Annual Report

October 1, 1979 to September 30, 1980

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**Princeton
Plasma Physics
Laboratory**

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Annual Report Covering the Period October 1, 1979 to September 30, 1980

**Princeton University
Plasma Physics Laboratory
Princeton, New Jersey**

PPPL-Q-38

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Cover The Poloidal Divertor Experiment
Photographed by John Peoples,
Joseph DiBartolo, and
Edward Farris

Preface

During FY80, the joint experimental program of the Princeton Large Torus (PLT) and Poloidal Divertor Experiment (PDX) made significant progress towards the development of advanced tokamak techniques lying at the interface of physics and reactor engineering. Concurrently, new insights were gained into the basic physical phenomena of tokamak plasmas.

In PLT, radio-frequency (rf) heating in the ion cyclotron range of frequencies produced ion temperatures over 2 keV, with heating efficiencies that compared favorably with neutral-beam heating performance. Neutral-beam injection at the 3-MW level was used to generate plasma ion temperatures of 7 keV and to investigate transport of energy, momentum, and particles under highly collisionless conditions.

The PDX divertors were put into initial operation and demonstrated the predicted effectiveness of the poloidal divertor in channeling the outflow of tokamak particles and energy along the divertor separatrix to the neutralizer plates. The neutral-beam-injection system developed at the Oak Ridge National Laboratory performed successfully reaching over 2.5 MW with the initial two beamlines. The combination of the divertor and the neutral-beam heating system allowed exceptionally high plasma densities to be supported in the absence of disruptions.

A number of smaller experiments, aimed at the demonstration of advanced toroidal confinement concepts, achieved significant progress. The spheromak formation scheme of the S-1 machine was put to a preliminary experimental test in a smaller prototypical device, and was found to be highly effective. The S-1 project itself progressed

into the fabrication stage. The ACT-1 and H-1 experiments demonstrated new techniques for rf heating and current driving.

The Theory Division obtained extensive new results on the finite- β MHD stability properties of tokamaks and guided the design of the S-1 formation scheme by means of resistive-MHD simulations. A fundamentally new approach to rf current driving was discovered. The newly organized Applied Physics Division carried out extensive analyses in support of the International Tokamak Reactor (INTOR) and the Fusion Engineering Device (FED), as well as on behalf of the ongoing tokamak experiments and the proposed Advanced Toroidal Facility (ATF).

In the Tokamak Fusion Test Reactor (TFTR) project, building construction achieved dramatic progress, and a wide range of machine components entered the final manufacturing stage. The success of initial neutral-beam-injector tests in achieving currents over 60 A at 120 keV from a single source was particularly encouraging. The Central Instrumentation Control and Data Acquisition (CICADA) computer system was installed in the TFTR control room. Plasma diagnostics began to advance on a broad front, and work on deuterium-tritium-related systems was under way. Design studies for a tritium-breeding module were completed.

In summary, the past year has proved unusually fruitful in terms of plasma research, and has also reflected the continuing evolution of the Laboratory towards the solution of practical engineering problems and the initiation of reactor-related activities.

Princeton Large Torus (PLT)

The Princeton Large Torus (PLT), shown in Fig. 1, was first operated in December 1975. Ohmic heating experiments, with plasma currents ranging up to 650 kA, emphasized the study of MHD stability, plasma confinement scaling, and the identification and control of impurities. Neutral-beam experiments began in 1977, and in 1978 ion temperatures of 6.5 keV were reached. Concurrently, rf heating in the ion cyclotron range of frequencies was begun at low power. The results were encouraging, and during FY79 rf power absorbed by the plasma was increased to ~ 350 kW while plans were made for experiments at still higher power.

Major Activities

Summary

During FY80, the experimental research program on the Princeton Large Torus was equally divided between heating experiments based on neutral-beam injection (powers up to 3.4 MW) and on absorption of ion cyclotron waves in the ion cyclotron range of frequencies (powers up to 0.75 MW). The major result from neutral-beam heating was the achievement of 7 keV ion temperatures and ion collisionality $\nu_i = 5 \times 10^{-3}$. This value of ν_i is one order of magnitude lower than that previously

Figure 1. The PLT machine in 1978. (781167)

attained and represents the realization of collisionality regimes expected in reactor plasmas. It was achieved without degradation in plasma behavior. The major result from ion cyclotron (ICRF) heating was the achievement of routine coil excitation powers of 1 MW, with resulting ion temperatures of 2.4 keV. Allowing for the moderate levels of rf power delivered to the plasma waves (≤ 0.75 MW), these ion temperature increases equal the best PLT neutral-beam heating results.

The Laboratory's major device operation during FY80 was composed of 60% runtime, divided between PLT and PDX, and 40% downtime. The principal components of the PLT downtime were recovery from the TV Thomson Scattering (TVTS) window implosion of September 1979, assorted small vacuum problems primarily due to the getters, reappraisal of the Coil 6 fix (see FY79 annual report), installation of a shunt to simulate the toroidal field ripple resulting from the Coil 6 failure, equilibrium field (SF) power supply problems, and a planned opening in September 1980 for installation of the lower hybrid heating coupler, new ICRF coils, and replacement of the stainless steel ring limiters with carbon limiters. The actual runtime on PLT amounted to about seven weeks for neutral beam heating, seven weeks for ICRF heating, and one week for ohmic heating.

PLT Neutral-Beam Heating

The major beam-heating effort during FY80 was to identify the PLT machine operating parameters which are important in achieving the highest ion temperature results. Since the ion temperature is inversely proportional to the number of particles sharing the power, the most important parameter is density control, which must be effective during the intense neutral-beam heating in order to avoid the large density rise normally associated with injection. Effective density control is achieved by titanium gettering for approximately five minutes at three toroidal locations between discharges such that the neutral H_2 fill gas is pumped into the walls at rates ≥ 50 Torr- ℓ /sec. With effective density control, 2.5 MW of beam injection (2 Co + 1 Counter) can achieve an ion temperature ~ 7 keV with $\bar{n}_e = 1.5 \times 10^{13} \text{ cm}^{-3}$ and $\bar{n}_e(0) \approx 5 \times 10^{13} \text{ cm}^{-3}$. Without effective density control, 3 MW of beam injection would raise $\bar{n}_e$ to $5 \times 10^{13} \text{ cm}^{-3}$ and $n_e(0) = 10^{14} \text{ cm}^{-3}$, so that the final temperature would be lower even with the same heating efficiency. The second important parameter is control of moderate-Z impurities (mainly iron and titanium) which originate from the vacuum walls (50 cm from the center of the plasma), the in-out limiters (45 cm), the ICRF

shields (48 cm), and possibly as a film on the up-down carbon limiters (36-40 cm). Control of these impurities at low plasma densities is achieved primarily by good position control, and by first going to a higher density (with a lower impurity content) and then reducing it to the lower density required for the high ion temperature without increasing the impurities. These methods are apparently influenced by subtle changes in the vacuum conditions. The consequence of poor impurity control is that central radiation levels $\sim 30\%$ of the beam power (i.e., ~ 1 MW) occur, often coinciding with changes in the MHD activities ($m = 2$ or minor disruptions).

Parameters which are demonstrably less important in achieving the highest possible temperatures include 20% reductions in plasma current or toroidal magnetic field, as well as a single 2.5% peak-to-peak local ripple in the toroidal B field. The ripple experiment was performed by inserting a shunt in one of the TF coils.² The ripple could be introduced with only a 10 minute interruption in the run so that effective comparisons could be achieved. The results are listed in Table I and indicate no discernible differences in heating efficiency.

TABLE I

Parameters	2.5% Ripple	No Ripple
$\bar{n}_e(10^{13} \text{ cm}^{-3})$	2.0	1.8
T (keV)	6.3	6.4
$P_B(\text{MW})$	2.3	2.4

Much of the experimental effort during FY80 was in documenting the various transport processes (ion thermal energy, electron thermal energy, toroidal momentum, particle confinement, and injected energetic beam confinement) during beam heating.³ Even the poorest PLT beam-heated plasmas routinely have factors of 10 smaller ion collisionality ν_i^* than available on other tokamaks. Thus, the transport processes and various transient phenomena observed in PLT can quantify the expectations of reactor-grade plasmas.

Ion Heating

The highest achieved ion temperatures (Fig. 2) of about 7 keV were measured with the charge exchange analyzer, including central neutral doping from a diagnostic beam. The passively measured energy distribution is quite curved at low energies. This curved spectrum is due to the

fact that the charge exchange analyzer makes a line integral through colder regions of the plasma. However, another interpretation of this curvature

Figure 2. The passive (o) and active (Δ) charge exchange spectra for the hottest PLT plasma. D^0-H^+ neutral-beam injection (2.4 MW) produced $T_i = 7$ keV and $v_i = 5 \times 10^{-3}$. (806994)

that the central ion energy distribution is non-Maxwellian, and that the central temperature is colder than the temperature derived from the slope of the high energy region of the spectrum. The diagnostic beam provides a local enhancement of the charge exchange production at the plasma center. Analysis of the enhanced signal indicates that the ion energy distribution is Maxwellian from 1/3 to 5 times T_i .

The ion heating observed on PLT during neutral-beam injection is found to be in good agreement with the usual model for ion energy transport, which includes neoclassical thermal conduction. The thermal convection term in the ion energy balance is large and quite uncertain at low densities, leaving considerable room for possible anomalous ion thermal conduction. At the moderate densities in PLT, however, thermal neutrals originating at the walls and limiter cannot penetrate into the central region of the plasma, and the particle source rate is dominated by the injected beam. Under these circumstances, the central particle confinement time and the concomitant ion thermal convection can be evaluated with some confidence. The resulting ion power balance leaves relatively little room for further anomalous effects. Figure 3 illustrates a 6.3 keV

ion temperature case,²³ for which the calculation of the ion temperature time evolution cannot allow even a $3 \times$ enhancement over neoclassical conduction losses.

Figure 3. Time evolution of the central ion temperature for a high power, "moderate density" PLT neutral beam injection case. (806337)

Electron Heating

At low densities and high temperatures an improvement in central energy containment occurs while the gross electron energy confinement is approximately constant. At the highest power levels this regime is now inaccessible, however, due to increased central core radiation. A recent scan of electron heating (Fig. 4a) as a function of plasma density using D^0 beams show that in the moderate temperature and density range for PLT

Figure 4. a) $T_e(r)$ before injection ($t = 350$ msec) and during injection ($t = 525$ msec) for 2 and 4 D^0 beams. The temperature profile was measured by the Fourier transform spectrometer ($2\omega_{ce}$ radiation) diagnostic. b) $T_e(r)$ obtained with 0.7 MW of ICRF in the deuterium minority, 23 the majority mode ($B = 3.2T$). The temperature profiles were measured by the Thomson scattering and $2\omega_{ce}$ diagnostics. (81X0129)

little degradation of heating efficiency occurs as the plasma density increases (Fig. 5) and beam penetration is reduced. The electron heating, moreover, is found to be linear with respect to the input beam power, up to the presently achieved limits of $P_e(H^+) \sim 2.0$ MW and $P_e(D^0) \sim 3.0$ MW.

Figure 5. Electron temperature before, during, and after D^0 beam injection as a function of electron density. (806348)

From the density scan results, it would be tempting to conclude that electron heating efficiency is insensitive to beam penetration. However, the large dn_e/dt and central core radiation could mask a potentially strong heating efficiency at low density. From the linear dependence of the electron temperature rise on beam power, it is a temptation to conclude that electron energy confinement is independent of T_e . However, the fact that ion-electron coupling and beam-electron heating decrease rapidly as T_e increases makes the dependence of τ_{ee} on T_e not directly derivable from this data set.

It can be concluded: 1) that effective electron heating is possible in plasmas with reduced beam penetration, and 2) that the continued application of higher beam powers in future tokamaks can be expected to produce corresponding increases in electron temperature if impurity radiation and plasma density can be controlled.

Energetic Ion Confinement

The fast ion charge exchange spectrum, and beam induced fusion neutron production, give confidence that the injected energetic beam ions are confined and slowed down classically. In FY80, two improvements to these observations were made. A component to the fast ion population was observed in the Co direction during Counter-only injection (Fig. 6). These are ions which have been pitch-angle scattered into trapped-particle orbits, with the result that they spend some time traveling in the opposite direction. Their banana width is so large that the reflected orbit occurs in an outer spatial region where the neutral density is large and where,

therefore, the probability for charge exchange and subsequent detection is high. The observation of these particles is a confirmation of neo-classical orbit theory for energetic ions. Moreover, the reflected flux could be eliminated by reducing the plasma current so that the loss region encompassed this region of velocity space.

Figure 6. Measurement of the charge exchange spectra for Counter-only injection including a large Co-going ion current. These reverse ion currents arise from neoclassically reflected orbits. (See inset.) (809080)

The use of the neutron emission to determine the confinement of the energetic injected ions is limited by the ability to absolutely calibrate the neutron emission detection system. The PLT neutron emission has been calibrated using indium foils⁴ which are activated by the $^{115}\text{In}(n,n')^{115m}\text{In}$ threshold reaction whose neutron energy dependent cross section greatly reduces the influence of scattered neutrons (i.e., of degraded energies). The indium calibration is accurate to $\leq 40\%$ while previous calibration techniques were accurate to factors of 2 to 5. Moreover, a poloidal array of the foils allows a mapping of the local neutron flux which yields the Shafranov shift of the magnetic axis plus the outward drift orbit displacement of the central beam ions of a total of 10 cm during high power Co neutral beam injection (Fig. 7).

ICRF Heating

The two basic heating regimes in PLT ICRF heating experiments are the two-ion regime, where the wave damping is provided by a minority species, and second harmonic regimes, where the wave damping occurs on the majority species. Each can produce energetic ions that are well confined in PLT and, consequently, can efficiently heat the bulk ions and electrons.⁵ Half-turn loop antennae excite waves from the low field side of PLT which propagate to the damping zone in the core of the plasma. Wave excitation is available at 25 MHz and 42 MHz, with different regimes requiring different toroidal magnetic fields (Table II).

Figure 7. Poloidal emission profile of d-d neutrons as determined by the placement of indium activation foils on the PLT vacuum vessel. The major radius of the neutron-emitting plasma is outshifted about 8 cm from the vacuum vessel center. (806097)

PLT runtime was insufficient to explore and optimize each of these available heating regimes. Instead, each of these modes was tested at low powers to indicate that, indeed, energetic ion tails were produced in all regimes, and a more complete documentation was made for the ^3He minority heating.

^3He Minority Heating

The bulk of the ICRF work during FY80 has been with the ^3He minority mode at 2.5 T. This regime allows easily-produced, good PLT discharges (i.e., at a large field and therefore plasma current) so that there is good confinement of the energetic ^3He ions. The use of a ^3He tail also maximizes the power to the bulk ions (deuterons), since the critical energy for ^3He is higher and the coupling stronger than for hydrogen or deuterium. Further, the direct charge exchange losses for the energetic tail are minimized. By the end of FY80, the ^3He minority regime was operating reliably with 1 MW of power into the coils and 0.8 MW going into the plasma for durations of 0.2 sec. At the highest rf powers, the thermonuclear d(d,n) ^3He neutron flux (Fig. 8) is increased by more than a factor of 500 to $\sim 5 \times 10^{11}$ n/sec. The deuterium temperature increases by ~ 1.7 keV to ~ 2.4 keV as determined both by the neutron emission and the charge exchange system. Collimated neutron energy spectral measurements and mass resolved charge exchange measurements indicate that the bulk deuterons are Maxwellian. The neutron emission has been found to be toroidally uniform from activation measurements of the indium foils [$^{115}\text{In}(n,n')^{115}\text{In}(4.5h) \rightarrow ^{115}\text{In}$] placed on the PLT vacuum vessel. This result suggests that local excitation and trapping of energetic deuterons near the antennae is negligible. Significant electron

TABLE II				
rf Frequency (MHz)	Mode	Gases		Toroidal Field (T)
		minority	majority	
25	two-ion	D	H	3.2
		H	D	1.6
		D	^3He	3.2
		^3He	D	2.4
42	two-ion	H	D	2.8
42	second harmonic		H	1.4
			^3He	2.1

Figure 8. Neutron emission and derived deuterium temperature for the ^3He minority during ICRF heating. The shaded region indicates the duration of the rf excitation (0.8 MW). The inset shows the high resolution neutron energy spectrum with the expected Doppler width of a 2 keV plasma. The charge exchange deduced ion temperature (Δ) agrees reasonably with the neutron T_i and the spectra (inset) also indicate a Maxwellian deuterium population. (803908)

heating has been observed, although the level depends strongly on the impurity radiation from the plasma.

The radiation losses during ICRF heating are due to a combination of increased electron density, influx of high-Z impurities, and radiation of low-Z impurities in the periphery. The power input occurs mostly in the plasma interior (Fig. 9), whereas the radiated power usually arises mainly near the periphery.

Due to the double charge exchange for ^3He , direct measurement of the ^3He energy distribution has not proven to be practicable as yet. However, we have observed high $d(^3\text{He}, p)\alpha$ reaction rates, which are induced by the energetic ^3He tail reacting with the bulk deuterium plasma. This reaction produces a 14.7 MeV proton which has so much

Figure 9. Deposited and radiated powers during ^3He minority ICRF. The increase in central radiation can be accounted for entirely by the plasma density rise during the rf pulse. Nearly the entire ICRF power is eventually radiated away from the plasma periphery (809072)

momentum that it is completely unconfined in PLT. The loss is caused by curvature and grad B drifting of the energetic protons, such that these particles are lost down and outward in a pattern that was verified by measurement of the poloidal distribution of the energetic proton induced $^{56}\text{Fe}(p,n)^{56}\text{Co}(79d)$ activity on the PLT stainless steel ring limiters (Fig. 10). Time resolution of the $d\text{-}^3\text{He}$ reaction rate was achieved using a silicon surface barrier detector (Fig. 10) placed on the horizontal midplane. The ICRF induced $d\text{-}^3\text{He}$ reaction rates as high as 10^{13} sec^{-1} indicate a fusion power production of ~ 50 watts. The observed $d\text{-}^3\text{He}$ reaction rates are consistent with the expected production by the ICRF generated ^3He tail and indicate the production and confinement of ^3He particles up to ~ 80 keV. The $d\text{-}^3\text{He}$ reaction rate and the bulk deuterium ion temperature are optimized when the toroidal magnetic field is such that the ICRF ^3He resonant layer is ~ 10 cm outside of the vacuum vessel minor axis (Fig. 11). This optimization is consistent with placing the ICRF ^3He drift orbits or, alternatively, with placing the two-ion hybrid layer near the center of the plasma.

The ^3He minority ICRF heating experiments at the 0.8 MW level are very similar to the early neutral beam heating experiments at the 1 MW level. As with the beams, control of the plasma density and impurity influx are important. In this respect, measurements of the outflux of low energy neutrals⁶ (Fig. 12) away from the limiter indicate an increase in the edge neutral density during the rf,

Figure 10. a) Loss orbits of 15 MeV protons created in the center of the PLT plasma by the $d(^3\text{He},p)\alpha$ reaction. b) Monte Carlo calculation of the poloidal escape distribution of 15 MeV protons compared to the poloidal distributions of $^{56}\text{Fe}(p,n)^{56}\text{Co}$ activation in the PLT steel limiters and caused by the 15 MeV protons. (806996)

Figure 11. a) Time evolution of the 15 MeV proton emission of $d(^3\text{He},p)$ reactions due to the energetic ^3He tail and the 2.5 MeV neutron emission $d(d,n)$ reactions due to the bulk ion heating. b) Density evolution indicating the ^3He gas puff duration. c) Scan of the proton and neutron emission as the toroidal field was varied. The ^3He tail was most energetic and the ion temperature was highest when the cyclotron layer was slightly outshifted from the PLT minor axis. (806995)

which might explain the observed density rise during the ICRF heating. As with the neutral beam heating, this density rise must be controlled at higher rf powers. Interestingly, the increase in the low energy neutral outflux also occurs for beam heated plasmas but is not observed on gas puffing experiments which program even larger density rises.

Figure 12. Time evolution and spectrum of the neutral emission away from the limiter during a) 0.2 MW of H minority ICRF b) 1.7 MW of D^+-H^+ neutral beam heating, and c) intense gas puffing. (806070)

Deuterium Minority Cases

For a D minority in an H or ^3He plasma, the minority fundamental resonance is at a higher magnetic field than for the majority. The use of the higher magnetic field allows somewhat easier PLT operation at densities $n_e \sim 5-6 \times 10^{19} \text{ cm}^{-3}$, where these ICRF modes can penetrate to provide central heating in plasmas with the longer electron energy confinement times associated with higher density operation. Preliminary ICRF results (Fig.

4b) indicate that extremely efficient central electron heating was obtained in some cases in these high density deuterium minority modes. It is not clear whether these results arise from direct wave damping on electrons or the increased electron-ion coupling at the higher densities. This electron heating regime has not been fully explored, but the sensitivity of these preliminary results to the deuterium minority concentration suggests a strong correlation of the heating with the wave dispersion relation.

Second Harmonic Regime

Initial heating results for the second harmonic regime have been obtained in hydrogen with a single coil excited at 42 MHz. An ion energy distribution consistent with Fokker-Planck theory has been observed out to 60 keV (Fig. 13). The bulk heating estimated between 1.5 keV and 5 keV is sizeable even at moderate power levels. Note that even this conservative estimate of the energy added to the hydrogen ions gives a heating rate of $\sim 3.5 \times 10^{13}$ eV/kW-cm², which is comparable to that achieved in the D-H two-ion regime. The ion distribution is similar to the minority heating regime except that the bulk population is a monotonically decreasing non-Maxwellian distribution, consistent with the complete Fokker-Planck theory including finite Larmor radius effects in the quasi-linear rf operator.

Mode tracking is not essential for the second harmonic regime in PLT. The loading exhibits moderate to low-Q modes which provide adequate coupling throughout the rf pulse. This result can be attributed to the influence of the ion Bernstein wave on the second harmonic damping in a fashion similar to that at the two-ion hybrid layer.

Fluctuations and Stability

In PLT, as in all tokamaks, observations of MHD oscillations, density fluctuations, and impurity transport are important for the information they may yield about the plasma transport and limitations to the plasma parameter range. In this context, the intensive external heating available on PLT makes several of these phenomena more pronounced.

High-Frequency Fluctuations

For ohmically heated PLT plasmas, the amplitude of the microwave signal scattered from density fluctuations⁷ has been measured (Fig. 14) indicating that the perpendicular wavelength is of the order of the ion gyroradius. By assuming that the

Figure 13. Charge exchange measurement of the proton distribution produced by second harmonic heating of a hydrogen plasma ($f = 42$ MHz, $B_0 = 14$ kG, $\bar{n}_e = 1.7 \times 10^{13}$ cm⁻³, $P_{rf} = 140$ kW) and the time evolution of the bulk hydrogen temperature (for the 1.5-5 keV energy range). The dashed line shows a typical hydrogen minority heating case with similar rf power. (809015)

observed turbulence is isotropic in the perpendicular plane and that $K_{\parallel} \ll K_{\perp}$, then $\langle \bar{n}_e \rangle_{rms} / \bar{n}_e \approx 1\%$. The level of density turbulence was enhanced by a factor of two when the ion temperature was increased by neutral beam injection from 1 keV to 4 keV. At higher ion temperatures, a new type of fluctuation, was occasionally observed which features spikes at frequencies ~ 50 -200 kHz (Fig. 15a), was observed by soft x-ray diode arrays indicated oscillations at these frequencies in millisecond bursts, propagating in the ion diamagnetic direction and linked by $m/n = 1$ helicity, suggesting a long coherence length and macroscopic structure. Although these fluctuations tend to occur only on those discharges with $T_i > 4$ keV, some discharges with $T_i > 4$ keV were also obtained with little or no fluctuation.

Figure 14. Spectral density (and scattered signal-insert) for PLT ohmic discharges. (809016)

Figure 15. Both the microwave scattered signal a) and soft x-ray chord signals b) exhibited similar high frequency oscillations (50-200 kHz) on the same type of high ion temperature neutral-beam heated discharges. The exact relation between these two oscillation signals, if any, has not yet been established. (809079)

Sawtooth Oscillations

The influence of external heating (either neutral beams or ICRF) is often to make the sawtooth amplitude $(\Delta T_e)/T_e \sim 0.3$ period (≤ 50 ms), and the radial extent ($r/a \sim 0.5$), all larger. A variety of new phenomena associated with these sawtooth oscillations became observable.

Figure 16 shows the Fe XXIV resonance line brightness which drops about 70% in ≤ 0.1 ms, near the plasma center. The ionization and recombination times of Fe XXIV are 5-10 ms, and the signal (collisional excitation rate) is almost independent of T_e (above 0.1 keV) so that the large central drop must be a transport effect rather than an atomic process. Fe XXIII shows the same oscillations while Fe XXII has almost no oscillations, and lower ionization states show only a weak inverse sawtooth. Inverting the signals into radial profiles indicates that the total amount of Fe XXIV has been unchanged by the internal disruption. The intensity fluctuations of the Fe XXIV light are ascribed to a rapid mixing of plasma near the center and around 15 cm.

The flux of runaway electrons to the limiter increases for $\sim 2-5$ ms after the internal disruption. The time from the internal disruption to the hard x-ray maximum increases when the electron density is increased and is somewhat longer to ICRF heated discharges than for neutral beam heated discharges. One possible interpretation of these phenomena is that the runaway electrons transport to the limiter from the $q = 1$ surface, where they have undergone a spatial redistribution as a result of the internal disruption. The runaway electron confinement times are about $V_e/c \approx 1/10$ of the bulk electron energy confinement times as if both processes were determined by parallel heat conduction along perturbed magnetic surfaces.

