the ignition experiment is to develop the physics of plasma self-heating and ignition, about which little is yet known. It is clear that quantitative estimates must be made as to whether ignition will be achieved, based on existing experiment and theory. From these estimates a margin for ignition can be established, to be considered with other engineering and costing parameters in the design of the machine.

Table IV summarizes the more prominently discussed scaling laws for energy confinement time. An auxiliary constraint is the beta limit due to Troyon, $\beta \leq 0.03 I_p / aB$. A natural definition of the ignition margin is the ratio of the alpha power released to the heating power needed to maintain the plasma at ignition conditions, according to a given scaling law. Plasma conditions are taken to be $T = 10$ keV, with a density such as to achieve the Troyon β limit. Ignition margins predicted for ISP parameters (see Table II) are noted in Table IV.

The three scaling laws quoted in Table IV give different results, and still other possible scaling laws deserve consideration. Since the engineering of the

Table IV. Empirical Scaling Laws for Energy Confinement Time.

To get energy confinement time in seconds τ_E , use density (n) in 10^{20} m^{-3} , radius (a) in meters, major radius (R) in meters, magnetic field (B) in Tesla, current (I_p) in MA, temperature (T) in keV, and power (P) in MW. Dimensionless parameters are q , κ (elongation), and M (average ion mass units).

Neo-Alcator:

$$\tau_E = 0.07 n a R^2 q^{1/2} M^{1/2}, \text{ predicts an ignition margin of } \sim 4.$$

Mirnov:

$$\tau_E = 0.45 I_p a \kappa^{1/2}, \text{ predicts an ignition margin of } \sim 3.5.$$

Kaye-Goldston:

$$\tau_E = 0.055 n^{0.26} a^{-0.49} R^{1.65} \kappa^{0.28} I_p^{1.24} B^{-0.09} P^{-0.58} M^{0.5}, \text{ predicts an ignition margin of } \sim 1.1.$$

ignition device needs to proceed on some definite assumptions regarding plasma confinement and ignition margin, ITOC has offered the guidance that a figure-of-merit X be adopted as follows:

$$X = (B^2 a \kappa^{1/2}) / q > 20.$$

This rule is obtained by combining neo-Alcator scaling (quoted in Table IV) with the Murakami density limit, $n \leq 1.5 B \kappa^{1/2} / (Rq)$, and including a safety margin for deterioration relative to the confinement thus predicted. The designs for ignited tokamaks considered in FY85 did achieve X in the range of 20; this is to be compared with $X \approx 12-15$ for TFCX and $X \approx 8$ for TFTR. In addition, ITOC recommended that the plasma current should be made as large as possible—preferably greater than 8 MA.

Present experiments with divertors have achieved a type of plasma performance that is quantitatively and qualitatively different from that obtainable in limiter discharges. The divertor plasma edge is sharper and at higher temperature and density, and the energy confinement is about twice as high. If the so-called H-mode (for high-confinement mode) persists with high-power heating, then there are considerable advantages for the ignition experiment. Because of the potential attraction of a divertor, a divertor option will be developed in FY86.

SUMMARY AND OUTLOOK

A compact, high-field, short-pulse, ignition machine could be built at the Princeton Plasma Physics Laboratory for about \$300 M, if existing equipment is

Figure 6. Composite drawing of the Ignition Studies Project design of FY85.

employed. A cutaway view of the integrated device is shown in Fig. 6. The primary uncertainties in the design concern large stresses in the toroidal coil or the sliding joint to relieve those stresses. The uncertainties in plasma physics continue to push towards higher intrinsic

confinement capability, now expressed with the figure-of-merit $X = (B^2 a k^{1/2}) / q$. At the end of FY85, X was in the range of 20, but pressures to assure ignition will be pushing X higher in FY86.

Other laboratories and research groups have been developing complementary design approaches. In FY86, it will be necessary to converge on a single approach, and to decide on the feasibility and desirability of a divertor, which is not yet well-studied in the context of a compact ignition tokamak.

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ENGINEERING DEPARTMENT

The Engineering Department continued, in FY85, to adjust to a reduced Laboratory-wide budget, and to further shifts from new work-type activities to the operation of existing machines. A reduction of about 13% in Department staff was realized by the transfer of personnel to the TFTR core group, by a modest reduction in force (RIF), and by attrition and retirements.

Use of the Computer-Aided Design and Drafting (CADD) facility increased as more experience was developed by a greater number of operators. Two additional workstations were ordered for delivery and installation of FY86.

Two new design and fabrication efforts were pursued during the year. The PBX-M (Princeton Beta Experiment Modification), the alteration of coil systems and the increase of power supplies used on PBX, was organized and work started on conceptual designs. Formal project approval will be sought in FY86, with work to be completed in FY87. The S-1 Spheromak Upgrade was started, with work on a new flux core and current transformer. The new flux core and its associated bus work will provide S-1 with increased capability and reliability, while the current transformer will provide additional plasma heating. Work on this upgrade will be complete in FY87.

The Engineering Analysis Division became involved in support of a new initiative, the Ignitions Studies Project (ISP). This, like the Tokamak Fusion Core Experiment, is an effort to explore options for future fusion research machines.

Support of TFTR consumed the bulk of the Engineering Department resources. A major machine opening occurred at which time additional first-wall and protective hardware were installed. At the same time, two additional neutral beamlines were positioned and attached to the machine. The Engineering Department made a major contribution in this effort. In addition, substantial effort was expended by the Engineering Analysis Division to model the TFTR and to fully define the maximum operating envelope of the machine.

Continued emphasis was placed on increased efficiency and safety during FY85. Indirect costs were cut and training in the safety area was intensified. Both of these efforts will be stressed in FY86.

In the following sections, details of the activities of each of the four Engineering Divisions are described.

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.

Systems Group

The Systems Group provides overall systems support for large experiments, from the preconceptual design stage to the start of operation. Most of the work of the Systems Group for this fiscal year was in support of the Ignition Studies Project (ISP) and the TFTR Magnetic Reconfiguration Studies.

Ignition Studies Project

System studies were performed to define design points around which more detailed analyses would be performed, and to clarify the relationship between competing device concepts.¹ A new systems code was developed to facilitate these studies. Key features of the code are the ability to reasonably predict mechanical stresses in critical areas, calculate temperature rises in toroidal-field and ohmic-heating coils in the presence of nuclear heating and skin current effects, and estimate plasma performance for a variety of confinement models.

A study was initiated to investigate the feasibility of a sliding electrical joint for the toroidal-field coils on ISP. A workshop on sliding electrical joints was held at PPPL. An instrumented test facility for sliding joints was constructed. The test stand can provide the same current density on the test joint that would be seen on ISP. A contact load of up to 500 lbs may be applied, and a variety of slide speeds can be selected. A number of candidate joints were evaluated during the six months of testing.² One of the candidates, the small Westinghouse joint HM103, was shown to be acceptable for use in the expected operating conditions of ISP. Regardless of the final configuration chosen for ISP, the data from this study will be a useful input in design of future machines.

Tokamak Fusion Test Reactor

Studies by the Systems Group were instrumental in exploring possible magnetic reconfiguration options for the Tokamak Fusion Test Reactor (TFTR). The goal of the TFTR Magnetic Reconfiguration Study is to propose changes to the Magnetic Confinement Systems in order to improve the confinement time and, thus, surpass breakeven and achieve $Q \sim 2$, where Q is the ratio of the fusion energy coming from the plasma to the heating energy supplied to the device. The purpose of the Systems Group's efforts was to optimize the magnetic design with respect to physics constraints, site limitations, power supply availability, and configurational constraints. The two options developed by the Magnetic Reconfiguration Group were a bean option and a hybrid (limiter/divertor) option.

Electromagnetics Branch

The Electromagnetics Branch carries out design and analysis activities related to magnetic-field systems and their interaction with the associated electrical and mechanical systems.

During this fiscal year, the Branch provided support for a variety of program objectives with most of its effort focused in TFTR. In addition, the effort to accurately model the engineering effects of plasma disruptions was continued. Work was initiated on a model which would determine the position of a disrupted plasma as a function of time and, from this, obtain a profile of the forces on the vacuum vessel and poloidal coils during the disruption. The "SPARK"

eddy current analysis code was refined and, in cooperation with the Thermomechanical Branch, the coupling between mechanical damping and eddy currents was investigated further. This is illustrated in Fig. 1 which shows the predicted response of a cantilever beam for the coupled and uncoupled solutions.

Tokamak Fusion Test Reactor

The Electromagnetics Branch was involved in the EAD effort to define the operational capabilities of TFTR beyond the original design parameters. Improved performance of TFTR will require a greater output from the available power supplies. Several alternatives for obtaining longer toroidal field flat-top times or higher toroidal field currents were proposed. One alternative involved shortening the tail portion of the toroidal field pulse by inserting a dump resistor. Other proposed alternatives included reduction of circuit impedance by upgrading the current limiting reactors, addition of rectifiers to allow a faster rise and to draw more power and energy from the utility line, and improving the voltage regulation and power factor by using phase correction capacitors. Cost and schedule estimates were developed for each alternative.

The power chain, from the motor generators (MG) to the conversion equipment, was investigated in order to define the ultimate limits of all components. This included investigation of MG operation at extended voltage, overcurrent, extended speed range, and extended time. Performance limits of diodes, thyristors, and conversion transformers were also investigated.

Figure 1. Uncoupled and coupled solutions for eddy currents and mechanical motion in a cantilever beam.

Fault analyses were conducted in order to predict the effects of grounding switch failure during machine operation at 24-kA ohmic heating and equilibrium field. These faults were modeled using a circuit program analog which traced the currents and forces on each coil as a function of time.

As part of the Operations System Engineering Support (OSES) Project, the Branch made a significant contribution to the direction and creation of the power supply models. Numerous other electromagnetic analysis tasks were carried out in support of the TFTR Project. One of the more important was the establishment and updating of the computerized TFTR Magnetic Material Inventory. This provides start-up field perturbation information and forces on iron objects in the machine vicinity.

Heliac

A complete user's guide for the program HELIAC (which calculates vacuum magnetic surfaces on non-axisymmetric three-dimensional toroidal geometries) was made available on the Magnetic Fusion Energy (MFE) Cray computers; updates and changes are documented on an online bulletin board. The program has been used by the designers of the Australian heliac (SHEILA) and to find magnetic surfaces in other geometries at PPPL and at several other laboratories.

Princeton Beta Experiment

In support of the Princeton Beta Experiment (PBX) Upgrade, electromagnetic forces on the passive coils were calculated. The shaping-field power supplies were analyzed to check for overvoltages or overcurrents during a disruption.

Ignition Studies Project

Significant cost savings on ISP can be realized if the existing PPPL power source can be expanded to meet requirements. A study was performed to determine whether this is feasible. Different methods for augmenting the PPPL power source were investigated. A staged approach was found to be the most cost-effective. The basic stages were substation expansion, addition of a storage battery facility, and expansion of the MG set. A costing algorithm was generated for the individual stages and for the composite of all stages.

SPARK Code

The "SPARK" code was extensively refined during FY85. A capability for calculating power dissipation, which can be used with thermal analysis codes, was developed. Figure 2 shows the power dissipated per unit volume in a toroidal-field coil case during a toroidal field ramp-up. The ability to handle nonplanar geometries, without taking advantage of symmetry, was added. This is illustrated in Fig. 3 which shows eddy currents due to a vertically moving plasma.

Figure 2. Contours of power dissipation in a toroidal-field coil case during a toroidal field ramp-up. (86A0209)

Figure 3. Eddy currents due to a vertically moving plasma. (86A0210)

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 Project, the TFTR Magnetic Reconfiguration Studies, and the Ignition Studies Project.

Finite element analysis (FEA) capabilities were enhanced by the computer aided-design (CAD) system. The finite element model (FEM) formatter on the CAD system substantially automates the process of generating a model.

Princeton Large Torus

A detailed thermal analysis of the Princeton Large Torus (PLT) rotatable graphite limiter was completed and benchmarked against measured data. Additionally, a three-dimensional mesh and geometry generator was added to the existing model of the PLT rotating limiter. The finite difference code used in the analysis was updated to include sublimative weight loss.

Advanced Toroidal Facility

Finite element stress analyses were performed to validate the design of the Advanced Toroidal Facility (ATF) poloidal-field coils that were manufactured at PPPL for the Oak Ridge National Laboratory.

TFTR/TFM/OSES

During the past fiscal year, a substantial effort was devoted to engineering support of the TFTR Project. Much of the work related to TFTR centered around the Operations System Engineering Support (OSES) Project which is performed under an EAD-directed subcontract by Grumman Aerospace Corporation. One objective of the OSES Project is to determine the stress levels in the poloidal-field coils on TFTR. This includes obtaining, on a turn-by-turn basis, the electromagnetic loads, thermal environment, and stresses in the conductors and the epoxy/glass insulation. In addition to monitoring and verifying the work of the subcontractors, the Thermomechanical Branch took on the responsibility to perform the finite element analysis for five of the nine poloidal-field coil stacks on TFTR.

The Branch lent support to the TFTR Project in numerous other areas as well. The TFTR bellows were extensively analyzed. Both thermal and electromag-

netic loads were used. These analyses were used to determine the allowable bellows temperature limits for TFTR operation, as well as operating limits for the surface pumping system and cover plate heating.

The ongoing design and analysis of the TFTR bumper limiter was completed.³ The dynamic response of the structure due to transient loads was analyzed with a finite element model.

Additional thermal and mechanical analyses of the TFTR toroidal-field coils were initiated. These analyses will be used to study the behavior of the coils under upgraded loading conditions. The mechanical model includes every turn of the copper coil and the variations in coil case shape (see Fig. 4). The thermal model of the coil conductor includes the distribution of current as a function of electrical resistivity at a cross section. A three-dimensional SPARK model of the TF coil case was developed to analyze eddy current heating.

TFTR Diagnostics

Engineering support for TFTR Diagnostics was provided in several areas. Numerous short-term analysis, design, and installation tasks were completed.

TFTR Neutral-Beam Upgrade

The TFTR neutral beams will eventually be upgraded to run 2-sec pulses. All of the heat-absorbing components in the beamline were analyzed, and new parts were redesigned where necessary.

TFTR Magnetic Reconfiguration Study

The Thermomechanical Branch provided engineering coordination for the TFTR Magnetic Reconfiguration Study. Mechanical and thermal analyses were performed on two leading configurations in order to assess the mechanical adequacy of the existing TFTR structure when subjected to loadings produced by the new configuration.

Radiation Analysis Group

The Radiation Analysis Group provides radiological and radiation-related analyses, evaluations, and assessments for the design, operation, and instrumentation of the fusion devices at PPPL. The main focus of the group is in the area of radiation transport and computational modeling. The primary responsibilities of the group include the analyses of the bulk and experimental shielding for TFTR, air dispersion analysis in preparation for radiological assessment of TFTR fusion operations, and radiological support for projects such as the ISP.

Radiation Analysis for TFTR

A comparison and review of the computational models of the TFTR constructed for radiation trans-

Figure 4. Three-dimensional model of toroidal-field coil case. (86A0208)

port analysis was made to assess the limitations of lower-dimensional modeling compared to more rigorous three-dimensional Monte-Carlo methods. This was important since the global radiation characteristics of the TFTR facility were determined on the basis of large scale two-dimensional discrete ordinates calculations. The results confirmed that the two-dimensional and even one-dimensional models which were used on the TFTR gave very reliable results for integral quantities (see Fig. 5).

Figure 5. Comparison of neutron-flux calculations from one-dimensional, two-dimensional, and three-dimensional models at the TFTR midplane.

This year also provided a comparison of the three-dimensional model to some preliminary experimental measurements in the Test Cell; agreement of the neutron fluences was within a factor of two.

Other transport work included a parametric analysis of the neutrons streaming through the major penetrations of the Test Cell floor, and a comprehensive transport evaluation of the off-site dose levels for the TFTR.

Shielding Analysis for TFTR Diagnostics

The objectives of this work were to provide estimates of radiation-induced noise levels in different diagnostics and to optimize the shield designs. Detailed three-dimensional analyses to determine radiation-induced noise were performed for the X-ray pulse-height analyzers, and the X-ray imaging systems. Shielding optimization for polyethylene/lead and water-extended-polyester/lead two-layer systems was also carried out using realistic response functions. Some of the analysis also included the details of electron-photon coupling and the effects of local geometric perturbations.

Meteorological and Radiological Analysis

The first year of on-site meteorological data for PPPL was compiled and correlated. These data are essential for predicting the impact of long-term and accidental releases of radioactive effluents.

