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TFTR and Other Large Tokamaks

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Introduction

The near-term goal of fusion research is to produce deuterium-tritium plasmas with temperatures above 10 keV and Lawson numbers $n\tau_E$ above 10^{14} cm^{-3} sec. As indicated in Fig. 1, experiments entering this parameter range will be able to satisfy Lawson's break-even criterion, where the fusion power output equals the required plasma-heating-power input ($Q = 1$). The ultimate reactor goal is to reach equilibrium-burn conditions, where the energetic alpha particles generated by the D-T reaction are sufficient to maintain the plasma temperature against all heat losses ($Q = \infty$).

At the outset of the international controlled-fusion research effort in the 1950's, Lawson's goal seemed intimidatingly remote from experimental capabilities. During the following ten years, substantial scientific progress was made, but the rate of advance in the Lawson diagram was not such as to inspire confidence that the fusion program would reach fruition within the lifetime of its pioneers. The notable success of the Kurchatov Institute's T-3 tokamak during 1968-69 brightened the outlook considerably. The tokamak configuration was recognized as a cost-effective experimental tool and has permitted steady progress during subsequent decades.

World-wide recognition of the favorable experimental opportunity for entry into the reactor plasma regime led to the initiation, in the mid-1970's, of four large new tokamak projects (Table I). Plans for the Joint European Torus[1] (JET) were defined in 1971-73: the very large plasma size and high current of the JET plasma offered a potential for exceeding the Lawson break-even criterion and possibly even reaching ignition in D-T plasmas. The Tokamak Fusion Test Reactor (TFTR) was designed in early 1974 with more limited goals: the achievement of approximate break-even by the fusion reactions of energetic neutral-beam-injected deuterons thermalizing with a tritium bulk plasma.[2] For this "two-component" approach to break-even, plasma temperatures in the range 5-10 keV are still needed, but the Lawson number can be reduced to the low 10^{13} cm^{-3} sec range. The JT-60 device was designed at approximately the same time to carry out a program of sophisticated divertor and radio-frequency heating experiments in hydrogen plasmas.[3] Soviet plans were initially focussed on achieving reactor-level D-T operation, using the very large T-20 facility, but were revised in the latter part of the 1970's towards long-pulse hydrogen-plasma studies in the smaller T-15 device[4] -- the only one of the "big four" tokamaks to introduce the advanced technology of superconducting toroidal-field coils. TFTR, JET, and JT-60 are now in experimental operation, and the construction phase of T-15 is nearing completion.

2. Initial TFTR Experiments

In the early morning hours of December 24, 1982, TFTR produced its first plasma -- a 50-kA tokamak discharge lasting 50 msec. A schematic of the TFTR device (Fig. 2) shows the basic configuration of the machine. Meanwhile, the TFTR plasma current and toroidal magnetic field strength have been brought up to their full design values (Fig. 3), and the four neutral-beam lines have been installed (Fig. 4). Initial beam-heating experiments have ranged up to 14 MW, using deuteron energies of ~90 keV. During 1986-87, the TFTR neutral-beam system will be raised gradually to the 27-MW, 120-keV level, with pulse durations up to 2 sec. To handle the very large associated heat loads (~50 mJ), the small-R side of the vacuum vessel has been armored with a continuous "bumper limiter" made of graphite tiles (Fig. 5). At plasma densities above $\sim 5 \cdot 10^{13}$ cm^{-3}, the resultant plasma purity has proved to be quite satisfactory ($Z_{eff} = 1-2$), even for neutral-beam-heating powers in the 10-MW range.

Initial ohmic-heating experiments[5,6] (Fig. 6a) reached energy confinement times above 0.4 sec and confirmed the "neo-Alcator" scaling law for τ_E, which is notable for its proportionality to plasma density and its favorable cubic dependence on plasma size. Experiments raising the density into the range above $5 \cdot 10^{13}$ cm^{-3}, however, proved the existence of a clear τ_E-saturation phenomenon (Fig. 6b). This finding supported the overall confinement-scaling model proposed for tokamaks in Ref. 8: As the plasma pressure is raised either by increasing the density or the temperature, the favorable neo-Alcator scaling gives way to Goldston-type scaling, with τ_E decreasing in roughly inverse proportion to the poloidal beta value $\beta_p = 8\pi\ nT/B_p{}^2$, where B_p is the poloidal field strength. While an ultimate limitation of β_p is to be expected on the basis of MHD stability theory, the early onset of the Goldston phenomenon is clearly anomalous -- as well as problematical for the achievement of ignition conditions in a tokamak plasma of moderate size.