The thermonuclear neutron emission on PLT during ohmic heating, $H^0 \rightarrow D^+$ beam heating, or ^3He minority ICRF heating, is observed to decay rather slowly to a minimum in about 5 ms (fluctuation magnitude $\sim 10-20\%$) after the internal disruptions. The neutron sawtooth can be reasonably described by solving the time evolving energy balance in the presence of an internal disruption. The key features are that there is some degradation of the ion energy confinement in the 5 ms following the internal disruption which cannot be accounted for by electron-ion coupling. A sawtooth-like redistribution of the ion energy or a 50% enhancement of convection or conduction could explain the observations. Furthermore, after about 5 msec, the neutron emission rises at a rate too rapid to be explained by classical electron-ion

coupling. The most probable energy influx is due to the inward convection which is simultaneously observed as the density buildup between sawteeth. An inward directed velocity ≈ 30 cm/sec could explain the experimental observations and is of the magnitude of the expected Ware pinch near the plasma center.

When the deuterium plasma is heated with deuterium neutral beams ($D^0 \rightarrow D^+$), or when a ^3He plasma is heated with deuterium minority ICRF, then the neutron emission arises from the interaction of the bulk plasma with the energetic tail ions. These neutron oscillations are observed as a small drop ($\delta I_n/I_n \leq 3\%$) decaying to a minimum about 5 ms after the internal disruption⁸ (Fig. 16). The time evolution of the neutron emission was modelled by solution of the Fokker-Planck equation describing the energetic ions. The neutron

Figure 16. Typical phasing of hard x-ray signals, thermonuclear fusion neutron production, line average density, beam induced fusion neutron production, and Fe XXIV emission with the sawtooth behavior. These signals are a composite of several different discharges. (809082)

sawteeth could be explained entirely by the time evolution of the electron drag on these ions.

Fast Ion Disruptions

It is observed with high power neutral beam injection (>2 MW) into PLT plasmas with small minor radius, small toroidal fields, or large central radiation, that a type of disruption can occur which strongly influences the energetic, injected ions and only modestly influences the plasma current, the electron temperature, and the electron density. These "fast ion disruptions" are characterized by $\sim 50\%$ drops in the beam-induced neutron emission in times ≈ 2 msec (Fig. 17).

Figure 17. Time evolution of the beam induced neutron emission, the perpendicular fast ion charge exchange outflux, and the tangential fast ion charge exchange outflux during a fast ion disruption (809081)

Simultaneously, the energetic charge exchange outflux rises first and then drops by 50% . The rise is observed primarily in V_{th} directions perpendicular to the beam direction and may be due either to enhanced pitch angle scattering or energetic ion transport to the plasma edge (where the neutral density is large). The neutron emission and charge exchange outflux is apparently influenced directly by a precursor $m \approx 1$ MHD mode of short duration and significant extent ($r \approx 25$ cm).

Impurity Transport

Experiments and computer simulations indicate that high-Z impurities move across the magnetic field during stable, stationary discharges with a velocity of the order of 10^3 cm/sec. corresponding to a diffusion coefficient of 10^4 cm²/sec. The outward radial motion has been seen in argon seeded discharges,⁹ where hydrogen-like argon, produced in the central region of the discharge, has been seen to diffuse to outer radii (Fig. 18). A corresponding diminution of the long lived helium and hydrogen-like charge state in the central region has also been observed (Fig. 19) as a deviation from coronal equilibrium.¹⁰ Since ionization

and recombination times decrease with increasing density, these deviations caused by transport become more pronounced at lower density.

Figure 18. Modelling of argon seeded discharges with the MIST code. The total argon density of $5.3 \times 10^{19} \text{ cm}^{-3}$ is assumed to be independent of radius. The concentration of hydrogen-like Ar^{17+} is calculated assuming (I) coronal equilibrium with charge exchange recombination and (II) diffusion with a diffusion coefficient of $10^6 \text{ cm}^2/\text{sec}$ and charge exchange recombination with a central neutral density of $3 \times 10^{19} \text{ cm}^{-3}$. The circles show total argon content derived from K_α union, the dots hydrogen-like argon concentration from recombination edges. The corresponding x-ray spectral are shown in subfigure (a). (809089)

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Figure 19. Observed deviations of the relative charge-state distribution of Fe XXIV and Fe XXV from coronal equilibrium, n/n_s , as a function of the central electron density, n_e . The deviations from coronal equilibrium, $n_{\text{Fe XXIV}}/n_{\text{Fe XXV}} - n/s$, are determined by the ratio of the ionization time for a Fe XXIV ion, $T = 1/sn_e$, and the confinement time τ of a Fe XXV ion. The value of $\tau = 5 \text{ ms}$ deduced from experimental data is interpreted as the confinement time of a Fe XXV-ion within the central region ($r \leq 10 \text{ cm}$) of the plasma column, where, due to the radial electron temperature profile, the (1s-2p) resonance lines of Fe XXIV and Fe XXV (used for the observations) are excited. (806114)

Radial profiles of impurities, summing over all charge states, tend to be relatively flat, indicating that accumulation of impurities in the central region does not occur.

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Poloidal Divertor Experiment (PDX)

The Poloidal Divertor Experiment (PDX), shown in Figure 20, is a large tokamak built to investigate:

- Development and determination of the effectiveness of poloidal divertors, magnetic limiters, and other techniques for controlling impurities in large, high-temperature, collisionless tokamak plasmas; in particular, development of a shielding divertor for use with long-pulse reactors.
- Determination of the confinement scaling as a function of collisionality for the range of parameters from present-day plasmas to those of reactor-like plasmas; use of divertors to control the effective Z and of neutral beam heating to control the plasma temperature.

- Optimization of the plasma cross-section under conditions of relatively "flat" current distributions, which are produced in conjunction with effective divertor control of the density of neutral species and impurities.
- Determination of the maximum β for a stable plasma confined in a tokamak under nearly optimum conditions of impurity control and cross-section shaping.
- Development of plasma refueling techniques that are compatible with impurity control in reactor-like plasmas.

The first nondivertor plasmas were prepared in PDX in February 1979. After two months of operation, during which circular cross-section plasmas with currents up to 500 kA were obtained, experiments were suspended for installation of the

Figure 20. The Poloidal Divertor Experiment. (806834)

divertor system components. Results from the initial period of operation were presented at the Ninth European Fusion Conference in September 1979¹.

Major Activities

Summary

In the first quarter of FY80, the installation of the divertor components was completed. Power tests of the divertor coils and the reestablishment of circular discharge operation took place in December 1979. The first divertor plasmas were obtained in January 1980. In mid-February, after initial investigations of the divertor operation, the machine was opened for internal inspection and repair and the installation of parts for the first stage of the neutral beam heating system. The basic features of the divertor plasmas were described in a paper presented to the 4th International Conference on Plasma Surface Interactions, Garmisch-Partenkirchen, April 1980².

Beam injection experiments began in April and then, during May and June, several aspects of the

operation of the divertor were investigated in both ohmic and beam heated discharges. The results of this period of experiments were given at the 8th International Conference on Plasma Physics and Controlled Nuclear Fusion Research in July 1980³.

The machine was opened again in July for repairs and the installation of new diagnostics. Experiments recommenced in August in rotation with PLT, and then in September an intensive period of experimentation on PDX began when PLT was opened for refurbishing.

In all, seventeen weeks of experimental running time were available between January 1980, when full operation recommenced, and the end of FY80. During this period, some 5500 high power discharges were run, of which 70% were divertor discharges and 30% were circular. Of the divertor shots, 80% were in the standard-Dee configuration with the remainder in the square and inverse-Dee configurations.

Significant milestones in the PDX program, which were passed during the year, include:

January 1980	First divertor plasmas: $B_T = 1.7 \text{ T}$, $I_p = 280 \text{ kA}$, $n_e \sim 2 \times 10^{13} \text{ cm}^{-3}$.
February 1980	Measurements of particle and energy flow into divertors. Divertor plasmas with $Z_{eff} = 1.3$.
April 1980	Neutral beam injection: 900 kW at 35 keV for 200 msec; $\bar{n}_e \sim 3 \times 10^{-3}$.
May 1980	During ohmic heating $\bar{n}_e$ was raised to $4 \times 10^{13} \text{ cm}^{-3}$, $6 \times 10^{13} \text{ cm}^{-3}$ during beam heating.
June 1980	Injection from two beams at 2.4 MW. Single-null divertor configurations produced.
August 1980	Measured the deposition profile of injected solid hydrogen pellets. Reduced q_0 below 2 for short periods in ohmic discharges.
September 1980	Neutral beam injection, $P = 2.8 \text{ MW}$. During beam heating $\bar{n}_e$ reaches $\sim 8.5 \times 10^{13} \text{ cm}^{-3}$.

Fabrication, Testing and Discharge Cleaning

A cross section through the PDX vacuum vessel and coil systems is shown schematically in Figure 21. Before initial divertor operation, the external supply conductors for the internal windings were carefully tested electrically and mechanically, and some small deflections were measured in the conductors feeding the divertor windings. As a precaution, the toroidal field, divertor and plasma currents have been held to 2/3 their final design values to limit the forces on the electrical joints while additional bracing for them is completed.

Within the vacuum vessel, all the surfaces in contact with the plasma (the limiters, divertor neu-

tralizer plates, liner and diagnostic components) are made from 99%-pure titanium. The vessel is evacuated by turbopumps with a combined speed of 3 kℓ/s for hydrogen to a base pressure of 10^{-7} Torr. Titanium gettering can be applied in half of the twenty divertor burial cells formed by aluminum curtains in the domes of the vacuum vessel. No gettering has been applied in the main plasma chamber. The titanium was originally deposited at rates up to 5 g/hr in total which produced a pumping speed of $> 200 \text{ kℓ/sec}$ for hydrogen and a base pressure of $\sim 10^{-8}$ torr. Following the internal inspection in July 1980, the gettering was reduced somewhat, particularly in the upper dome, due to concern over the formation of loose titanium

Figure 21. Schematic cross section through the PDX vacuum vessel and coil systems. Coil identification: TF - toroidal field, OH - ohmic heating transformer, DF, CF - divertor fields, EF - equilibrium control field, NF - nulling field (for start-up). (803771)

flakes on some exposed surfaces. Such flaking was considered a possible cause of some large bursts of titanium influx which had been observed in divertor discharges.

The glow discharge cleaning technique, which proved most successful during the early operation of PDS 45, has been largely discontinued because it appears to damage the internal insulators supporting components of the divertor system. This damage does not occur during the pulse discharge method which has superseded the glow method. However, the pulse discharge method is not effective in cleaning the remote regions of the divertor domes, even when the divertor fields are energized during its application, and as a result the conditioning process is now slower.

Initiation, Control and MHD Properties of PDX Discharges

For the initiation of divertor plasmas, the poloidal field system of PDX was designed to produce a hexapole null in the vertical magnetic field at a small major radius, to cause the discharge to form away from material boundaries. However, it became clear that transient fields from currents induced in the toroidally continuous vacuum jackets of the divertor coils were of predominant importance during initiation, and so the scheme has been modified. In practice, an octopole null can be created for start-up near the vacuum vessel center by cancelling the divertor and eddy current fields with a small applied dipole field. However, experience has shown that the plasma can be started most readily when the ap-

plied field is adjusted to produce initially a quadrupole null at a radius of about 1.6 m. The current buildup from 20 to 100 kA remains very sensitive to the applied vertical field and its rate of rise, but with careful programming of the field and feedback control of the position, divertor discharges can be started reproducibly.

PDX is equipped with feedback control systems for the plasma current, radial position and line-average electron density. These systems enable the discharge to be developed in a predetermined manner and are particularly useful in obtaining reproducible plasmas for confinement studies and comparisons of the different magnetic configurations.

Flux surface contour plots for typical MHD equilibria during the current flattop in PDX divertor discharges are shown in Figure 22. These plots are computed solutions of the MHD equilibrium equations satisfying as boundary conditions,

Figure 22. Flux contour plots of MHD equilibria that have been obtained in PDX. The divertor winding and plasma currents are the same in each case. Plasma elongations up to 1.4 have been maintained with active feedback. (803950)

the measured coil and plasma currents and the poloidal magnetic field measured with loops around the plasma. The discharge can be moved from one divertor configuration to another by varying the applied vertical field, thereby changing the radius R_m of the magnetic axis, while the divertor coil currents are held fixed. The transition

from the standard-Dee through the four null or square configuration to the inverse-Dee is demonstrated in Figure 23 which shows the line densities across the inner and outer divertor throats as the plasma radius was varied while the line density across the main discharge was held constant. The location of the separatrix at the outside midplane of the plasma has also been verified by moving the outside limiter to intercept the power and particle flow into the divertor. The measured position agrees closely with that calculated from the equilibrium code.

Figure 23. Transitions between the divertor configurations produced by shifting the major radius of the plasma. The electron densities across the divertor throats were measured with 8-mm microwave interferometers. (806941)

In divertor operation, the vertical field gradient varies greatly across the vacuum vessel midplane leading to vertical elongation of the plasma for both small ($R \sim 1.2$ m) and large ($R \sim 1.6$ m) major radii (Fig. 21). These elongated plasmas, while being of interest since they may allow operation at higher values of β and may be more stable against disruption⁶, are unstable against vertical displacement from the midplane. To stabilize such vertical motion passively, pairs of divertor coils that are mirror symmetric about the midplane are connected in parallel and then the parallel units are connected in series to the divertor power supply. This creates an effective copper shell in which currents will be induced to oppose any vertical motion of the plasma. Such resistive stabilization also renders the instability more amenable to long-term stabilization through active feedback control. A power amplifier has been installed in one leg of the parallel divertor connections to provide this control. Experiments have shown that the system can maintain vertical stability over the

full range of plasma major radii and that the plasma can also be held displaced from the midplane, thereby creating divertor configurations with a single magnetic null. The formation of such a single null configuration is shown in Figure 24: the discharge was initiated on the midplane and then shifted upwards by 5 cm over the period 100-800 msec.

Figure 24. Transition from a standard-Dee to a single-null divertor configuration produced by shifting the plasma vertically by 5 cm over the period 100-800 msec. (806660)

MHD fluctuations in the PDX plasma are monitored with external magnetic pickup coils, a soft x-ray imaging system, and the electron cyclotron emission radiometer. In general, standard-Dee configurations have a relatively low level of impurities and are characterized by a low level of $m = 2$ activity and 10% sawtooth oscillations in the electron temperature with periods of 5-15 msec. These discharges run reproducibly and stably at $q_a \sim 3.1$ (q_a is the safety factor calculated for an equivalent circular plasma); the minimum q_a obtained in the Dee configuration was 2.0. Major disruptions have resulted in a total current decay time as short as 2 msec although typical disruptions are longer. Circular discharges with a titanium limiter have a larger impurity content and under our present conditions are more likely to

have $m = 2$ activity than the divertor discharges. However, stable circular discharges with sawtooth activity have also been routinely produced. Figure 25 shows an example of the x-ray imaging-array data for a circular discharge in which a continuous $m = 1$ oscillation was present in the core of the discharge.

Figure 25. Soft x-ray detector array data for a circular discharge in which a continuous $m = 1$ oscillation was present in the core of the discharge. The displacement of the core due to the mode is about 15 cm. (806834)

Impurities

Impurities in PDX are monitored with ultraviolet and soft x-ray spectrometers. Several forbidden lines in the spectra of highly ionized states of titanium have been identified in the radiation from PDX plasmas.^{7,8,9} Comparisons between the impurity behavior in standard-Dee divertor and circular plasmas have been made for discharges with the same toroidal field $B_t = 1.7$ T, plasma current $I_p = 300$ kA, major radius $R_0 = 1.4$ m, and line-average density $\bar{n}_e \approx 3 \times 10^{19} \text{ cm}^{-3}$. For the divertor discharges the mean separatrix radius was 0.38 m while for the circular discharges the limiter radius was 0.42 m. The comparisons are complicated by the occurrence of some erratic bursts of titanium influx into the divertor discharges and by the appearance of two types of circular discharge: the first type is characterized by a flat radiation profile dominated by carbon and oxygen radiation and exhibits sawtooth activity; the second has a centrally peaked radiation profile due to titanium radiation and exhibits $m = 1$ activity without sawtooth oscillations.

Indications of the impurity behavior can be obtained by comparing emission line intensities for the different discharges as shown in Figure 26. The central titanium radiation (Ti XIX (169A)) during the steady-state portion of the discharge is a

Figure 26. Impurity line intensities for standard-Dee and two types of circular discharge in PDX. The C III, O VI and Ti XIX emission comes from the periphery of the discharge; the Ti XX emission from the center. (806464)

factor of 10-15 less in the sawtooth than in the $m = 1$ circular discharges. There is a further reduction by a factor of 5 between the divertor and sawtooth circular discharges. Equivalent reductions in the central titanium density cannot be inferred, however, as the Ti XIX radiation is sensitive to the temperature profile in the discharge at the temperatures involved, $T_e(0) \approx 800$ eV. The differences in the low-Z impurity radiation from the edge between the circular discharge types are also apparent.

Fig. 27 shows data from the soft x-ray pulse-height spectrometer for the different discharges. The substantial reduction in the enhancement of the x-ray continuum radiation by impurities at the center in divertor discharges is clear.

In general, the divertor plasmas are cleaner than the circular plasmas, although with care circular discharges with a low Z_{eff} can be produced. The divertor seems most efficient at reducing the high-Z impurity content while also producing a modest reduction in low-Z elements. The random bursting of titanium influx into the divertor plasmas is not yet understood and can, at times, produce instantaneous levels of titanium emission from the plasma core which are comparable to those in clean circular discharges.

Confinement and Energy Balance in Ohmic Discharges

For studies of confinement, the evolution of the electron-temperature profile has been

Figure 27. Radial profiles of the x-ray continuum emission. The data indicate that the impurity level is lowest in the divertor discharge since the profiles of n_e and T_e are very similar in the three cases. (806203)

measured with the five-chord soft x-ray pulse-height analyzer. The TVTS system has provided partial profiles of both the electron-temperature and density at one time during the discharges, while a single-frequency electron cyclotron emission detector has been used to follow the time evolution of the temperature at one location in the plasma. Electron density profiles are measured with a two-dimensional, nine-chord, 2-mm microwave interferometer supplemented by a methyl alcohol laser interferometer¹⁰ for high density measurements. The ion temperature is determined by a two-chord, ten-energy channel charge exchange spectrometer, the Doppler broadening of impurity line radiation and, in the case of deuterium plasmas, neutron emission.

Fig. 28 shows the ranges in the density and temperatures covered in the confinement studies of standard-Dee ohmically heated discharges. The confinement properties of the other divertor

configurations have not yet been extensively studied, but indications are that the confinement times are similar to those obtained in the standard-Dee case. In Figure 29, the total energy confinement times and Z_{eff} calculated from the plasma resistivity are shown for both divertor and circular discharges. The confinement times for the two configurations are very similar, but for the circular

Figure 28. Ranges in the plasma density and temperatures covered in the confinement analysis for divertor discharges: $B_t = 1.7$ T, $I_p = 300$ kA, $R = 1.4$ m, $a_{sep} = 0.38$ m. (806188)

discharges the effective ionic charge is higher, typically $Z_{\text{eff}} \approx 2$, whereas for the divertor case $Z_{\text{eff}} \approx 1$ in hydrogen and deuterium and $Z_{\text{eff}} \approx 2$ in helium even at low densities. There is a clear trend for confinement to improve with the mass of the ion species: helium discharges generally have a lower loop voltage and have a higher electron temperature than equivalent hydrogen discharges.

Figure 29. Total energy confinement time τ_E and Z_{eff} calculated from the plasma resistivity for varying densities in divertor and circular discharges. An improvement in the confinement time with the mass of the ion species is evident. The line plotted represents the energy confinement scaling law being used in the reference design of the INTOR device. (809070)

The plasma energy balance has been studied using a 19-channel bolometer array, a thermocouple array on the neutralizer plates and thermocouples on the limiter and other surfaces exposed to the plasma. Generally, circular discharges have $\approx 30\%$ of the input power radiated and $\approx 25\%$ absorbed on the limiter. For divertor discharges, $\approx 50\%$ of the input flows to the divertor neutralizer with $\sim 20\%$ being radiated from the main plasma volume.

Neutral Beam Injection

The first phase of the Joint Oak Ridge National Laboratory/PPPL Heating Project has gone into operation on PDX. This phase comprises two neutral injectors each having a rating of 1.5 MW at 50 keV for a 500 msec pulse. The beams are oriented to inject 9° from the perpendicular in the Co direction. They have been operated at full power with pulse lengths of 300 msec so far.

Results for the case of 2.6 MW deuterium beam injection into a deuterium standard-Dee plasma are shown in Figure 30: substantial ion

Figure 30. Waveforms of the plasma current and surface voltage and the evolution of the density and temperatures during 2.6 MW D^+ injection into a D^+ standard-Dee plasma (809107)

and electron heating during the injection are evident. The central electron temperature, which was obtained from the cyclotron emission calibrated against Thomson scattering data, shows the appearance of very large sawtooth oscillations with a period ≈ 25 msec during the beam pulse; prior to injection the sawtooth period is ≈ 8 msec. There is a tendency for the density to drop during injection. This is partially overcome by the gas feedback control which increases the gas flow in an attempt to maintain the pre-programmed level.

The power emitted from the plasma (inferred from bolometer data) increases during beam injection, but remains a small fraction of the input power, ~ 25 percent of the total for divertor discharges and ~ 30 percent for circular discharges. The evolution of the radiation and its radial profile for hydrogen discharges with 1.1 MW deuterium injection are shown in Figure 31. Some of the increase in power registered by the bolometers may arise from enhanced charge exchange losses from the plasma during injection. Spectroscopy indicates that there is no substantial buildup of impurities during the beam pulse, and this is supported by the sustained drop in the loop

Figure 31. Time evolution and radial profiles of the power radiated from divertor and circular hydrogen discharges before and during injection of 1.1 MW D⁺; $I_p = 300$ kA, $\bar{n}_e = 3.5 \times 10^{13} \text{ cm}^{-3}$. (806185)

voltage. The contributions to Z_{eff} from the main impurities in PDX, as determined by the soft x-ray analysis for both divertor and circular discharges during beam heating, are shown in Table III. A full analysis of the confinement during beam heating is now proceeding.

With neutral injection it is possible to use gas-puffing to raise the plasma density significantly above the levels achievable with ohmic heating alone. A benefit of divertor operation with gettering is that by terminating the gas flow before the end of the beam pulse, the density can be

brought down rapidly to a level which can be sustained without disruption by the ohmic heating alone.

Figure 32 shows the ranges of the parameters q_a^{-1} and $\bar{n}_e R/B_t$ which have been obtained in ohmic and beam heated discharges in PDX. The maximum density obtained with ohmic heating corresponds to $\bar{n}_e R/B_t \approx 4.5 \times 10^{19} \text{ m}^{-2} \text{ T}^{-1}$, while with 2 MW of neutral injection $\bar{n}_e R/B_t \approx 9.5 \times 10^{19} \text{ m}^{-2} \text{ T}^{-1}$ has been reached without disruption at $q_a \approx 3.1$.

Figure 32. Plot of the reciprocal of the aperture q -value against the density confinement parameter $\bar{n}_e R/B_t$ achieved in PDX. For divertor discharges ' q_a ' is calculated by assuming an equivalent circular discharge. (806929)

Particle and Energy Flow Into the Divertor

Measurements have been made with a single Langmuir probe in the outside scrape-off region

TABLE III
Contributions To Z_{eff} In Neutral Beam Heated Discharges
Soft X-ray Analysis

	Circular (Sawtooth)		Divertor (Sawtooth)	
	Before Beam (360-540ms)	During Beam (540-720ms)	Before Beam (240-420ms)	During Beam (420-600ms)
$T_e(r = 2.5 \text{ cm}) [\text{keV}]$	1.0	1.40	.88	1.23
$n_e [10^{13} \text{ cm}^{-3}]$	3.2	3.5	3.2	3.1
Z_{chlorine}	.02	.02	.002	.004
Z_{titanium}	.07	.06	.005	.02
Z_{iron}	.02	.007	—	.01
Z_{oxygen}	.16	.09	.02	.1
Z_{carbon}	.06	.03	.008	.04
Z_{hydrogen}	.97	.98	.99	.98
Z_{eff}	1.3	1.2	1.03	1.15

on the equatorial plane. The results are shown in Fig. 33. For the standard-Dee discharge, the density reached a plateau as the probe was inserted from the outside up to 3 cm into the region between the outer and inner separatrixes on the large major radius side (Fig. 22b). The plateau density was in the range $4\text{--}15 \times 10^{12} \text{ cm}^{-3}$ with the range arising from uncertainty in the effective probe area. Outside the plateau, the density creased exponentially with a characteristic distance of 1-2 cm. The electron temperature was $\approx 10 \text{ eV}$ at 1 cm outside the separatrix. In the case of inverse-Dee and circular plasmas, there was no plateau but the temperature and density were of the same order as in the standard-Dee case.

Figure 33. Probe measurements of the electron density in the scrape-off region at the plasma mid-plane. The electron temperatures are $\sim 8 \text{ eV}$ near the separatrix or plasma boundary defined by the limiter. The coefficient λ is the characteristic length for the exponential decay in the density outside the boundary. (804970)

Langmuir probes have also been used to measure the plasma parameters near the neutralizer plates. For a main plasma density of $3.3 \times 10^{13} \text{ cm}^{-3}$, the probe yielded an electron temperature of $\sim 10 \text{ eV}$ and density of $4\text{--}7 \times 10^{12} \text{ cm}^{-3}$. The line density across the scrape-off near the plate from the probe data was $2\text{--}4 \times 10^{13} \text{ cm}^{-2}$, in fair agreement with the microwave interferometer measurement of $4 \times 10^{13} \text{ cm}^{-2}$ across the divertor throat.

The energy deposition on the neutralizer plates has been measured with a thermocouple array located on the upper pair of plates (Fig. 21). The temperature profile from the thermocouples is in good agreement with time resolved infrared TV measurements of the neutralizer-plate surface temperature. Figure 34 shows the energy deposition profile on the plates for a standard-Dee discharge heated by a 2 MW beam for 200 msec. Approximately 50% of the total input energy flows

Figure 34. Energy flux to the inner pair of neutralizer plates for a standard-Dee discharge with a 2.1 MW beam injection for 200 msec. After subtracting direct beam power losses (reionization, sputtering through, charge-exchange) the total input energy for the discharge was 530 kJ and the flux to the plates was 330 kJ. (806911)

to the neutralizer plates and of this, 90% flows onto the plate on the large major radius side. During operation with the single null divertor configuration (Fig. 24), the deposited power became equally divided between the inner and outer plates.