In addition to this effort, work was continued on a comprehensive radiological assessment analysis software package. The source evaluation package calculates the outgassing of tritium from machine components and the build-up of radioactive nuclides in air due to neutron activation. The dispersion package evaluates the consequences of the release of a radioactive effluent, using the on-site meteorological data. This package was extended to include direct linkage to some standard United States Nuclear Regulatory Commission (US NRC) codes which allow for the evaluation of routine and accidental releases. In addition, the Radiation Analysis Group participated in the International Comparison of Computer Codes for Modeling the Dispersion and Transfer of Tritium Released to the Atmosphere.

Experimental Shielding Analysis

The Experimental Shielding Program, a joint effort by the Nuclear Engineering Branch of the TFTR Technical Systems Division and the Radiation Analysis Group, was continued this year. The primary objective was to validate the neutron and gamma transport calculations and dose level predictions for TFTR. Detailed three-dimensional modeling of the TFTR diagnostics basement was done in order to compare the calculated neutron and gamma-ray fluences in the basement with measurements. The integral neutron fluences above 0.4 eV from D-D operation were calculated using Albedo Monte-Carlo methods, while detailed spectral results above 0.75 MeV were calculated using a detailed Monte-Carlo model which includes the major machine components in the Test Cell and the details of the major penetrations from the Test Cell substructure into the basement. The agreements were within the overall experimental uncertainties for the neutron fluence. More significantly, the computational results were sufficiently reliable to use as a basis for rejecting some of the experimental data.

Radiation Analysis for ISP

A continuing effort was devoted to supporting the radiation analysis work for ISP. Although this level of effort was less than for TFCX, the problems posed covered a broad range of nuclear issues which included: (1) Test Cell wall thickness requirement; (2) Nuclear safety regarding air activation, water activation, LN₂ activation, material activation; and (3) an assessment of the sensitivity of the insulator responses to the transport modeling.

ELECTRONIC AND ELECTRICAL ENGINEERING DIVISION

The Electronic and Electrical Engineering Division was reorganized during FY85 in an effort to adjust to manpower changes resulting from modified Laboratory program goals due to budget constraints. During this transition period, the Division maintained a high quality of performance and increased the efficiency of its operations.

In FY84, a considerable effort was made in the strengthening of safety programs. This effort had measurable success: for FY85, the Division had no major accidents or mishaps.

The main focus of work during the fiscal year was placed on support of ongoing programs rather than in the development of new equipment and construction items. Among the major programs undertaken by the Division were the 2.45-GHz Lower-Hybrid Current-Drive study for TFTR and the Energy Conversion System Upgrade, also for TFTR. The latter program crossed branch lines within the Division and has resulted in significant improvements in system performance.

Other major programs undertaken by the Division include the Neutral-Beam Upgrade and the Repeating Pellet Injector (RPI) Project. The RPI Project is a prime example of a difficult program successfully performed in record time due, in large part, to the dedication of multidivisional staff working in close concert with project management.

The changing nature of the Laboratory staff has resulted in a significant percentage of fabrication work being performed by outside vendors. The Division has reorganized so as to insure timely and high quality performance by these suppliers.

Diagnostics Branch

Analog Engineering Section

At the start of FY85, an engineering team was formed to investigate reliability and performance anomalies associated with the neutral-beam local control centers. Numerous designs were reviewed and redesign of selected analog and digital circuits were undertaken. These changes have resulted in improved reliability and performance.

The Langmuir probe driver system was designed, developed, and delivered to the Radio Frequency Test Facility (RFTF) in early 1985. The system is capable of controlling and monitoring 30 Langmuir probes from its wire remote control circuitry.

The safety isolation system for the TFTR neutral beam was installed. This system accommodates approximately 2,000 channels, which are comprised of digital status and control signals and analog monitoring and control signals. In addition, the TFTR neutral-beam modulator/regulator low-voltage power supplies were redesigned to eliminate radio-frequency interference susceptibility, and additional channels

were added to the TFTR neutral-beam pyrometer interlock, which permits monitoring of the four heating neutral beams. A log amplifier for the hard X-ray diagnostic was also built and tested. This amplifier expands the dynamic range of the system by allowing greater resolution of small signals. A total of five channels were installed.

A program was established to review reliability problems experienced in field coil power conversion control systems and to correct these problems by redesign of, or modification to, existing circuits, as required. A team of engineers has been working on this program and noticeable improvement in control circuit reliability has been realized.

Electronics Section

The fiber-optic analog data links for TFTR neutral beams were completed in FY85. These links provide accurate and stable transmission of analog signals in the range of dc to 1 MHz. The fiber-optic isolation provides safety in processing signals originated at high voltage.

Design work was completed and construction started on the TFTR neutral-beam wafer instrumentation system. This system (Fig. 6) accurately measures

Figure 6. Neutral-beam wafer instrumentation system electronics. (B6E0315)

changes in the temperature of water cooling and neutral beams, permitting calculation of the beam power injected into the plasma.

The TFTR neutral-beam permissive generator was modified to provide optical pellet injector permissive signals. These signals are used by the pellet injector controls to assure that large pellets are not injected into the plasma unless the neutral beams are active. This prevents possible damage to the vacuum vessel walls if the pellet is not intercepted by the plasma.

Extensive redesign and modifications were made to the Rochester Instrument's coil protection system on TFTR. The changes improved reliability and accuracy and provided greater protection for the coil systems.

Two units were designed and constructed to support the Repeating Pellet Injector Project. These were a preamplifier/amplifier for diagnostic systems, including the pellet motion detectors and the H_α detector,

and a clock control unit for triggering CAMAC digitizers.

Instrumentation Section

The Multichannel Infrared Interferometer (MIRI) diagnostic, with five electron-density channels and one broadband poloidal current channel, was operated on TFTR this fiscal year. Remotely controlled and magnetically hardened electronics were developed for the MIRI high-voltage supply and gas controls. The system was increased to ten electron-density channels and two poloidal current channels. A gas injection system analog feedback interface and a neutral-beam injection system permissive interface were also added.

The Repeating Pellet Injector (RPI) was installed and operated on TFTR. The RPI injects pellets of frozen hydrogen or deuterium into the tokamak producing a rapid increase in plasma density. Its control electronics were designed and installed on an advanced schedule by the Instrumentation Section. The RPI gun was designed and built by Oak Ridge National Laboratory. Figure 7 shows an example of the time evolution of electron density increase upon injection of three sequential pellets as measured by MIRI. Design was started on the multi-shot Deuterium Pellet Injector (DPI) which will replace the RPI next year.

The torus vacuum pumping system controls for TFTR were completely redesigned, installed, and tested this summer. The improved system consists of a single General Electric programmable logic controller, a logic mimic control panel, and remote CICADA interfaces. Additional diagnostic vacuum control systems were built and installed on TFTR. A comprehensive effort was undertaken which upgraded the 205 MKS Instruments, Inc. ion gauge controller units for improved performance, reliability, and to render them fail-safe operation.

Figure 7. Abel inversion of electron density of triple pellet shot.

Electro-Optics Section

The task of designing a high-speed state-of-the-art transient digitizer controller module for CICADA was

undertaken. The resulting design satisfied both CICADA 912 and 914 module requirements, and 20 modules were produced. In addition, one megaword infrared television (IRTV) memory was designed and installed to provide added data acquisition capacity for the plasma TV system on TFTR.

The neutron activation diagnostic is used to measure plasma neutron fluence and energy distribution. Samples are transported from the counting room to the Test Cell, exposed to the neutron field, then returned to the counting room where the induced radioactivity is measured.

Hardware for the Fast Automatic Transfer System (FAST) on TFTR was received from Reactor Experiments and interfaced to CICADA. Software was written for the controller, a CAMAC microprocessor. An IBM-XT personal computer is used for data acquisition and analysis. It will also be used to control the system. Data archival will be on a VAX computer by modem transfer.

Work was initiated on the motion control system for the TFTR Horizontal Charge-Exchange diagnostic. Accurate positioning of the horizontal charge-exchange analyzers from the TFTR control room will be made possible with this system.

The disruption thermal monitor, a 15-channel, two color photometer operating near 900 nm, was completed and was installed. A coarse one-dimensional image of the limiter is carried by fiber-optics to the lower data acquisition room where the output of each fiber is split and imaged in narrow bands onto photodiodes.

Radio-Frequency Branch

High-Frequency Radio-Frequency Section

The High-Frequency Radio-Frequency Section undertook management of the Electronic and Electrical Engineering Division work for the TFTR diagnostic neutral-beam system. Activities on the system were restructured in April 1985 using composite crews from both the Radio-Frequency Branch and the Power Branch. The system was installed by the end of the year. Additionally, two engineers and one technician worked full time supporting operations and maintenance of the TFTR modulator/regulators.

Early in FY85 a filament failed in one of the three 2.45-GHz klystrons on PLT; this tube was returned to Varian for rebuilding. While the klystron was being rebuilt, the remaining two tubes were consistently operated at 950-kW source power to PLT, which is a substantial power increase over previous operations.

In addition to operating and maintaining the 800-MHz lower-hybrid resonance-heating system on PLT, transmission lines and coupler assemblies were redesigned to accommodate new fast-wave experiments. New components were fabricated and about one half were installed by September 1985.

A conceptual design for a system using 5 MW of radio-frequency power at about 2 GHz for current-

drive experiments on TFTR was completed in December 1984 (under a subcontract with McDonnell Douglas). This system, which will utilize the transfer of 1.5 MW of power at 2.45 GHz from the PLT system, includes a plan for the purchase of four 1-MW klystrons to be installed on TFTR to supply additional power.

The 60-GHz electron-cyclotron resonance-heating system used on the Poloidal Divertor Experiment (PDX) in 1983 was connected to PLT and recommissioned. One gyrotron developed a water leak at its output window and was sent to Varian for repair. Operation refinements on the remaining gyrotron resulted in a power output of 200 kW into a dummy load; it was then used into a side port launcher.

Low-Frequency Radio-Frequency Section

During FY85, an unused 25-kHz TFTR breakdown oscillator was converted to 1.8 MHz for use with the TFTR diagnostic neutral-beam (DNB) system on TFTR. The redesign and conversion was completed in the Radio-Frequency Branch shops, and then the system was delivered and installed at D-Site. The breakdown oscillator had no significant technical problems and is currently operating required.

Another portion of the TFTR diagnostic neutral-beam system provided by the Radio-Frequency Branch in FY85 was the high-voltage enclosure (HVE). The design and fabrication of this room-size, stainless steel enclosure containing all of the radio-frequency and high-voltage interface circuits for the DNB ion source was started in April 1985. It was delivered, installed, and commissioned in the TFTR Test Cell at the end of FY85.

Two of the ICRF heating systems on PLT were converted to 30 MHz and upgraded to operate at power levels of 3.0 MW each. These systems have been operating routinely on PLT, with a minimum of technical problems, throughout FY85. In addition, the fabrication, installation, and checkout of two 80-MHz, 0.75-MW radio-frequency systems for harmonic ion cyclotron radio-frequency (ICRF) experiments on PLT were completed in FY85. These systems are now ready for PLT experimental operations.

In late FY85, a program was started to generate a conceptual design for the upgrading of the PLT 30-MHz and 80-MHz ion cyclotron radio-frequency systems for eventual use on TFTR. This design will include a frequency change to 50 MHz for all systems; installation of transmission lines from C-Site to the TFTR Test Cell; complete radio-frequency interface with the TFTR vacuum vessel; and integration of all control and monitoring functions with the Tokamak Fusion Test Reactor CICADA computer.

A program to upgrade the hard tube amplifier on PBX, and to replace its capacitor bank with a transformer/rectifier power supply was started in August 1984 and completed in April 1985. This system is operational and ready for use by PBX for pulse-discharge cleaning.

Power Branch

AC Power Section

The AC Power Section continued to provide installation and operational support to TFTR, including supervising synchronizing tests for motor generator (MG) sets Nos. 1 and 2, supporting various magnetic-field systems aspiring toward their respective design levels, and providing for future equilibrium-field parallel operation. Investigation began into control system modifications required to allow MG operation in the "super-pulse" region.

The Section's broad range of Laboratory tasks included:

- Planning, coordinating, and monitoring implementation of a Laboratory-wide, subcontractor-conducted, ac distribution preventive maintenance program. This program identifies numerous inoperative and fault-prone components, leads to their repair and replacement, and thus enhances power system reliability.
- Completion of electrical design, procurement, testing, and start-up for the Repeating Pellet Injector system.
- Investigation, testing, and resolution of TFTR neutral-beam associated equipment and supply problems. Also, power and controls were installed and tested for neutral beamlines 2 thru 5 and the 1000-watt helium refrigeration system.
- Completion of the design for a new 5-kV feeder to CICADA's substation, eventually providing for immediate accessibility to TFTR's emergency diesel generator. In addition, a new secondary unit substation was designed, procured, and installed to power the new Emergency Service Building.
- Initiation of a TFTR spare electrical parts study that, when completed and implemented, would decrease a system's downtime that is presently attributable to procurement of replacement components.

The Section continued its review, inspection, and supervision of construction-related activities, and served as technical consultant for investigations into electrical billing, energy management, energy co-generation, and peak shaving. Also included were an investigation and recommendations on fire retardant coatings and blankets in response to a Factory Mutual Research Corporation review of PPPL, which addressed C-Site, MG Basement cables.

Motor Generator Section

In FY85, C-Site motor generator operations continued normally along with the following accomplishments:

Ten motor-operated safety disconnects were received. These newly purchased units were inspected by PPPL technicians. Twenty-one important

items in each disconnect required reworking to make the units function properly. The work was completed January 15, 1985 by Memco personnel at no additional charge of PPPL. With the installation of 80% of the disconnects and their Kirk-key interlocks, the dc pulse power distribution demands of PLT, PBX, S-1 Spheromak, and the Radio-Frequency Test Facility were met. Discharge cleaning of either PBX or PLT is now possible while the other machine is in full operation.

In June 1985, the water system preventive maintenance contract (for TFTR and C-Site Water Systems) was renewed at reduced cost. This was a result of reduced-work scope and reestimates of work remaining in the contract.

A computerized rotating equipment alignment system was purchased for use by PPPL motor generator technicians. Use of the system has reduced the time required for aligning machines. It is used extensively, and man-hour savings have been significant.

Neutral-Beam Power Section

Installation of TFTR heating neutral-beam electrical apparatus was continued from previous years. Installation of ion source power supplies was completed. Work also continued on design, fabrication, and start-up of CICADA interface equipment, as well as on the control elements for beamline vacuum and cooling subsystems. Figure 8 shows one portion of the CICADA/neutral-beam interface in use.

Figure 8. A portion of the CICADA/neutral-beam interface. (85E1165)

In April 1985, approximately one-half of the section personnel were detached for extended temporary assignment as TFTR heating neutral-beam operators. Neutral-Beam Operations assumed responsibility for the work performed by these personnel from that time and, hence, the involvement of the Section in TFTR neutral-beam heating activities decreased substantially. The Section continued to be involved in improvement tasks, such as the long-pulse modification for the TFTR power supplies. For the long-pulse design,

fabrication and test of required changes in the instrumentation and control systems are to be completed in FY86.

The Section contributed substantially to the design, fabrication, installation, and start-up testing of the TFTR diagnostic neutral-beam system. Contributions were concentrated primarily in the areas of Accel raw dc power, Decel power supply, and auxiliary functions such as (vacuum) getter power and bending magnetic supplies.

The Section participated in the characterization (determining limitations) of the TFTR field coil power conversion (FCPC) control system's supplies. Substantial contributions were made to the FCPC/CICADA interface specifications as well as to the specifications for the PBX Modification shaping-field power supplies. In addition, the FCPC supplies were carefully tested and evaluated to determine adequacy of performance.

Rectifier Section

The Rectifier Section continued to support the operation of the PLT, PBX, S-1 Spheromak, and TFTR machines. Significant contributions to TFTR include: design, fabrication, and testing of an horizontal-field bidirectional power supply, including a new digital complementary-type firing generator using a phase lock loop and inversion limit calculator; installation and test of 14 new surface pumping power supplies; and design, fabrication, and installation of equilibrium-field paralleling cable, links, and link boxes.

A feasibility study on battery peak shaving or load leveling was initiated and received favorable interest from DOE, Electrical Power Research Institute (EPRI), and public power companies.

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 FY85 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 included a continuation of the studies of the TFTR MG No. 1 and No. 2 rotor runout. The implementation of recommendations resulting from these studies succeeded in reducing the runout to acceptable levels. Another major contribution of the Group resulted in additional mechanical support being provided for TFTR poloidal-field bus work.

The Engineering Services Group provides skilled

technicians to perform maintenance, fabrication, and installation work for the various MED branches and for other organizational groups within the Laboratory. The Engineering Services Group is organized into several shops by skill. The electrical shop pulls heavy cable and performs electrical work up to 480 V, both for the major experimental devices and the smaller individual laboratories at PPPL. The electrical shop also installs control wiring, interconnecting computer cabling, and some instrumentation wiring. The metal shop and weld shop fabricate various mechanical structures. The plumbing shop maintains water systems for the experimental devices as well as fabricating new systems. The carpenter shop builds wooden structures, platforms, and enclosures. They also fabricate special molds and forms for coil winding as well as models for development studies.