This inauspicious trend was confirmed in TFTR. While the use of beam-heating powers in the 10-14 MW range permitted the achievement of high central plasma temperatures at moderate plasma densities [$T_i(o) \gtrsim 10$ keV, $T_e(o) \gtrsim 5$ keV, at $n(o) \lesssim 5 \cdot 10^{13}$ cm^{-3}], the general scaling of confinement followed the Goldston model (Fig. 7). Since this type of scaling law corresponds to a heating-power dependence of the form $\tau_E \propto P^{-1/2}$, with the temperature increasing only as $P^{1/2}$, the projected values of $n\tau_E$ and $T(o)$, even using the full heating powers available on TFTR, would be limited well below the Lawson curve.

Since the TFTR experimental strategy was based on quite prudent expectations in regard to anomalous tokamak confinement, the original TFTR project goals are expected to be readily achievable even on the basis of Goldston scaling. The TFTR plan calls for the production of "1-10 MJ of fusion energy in plasmas of 5-10 keV temperature and $n\tau_E$-values of 10^{13} cm^{-3} sec." These specifications correspond to the attainment of approximate break-even conditions by means of the two-component energetic-ion reactions. The demonstration of the corresponding plasma regime would open the way to a capability for efficient generation of quasi-steady-state D-T neutron fluxes. Experiments that will successfully prototype this operating mode in D-D plasmas are expected to be carried out in TFTR during 1986-87.

Meanwhile another interesting experimental option has developed on TFTR, which may turn out to be of considerable long-term significance to the development of the tokamak reactor concept. When the central plasma density is raised to high values by means of pellet injection (Fig. 8), the relaxation time $\tau_p(o)$ of the central density profile is found to be remarkably long[9,10] -- corresponding to $n(o)\ \tau_p(o)$-values well above the $3 \cdot 10^{14}$ cm^{-3} sec level required for ignition. Under these conditions, the nominal Lawson number $n(o)\tau_E$ is in the range 1.0-$1.5 \cdot 10^{14}$ cm^{-3} sec. [In view of the substantial fraction of radiation cooling -- including hydrogen

Bremsstrahlung at ~20% of the input power level -- the Lawson parameter describing purely transport-related heat losses within the central plasma region is actually considerably larger than the quoted $n\tau_E$-number.]

As indicated in Fig. 8, the plasma temperatures associated with the high-density TFTR regime are still only in the ~1.5 keV range; however, the prospects of combining the desirable high-$n\tau_E$ feature with the high central temperatures achieved in the TFTR low-density experiments appear to be quite favorable. The basic idea is that strong peaking of the density profile permits the coexistence of high levels of fusion-power generation [proportional to $n^2(o)$] in the central region, alongside low levels of heat outflow at the plasma edge, even for Goldston-type scaling [proportional to n^2_{edge}]. Exploration of the effectiveness of this profile-shaping approach to the tokamak reactor plasma regime will be a second principal element in the TFTR experimental program for the next two years. To assist in the controlled heating of dense plasma cores, a 5-10 MW rf-capability (ICRF) is being transferred to TFTR from the PLT device.[12]

TFTR is scheduled to enter D-T-plasma research in early 1989. To minimize the technical problems of machine activation and maintenance, the D-T phase will be limited to about one year. The current plan is to investigate both the low-density and high-density operating modes, with a view to an initial assessment of the role of alpha-particle phenomena.

3. JET, JT-60, and T-15

A schematic of the JET device is shown in Fig. 9; some idea of its physical size is given by the interior view of the vacuum vessel in Fig. 10. In regard to plasma cross section, the physical size of JET is probably fairly close to the ultimate requirements of a tokamak reactor -- but the plasma major radius will, of course, have to be enlarged significantly to accommodate a tritium-breeding blanket and neutron shields surrounded by superconducting toroidal-field coils.