Impurity Shielding and Plasma Fueling

A preliminary series of experiments has been undertaken to study the possible shielding of the PDX plasma by the divertor scrape-off from any influx of impurities from the discharge chamber walls. Nonperturbing quantities of silicon in atomic form produced by laser ablation of a thin film (incoming energy $\sim 5 \text{ eV}$, 300 μsec pulse) and in the gaseous form of SiH_4 (energy $\sim 0.02 \text{ eV}$, 25 msec pulse) have been injected from outside the discharge and the relative quantities of silicon entering the discharge have been measured spectroscopically. The ratio of the amount of silicon entering the discharge, normalized in each case to the amount injected, for the laser ablation and gas injection sources was found to be ≥ 8 , indicating shielding of the low energy particles.

The laser ablation technique has also been used to inject atomic scandium for studies of impurity transport. The first measurements have indicated an inward radial velocity for the scandium of 60 m/sec in the outer regions, $0.24 \text{ m} < r < 0.33 \text{ m}$, of the discharge.

There is a substantial difference between divertor and circular discharges in the gas feed required to maintain the plasma density, the diver-

tor discharges require up to an order of magnitude more hydrogen or deuterium. In Figure 35, the gas flow needed to maintain the given density in a hydrogen standard-Dee discharge is plotted together with the total particle loss rate from the discharge N/τ_p^* inferred from the initial rate of decay of the plasma density when the gas feed was abruptly terminated. Although the outflow remains fairly constant, the required influx rises with density, indicating that the discharge is shielded from the incoming gas. When the density is being increased by gas puffing during beam injection, the neutral gas pressure outside the plasma rises as high as 1 mTorr in divertor operation.

Figure 35. Gas inflow needed to maintain the given line-average density, and the particle loss rate N/τ_p^* for divertor discharges. (806945)

As an alternative to gas fuelling, injection of solid hydrogen pellets has begun on PDX using the gas-driven single pellet injector developed at Oak Ridge National Laboratory. Thomson scattering profiles of density and temperature with and without pellet injection are shown in Figure 36. More than 80% of the pellet charge penetrated the scrape-off and was deposited in the discharge. The pellet injection did not adversely affect the discharge or its stability.

Figure 36. Thomson scattering profiles of the temperature and density with and without injection of 1 mm diameter solid hydrogen pellets at a velocity of 800 m/sec into a standard-Dee discharge. The profiles were obtained on successive shots. (809138)

TFTR Limiter Tests

A series of some 200 beam-heated circular discharges was run in PDX using a prototype limiter for TFTR. The limiter was made of graphite coated with a layer of titanium carbide. The maximum beam power was 2 MW for a 200 msec pulse and the peak energy flux to the limiter was estimated to be 2 kW/cm². The effect on the limiter is being studied with various surface analysis techniques.

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The Spheromak

The name "spheromak" designates a spheroidal plasma confinement configuration advantageous for controlled fusion. The spheromak configuration is characterized by magnetic field lines that are closed, as in a tokamak, and by a coil-blanket topology that does not link the plasma, as in a mirror machine. The magnetic field configuration of the spheromak includes both toroidal and poloidal components, but the toroidal component is maintained entirely by plasma currents, and therefore vanishes outside the plasma. There are no external toroidal field coils that link the plasma. The outward pressure of the toroidal field and of the plasma is balanced by the inward pressure of the poloidal field.

The S-1 experiment will feature an electrodeless "slow" spheromak formation technique to produce a 500-kA plasma toroid, $a = 25$ cm, $R = 40$ cm. The formation scheme is based on a transfer of poloidal and toroidal magnetic flux into a plasma from a flux core.¹⁵ The recently built Proto S-1 device has successfully demonstrated⁵ the effectiveness of this PPPL-proposed spheromak formation scheme.

Development of the S-1 formation scheme (Fig. 37) was greatly aided by extensive two-dimensional resistive MHD simulations.⁶ An initial poloidal field is generated by a toroidal current inside a ring-shaped (toroidal) flux core, and is weakened on the small-major-radius side of the core by the superposition of an externally generated vertical field. The core also contains a toroidal solenoid, which generates a toroidal field in its interior. When the toroidal solenoid is energized, it induces a poloidal current in a sleeve-shaped plasma surrounding the ring. The associated toroidal field distends the poloidal-field sleeve, stretching it towards the magnetic axis where the poloidal field is weakest. As the toroidal core current is reduced through zero and "crow-barred" at a negative value, a large and increasing toroidal current is induced in the plasma. Magnetic reconnection of the poloidal field then occurs, and a separated plasma toroid, the desired spheromak configuration, is created and then held in the externally generated steady-state equilibrium field.

Major Activities

Proto-S-1

The machine configuration and the main components of the Proto-S-1 device are scaled down (1/6) versions of the main S-1 device. The flux core of 15-cm major radius and 3-cm minor radius contains the poloidal flux coil (PF, 3-turn toroidal winding) and the toroidal flux coil (TF, 40-turn poloidal winding). The core is covered by a 3-mil-thick stainless-steel metallic liner which provides a vacuum enclosure around the core and also tends to symmetrize the induced fields during the initial breakdown stage.

When the PF and TF coil currents are pulsed in an appropriate sequence, a plasma discharge is created. Framing-camera observations show that a few microseconds after the initiation of the TF current a plasma sleeve is created around the core, which then expands on its small-major-radius side and finally transforms into a localized plasma in the intended spheromak equilibrium position. Many plasma discharges have been made in H_2 , He, and Ar gases with best results obtained by filling the vacuum vessel with 20-50 m Torr of helium.

To demonstrate the formation of the spheromak field configuration, the time evolution of the highly reproducible magnetic fields was measured directly by movable magnetic probes (2-mm diameter, 20-turn loops). Fig. 38 depicts the evolving toroidal and poloidal magnetic fields at the midplane. The spheromak equilibrium configuration, with the toroidal field vanishing at the plasma edge and with the poloidal field reversing at some value of major radius R , is established 12-14 μ sec after the start of the plasma discharge (TF-current start). This fully formed configuration remains intact for about 12 μ sec. The time evolution of the toroidal field contours is shown in Fig. 39.

Following the establishment of the desired configuration, the spheromak plasma shrinks gradually to $R \approx 3-4$ cm, while the poloidal and toroidal fluxes trapped in the plasma decay by

QUASISTATIC FORMATION USING INDUCTION

Figure 37. S-1 Spheromak formation scheme. (806488)

resistive diffusion. At about $t = 25 \mu\text{sec}$, the sudden appearance of a nonuniformity in the framing camera pictures suggests the onset of a nonaxisymmetric instability.

0.5 sec. TC Discharge Starts
10.5 sec. TC - CRB

Figure 38. Time evolution of the magnetic field at the mid-plane; toroidal field (left) and poloidal field (right). $t = 0$ corresponds to TF current start. TF and PF currents are crowbarred at $t = 10 \mu\text{sec}$ and $t = 12 \mu\text{sec}$ respectively. (803815)

Plasma density and temperature were monitored by double Langmuir probes (voltage-swept) and CO₂ laser interferometry. For helium discharges, the plasma density, measured at $R = 5 \text{ cm}$ and $t = 16 \mu\text{sec}$, was $1.2 \pm 0.6 \times 10^{19} \text{ cm}^{-3}$, and the central temperature reached its highest value $25 \pm 5 \text{ eV}$ at $t = 15$ to $18 \mu\text{sec}$.

Computer simulation for the present spheromak formation experiment by a resistive two-dimensional MHD code⁶ shows good qualitative agreement with the experimental data.

In conclusion, the feasibility and effectiveness of the quasistatic S-1 spheromak formation scheme has been verified experimentally.¹⁷ The resultant spheromak configuration lasts about 15 – $20 \mu\text{sec}$ ($\sim 50 \tau_{\text{Alven}}$), which is a significant duration, since the classical magnetic diffusion time of the plasma ($T_e = 20 \text{ eV}$) is expected to be of the same order ($50 \mu\text{sec}$). Utilizing about $1/4$ – $1/3$ of the flux change from the core, the maximum toroidal and poloidal plasma currents are found to be roughly 20 kA and 50 kA respectively. Future experiments

Figure 39. Time evolution of toroidal field contours, at intervals of 100 gauss $t = 12 \mu\text{sec}$, $16 \mu\text{sec}$, and $20 \mu\text{sec}$. TF coil current is crowbarred at $t = 10 \mu\text{sec}$ (B1X2017).

on the main S-1 device are expected to provide more detailed information on the MHD-stability and transport characteristics of the spheromak configuration.

S-1

The S-1 design reported in the FY79 Annual Report was refined and improved in FY80. The pinch coils, for example, were found to be unnecessary and were eliminated and the axis of symmetry was rotated from vertical to horizontal to provide better access for diagnostics and auxiliary heating. The resulting configuration is shown in Fig. 40 and the major parameters are given in Table IV.

TABLE IV
Machine Parameters

R_{plasma}	0.4 meters
a_{plasma}	0.25 meters
I_{plasma}	0.5 MAmps
$R_{\text{flux core}}$	1.0 meter
$a_{\text{flux core}}$	0.19 meters
Toroidal flux swing 0.1 Volt seconds	
Poloidal flux swing 0.5 Volt seconds

Figure 40. Perspective view of the S-1 Spheromak (806659)

The heart of the S-1 device is the flux core shown in cross-section in Fig. 41. It contains the pulsed windings that induce both the toroidal (TF) and poloidal (PF) flux in the plasma. In addition, it contains a 2-turn winding which comprises a part of the equilibrium field (EF) circuit. These three sets of coils are wound on a glass reinforced (G-10) form which is covered by a thin Inconel vacuum tight enclosure (liner). This liner prevents out-gassing of insulating materials and is sized to allow the poloidal and toroidal fluxes to be expelled from the flux core.

The EF coil system has a variable field index capability ($-0.03 \leq n \leq +0.35$) enabling both prolate and oblate spheromaks to be produced. The prolate configuration is predicted to be tilt unstable, and the oblate tilt stable. The experimental program will investigate these configurations and test stabilization methods.

Detailed engineering designs were initiated early in FY80 and by year's end orders had been placed for the EF coil copper, energy storage capacitors, the ignitron switch tubes, the splinnings for the Inconel liner and the stainless steel domes for the vacuum vessel (Fig. 42). The fabrication program is scheduled to be completed in December 1982 with experimental operations starting in January 1983.

Smaller Devices

Experimental research on main-line devices — PLT, PDX, and the forthcoming TFTR — is supplemented at PPPL by investigations using a family of flexible smaller machines which lend themselves well to accelerated studies of novel techniques and concepts in controlled fusion. Included in this family are the alkali-metal-ion plasma Q-1 device (retired, at the year's end, after two decades of service), the QED arcjet linear, high-density plasma device, the steady-state linear high-magnetic-field H-1 machine, and the steady-state toroidal ACT-1 device.

Major Activities

Summary

A new concept which received experimental confirmation this year is the gaseous divertor, whereby the plasma diffusing away from the periphery of a fusion reactor chamber would be channeled into the divertor chamber, and de-ionized and collected there in a region of low-density neutral gas, rather than by hitting a metal collector plate. The new scheme avoids problems of excessive heat load and sputtering damage, but the critical question has been whether the outflowing plasma will be able to hold back the neutral gas, preventing it from flowing into the reactor chamber. A simulation experiment on the QED arcjet device has given a positive answer to this key question.

Several features of radio-frequency plasma heating are especially attractive to fusion physicists and engineers. In the ICRF mid-frequency range, the rf power levels needed for igniting a reactor are already state-of-the-art. Moreover, the possibility of waveguide coupling to the plasma within the reactor chamber offers a power-feed method almost impervious to neutron damage. However, propagation of rf power in the ion-cyclotron range of frequencies (ICRF) tends to require waveguide dimensions too large for practical reactor use. A recently proposed ICRF scheme would use ion-Bernstein waves for rf-power propagation in the plasma and, as a corollary, would permit the use of much smaller sized waveguides in the coupling unit. An important experiment on

the ACT-1 apparatus has verified that ICRF power can be efficiently propagated in the ion Bernstein mode, and that proper selection of parameters can cause this power to be absorbed, as desired, deep within the plasma.

A final topic in this overview of PPPL advanced-concept experiments is radio-frequency current drive. Successful operation of rf current drive would imply that a tokamak reactor could be operated in a steady-state mode, rather than pulsed, eliminating serious problems associated with repeated start-up and shutdown of the fusion plasma. Successful, albeit low-power, experiments on rf current drive were performed this year on both the H-1 linear machine and on the ACT-1 toroidal device. Preparations for ACT-1 experiments at the 100 kW rf-power level are almost complete and the coming year should provide the much awaited results of high-power operation.

Nonlinear Drift Waves and Anomalous Diffusion in Q-1

The presence of impurities in a plasma can drive drift waves into instability. The destabilizing mechanism is the viscosity of the impurity ions; the free energy to drive the instability is provided by their reversed density gradient. On the Q-1 device, experiments with cesium impurity ions injected into a potassium column of plasma have provided quantitative agreement for the linear characteristics of this observed instability compared to a local slab-model kinetic theory including collisions.

Experimental investigations over this past year have focused on the nonlinear evolution of this instability. By pulsing the impurity-ion injection, the development of the instability has been observed through the linear exponential growth phase into nonlinear saturation, where strong radially outward anomalous diffusion is driven by a wave-particle interaction. The anomalous diffusion coefficient, D_A , has been calculated from the observed response of the plasma density (Fig. 43). The excellent agreement between the observed D_A and the result of Dupree's nonlinear drift-wave turbulence theory,¹ D_D , gives strong

Figure 43. Anomalous diffusion coefficient, D_A , versus normalized wave amplitude, $\tilde{n}/n$. Data points represent $r = 4$ (± 1) mm; $1.7 \text{ kG} < B < 3.8 \text{ kG}$ (most are $B \approx 2.5 \text{ kG}$); $n \sim 10^{10} \text{ cm}^{-3}$; $0.5 < f < 0.9$; $z = 1, 30$, and 60 cm ; $m = 4$ (only mode present); $\tau = 2.67 \text{ msec}$; $\lambda_e = 3.5 \text{ cm}$. Curve labeled D_D is anomalous diffusion coefficient from Dupree's theory; straight line is large $\tilde{n}/n$ asymptote of curve. $D_B = cT/16 eB$ is Bohm diffusion coefficient. (809098)

support to the hypothesis that transverse ion trapping by drift-waves provides the mechanism both for enhanced diffusion and for amplitude saturation.

The implications for impurity transport in a tokamak are that the drift-wave fluctuations at the plasma edge can drive strong anomalous diffusion of impurity ions, which may explain the non-neoclassical recycling of impurities at the edge. In fact, the drift-wave fluctuations causing the anomalous transport may themselves be destabilized by the impurity ions.

The H-1 Linear Test Plasma Radio-frequency Current Drive

Two aspects of lower hybrid heating were explored in 1980 on H-1. In the first, electrostatic waves generated by ring exciters at 50-100 MHz drove directed electron currents in collisionless as well as collisional plasmas. Currents on the order of 100 mA were driven in a "hot" helium plasma (approximately 11 eV) at power levels of approximately 100 W. Current saturation at a drift velocity corresponding to the ion sound speed, expected in linear plasmas, was observed. The frequency and wavenumber dependence behavior expected for the current drive were verified.

Ponderomotive Cratering

A second nonlinear experiment on H-1 studied lower hybrid wave excitation at power levels approaching 1 kW/cm^2 , about 20% of that planned

for lower hybrid heating on PLT. Operation at full power witnessed a sharp rise in waveguide reflection — up to approximately 40% within 40 μsec after pulse initiation. Detailed probing revealed that, on this same time scale, a localized plasma crater (Fig. 44) formed within 5 mm of the mouth of the waveguide. The calculated rf electric field at full power was 1.4 kV/cm . The rf pressure from the applied field is sufficient to account for the observed density crater by ponderomotive pressure. This phenomenon will place an upper limit of approximately 5 kW/cm^2 to the power flux that can be passed through the surface layers of a tokamak plasma.²

Figure 44. Top trace: RF signal $\propto E_z^2$ measured 2-3 mm from the waveguide in the surface plasma. Probe was 1 cm above midplane. Bottom trace: time evolution of the density crater formed by an 8 kW lower hybrid pulse. The probe was moved along a trajectory identical to that in the top trace. (803650)

A Novel ECRH Antenna

In electron cyclotron heating of plasmas, there is a long-recognized difficulty in the use of antennas placed at the outside of a torus. Ordinary-mode radiation ($\vec{E} \parallel \vec{B}_0$) does not interact unless the plasma is hot and dense. Extraordinary mode radiation, on the other hand, is reflected from a region well outside the natural absorbing layers. Work on the H-1 device has led to the development of a hybrid system in which radiation in the ordinary mode is beamed from the outside of the torus. Waves not absorbed on the first pass are reflected from a corrugated reflector (Fig. 45). If the polarization of the incident rays is oriented at 45° with respect to the axis of the corrugations, the polarization of the reflected signal is rotated by 90° . Therefore the reflector, placed on the inside (small major-radius side) of the torus, serves as a secondary source of extraordinary mode radiation. Since the reflected radiation propagates

Figure 45. Passive mode converter to be placed on the inside of a plasma torus. If the incident ordinary mode ($\vec{E} \parallel \vec{B}_0$) is polarized at 45° with respect to the direction of the triangular troughs, the polarization of the reflected signal rotates by 90° and the wave propagates in the extraordinary mode to the absorption resonance at $\omega \approx \omega_{ce}$. (806171)

into a region of increasing magnetic field, the absorbing ECR layers are now accessible, so that the plasma is heated on the first bounce.³

Experiments on the Steady-State ACT-1 Toroidal Device

ACT-1 (Advanced Concepts Torus-1) is a steady-state, 5.6 kG toroidal device designed primarily for studies of radio-frequency heating and current generation. It produces a toroidal plasma with minor and major diameters of 20 cm and 118 cm respectively. The machine construction was completed in August 1979 and it has been in operation for one year. Research on ACT-1 is presently concentrated on lower hybrid waves and ion cyclotron waves and some of the highlights are described in the following.

Current Generation of Lower Hybrid Waves

Standard tokamaks are capable only of pulsed operation, since the toroidal plasma current is driven by an inductive method. Obvious advantages of a steady-state tokamak reactor include a longer first-wall life due to the absence of cyclic thermal stresses, elimination of a thermal storage system for continuous power production, and removal of the ohmic heating coils. In principle, a steady-state current can be driven by radiofrequency waves, and a low-power rf current-drive

experiment has been carried out in ACT-1. Up to 10 amperes of current were driven by 500 watts of unidirectional lower hybrid waves at 160 MHz.⁴ As expected, the direction of the wave determines the direction of the current as shown in Figure 46. It was found that the current generation efficiency could be substantially improved by adding a small vertical field (approximately 1.5 G) which confines the current-carrying electrons that resonate with the wave. Because of these encouraging results, the power level is being upgraded to 100 kW to drive currents in the kiloampere range.

Ion-Bernstein Waves

Ion-Bernstein waves are investigated in ACT-1 to develop a reactor heating concept using waveguides that operate in the ion cyclotron range of frequency (60-150 MHz) where rf high-power sources are readily available. Ongoing theoretic-

Figure 46. (a) Integrated Rogowski-loop signal for current measurements. (b) Current generated by a 200-watt, 120- μ sec rf pulse with $\vec{v}_g \cdot \vec{B}_0 > 0$ ($\vec{v}_g$ denotes the group velocity of the wave). Top trace shows the rf pulse and bottom trace shows the Rogowski loop signal. (c) $\vec{v}_g \cdot \vec{B}_0 < 0$. (803627)

cal⁵ and experimental⁶ investigations show encouraging results which scale very favorably to reactor parameters. The waveguide-coupling calculation indicates a natural matching of more than 90% power transmission without active tuning elements, reducing the electric field inside the waveguide to a tolerable level during the anticipated high-power rf heating. Wave accessibility and absorption calculations⁵ show that a mode-transformation into a weakly-damped ion Bernstein wave significantly enhances the wave penetration into the reactor plasma core, and proper placement of the ion cyclotron harmonic resonance layer results in efficient wave power absorption.

In an ACT-1 hydrogen plasma ($T_i \approx 1-2$ eV), the physics of wave excitation, mode-transformation, and propagation have been investigated in detail.⁶ Experiment has confirmed that the finite-ion-Larmor radius mode-transformation process near the lower-hybrid resonance layer ($\omega \approx \omega_{UH}$) results in a strong excitation of $\omega \approx 2\Omega$ ion Bernstein waves, in excellent agreement with theory. Figures 47(a) and (b) show the measured interferometric patterns of the excited ion-Bernstein waves and the resulting wave dispersion relation. Fig. 47(b) demonstrates the backward propagating nature of the ion Bernstein wave where the radial phase front moves toward the antenna in a direction opposite to the group velocity, while Fig. 47(c) displays the experimental (points) and theoretical (solid curves) dispersion relations for various ion temperatures.

CO₂-Laser Scattering Experiments

Wave detection in the ACT-1 experiments is presently carried out with probes which cannot be used for wavelengths shorter than 1 mm. A CO₂-laser scattering setup has just been installed to detect density fluctuations associated with waves. This nonperturbing technique, which can measure wavelengths in the range of 0.01-1 cm, will be used to investigate linear mode conversion in lower-hybrid waves. Also, CO₂-laser scattering off externally-launched ion Bernstein waves may lead to a new diagnostic technique to measure hydrogen ion temperatures deep within fusion plasmas.

Nonlinear Wave Experiments on the L-3 Linear Device

The L-3 is a steady-state 2 kG linear device built for nonlinear wave studies. It is 4 meters long with a 10 cm plasma diameter. Nonlinear effects can play an important role in high-power rf heating experiments, particularly in the lower hybrid wave heating of tokamak plasmas. Detailed investiga-

Figure 47. (a) Interferometer traces. Parameter on each curve is ω/Ω_{UH} ($r = 2$ cm), $f = 12-13$ MHz, $B_z(r = 2$ cm) = 4.3 kG. (b) Interferometer trace for various time delays, Δt . Parameter on curves is $\omega \Delta t/2\pi$. Wave dispersion relation. Dots are experimental points and solid curves the theoretical values obtained for various ion temperatures. $p_e = 7.0 \times 10^6$, $n_e = 10^{20}$ cm⁻³. (803746)

tions of nonlinear wave propagation,⁷ coupling⁸, and parametric decay⁹ of lower hybrid waves have been carried out and the results are in good agreement with theory.

The L-3 will be phased out in FY81 to make room for another device.

Simulation on the QED-1 Device of Gaseous-Divertor Operation

In an operating steady-state fusion reactor, plasma from the periphery of the reaction chamber (including fusion-product helium ash) will be channeled out to a divertor chamber, neutralized, and partially pumped away. A conventional divertor, using a metal collection plate, would experience substantial heat load and sputtering damage. In the Gaseous Divertor concept,¹¹ a

low-density neutral gas, rather than a solid plate, will be used for collecting and deionizing the scrape-off plasma. The major question for the gaseous divertor concept is whether the scrape-off plasma flowing toward the divertor chamber can hold back the low-density gas used in the collector region. A simulation experiment on the QED-1 device has given an experimental answer to this critical question: yes.

The QED-1¹² (Quiet-Energetic-Dense) device produces a hot ($T_e \approx 1\text{--}10\text{ eV}$) isothermal, current-free plasma. In this machine, a plasma column of 1-2 cm diameter comes out of an arcjet plasma gun and streams along the QED-1 main-section magnetic field into a burial chamber, where the plasma recombines and where the resulting neutral gas is pumped away. High-speed differential pumping ensures a low background pressure in the experimental region, and thus a uniform plasma. Plasma densities of $n_e = 10^{12}\text{--}10^{15}\text{ cm}^{-3}$ and temperatures $T_e = 3\text{--}10\text{ eV}$ have been obtained for various gas discharges, i.e., hydrogen, deuterium, helium, and argon. The flowing QED-1 plasma lends itself to the investigation of particle and heat transport in a simulated divertor scrape-off regime, and provides data on particle getting, plasma collection, sputtering yield, and plasma-neutral gas interaction.

Plasma — Neutral Gas Interaction

The gaseous divertor concept is a viable alternative for future divertor design if neutrals can collect and deionize the plasma while simultaneously being prevented, by the incoming plasma, from diffusing out of the divertor chamber into the reactor region. In the QED-1 simulation experiment, both of these effects have been confirmed. When neutral and plasma pressures are comparable, a stable stationary deionization region is formed. The position of this region can be shifted either by increasing the neutral or the plasma pressure. The QED-1 experiment also shows that the flowing plasma can support a high neutral-pressure gradient, with a factor of approximately 10 increase over the no-plasma case.¹³ In Figure 48, the pressure profiles of neutral H and He are plotted along the length of the divertor with H plasma flowing from the right. When the plasma temperature upstream is raised, the neutral pressure difference is also increased. The pressure gradients are much larger than those in the absence of the plasma, verifying the occurrence of interaction between the plasma and the neutral gas. Because the cross section for charge exchange is large compared to that for ionization, we conclude that the dominant interaction is between ions and neutrals.

Figure 48. Profiles of neutral pressure along the divertor axis. Plasma of density $n_e \sim 5 \times 10^{13}\text{ cm}^{-3}$ flows in from the right. Upstream T_e is indicated on each curve. (803739)

The important atomic processes in this experiment are charge exchange, ion-neutral elastic collisions, ionization, and recombination. The first three are mechanisms for plasma energy loss and the first two are mechanisms for momentum transfer from ions to neutrals. Energy loss reduces the plasma temperature until recombination dominates, causing the plasma to deionize. Momentum transfer exerts a frictional force on the neutrals, maintaining the necessary pressure gradient.

Simulation of the He Enrichment Scheme

Also investigated in QED-1 was the concept of He enrichment, in which the decay length of He neutral gas pressure can become shorter than that of H in the scrape-off region. In a fusion reactor this phenomenon can serve to refuel deuterium/tritium while, simultaneously, helium ash is pumped out. This He enrichment can occur because of the large charge exchange cross section between H^+ and He^0 in the scrape-off region (i.e., in the connection regime between the main plasma and the divertor). In one phase of the divertor-simulation experiment on QED-1, extra hydrogen neutral gas was backed into the divertor chamber. Under this condition, the decay length of helium pressure toward the main plasma was measured to be shorter than that for hydrogen. Further study is currently underway, following up on this encouraging preliminary observation of helium enrichment.