Mechanical Technology Branch

The Mechanical Technology Branch consists of two engineering sections: the Diagnostics and General Fabrication Section and the Materials Test and Machine Design Section. In addition, the Branch includes the Mechanical Drafting Group and the Machine Shop Services Group.

Diagnostics and General Fabrication Section

The Diagnostic Neutral Beam (DNB), one of the largest and most complex diagnostic on TFTR, was completed in FY85. This diagnostic will be used in conjunction with the Horizontal and Vertical Charge-Exchange diagnostics to obtain plasma ion temperatures. The DNB vacuum enclosure and high-voltage enclosure ride on tracks that allow the diagnostic to view the plasma from a radial or tangential position. The total weight of the system exceeds 12 tons. The Diagnostics and General Fabrication (D&GF) Section designed, tested, and installed the DNB which is presently being tested on TFTR. Figure 9 shows the DNB during the installation phase.

During the summer of 1985, five additional channels were added to the Multichannel Infrared Interferometer (MIRI). The MIRI diagnostic will be used to monitor the plasma density of TFTR.

The Vertical X-Ray Crystal Spectrometer (VXCS) was also installed during FY85. This diagnostic is used to measure the ion temperature and plasma toroidal rotation velocity on the TFTR. This diagnostic features a 20 ft x 15 ft x 1 ft polyurethane bag used to contain the helium atmosphere for the X-ray paths. The VXCS is scheduled to become operational in January 1986. The D&GF Section installed this diagnostic.

During FY85, the Horizontal X-Ray Pulse-Height Analyzer was relocated to the TFTR Neutral-Beam Test Cell to provide neutron shielding for this diagnostic during four-beam operation. The D&GF Section was responsible for the design and installation required for the move. In addition, the Section was also involved in the design and installation of the TV

Figure 9. The TFTR diagnostic neutral-beam installation. (85E0952)

Thomson Scattering (TVTS) calibration and alignment probe on TFTR. This device allows the TVTS diagnostic to be aligned and calibrated while under vacuum.

Materials Test and Machine Design Section

In FY85, the Materials Test Laboratory performed a total of 186 tasks, approximately 80% of which were

Figure 10. Mechanical testing of the neutral-beam pivot bellows. (85E0825)

for TFTR. As in previous years, these tasks involved a wide range of PPPL operations including: Thermal response tests of limiter tiles and thermocouples; neutral-beam pivot bellows mechanical tests (Fig. 10); modification of field coil power conversion and safety disconnect switches; proof testing of lifting fixtures; testing of components in high ambient magnetic fields; metallurgical investigations and special purpose transducer and instrumentation design and fabrications. Some enhanced features were added to the real-time data acquisition and display system developed earlier for TFTR Motor Generator No. 1 and Motor Generator No. 2 operations.

During FY85, the Machine Design Section was combined with the Materials Test Section. Machine design activities included continued work on the Lithium Blanket Module (LBM) and the movable limiter. The fabrication of the LBM was completed at GA Technologies, Inc., and the disassembled components were shipped to PPPL. After reassembly, the LBM was tested on the Engineering Test Station, completing the preliminary acceptance test program. The LBM was again dismantled and then shipped to the École Polytechnique Fédérale de Lausanne in Switzerland for nuclear testing in their LOTUS facility. Work on the TFTR movable limiter included the completion of the actuator life cycle tests and refurbishing of the limiter and actuator during the machine opening of June-August 1985.

The Mechanical Technology Branch was also active in the planning for the PBX Upgrade. The Branch coordinated the PBX Upgrade scoping study and Branch engineers were involved in the conceptual design of coil supports as well as assembly planning.

Vacuum and Cryogenic Branch

Vacuum Section

During FY85, the majority of projects supported by the Vacuum Section were associated with the TFTR program and the Advanced Toroidal Facility (ATF) Poloidal Field Coil Program for the Oak Ridge National Laboratory.

The projects supported for TFTR include the neutral beams, the pellet injector, the non-tritium gas injection system, the diagnostic neutral beam, and the bumper limiters. All of these systems, for which the Vacuum Section provided varying levels of fabrication, installation, and operational support, are now operational. The gas injection system, which was designed, fabricated, and installed by the Vacuum Section, is shown in Fig. 11.

The Vacuum Section fabricated the inner and outer coil supports in addition to the press-curing molds and much of the tooling for the inner, mid, and outer ATF vertical-field coils. The largest mold was 20 ft in diameter and was fabricated from 2-inch-thick carbon

Figure 11. Installed non-tritium gas injection system. (86E0329)

Figure 12. Fabrication of an Advanced Toroidal Facility inner-coil support. (85E0549)

steel. The supports were fabricated from Type 304 stainless steel. Figure 12 shows a segment of the inner coil support during fabrication. All of these components were completed and delivered during FY85.

In support of the S-1 Upgrade program, the Vacuum Section procured new, explosively formed inconel liners (Fig. 13), started fabrication of the vacuum feedthrough assemblies, and completed the fabrication of a spare center vacuum vessel segment.

Figure 13. Explosively formed S-1 Spheromak flux core vacuum liners. (85E1375)

Other programs included the design and fabrication of the 2.45-GHz window arrays on PLT and general support to the diagnostic devices and machine vacuum systems on the various devices at PPPL.

Cryogenics Section

Commissioning of the TFTR 1070-watt helium refrigerator was the primary focus of the Cryogenic Section's activities. Early in FY85, a contract for the operation and maintenance of the refrigerator was awarded to CVI, Incorporated, of Columbus, Ohio. An operator training program commenced in March 1985. During the training program, the electrical, hydraulic, and process systems were tested and put into opera-

Figure 14. Refrigerator control console for the 1070-watt helium refrigerator system for TFTR. (86E0328)

tion. Following this, the combined system was operated in a closed-loop configuration in April. By June, the system was liquefying helium and storing it in the 1500-gallon dewar. The system began supplying liquid helium to the neutral-beam test stand in August. The refrigerator control console is shown in Fig. 14.

Coil Systems Branch

During FY85, the Coil Branch was involved in work for several major projects including the TFTR, the Advanced Toroidal Facility, the TFTR Bumper Limiter and Protective Plates, and the Ignition Studies Project (ISP).

The Coil Branch successfully completed the removal of TFTR's entire toroidal-field ring bus, stripping 100% of its insulation and refurbishing each conductor with new insulation prior to reinstallation. Concurrently, Coil Branch personnel fabricated and installed the necessary structural supports for the

Figure 15. The Advanced Toroidal Facility vertical-field coils in final fabrication. (85E0930)

Figure 16. Electrical tests of an Advanced Toroidal Facility coil. (84E1689)

poloidal-field lead stems and bus runs. All toroidal-field and poloidal-field coil and bus joints were visually inspected, resistance checked, and reworked as required. In addition, all poloidal-field systems were checked for polarity. New components were designed, installed, and tested to permit a new mode of poloidal-field system operation. This new mode, mode D, changes the function of some shaping-field coils to ohmic-heating coils to add additional volt seconds.

During FY85, the Coil Branch completed the design and fabrication of a total of six vertical-field coil assemblies for the Oak Ridge National Laboratory Advanced Toroidal Facility (ATF). This was one of the largest projects undertaken for an outside laboratory by the Coil Branch. The vertical-field coil assemblies vary in size from 10 to 20 ft in diameter (Fig. 15). The outer vertical-field coil assembly exceeded 15,000 lbs. The height of the outer vertical-field coil bundle exceeded that of the TFTR Stack No. 9 poloidal-field coil, and the conductor cross section (2.5 in. $\times$ 1.75

in. with a 1.00-in. diameter cooling passage) was the largest for any poloidal-field coil manufactured by the Coil Branch. This conductor size presented many challenges during fabrication. Figure 16 shows one of the ATF coils during electrical tests and Fig. 17 shows a coil with supports being prepared for shipping. The final shipment of the largest vertical-field coil assembly to Oak Ridge, Tennessee is shown in Fig. 18.

Coil Branch personnel were involved with the fabrication, testing, and installation of all components of the bumper limiter and final protective plates housed within the TFTR vacuum vessel. The bumper limiter plates protect the inner wall of the vacuum vessel 360° toroidally and $\pm 60^\circ$ poloidally from peak plasma power densities of 420 W/cm². This assembly is comprised of water-cooled inconnel backing plates onto which 1,900 carbon tiles were mechanically fastened. The protective plates cover the wall opposite the bumper limiter 130° toroidally and 63° poloidally. These plate assemblies, shown in Fig. 19, are also

Figure 18. Shipment of the Advanced Toroidal Facility outer vertical-field coil to the Oak Ridge National Laboratory from PPPL. (85E1208)

Figure 17. The Advanced Toroidal Facility outer vertical-field coil being prepared for shipment. (85E1204)

comprised of water-cooled inconnel backing plates onto which 600 carbon tiles are attached. The protective plates protect the inner wall of the vacuum vessel from normal neutral-beam operation up to 650 W/cm² and fault conditions to 2.8 kW/cm². The tiles attached to the protective plates are coated with titanium carbide on the face only. Thermocouples on both the bumper limiter and the protective plates and their coolant lines are routed through vacuum feedthrough assemblies mounted on the outside of the vacuum vessel.

In support of the S-1 Upgrade Program, the Coil Branch proceeded with the design of a higher-current capacity flux core, released subcontracts for major components, and began assembly. This program is expected to be completed in early 1986.

The Coil Branch continued to support the Ignition Studies Project (ISP) design effort, which is an offshoot of the earlier Tokamak Fusion Core Experiment

Figure 19. Interior view of the TFTR vacuum vessel showing bumper limiters and protective plates. (85E1156)

(TFCX) effort. The ISP design goal is to achieve an ignited plasma in a minimum-cost device. Consequently, the ISP device is a compact, high-field tokamak with nitrogen-cooled copper coils. As part of the multi-laboratory design team, the Coil Branch contributed to the designs of the toroidal-field and poloidal-field coil systems, to the materials selection and design allowable task force, and supplied technical personnel to assist in the actual testing of high-current sliding contacts for possible use in a demountable toroidal-field coil concept. Several machine concepts were studied during FY85, including demountable toroidal-field coils, various means of toroidal-field coil support, and poloidal-field coil placement.

COMPUTER DIVISION

In FY85, the Computer Division provided computing support to the Laboratory's projects and programs. Tokamak Fusion Test Reactor data acquisition, which at the time of TFTR start-up was nearly 2.5 megabytes per shot, now exceeds 12 megabytes per shot. The TFTR control room is shown in Fig. 20. Four VAX computer systems were "clustered," enabling users to utilize easily and efficiently all the systems for data acquisition, data reduction, and communication with the supercomputers at the National Magnetic Fusion Energy Computer Center in Livermore, California. The

Figure 20. The TFTR control room. (85A0204)

PBX/PLT/S-1 Spheromak support was enhanced by the use of a VAX-based supplement to the KL-10-based system. Personal computers became more popular as programming, presentation, and magnetic tools.

A listing of publications by Computer Division personnel is given in Refs. 4-6.

Software and Hardware Central Systems Support for TFTR

The CICADA (Central Instrumentation, Control, and Data Acquisition) System currently supports over 40 distinct systems of diagnostic and engineering applications on TFTR. Over 20,000 points in a total of 273 CAMAC [Computer-Automated Measurement and Control (System)] crates are monitored every two seconds, and over 7,500 points are controlled. For each shot, approximately 300 results waveforms are automatically computed and available for display or for transmission to another system for subsequent analysis.

Software support accomplishments in FY85 included the following:

- The Device Control System was enhanced to support multiple CAMAC links per subsystem computer, which provides additional subsystem independence and support for an increased number of interface points.
- Raw data files were restructured to minimize the number of I/O's (inputs/outputs) in order to optimize data acquisition throughput.
- Parallel execution of graphics codes has increased the graphics speed. Rates of 800,000 points per minute have been demonstrated.

Hardware support in FY85 focused on upgrading performance and improving reliability.

- The Block Transfer System, which was developed during FY83 and FY84, was activated and is acquiring TFTR experimental data. This system allows blocks of data to be shipped from

TFTR CAMAC crates over a communications link directly to central application computers at an effective rate of 240 kilobytes per second.

CICADA Neutral Beam, Diagnostics, and Facilities Applications Support

The second neutral beamline was made operational in 1985. The Neutral-Beam Clock System, which provides an independent clocking system for each of the four beamlines, was designed, fabricated, integrated, and tested on Beamlines 3 and 4. All of the Neutral-Beam CAMAC installation and fabrication work for support of the four beamlines and the test stand was completed. The Neutral-Beam Thermocouple System was installed for all four beamlines. The Neutral-Beam Real-Time Waveform Display Systems were designed and fabricated.

A new Master Control System was implemented in order to allow Physics Operations the ability to reload efficiently the Real-Time Plasma Feedback Systems from a central station. The Gas, Plasma Position and Current Control, Master Clock, and the Magnetics Systems were interfaced with this new Master Control System.

The Trending System, which supports the acquisition and display of a time history of user-defined monitor points throughout the facility, was made operational.

The Michelson Interferometer, Multichannel Infrared Interferometer, Neutron Multichannel Collimator, and Fusion Products diagnostics were implemented and integrated into the real-time system. Other diagnostic systems were enhanced.

Support of PLT, PBX, and S-1 Spheromak

The DEC-based Data Acquisition System (DAS) continued to provide support for PLT and PBX experimental operations. The DAS System regularly archived up to 2.5 megabytes of data per plasma discharge and performed real-time data reduction. The S-1 Spheromak diagnostics were successfully migrated to the DAS Supplemental VAX System (DAX) in an effort to reduce the level of saturation and provide a migration path toward the successor VAX-based DAS.

Migration of some PLT and PBX diagnostics from DAS to DAX was also started in FY85. A significant achievement was the first-time capability for simultaneous operation of two experimental machines (S-1 and PBX or S-1 and PLT) on the DAX System.

New Computer Systems

During FY85, the TFTR data analysis VAX-based computer was upgraded from a VAX-11/780 to a VAX-8600. At the end of the run in April, for every shot, five megabytes of shot data were transferred from the CICADA System to the VAX Cluster where the data was further analyzed and reduced.

The VAX-11/780 became a supplemental computer to the User Service Center's (USC) DEC-based KL-10 computer. In the winter of FY86, this computer system will also be upgraded to a VAX-8600 system as the KL-10 computer is retired. Conversion efforts to prepare for this upgrade are underway.

All of the VAXes were integrated into a VAX Cluster configuration, allowing for backend sharing of all disk resources, maximum utilization of all CPUs [Central Processing Unit(s)] in the cluster, common system support of operating systems and utilities, and unified solutions to problems facing the cluster. This cluster configuration is also modularly expandable to accommodate any programmatic changes that may be required.

Use of the Personal Computer

The personal computer became prevalent during FY85 as a scientific workstation and as a management tool. There are approximately 200 personal computers being used as terminals, stand-alone testing systems for CAMAC systems, and as management tools.

References

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- H.A. Murray, "High Current Electrical Joint Design and Evaluation," *ibid.*
- J.J. Zatz, "Dynamic Analysis of the TFTR Bumper Limiter," presented at the 8th International Conference on Structural Mechanics in Reactor Technology (Brussels, 1985), to be published.
- H.P. Furth, A.H. Glasser, W. Park, et al., "The $q(0) < 1$ Regime of the Tokamak," in *Controlled Fusion and Plasma Physics* (Proc. 12th Europ. Conf., Budapest, Hungary, 1985), L. Pócs and A. Montvai editors, Contributed Papers Vol. II (European Physical Society, 1985) 358.
- K.W. Hill, M. Bitter, M. Diesso, et al., "Tokamak Fusion Test Reactor Prototype X-Ray Pulse-Height Analyzer Diagnostic," *Rev. Sci. Instrum.* 56(1985) 840.
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PROJECT PLANNING AND SAFETY OFFICE

Until May 1, 1985, the Project Planning and Safety Office had three organizations under its purview. These were the Planning Office, the Project Management Systems Group, and the Project and Operational Safety Office. On May 1, 1985, the Project Management Systems Group was transferred from the Project Planning and Safety Office to the Controller's Office. This was done to increase the coordination between the Project Management System and the Laboratory's Budgeting and Accounting System. In subsequent Annual Reports, Project Management Systems will be included in the Administrative Operations' Section.