The JET achieved first experimental operation in July, 1983 and quickly distinguished itself by extending the favorable confinement-scaling of the ohmic-heating regime to τ_E-values above 0.8 sec.[13] The measured empirical scaling law was found to be fairly similar to that reported for TFTR (Fig. 6). Again, there is a tendency toward saturation of τ_E in the ohmic-heating regime -- though the density range that has been investigated thus far is not as large as in TFTR. Auxiliary-heating experiments in JET, using up to 6 MW of ICRF heating and 7 MW of neutral-beam injection, have also encountered Goldston-type results for the plasma confinement and temperature.[14] The planned introduction, in early 1987, of pellet injection to increase the density in the central region of the JET plasma should permit significant advances in $n\tau_E$, and the availability of increasing levels of ICRF heating power (up to 15 MW) will facilitate the simultaneous achievement of high temperatures in the dense plasma core. The availability of an outer separatrix on JET also offers the option of reducing Goldston-type transport by means of the "H-mode" transition, which was discovered in the ASDEX divertor experiment,[15] and extended to "open divertors" in the D-III device.[15] Like TFTR, JET is designed to be compatible with D-T operation; it is expected to enter this phase of its program in the early 1990's.

The JT-60 began experimental operations in April, 1985. As indicated in the schematic (Fig. 11), the design is dominated by a single-null outside divertor. This feature of JT-60 has already been effective in providing stable high-purity ohmic-heating operation,[17] and may prove to be particularly valuable for exploitation of the H-mode transition. Another unique feature of JT-60 will be the availability of a 24-MW system for plasma heating and current drive using lower-hybrid-frequency waves, along with 6 MW of ICRF heating power. While JT-60 was not designed for D-D or D-T operation, it has the potential to achieve a prototypical $Q \sim 1$ regime in hydrogen, like that planned for TFTR, in the course of bringing its 20-MW neutral-beam system up to full power during 1986-87.

A schematic of the T-15 is shown in Fig. 12. The use of superconducting niobium-tin coils in this machine represents a major forward step in tokamak technology -- but the much greater engineering challenges of this approach, relative to the three large copper-coil tokamak projects, have also resulted in a longer construction schedule, with completion currently projected for the latter part of 1987. Another promising line of technological innovation on T-15 is the use of high-powered gyrotrons for plasma heating at the electron cyclotron frequency (ECH). Preliminary experiments on T-10 have shown that the ECH approach is not only effective as a bulk-heater but can provide an exceptional degree of detailed control over the plasma temperature profile.[19]

Physical insights gained in the T-10 experiment have provided a principal inspiration for the current generation of tokamak-improvement schemes.[11] The T-15 will also be equipped with high-powered neutral-beam heating, but must be limited to hydrogen operation in order to protect the superconducting coils from neutron irradiation.

4. Major Next Steps

During the next several years, TFTR, JET, JT-60, and T-15, along with other important tokamak experiments, are expected to provide the scientific and technological data base for further advances toward the reactor goal. A substantial degree of cooperation among the four large tokamak projects has already emerged in the present phase of research. The establishment of an international controlled-fusion-research plan, with major collaborative projects, would be a logical approach for the next phase.

The two main tasks that remain to be accomplished on the way to a practical tokamak fusion reactor are: (1) achievement of ignited (or high-Q) equilibrium burn; and (2) development of fusion reactor hardware (including nuclear systems and superconducting coils). The D-T experiments in TFTR and JET may go a considerable way towards the study of alpha-particle physics and even transient ignition, but an investigation of controlled equilibrium-burn conditions would be desirable as a high-confidence basis for planning the operation of an ignited (or high-Q) reactor. The necessary experience would be gained in a relatively modest-sized next-step ignition project (Fig. 13) which could be initiated in the late 1980's and be in experimental operation around the end of 1992. A more ambitious engineering test reactor project would be designed on the basis of the present generation of large tokamaks, with construction starting in the early 1990's. The data base for optimal D-T operation would be supplied by the ignition experiment, beginning around 1995. A well-integrated effort consisting of these principal elements, with extensive supporting research and development, could realistically aspire to the achievement of fusion-reactor operation around the year 2000.

Acknowledgements

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References

Unfinished.

Figure Captions

1. Historic advance of toroidal confinement experiments within the Lawson diagram.

2. Schematic of the TFTR device.

3. Plasma current and loop voltage of the TFTR in 5.2 T ohmic-heating operation.

4. The TFTR faculty, showing neutral-beam lines in the foreground.

5. Interior of the TFTR vacuum vessel

6a. The energy confinement time τ_E in the TFTR ohmic-heating regime tends to follow the neo-Alcator scaling law, where R and a are the major and minor radii, and q is the MHD safety factor.