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Theory

Theoretical research will continue to play an important role in the magnetic fusion research program of the 1980's. This program will have two central features: (1) the design and construction of a Fusion Engineering Device (FED); and (2) aggressive fusion research aimed at optimizing the tokamak configuration as well as assessing the promise of various alternative fusion concepts such as spheromaks, reversed field pinches, and stellarators. Theoretical work will be needed in both areas.

Theoretical research in support of a Fusion Engineering Device entails both invention of new design options and evaluation of the many trade-offs that must be made. This work must be firmly based on well-understood and experimentally verified theoretical principles in order that extrapolations from current experiments to the Fusion Engineering Device can be made quantitatively and with good confidence. The paragraphs below report new work on disruptive instabilities, nonlinear ballooning modes, drift waves, ergodicity, and lower-hybrid heating. All these areas bear directly on the physics of a Fusion Engineering Device. Recent work on the physics of driving steady-state currents in tokamaks has shown the possibility of achieving steady state tokamaks using ion-cyclotron (40 MHz) or electron cyclotron (110 GHz) energy sources, thereby adding a new design option for future large tokamaks.

The tokamak configuration may or may not emerge as the most promising for a magnetic fusion reactor. Among the tokamak's liabilities are the engineering difficulties associated with a low value for the aspect ratio (needed to achieve high plasma pressure), and the disruptive instability. The PPPL Theory Division is, therefore, investigating other toroidal magnetic configurations which avoid one or more of these liabilities. Our recent work on spheromaks, reversed-field pinches, and stellarators builds our knowledge of the strengths and weaknesses of these configurations *vis-a-vis* the tokamak.

Major Activities

Causes of Major Tokamak Disruptions

Major disruptions present perhaps the most serious design problems for reactor size tokamaks.¹ Because of the large energy (~300 MJoules), a disruption in a device of the size of the International Tokamak Reactor (INTOR) could produce vaporization of kilograms of wall material if the deposition were spatially localized, in addition to serious thermal wall stresses and coil stresses.

There now exists a fairly large body of experimental data which indicates that the major disruption is associated with the development of a large $m/n = 2/1$ magnetic island, where m, n refer to poloidal and toroidal mode numbers. The disruption itself may be caused by either the $2/1$ mode becoming large enough to destroy magnetic surfaces by overlap with a $3/2$ island, or by contact of the $2/1$ island with the limiter. Knowledge of the time history of the current density profile immediately preceding disruptions can reveal the mechanism through which confinement is destroyed. In a strongly sheared magnetic field, magnetic islands saturate at a narrow width and are thus fairly innocuous. But in a flat current profile, with q on axis > 1 , the state of minimum magnetic energy is one with a rather large island.

Fig. 49 shows a radial extent of the $2/1$ and $3/2$ islands as a function of q_0 and the value of q at the limiter, for four values of $q(0)$ with a moderately flat current profile. These widths are obtained from a relatively simple quasilinear theory for the development of a single island state. It is clear that this analysis cannot predict the complicated nonlinear behavior expected when islands of different helicities overlap, but it can be used to discover whether or not overlap is expected, and it can be done rapidly enough to monitor an actual experiment.

Figure 49. Magnetic island with versus q_e for four values, $q(0)$. (802133)

As more experimental data becomes available, this method should give a clear resolution of the necessary and sufficient conditions for disruption.

Nonlinear Ballooning Modes

The nonlinear behavior of ballooning unstable plasmas is expected to be an important consideration in high- β reduced (large aspect ratio) tokamak equations. Only modes with low toroidal mode number n are perturbed initially. In the nonlinear phase, sharp current sheets form in the plasma. At this stage, the calculation normally breaks down. However, by introducing an artificial field into the problem, the sharpness of the current sheets can be limited, and a 3-dimensional equilibrium can be obtained. The artificial field is an independent field which behaves exactly like the real magnetic field. The true final equilibrium state then can be determined by reducing the artificial field to zero. This method was first used to study the current singularity in the nonlinear internal kink², and the convergence study showed that the current sheet indeed becomes singular as the artificial field is reduced.

Fig. 50 shows a 3-D equilibrium state obtained with the small artificial field included. The poloidal magnetic function A , pressure P , and toroidal current density J are shown on three poloidal planes at toroidal angles $\psi = 0, \pi/2$, and π , respectively. The pressure contours which move with the plasma show a large shift while the A contours change very little. Note the sharp current spikes at $\psi = 0$ and π . As the artificial field is further reduced, the profiles remain about the same, except the current peak becomes much steeper.

The current singularities resulting from the nondissipative model indicate that the ideal ballooning modes do not saturate with a regular pro-

file. Instead, the ordering assumed will eventually break down and the resistive effects will become important.

Figure 50. Contour plots of the poloidal flux function A and pressure P at various toroidal angles ψ . The current density J on the equatorial plane (the heavy line in the contours) is also shown. (802214)

Integral Equation Analysis of Drift Wave Eigenmodes in a Sheared-Slab Geometry

The investigation of the stability of drift waves in a sheared-slab geometry has been actively pursued in numerous recent publications. In particular, it has been shown that the drift wave is actually marginally stable or damped, when it was believed for many years that the drift wave was unstable. However, these calculations have dealt with long radial wavelength eigenmodes. At shorter radial wavelengths it becomes necessary to deal with an integral equation.³ In recent work at PPPL, this generalized equation has been solved by means of a Ritz method, where the unknown function $\phi(x)$ is expanded in terms of basis functions to convert the integral equation into a matrix equation. Although a comparison between eigenfunctions generated by the differential and integral equation methods show quantitative differences, the integral formulation has never yielded an instability when the differential formulation yielded a marginally stable or damped mode, provided that a sufficient number of basis functions are employed for numerical accuracy.

One of the interesting problems of nonlinear dynamics is that of understanding how simple, deterministic equations can yield apparently random solutions.⁴ A better understanding of this phenomenon could be useful in the fusion effort since many of the fundamental equations that model fusion systems are deterministic, and stochastic behavior is an important part of the physics of such devices.

Hamiltonian systems with a small number of degrees of freedom provide one of the simplest examples that exhibit this kind of behavior. The area-preserving mappings of two-dimensional surfaces onto themselves are in turn the simplest models that retain the character and complexity of Hamiltonian systems. It is such mappings that have been studied in the work described here. One example of such a mapping is generated by following magnetic field lines from one traversal of a cross section of a toroid to the next traversal. This is the standard way of generating magnetic surfaces in a toroidal configuration, and physically corresponds to the orbit of an electron which follows the magnetic field precisely.

There are, in fact, three types of orbits: (1) Periodic orbits, whereby after a finite number of traversals around the torus, the electron returns to its initial position and velocity. Such orbits correspond to rational magnetic surfaces; (2) stochastic orbits, whereby the electron orbit randomly fills an area in the poloidal plane; (3) a theorem of Kolmogorov, Arnold, and Moser (KAM) established the existence of orbits that fill a line in the poloidal cross section, the irrational magnetic surfaces (called KAM surfaces in nonlinear dynamics).

It is apparent from numerical work that KAM surfaces do not exist for nonaxisymmetric magnetic perturbations larger than a critical value. Such a perturbation could signal the sudden connection of field lines from the inner regions to the outer regions.

The previous method for estimating the critical perturbation size is known as the overlap of resonances. An example is found in the discussion of disruptive instability. It can give reasonable results with errors of less than a factor of two but does not lend itself to further refinement. In the present work a different tack is taken, and the stability of periodic orbits close to a given KAM surface is studied. The relation between the stability of these orbits and the overlap of resonances has been studied by numerical work which establishes a close connection between the existence of KAM surfaces and the stability of nearby periodic orbits. The KAM surfaces exist only when the nearby orbits are stable. This is an intuitively

reasonable picture and leads to a criterion that can be evaluated and refined to arbitrary accuracy.

Nonlinear Coupling Calculations for Lower Hybrid Heating

The advantages of plasma heating in the lower hybrid frequency range are several: (1) For plasma densities typical of toroidal confinement devices, the lower hybrid frequency lies in a range where large amounts of power can be generated with currently available technology. (2) The plasma impedance is comparable to the impedance of free space. Therefore, efficient coupling is possible in principle with relatively simple launching structures. (3) The size of the launching structure, which is comparable to the free space wavelength by virtue of (2), is substantially smaller than the plasma size in current large tokamaks. (4) The wave can, in principle, be efficiently absorbed by several collective plasma processes.

Efficient coupling of external sources to lower hybrid waves demands a structure which generates a parallel electric field $E_{\parallel} = \mathbf{E} \cdot \mathbf{B}_0/B_0$, with most of its spectral content in the region $n_{\parallel} - k_{\parallel} - C/\omega > 1$. Current emphasis in most high power experiments has been placed on phased rectangular waveguide arrays in which each waveguide is driven in its fundamental mode and phase shifts between adjacent guides generate the slow wave spectrum. The linear theory describing the coupling between such structures and an inhomogeneous plasma has been developed in detail and confirmed experimentally on a small linear plasma device.

Our contribution extends these calculations to the nonlinear regime where power fluxes are large enough so that the wave pressure becomes comparable to the plasma pressure in the coupling region. This "ponderomotive" pressure, localized to the region in front of the guides, pushes the plasma along the field lines away from regions of high field intensity, thereby creating cavities in the density in just the region most important to the coupling. Previous treatments have attempted to analyze this process via 1-dimensional models, which clearly have their shortcomings in view of the pronounced two-dimensional structure of the nonlinear density profile found from our computations (Fig. 51).

These results are in reasonable quantitative agreement with more recent high power experiments on the linear H-1 device, and indicate that the reflection coefficient at the coupler-plasma interface is much less sensitive to waveguide

phasing at high power than predicted on the basis of linear theory.

Figure 51. Sample surface plot of the density in front of a two-waveguide array. (802458)

Current-Drive by ECRH and ICRF Heating

The operation of a tokamak is dependent upon the maintenance of a toroidal electric current. For a fusion reactor based upon the tokamak concept to become an economic reality, this toroidal current must be produced both cheaply and in long pulses. Long pulses are required in order to limit the metal fatigue arising from the heat stress to which the structural components of the tokamak are subjected in a pulsed device. Recently, two new methods have been proposed to drive continuously the toroidal current.⁵ One method utilizes rf waves in the ECRH range of frequencies; the other utilizes waves in the ICRF frequency range.

The first method employs electron-cyclotron waves to increase the gyroenergy, but not necessarily the parallel energy, of electrons moving in one direction parallel to the magnetic field. The electrons accepting this energy collide less frequently with the ions than previously, so that an asymmetry develops, with the electron population moving on average in the direction of the less collisional electrons. By momentum conservation, the ions must drift in the opposite direction.

The advantage of driving current in this manner is that electron-cyclotron waves may be easily brought into the tokamak to interact with relatively high velocity, and hence collisionless, electrons, which are the most efficient current carriers. It is reasonable that the waves could be absorbed entirely by electrons with velocities about four times

the thermal velocity. In the medium size D-T fusion reactor, operating at an average temperature of 20 keV, the current could then be carried at a power cost of about 3% of the fusion power output.

The method utilizing the ICRF range of frequencies relies upon the presence of a minority ion species. Minority ions traveling in one parallel direction are heated by the rf waves, resulting in a relative drift between the two ion species, much in the same way that ECRH induces a drift of electrons relative to ions. The idea here is that the ion species have disparate ion charge states so that the electrons drift with the more collisional (higher charge state) species. The resulting current can be maintained with an efficiency approaching that of the other steady-state methods if the minority charge state is large enough.

Modular Torus With Twisted Toroidal Field Coils

A modular stellarator configuration utilizing properly shaped toroidal field coils has important advantages as a reactor over a tokamak or conventional stellarator. Since there are no continuous helical windings, the entire magnetic configuration can be set up by a single coil system. Figure 52 shows a model of a twisted coil system. An analysis of the forces on the coils indicates that there is no inwardly directed force. Thus, the support structure can be located outside the coils. This, together with the modularity, greatly simplifies construction and maintenance. Access to the blanket and reactor core is improved. The MTT can be operated in steady state. Since no ohmic heating current is required for equilibrium, the device should not be plagued with disruptive instabilities.

The PPPL Theory Division has investigated coils with both "twists" and "warps". The rotational transform profiles generally show the

Figure 52. Model of coils for a modular stellarator with twisted coils. (802131)

transform to be increasing with radius until $r/a \sim 0.6$, where flattening occurs followed by a decrease due to the increasingly important negative contributions of the higher modes in the Fourier series representation. Transforms of $i/2\pi \sim 1$ can be obtained for typical parameters.

Formation and Stability of Spheromak Plasmas

The S-1 Spheromak, now under construction at PPPL, employs novel methods of plasma formation as described in an earlier section of this report. A sophisticated axisymmetric resistive MHD code has been developed⁶ to model these formation processes including interaction back on the external circuits. This code shows that the magnetic reconnection processes necessary to separate the spheromak plasma from the ring will spontaneously take place. As a consequence, the "pinching coils" of the original S-1 design are superfluous and have been eliminated from the present design.

One of the most troublesome and fundamental instabilities of the spheromak configuration arises from the tendency of the plasma to tilt so as to align its magnetic moment with the externally imposed equilibrium field. The free energy driving this instability is large, arising from the interaction of the toroidal plasma current with the currents in the external field coils. The global, almost rigid nature of the instability makes stabilization due to magnetic shear or finite gyration radius effects seem unlikely.

Analytic studies of this mode have been confined to treatment of small departures from a spherical configuration or to cylindrical models. Since the mode could have serious consequences, it is important to understand its parametric dependence on the plasma shape, size of the central flux hole, the presence or strength of an external toroidal field, the q -profile, and the extent to which conductors in the vacuum region can provide stabilization. The application of linear ideal MHD stability programs to numerically generated equilibrium solutions should provide this understanding.

A typical spheromak result is given in Fig. 53, where the growth rates for $n = 1$ modes are given for a low- β device with q varying from 1.0 at the axis to 0.01 at the plasma surface as functions of the shape of the plasma cross section. For a classical spheromak plasma with a small flux hole, the system is unstable with respect to a tilting mode which is primarily a superposition of $m = \pm 1$, $n = 1$ modes of equal amplitude but of opposite phase. As the plasma shape becomes oblate, the

growth rate of this mode decreases, but at some point a second, shifting, instability sets in. This shifting instability is essentially a rigid horizontal translation of a superposition of equal amplitude $m = \pm 1$, $n = 1$ modes with the same phase. As the plasma is made more oblate, the growth rate of the shifting mode continues to increase while the tilting mode growth rate decreases and finally becomes stable.

Figure 53. Free boundary, $n = 1$ mode in a force-free spheromak with q varying from 1.0 at the magnetic axis to 0.01 at the plasma surface. The shape of the surface is denoted by δ as shown. (B02374)

These results were obtained without the presence of a conducting shell. It is clear that placing a perfectly conducting wall just outside the plasma should provide stabilization. The geometry of the spheromak necessitates that such a

shell give rise to topologically spherical boundary conditions rather than the usual toroidal ones in the vacuum region. The shell must be fairly close, on the average, so that the eddy currents generated in the shell can affect the bulk of the plasma. For the configuration denoted by $\delta = 2$ in Figure 53, a spherical wall of average distance 0.7 minor radii from the plasma will provide stabilization. Increasing the flux hole or aspect ratio allows the stabilizing wall to be 1.2 minor radii.

The possibility of providing stabilization by a purely vertical or a purely horizontal wall has also been investigated. The tilting instability is stabilized with either of these with almost equal effectiveness, while the shifting instability is more easily stabilized by a horizontal wall.

Effects of Impurity Radiation on Reversed-Field Pinch Evolution

Both spheromak and reversed field pinch plasmas depend on ohmic heating to raise the plasma temperature past the peak of the radiative cooling caused by the presence of oxygen impurity atoms. The peak of this cooling curve lies near $T_e \approx 25$ eV. Two conditions must be satisfied for this to occur. First, the ohmic heating power must exceed the maximum cooling rate. Second, the en-

ergy expended in heating the plasma to a temperature $T_e \sim 40$ eV, must be a small fraction of the magnetic energy stored in the poloidal magnetic field or else a serious erosion of the poloidal field will result. The first criterion is evidently one involving impurity concentration, plasma density, and current density. The second criterion involves device size and plasma density.

A transport code for reversed-field pinches, which embodies classical transport and impurity radiation losses, has been developed and applied to the three devices: ZT-S and ZT-40 which are at Los Alamos Scientific Laboratories (LASL), and RFX, a future experiment in the United Kingdom.

Our results show that ZT-S had much too high a density (or was too small a device) to break through the radiation barrier. The ZT-40 device is predicted to work well for oxygen concentrations below 0.4%, but to experience grave difficulties at 1.6% (given an assumed density of 5×10^{14} cm⁻³). The RFX parameters produce a successful device at 2% oxygen impurity concentration due to a low density.

Clearly, oxygen impurity radiation cooling remains a key issue for reversed-field pinch and spheromak devices.

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Tokamak Fusion Test Reactor (TFTR)

The primary objectives of the Tokamak Fusion Test Reactor (TFTR) are the generation and confinement of 5-10 keV reactor-grade plasmas in the tokamak magnetic-field configuration, and the production of fusion energy, on a pulsed basis, from the reaction of deuterium (D) and tritium (T). The TFTR will be used to study the physics of burning plasmas and the engineering aspects of a D-T burning tokamak operating with reactor-level plasma conditions. The overall TFTR program is intended to produce scientific and technical information, component hardware, and the experience necessary for the future design, construction and operation of experimental fusion power reactors.

Major Activities

All major TFTR machine components have been ordered from approximately twenty domestic and foreign vendors. These components include: motor generator sets; toroidal and poloidal field coils and coil cases; machine superstructure; vacuum vessel; neutral-beam injectors; and various power systems.

Progress during FY80 centered on facility construction, component manufacturing and installation. Construction of the experimental complex is proceeding as planned; three of the four walls of the test cell are completed and installation of the substructure continues (Fig. 54). The test cell and the hot cell/neutral-beam test cell will be ready for occupancy in 1981. Cables and equipment are being installed for the below-ground level of the neutral-beam power conversion building. Installation work for the motor generator building and field coil power conversion building continues. The two 350-ton stators were completed and installation was initiated.

TFTR Flexibility Modification

The objective of the TFTR Flexibility Modification (TFM) is to extend plasma performance of the tokamak. The original scope called for a fourth neutral beam, increasing the pulse length (to 1.5 sec) of all four beams, adding a first wall to the vacuum vessel, gettering for impurity control, and

Figure 54. TFTR construction site. (804829-22)

increased maximum beta. During FY80, additional responsibilities of providing updated radiation shielding and preparing a lithium blanket experiment were added to the original scope of the TFM program.

At the beginning of FY80, both titanium (Ti) sublimation and zirconium/aluminum (Zr/Al) bulk gettering (gas-absorbing) systems were being designed. Later, however, certain experiments in PDX and input from the actual design of these systems made it clear that only the Zr/Al system should be pursued. This decision was based more on the practical needs of TFTR than on any clear superiority of the Zr/Al system over the Ti system. It should also be noted that additional impurity control research and development has led to the preliminary decision to use TiC coated POCO graphite tiles for the first wall.

In the design of the first wall, which is comprised of bumper limiters, movable limiters, protective plates and bellows coverplates, plasma disruption scenarios were adopted from which disruption loads were calculated. In addition to the normal plasma heat loads, the first wall is subjected to neutral beamline shine-through. These loads have presented one of the major engineering challenges thus far encountered in the TFM project and have led to a two-phase approach. The first phase will first provide a set of protective armor adequate for the operation of TFTR with ohmic heating only (and possibly one beamline). The second phase will provide for full TFM capability.

During FY80, TFM undertook and completed the conceptual design of an ion cyclotron range of frequency (ICRF) heating system compatible with the requirements and the available facilities of TFTR.

The Lithium Blanket Module (LBM) is an experiment, managed by TFM and funded by The Electric Power Research Institute (EPRI), which will develop a prototype tritium breeding blanket. It will be about one meter square and will fit into one of the TFTR bays. A further description is in the section on the TFTR Blanket Module Experiment.

Safety

A system was developed and approved for the generation of Operations Safety Requirements that define the conditions, safe boundaries, and management controls necessary for safe TFTR operation.

As a result of the Laboratory's evaluation of surface pumping and a corresponding increase in tritium inventory, the safety groups performed calculations to determine the worst case doses at the exclusion zone boundary (EZB) for various accident scenarios involving the release of tritium. In no case was the EZB dose higher than a fraction of DOE dose criteria for TFTR.

A failure analysis of the control electronics for the TFTR gas injection system was performed for various loss-of-power scenarios. It was concluded that from the safety viewpoint, emergency power is not required for this system.

A significant portion of the Final Safety Analysis Report has been prepared, and the completed document is scheduled to be submitted to DoE by December 31, 1980. It must be completely reviewed and approved by DoE prior to the initiation of TFTR experimental operations.

Vacuum Vessel

The vacuum vessel being fabricated by Chicago Bridge and Iron is now approximately 60% complete. Almost all of the twenty subassemblies have passed through the initial fabrication phase, i.e., rough machining, diagnostic port and neutral-beam duct nozzle forming (Fig. 55), internal bracket installation, heating/cooling jacket closure-bar forming, and all shell welding and post weld heat treatment. The second phase is now underway and consists of final machining, dielectric joint assembly, bellows installation, vacuum testing and heating/cooling jacket fabrication. The dielectric joint installation is complete on two subassemblies and one subassembly is fitted with a bellows (Fig. 56).

Figure 55. Neutral beam nozzle fitted and welded to vacuum vessel section. (804618)

Delivery of virtually all of the material that is required by Chicago Bridge and Iron is on schedule. This includes the stainless steel plate and forgings, high strength fasteners, tritium nut plates, dielectric material (polyamide PMR-15), vacuum testing equipment, Inconel 625 bellows and heating/cooling system dielectric joints.

Figure 56. Optical survey of "C" segment subassembly (804619)

Other vacuum vessel equipment has been designed and ordered, including the seals and limiter actuators. The final design of the diagnostic port high vacuum seals has been established and calls for a dual metal seal with an integral compression limiter between them.

The limiter actuator "fabrication and test" contract was placed with Lamco Industries, Inc. The actuator was modified to incorporate a new feature where cooling tubes will pass through the center of the actuator. These tubes will supply coolant to the limiter blade, reducing the blade

operating temperature area and, thus minimizing plasma impurities.

Experimental Area Systems

Installation and Assembly Engineering and Remote Handling

Work has shifted to the development of assembly tooling and preparation procedures for initial assembly operations. Work on the remote systems included an update of the already completed specifications for the bridge mounted manipulator, and the completion of the in-vessel manipulator specification.

Approximately 50% of the installation and assembly procedures were completed in preliminary form.

Tritium and Nontritium Gas Systems

Tubing and component installation within the tritium storage and delivery system glovebox was completed, and component testing has been initiated.

The large piezoelectric valve design was reviewed, and fabrication for TFTR usage has begun. The valve was successfully tested at the Mound Facility.

In order to control gas injection (tritium and nontritium), a microprocessor will be utilized.

The vendor of the tritium cleanup system, CVI Corporation, has completed the redesign of the tritium vault cleanup system skids. Vessel fabrication has been initiated and component procurement continues.

A contract was negotiated for the process tritium monitors, but procurement has been deferred until FY82.

The non-tritium gas delivery system was awarded to Amer Industrial Technologies, Inc. The PPPL vacuum shop has been selected to build the gas injection valve assemblies, both for tritium and nontritium use.

Cooling Water Systems

Installation of all major equipment for the cooling water systems has been completed.

Electrical Buswork

Designs were completed for the dc bus bars that will supply energy to the poloidal and toroidal field coils. The designs include definition of conductor configuration, size, supports, insulator system, and bus joints.

Detailed electrical, thermal and mechanical calculations were made to demonstrate the adequacy of the bus system.

A specification delineating the bus bar requirements was issued to industry for bids, and the order was placed with Gran-Cal. The bus, bus bars, and support structures for the poloidal field interconnection were released for manufacturer design.

Torus Vacuum Pumping System

The contract for the high vacuum pumping ducts was awarded to PX Engineering, and design for the ceramic break assembly was completed.

The preliminary design of the getter assemblies was accomplished, and fabrication of a single cartridge test article and three cartridge prototype assemblies was commenced.

Assembly of all foreline trap assemblies was completed, along with acceptance leakage and conductance measurement tests.

Cryogenic Supply Systems

The bulk of hardware for the cryogenic supply system has been placed with CVI Corporation. The 3.8°K helium refrigerator has been delivered to PPPL. A change in the original contract now provides for full control of the refrigerator by Central Instrumentation Control and Data Acquisition (CICADA).

Delays were encountered in the manufacture of the 1500-gallon liquid helium dewar needed for the supply system. A major obstacle was overcome by eliminating code stamping of the pressure vessel, since no code exists for operation at 3.8°K.

The cryogenic piping system for the neutral beam test cell is under subcontract. Two major changes that will affect partial deliveries include TFM requirements changing services to neutral beamline No.5 from neutral beamline No.1 and the corresponding changes in layout work in the neutral-beam test cell area.

The controller sequencer safety interlocks for the cryogenic system will operate by means of a programmable controller.

Instrumentation and Control

Flow elements, electronic transmitters, and thermocouple and test wells were delivered to PPPL for instrumentation and control of the water system.

Control wiring diagrams, instrument installation details, and instrumentation lists for the water system have been completed.

Electrical Distribution

Design criteria were developed for grounding of all electrical and nonelectrical equipment in the experimental areas.

Cable tray and conduit layout drawings were completed for the pump room of the neutral-beam power conversion building. In addition, a specification was approved for a 480 V motor control center and several 480 V: 208 V/120 V transformers and distribution panelboards. The low voltage equipment will be used to supply control power for the cooling water electrical systems.