PLANNING OFFICE

In FY85, the Planning Office reviewed and updated the Princeton Plasma Physics Laboratory's (PPPL) Technology Program Plan and prepared PPPL's FY84 Technology Transfer Report. The Planning Office continued to serve as the single point of contact for PPPL with the Department of Energy (DOE) on Automated Data Processing Equipment (ADPE) matters. Several ADPE policy and procedures documents were prepared by this office.

PROJECT MANAGEMENT SYSTEMS

In a move to support the integration of the Performance Measurement System (PMS) with other PPPL financial systems, the Project Management Systems Group was transferred to the Controller's Office during FY85.

Efforts continued during the year towards maintaining PPPL's Performance Measurement System as a management tool that is used by both the project and engineering departments for cost and schedule control. Ongoing efforts include:

- Formal work estimation and authorization processes.
- Monthly progress statusing and variance analysis.
- Utilization of PMS output in monthly management and Department of Energy meetings.

The PMS represents TFTR, Experimental Projects, Ignition Studies Project, General Plant Projects, and miscellaneous work estimated at the job level. These

estimates are based on detailed activity schedules integrated with manpower and nonlabor cost estimates. Output data generated from PMS include (see Figs. 1-4 for sample reports):

- BCWS (budgeted cost of work *scheduled*).
- BCWP (budgeted cost of work *performed*).
- ACWP (*actual* cost of work performed).
- Schedule and cost variances (BCWP minus BCWS and BCWP minus ACWP).
- Labor and cost distribution (planned, forecasted, and actual).
- Detailed activity bar chart schedules.

This data provides the following:

- Engineering Department management with staffing plans and forecasts.
- Management with an early warning of potential cost or schedule impacts.
- Line managers, physicists, and engineers with a plan and schedule to work by and monitor.
- PPPL and DOE management with project status with respect to both cost and schedule and including projected year end costs.
- Engineering and project management with monthly charges to their divisions and projects.

Figure 1. Manpower distribution curve for Electronic and Electrical Division technician labor. Note: BSLN = PMS baseline, PPL = on board staff, T&M = time and materials labor, SC = subcontract labor, STAT = PMS forecast. (86A0234)

TFTR PROJECT
FY86
SUMMARY

RECOMMENDED CORRECTIVE ACTION PLAN:
None required

J. M. Dade ^{1/26/85} *11/26/85*
JOB ENGINEER DATE DIVISION HEAD DATE
PREPARED BY CC MANAGER: DIRECTED ACTION
K. M. Dade ^{12/21/85} *FDR due 11/1/85*
COST CENTER MANAGER DATE

Figure 2. Variance analysis report used to highlight cost and schedule variances, their causes, impact on other work, and corrective action.

[illegible]

Figure 3. Detailed work plan and current progress status for a typical job.

**PROJECT AND OPERATIONAL
SAFETY OFFICE**

This office continued to work closely with TFTR and other PPPL projects with heavy emphasis placed on day-to-day interactions and on close support of project personnel. The health physics staff was increased to reflect the needs of the program and the increased emphasis on environmental issues. In May, PPPL published its third Annual Environmental Report. This document reported on PPPL's environmental monitoring program and reviewed PPPL's compliance with government regulations. A review of the old

TFTR PROJECT
FY86
SUMMARY

Figure 4. Incremental and cumulative performance curves for TFR Neutral Beams. (86A0233 and 86A0232)

Forrestal C-Site sewage plant indicated that its former operation and shutdown were environmentally acceptable.

An Environmental Protection Agency (EPA) certification procedure was initiated for PPPL's radioactive analysis laboratory. A joint effort was undertaken with the Idaho National Engineering Laboratory to produce a procedures manual for PPPL that would standardize analysis procedures and would help in the certification process. A tritium enrichment process was developed in order that environmental levels of tritium could be detected and to provide required baseline data. A program was also initiated to establish off-site air particulate and tritium in air monitoring in FY86. Radioactive environmental analysis procedures (see Fig. 5) were established for vegetations, soils, water, and urines.¹

Health physics surveys, electrical inspections, and overall safety reviews continued for all PPPL projects. A complete survey of the TFTR Energy Conservation System Kirk-key interlock systems was undertaken

Figure 5. Alkaline permanganate and azeotropic distillation for environmental sampling procedures. (85X3217).

and necessary hardware changes were installed and tested. A program to update the TFTR access and operating procedures, in line with Health and Safety Directives, was initiated. Emphasis was also given to the formalization of the electrical rubber glove testing program. Capacitor bank accessing procedures were instituted and, to complement the procedures and to ensure safe operation, employees were trained and certified as accessors. A procedure for electrical emergency response during life-threatening situations was initiated and is currently under review. In addition, increased communication to employees was promoted by use of the Laboratory *PPL HOTLINE* publication and safety bulletins.

Reference

'O. Griesbach and J.R. Stencel, "An Environmental Monitoring Program for a Fusion Test Reactor," in *Environmental Radiation '85* (Proc. 18th Midyear Topical Symposium of the Health Physics Society, Colorado Springs, CO, 1985) 227.

QUALITY ASSURANCE AND RELIABILITY

The Quality Assurance (QA) Program emphasis changed during FY85 because of the decrease in Laboratory construction, fabrication, and procurement activities and because of the increased emphasis in machine operations. During FY85, the QA Program had two primary objectives: simplification of existing QA policies, procedures, and systems based upon a cost/benefit analysis and the development and implementation of strategies designed to support the Laboratory's response to decreasing budgets. The following are some of the major highlights during the year:

- The Quality Assurance Program was reorganized. The original five functional groups were reduced to three, facilitating communication and providing a more efficient utilization of available skills. This reorganization was accompanied by the physical consolidation of the QA staff at C-Site, which provided for further efficiency and morale benefits.
- Selective reductions in the scope of QA Programs were introduced, permitting the reassignment of personnel to functions more appropriate to the current operational environment. For example, daily roving inspections of all on-site construction projects were eliminated in favor of one or more tollgate acceptance inspections at critical stages of a project.
- A single commercial standard (ANSI/IPC 610 A) for electronic assemblies was adopted. This was a joint Engineering Department, Procurement Division, and Quality Assurance Program action. It was accompanied by extensive training of technical support and inspection personnel and by the screening and indoctrination of sup-

pliers. Results are just now becoming evident in the generally improved reliability of installed electronics.

- The Quality Assurance Mechanical Calibration Laboratory's performance was reviewed and the calibration interval selectively increased. This interval extension was based upon a marked decrease in instruments requiring adjustment or repair. During FY84, at the start of the program, out-of-tolerance conditions were observed in about 20% of the instruments being processed. This dropped to less than 5% in FY85, a result of improvements introduced by the Laboratory shops.
- The Princeton Plasma Physics Laboratory was selected by DOE-OFE to host and chair the Third Fusion Quality Assurance Workshop. The Workshop, held on 24-26 July 1985, was attended by Operations and Quality Assurance personnel representing all the U.S. fusion research facilities. The primary topics were Operations Quality Assurance Strategies and Interlaboratory Cooperation.
- The TFTR Trouble Report System was further enhanced by the introduction of a quantitative measurement of system and subsystem availability. Papers on this topic were presented at the Third Fusion Quality Assurance Workshop and at the Eleventh Symposium on Fusion Engineering.

Despite the 27% reduction in QA staff that occurred during FY85, all of the major objectives of the Laboratory's Quality Assurance Program were met and significant improvements in the services available to Laboratory projects were implemented.

ADMINISTRATIVE OPERATIONS

In FY85, emphasis was placed on maintaining the quality of administrative services in the face of reduced Laboratory budgets. It is the Laboratory policy to match reductions in controllable G&A and other overhead expenses as closely as possible to the overall reductions in program funding.

During FY85, the Princeton Plasma Physics Laboratory (PPPL) staff was reduced from 1293 on October 1984 to 1121 at year's end, a reduction of 13%. This was accomplished primarily through voluntary means—attrition and a special voluntary retirement program for employees over 60 years of age with 10 or more years of service. However, in June 1985, the Laboratory implemented a general Reduction-in-Force (RIF), involving 30 people, to meet budgetary limits and reduced workload. In the same period, Subcontract labor at the Laboratory was reduced 46% (from 263 to 142), with substantial additional reductions planned for FY86. These reductions, and the rebalancing of effort throughout the Laboratory, absorbed substantial effort at all levels of management. The resulting composition of PPPL on September 30, 1985 was:

Fiscal Year 1985 Staff Composition.

Faculty	2
Physicists	117
Engineers	240
Technicians	519
Other	243
Total	1121

A key development in FY85 for the Laboratory as a whole was the work and report of the so-called "Blue Ribbon Panel." In May 1985, at the request of the DOE, Princeton University appointed a Panel composed mainly of present and former Research Laboratory Directors to review the effectiveness of PPPL management systems. The Panel consisted of the following members:

Dr. Frank Hereford, Chairman	President, University of Virginia
Dr. Carl O. Bostrom	Director, Johns Hopkins Applied Physics Laboratory
Dr. Clark Ice	Former Director, Savannah River Laboratory
Dr. Christopher Kraft	Former Director, NASA's Manned Space Flight Center, Houston, TX

Dr. Wolfgang Panofsky Former Director,
Stanford Linear
Accelerator Center

Dr. Alan Schriesheim Director, Argonne National
Laboratory

The Panel employed a management consultant to provide information and analysis and focused on a number of areas selected by DOE, including assignment of technical personnel to projects (matrix), technical decision making processes, performance measurement systems, quality assurance activities, TFTR computing capabilities (CICADA), procurement, etc. The work of the consultants and the Panel, over a five month period, involved over 200 interviews with PPPL managers and resulted in two principal conclusions which are quoted from the October 1985 report:

- The Princeton Plasma Physics Laboratory "enjoys an enviable worldwide reputation for its scientific achievements, and the Panel's findings and conclusions fully confirm this judgement."
- "The current management practices are appropriate to the Laboratory's mission and the Panel did not find that significant cost reductions could be achieved through their modification."

Turning to the Administrative Operations Area, activities of note in FY85 were the following:

- The area continued to use and develop management-by-objectives, and about 75% of the major FY85 objectives were successfully accomplished during the year. Many of the remaining objectives were carried into FY86, due to midyear staff reductions.
- Quarterly reviews of indirect costs and related management objectives were continued with line managers, including representatives of Projects and Departments.
- Controllable G&A expenses were reduced 6.4% from FY84 to FY85, with further reductions to take effect early in FY86.
- Steps were taken to consolidate Laboratory space in light of staff reductions.
- Responsibility for the Performance Measurement System (PMS) was transferred to the Controller, where PMS data base management and reporting could be better integrated with that for budget and accounting.
- Compensation administration was improved through broadening market indicators for our various staffs, benchmarking key management

positions, and improving our internal data analysis capabilities.

- The process of integrating the Forrestal security force with the Emergency Service Unit was completed in FY85, with substantial budget savings. The search for a qualified Head for the combined force neared completion at year end.

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 facilities, systems, and equipment at A-, B-, C-, and D-Sites. Table I shows the gross square feet (GSF) maintained by PPPL at each site during FY85.

Table I. Princeton Plasma Physics Laboratory FY85 Square Foot Occupancy.

Location	GSF
A-Site	209,811
B-Site	140,088
C-Site	450,363
D-Site	218,723
Trailers (C- and D-Sites)	18,470
Total	1,037,455

Project Engineering

The Project Engineering Branch was responsible for planning, engineering, and coordinating General Plant Projects (GPP) funded projects and energy-funded retrofit projects during FY85. Table II summarizes the number and value of active projects at year-end.

Energy Conservation

The Laboratory's energy management and conservation activities continued at an aggressive pace in FY85. This was primarily due to the implementation of energy retrofit projects and an intensified effort to address energy conservation opportunities in physical plant preventative maintenance operations. The results of these intensified activities produced a 49.1% reduction in the FY85 Laboratory Buildings Energy Utilization Index (Btu/ft²) versus the 1975 Base Year. Thus, in FY85, PPPL not only met but exceeded the

Table II. Fiscal Year 1985 Project Summary.

	Number of Projects	Value (\$K)
Energy Conservation		
Retrofits		
Previous fiscal years	15	\$1,906
Current FY85	4	847
Studies		
Previous fiscal years	4	209
Current FY85	3	195
	26	3,157
General Plant Projects		
Authorized		
Previous fiscal years	5	1,928
Current FY85	19	1,540
Proposed FY86/87		
Conceptual Design Studies	11	120
	35	3,588
Other Engineering Support	26	791
TOTAL ALL CATEGORIES	87	\$7,536

energy use reduction goals established in Executive Order 12003 on July 20, 1977. Another noteworthy energy conservation achievement was the reduction in the total Laboratory (buildings and experimental operations combined) energy Utilization Index versus the 1975 Base Year. This was quite an accomplishment considering that existing experimental devices and their activities increased fourfold and the square footage of occupancy increased 99%. These reductions, when normalized (FY85 versus 1975), resulted in a savings of \$1,019,000 in electric and \$1,143,000 in fuel oil costs. This achievement required the full commitment and support of Laboratory management, the cooperation and efforts of personnel employed in all disciplines at the Laboratory, implementation of cost-avoidance projects, and the use of innovative engineering techniques.

Complementing earlier energy conservation efforts, two distinctly different types of energy management systems were completed in FY85: the Energy Monitoring and Control System (EMCS) and the Power Line Carrier System (PLCS). The EMCS is a "hard wired" system which is designed for comprehensive and complex operational conservation tasks. The PLCS, a less sophisticated system, communicates and controls applications via frequency signal using the existing facility wiring net. Installation of the EMCS included microprocessors, data gathering network, field sensors, control valves, motors, fans, and other recording devices. This is an "initial phase" which addresses applications at A- and C-Sites. The EMCS system is expandable to accommodate all sites through the existing Central Processing Unit. Installation of the

PLCS included a controlling microprocessor, transponders, transceivers, receivers, data gathering network, and field sensors. This is also an "initial phase" which presently addresses applications only at C-Site.

Additional energy retrofit projects completed in FY85 were the night temperature setback systems, the C-Site outdoor high efficiency lighting upgrade, the C-Site solid state ballast lighting retrofit, and the retrofit of small motors.

To keep maintenance personnel up-to-date in energy conservation procedures and equipment operations, periodic training sessions were conducted. In addition, special in-depth energy conservation symposia and seminars were attended by PPPL engineers in order to further enhance and to implement energy management and conservation measures.

Throughout the Laboratory, the employee awareness program provided additional energy savings and cost avoidance. Public relations interface with Laboratory staff was maintained through the *PPL HOTLINE* newsletter. With the DOE theme, "Energy Security for Peace and Prosperity," Energy Awareness Week was conducted at the Laboratory in October. Posters encouraging energy conservation were displayed on bulletin boards throughout the Laboratory. Overall, employee cooperation and energy conservation awareness was high. All contributed to an effective Laboratory-wide energy management and conservation program.

Plant Maintenance

The PM&E Division's work load has continued to increase significantly over the past six years. Fiscal year 1985 saw 4,512 service calls, 2,751 major (requiring four or more hours of labor to complete) work orders, and 1,500 preventative maintenance (PM) work orders, for a total of approximately 94,000 scheduled man-hours, as compared to approximately 65,000 scheduled man-hours in FY78. Office moves, additions of computers and word processing equipment, and increased security measures significantly added to the work load. Concurrently, with the increased work load, PPPL experienced a budget cut requiring a reduction in Plant Maintenance staff from 154 full-time employees in FY84 to 127 in FY85.

A Plant Maintenance work order review and control system, which carefully allocates Plant Maintenance resources, was established. This system controls work order initiation, backlog limitations, work project approval, and office/space rearrangements.

The computer-based work order system, which was developed in-house, was expanded to control minor work orders (requiring less than four hours of labor). Detailed management information that categorizes the type of work is now readily available allowing simplified calculations for the Annual Work Plan and for future work load projections. The computer, an IBM PC AT, captures information from the work order system and generates reports that were previously compiled manually by a clerk, thus reducing the clerical function and, at the same time, increasing accuracy and reliability. These reports include such

information as work backlog by trade, current status of work orders, weekly work schedules, and comparisons between actual time spent versus estimated time for each job.

The computer-based Preventive Maintenance (PM) Program, in effect for the past two years, has reduced downtime of equipment to very low levels. Maintenance history shows that with this reduced equipment downtime a decrease in PM by approximately 30% will be possible without adverse affects.

Several physical plant upgrading projects were completed in FY85. High-maintenance, reciprocating air compressors in the C-Site Motor Generator (MG) Building were replaced with rotary-screw types. The replacements were installed with satisfactory results (no downtime, better air quality, and less PM). A new diesel canal pump engine which meets the requirements of the fire underwriters was also installed. Spaces were modified to provide new labs, and major safety-related building changes and energy-saving projects were completed in FY85.