6b. The favorable τ_E-scaling of Figure 6b saturates at high densities, in agreement with Goldston's H-mode scaling.

7. The energy confinement time in the TFTR neutral-beam heating regime tends to follow Goldston's L-mode scaling.

8. Pellet injection with ohmic-heated TFTR plasmas produces strong and persistent central peaking of the density profile.

9. Schematic of the Joint European Torus.

10. Interior of the JET vacuum vessel.

11. Schematic of the JT-60.

12. Schematic of T-15.

13. Relative dimensions of the Compact Ignition Tokamak (CIT) and the INTOR.

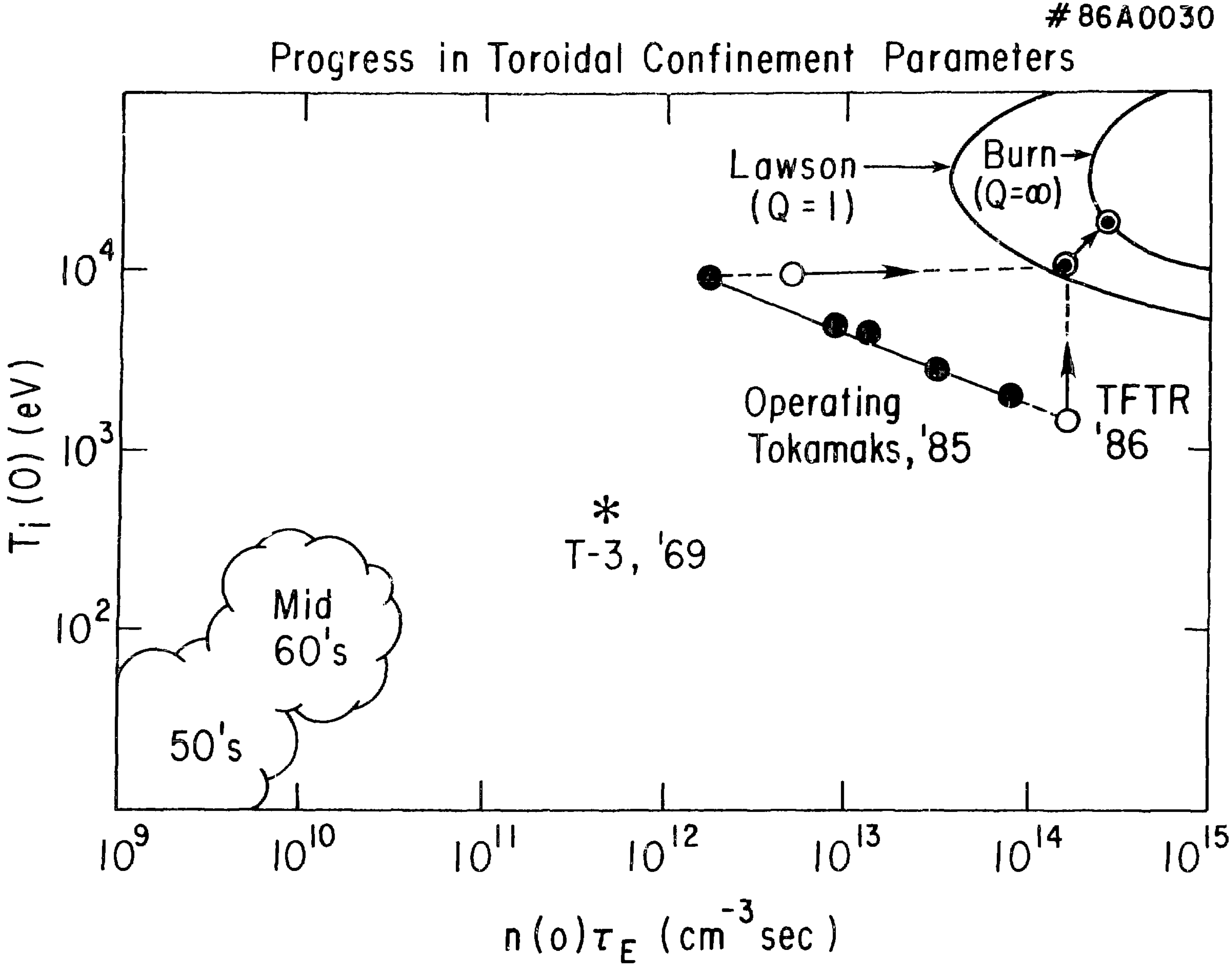

#86A0030
Progress in Toroidal Confinement Parameters
Lawson (Q = 1)
Burn (Q=∞)
10^4
10^3
10^2
$T_i(0)$ (eV)
Operating Tokamaks, '85
TFTR '86
*
T-3, '69
Mid 60's
50's
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
$n(o)\tau_E$ (cm^{-3} sec)