Cable tray and conduit layout designs for the test cell and basement area were revised to reflect the latest available information on experimental systems. The tray/conduit systems depicted on the drawings will be used to interconnect cables of the vacuum, cryogenic and cooling water electrical systems. Material take-offs were updated for the experimental area cable tray, conduit, and cable in preparation for timely purchase to support the installation/assembly and preoperational test schedules.

Neutral Beam Systems

Neutral Beam System Test Facility

At the beginning of FY80, ion source operation at Lawrence Livermore National Laboratory (LLNL) was below 60 kV; but by the end of January 1980, 50 A operation for 500 msec pulse length was reliably achieved. Since then, industrial suppliers McDonnell Douglas and Hughes have delivered accelerator structures that have operated with the Lawrence Berkeley Laboratory (LBL) ion sources up to 120 kV with currents in excess of 60 A.

During FY80 the beamline was finished, the ion dump and magnet installed, and the calorimeter thermistors replaced with thermocouples. Shielding and the duct and target tank were commissioned. Reliable operation of the cryosystem, including the regeneration mode, was demonstrated.

Power System

Critical components of the neutral-beam power system have been tested and delivery has begun.

Several production-type, high-voltage switch tubes were built by RCA and delivered to PPPL.

Beamline Assembly

Two vacuum enclosures have been received at PPPL. Vacuum enclosure No. 1 is ready for installation of thermal shielding. Bending magnets No. 1 and No. 2 were installed in the vacuum enclosure. All eight cryomodules required for neutral beamline No. 1 were assembled and tested.

TFTR Diagnostics

The diagnostics system for TFTR has progressed on many fronts. Some of the complex diagnostics have reached the stage of final design review, with many more passing through a preliminary review. Fabrication of many components has started, work on integration of the diagnostic system with the tokamak, the facilities and the data acquisition (CICADA) system has been sustained; many prototype components have been tested on PLT or PDX; laboratory development has been continued.

In preparation of equipment that can operate with tritium, high tokamak vacuum vessel temperatures and in high-level radiation environments, some important steps have been taken. An experimental study of the effects of buildup of tritium on the surfaces of electron-sensitive detectors has been completed. A common vacuum effluent system has been designed; turbomolecular pumps for tritium handling have been ordered; a gas analyzer for discriminating between hydrogen isotopes has been demonstrated to work satisfactorily with tritium. New vacuum sealing techniques that will withstand the 250°C bakeout requirement have been developed for the necessary window materials, and the sensitivity of windows to both neutrons and soft x-ray bombardment has been studied. Among detectors that have now been qualified against the projected radiation levels are channel electron multipliers and gridded ionization chambers.

Some of the diagnostics being prepared for the first operation of TFTR are now being built. The Rogowski coils and diamagnetic loops which will be trapped in the tokamak vacuum vessel are nearing completion; their instrumentation is ready and awaiting full implementation and testing with the CICADA system. The 1-mm microwave system for electron density measurement, which will be incorporated into the tokamak control system, is far advanced in design, and some of the principal components have been delivered. The test data using a reflection system for the microwaves in the mock-up of the TFTR vacuum vessel are very encouraging. The standard neutron counting system has been fully designed. The pressure gauges for the tokamak as well as for the numer-

ous individual diagnostic vacuum boxes have been ordered, and the circuitry to integrate them into the vacuum controls is progressing. A number of spectrometers have been ordered or are at various stages in the procurement process. The success of the simple hydrogen monitor and near-ultraviolet survey instruments on PDX is encouraging for the instruments being built for TFTR. Periscopes for operation of the TV viewing system of the plasma have been ordered, and it is now planned to use them for remote inspection of the inside of the vacuum vessel and far infrared measurement of the wall temperatures during pulsing and calorimetry of the neutral beams. The final design of the 80 kV diagnostic neutral beam will be completed shortly.

Improvement of the diagnostics resulting from work on PLT and PDX has continued. The prototype methyl alcohol interferometer on PDX has measured a density of 10^{14} cm^{-3} , and sawtooth oscillations have been observed. The platinum bolometer has worked effectively, and the CO_2 laser for demonstration of ion temperature measurement by forward scattering is now installed on PDX. The difficulty of making the heavy ion beam experiment for measuring plasma potential on PLT work will lead to a downgrading of the TFTR experiment to look only at the potential near the edge. Since the experiment still has extreme signal-to-noise problems, the system was recently modified for higher beam current and power resolution to see if the measurement is at all feasible. A new small thin-foil ionization chamber developed to replace the surface barrier detectors in the x-ray imaging systems at high neutron fluxes was tested satisfactorily on PDX. Many components of the TVTS system on PDX, which are very similar to those for TFTR, have just been installed.

In laboratory developments, a fast mechanical motion system for the Fourier transform spectrometer has been tested. Improvements in the far-infrared lasers to increase their stability and turnability have been made. A prototype of the charge exchange analyzer has been provided to the Lawrence Berkeley Laboratory (LBL) test stand and a calibration ion source is now being set up in the PPPL Charge Exchange Laboratory. X-ray crystal spectrometer studies with a new multi-wire proportional counter have been successful, and detailed studies are being made of collimator configurations in the neutron test facility prior to final design of the neutron spectrometers.

The fiscal year closed with a very intensive engineering effort to complete the final design of the diagnostic systems in order to sustain the fabrication schedule for full operation of TFTR in 1982.

Central Instrumentation, Control and Data Acquisition

During FY80, the major CICADA effort has shifted from construction to assembly and operational testing of the various components. Essentially all the major components related to construction have been procured. Thirteen SEL 32/75 computers are operating in the CICADA computer room (Fig. 57), and installation of the console and terminal operating stations in the TFTR control room is approximately 50% complete (Fig. 58).

Figure 57. CICADA Computer Room. (804828)

Figure 58. TFTR Control Room. (804835)

Clock, CAMAC, and television links have been installed in the experimental power building for testing of neutral beam, power conversion, and diagnostic equipment. The motor/generator CICADA interface racks are installed in the motor generator control room and the power conversion racks are assembled and ready for installation.

The first eleven tokamak application programs for the motor/generator are operational. Diagnostic application programmers are now using the computer system to support diagnostic development. Stand-alone systems configured around a microprocessor controlled CAMAC crate have been delivered to Transrex and Mound Laboratories to be used in two diagnostic experiments.

Applied Physics

The newly formed Applied Physics Division is charged with responsibility for those activities, formerly within the Experimental and Theoretical Divisions, which pertain to the conceptualization, design, and operation of future plasma devices. Specific areas included are: tokamak modeling; materials physics; magnetics; reactor physics; data analysis; and special projects. The scope of work within the Division encompasses experiments on present tokamaks (and in support laboratories) which are relevant to the design problems of future devices, modeling of operating machines, and tokamak model development, as well as the direct application of results and models to machine design. This integration of work on existing devices with machine design has proven particularly efficacious.

Major Activities Tokamak Modeling

Activities during FY80 included applied theoretical support of PLT and PDX, and involvement in the planning and design of TFTR, INTOR, ETF, ZEPHYR, and FED. The major activities are as follows:

PLT

A multispecies impurity transport code was used to assist in the analysis of spectroscopic data¹. The data for iron showed a very large inward shift of the observed charge states, well beyond that which can be explained by neoclassical transport and/or charge exchange recombination in these ohmically heated discharges. Substantial anomalous convective motion appears to be required in addition to diffusive transport terms. It also has become clear that remaining uncertainties in atomic rate coefficients and electron temperature profiles often make detailed transport conclusions difficult to derive from current tokamak spectroscopic observations.

TFTR

Calculations of the expected operating parameters for TFTR were performed to assist in plan-

ning the machine operation. These included "point modeling" with a survey of input power and impurity limits, studies of the plasma edge parameters,² studies of the effects of both favorable and unfavorable confinement scaling in TFTR, and a thorough study of ripple effects, current drive, and beam heating efficiency as a function of injection angle. As an example, Fig. 59 shows the predicted heating efficiency for a single beamline in various configurations on TFTR.

Figure 59. Predicted heating efficiency + (integrated plasma heating over inner half plasma volume) - (total injected power) for a beamline as a function of R_{tang} for precompression case TDV308 and full current case TDV318. Ripple effects are included. (806778)

ETF/INTOR/FED

Support of INTOR, ETF and FED was carried out with transport code simulations, divertor simulations, and development of new plasma heating schemes.

An example of the transport simulation results in Fig. 60³ indicate that the required heating pulse and average pressure ratio $\langle \beta \rangle$ at ignition in INTOR display marked variation over the narrowest possible range of electron energy confinement which can reasonably be extrapolated from existing experiments. This work has helped stimulate further investigations of this important issue

during the preliminary stages of the FED design. An example of one of the other physics issues investigated for INTOR shows (Fig. 61)³ that much lower helium pumping fractions were required for reactor ignition than had previously been expected. An analytic model confirmed this result.⁴

Figure 60. (a) $\langle \beta \rangle$ at ignition and (b) heating pulse t_{ig} to ignition with various x_e and with $x_e = 5 \times 10^{17}$ (n_e, T_e keV^{2/3}). (792140)

One of the major INTOR design efforts in 1980 centered on the planning of a poloidal divertor system. The divertor is to be used to handle the heat and particle outflux from the ignited INTOR plasma. A calculation was done for the gas transport in divertor chambers. A Monte Carlo code, DEGAS, was written and a sample particle trajectory is given in Fig. 62. The code calculates the transport of neutral gas (D, T, DD, DT, TT, He) in a fixed plasma. In steady state, all of the helium produced by fusion ($\sim 0.01 n_D$ /sec) has to be exhausted from the vacuum vessel. An early result by a Japanese group⁵ suggested that a divertor might selectively pump helium ("helium enrichment"). Early results⁶ indicated that very little, if

Figure 61. Helium fraction vs pumping fraction for long pulse scenarios at $t = 15$ sec. (803664)

any, enrichment occurs, which was confirmed by a later paper from the JAERI group⁷. However, the enhanced pumping rates present in a divertor⁶ lead to sufficient helium exhaust rates for INTOR. The calculational results also indicated that the pumping speed for pumping ducts which see a recycling plasma is enhanced over the normal room-temperature vacuum pumping speed. This is because the recycled neutrals are "hot," and "cool off" as they move down the pumping tube. This enhancement can be as large as a factor of 30, and is typically ~ 10 .

Figure 62. Sample particle trajectory for a 9×10^{12} , 250 eV plasma. (803443)

Advanced Code Development

Work has continued on basic code development. A 1-1/2-D tokamak transport code has been upgraded with a fully 2-D neutral gas treatment (Seurat). In addition, the code has been documented, and modularized. A neutral beam treatment is being installed in the code will be applied to PDX and other noncircular tokamaks in 1981.

Preliminary documentation of BALDUR was completed, and a code manual will be published in 1981.

Advanced Heating Methods

One of the more significant problems with large tokamaks is the difficulty of heating with positive ion neutral beams ($E < 150$ keV) which do not penetrate well. A novel method is to use high energy neutral beams of heavy atoms ($A \geq 6$) formed by producing Li^+ , C^+ , O^+ , etc., accelerating the negative ions to $\sim \text{MeV/amu}$, neutralizing them with 50-100% efficiency, and injecting them into the tokamak where they heat the plasma by Coulomb collisions and possibly drive currents.⁸ Such beams offer the promise of high reliability, low pumping requirements, good plasma penetration, and high efficiency. The expected impurity accumulation is less than the helium ash build up. The beams are low-Z impurities which would be expected to be fully ionized and thus have low radiation levels.

Materials Physics

TFTR/TFM Impurity Control

Plasma impurities constitute a formidable barrier to realizing the full operating potential of TFTR, and are especially deleterious to achieving maximum values of the fusion power gain. Furthermore, the control of impurities in this device will be a particularly difficult problem, owing to the large particle and energy fluxes expected in the TFM mode. In consideration of this, work continued in FY80 on ways to ameliorate the impurity problem.⁹

One of the principal activities of the impurity control effort was the optimization of the configuration for the limiters and other protective armor in TFTR. Fig. 63 shows the three structures upon which the dominant thermal loads will be incident. The axisymmetric bumper limiter¹⁰ is intended to absorb the major plasma heat load as well as perpendicular-injection neutral beam heat loads due to incomplete ionization of the beam by the plasma. This limiter has a coverage of $\pm 60^\circ$ poloidally from the torus midplane and extends

Figure 63. Diagram of the limiters and protective plates in TFTR. The bumper limiter covers the entire toroidal circumference. The protective plates are located in areas irradiated by the neutral beams. (803696)

around the entire toroidal circumference. The peak heat load¹⁰ on these limiters during normal high power neutral injection is $\leq 1 \text{ kW/cm}^2$ owing to its large surface area ($\sim 20 \text{ m}^2$).

An array of three moveable limiters is located in one toroidal position. These actively cooled blades have a total surface area of $\sim 1 \text{ m}^2$ and, consequently, a much higher energy flux ($\sim 15 \text{ kW/cm}^2$) than the bumper limiter. They will be used in compression scenarios for short times.

The neutral beam shine-through for tangential injection is absorbed by protective plates located where required on the outer vessel wall subtending $\pm 30^\circ$ from the midplane.

Another major aspect of impurity control work has been materials research aimed at finding layered composites with substrates having good thermal characteristics (copper or graphite), and coatings or claddings which are intended to provide good surface properties (e.g. low sputtering, low tritium retention). This research involved groups at Argonne National Laboratory¹¹ and Sandia National Laboratories^{12,15} as well as PPPL.¹³ Data indicates that the best coating system is TiC chemically vapor-deposited on graphite. It has a lower sputtering yield than pure graphite and can

withstand the 1 kW/cm^2 thermal flux. Among the claddings, vanadium explosively bonded to a copper substrate would also satisfy the TFTR thermal/surface properties requirements, although eddy current forces which occur during plasma disruptions are large due to the high electrical conductivity of copper.

The third major area of the impurity control work has been the design of a gettering system to reduce recycling and low-Z impurity content. The most promising solution is a Zr/A1 alloy bulk getter³. It operates in the range of $200\text{--}400^\circ\text{C}$, which is compatible with the plasma radiative heat load. Hydrogenic species can be desorbed by increasing the getter temperature to $600\text{--}700^\circ\text{C}$. This facilitates tritium operation of TFTR, since the maximum amount of tritium allowed in the getter will be limited. The getter inversibly pumps active impurities (C, N, O) at all temperatures above 200° . The fatigue lifetime due to repeated temperature cycling has been measured¹⁶ to be equivalent to two years of TFTR operation.

INTOR/ETF/FED Mechanical Divertor

Several concepts for a mechanical divertor, or pumped limiter, have been presented in the last few years. A study was made to adapt these designs to the INTOR/ETF/FED device with the goal of solving the heat load and structural problems which were present in most previous concepts. The result of the study is a large-area toroidal belt limiter, which has channels along each edge to allow a fraction (1-10%) of the edge plasma particles to escape behind the limiter where they can be neutralized and pumped. The peak heat load is $\sim 150\text{ W/cm}^2$. An elevation view cross section of the upper half of the INTOR/ETF/FED vacuum vessel, showing the location of the pump limiter, is shown in Fig. 64. The results of the study¹⁷ indicate that the pump limiter is an interesting concept which warrants further effort for reactor type devices.

Magnetics

PDX

The poloidal magnetic field pattern is the key factor which governs the plasma initiation phase. To examine the field pattern, a set of transfer functions were constructed by individually exciting the poloidal power supplies in the absence of plasma and measuring the vertical magnetic field with a set of flux loops specially introduced on the machine midplane.¹⁸ The experimental results show (1) that the circular plasma can build up even in relatively strong quadrupole fields, and (2) that in

Figure 64. Cross section of mechanical divertor limiter for INTOR. Lines of constant poloidal magnetic flux are shown superimposed on the limiter. The support legs are helical and form channels parallel to the particle flow direction to increase the particle trapping efficiency. (803784)

noncircular divertor operation, the plasma tends to form initially at $R = 1.2\text{ m}$ or $R = 1.6\text{ m}$, where the field gradient is negative (quadrupole field pattern).

In addition to this work, the magnetic axis (R_m) in the PDX was determined by first measuring the flux function (ψ_p) produced by the plasma alone, and then comparing it with the values computed for various R_m from the equilibrium MHD equations¹⁹. In the experiment $\psi_p = \psi_{\text{mes}} - \psi_{\text{ext}}$ was determined by subtracting from the flux (ψ_{mes}), measured with magnetic flux loops the external contributions (ψ_{ext}) from poloidal field coils and eddy currents in their casings and in the vacuum vessel determined from the transfer functions and coil input current waveforms. The measured magnetic axis was consistent with other measurements, such as behavior of the plasma density and the heat deposition in the divertor chamber during radial and vertical motion of the plasma.

Another PDX activity has been the investigation of the stability of elongated plasmas against vertical displacement. By holding the plasma at various major radius locations²⁰ ($R = 1.15\text{--}1.60\text{ m}$) the growth rate of the instability was determined

and found in good agreement with theoretical predictions. The so-called passive stabilization, provided by currents induced in the divertor coils in parallel connection, was found to slow down the instability growth sufficiently to make the vertical plasma position amenable to external feedback for a wide range of the magnetic decay index ($-2 \leq n \leq 0$).

INTOR

A preliminary optimization has been made of the axisymmetric poloidal divertor configuration for the INTOR device¹⁷. Engineering aspects as well as physics requirements were included in order to assure some self-consistency. Consideration was given to; maintainability, simplicity, and compactness of both the coils and the divertor structure; the shielding of the toroidal field coils near the divertor channels; the forces on the toroidal field coils; the divertor dimensions required for energy removal, ash removal and impurity control; β -limits; plasma position control; and separatrix control.

A single-null divertor with an external-coil poloidal configuration was chosen for INTOR because of better maintainability. These advantages are at the expense of a significant increase in poloidal field power requirements, and forces on the toroidal field coils.

However, the single-null divertor simplifies the configuration and increases the area available for neutron shielding. Also, it can ease the problem of providing access to divertor chambers for component removal. Fig. 65 shows a single-null divertor

Figure 65. INTOR single null divertor magnetic field configuration for $\beta = 5.5\%$. (803829)

magnetic field configuration for $\beta = 5.5\%$. It is possible to provide 0.5 m of inner channel and 2.0 m of outer channel with this divertor. The plasma is mildly D-shaped, which is easier to form with a simple coil arrangement in the center core.

It is important to maintain the magnetic separatrix within the divertor channel during plasma heating. In the absence of separatrix control, the separatrix line in the divertor chamber will shift when the vertical field is adjusted to maintain the magnetic axis during the β -increasing stage. In order to improve the separatrix control, two pairs of coils located outside the toroidal coil are introduced to produce a quadrupole field pattern with the null point arranged at the stagnation point and the field oriented in the vertical direction. From $\beta = 0.24\%$ up to $\beta = 5.5\%$, the coils control the separatrix lines well within the tolerable limit, even if the coils are located outside the toroidal coils.

Reactor Physics

Resistive Toroidal-Field Coils for Tokamak Reactors

One apparently major disadvantage of the tokamak is the inherent inaccessibility of the vacuum vessel and internal PF coils interlocking the TF coils, and the difficulty of access to blanket modules inboard of the vacuum vessel. This disadvantage can be eliminated by the use of TF (toroidal field) coils that are readily demountable. The resulting tokamak reactor is no more inaccessible than a light-water fission reactor, for example, where complete accessibility is obtained upon removal of the cap of the pressure vessel.

The requirement that the TF coils be readily demountable, with minimal reactor downtime and minimal impact on TF coil performance, dictates that the TF coils be water-cooled resistive coils fabricated of copper or aluminum. Resistive coils have other important advantages over superconducting coils. They are unaffected by pulsed fields, require less shielding against neutron irradiation, have simple refrigeration systems, and can be factory-built and transported (disassembled) to the reactor site.

The TF coils of a tokamak reactor must operate in the steady state. At the values of $\langle \beta \rangle$ now thought to be achievable in tokamaks (6 to 10%), the magnetic field required for satisfactory performance of tokamak reactors in at least some applications can be sufficiently low so that steady-state operation of resistive coils is quite feasible. In such circumstances the problems of mechanical and thermal fatigue are essentially eliminated.

Resistive TF coils can be made to operate in the steady state by making them sufficiently massive. The massiveness of the coils results in an acceptable resistive power dissipation — that is, comparable with the sum of power losses in the other reactor components (PF coils, blanket coolant systems, plasma heating systems, pumps, HVAC).

The optimization of the size of resistive TF coils for certain types of tokamak reactors^{21,22} has been analyzed. An extensive discussion of the reactor features that are possible using such coils is given in Ref. 23.

Fig. 66 shows the variation of resistive dissipation P_{res} of the TF coils with the peak magnetic field B_m at the coil windings ($R = R_m$) for a family of rectangular geometries that produces a neutron wall loading of 0.5 MW/m^2 . For fixed shape parameters there is a geometry of minimum P_{res} at 200 MW or less. For coil radius $a_c \approx 5\text{--}6 \text{ T}$, P_{res} is only slightly above, and the coil mass considerably below, the values at the minimum.

The stress distribution in a TORFA-type resistive copper coil was determined by means of a

Figure 66. Variation of TF coil power loss with B_m for a constant neutron wall loading of 0.50 MW/m^2 . R_c is the coil major radius, a_c is the coil minor radius, d is the radial build, and R_m is the position of maximum field $B = B_m$ (at the coil windings). (803027)

finite element (250 elements) analysis (MSC Nas-tran). The points of inflection in the upper and rear legs of the coil (where the bending stresses are minimum) are the areas most suitable for the inclusion of a joint. For a field at the coil windings of 7.5 T , the principal and shear stresses in these areas are of the order of 33 MPa . These stress levels are well within the capabilities of copper.

The advantages and disadvantages of several types of butt and lap joints, together with bolting and hydraulic clamping techniques have been examined. Fig. 67 illustrates a TF coil with bolted lap joints located at positions of zero bending stress on the outboard legs and finger joints on the in-board side. This joint position allows removal of the blanket modules by simple vertical translation but requires disassembly of the OH solenoid before its removal. For a TORFA-sized coil, fabricated from 5-cm thick plates and $1\text{--}2 \text{ m}$ deep, as many as 50 fingers would be required. For both the finger and lap joints, the magnetic tensile load is transferred by shear pins which also serve as current joints²⁴.

A great advantage of purely hydraulic clamping (i.e. without bolts), when used with an external shear restraint in the joint area, is that the joint can literally be dismantled by simply releasing the oil pressure to the hydraulic jacks.

Figure 67. Demountable resistive toroidal field coil with bolted lap joints. (81P0008)

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TFTR Blanket Module Experiments

In 1979, the Electric Power Research Institute (EPRI) sponsored a Technical Planning Study on the subject of TFTR Fusion Blanket Experiments. The report resulting from that study¹ recommended (1) that an Engineering Test Station (ETS) be implemented for the structural support and servicing of blanket modules adjacent to the vacuum vessel of the TFTR, and (2) that the first blanket module be designed for tritium-breeding experiments.^{1,2} In October 1979, a second EPRI sponsored program was initiated at PPPL to carry out the above recommendations.

Major Activities

Engineering Test Station (ETS)

The purpose of the ETS is to provide structural support and utilities/instrumentation interfaces for blanket module experiments located adjacent to the vacuum vessel of the Tokamak Fusion Test Reactor. As shown in Fig. 68, the ETS is cantilevered from outside the TFTR igloo shield, so that it can be readily removed from one bay and installed in another. A detailed engineering design of the ETS has been completed, and the Final Design Review was held in August 1980.

Lithium Blanket Module

The major part of the EPRI-sponsored program consists of the design, fabrication, and operation of a Lithium Blanket Module (LBM), which will contain a solid lithium compound for tritium breeding upon irradiation by TFTR fusion neutrons.

The principal goal of the LBM program is the development of improved confidence in the design basis of fusion reactor blankets by comparing the neutron transport and tritium breeding performance of lithium-containing blanket module configurations in a tokamak environment with computational predictions, and upgrading the design tools in selected areas to improve agreement between prediction and measurement. The LBM measurements will provide reference data on spatial profiles of neutron fluence and spectrum, as well as the profile of tritium breeding in the central region of the module.

Figure 68. Lithium Blanket Module and its interface shield plug in retracted position on the Engineering Test Station. (803487)

The LBM program will also afford first time operational experience in the design, fabrication, remote handling, electromagnetic isolation, instrumentation, control, and safety aspects of a fusion reactor blanket module integrated into a tokamak operating with deuterium-tritium fuel.

Geometric Aspects

The ETS will hold blanket modules with lateral dimensions up to 78 cm X 84 cm, or nearly as large as the optimal size for isolated modules as determined in studies for the International Tokamak Reactor (INTOR) project. Preliminary neutronics analyses indicate that the tritium breeding characteristics of the central region of the LBM

will be uninfluenced by neutron backscattering into the sides of the LBM, or by leakage of neutrons from the LBM out the sides.

Program Phase

The LBM program will comprise the following four phases:

- Phase I: Program definition and design of the LBM.
- Phase II: Fabrication of the LBM.
- Phase III: Check-out, installation, and acceptance testing at PPPL.
- Phase IV: Program of experiments and analysis.

The first LBM experiments in Phase IV will make use of TFTR D-D neutrons during the period preceding first D-T operation.

All four phases of the LBM program will be performed by a single industrial subcontractor to PPPL. As a result of a competitive procurement, the LBM subcontract was awarded to the General Atomic Company of San Diego at the end of FY80.

Fusion Energy Calorimeter

In a pulsed fusion reactor such as the TFTR, the fusion energy production per pulse can be monitored by means of an adiabatic total neutron-absorption calorimeter located just outside the vacuum vessel wall. In each fusion pulse the neutron moderating region of the calorimeter will experience a temperature rise proportional to the absorbed fusion-derived energy. A neutron calorimeter under consideration for the TFTR, in fact, represents a primitive first step toward a power-producing blanket.

From the points of view of sensitivity, safety, ease of handling, and cost, certain oils that are pure hydrocarbons appear to be the most suitable liquid moderating media, with polyethylene (CH_2) as a back-up solid candidate. Temperature increases, ΔT , would be measured by thermopiles and platinum-resistance thermometers distributed along the major radial axis.