The above work was accomplished with the aid of the introduction of Plant Maintenance administering a labor-hour force of outside contractors. Twenty-five projects were completed within budget without any increase in manpower. Yearly contracts for all trades were awarded to outside contractors to supply manpower on demand on a cost-per-hour basis. Using design drawings and material supplied by PPPL, project costs and quality were controlled. A total of \$188,000 was expended in FY85. Because of the strict controls, careful administration, and strong cooperation from all the factions at PPPL this has been a very successful program.

Maintenance Training

In-house training in maintenance procedures continued to receive strong support in FY85. Ten PM&E employees attended in-house classes for two hours, twice weekly for an eight-month period. This was the eighth year that these vendor-designed (Technical Publishing Company) courses were given. With the reduction of manpower in Plant Maintenance, this program is more important than ever; it enables the staff to work more efficiently. Safety training also 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 pyrotechnics and radiation safety. Unfortunately, due to budget restraints, the general apprentice training program had to be eliminated.

Maintenance Safety Support

Continuation of the safety program in FY85 resulted in 230 safety-related work orders being issued that totaled 1319 man-hours of effort. These safety work orders were completed in a minimum amount of time, with accurate tracking and reporting made possible with the computerized work order system. The PM&E Division continues to add to a Laboratory safety

record of 606 consecutive days by a Division without a lost-time accident.

Library

Library operations and activities continued apace in FY85 as 3,075 books, 1,183 journal articles, and 513 technical reports were circulated to the PPPL staff. A total of 1,097, or 23% of these materials, were borrowed from other libraries, most from within the Princeton University system. A total of 1,241 fusion-related journal articles and 830 technical reports were cataloged by the Assistant Librarian, and cards were produced for the card catalog and monthly Acquisitions Lists. The possibility of cataloging the journal articles and technical reports online and providing Laboratory-wide access to this file was investigated by the Librarian. The highlight of the year was the purchase of an IBM/PC XT microcomputer for the Library, which was extensively used in information retrieval and telecommunications, as described below.

Computerized Information Retrieval Systems

A total of 386 literature and reference searches were performed in 1984-85 on the DOE/RECON, DIALOG and NASA/RECON systems. The file searched most frequently on DOE/RECON was the Energy Data Base, and the DIALOG files searched most often were INSPEC (the online equivalent of *Physics Abstracts*, *Electrical and Electronics Abstracts*, and *Computer and Control Abstracts*) and NTIS (the National Technical Information Service's data base). Extensive use was made of the Research Libraries Information Network (RLIN) data base to locate books requested by PPPL users. (RLIN is the online cataloging tool of over 30 major research libraries throughout the country and has been used by Princeton University to catalog its collection of monographs and serials since 1980.) The PPPL Library will soon have dial-up access to Princeton's Geac acquisitions system, which contains status information for books ordered by the Princeton University libraries, as well as the Geac circulation system. This capability will be extremely useful for locating books and serials requested by PPPL patrons. A "REQUESTS" data base, using Enable software on the IBM/PC XT, has been designed by the Librarian to keep track of the requests for materials which must be borrowed from sources outside the PPPL Library. This information will be extremely valuable in the continuous evaluation of the Library's collection development policy. The Library also uses the Laboratory's PUBSYS system to retrieve relevant budgeting, accounting, and personnel information.

Telecommunications

By using YTERM emulation software, the Library's PC can be used to access the University's 3081 mainframe computer, and since the Engineering

Library also has a PC, messages can be sent to each other using PCTTRANS, one of the University's versions of electronic mail. This is particularly useful for sending borrowing requests. The next objective is to establish the communications links between the Library and Laboratory terminals for sending messages and such bulletin board notices as daily lists of new books and journals received.

Information and Administrative Services

The Information and Administrative Services Branch includes all Laboratory services supporting the preparation and dissemination of information pertaining to PPPL's program. Included are photography, graphic arts and technical illustration, word processing, printing, technical information, and public and employee information. Various administrative services—specifically, telecommunications, conference coordination, mail, and travel services—are also provided.

Public and Employee Information

The Public and Employee Information Section of the Information and Administrative Services Branch is responsible for providing up-to-date information on PPPL's program for members of the general public, the news media, representatives of government and industry, and employees of the Laboratory. The section maintains an information kit consisting of brochures and information bulletins that are written for the layman. An employee newsletter, *PPL HOTLINE*, is published monthly. The staff coordinate an active speakers bureau, Laboratory tour program, as well as media relations and community outreach activities.

During FY85, two major public information projects were undertaken. The PPPL Overview brochure was completely rewritten to reflect recent experimental achievements and to stress PPPL's technological capabilities. The new booklet, issued in April 1985, is the eighth edition of this publication. In September 1985, a new multi-image slide/sound show made its debut. The show, which makes use of three projectors and a dissolve unit, provides a clear and concise introduction to PPPL's fusion program and will be used to orient Laboratory visitors prior to tours. In FY86, the show will be recorded on video tape to allow showings off-campus, including distribution to area science teachers.

In October 1984, a news conference was held at the annual meeting of the Division of Plasma Physics of the American Physical Society in Boston to announce that major strides toward the goal of developing a soft X-ray laser had been made by a PPPL team headed by Szymon Suckewer. Considerable media interest was drawn to the achievement, with articles appearing in the *Wall Street Journal*, the *Christian Science Monitor*, as well as state and local newspapers.

The PPPL tour program continued to draw a large number of visitors during FY85, despite the fact that access to TFTR was limited due to extensive con-

struction in the spring and summer. During FY85, over 4,000 individuals toured the Laboratory.

The Princeton Plasma Physics Laboratory's Community Outreach Program continued in FY85 with the goals of fostering a broad base of local public understanding of the Laboratory's program and forging closer communication links with local government, industry, and educational groups.

Fiscal year 1985 Community Outreach activities included the continuation of the monthly TFTR Open Houses, each attended by an average of 80 people. Meetings with representatives of local governments, industries, and civic groups were continued to provide an overview of PPPL's fusion program and a tour of TFTR. Several groups of teachers from area schools attended similar programs throughout the year. The Laboratory's Summer Work Grant Program was continued during the summer of 1985. Under this program, eight outstanding high school students assisted PPPL scientists or engineers in research and technical projects. Both students and their Laboratory supervisors found the program to be extremely beneficial. Also as part of Community Outreach in FY85, the Laboratory began a "Science on Saturday" seminar program designed to expose students to ideas and facilities not normally part of the high school curriculum. The five-week series of lectures, demonstrations, and tours covered a variety of topics on the frontiers of scientific inquiry. Thirty-five students attended the seminars. Plans were developed to expand the number of students and schools participating during FY86.

Graphic, Photographic, and Printing Services

While the demand for graphic art services continued to increase at a significant rate (15%) during FY85, total photographic service production fell approximately 10% and demand for centralized duplication services was off approximately 15% from FY84. Very substantial increases for all services were recorded for FY83 and FY84.

The decline in demand for photographic service in FY85 was largely in the area of location photography, reflecting a lessened need for the documentation of construction activity. This is commensurate with the continuing increase in demand for line art, as new data must be documented for PPPL's four major operating devices.

The decrease in production within PPPL's centralized duplicating facility from 5.5 million impressions in FY84 to 4.7 million in FY85 may be explained by a lower demand for procurement and proposal documentation compared to FY84.

Early in FY85, the in-house duplicating facility phased out all offset press equipment and began performing operations exclusively on two high-speed duplicators, a Xerox 9200 and a Xerox 9500 V.R. Faced with aging equipment, a reduced operating budget, and an anticipated relocation of the duplicating facility to a smaller area, proposals for a reconfiguration of equipment were solicited in May 1985. The

result of this action at the end of September 1985, was the purchase of the Xerox 9500 V.R. at a very favorable price.

The number of individual printing procurements through the U.S. Government Printing Office in FY85 totaled 65 with a total dollar outlay of \$74.4K.

Word Processing Service

The Word Processing Committee was requested to investigate potential electronic typewriter replacements for the IBM Selectric IIs. The new model would become the standard low-end word processing tool for the Laboratory. Xerox Memorywriters were selected, and several were procured during the year.

The mid- and high-end standard word processing equipment continued to be NBI. Since there already existed an extensive NBI network, the number of new acquisitions required during the year was small—two terminals and two printers. Furthermore, changing requirements among various departments enabled most needs to be met by internal transfers of equipment.

The total reported word processing production for the Laboratory was 156,469 pages, which was roughly equal to the FY84 production level. The Word Processing Center share was 16,733 pages or 11% of the total.

In-house training for 14 staff was provided by Word Processing Center personnel.

Maintenance records on the three NBI central units showed that users enjoyed favorable uptime: MUTT, 96%; JEFF, 98%; and A-Site, 99%.

Telecommunications Services

The Telecommunications Services Section of the Information and Administrative Services Branch is responsible for the provision of cost-effective voice communication services. The Section supervises and coordinates repairs and installations, oversees the telephone billing process, and recommends hardware. During FY85 the staff handled 3,500 requests for moves, installations or changes in telephone service. Changes occasioned by the 1984 divestiture of AT&T created a need for more complex record keeping and the requirement to deal with a greater number of vendors. Budgetary constraints during FY85 led to a consolidation of the telephone operator and C-Site receptionist position with some resulting loss of manpower.

Several major projects were underway during FY85. Substantial progress occurred in the conversion of PPPL's radio communication system from VHF to UHF. Recommendations made as a result of a FY83 study involving USDOE consultants were implemented in FY85. Installation of the new UHF system will be completed during the first quarter of FY86.

Work continued on the procurement of a digital telephone switch to replace PPPL's current centrex system. The schedule now calls for a contract to be awarded during the second quarter of FY86, with a target date of early FY87 for installation.

Work was completed during FY85 on the installation of an emergency public address evacuation system for C-Site to interface with the existing system at D-Site. The new system became operational in the summer of 1985, providing enhanced employee protection in the event of fires, power failures, or natural calamities.

Finally, studies were completed on the installation of a 40-station intercom system in the TFTR complex. Plans were approved by USDOE, with installation scheduled to occur in FY86.

Personnel

The following major activities occurred within the Personnel Division during FY85:

- A Voluntary Separation Plan was established, after approval by Princeton University and DOE, and offered to employees age 60 and over, with a minimum of ten year's service. The Plan, which offered financial incentives to employees eligible for retirement in FY85 or FY86, was highly successful. Some 68 employees entered the Plan.
- The Laboratory experienced a Reduction-in-Force (RIF) in FY85. After substantially reducing subcontract employees and taking advantage of voluntary separations and normal attrition, the Laboratory had to resort to an involuntary reduction of 30 individuals to live within the reduced budgets. The RIF occurred on July 1, 1985.
- An Outplacement Program was initiated in connection with the reduction-in-force. A professional outplacement organization, Right Associates, provided in depth, personalized counseling for each of the affected employees. Additionally, an outplacement center was temporarily established to provide the affected employees with secretarial support, phone coverage, interviewing space, etc. By the end of the fiscal year, the majority of the displaced employees had obtained other employment.
- Emphasis on employee development activities was continued in FY85. Two senior managers participated in a two-week, technical management program offered at the Massachusetts Institute of Technology. Workshops were continued in FY85 by Blessing White, Inc. to strengthen subordinate and supervisor understanding, to assist employees in focusing on their career objectives within their present jobs, and to help employees achieve productivity increases. Additional courses, offered by Princeton University, and individual counseling, were made available to develop supervisory capabilities, communications effectiveness, understanding of the managerial process, and other work-related skills for supervisory and nonsupervisory personnel.

- To ensure that Laboratory salaries are accurately measured versus the market, the Compensation Section broadened its capabilities for comparative analyses and job benchmarking through the use of new salary surveys, such as the Salary Information Retrieval System (SIRS), the Hansen Professional Surveys, and locally, the Delaware Valley Personnel Association and Princeton Personnel Association. The Compensation Section also developed a Performance and Salary Range Penetration Matrix that enabled supervisors to determine salary increases, which were better related to performance, for employees on the various staffs. The use of the Matrix enabled employees to be placed logically within salary grades and helped create more equitable salary relationships.
- The Personnel Division published three Laboratory-wide policies dealing with: (1) Reduction-in-Force procedures, (2) Conditions of Employment, including matters such as shift differentials, overtime assignments, medical evaluation, etc., and (3) Laboratory Rules of Conduct and Performance and procedures governing disciplinary actions.
- The Personnel Office designed and implemented a Bi-Directional Data Transfer System between the Laboratory and Princeton University main campus data bases. This eliminated duplicate data entry, improved the present data bank, and provided main campus with the information it is required to maintain.

Occupational Medicine and Safety Office

The Occupational Medicine and Safety (OM&S) Office provides services to Laboratory personnel and organizational units in occupational medicine, health counseling, alcoholism rehabilitation, worker's compensation administration, industrial hygiene, hazardous materials control, radiation exposure monitoring, industrial safety, safety training, fire prevention, emergency planning, safety management auditing, and safety policy administration. It also provides consultation and guidance to Laboratory management in health matters and assists the Personnel Division in disability absence administration and the employee assistance program.

Computerized data bases were created for: accident analysis; safety training needs, safety courses presented, and the training status of individual employees; the hazardous materials inventory; and hazardous materials labels.

The safety branch coordinated the revision of 15 of the Laboratory's Health and Safety Directives. Health and Safety Directives are issued by the Laboratory Director and constitute the basic policy document for employee safety. This project brought our safety management system into closer congruence with the Laboratory's needs and with regulatory requirements.

The downward trend in accidents experienced in FY84, was continued. The integrated Safety Performance Index dropped from 2.5 in FY84 to 1.9 FY85. The Laboratory's safety record was recognized by both the National Safety Council and the U.S. Department of Energy with presentations of awards. A presentation ceremony was held in which Mr. C. Edwin Max, President of the N.J. Safety Council, awarded the Laboratory its Award of Honor—the only one granted to a noncommercial research laboratory in the United States. Mr. D.J. Carden, DOE Princeton Area Manager, then presented a DOE safety award.

The Industrial Hygiene Section drafted a new Health and Safety Directive, approved by the Executive Safety Board and the Laboratory Director, which creates a policy and a mechanism for the Laboratory to come into compliance with both the newly enacted N.J. Worker and Community Right to Know Act and the newly effective OSHA (Occupational Safety and Health Administration) Hazard Communication Standard. At the time of this writing, the Federal program covers only the manufacturing segment of the nation, but DOE policy requires all its contractors to comply with it. The Laboratory is also required to conform to those parts of the N.J. Act which apply to research and development laboratories. The Laboratory's compliance program will consist of a broadening of the scope of the chemical safety course, which has been presented for several years, and the creation of the required container labels by computer.

This was the first full year for OM&S to have responsibility for the coordination of the Laboratory's Area Safety Coordinator Program. This responsibility was placed in the Industrial Safety Section of the Safety Branch. In response to requests from the Coordinators, separate monthly meetings were organized for them to discuss safety topics and receive assistance in problem solving. As a result of the time and efforts of these Area Safety Coordinators, many potentially hazardous situations were rectified before anyone was injured.

Public Safety

Two protective organizations, Emergency Services and Forestal Security Units, merged in FY85 forming the Office of Public Safety. This consolidation allows the present fire, first aid, and hazardous material response personnel to perform both the duties of security officers as well as fire fighting/emergency medical technician functions, thereby helping to reduce costs in excess of \$300,000. This newly formed group is a division of Princeton University's main campus Public Safety Department. Providing round-the-clock, 365-day coverage for Forestal Campus, this Division consists of one Associate Director, five fire Captains, five fire pump Driver-Operators, and 15 Emergency Services Officers (ESOs). The ESOs are assigned daily to security posts; however, when emergency conditions exist the ESOs respond and assume interchangeable duties.

During FY85, the Public Safety Unit reviewed and updated the Laboratory's Emergency Preparedness

Plans, consolidating the original 26 supplements into a condensed and workable four-volume plan.

In August, ground was broken for the erection of a new medical dispensary, which is being attached to the present emergency vehicle building. The new Emergency Services Unit (ESU) addition will provide about 750 sq ft to house fire Captain and Security supervisor offices and training facilities. This construction is expected to be completed sometime in the spring of FY86.

On August 15, the ESU responded to a smokey fire condition in the TFTR Pump House. Despite the extremely hot day and high humidity, the fire fighters had the fire under control within five minutes. Surrounding communities' volunteer fire and first aid units were summoned to help with the emergency.

The ESU, along with the AC Power Division, Occupational Medicine and Safety, the Project Safety Office, Plant Maintenance, and TFTR, identified potential hazardous areas and conditions at PPPL and will formulate emergency response procedures that will deal with life-threatening conditions and prevent or minimize property damage.