Figure 1

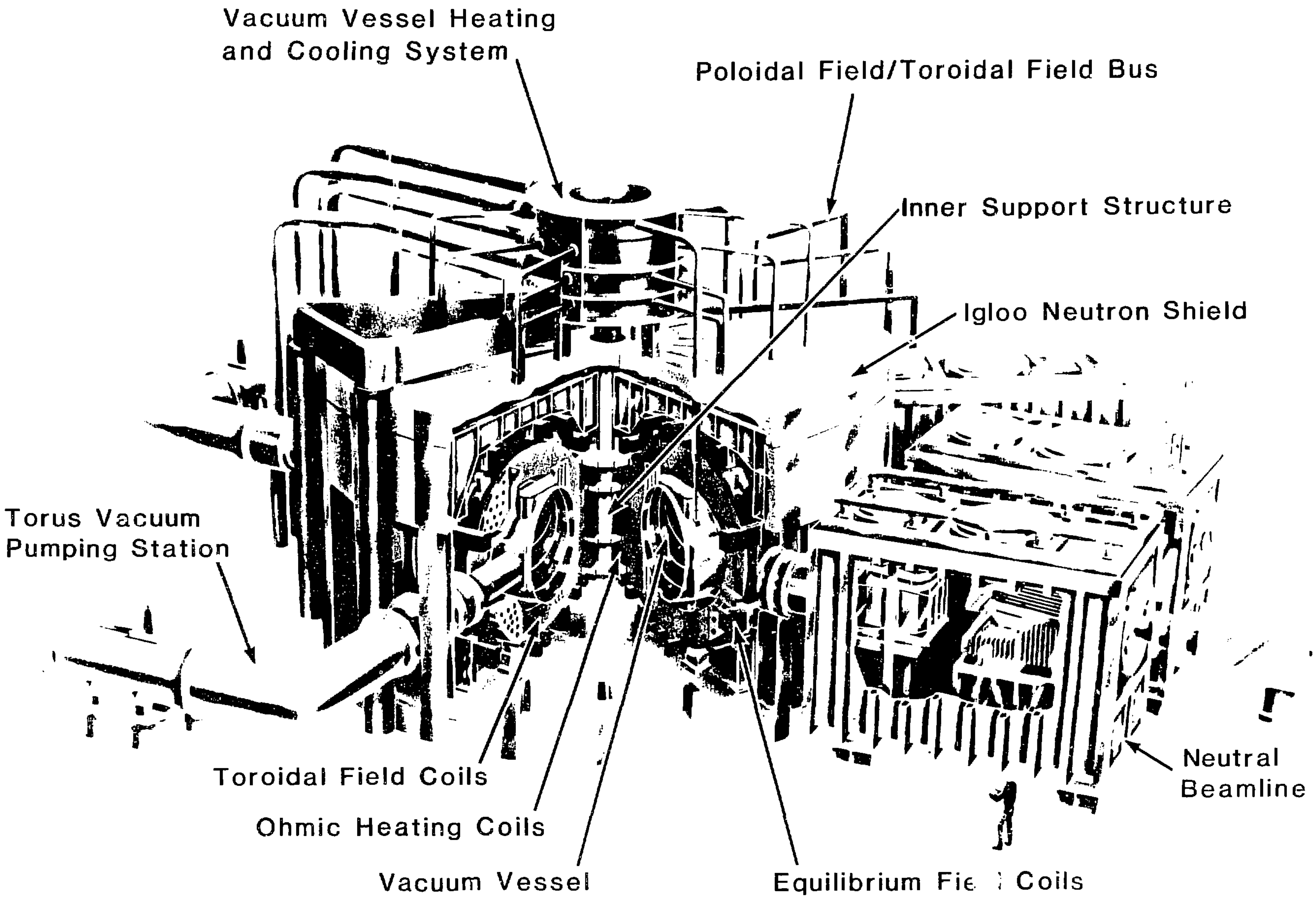

Vacuum Vessel Heating and Cooling System
Poloidal Field/Toroidal Field Bus
Inner Support Structure
Igloo Neutron Shield
Torus Vacuum Pumping Station
Toroidal Field Coils
Ohmic Heating Coils
Vacuum Vessel
Equilibrium Field Coils
Neutral Beamline