Power Deposition

Calculations of the radial profiles of energy deposition in CH_2 are shown in Fig. 69 (ANISN code). The input source spectrum and intensity

were calculated by the DOT code, and include ambient gammas and neutrons scattered from adjacent TFTR components. Almost half the incident neutron energy deposited near the front face is due to sub-14 MeV neutrons. About 10% of the total energy deposited at the front face is gamma radiation. Ambient gamma rays from the TFTR structure incident on other faces can be stopped by approximately 6 cm of lead shielding.

Maximizing the lateral extent of the moderator appears to be the optimal method for ensuring adequate isolation of the central region from boundary effects. The half-width of the moderator (~40 cm in each direction) is sufficiently large so that scattered low energy neutrons entering the sides, either by reflection of neutrons moderated in the CH_2 or from the TFTR ambient, are found to have 10% or less effect on the energy deposition along the major radial axis.

Figure 69. ANISN calculations of energy deposition profiles in a polyethylene moderator. (603649)

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Advanced Toroidal Facility

PPPL is carrying out engineering and physics scoping studies to determine the technical features and programmatic objectives of a possible new toroidal facility to be fabricated at Princeton. The overall objective of this project is to provide a test facility for the advanced concepts that will be required to optimize a toroidal fusion reactor. This project will parallel and complement the Fusion Engineering Device (FED) Project.

Since the FED schedule calls for operation at the beginning of the 1990's, the permissible level of design innovation will be limited by the time constraints of the experimental R & D program. Some of the most advanced — and theoretically promising — approaches to a commercial tokamak design will remain to be developed during the 1980's and early 90's by a program of less costly, non-D-T experiments, operating in parallel with the FED project.

In order to provide a credible basis for the introduction of major improvements over the FED design in a follow-on Commercial Reactor Feasibility Demonstration, the prototypical Advanced Toroidal Facility (ATF) demonstrations must take place at a substantial level of performance. The plasma parameters must be reactor-like, as in the TFTR: the size must be sufficient to allow multi-megampere plasma currents; the plasma duration must, at a minimum, approach the 100-second range, and should preferably approach steady state. The ATF is therefore envisaged as having a plasma of TFTR size, along with superconducting toroidal-field coils. Since D-T operation is not required for the ATF, consumption of space for shielding of the superconductor can be avoided. The appropriate coil size is therefore considerably smaller than for the FED — roughly comparable to the toroidal-field coils under development at the Large Coil Test Facility at ORNL.

The advanced tokamak program will ultimately require a central facility with capabilities for producing reactor like plasmas in quasi-steady-state. During the past several years, a number of studies were carried out on the utilization of the physical plant of the TFTR project for a follow-on device, either of the pulsed-ignition type (ITR) or the long-pulse superconducting type (SLPX 1, 2 and 3).

These studies have shown that major savings in cost and schedule can be realized by utilizing the resources of the TFTR site. An ATF of multi-megampere capability could be put into operation as early as 1987.

The objectives of the ATF are as follows:

- **Steady State.** While steady-state operation of the "plasma driver" is not known to be a requirement for a commercial reactor, the resultant simplifications are clearly important. In the case of the tokamak, the driving of the plasma current has already been demonstrated by theoretical analysis and by small-scale experiments. Current driving needs to be developed towards optimum efficiency, and must be demonstrated in reactor-like plasma conditions, where the resistive current-decay time is long compared with the plasma energy confinement time.
- **Stability.** Avoidance of disruptions is of basic importance in facilitating the mechanical design of a tokamak reactor. Profile control by local heating and/or the addition of weak stellarator fields could solve this problem, while allowing larger plasma currents and higher β 's to be reached.
- **Impurity Control.** If the benefits of the present poloidal divertor system could be obtained in simple field geometry — possibly based in part on mechanical, rather than magnetic plasma handling — the complexity of the tokamak reactor magnetics could be reduced substantially. The development of plasma-physical methods (such as the driving of rotary flows or the utilization of cyclotron-resonance effects) for enhancing the diffusion of impurity ions from the central plasma could be helpful in achieving this goal.
- **Radio-Frequency Methods.** The replacement of neutral-beam heating by a suitably efficient method of radio-frequency heating could provide substantial reductions in cost and simplifications in reactor shielding design. Application of rf power to the current driving problem has such a broad potential

for optimizing the tokamak as a reactor, that it could be considered a prime objective of the ATF.

- *Density Control.* Quasi-steady-state control of the plasma density profile is not known to present any critical problems, but needs to be prototyped at the level of the ATF plasma parameters.
- *Coils.* The use of superconducting coils in the ATF is appropriate, both as a convenience for quasi-steady-state operation, and as a moderate-scale pretest of reactor coil technology. Stellarator features could be incorporated either directly or in auxiliary form into the ATF coil system.

- *Wall Technology.* Many of the first-wall materials problems of a reactor are related to nonnuclear phenomena, such as sputtering and thermal overload. An extended technological program under reactor-relevant, but nonradioactive, conditions would be a valuable incidental contribution of the ATF.

At the present time, the Laboratory is moving forward to make a concrete ATF proposal. The initiation of ATF experimental operation in FY88 requires that a preconceptual design should be identified during FY81, and that the actual fabrication of the ATF should begin in FY83.

Advanced Projects Design and Analysis

The Advanced Projects Design and Analysis Division (APDAD) is a relatively new organization that was formed in the spring of 1979. The Division's role is to support the Laboratory's physics program and the national fusion effort by providing planning and evaluation of new and upgraded experiments, conceptual and preliminary design services, and systems integration services. In addition, APDAD 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, magnetics and coil design, and remote handling.

The Division consists of an administrative unit and five technical branches, with the latter further divided into sections according to specialty.

Major Activities Analysis Branch

Assigned to this branch are the highly specialized analysis activities critical to the development of the fusion program. It requires a well experienced staff capable of using advanced, specialized equipment and a library of computer programs. Three principal specialties are identified: magnetic field analysis; radiation and nucleonics analysis; and finite element analysis.

Magnetic Field Design

One of the major efforts in the Field Design Section was the completion of analytical work for all of the magnetic systems in the S-1 (Spheromak) device. This effort included the modeling of electrical circuits and their magnetic linkage with the passive components, in order to anticipate eddy current degradation of the power circuits and the effect upon plasma buildup. Progress was made in expanding the eddy current codes, and the group was called upon to install one of these programs at the Max Planck Institute at Garching, West Germany.

A feasibility study was made for a new stellarator that would utilize the PLT toroidal field coil

system. One of the four windings is illustrated in Figure 70; these are the helical windings that occupy the space between the toroidal field coils and the vacuum vessel.

Figure 70. One of the four windings designed for a new stellarator. (804964)

Effort was continued in converting batch type programs into interactive time-sharing codes with emphasis on graphic outputs. The upgrading of these programs has been given a high priority because of the fast response capability of representing coil and flux patterns for analysis and presentation in reports.

For the Engineering Test Facility (ETF), initial studies were undertaken on several ohmic heating and plasma shaping field coil systems, as well as on different diverted plasma configurations. This work was done in conjunction with the Massachusetts Institute of Technology (MIT) Fusion Laboratory.

In order to help analyze the D-shaped coil characteristics, a program was developed which generated pure tension coils for various numbers and builds of toroidal field coils. This code was applied to the ETF coil analysis.

Radiation Analysis

One of the major accomplishments of the radiation analysis group in FY80, was the culmination of the TFTR baseline radiation analysis calculations in a comprehensive report.¹ It has about 150 figures and tables and summarizes the work originally released in over a dozen technical memoranda.

Also during FY80, an updated set of cross sections for particle transport calculations and radiation analysis was incorporated into the radiation analysis system on the IBM 3033.

Calculations in support of the mechanical design of the shielding for TFTR represented a considerable portion of this group's effort. For example, the igloo needed to achieve the desired attenuation levels for TFM was redefined.

The group also performed calculations to provide data for refining the planned operational scenarios for TFTR, and assistance was given to other groups who wanted help in using the particle transport codes and data for their own applications.

Finite Element Analysis

In a joint undertaking between the Grumman Aerospace Corporation and PPPL, a finite element method (FEM) analysis of the PDX structure was completed. The coil support structure and coil cases were studied in detail using linear and nonlinear analysis. A finite element idealization of the structure that was analyzed is shown in Fig. 71. A new FEM technique called "substructuring" was employed in the analysis.

A large software package that is used in FEM analysis, the MSC/NASTRAN version 60.0, was purchased, installed, and tested on the general purpose computer. FEM data created by Ebasco/Grumman for TFTR were installed on the general purpose computer and rerun using the newly purchased NASTRAN. Models representing the TFTR toroidal field coil and vacuum vessel are now fully operational on the general purpose computer.

A number of other FEM analyses were completed during FY80. Examples are the toroidal field coil substructuring stress analysis for the superconducting long pulse experiment (SLPX)² and the simulation of the titanium/aluminum gettering plates for TFM.

Mechanical Branch

Covering a broad spectrum of mechanical engineering, this branch is organized into three sections: Engineering Mechanics, Mechanical

Figure 71. Finite element idealization of the PDX tokamak. (808110)

Design, and Mechanical Drafting Services. The technical specialties represented cover the mechanical design aspects of the fusion device proper, including coils, vacuum vessel, structure and materials. In addition to serving APDAD needs, the Mechanical Drafting Services group provides drafting for other divisions and maintains the backup tracing files (disaster file) for all of PPPL.

During FY80 several Mechanical Branch personnel were engaged in monitoring and guiding the engineering effort applied to three TFTR systems: the vacuum vessel and surrounding structures; the coil systems; and diagnostics.

Structural Dynamic Analysis

Mechanical Branch personnel have analyzed the mechanical dynamic response of TFM designs when subjected to forces produced by plasma disruptions. When a plasma disrupts, the

magnetic field caused by the plasma current collapses and induces large eddy currents in any metallic structure in the immediate vicinity of the plasma. The large eddy currents interact with the existing toroidal field (TF) and poloidal field (PF) and produce large impulsive loads on these metallic structures. The typical analysis of this situation used to be a static stress calculation of the full "superconducting" (flux-preserving) loads. For TFM this proves to be overly pessimistic and a true dynamic analysis of the mechanical structure must be performed.

The simultaneous attenuation of the current-induced loads due to inductive effects, and of the mechanical stresses due to inertial effects, has allowed the TFM design effort to proceed. The surface pumping systems and the bumper limiter have been analyzed in this manner.

Spheromak Structural Analysis and Design

Mechanical Branch engineers contributed to the mechanical design of the machine structure and vacuum vessel on S-1 (Spheromak), and performed a structural analysis of the internal flux core and the vacuum vessel. Several FEM computer codes available at PPPL were used in these analyses. Of special concern was thermal stress induced in the Inconel liner of the flux core due to eddy current heating during plasma formation. To reduce this stress a low modulus urethane has been adopted as the potting compound which connects the liner to the epoxy glass flux core. Design of the external poloidal field coil supports has also been accomplished during FY80, and a FEM model has been developed to analyze the combined magnetic and atmospheric loading on the vacuum vessel and coil support structure. Preliminary layouts of the experimental area were also produced during this period.

Electrical Branch

In evaluating the feasibility of new proposals, this branch addresses issues concerning the suitability of existing energy storage and conversion systems to meet the new need, or selection of the best course if new equipment is required. As the program advances, ever increasing attention is paid to analysis and simulation of electrical and control systems. The branch provides unique capabilities in planning and design of specialized power systems, large motor generation systems, rectifier systems and their control, and electrical systems analysis in all these areas.

During FY80, personnel of the Electrical Branch worked primarily in three major areas: the

TFTR neutral-beam power supply and controls; the TFTR pulsed power systems; and electrical systems for the ETF.

TFTR Neutral-Beam Power Supply and Controls

APDAD personnel provided technical management of subcontracts for the following major equipment for TFTR neutral beams: neutral-beam power supplies, high voltage switch tubes, and sweep magnet power supplies. In addition, they provided engineering coordination during construction of the neutral-beam test facility and the TFTR facility in general.

In the area of TFTR neutral-beam instrumentation and control, APDAD personnel provided design and project engineering for the neutral-beam fault detection system, cryogenics control and instrumentation, neutral-beam test cell control room, beamline instrumentation, and CICCADA interface. In fiscal year 1980, contracts were placed based on PPPL specifications for ground-to-space coaxial and triaxial cable, hermetic feedthroughs, electrical connectors, and control and instrumentation cable. An effort continues in evaluating selected electronic sensors and discrete components in a magnetic field and radiation environment.

TFTR Pulsed Power System

Studies were made of induced voltages generated by magnetic fields in the substructure under the TFTR torus, and the effects of these voltages on the plasma were analyzed.

An analysis was conducted to determine voltage drops in the ac distribution system that would result from pulse loads and fault loads of neutral beams in the newly-constructed neutral-beam test facility.

Engineering Test Facility

An APDAD engineer served as Manager of the Electrical Branch of the ETF Design Center located in Oak Ridge, Tennessee. Included in his responsibilities were the power supplies for superconducting and normal coils, motor/generator sets, ac distribution, plasma control, and diagnostics. A view of the preconceptual design of the ETF tokamak is shown in Fig. 72; this machine is a predecessor to the Fusion Engineering Device that is now under design at Oak Ridge.

APDAD personnel set up an analytical model of the ETF vacuum vessel for use in determining induced voltages in the structure and consequent effects on the plasma, on structural forces, and on

FED REFERENCE DESIGN ELEVATION VIEW

Figure 72. Engineering Test Facility (predecessor to the Fusion Engineering Device), courtesy of Oak Ridge National Laboratory. (81X2063)

heat loads to the cryogenic coolants. Analytical contributions were also made in setting up the systems code that was used to assist in optimizing system cost and operating parameters.

Integration Branch

This branch is responsible for unification of the overall design and must ensure that all factors driven by considerations of assembly, remote handling, diagnostics, experimental access, utilization of test cell space, and machine-specific auxiliary systems are taken into account. Technology areas currently represented in this branch include vacuum pumping systems and vacuum enclosures, vacuum seals, cryogenic refrigeration and cryopumping, gettering systems, remote handling, and diagnostics. A future area will be superconductive coil technology.

During FY80, the Integration Branch took part in planning for TFTR installation, assembly, remote handling, and shielding and provided coordination and management of the large effort associated with engineering of diagnostics for TFTR.

Figure 73. M-3 full-scale mockup of the TFTR vacuum vessel. (804216)

Further contributions to the engineering of TFTR included monitoring the design and procurement of vacuum pumping and cryogenic refrigeration equipment, and designing and procuring components of the neutral beam vacuum enclosures.

Other activities included the design and construction of apparatus to test the TFTR vacuum vessel bellows, a critical component of the TFTR machine. Strain gauges will be fitted to the bellows convolutions in certain locations, and design loads will be applied to the bellows by means of hydraulic cylinders, while the former are under vacuum. Testing will continue until the anticipated TFTR lifetime cycles have been surpassed.

The M3 mock-up, Fig. 73, is a full-scale model of about one-fourth the TFTR tokamak. This mock-up, with a stainless steel vacuum vessel and wooden model coils, has proven to be indispensable in developing assembly procedures and tooling. The mock-up vacuum vessel is capable of being evacuated to a hard vacuum, so it is possible to run and test the TFTR turbomolecular vacuum pumps, and test procedures for demounting and resealing the vacuum vessel port covers. At present, the top section is being modified to accommodate the vacuum vessel heating and cooling ductwork and part of the radiation shielding. As this work proceeds, components and tooling will be fitted in place to ensure that there will be no interferences in assembly of the TFTR machine.

Plans have been made to use this mock-up to experiment with remote handling procedures. These plans include the design and development of an in-vessel manipulator capable of removing and replacing limiters and protective plates. An electrical servo-manipulator arm of the type being purchased for the remote handling system is shown in Figure 74. Plans are also being made to

test the feasibility of remotely cutting apart a one-tenth segment of the TFTR vacuum vessel. This will be done to prepare for the possible eventual removal of a segment or a toroidal field coil.

Figure 74. Servo-manipulator arm for TFTR remote handling courtesy of Tele-Operator Systems Corporation. (81X2064)

REFERENCES

1. L.P. Ku, Nuclear Radiation Analysis for TFTR, PPPL-1711 (September 1980) 217pp.
2. P. Rogoff and J. File, SLPX-1 — TF Coil Stress Analysis PPPL-1505 (November 1979) 130pp.

Engineering

The Engineering Division is composed of two branches, two separate sections, and Division Administration.

Power Branch

The AC Power Section, the Rectifier Section, and the Neutral Beam Power Section handle the functional responsibilities of this branch.

The branch provides the ac and dc power and energy engineering services for the Laboratory and associated devices. Such services include the design, fabrication, and installation of high-energy electrical storage systems, the maintenance of adequate line power for the Laboratory, and high-voltage direct current power for the neutral-beam sources used in experimental programs.

Diagnostics Branch

Five sections are included in this branch: Electronics, Instrumentation, Diagnostics Projects, Electro Optics, and Mechanical Engineering. A large variety of electronics and electro optic circuitry is provided. Other services encompass the design and fabrication of special microwave and laser devices for plasma diagnostics, the mechanical engineering required for placement of diagnostic equipment, construction of machine supporting structures, power radio-frequency (rf) accessories, and the maintenance of Laboratory deionized water systems. The Diagnostics Projects Section, added to the branch in FY80, is responsible for systems engineering required for the diagnostics devices to be used on the TFTR.

Controls Section and Radio-Frequency Section

There are two sections which are not associated with either of the two main branches of the Engineering Division: The Controls Section and the Radio-Frequency Section. The Controls Section has responsibilities involving device and related supervisory and annunciation controls. It is heavily engaged in computer aspects of such controls pertaining to automatic protection of experimental machine equipment and personnel. The

Radio-Frequency Section is responsible for the design, construction, and installation of high-power rf generators and neutral-beam vacuum tube modulators.

Power Branch

AC Power Section

The reliability of the Laboratory's distribution system (4.16 kV and above) was improved by additions and the inauguration of infrared tests.

Only four high temperature points were found, and considering the size and age of the system, this fact was very encouraging. The test results aided greatly in executing repairs and replacements.

New positive acting relays replaced existing units in the tripping circuits of 18 circuit breakers, decreasing possible trip failures due to relay malfunctions.

Metal oxide surge arrestors were added at the secondary of a 30 MVA transformer serving high and variable pulsed loads.

A study of the control and protective system relative to the power circuit breakers was initiated late in the year. Preliminary results indicate the desirability of incorporating modern circuits and components (redundant trip coils, etc.) into the existing system.

Although there has been no accident involving existing transformers and capacitors containing PCB, procedures were implemented to continue this record and dispose of the material in the safest manner.

At the end of FY80, good progress was evidenced on the integration of the TFTR power system into the existing one. Test procedures were being written in preparation for acceptance of the numerous components and subsystems.

Rectifier Section

A series of changes were made to the SF power supply used on both PLT and PDX in order to upgrade it for more reliable operation under existing load conditions, and to increase the current available for future operations.

The thyristor gating circuits were redesigned to eliminate periodic adjustments of the balancing circuits, the effect being to minimize automatically the 60, 120, and 360 cycle ripple at the supply output. The master gate drive boards were redesigned to eliminate misfires of the power thyristor gates. Metal Oxide Varistors added set voltage limits on the thyristors.

New higher voltage and higher current thyristors were installed in both rectifier and crowbar circuits. (Fig. 75). Thirty-six of these units are used in the rectifier and crowbar circuits and a maximum of 15 kA is available.

Figure 75. New SF thyristors mounted as one rectifier arm. (806906)

A new power transformer, in the process of procurement at the end of the year, will result in increasing the SF peak power output from 37.5 MVA to 72 MVA.

Good progress was made on an extensive upgrading of the ohmic heating rectifier system. This equipment is in constant use by either PDX or PLT, and is probably the most important single machine accessory at the laboratory.

Installation of part of a new and improved local control system was completed and fabrication of a local control timer was under way at year's end.

A prototype circuit for a new ignitron hard firing system was tested successfully, and long lead time components were on order.

Safety aspects of the OH system were improved to meet the latest PPL regulations.

The poloidal coil and toroidal coil power supplies for the Proto S-1 were completed and operated in the machine successfully. During September the pinch coil supply was completed and successfully tested with a dummy load.

Circuit analyses were made for Spheromak coil system power supplies and were adapted to changing requirements as pre-Spheromak experiments were being run. The plan is to power the EF coils with two MG sets, while the other two coil systems are to employ three capacitor bank discharge supplies.

Capacitor and ignitron manufacturers were visited, after which a capacitor specification was generated and bid invitations were sent out. The successful bidder was Aerovox with a new high density, high stress, 80% reversible voltage capacitor. D-size ignitrons were chosen, as it was determined that they would provide better performance and system flexibility at less cost than would the larger E-size tubes.

Neutral Beam Power Section

The completion and installation of power supplies and controls for the PDX 6 MW neutral beam installation was accomplished. Two beamlines were connected to the machine and operated. These lines have been operated at 4 MW, portending meeting or bettering the projected goal of 6 MW with all four beamlines installed.

This section participated in the apparatus "tuning" leading to the achievement of 80 million °C plasma temperature during the fiscal year.

Diagnostics Branch

Electronics Section

The electronics for the TFTR voltage, diamagnetic, and Rogowski loops were designed and prototypes fabricated. An important feature of the loop voltage unit is the use of four subchannels to provide data at separate spans of the amplitude range. One of the four is to measure high disruption voltages, the other three to provide the amplitude spans for normal data.

The PDX Radial Field Amplifier and the appurtenances required for satisfactory operation into the PDX DF coil system were installed and operated. The amplifier is used as the output device for a plasma vertical position feedback system.

Specifications include an output current of 1,000 amperes peak from dc to 16 Hz and a peak potential of 100 volts from 16 Hz to 1 kHz into a load of 1 mH and 10 m Ω .

The feedback error signal applied to the amplifier input stage is derived from a number of voltage pickup loops placed at suitable locations around the machine. These loop signals are processed and summed in an electronic controller to produce the amplifier input signal. The output power amplifier stage utilizes 4,320 power transistors in a modified quasi-complementary circuit to produce the required output. Direct coupling is used throughout. Both local and remote control are used, as the amplifier is located one story below the machine and two stories below the machine control room.

In order to prevent damage to the amplifier from possible high disruption voltage appearing at the DF coils, a set of two thyristors across the amplifier output line and two from line to ground are incorporated. (Figure 76) Thyristor firing is accomplished by four-layer switching diodes such that a positive or negative potential above 400 volts will cause thyristor conduction into 40 m Ω loads for energy dissipation.

Figure 76. Protective thyristor assembly, PDX radial field amplifier. (804909)

At the end of FY80, design was well under way on a system to control TFTR gas injection, and to monitor and display gas pressure. This system is CICADA controlled and monitored. A microcomputer is employed to provide extremely flexible control of gas flow before and during the machine pulse. Modes available will include steady and pulsed flow, both with or without feedback, and the capability of preprogrammed flow options that permit arbitrary flows during a machine event.

Preamplifiers for use with silicon surface barrier type x-ray detector arrays on PDX were designed, built and installed. Twenty amplifier cards plus a circuit card used for checking calibration are contained in each amplifier module. Each amplifier card is equipped with an auto-zero loop to correct for detector dark current, and a calibration driver, both actuated from the timer.

A large number of electronic units for various diagnostics applications on TFTR were designed and fabricated by this section. In addition, the number of previously designed operational units on existing machines was expanded to meet increased experimental requirements.

Instrumentation Section

The prototype of a gridded ion chamber x-ray detector to be used on TFTR (Fig. 77) was designed and fabricated. This detector type was chosen because of its greater immunity to radiation damage compared to that of the silicon surface barrier detector. The prototype was tested on the PDX machine and was found to perform with sufficient speed (thought to be a questionable parameter for the chamber detector) for the application.

Figure 77. Disassembled gridded ion chamber prototype for TFTR. (804939)

A multichannel interferometer¹ was completed and installed on the PDX machine. Operating at 140 GHz and comprising 10 channels, this system has several features made necessary by the physical and electrical characteristics involved in the PDX application.

Space considerations, and the fact that the plasma paths are unequal due to vacuum vessel and divertor coil construction, made it imperative to depart from the normal interferometer design and fabrication practices. For PDX, the two signal sources (one for each five channels) and associated electronics are separated from the power splitters and other appurtenances for transmission and reception.

The system has been used successfully on PDX to obtain data on plasma density profiles.

Two similar feedback control systems for ICRF high power generators operating at 25 MHz and 42 MHz were designed and installed for use on PLT. Each system serves to aid in producing an output rf pulse shape that is reasonably close to that selected by the user in spite of plasma load variations encountered during the pulse.

Additional section activities for the year included: completion, test, and calibration of a two-channel, 75-115 GHz receiver for PDX electron temperature measurements; installation of a 147 GHz - 170 GHz radiometer for PLT; development progress on a 1-mm interferometer for TFTR; and a large amount of engineering design work done to improve diagnostics on the active experimental machines.

Diagnostics Projects Section

While budget limitations kept the manpower level low for this section, significant progress was made in moving a number of diagnostics from concepts to the preliminary design stages. The more important details of this work are described as follows.

- **Electron Beam** — The design approach was revised, cutting estimated cost in half.
- **Rogowski/Diamagnetic Loops** — Various methods of coil mandrel fabrication were investigated, and a search was conducted for high temperature and radiation resistant wire and insulating materials.
- **Neutron Collimator** — The effects of plasma viewing requirements on various collimator positioning techniques were studied.
- **Microwave Interferometer** — A system specification defining performance parameters, local and automatic control functions, and CICADA interface was written.

- **Plasma TV** — The periscope design was reviewed and a tradeoff study initiated to improve access capability.
- **X-Ray Imaging System** — Mass storage concepts were reviewed, including the FM magnetic tape method developed by Scientific Applications, Inc.
- **Neutron Activation System** — The design approach was revised, greatly simplifying irradiation site configuration and improving the remote maintenance capability.
- **Epithermal Neutron** — A system electrical definition was produced, and a specification for a multi-decade counting amplifier was written.
- **Neutron Test Laboratory** — Specifications were developed and vendors were evaluated for a "stand-alone" computer system to be used in the neutron test facility.
- **Grounding** — The conceptual approach and specification of the power and grounding system for all diagnostic electrical racks and modules used in the TFTR facility was generated.
- **Radiation Studies** — A test program for evaluation of mass memory storage devices under radiation conditions expected in the facility basement and data acquisition areas was set up and coordinated.