Other tasks performed by the ESU include:

- Certifying 110 employees in CPR.
- Recertifying 180 employees in CPR.
- Training 21 employees in first aid.
- Training 120 employees in basic fire extinguisher usage.
- Issuing 1,290 flame permits.
- Issuing 91 penetration permits.
- Responding to 27 first aid calls.
- Responding to 38 fire calls.
- Responding to 3 hazardous material cases.

Procurement

Continuing efforts to reduce costs in FY85 resulted in a more than 30% staff reduction in the Procurement Division.

Each year the DOE works with its prime contractors towards improving their socioeconomic performance; subcontracting plans are reviewed for possible use of S/DB firms; conferences are attended and information disseminated about research and support service activities; and, in general, a concerted effort is made to encourage the use of S/DB firms. Percentage goals for small businesses and socioeconomic disadvantaged businesses are established in the prime contract with the DOE. In 1985, the Laboratory's aim was 45% of procurement dollars for small businesses and 2.4% for socioeconomic disadvantaged businesses. Through the diligent efforts of the Procurement staff, the Division exceeded its percentage of goals for small business by 22% and disadvantaged business by 62.5%.

During the first quarter of FY85, a totally revised "Procurement Manual of Policies and Procedures" was approved by the DOE with a notation that compliance with said manual will insure adherence to the

"Federal Norm." in the fourth quarter of FY85, the Procurement Division underwent a successful Contractor's Procurement System Review (CPSR) conducted by Chicago Operations Office and Brookhaven Office personnel. Because of reduced budgets, staff training continued on a more selective basis. More consideration was given to individual skills that would benefit the Division. A total of eight people attended off-site procurement-related courses during the year.

After nine years, the end of FY85 saw the complete phase out of the industrial subcontractor, Ebasco, procurement activities.

Materiel Control Office

During the past two years, the primary efforts of the Materiel Control Office have been directed towards improving the control of capital equipment in order to obtain DOE validation of the Property Management System. In August of 1985, the DOE conducted a major appraisal of the property system. The Stockroom Branch received a rating of "good" with an overall appraisal rating of "satisfactory." The appraisers noted that the Laboratory had made significant improvements in the control and protection of equipment. Further improvements are presently underway for the coming year with equipment walk-throughs, custodian meetings, and implementation of the bar code inventory system. Approval of PPPL's Property Management System by the DOE achieved an important management objective; maintaining and improving the Property Management System will be a key management objective during FY86.

Two major automation projects were also initiated during FY85. They were: automation of the receipts processing system and bar coding of capital and sensitive equipment. These projects will increase the efficiency and effectiveness of the Stores and Warehouse Operations Branches. The gains in productivity will partially offset FY85 personnel losses and enable the Materiel Control Office to continue providing an acceptable level of service to the Laboratory.

Stockroom sales for FY85 were \$1.8 M with 104,000 stockroom withdrawals made by users. The reorganization of stock is 100% complete, and a location system is being implemented with a projected completion date of July 1986. Construction on the storage shed behind the C-Site stockroom was completed and has alleviated problems with storage of bulky and fast-moving inventory items. The Spare Parts section processed \$840 K in withdrawals, \$660 K in receipts, and had a combined (process, device, and maintenance spares) inventory of \$9 M with 9,700 line items.

In the Warehouse, the Receiving #3 and #4 functions were combined to improve the efficiency and effectiveness of the operation. Other improvements included a flow-thru conveyor, a separate equipment tagging location, and refinement to the staging and distribution systems. Over 20,000 receipts, deliveries, and shipments were made during FY85 by the Warehouse Operations Branch.

Storage space requirements have remained high despite an actual reduction in space at the Belle Mead facility. Equipment and material items processed through the Excess Property Section, as a result of Laboratory walk-thrus, transfers, and retirements, totaled 285 items with a value of \$1.5 M. Seventy-two items valued at \$500 K were received into the Laboratory from other government areas. The Hazardous Material Section made 19 shipments of hazardous wastes to approved disposal facilities, including 242 PCB capacitors. Sales of scrap metals to vendors was over \$11 K.

Safety continues to be an important objective of the Materiel Control Office. Fiscal year 1985 marked the third consecutive year without a lost work day accident. Safety meetings were held throughout the year and personnel were trained in safety on the job and at home.

CONTROLLER'S OFFICE

Reporting to the Deputy Director for Administrative Operations, the Controller's Office has responsibility for Budget, Finance and Accounting, and Information Resource Management. During FY85, the Performance Measurement System (PMS) Office was transferred to the Controller's Office from Technical Operations to improve the integration of the project management and financial systems. With budget reductions a dominant factor in FY85, the Controller's Office restructured its operations to conduct the Laboratory's business with a reduced staff. These reductions have been met by increases in efficiency without substantially changing responsibilities or the essential services provided by the various divisions and offices in this area. Significant benefits have resulted from improvements in data management and in the software which operates the financial systems. This has been helped by the implementation of an automatic accounts payable transfer procedure, and the introduction of PUBSYS.

Accounting and Financial Control Division

During FY85, the division staff was reduced by seven. This has resulted in a reorganization and reallocation of duties. The General Accounting and Accounts Payable branches are using a new system for accruing costs prior to the receipt of a vendor's invoice. This also provides a semi-automated method of liquidating the accrual upon payment of the invoice. An automated petty cash and emergency travel cash advance system was installed which generates transactions for the finance and accounting records, provides for more timely reimbursements and for operation with a smaller amount of cash on hand.

The Payroll Branch has standardized timesheets and time reporting to conform to the revised payroll classifications. A subcontract labor system was developed to calculate and record the cost of subcontract

labor from the timesheets received. The accrued cost is automatically liquidated upon payment of the vendor's invoice.

Princeton University and the Government established a separate bank account for activities funded by the DOE-modified letter of credit under the prime contract. Accounting procedures were implemented that enabled payments to be processed through this account.

The Accounting manual was completed, reviewed by DOE, and distributed to users. The manual is available in the PPPL Library for reference. An appraisal conducted of the Accounting and Financial Control Division based on the manual and real-time audits resulted in a "satisfactory" rating by DOE. In addition, the Accounting and Financial Control Division

participated in a number of audits by the Princeton University Internal Auditor and by the DOE Inspector General's Office. These included the Audit of Common Stores Inventories, the Audit of Capital Equipment, and the Audit of Input/Output Controls conducted by the Princeton University Internal Auditor, all of which found no major weaknesses in these areas.

Table III shows a summary of the financial activities for the last five years.

Budget Office

The usefulness of the Budget System to Laboratory management for budget status and control continued to improve during FY85. The Budget Manual was

**Table III. PPPL Financial Summary.
(Thousands of Dollars)**

	FY81	FY82	FY83	FY84	FY85
OPERATING (Actual Costs)					
Department of Energy					
TFTR Res and Develop Operations	\$ 2,314	\$ 2,945	—	—	—
TFTR Facility Operations	11,832	10,424	18,029	16,725	18,988
TFTR Tokamak Flexibility Mod	13,951	13,033	17,725	19,358	13,658
TFTR CICADA	2,437	4,044	8,588	10,327	9,578
TFTR Neutral Beams	1,870	6,253	24,410	22,166	23,475
TFTR Experimental Research	2,081	2,835	5,682	5,422	4,776
TFTR Diagnostics	7,706	8,973	14,143	13,146	10,124
TFTR Remote Handling	—	—	65	813	807
TFTR Tritium Systems	—	—	301	2,628	1,501
TFTR Pellet Injector System	—	—	—	129	1,049
PLT/PDX/PBX	23,271	18,893	17,846	18,501	14,425
RF Development	—	—	742	617	361
ACT-I	438	443	458	408	408
S-1	3,223	3,254	3,703	3,561	3,270
Ignition Studies Project	—	—	—	2,744	1,205
Theory	2,643	2,488	2,808	3,061	3,162
Applied Physics	807	1,280	1,352	655	833
Other Operating	364	495	418	457	1,379
Fusion Engineering Device	125	412	—	—	—
Change in Inventories	1,922	(237)	(3,169)	(599)	(721)
X-Ray Laser Development	251	266	313	16	743
Energy Management Studies	170	197	47	125	146
Department of Defense	280	297	77	278	228
Other Contracts	563	565	893	1,880	2,837
Total Operating	\$76,248	\$76,860	\$114,431	\$122,418	\$112,232
EQUIPMENT (Budget Authorization)					
Capital Equipment not					
Related to Construction	\$ 8,237	\$ 9,272	\$10,285	\$ 8,896	\$ 5,920
CONSTRUCTION (Budget Authorization)					
TFTR	\$25,000	\$31,600	\$ 1,800	\$ 255	—
General Plant Projects	610	1,400	1,000	1,000	1,532
Energy Management Projects	115	—	499	1,049	847
Total Construction	\$25,725	\$33,000	\$ 3,299	\$ 2,304	\$ 2,379

completed and approved by DOE. The preparation of the Field Task Proposals from the budget data base was routine, and the information was submitted to DOE ahead of schedule.

Substantial changes have been made in managing the budget at the Laboratory, and facilities have been provided to the users to enter the project budgets into the Accounting System and maintain these independent of the institutional budgets which are still maintained by the Budget Office. This enables the individual project to optimize plans around funding needs, staffing, and other factors without the customary institutional constraints that are present when considering the Laboratory as a whole. The individual project

budgets are then reviewed by the Program Committee and, in conjunction with the Budget Office, a program is developed that optimizes the project needs and meets the institutional constraints. Throughout the year this results in more management attention being drawn to the real needs of the projects and addresses conflicts with the institution as a whole. Towards the end of the fiscal year, the institutional and project needs of the Laboratory are clearly focused at the funding level. A flow diagram which shows the systems in place to bring this about is shown in Fig. 1. A typical report showing the Laboratory budget from a project and institutional standpoint is shown in Fig. 2.

The Budget Office, together with the Manpower

I
PRIMARY

II
SECONDARY

III
TERTIARY

Figure 1. Management Information Systems Application Program Structure. (86A0243)

Princeton University Plasma Physics Laboratory Controllers Office

Fiscal Year(FYR) - Current LABORATORY TOTAL	LABORATORY TOTAL							
	CC/PMS Bud Delta	Cost Center Budget	PMS Job Est Budget	Cur Month Expenses	Yr-to-date Expenses	Cur Year Cnsum	Cur Year Req	CC Budget Remaining
1100 DIRECT LABOR	-207	23,440	23,647	212	8,374	16,288	230	-1,452
1700 SUBCONTRACT LABOR	104	1,305	1,201	49	474	642	0	189
1800 DIRECT LP LABOR	-51	6,702	6,753	104	2,213	4,418	0	71
2200 COMPUTER DIV LABOR	-409	0,041	4,450	28	1,288	2,701	41	11
2300 MECHANICAL DIV LABOR	145	6,089	5,944	108	2,046	4,488	0	-445
2500 ELECTRICAL DIV LABOR	-972	6,741	7,713	66	2,035	4,698	0	-8
2600 ANALYSIS DIV LABOR	57	1,552	1,495	2	500	1,108	0	-55
2700 TECH CENTER SCL	-41	32	73	1	14	7	0	71
2800 TIME & MATERIALS SCL	789	1,430	641	0	737	804	0	-111
3000 DIRECT OVERTIME	-9	642	651	25	307	0	0	335
3100 TECH CENTER OVERTIME	115	599	484	4	215	0	0	384
3300 PU SECURITY	33	907	914	100	496	452	0	-1
3400 PU COMPUTING	8	1,181	1,173	0	352	0	0	829
3500 TRAVEL	-101	754	855	40	283	0	0	471
3600 ELECTRICAL ENERGY	20	5,821	5,801	0	1,915	3,905	0	1
3700 STOCKROOM WITHDRAWALS	-21	1,534	1,525	402	596	0	0	978
3800 PU MACHINE SHOP	-35	866	901	0	344	79	0	647
3900 OTHER EXPENSE	-136	1,971	2,107	-75	561	472	0	938
4100 MATERIALS & SERVICES	-2,169	12,926	15,295	209	3,096	4,622	2,207	3,001
4600 PU RENT & MAINTENANCE	0	1,134	1,134	92	471	563	0	0
4700 PU SERVICES	8	5,025	5,017	419	2,043	2,820	0	2
4800 MATERIALS & SERVICES W/O G&A	2	3,406	3,404	0	902	872	1,353	279
*TOTAL SUMMARY	-3,070	88,138	91,208	1,417	29,222	49,195	3,831	5,890
COST CENTERS 1000 TO 6999								

Figure 2. Example of Laboratory summary cost center versus Performance Measurement System (PMS) job budget estimates, together with current expenditures, by expense class. (88A0242)

Control Office, continued to play a major role in manpower planning at the Laboratory. This was especially important in FY85 since the PPPL staffing was reduced from almost 1,300 to about 1,120. This was brought about by a reduction-in-force and an incentivized Voluntary Separation Plan, both of which required significant planning on the part of the Budget Office. Coupled with this, the indirect expenses at the Laboratory were under considerable pressure over the FY85 period. Careful review and analysis of the real needs in the indirect area were undertaken, and quarterly Indirect Cost Reviews were organized and administered by the Budget Office. During the period FY83-FY85, considerable attention was paid to the efficient and cost effective management in all of these areas.

Information Resource Management

The thrust of Information Resource Management (IRM) established in FY84 continued in three main directions.

The extension of the Princeton University Computer Center (PUCC) to PPPL, via a local computer, enabled the selective transfer of operating systems from the variable-cost resource, the PUCC IBM 3081, to a fixed-cost resource, the PPPL IBM 4361. This has contributed to a reduction in mainframe cycles and their related cost.

The development of PUBSYS, an inquiry and reporting system that is executed through CMS/RAMIS, relieved the dependence on CICS, an expensive teleprocessing monitor, and provided the user community with select, timely, and more meaningful reports at lesser cost. The PUBSYS was expanded to include budget, personnel, and procurement data. The advent of PUBSYS has enabled the Accounting and Financial

Control Division to reduce staffing and costs by reducing the number of rote financial reports formatted, printed, and distributed throughout the Laboratory. The Job Cost Report and the Labor History reports were modified, and transaction file reporting was added to PUBSYS to further reduce the need for routine weekly and monthly reports. A CHAIN procedure was developed for PUBSYS to enable the user community to execute a series of report requests on differing data sets with a single command.

The wider introduction of personal computers has enabled down-loading systems from the PUCC mainframe for application development and processing to relieve delays in throughput and to reduce the mainframe cycle costs that would necessarily be incurred. Smaller systems have also been moved to the personal computers, and the effort for further networking continues.

All this contributed to cost saving in spite of significant growth in usage. Although the Performance Measurement System (PMS), Work Approval Form (WAF), Automatic Work Approval Form Transfer (AWAFT), Equipment Tracking and Control System (ETACS), and Accounts Payable Transfer System moved into full production over the period, the computer costs for FY85 were reduced by \$150 K.

A personnel data transfer system was developed to capture information from the Princeton University personnel files and move these data to PPPL's files. The matched file data provided greater precision and eliminated the effort of duplicate file maintenance. The AWAFT system was enhanced to take PMS budgets and record them in the finance and accounting system.

Computer account control was installed to enable Information Resource Management to assign and allocate funds, resulting in further economies in resource usage.