Figure 2

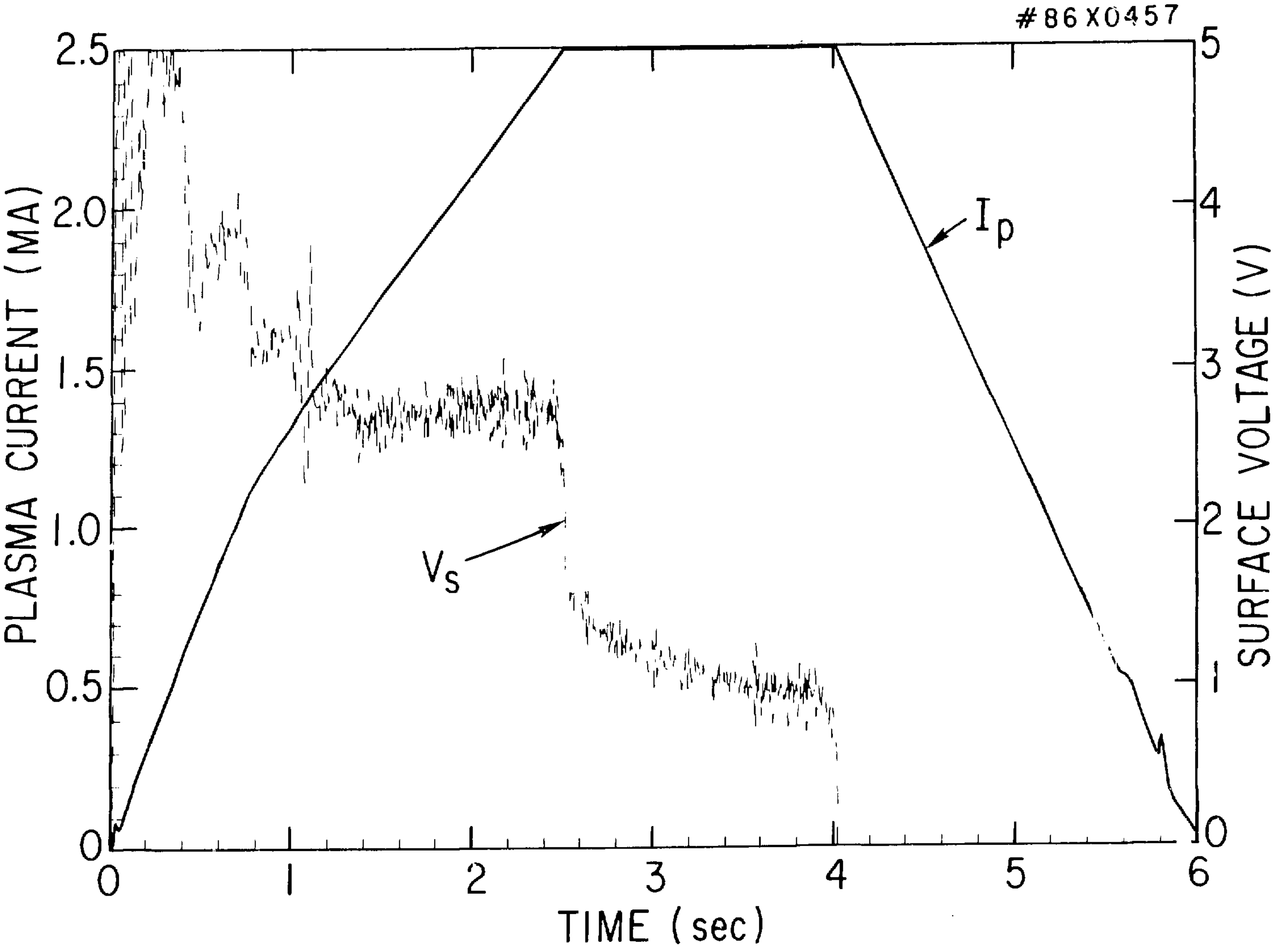

#86X0457
PLASMA CURRENT (MA)
2.5
2.0
1.5
1.0
0.5
0
SURFACE VOLTAGE (V)