Electro Optics Section

An improved bolometer system for the TFTR array was developed to measure radiated power from the plasma. Unlike the units used previously on PLT and PDX, the new unit employs a 3.5 micron thick platinum film resistor. The Pt film absorbs the radiation, changing its temperature and resistance as a result. This device will not incur damage from the neutron and gamma ray environment associated with TFTR.

The section, in coordination with the Diagnostics Projects Section, engaged in engineering design, estimating, testing, and evaluating components and systems to be used on the TFTR. Included were: components for Thomson Scattering; CCD's; plasma TV periscope; a microprocessor controlled CCD Camera; and the Video Data Acquisition System.

Mechanical Engineering Section

Four new ICRF antennae (load coils) complete with machinable glass ceramic covers, Faraday shields, high-voltage vacuum feedthroughs, and coaxial transmission line sections, were designed, fabricated, and installed for use on PLT.

An optical system (Fig. 78) incorporating a variable speed fast rotating mirror in a helium atmosphere, combined with a monochromator, was completed for PLT during the fiscal year. It allows repeated scanning of selected spectral lines in the visible and near ultra-violet range of a tokamak discharge.

Figure 78. Scanning optical system for PLT. (803057)

Another device completed during the year was a scanning bolometer assembly for the PLT. The assembly consists of a small anodized aluminum plate on which a set of three thermally and electrically isolated bolometers are mounted. The assembly can be moved linearly and angularly.

Other devices completed during the year were ICRF antenna probes for PLT and a window changer for TFTR. Mechanical design and fabrication of assemblies for the PDX microwave scattering system and an x-ray wave detector for that machine were also completed.

Piping, valves, and controls necessary for running confinement system (C.S.) deionized water through the system's two 1825-ton chillers in parallel or series were completed early in the year.

Controls Section

Remote and local controls provided for various PDX diagnostics were improved or completed, extensively documented, and maintained. Among them were controls for limiters, the x-ray pulse-height analyzer, bolometer, monochromator, fast probe, Thomson Scattering, and CO₂ laser scattering experiments. Controls for the FIDE fast ion diagnostic experiment were being installed at the end of the year. Preliminary engineering for the CO₂ laser fluctuation experiment (Bell Labs/PDX) was completed and most associated equipment had been ordered, also by the end of the year.

PDX getter controls were tested. In order to simplify PDX operations, these controls were aug-

mented with individual regulators, feedback controlling getter power rather than current.

PDX and PLT machine operating controls were maintained and upgraded as required. PLT lower hybrid controls were installed. A large number of various controls and protective feature modifica-

tions were required to accommodate PDX coil circuit changes, including those for the Radial Field Amplifier.

An area interlock system was installed to restrict access to the 4th floor and crane ladders in PDX and PLT areas during high current plasma operations.

A CAMAC based coolant flow monitoring system for thermal protection of the PLT TF, OH, and SF coils was installed. This system, using a local LSI11 microcomputer for remote intelligence, along with a 4K mailbox memory to facilitate communication with data acquisition computers, required significant software development as well as electronic design and fabrication.

A control system was designed, fabricated, and successfully operated for the mechanical full-scale mock-up of the TFTR neutron activation diagnostic.

RF Section

During the fiscal year the PLT ICRF program was followed in accomplishing the upgrading of the 25 MHz generator for operation at longer pulse durations, the modification of one 2.5-MW, 55-MHz generator to operate at 42 MHz, and completion of the second 2.5-MW module with its transmission and coupling system. (Fig. 79)

Engineering design, construction, and testing accomplished for the PLT lower hybrid experiment scheduled for FY81 was another of the sec-

Figure 79. The PLT ICRF 2.5 MW HPA/HPA enclosure and portions of 6 1/4-inch transmission line system. (794399)

tion's activities. The object of the experiment is to demonstrate the viability of lower hybrid plasma heating with 1.2 MW of 800 MHz rf power.

One of the serious problems encountered in this heating method is that of the required high power density and consequent high electric field occurring inside the waveguide, especially with mismatched load. The problem becomes even more formidable when extremely long pulse oper-

ation is used. A test stand was set up in order to gain experience with and condition the guides to allow a 200 kW, 100 msec rf pulse to pass through each guide in vacuum without arcing (prior to operation into PLT). During the test stand operations a processing and conditioning procedure was established to eliminate the gas breakdown problem.

In short, it was found that vacuum baking the guides at 325°C (higher temperature causes guide warping) for 8 hours increased the power handling capability to 150 kW per guide, window arcing being the remaining limitation. The use of an rf conditioning (seasoning) process, in which rf is run through the guides at gradually increasing power levels was found to complete the solution to the problem. The test stand operations resulted in successful tests of all the major rf components of the system at the maximum power required, and the confidence in successful operation on PLT has been greatly enhanced.

REFERENCE

1. R. Bitzer, *et al.*, PDX Multichannel Interferometer, PPPL-1714 (October 1980) 37pp.

Fabrication, Operations and Maintenance

The Fabrication, Operation and Maintenance (FOM) Division was created in the closing days of fiscal year 1979 to provide PPPL with the services indicated. Elements of the previous Machine Design and Fabrication Division were incorporated in the new organization. FOM is made up of five branches, one independent section, a quality control function and a special projects group.

The five branches are Administrative, Coil Systems, Energy Systems, Installation and Maintenance, and Vacuum and Cryogenic Systems. Activity of the five branches are largely self explanatory. General descriptions are included in the following branch reports. The Engineering Services section reports directly to the Division Head and provides skilled technicians that work for the various branches on request. This section is also available to all groups at PPPL.

Quality Control (QC) consists of a group of five people organized to oversee the TFTR coil shop. They report directly to the FOM division head and are audited by the TFTR quality assurance group. The QC group was occupied one hundred percent on TFTR coils during FY80.

Special Projects is a group established in FY80 to support FOM as well as any other requests for design and/or execution of unusual engineering efforts. During FY80 the two major problems that it addressed were special supports for some PDX bus work and development of a "bow coil". The latter is a demountable type of "D" coil that could be helpful in future research machines and fusion reactors.

Major Activities

Coil Branch

During the year, the branch not only completed the major pieces of tooling required for the TFTR large coil program, but also wound and assembled most of the coils for the lower four stacks. By year's end, two of the four stacks were completed and awaiting potting; the third was completely wound; the fourth was 40% complete in the winding stage.

Fig. 80 shows the winding of Stack 8 coil (the coil diameter is 26 ft). A Stack 7 coil is seen in

storage on the winding spider. Fig. 81 shows the ground wrapping area with Stack 6 in the final stages. Fig. 82 shows a Stack 7 coil suspended on insulating slings ready for turn-to-turn electrical test. The coil casting oven (without the roof) and a trial set-up of the Stack 6 mold is shown in Fig. 83. The epoxy mixing tanks (the maximum batch mix is 200 gal) are in the foreground.

Figure 80. Winding station #2 — TFTR Large Coil Program. (804478)

Figure 81. Ground wrap area — TFTR Large Coil Program. (804474)

The majority of the branch's other efforts have been in support of the Spheromak Program. Two 1/8-scale flux cores have been built for the Proto-S-1 Device. Figure 84 shows the completed flux core toroid and Figure 85 shows the coil installed in the device. The Proto-S-1 device has been successfully operating to provide backup data for the full-scale S-1.

The design of the EF coil systems and the flux core for the S-1 have been 80% completed. Design of tooling for in-house fabrication of the EF coils has been started.

A shunt system has been designed and is under construction for the PLT. Alternate groups of three TF coils will be shunted to provide a TF field ripple as high as 6.2%.

Figure 82. Turn-to-turn test setup — TFTR Large Coil Program. (804345)

Figure 83. Oven and epoxy tanks — TFTR Large Coil Program. (804473)

Figure 84. Proto-S-1 flux core. (806883)

Figure 85. Installation of the Proto-S-1 flux core. (806884)

Energy Systems Branch

The Energy Branch was established during FY80 with the activation of the MG Operations Section which is the first of four operations sections. All MG operators and maintenance personnel were transferred from the Engineering Services Section to the MG Operations Section. The primary function of the section is to provide operations and maintenance, both preventive and corrective, and to minimize downtime of the experimental machines due to possible failures of their power supplies. Additionally, it provides technician support for new installations or modifications instigated by the AC Power Section of the Engineering Division, as well as a continuing program for updating the existing MG system. Anticipating the increased activities attributable to the imminent start up of the TFTR power supplies, the personnel of the maintenance group was very nearly doubled during FY80.

Figure 86. Signal patch panel for new 8-channel recorders. (804904)

Among major activities in this branch during the year was the acquisition of the four 8-channel, pressurized ink recorders which were installed to replace antiquated instruments on the MG duplex board. The recorders were installed with inspection designed patch panels which greatly increase their versatility and usefulness as a diagnostic and trouble-shooting tool (Fig. 86). A new dc circuit breaker tester was also installed to maintain and calibrate the high-speed circuit breakers (Fig. 87). The tester is air-cooled and supplied by a 480-volt, three-phase, 100-A pulse to a short-circuited breaker. This permits load-testing and calibration of spare breakers without any interference with existing operations. Finally, a 1.0-MVA power supply was provided for tests of the TFTR helium refrigeration unit.

Figure 87. New dc circuit breaker tester (30,000 amps dc). (804908)

In addition, the section continued to supply daily operation of the MG sets, the EF/SF and OH rectifiers, and the chilled deionized water systems in support of regular PLT, PDX and H-1 machine operations. At the same time, both the oper-

ator and maintenance groups began training in support subsystems that will be required for the start up of the TFTR MG sets.

Additional tasks undertaken during the fiscal year include:

- Installed sump pumps in cable vaults in the 138 kV yard

- Installed lightning arresters on the XQT-1 transformer

- Installed flexible connectors on XQT-2, XST-1 and XST-2 transformers

- Replaced insulators on VD-6, Sub-1 in 26-kV switchyard

- Installed vacuum contactors in Q6 switch house

- Grounded reactor pads in 138-kV switchyard

- Installed 4 kV metal-clad switch and primary power for LHRH

- Ran cable and hookup for TFTR power systems annunciator on Panel 18F in MG control room

- Hi-potted and meggered all new high-voltage installations before they were energized

- Made high-voltage terminations on pole transformers for neutral-beam power supply

- Cleaned tubes on both chiller condensers

- Altered design of voltage-divider mounts in high-speed breakers to eliminate continuing maintenance problem

- Obtained correct bearings for liquid rheostat electrolyte pumps and installed automatic greasers on these pumps and on all motor and generator blower systems

- Replaced selenium rectifiers with silicon rectifiers in the dc power supplies of the liquid rheostat controls

- Updated the control logic for the Hi-Tower control valve to minimize the possibility of cooling tower basin overflow in the event of power failure

- Repaired the rocking-arm voltage regulator for the dynamic breaking MG set

- Improved high-speed breaker test procedure to include checking of integrity of tripping coils

- Prepared initial sketch for plans to provide office space for the Energy Systems Branch.

Installation and Maintenance Branch

During FY80 the main effort of the I&M Branch has been the design and fabrication support of TFTR related projects. Included in this category were the continuing construction of the TFTR

mockups, the neutral beam calorimeters, the neutral beam support systems, the neutral beam test cell and the TFTR shielding. The Materials Testing Laboratory (MTL) was also heavily involved in the instrumentation and testing of TFTR components as well as planning for the TFTR power tests.

In November 1979, the Division accepted responsibility for the TFTR vacuum vessel mock-up. In an accelerated program, basic repairs were made to the vacuum vessel and the balance of the mockup was fabricated. The basic mock-up was completed by April 1980 and included the vacuum vessel, the inner support structure (ISS), the TF coils, and the lintels and columns. In subsequent months the PF coils and the umbrella structure were added (Figure 88).

During the year several activities took place in conjunction with mock-up development. These included trials of the remote cutter unit received from Grumman Aerospace Corporation for parting the TFTR vacuum vessel; fabrication, testing and redesign of the voltage loop and the neutron activation monitor for the diagnostics group; fabrication of the neutral beam duct mock-up to be used in handling trials; broken bolt removal and air drill trials to gain technical information for the TFTR maintenance programs; preparation for metal seal installation trials; and preparation for the fatigue testing of a vacuum vessel bellows.

Figure 88. The TFTR M-3 mock-up. (808022)

The machine shops were chosen to fabricate the neutral beam calorimeter mechanisms for the TFTR, and work started in January 1980. Two of the four units were completed late in the fiscal year, and the two remaining units are expected during the first half of FY81. The fabrication of the copper components was awarded to High Vacuum Equipment Corporation of Hingham, Mass., in February 1980. The first three units were received late in FY80, and the fourth unit was re-

ceived in October 1980. The instrumentation and assembly of the calorimeters was initiated late in FY80 and is expected to be completed by May 1981.

The fabrication of the TFTR neutral beam support systems was completed by Eagle Machine and Tool Company Incorporated of New York, with the final unit being delivered in March 1980 (Figure 89). Two units have been installed under the neutral beam vacuum enclosures.

Figure 89. Delivery of neutral-beam support system. (804154)

Design layouts of the shielding structure and support structure for the TFTR neutral beam test cell were completed, and detailed designs are now in progress. The shielding structure consists of precast, post-tensioned concrete wall, roof and longitudinal beam elements, which enclose the neutral beam device and provide shielding against neutrons generated by the ion sources. The shielding structure utilizes 24-inch-thick concrete and is designed so that internal framing support members are not required. The support structure consists of individual pedestals for the vacuum enclosure and target tank. Structural framework supports the forward bellows, transition duct and substitute absolute valve under the combined action of static, pressure and seismic loads. This work is scheduled to be completed by April 1981.

In March 1980, the I&M Branch took over the responsibility for the coordination of the mechanical design of the TFTR radiation shielding. Despite funding and manpower problems, a scoping study of the work requirements was completed together with a set of conceptual designs for the igloo shielding. In addition, several costing studies were produced.

During FY80, a total of 115 jobs were performed by the Materials Testing Laboratory (MTL). Among the long-term jobs were:

- Preparation for TFTR power tests

- Instrumentation of TFTR NB calorimeter
- PDX strain gage instrumentation upgrade
- Preparation for TFTR vacuum vessel bel-lows test

Approximately 25% of all work performed, was done directly for TFTR, approximately 60% for the coil shop, 10% for PDX and the remaining 5% for the vacuum shop.

As in previous years, the MTL maintained and loaned equipment, primarily recorders and signal conditioning systems, to all groups at PPPL. Maintenance of equipment has been facilitated by the addition of a senior level technician with extensive experience in the maintenance of electronic equipment.

The I&M Branch has provided resident engineers for the PDX and the TFTR devices. A continuing work load includes the coordination of the PIT/PDX trouble reporting system, the issuing of operational status reports, and the preoperational power testing and checkout of various auxiliary systems and equipment.

The analysis and design of the Engineering Test Station (ETS) was also performed by the I&M Branch. This device was designed to remotely locate and provide structural support for various blanket module experiments adjacent to the TFTR vacuum vessel. The project was funded by the Electric Power Research Institute (EPRI).

During FY80 the operations of the model shop were assigned to the I&M Branch. A model of the Engineering Test Station and two $\frac{1}{4}$ -scale models of the TFTR device were produced. Work has started on a model of the TFTR tritium systems which will be completed in FY81.

Vacuum and Cryogenic Branch

The Vacuum Section continued its responsibility for the design, fabrication, and installation of vacuum and cryogenic systems. It also remains responsible for initial start-up checkout of such systems, in addition to providing general support for maintaining and upgrading operating Laboratory systems.

An engineering staff does design work and a group of approximately fifty technicians fabricate and install vacuum system components.

The major effort during FY80 has been the assembly and testing of neutral beam systems. The PDX neutral beams were tested and repaired prior to installation. Two of the PDX neutral beams were installed during FY80. A much larger effort has been the TFTR neutral beam assembly, which began in October 1979. At that time, planning, design and ordering of assembly fixtures, stands,

cryo test facilities and tools was already in progress.

Figure 90. TFTR neutral beam vacuum enclosure #1 arriving at PPPL. (804164)

Figure 91. Cryo-module assembly area in operation. (804483)

During the first few months of 1980 the hardware and components for the neutral beam assembly began to arrive. The large assembly stands, the cryo test tank and a liquid nitrogen

Figure 92. TFTR neutral beam bending magnet during final assembly (804485)

transfer line were assembled and installed. In April the first two bending magnets arrived from Lawrence Berkeley Laboratory. In May the vacuum enclosure #1 arrived (Fig. 90). At that time, essentially all of the major component fabrication was in progress either in PPPL facilities or with outside vendors (Figs. 91 and 92).

During July two of the vacuum enclosures were in-house and mounted on their support structures for alignment and orientation (Fig. 93). The magnets were in the process of being installed and optically aligned. The assembly of cryo-modules continued and module #1 was ready for full testing at cryogenic temperatures under vacuum (Fig. 94).

Figure 93. TFTR neutral beam vacuum enclosure #2 being unloaded. (804487)

Work on the first calorimeter progressed rapidly and on schedule. By the end of September the first cryo-array, consisting of eight cryo-modules, was completed and ready for mounting on the vacuum enclosure lid. Except for the instrumentation connection, calorimeter assembly #1 was essentially completed.

Figure 94. Cryo-module #1 under vacuum and cryo testing (804490)

Other projects actively supported by the Vacuum and Cryogenics Branch include TFTR vacuum seals, the TFTR diagnostic neutral beam, the S-1 vacuum system, and technician support for machine diagnostics.

Engineering Services Section

This section provides tradesmen for all branches of FOM and any requesting experimental activities at PPPL. Trades available include carpenters, electricians, metal smiths, plumbers, welders, millwrights and general technician service.

Service by this group in FY80 was concentrated in support of TFTR projects. Expansion of the coil winding capability for large coils made possible winding of Stacks 8 and 9 on the "small" winder. In addition, a full crew of technicians was supplied to the Coil Branch, enabling TFTR coil

fabrication to go on three shifts. Technicians were also provided to support the Vacuum and Cryogenic Branch in their work on the TFTR neutral beam assemblies. A small but continuous effort was also supplied on both the M-2 and M-3 TFTR mock-ups. This included updating to follow design changes and development of assembly and remote handling techniques.

In other areas of PPPL, Engineering Services provided operating support to PLT and PDX and assisted with the installation of neutral beams on PDX. The Proto S-1, a spheromak device, was built and put into operation during FY80. Engineering Services technicians provided a large portion of the manpower for the fabrication of Proto S-1.

Projects Office

During FY80, the Projects Office was established in the Technology Department. This office is a division-level office reporting directly to the Head of the Technology Department. The primary responsibility of this office is to assure uniform management of PPPL projects in the range of 1-50 million dollar total estimated cost. This includes proposal preparation, cost and schedule, definition of the scope of work, technical interface control, design review, quality assurance and safety review.

The first project to come under the purview of the Projects Office was the ORNL/PPPL PDX 6-Megawatt Neutral Beam Project, undertaken jointly by PPPL and Oak Ridge National Laboratory (ORNL). The technical scope provides for the fabrication and installation of four beamlines on PDX. Each line will be capable of injecting 1.5 megawatts of 50 keV neutrals. Pulse length will exceed 300 msec. The existing PLT power supplies will be upgraded to provide the 50 keV energy and made transferable between PLT and PDX.

The Oak Ridge National Laboratory (ORNL) has responsibility for the development, production and qualification of the 1.5 megawatt sources (Fig. 95). They also provide the calorimeters and their enclosures, as well as doing the bulk of the beamline mechanical design. PPPL has responsibility for the power systems, system integration, beamline manufacture, installation and overall project management.

The ORNL/PPPL PDX 6-Megawatt Neutral Beam Project was started in April of 1978 and was originally scheduled for completion in December of 1979. Project total estimated cost is \$12.2 million. During fiscal year 1980, all power systems for this project were completed, the four beamlines were completed, and six sources were fully qualified. The six sources include four production sources, one spare and the prototype.

Development of the PDX ion source by ORNL is an outstanding success, achieving 2 MW and 53 keV for 100 msec and 1.5 MW and 50 keV for 500 msec.

Two beamlines were installed on PDX by June 1980 and operated to full power (Fig. 96). Installa-

Figure 95. Fifty-keV, 1.5 megawatt neutral beam ion source. (808104)

tion of the remaining two beamlines was deferred to the first quarter of fiscal year 1981 to facilitate PDX experimental operations. Actual costs for this project will not exceed the total estimated cost.

In June 1980, the Projects Office was asked to accept responsibility for the PDX Electron Cyclotron Heating Project. Two gyrotron oscillators will be used to provide 400 kW of 60 GHz heating to the PDX plasma. The project was defined during fiscal year 1980, a management plan was prepared and area preparation was undertaken. Actual fabrication and installation will take place in fiscal years 1981 and 1982.

Figure 96. First of four 1.5 megawatt beamlines in place on PDX. (804153)

Computers

During FY80 the two laboratory staffs supporting the Data Acquisition System (DAS) and the PPPL Computer Center, consisting of the User Service Center (USC) and the General Purpose Computer (GPC), were combined to form the Computer Division of the Technology Department.

The Computer Division is responsible for the planning, implementation, and maintenance services for these three systems. The Division is divided into four groups: an Applications Programming Section provides the scientific programming support for PLT, PDX, and TFTR data analysis; the Systems Programming Section develops operating system enhancements and maintains the software for these systems; an Operations Section schedules the operators in the two computer rooms housing the DAS and the USC-GPC computers; and a Hardware and Special Projects Section is responsible for the Laboratory's data communications facilities and for data acquisition.

Major Activities Data Acquisition System

During FY80, the DAS has continued to provide an increasing range of services to the PLT and the PDX experiments. The number of diagnostics and the volume of data recorded on PDX has increased approximately 50% during FY80. Currently 1.4 million bytes of data from 34 diagnostics are being stored for each PDX pulse. Some major accomplishments this year include: the completion of a new display system that allows the automatic plotting and hard copying of a series of displays in the control room; the conversion of the CAMAC system to a commercial fiber-optic link which increases reliability and noise immunity; and the introduction of support for an arbitrary waveform generator. The arbitrary waveform generator produces the reference voltage waveforms needed to produce and control the plasma discharge. The computer support allows exact recording of these waveforms for subsequent replay, and also allows interactive programs to be used to modify the waveforms.

Increased use was made of a facility called the archive database during FY80. This database collects machine parameters, some reduced physical results (e.g., plasma current and density), and operator comments. Reports generated from this database are used to review earlier work to develop more detailed data analyses.

User Service Center

The terminal system that was developed originally for the USC and the GPC has been expanded considerably to include the DAS KL-10 and the DAS VAX 11/780. Both the dial-up 1200 baud service and the many terminals at C-Site, including those in the LOB, can select entry to any one of the four computer systems.

A File Transfer Facility (FTS) has been developed that allows text files to be transmitted between the USC, the GPC and the Princeton University's IBM 3033. This has greatly improved the access of various groups throughout the laboratory to accounting system files.

General Purpose Computer

The General Purpose Computer will be decommissioned sometime in FY81. Plans to accommodate the users of the system on other Laboratory computers, the University computer, or the National Magnetic Fusion Energy Computer Center in Livermore, are under development.

TFTR Support

A separate group within the Applications Section has been formed to work on the development of the TFTR diagnostic software. This group has been writing user requirement documents and software functional specifications. They have designed and developed a CICADA applications program in support of the TFTR Charge Exchange Calibration Lab and they are converting the PDX X-Ray Imaging diagnostic to the CICADA system.

Administration

Fiscal Year 1980 was very active for the Laboratory administration. The Administration Department continued to experience rapid growth in both activity and in physical plant. At September 30, 1980, the physical plant space had grown to 802,780 gross square feet (GSF), an increase of 37% over the preceding fiscal year.

	Government Owned (GSF)	University Owned (GSF)
A Site	43,982	158,298
B Site	0	73,500
C Site	527,000	0
Total	802,780 GSF	

The total Laboratory staff increased 15% by the end of FY80, while the Administration Department's staff grew by 11%. The composition of PPL at September 30, 1980 was as follows:

Faculty	4
Physicists	110
Engineers	226
Technicians	524
Others	348
Total	1,212

Personnel

The major thrust of the Personnel Office program in FY80 centered around the complete redesign of salary administration and the continued heavy volume of recruiting and selection activities.

Within the area of salary administration, the Personnel office redesigned the classification structure (Ranks) and salary ranges of the Engineering and Scientific Staff, Administrative Staff, Research Staff (structure only) and the Material Control and Transportation Staff. The implementation of the new classification systems for the Laboratory and Shop Staff and the Office Staff is planned for FY81.

Additionally, the office developed a competitive salary policy. Effective with the FY82 salary

review cycle, all merit increases will be administered on 1 October rather than July. The Compensation Section of Personnel established job evaluation committees for the purpose of evaluating the job level of existing staff and new positions.

In the area of recruiting and selection, Personnel continued an extensive hiring program. Approximately 300 employees were hired during the fiscal year. Several new programs were undertaken, designed to generate a greater applicant flow. These included: college recruiting; a new advertising campaign; attendance at professional career and minority placement workshops; and open house recruiting sessions.

Additionally, the Personnel Office developed, in draft form, a Personnel Practices Manual.

A Training and Development Manager joined the Laboratory and has initiated several technical training programs, supervisory development workshops and performance appraisal seminars.

Plant

Fiscal Year 1980 was a significant year for the Plant Engineering Division. The new Laboratory Office Building (LOB), occupied in December 1979, was the first in a series of TFTR-related facilities which will become operational during the early 1980s. In June of 1980, a new central chiller plant and its cooling tower were placed in service, providing chilled water through a new distribution system to the LOB and to other TFTR-related spaces.

In the area of plant maintenance, the Laboratory averaged approximately 25 work requests per day, or 6,250 work requests for the year. The planning and scheduling process was streamlined to identify high priority work.