PPPL Invention Disclosures for Fiscal Year 1985

Title	Inventor(s)
Cyclotron Acceleration Enhancer of Muon Fusion	R. Kulsrud
Lathe Tailstock Rotatable Support	K. Mann
High Voltage High Current RF Bushing	G. Grotz
Z Pinch Modified by Helical Coils	H. Furth D. Monticello
Penetration Seal-Fire, Smoke 3-Hour Stop Penetrations Containing Low Ignition Temperature Materials Within Penetration	S. Cavalluzzo
Method and Apparatus for Ramp-up of Tokamak Current Using RF Waves Together with Inductively Driven Relativistic Electrons	N. Fisch C.F.F. Karney A. Boozer
CAMAC Link Data Monitor	P. Sichta
High Current Capacity Electrical Joint	P. Bonanos
Arc Suppressors for Waveguide Grills	R. Motley W. Hooke
Compact Waveguide Power Divider with Multiple Isolated Outputs	C.P. Moeller
Poloidal Flux Transformer for Spheromak Current Drive and Heating	A. Janos M. Yamada H. Furth
Flux-Amplifying Inductive Spheromak Gun (Generator)	M. Yamada A. Janos T. Uyama
Annular X-Ray Laser Target	H. Milchberg
Axial Thick-Fibre Target for X-Ray Laser Production	H. Milchberg S. Suckewer D. Voorhees
Trimable Limiter	R. Budny D.K. Owens
Disc-Blade X-Ray Laser Target	S. Suckewer C. Skinner D. Voorhees
Soft X-Ray Laser	S. Suckewer
High Temperature Brazing of Al_2O_3 to Ti6242	R. Walls H. Evans
Radio Frequency Coupler for Enhanced Production of Runaway Electrons to Stabilize MHD Instabilities & Reduce Transport Loss in Toroidal Plasmas	T.K. Chu
Anomalous-Viscosity Current Drive	T. Stix M. Ono

Title	Inventor(s)
<i>Polarization: Converters for Circular Waveguide Modes</i>	J. Doane
Disruptionless Tokamak	J.G. Murray
<i>Fusion Start-up and Burn Control with Insulated Limiter Plates</i>	J.G. Murray
Fusion Reactor Fueling with Cross Current Assist	J.G. Murray
Thermonuclear Inverse Magnetic Pumping Power Cycle	D. Ho R. Kulsrud
Nonmagnetic Lubricationless Air Motor	R. Cutler
Isotope Separation in a Space Environment	F. Perkins
Hydromagnetic Electrolytic Cell	R.G. Mills
Charge-Exchange Plasma Thruster	S. Yoshikawa
DC Break for B Through Y Band Circular Waveguide Flanges	R. Cutler
High Power Factor Magnet Power Supply	D. Ashcroft
Periscope-Camera System for Visible and Infrared Imaging Diagnostics on TFTR	S. Medley D. Dimock S. Hayes D. Long J. Lowrance V. Mastrocola G. Renda M. Ulrickson K. Young
A Symmetric, Portable Plasma Magnetron	S. Yoshikawa
High Speed Block Mode Transient Digitizer Controller	S. Hayes
D ⁺ Detector	D. Buchenauer W. Heidbrink K. McGuire
Magnetically Confined Plasma Discharges and Plasma Jets for Chemical Waste Destruction	W. Hooke D. Jassby M. Machalek A. Nagy
Tokamak Radial Insulators	J.G. Murray F. Lawn G. Bronner
Biased Grids	J.G. Murray G. Bronner
Biased Limiter (Diverter)	J.G. Murray J. Frankenberg G. Bronner
Radial Potential Control	J.G. Murray G. Bronner
Bias Toroidal Electrodes	J.G. Murray G. Bronner

Title	Inventor(s)
Rotating Shield Roof for High-Field Ignition Experiment (HFIX) Test Cell	J. Commander
Multiphoton Excitation of Ions for X-Ray Lasing	C. Skinner S. Suckewer C. Clark M. Littman T. McIlrath R. Miles E. Valeo
Heated Cover/Deflector for Directed Deposition of Materials by Evaporation	J. Timberlake T. Bennett
Covered Crucible with Perforated Bottom for Downward Evaporation	T. Bennett J. Timberlake S. Cohen

GRADUATE EDUCATION: PLASMA PHYSICS

The Plasma Physics Program was first offered at Princeton University in 1959 and two years later was incorporated into the Department of Astrophysical Sciences. The constant aim of the Program has been to provide pertinent graduate education in an environment that, over the past three decades, has seen enormous changes in the fields of plasma physics and controlled fusion. In this period, the Program has established its own traditions of education—centered on fundamentals in physics and applied mathematics and training—based on intense exposure to the cutting edge of research in plasma physics.

Graduate students entering the Plasma Physics Program at Princeton University spend the first two years in classroom study, acquiring a firm foundation in the many disciplines that make up plasma physics: classical and quantum mechanics, electricity and magnetism, fluid dynamics, hydrodynamics, atomic physics, applied mathematics, statistical mechanics, and kinetic theory. Table I 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 II). 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.

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, have full access to Laboratory facilities, and learn firsthand the job of a research physicist. First-year students assist in experimental research areas, including TFTR diagnostics development, PLT, PBX, ACT-I, S-1 Spheromak, 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 takes place under the guidance of a member of the PPPL staff, although thesis students bear a greater responsibility for the content of their projects than do first and second-year students. Of the thirty-eight graduate students in residence this past year, twenty-two were engaged in thesis projects—twelve

Table I. Plasma Physics Courses Offered and Instructors.

Course Number	Course Title	Instructor
Fall 1984		
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	G.M. Rewoldt
AS 559	Nonlinear Interactions in Plasma	R.B. White and J.A. Krommes
Spring 1985		
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	G.M. Rewoldt
AS 560	Advanced Magnetohydrodynamics	S.C. Jardin

Table II. Astrophysical Sciences/Plasma Physics Faculty.

Faculty Members	Title
Thomas H. Stix	Associate Chairman, Department of Astrophysical Sciences, and Associate Director for Academic Affairs, PPPL
Liu Chen	Principal Research Physicist and Lecturer with rank of Professor
Harold P. Furth	Professor of Astrophysical Sciences Research
Stephen C. Jardin	Research Physicist and Lecturer with rank of Associate Professor
Charles F.F. Karney	Research Physicist and Lecturer with rank of Associate Professor
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 M. Rewoldt	Research Physicist and Lecturer with rank of Associate Professor
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
Roscoe B. White	Principal Research Physicist and Lecturer with rank of Professor
Shoichi Yoshikawa	Principal Research Physicist and Lecturer with rank of Professor

Table III. Recipients of Ph.D. Degrees.

Steven C. Cowley	
Thesis:	Some Aspects of Anomalous Transport in Tokamaks: Stochastic Magnetic Fields, Tearing Modes and Nonlinear Ballooning Instabilities, August 1985
Advisor:	Russell M. Kulsrud
Employment:	Culham Laboratory, United Kingdom
John A. Goree	
Thesis:	The Backward Electrostatic Ion-Cyclotron Wave, Fast Wave Current Drive, and FIR Laser Scattering, July 1985
Advisor:	Masayuki Ono
Employment:	Department of Physics and Astronomy, University of Iowa
Darwin D.M. Ho	
Thesis:	Transport, Convective Equilibrium, and Reactor Physics in Stellarator Type Devices, August 1985
Advisor:	Russell M. Kulsrud
Employment:	Lawrence Livermore National Laboratory
Howard M. Milchberg	
Thesis:	Studies of Population Inversions and Gains for XUV Laser Development in a Recombining Plasma Column, February 1985
Advisor:	Szymon Suckewer
Employment:	AT&T Bell Laboratories
Frederick N. Skiff	
Thesis:	Linear and Nonlinear Excitation of Slow Waves in the Ion Cyclotron Frequency Range, November 1984
Advisor:	Masayuki Ono and King-Lap Wong
Employment:	Centre de Recherches in Physique des Plasmas, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland

on theoretical topics and ten on experimental topics. Table III 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 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 Science 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 University's Department of Astrophysical Sciences has had significant impact on the field of plasma physics. One hundred sixteen 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. And this process continues as the Laboratory trains the next generation of scientists, preparing them to take on the challenging and diversified problems of the future.

GRADUATE EDUCATION: PLASMA SCIENCE AND FUSION TECHNOLOGY

Culminating more than a decade of cooperative effort between the Princeton Plasma Physics Laboratory (PPPL) and Princeton University's School of Engineering and Applied Science (SEAS), the new Interdepartmental Program in Plasma Science and Fusion Technology was formally approved during the past fiscal year. This action brought together all five departments of SEAS: Chemical Engineering, Civil Engineering, Computer Science, Electrical Engineering, and Mechanical and Aerospace Engineering. Its predecessor, the Fusion Reactor Technology Program, involved only the Chemical Engineering Department. The new arrangement removes the hardship formerly imposed on graduate students wishing to study fusion but having backgrounds in other than chemical engineering.

During this period graduate student enrollment remained level (11 students), again aided by continuation of a grant from the State of New Jersey Commission on Science and Technology that provided half support for four of these students, with PPPL furnishing the balance. Faculty support also remained constant with professors in four of the five SEAS departments participating.

Although fifty percent of the State grant was originally designated to implement the Cooperative Industrial Program in Plasma Science and Fusion Technology, the identification of appropriate mid-career engineers and of companies willing to provide the matching funds proved difficult. As a result, only the half of the grant intended for graduate students was expended this fiscal year, and permission was obtained to spend the remaining half in FY86 for further graduate student support. Midway through the fiscal year, additional support was received from the State for construction of a Polymer Research Laboratory on the Forrestal Campus. A ribbon cutting ceremony for this new facility and the first annual meeting of its Advisory Committee have recently taken place.

PROGRAMS

Now in its fifth year as a participating university in the U.S. Department of Energy's Magnetic Fusion Energy Technology (MFET) Fellowship Program, Princeton had two recipients of this prestigious grant in residence during FY85. A former fellow spent the period completing his dissertation and working on the Lithium Blanket Module (LBM) experiment investigating the measurement, with an uncertainty of less than 5%, of the minute amounts of tritium produced in the LBM's lithium oxide pellets.^{1,2} This work is being

continued by another MFET fellow who is entering his second year. The students work in the recently established Chemical Engineering Laboratory (adjacent to the Polymer Research Laboratory mentioned above).

The Princeton Plasma Physics Laboratory was host this summer to a graduate student from the Massachusetts Institute of Technology who elected to complete his practicum assignment here. This period of practical work combined with independent research is a requirement of all MFET fellows, and the Laboratory's strong radio-frequency program attracted the student. At the same time, a Princeton student chose the Argonne National Laboratory as the site for his summer practicum.

Although the Cooperative Industrial Program in Plasma Science and Fusion Technology had only two participants during the past fiscal year, one of these (on loan to PPPL from Bechtel) successfully completed the program and was presented his certificate during a luncheon at Prospect House. Toward the end of the period, due in large measure to a more narrowly targeted recruiting strategy, increased interest in the program has been generated, a new format is being considered, and selection of a candidate for participation in PPPL's Process Plasma Research Program is imminent.

ACTIVITIES

As FY85 drew to a close, eight of the students who were enrolled in the Interdepartmental Program last year had returned to continue their studies; one received the M.S. degree and departed; two dropped out of the program. There were three entering students, one of them a Magnetic Fusion Energy Technology fellow. Six of the group are receiving half their support from PPPL, and two are entirely supported by the Laboratory. The remaining three students have fellowships. Their activities are detailed in Table I.

During the FY85 period the Interim Committee for Graduate Study in Plasma Science and Fusion Technology completed its work and disbanded. Two new committees were established: the Interdepartmental Committee to deal with matters primarily academic in nature (admissions, curricula, etc.) and the SEAS/PPPL Cooperative Program Committee, dealing with primarily programmatic matters of identification of suitable joint SEAS/PPPL tasks.

In attendance at dedication ceremonies for the newly completed Polymer Research Laboratory, located in Building 1-A at A-Site, was Dr. Edward Cohen, Executive Director of the New Jersey Commission on Science

Table I. Interdepartmental Program in Plasma Science and Fusion Technology Graduate Students.

P. Pang^c	
Thesis Topic:	Polymers
Advisor:	J.K. Gillham
Department:	Chemical Engineering
J.R. Gilland^c	
Thesis Topic:	Magnetoplasmadynamic (MPD) Thruster Scaling
Advisor:	R.G. Jahn/A.J. Kelly
Department:	Mechanical and Aerospace Engineering
K.W. Goossen^a	
Thesis Topic:	Fast Response Detectors
Advisor:	S.A. Lyon
Department:	Electrical Engineering
J.S. Lee^b	
Thesis Topic:	Coupled Mechanical/Electrodynamic Analysis
Advisor:	J.H. Prevost/P.C.Y. Lee
Department:	Civil Engineering
G.D.C. Dhondt^d	
Thesis Topic:	Radiation Damage
Advisor:	A.C. Eringen
Department:	Civil Engineering
R. Myers^c	
Thesis Topic:	Plasma Propulsion
Advisor:	R.G. Jahn/A.J. Kelly
Department:	Mechanical and Aerospace Engineering
J.F. Quanci^a	
Thesis Topic:	Tritium Recovery Experiments
Advisor:	R.G. Mills/D.L. Jassby
Department:	Chemical Engineering
D.-S. Shen^b	
Thesis Topic:	High Speed Detectors
Advisor:	S. Wagner
Department:	Electrical Engineering
S. Chaturvedi^d	
Thesis Topic:	Undecided
Advisor:	R.G. Mills
Department:	Chemical Engineering
Y.-G. Kim^c	
Thesis Topic:	Undecided
Advisor:	P.C.Y. Lee/J.H. Prevost
Department:	Civil Engineering
D.W. Roberts^a	
Thesis Topic:	Undecided
Advisor:	W.D. Langer
Department:	Astrophysical Sciences

^aSupported by Fellowship.

^bSupported by the Princeton Plasma Physics Laboratory.

^cSupported 50% by State of New Jersey, 50% by the Princeton Plasma Physics Laboratory.

^dSupported 50% by the Princeton Plasma Physics Laboratory.

and Technology, the group responsible for a \$30,000 State grant in support of this activity. Graduate students will use the new facility to study the effects of radiation on polymers, an important topic for coil design. The ribbon cutting ceremony is shown in Fig. 1.

Meeting for the first time, the Polymer Laboratory Advisory Committee requested that the laboratory staff, in conjunction with PPPL management, generate a mission statement for the new facility. They noted specific points concerning the current research effort, and suggested other pertinent areas for research including the study of thermoset polymers and the development of semiconducting polymers as high-energy-neutron spectrometers using the proton-recoil method for determining neutron energy.

DEPARTMENT CURRICULUM

In addition to the graduate program, the Chemical Engineering Department offers a strong undergraduate curriculum to stimulate interest in fusion. A mini-course on fusion is included in Chemical Engineering 101, designed primarily for A.B. students to satisfy their science requirement, but 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 it has been elected by graduate students of four different departments.

Each year Chemical Engineering 417 welcomes as auditors several 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,

Figure 1. Graduate student Peter Pang watches as Professor John K. Gillham of the Department of Chemical Engineering cuts the ribbon during dedication ceremonies for the Polymer Research Laboratory at A-Site. Professor Gillham is in charge of the new research facility. (85A0401)

two sets of consultants for the teams and a selection board to evaluate the final design. In some years younger staff members are assigned as members of the teams. Oral presentations before the board are a fairly realistic preview of the "real world's" contractor selection procedures.

Chemical Engineering courses relating to the Plasma Science and Fusion Technology Program are given in Table II. With the addition of the remaining SEAS departments to the program, other pertinent courses, both on the graduate and undergraduate level, are recommended to the students. These are listed in Table III, together with three courses of interest in Astrophysical Sciences.

References

- ¹D.L. Jassby, J. File, P.C. Bertone, *et al.*, "The TFTR Lithium Blanket Module Program," *J. Fusion Energy* 4 (1985) 57.
- ²P.C. Bertone, "Measuring Nanocurie Quantities of Tritium Bred in Metallic Lithium and Lithium Oxide Samples," *Fusion Tech.* 8 (1985) 918.

Table II. Chemical Engineering Courses Relating to the Plasma Science and Fusion Technology 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 550	Fusion Reactor Technology	R.C. Axtmann R.G. Mills

Table III. Pertinent Courses in Allied Departments.

Graduate Courses of Interest

Chemical Engineering

- 544 Chemical Reactor Engineering
- 545 Mathematical Methods of Engineering Analysis II (also CE 502)
- 550 Fusion Reactor Technology

Civil Engineering

- 501 Mathematical Methods of Engineering Analysis I
- 502 Mathematical Methods of Engineering Analysis II (also CHE 545)
- 553 Advanced Structural Mechanics
- 576 Electromagnetic Interactions with Continua

Electrical Engineering

- 541 Electronic Materials
- 542 Surface Properties of Electronically Active Solids
- 543 Transport Processes in Solids

Mechanical and Aerospace Engineering

- 511 Experimental Methods
- 513 Dynamic Data Analysis
- 547 Optics and Lasers
- 583 Electric Propulsion

Astrophysical Sciences

- 551 General Plasma Physics I
- 552 General Plasma Physics II
- 553 Plasma Waves and Instabilities

Undergraduate Courses of Interest

Chemical Engineering

- 417 Introduction to Fusion Power
- 418 Nuclear Engineering
- 441 Chemical Reactor Engineering
- 445 Process Control

Civil Engineering

- 310 Computer Methods for Engineering Problems
- 463 Finite Element Methods in Structures and Mechanics

Electrical Engineering

- 471 Solid State Electronics I
- 483 Microwave Electronics

Mechanical and Aerospace Engineering

- 433 Automatic Control Systems
-

SECTION EDITORS

Tokamak Fusion Test Reactor
S. Duritt, Jr.

Princeton Large Torus
P. Colestock

Princeton Beta Experiment
B. LeBlanc

S-1 Spheromak
A. Janos

Advanced Concepts Torus-I
M. Ono

X-Ray Laser Studies
W. Tighe

Theoretical Division
J. Johnson

Tokamak Modeling
M. Petravic

Spin-Polarized Fusion Program
R. Knize

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Quality Assurance and Reliability
H. Howard

Administrative Operations
O. Burnett
M. Iseicz

Graduate Education: Plasma Physics
T. Stix

*Graduate Education: Plasma Science and Fusion
Reactor Technology*
R. Mills

GLOSSARY OF ABBREVIATIONS, ACRONYMS, SYMBOLS

A	Ampere
Å	Angstrom unit: 10^{-8} cm
ac	Alternating Current
ACT-I	Advanced Concepts Torus-I (at the Princeton Plasma Physics Laboratory)
ACWP	Actual Cost of Work Performed
A/D	Analog-To-Digital
ADP	Automated Data Processing
ADPE	Automated Data Processing Equipment
Alcator	A family of tokamak devices being developed and built at the Massachusetts Institute of Technology (from the Italian for high-field torus)
ALT-I	Advanced Limiter Test on TEXTOR (Jülich West Germany); Version I
ALT-II	Version II of ALT
amu	Atomic Mass Unit
ANL	Argonne National Laboratory
ASDEX	Axially Symmetric Divertor Experiment (Max-Planck-Institut für Plasmaphysik, Garching, West Germany)
ATC	Adiabatic Toroidal Compressor (Princeton Plasma Physics Laboratory, 1970's)
ATF	Advanced Toroidal Facility (a stellarator at Oak Ridge National Laboratory now in construction)
ATF-1	Advanced Toroidal Facility-1
AWAFT	Automatic Work Approval Form Transfer (System)
BALDUR	A Princeton Plasma Physics Laboratory one-dimensional tokamak transport code
BCWP	Budgeted Cost of Work Performed
BCWS	Budgeted Cost of Work Scheduled
CAD	Computer-Aided Design
CADD	Computer-Aided Design and Drafting (Facility)
CAE	Canadian Aviation Electronics (known as CAE Electronics Ltd.)
CAMAC	Computer-Automated Measurement and Control (System)
CAR	Computer-Assisted Retrieval
CAR	Cost Analysis Report
CCD	Capacitor Charge/Discharge
CCD	Charge-Coupled Device
CDX	Current-Drive Experiment
CEA	Commissariat à l'Énergie Atomique
CFFTP	Canadian Fusion Fuels Technology Project
CHERS	Charge-Exchange Recombination Spectrometer
CICADA	Central Instrumentation, Control, and Data Acquisition (System)
CICS	Customer Information Control System
CIPREC	Conversational and Interactive Project Evaluation and Control System
CIT	Compact Ignition Tokamak (goal of the Ignition Studies Project)
cm	Centimeter
COO	Chicago Operations Office
COS	Console Operating Station
CPSR	Contractor Procurement System Review
CPU	Central Processing Unit
CRAY	A brand of computer made by Cray Research, founded by S. Cray
CSR	Cost and Schedule Review
CTR	Controlled Thermonuclear Research
CY	Calendar Year
°	Degrees
°C	Degrees Centigrade
°K	Degrees Kelvin

D/A	Digital-To-Analog
D-D	Deuterium-Deuterium
D-III	Doublet-III—A tokamak located at GA Technologies, Incorporated
D-III-D	Doublet-III-D (recent upgrade of D-III, with D-shaped plasma)
D-T	Deuterium-Tritium
DARM	Data Acquisition Room
DAS	Data Acquisition System (on PLT, PBX, S-1)
DAX	DAS supplemental system (uses a VAX computer)
dc	Direct Current
DEC	Digital Equipment Corporation
DECAT	Drivers Energy Conservation Awareness Training
DEGAS	A PPPL computer code for studying the behavior of neutrals in plasma
DEMO	Demonstration Power Reactor
D&GF	Design and General Fabrication (Section)
DIALOG	An interactive online information retrieval system used by the PPPL Library
DIFFUSE	A computer code used to calculate the one-dimensional diffusion and trapping of atoms in a wall
DITE	Divertor and Injection Tokamak Experiment (Culham Laboratory, United Kingdom)
DNB	Diagnostic Neutral Beam
DOE	Department of Energy
DOE/RECON	An interactive online information retrieval system used by the PPPL Library.
DPI	Deuterium Pellet Injector
DSMA	Dilworth Secord Meagher and Associates (known as DSMA Atcon Ltd.)—Canadian
EAD	Engineering Analysis Division
ECE	Electron Cyclotron Emission
ECH	Electron Cyclotron Heating
ECRF	Electron Cyclotron Range of Frequencies
ECRH	Electron Cyclotron Resonance Heating
ECS	Energy Conversion System
EF	Equilibrium Field
EMCS	Energy Monitoring and Control System
EPA	Environmental Protection Agency
EPFL	École Polytechnique Fédérale de Lausanne, Switzerland
EPRI	Electric Power Research Institute
ERB	Engineering Review Board
ERP	Edge Relaxation Phenomena
ESO	Emergency Services Officer(s)
ESU	Emergency Services Unit
ETACS	Equipment Tracking and Control System
ETR	Engineering Test Reactor
ETS	Engineering Test Station
eV	Electron Volt
EZB	Exclusion Zone Boundary
FAST	Fast Automatic Transfer System
FCPC	Field Coil Power Conversion
FEA	Finite Element Analysis
FED	Fusion Engineering Device
FEDC	Fusion Engineering Design Center (Oak Ridge National Laboratory)
FELIX	An experimental test facility under construction at the Argonne National Laboratory
FEM	Finite Element Modeling or Finite Element Method
FER	Fusion Experimental Reactor
FIDE	Fast Ion Diagnostic Experiment
FIR	Far-Infrared
FLOPSY	Flexible Optical Path System
FPSTEL	Computer code used to solve the ripple-bounce-averaged Fokker-Planck equation numerically
FSAR	Final Safety Analysis Report
FTE	Full-Time Equivalent
FTS	Federal Telecommunications System
FWCD	Fast-Wave Current Drive
FWHM	Full Width at Half Maximum
FY	Fiscal Year (October 1 to September 30)
G	Gauss
G&A	General and Administrative (cost or expense)

GAO	General Accounting Office
GAT	GA Technologies, Incorporated
GDC	Glow Discharge Cleaning
GHz	Gigahertz: 10^9 cycles per second
GJ	Gigajoule, a unit of energy; 10^9 joules
gpm	Gallons Per Minute
GPP	General Plant Projects
GSA	General Services Administration
GSF	Gross Square Feet
HAIFA	Hydrogen Alpha Interference Filter Array
HAX	High-Level Data Analysis (system); uses a VAX computer
HEDL	Hanford Engineering Development Laboratory
HELIAC	A computer code used to calculate vacuum magnetic surfaces in nonaxisymmetric three-dimensional toroidal geometries
HERA	Helically invariant code
HF	Horizontal Field
HFIX	High-Field Ignition Experiment
HLDAS	High-Level Data Analysis System; equivalent to HAX
H-mode	High-Confinement Mode
HPA	High Power Amplifier
HTA	Hard Tube Amplifier
HV	High Voltage
HVAC	Heating, Ventilating, and Air Conditioning
HVE	High-Voltage Enclosure(s)
IBW	Ion-Bernstein Wave
ICH	Ion Cyclotron Heating
ICRF	Ion Cyclotron Range of Frequencies
ICRH	Ion Cyclotron Resonance Heating
IGNITOR	Ignited Torus
IMAPS	Interstellar Medium Absorption Profile Spectrograph
INEL	Idaho National Engineering Laboratory
INTOR	International Tokamak Reactor
I/O	Input/Output
IPP	Initial Protective Plates
IPP	Institut für Plasmaphysik at Garching, West Germany
IPSG	Ignition Physics Study Group
IR	Infrared
IRM	Information Resources Management
ISP	Ignition Studies Project (see CIT)
ISX	Impurity Study Experiment (at Oak Ridge National Laboratory)
ITOC	Ignition Technical Oversight Committee
ITR	Ignition Test Reactor
JAERI	Japan Atomic Energy Research Institute
JET	Joint European Torus
JT-60	JT stands for JAERI Tokamak and 60 means plasma volume in m^3 . An energy breakeven plasma testing device in Japan
kA	Kiloamperes
keV	Kilo-Electron-Volts
KFA	Kernforschungsanlage Jülich, W. Germany
KFK	Kernforschungszentrum Karlsruhe, W. Germany
kG	Kilogauss
kHz	Kilohertz
kJ	Kilojoule
ksi	Kilopounds Per Square Inch (Pressure, Stress)
kV	Kilovolt
kV A	Kilovolt Ampere
kW	Kilowatt
kW h	Kilowatt Hour
LANL	Los Alamos National Laboratory
LBL	Lawrence Berkeley Laboratory
LBM	Lithium Blanket Module
LC	Inductance Capacitance
LCCs	Local Control Centers

LCP	Large Coil Program
LED	Light Emitting Diode
LH	Lower Hybrid
LHCD	Lower Hybrid Current Drive
LHe	Liquid Helium
LHRF	Lower Hybrid Range of Frequencies
LHRH	Lower Hybrid Resonance Heating
LITE	Laser Injected Trace Element (System)
LITE	Long-Pulse Ignited Test Experiment (at the Massachusetts Institute of Technology)
LLNL	Lawrence Livermore National Laboratory
L-mode	Low-Confinement Mode
LO	Local Oscillator
LOB	Laboratory Office Building
LOTUS	Nuclear testing facility at École Polytechnique Fédérale de Lausanne in Switzerland
μm	Micrometer; equivalent to micron
μsec	Microsecond
m	Meter
MA	Megamperes
MARFE(s)	Region(s) of enhanced edge radiation localized poloidally on the inner-major-radius side of a plasma
MARS	Mirror Advanced Reactor Study (Lawrence Livermore National Laboratory)
Mb	Megabyte
MCNP	Monte-Carlo Neutron and Proton Code
MED	Mechanical Engineering Division
MeV	Mega-Electron-Volt
MFAC	Magnetic Fusion Advisory Committee
MFE	Magnetic Fusion Energy
MFETF	Magnetic Fusion Energy Technology Fellowship (Program)
MFTF-B	Mirror Fusion Test Facility at Lawrence Livermore National Laboratory
MG	Motor Generator
MHD	Magnetohydrodynamics
MHz	Megahertz
mil	A unit of length equal to 0.001 inch
MIRI	Multichannel Infrared Interferometer
MIST	A computer code which follows impurity species through various stages of ionization, charge-exchange, radiation, and transport within the plasma
MIT	Massachusetts Institute of Technology
MJ	Megajoules
mm	Millimeter
MPa	Mega-Pascal (Pressure, Stress)
msec	Millisecond
MTL	Material Test Laboratory
MVA	Megavolt Ampere
mW	Milliwatt
MW	Megawatt
NASA	National Aeronautics and Space Administration
NASA/RECON	An interactive online information retrieval system used by the PPPL Library
NASTRAN	A structural analysis code
NB	Neutral Beam
NBETF	Neutral Beam Engineering Test Facility
NBI	Neutral Beam Injection
NBI	NBI, Incorporated (word-processing equipment and service company)
NBLs	Neutral Beamlines
NBPS	Neutral Beam Power Supply
NBTC	Neutral Beam Test Cell
NCR	Nonconformance Report
NET	Next European Torus
nm	Nanometer
NMFECC	National Magnetic Fusion Energy Computer Center
NRC	Nuclear Regulatory Commission
nsec	Nanosecond
NTGD	Nontritium Gas Delivery
NTIS	National Technical Information Service

OFE	Office of Fusion Energy
OH	Ohmic Heating
OMA	Optical Multichannel Analyzer
OM&S	Occupational Medicine and Safety
ORC	Operations Review Committee
ORNL	Oak Ridge National Laboratory
ORR	Operational Readiness Review
OSES	Operations System Engineering Support
OSHA	Occupational Safety and Health Administration
OSR	Operational Safety Requirements
PADS	Procurement Automated Data Processing System
PBX	Princeton Beta Experiment
PBX-M	Princeton Beta Experiment Modification
pC	Pico Coulomb
PC	Personal Computer
PDC	Pulse-Discharge Cleaning
PDR	Preliminary Design Review
PDX	Poloidal Divertor Experiment
PEST	Princeton Equilibrium, Stability, and Transport Code
PF	Poloidal Field
PFC	Plasma Fusion Center (at the Massachusetts Institute of Technology)
PHA	Pulse-Height Analysis
PLANET	A two-dimensional transport code used to study the scrape-off region created by divertors and limiters
PLCS	Power Line Carrier System
PLT	Princeton Large Torus
PM	Preventive Maintenance
PM&E	Plant Maintenance and Engineering
PMS	Performance Measurement System
PMS	Performance Management System
P&OS	Project and Operational Safety
PP-Lasers	Powerful Picosecond Lasers
PPPL	Princeton Plasma Physics Laboratory
PSE&G Co.	Public Service Electric and Gas Company
psi	Pounds Per Square Inch
PUBSYS	PPL Public Information System (installed on the Princeton University IBM 3081 computer)
PUCC	Princeton University Computer Center
QA	Quality Assurance
QA/R	Quality Assurance and Reliability
QMS	Quadpole Mass Spectrometer
RAX	TFTR off-line data reduction system (uses a VAX computer)
rf	Radio Frequency
RFBA	Request for Baseline Adjustment
RFP	Request for Proposal
RFP	Reversed-Field Pinch
RFTF	Radio-Frequency Test Facility
RGa	Residual Gas Analyzer
RIF	Reduction-in-Force
RIV	Rapid Intervention Vehicle
RLIN	Research Libraries Information Network
rms	Root Mean Square
RPI	Repeating Pellet Injector; also Repeating Pneumatic Injector
rpm	Revolutions Per Minute
S-1 Spheromak	A compact toroid device (at the Princeton Plasma Physics Laboratory)
S-1 Upgrade	Version II of S-1 Spheromak
SCR	Silicon Controlled Rectifier
S/DB	Small and Disadvantaged Businesses
SDS	Safety Disconnect Switch(es)
SEAS	School of Engineering and Applied Science
sec	Second
SF	Shaping Field, equivalent to EF
SHEILA	Australian Heliac
SNAP	Time-independent power equilibrium code

SNL	Sandia National Laboratories
SOXMOS	Soft X-Ray Monochromator Spectrometer
SPAR	Special Products and Applied Research Division (known as SPAR Aerospace Ltd.)—Canadian
SPARK	A general geometry computer code that calculates transient eddy currents and the resulting fields
SPEB	Subcontract Proposal Evaluation Panel
SPICE	A general purpose circuit simulation code
SPRED	Survey, Power Resolution, Extended Domain Code
SPS	Surface Pumping System
Sr	Steradian
SR	Safety Requirements
START-UP	A computer code which evaluates free boundary axisymmetric equilibria and transport
STEP	Stellarator expansion equilibrium and stability code
SURFAS	A fast between-shot moments code
TAC	Technical Advisory Committee
TCV	Tokamak Condition Variable—a tokamak under construction at École Polytechnique Fédérale de Lausanne in Switzerland
TDC	Taylor-Discharge Cleaning
TEXTOR	Tokamak Experiment for Technologically Oriented Research (Jülich, West Germany)
TF	Toroidal Field
TFCD	Tokamak Fusion Core Device (see CIT)
TFCX	Tokamak Fusion Core Experiment (see CIT)
TFM	TFTR Flexibility Modification
TFTR	Tokamak Fusion Test Reactor
TiC	Titanium Carbide
TLD	Thermoluminescent Dosimeters
TMPs	Turbo-Molecular Pumps
TMX	Tandem Mirror Experiment at Lawrence Livermore National Laboratory
Torr	A unit of pressure equal to 1/760 of an atmosphere
TOS	Terminal Operating Station
TPI	Tritium Pellet Injector
TRANSP	Time-dependent transport analysis code
TSC	Tokamak Simulation Code
TSCALE	A computer code that scales plasma equilibrium parameters over a wide range of major radius and aspect ratio
TSDS	Tritium Storage and Delivery System
TVPS	Torus Vacuum Pumping System
TVTS	TV Thomson Scattering
UCLA	University of California at Los Angeles
UHF	Ultrahigh Frequency
USC	User Service Center, implemented on a Digital Equipment Corporation (DEC) PDP-10 computer
USGS	United States Geological Survey
USNRC	United States Regulatory Commission
UV	Ultraviolet
V	Voit
VAX	Digital Equipment Corporation computer; "Virtual Address Extension"
VC	Variable Curvature
VCD	Viscous Current Drive
VF	Vertical Field
VHF	Very High Frequency
VIPS	Visible Impurity Photometric Spectrometer
VUV	Vacuum Ultraviolet
VXCS	Vertical X-Ray Crystal Spectrometer
W	Watt
WAF	Work Approval Form (System)
WBS	Work Breakdown Structure
WKB	Wentzel-Kramers-Brillouin (a method for analyzing wave behavior if propagation characteristics depend on position)
XIS	(Horizontal) X-Ray Imaging System
XUV	Extreme Ultraviolet
ZrAl	Zirconium-Aluminum