Security has also been in a state of transition. A new card access system was initiated to provide better security for high-risk areas.

The transportation services section initiated a fuel conservation program, and has organized a Driver Energy Conservation Awareness Training Program (DECAT). Through the conservation program and with excellent cooperation from the

Laboratory staff, we were able to achieve an 18% reduction in fuel consumption over the past two years. The anticipated introduction of gasohol to the fuel inventory, and a new dispensing and monitoring system, will help us to maintain this reduced level of consumption. On August 18, 1980, the DECAT was initiated. This program will teach drivers to operate vehicles in a more fuel efficient manner, resulting in better gas mileage, lower maintenance costs, and reduced accident rates.

Energy conservation, in general, is becoming an ever-increasing factor in the operation of the Laboratory. During FY80 more than one-third of our janitorial crew was shifted to daylight hours to reduce the need for lights at night. Boilers were shut off during evening and weekend hours in the spring and fall. This resulted in a significant savings. Fuel oil consumption at C-Site alone was reduced from 446,000 gallons in 1974 to 342,000 gallons in 1979. At the same time, the building area at C-Site has increased from approximately 328,000 gross square feet (GSF) to a current total of approximately 527,000 GSF. Through the first 10 months of calendar year 1980, the Laboratory realized a 30% reduction in fuel consumption at C-Site, as compared to the same 10 months in 1975, while building area increased 61% over the same period. Compared to old consumption rates, this reflects a saving of over \$425,000 per year on C-Site fuel alone. A concerted effort by the Plant Engineering staff was required to achieve these savings while trying to minimize discomfort to employees, who have had to work with temperature settings of 65°F during last winter and 78°F this summer.

Facilities Construction

During FY80 several facility addition and improvement projects were undertaken by the Laboratory in support of the ongoing experimental

work. Construction of the TFTR Experimental Complex progressed rapidly. Major milestones were achieved during the summer with the completion of the new Motor/Generator Building and installation of the motor/generator sets was begun; the test cell roof beams were put in place and installation of the removable west wall of the test cell was begun at the end of the summer. Power yards and power supplies were installed for testing and development of the PDX and TFTR neutral beams, and an assembly and storage building for TFTR components was completed at C-Site.

The 95,600 GSF Laboratory and Office Building for TFTR and DOE staff was completely occupied by June. Installation of the TFTR Control Room equipment is underway. In addition, about \$500,000 was spent on general facility modification of existing space at A, B and C-Sites (see Table V).

Presently under construction is a much needed expansion of the Laboratory's Research Library, and an addition containing shops, laboratories, and offices for the research staff (see Table VI). In the planning stages are a number of facility improvement projects, as well as several new buildings to house the Laboratory's new experimental programs, and other activities related to its expanding role in the nation's fusion effort (see Table VII).

Emergency Services

A full-time Manager of Emergency Services was appointed in July, 1980. This new position has the responsibility of the fire fighting unit, first aid squad and heavy rescue team. A comprehensive evaluation of the unit's equipment, direction, management and personnel has now been completed. The unit is participating in a training program designed to expand the knowledge, confidence and expertise of all specialties.

TABLE V
COMPLETED PROJECTS

1. Maintenance Building Addition 6,000 GSF	\$595,500 Page Funds	6-80
2. Laboratory Office Building 95,600 GSF	\$5,820,000 Page Funds	6-80
3. Neutral Beam Power Supply Yard & Rectifier Test Stand	FY80 Operating Funds	9-80
4. Substations 18 & 19	1978 GPP Funds	9-80
5. Component Assembly & Storage Building 15,000 GSF	\$451,000 1979 GPP Funds	6-80
6. "C"-Site Sitework & Roadway Improvements	\$100,000 1978 GPP Funds	9-80
7. General Facility Modifications	\$500,000 1980 Operating Funds	9-80

TABLE VI
PROJECTS UNDER CONSTRUCTION

1. Laboratory Building, North Addition 4,200 GSF	\$477,000 1979 GPP Funds	3-81
2. Library Addition 2,800 GSF	\$485,000 1980 GPP Funds	3-81
3. TFTR Experimental Complex	Pace Funds	82

TABLE VII
PROJECTS IN PLANNING

1. LOB First Floor Offices 4,200	\$70,000 1980 GPP Funds	3-81
2. Emergency Vehicle Building 2,000 GSF	\$196,600 1978 GPP Funds	6-81
3. "C"-Site Perimeter Road & Drainage Improvements	\$75,000 1980 GPP Funds	6-81
4. Maintenance Building Office Addition 2,500 GSF	\$260,000 1980 GPP Funds	1-82
5. Experimental Research Wing Phase I 5,500 GSF	\$600,000 1981 GPP Funds	3-82
6. Experimental Research Wing Phase II 11,520 GSF	\$1,000,000 1982 GPP Funds	3-83
7. MG Building Office Addition 2,500 GSF	\$275,000 GPP Funds	
8. 1-F Clean Room Addition 2,500 GSF	\$275,000 GPP Funds	
9. Chilled Water System Improvement & Central Plant Chiller Installation	\$420,000	3-82

Rules and regulations have been designed and implemented to facilitate the future establishment of a full time Emergency Services Group. Additionally, procedures have been instituted for scheduled operations checks on all emergency vehicles and equipment.

The recent acquisition of a used 1,000 gallon per minute (gpm) fire pump has increased our response equipment to six vehicles. Currently, Emergency Services' vehicles consist of two 1,000 gpm fire pumpers, one ambulance, one heavy rescue truck and two chemical trucks.

With the cooperation of the Princeton University Security Office, an "Emergency Evacuation and Response Plan" is being developed. This plan will provide for fast and safe employee exits during any emergency situation that may develop within any structure at PPPL.

Accounting and Financial Control

During FY80, budget control methods were changed. The major revision was to control spending at the subprogram level. The revisions also required substantive changes in the procedures used for recording financial transactions

and in methods of projecting costs and expenses to year-end.

In order to meet these requirements, new systems and procedures were designed and implemented as follows:

- A method of projecting payroll costs to improve usefulness of financial reports in projecting operating costs to year-end including a subsystem for projecting the cost of employees to be hired to fill authorized positions.
- A method of charging-out the cost of sub-contract employees as Tech Center Labor when employed by the Tech Shops as supplemental work force.
- Automating the allocation of the scientific support cost centers at month-end, thereby bringing the data into the financial records a month sooner.
- Monitoring internal commitments of Tech Center Labor.
- Monitoring and controlling the delivery of materials under purchase orders and the costing of subcontracts to avoid cost overruns.

As a result of these changes in accounting methods and procedures, PPPL completed the four DOE Annual Operating Budgets (which totaled over \$50 million) within the prescribed limits

and with minimum underspending in each subprogram. A budget breakdown can be seen in Table VIII.

TABLE VIII
PPPL FINANCIAL SUMMARY (\$K)

PROJECT	1976/76A	1977	1978	1979	1980
Operating (B/O)					
CLOSED CONFINEMENT:	<u>27,634</u>	<u>23,073</u>	<u>23,883</u>	<u>22,887</u>	<u>28,623</u>
PLT Fabrication	1,771	0	0	0	0
Operations (inc. ST)	8,060	7,304	8,082	6,891	8,564
Coil Test	615	314	0	0	0
Neut. Beam Pwr. Supp.	2,228	1,289	0	0	0
Test Stand	468	296	0	0	0
ICRF	72	1,035	1,022	1,165	595
PDX Fabrication	9,361	8,547	4,528	746	53
Operations	2,664	3,608	8,258	10,989	10,067
N.B.	0	0	894	2,805	1,539
ATC	1,560	0	0	0	0
FM-1	835	0	0	0	0
H-1	0	666 ^a	522	291	205
Other	0	14 ^b	577	0	0
TFTR Diagnostics & Research	0	0	0	0	7,600
DEVELOPMENT & TECHNOLOGY:	<u>4,079</u>	<u>599</u>	<u>114</u>	<u>358</u>	<u>360</u>
H-1	838	0 ^a	0	0	0
Reactor Studies	427	456	0	0	0
Two Component Torus	2,814	0	0	0	0
Advanced Tokamak Studies	0	120	114	0	0
Other	0	23 ^c	0	0	304 ^d
Fusion Systems Engineering	0	0	0	358	56
RESEARCH:	<u>3,788</u>	<u>3,005</u>	<u>3,170</u>	<u>3,903</u>	<u>4,758</u>
Theory	2,530	2,008	2,378	2,459	2,438
Basic Experiments	1,000	668	638	1,161	2,010
User Service Center	258	329	154	283	310
REACTOR PROJECTS:	<u>1,325</u>	<u>10,556</u>	<u>13,080</u>	<u>19,406</u>	<u>16,400</u>
TFTR R&D	1,325	9,991	11,820	16,360	4,744
Research	0	241	640	975	4,885
Operations	0	324	620	2,071	6,771
TOTAL	<u><u>36,826</u></u>	<u><u>37,233</u></u>	<u><u>40,247</u></u>	<u><u>46,554</u></u>	<u><u>50,141</u></u>
Equipment (B/A)					
Capital Equipment Not Related to Construction	3,277	5,190	5,140	4,230	6,930
Construction (B/A)					
TFTR	20,500	75,000	71,000	38,844	21,468
General Plant Projects	950	1,455	1,350	1,250	1,000
PDX Neutral Beams	0	0	0	0	1,100

a) H-1 moved from Development and Technology in 1977.

b) People Injection Coil.

c) EPR RF Heating.

d) Fusion Reactor Material.

Management Information Systems

The MIS Branch experienced significant growth in the application areas served with data processing services, including the addition of an automated system for tracking purchase orders, an interactive terminal interface for allocation of period costs, a microfiche reporting system, and the introduction of a stockroom cataloging system.

These software extensions were coupled with additional hardware extensions. The number of terminal networks doubled from three to six, and the number of interactive terminals on the networks increased proportionately.

Significantly, all systems in place were maintained and kept functional during this period of expansion, and interfaces required for integration of old system with new ones were kept intact.

Procurement

During the year, 11,948 procurement actions with a total value of \$26.4 million occurred. This represented an increase of 17.8% in procurement actions over FY79 and a 32.6% increase in procurement dollars. These figures break down between purchasing and subcontracts as shown in Table IX.

In December 1979, a decision to implement the Procurement Automatic Data System (PADS) was reached. Purchase order data entry commenced in February, receiving report entry began in May, and requisition entry — formerly performed by Accounting — began in August. Currently, PADS report capability includes listing purchase orders in day sequence, summarizing purchase orders by source and type of business, producing receiving histories, identifying overdue purchase orders and other refinements.

In April, DOE required Public Law 95-507 reporting of the Laboratory. The Laboratory now submits a subcontract plan to DOE identifying both the estimated procurement dollars for the fiscal year and percentage goals of these dollars that will be awarded to either small business or small disadvantaged business. In addition to the subcontract plan, PL 95-507 also requires that all procurement actions in excess of \$100,000 be

advertised in *Commerce Business Daily*. As a result of these requirements, more formal records of transactions by size and type of business are now maintained.

Material Control

Substantial gains were made by the Material Control Branch this past year toward improving supply support to the Laboratory. The number of items carried in the storerooms was increased from 13,000 to 15,500 and a free goods area was established for use by customers. A van was obtained to expedite priority requirements and stock transfers, and a walk-in refrigerator was purchased for storage of shelf-life items. Additional stockroom space was acquired, but with the continuing growth of the Laboratory, space was a limiting factor in providing premium customer support. The Belle Meade storage area continued to grow from 10,000 sq. ft. in 1978 to 30,000 sq. ft. in FY80.

The stockroom inventory level exceeded \$800,000, while process spares and capital equipment inventories rose to \$8.5 and \$40.0 million respectively. Storeroom sales increased from \$655,000 in 1979 to \$1.0 million in 1980. More than 51,000 stock withdrawals were processed. Eleven stock catalogs were published and distributed, with four additional catalogs due for completion.

Computer systems plans were changed from a general purpose computer to an IBM system which will allow for an integrated material management system, interfaced with Procurement and Accounting. Significant additional work is required to implement this information system, but the systems and operational changes planned by Material Control for the coming year will result in greater customer support throughout the Laboratory.

Health and Safety

The Health and Safety Branch continued its support of TFTR functions: review of blueprints and specifications; design review of coils, structure and the vacuum vessel; Safety Analysis Report (SAR); coordinating environmental monitoring systems; assisting in radiation damage

TABLE IX
Summary of FY80 Procurement

Section	Actions	%Inc.	Dollars	%Inc.
Purchasing	11,394	17.8	\$13,102,405	56.8
Subcontracts	554	17.4	13,287,518	15.0
Total	11,948	17.8	\$26,389,923	32.6

assessment programs; surveying equipment at vendors' plants; and providing DOE assistance on TFTR construction safety.

In February 1979, a dispensary was opened for PPPL employees. To date the dispensary has been staffed with a full-time nurse and with the expectation of employing a medical doctor in FY81 or FY82. In the past year numerous minor medical services have been provided: blood pressure checks; referrals for medical diagnosis; and coordination of workmen's compensation.

Health and Safety training efforts have continued in FY80. All new employees now receive a safety orientation. Employees receive training in oxygen deficiency prevention and electrical safety. Advance basic radiation safety training was given to select groups and training in crane/ forklift safety and chemical handling continues.

The statistics on lost work day cases (LWC) and lost work days (LWD) has shown a significant improvement from 1975 to 1979. If this trend continues PPL will reach or be below the DOE average in the near future. In 1975 our LWC = 3.5 and LWD = 37 exceeded the DOE average of LWC = 1.1 and = 18 (these figures are normalized to 200,000 hours/year or 100 employees). In 1979 PPPL had reduced its accident frequency with the result that the Laboratory's that LWC = 1.4 and LWC = 18 were closer to the DOE average of LWC = 1.0 and LWD = 16.

Library

The objectives of the Plasma Physics Library during FY80 were to continue planning for the library extension and to finish our recataloging programs. Work was started on the addition to the library June 12, 1980. It is anticipated the library will be ready for occupancy by January 1981.

During this year all monographs and journals were transferred from the defunct Princeton-Pennsylvania Accelerator Library and have been completely recataloged. Additionally, the journals and books were recataloged into the Library of Congress schedule; and the Fusion Power Library merger with the Plasma Physics Library will completed next fall.

The library's holdings grew by 857 volumes, the largest increase in any one year. A primary reason for the large growth is the transfer from Princeton University's Firestone Library of 270 older monographs and journals. Not only has this substantial transfer increased the holdings, it has also improved the general overall quality of the collection.

The journal collection was strengthened this year by the transfer of 121 bound volumes to the Plasma Physics Library. With the addition of thirteen new titles, the library now receives 134 journals, including gifts. Thirty journals are routed from other libraries for staff use.

The library has been in a recataloging project with the Firestone Library whereby the complete journal collection was cataloged and records were brought up to date. When the expanded library is reopened, the complete collection of journals will be made available, thereby substantially increasing our total journal collection.

Information Services

During FY80, media interest in magnetic fusion energy reached an all-time high as evidenced by the number of requests for information, telephone interviews and Laboratory visits from print and broadcast journalists. Laboratory visits were arranged and hosted for representatives of CBS News, *The New York Times*, the *Washington Post*, *U.S. News and World Report*, as well as for local news media. Toward the end of FY80, the Information Services Branch provided assistance to several feature magazines preparing articles on magnetic fusion energy. Included among these were *National Geographic*, *Discover*, *Smithsonian Magazine* and *New Jersey Monthly*.

As in previous years, Information Services arranged Laboratory tours and speaking engagements for technical societies; industrial, educational and public interest groups. The Laboratory's brochures and information bulletins were updated to communicate recent experimental results on PLT and PDX and progress on the construction of TFTR.

In the area of employee information, the *PPL Hotline* was introduced as a means of rapidly communicating timely information Laboratory-wide. A General Writer was added to the Information Services Branch and given primary responsibility for the writing, editing and production of employee publications.

The need for photographic, illustrations and printing services increased during FY80 in proportion to Laboratory growth and the number of technical illustrations generated monthly during FY80 increased an average 30% over the previous year.

The Printing Services Section experienced a similar increase in demand with the total number of printing/duplicating impressions 20% over the FY79 level.

Graduate Education: Plasma Physics

Fostered by the physical proximity between PPPL and the academic departments on the main campus of Princeton University, a program of graduate studies in plasma physics has been pursued since 1959. Table X lists courses in the department. Seventy-nine physicists have now received doctoral degrees in this field. Many key positions for plasma research and technology in academic, industrial, and government institutions are today held by Princeton graduates. The teaching faculty for the plasma physics program, in Princeton's Department of Astrophysical Sciences, currently numbers nineteen members (listed in Table XI) who offer a variety of courses to thirty-nine graduate students now in residence. In addition, many PPPL staff members serve as advisors to graduate students who thereby receive training at the forefront of plasma research. The benefits of the program are many: to the University, PPPL represents an international center of excellence in a branch of scientific research which has large potential for social benefit; to PPPL, the teaching opportunities offer constant challenge and stimulation; for the plasma re-

search community, the program is a key source of highly qualified young scientists and future leaders.

There is a strong interaction between PPPL and the group of graduate students in the plasma physics program in the Department of Astrophysical Sciences at Princeton. Most of these students hold Assistantships in Research at PPPL, through which they participate in the on-going experimental and theoretical research. First-year students this past year were found working with the various experimental groups, including the PLT, PDX, ACT-1, Q-1, QED, L-3, H-1, and Proto S-1 groups. Second-year students assisted a number of members of the Theoretical Division. In addition, PPPL physicists shared their expertise each week with the students at a student-run, two-hour, Tuesday afternoon seminar. The students are, of course, regular attendees at the Laboratory's own seminars and colloquia. All of this experience provides a natural transition to doctoral thesis research which, again, is carried out in collaboration with PPPL staff members. Twenty students in the Department are now engaged in their thesis proj-

TABLE X
PLASMA PHYSICS COURSES OFFERED AND INSTRUCTORS

Fall 1979

AS551	General Plasma Physics I	S. von Goeler and T.H. Stix
AS553	Plasma Waves and Instabilities	F.W. Perkins, Jr.
AS556	Advanced Plasma Dynamics	R.L. Dewar and G. Rewoldt
AS558	Seminar in Plasma Physics	C.R. Oberman

Spring 1980

AS552	General Plasma Physics II	R.M. Kuksrud and S. Yoshikawa
AS554	Irreversible Processes in Plasma	J.A. Krommes and C.R. Oberman
AS557	Advanced Mathematical Methods in Astrophysical Sciences	M.D. Kruskal
AS558	Seminar in Plasma Physics	C.R. Oberman
AS561	Special Topics in Magnetic Confinement	H.P. Furth and P.H. Rutherford

ects, the numbers evenly split between experimental and theoretical topics. A list of thesis projects completed this fiscal year under the plasma physics program at Princeton is given in Table XII.

The academic work in the plasma physics program is broadly based in modern physics. The study of plasma physics requires the folding together of knowledge from electricity and magnetism, atomic physics, hydrodynamics, statistical mechanics and kinetic theory, and applied mathematics, together with diagnostic and data-handling methods from state-of-the-art laboratory physics. Techniques from many disciplines within theoretical and experimental physics find immediate application in plasma research and, by the same token, experience with plasmas can be transferred back to other areas in physics. But equally important — plasma physics is itself a large field, a young field, and a challenging field where success in research will have enormous impact on reaching a satisfactory long-range solution of the world's energy problems.

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TABLE XI
ASTROPHYSICAL SCIENCES/PLASMA PHYSICS FACULTY

FACULTY MEMBERS

TITLE

Thomas H. Stix	Professor of Astrophysical Sciences and Associate Director, PPPL for Academic Affairs
Robert L. Dewar	Research Physicist and Lecturer with rank of Professor
Edward A. Frieman	Professor of Astrophysical Sciences
Harold P. Furth	Professor of Astrophysical Sciences
Melvin B. Gottlieb	Professor of Astrophysical Sciences
Raymond C. Grimm	Senior Research Physicist and Lecturer with rank of Professor
Predhiman K. Kaw	Senior Research Physicist and Lecturer with rank of 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	Senior Research Physicist and Lecturer with rank of Professor
Carl R. Oberman	Senior Research Physicist and Lecturer with rank of Professor
Hideo Okuda	Senior Research Physicist and Lecturer with rank of Professor
Francis W. Perkins, Jr.	Senior Research Physicist and Lecturer with rank of Professor
Gregory Rewoldt	Research Staff and Lecturer in Astrophysical Sciences
Marshall N. Rosenbluth	Visiting Lecturer with rank of Professor
Paul H. Rutherford	Senior Research Physicist and Lecturer with rank of Professor
William H. Tang	Senior Research Physicist and Lecturer with rank of Professor
Schweichard E. von Goeler	Senior Research Physicist and Lecturer with rank of Professor
Shoichi Yoshikawa	Senior Research Physicist and Lecturer with rank of Professor

TABLE XII
RECIPIENTS OF PH.D DEGREES

Robert J. Kleva	Thesis:	Aspects of the Statistical Theory of Stochastic Magnetic Fields: Test Particle Transport and Turbulent Collisionless Tearing Mode	January 1980
	Advisors:	John A. Krommes and Carl R. Oberman	
	Employment:	University of Maryland	
Richard Marchand	Thesis:	Two-Dimensional Eigenmode Analysis of the Trapped Ion Instability	October 1979
	Advisor:	William M. Tang	
	Employment:	University of Maryland	

Roger D. McWilliams

August 1980

Thesis: Current Generation and Damping of
Finite Amplitude Lower Hybrid Waves
Advisor: Robert W. Motley
Employment: Department of Physics
University of California, Irvine

James Randall Wilson

September 1980

Thesis: Ponderomotive Force Effects on Resonance Cones and
Slow-Wave Coupling Above the Lower-Hybrid Frequency
Advisor: King-Lap Wong
Employment: Princeton Plasma Physics Laboratory

Graduate Education: Fusion Reactor Technology

In December 1972, a program in Fusion Reactor Technology was formally established in the Department of Chemical Engineering of Princeton University's School of Engineering and Applied Science, in collaboration with the Princeton Plasma Physics Laboratory. This program was built upon a long association between the Department and the Laboratory dating back to 1955 when Professor E.F. Johnson undertook pioneering work in molten salt blankets for tritium generation.

TABLE XIII
NUMBER OF THESES

Molten Salts	7
Fast Neutrons	5
Radiolysis & Syntuels	3
Advanced Fuels, Plasma Heating, Use of Waste Heat	3
Chemical Engineering Miscellany	3
Hydrogen Permeation of Metals	2
Tritium Recovery	1

The twenty-four master's theses and doctoral dissertation subjects treated during this program's history are categorized in Table XIII, the Engineering School Faculty in Table XIV, and the courses offered in Table XV. In addition to these courses, graduate students are encouraged to take courses taught in the Astrophysical Sciences Department listed in Table X in the previous chapter.

Students graduating this year and students in residence with thesis topics are summarized in Table XVI. Support of graduate students in this program has been a continuing problem; so we are very pleased to have the opportunity to assist

the Oak Ridge Associated Universities in beginning the Magnetic Fusion Energy Technology Fellowship Program.

Department Curriculum

In addition to the graduate education program, the Chemical Engineering Department offers a strong undergraduate curriculum to stimulate interest in fusion. A minicourse on fusion is included in Engineering 101, a divisional course of the School of Engineering and Applied Science. Engineering 101 is primarily for A.B. students to satisfy their science requirement, but is frequently selected by entering freshman engineering students. Junior and Senior independent work is also sponsored in fusion in keeping with Princeton's tradition of undergraduate thesis work. The two 400-series courses are suitable for both upperclassmen and graduate students and are often elected by graduate students in this and other departments.

Chemical Engineering 417 welcomes each year a few members of the professional engineering staff of the Laboratory as auditors. These people are specialists seeking a broader understanding of aspects of the laboratory work that differ from their own. To date, about 20% of the engineering staff have participated. This arrangement provides a unique opportunity for students to associate with working professionals in the topic of the course. To reinforce this opportunity, a key feature of the course is a machine design project. The class is divided into two teams for a competition. The professional staff members are divided into three groups, two sets of consultants for the teams and a selection board to evaluate the final designs. Oral presentations before the board are a fairly realistic preview of the real world's contract selection procedures.

**TABLE XIV
ENGINEERING FACULTY**

Faculty	Title
Robert C. Axtmann	Professor of Chemical Engineering
Ernest F. Johnson	Professor of Chemical Engineering
Robert G. Mills	Head, Engineering Program, Princeton Plasma Physics Laboratory and Lecturer with Rank of Professor

**TABLE XV
CHEMICAL ENGINEERING COURSES RELATING TO THE FUSION TECHNOLOGY PROGRAM**

Course Number	Title	Faculty
351,352	Junior Independent Work	Staff
451,452	Senior Independent Work	Staff
417	Introduction to Fusion Power	R.G. Mills
418	Nuclear Engineering	R.C. Axtmann
550	Fusion Reactor Technology	R.G. Mills, Staff

**TABLE XVI
GRADUATE STUDENTS**

Student	Thesis Topic	Degree	Advisor	Status
John D. Wright	Economic Utilization of Thermal Waste from Fusion Power Generation	M.S.E.	E.F. Johnson	Granted (1979)
Loris Rossi	Use of Molten Salts for Fission-Fusion Hybrid Reactor System	Ph.D.	E.F. Johnson	Granted (1980)
Robert E. Buxbaum	Recovery of Tritium from Liquid Lithium using Yttrium	Ph.D.	E.F. Johnson	Imminent
Charles H. Davis, Jr.	Fueling of Fusion Reactors		R.G. Mills	(On leave of absence)
Kun Jai Lee	Alpha Heating Deposition	Ph.D.	R.G. Mills	Imminent
Hsing H. Tseng	Molten Fluoride Blankets	Ph.D.	E.F. Johnson	3rd Year
Mutlaq H. Al-Morished	Vacuum Wall	Ph.D.	E.F. Johnson	2nd Year
Peter C. Bertone	(Entering Student)	Ph.D.	R.G. Mills	1st Year
Thozhur M. Kasturirangan	(Entering Student)	Ph.D.	R.C. Axtmann	1st Year