5
4
3
2
1
0
TIME (sec)
0
1
2
3
4
5
6
I_p
V_s

Figure 3

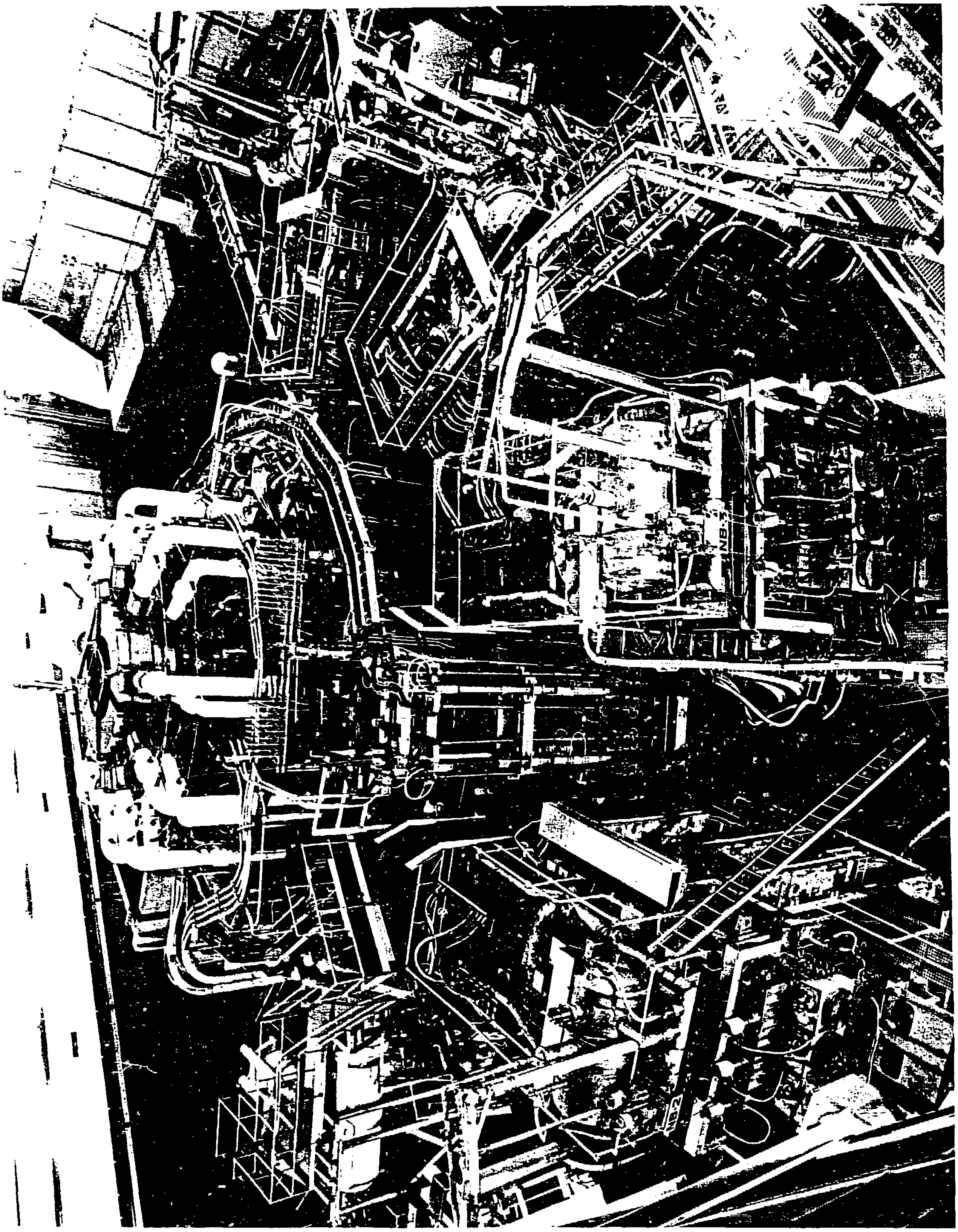


Figure 4

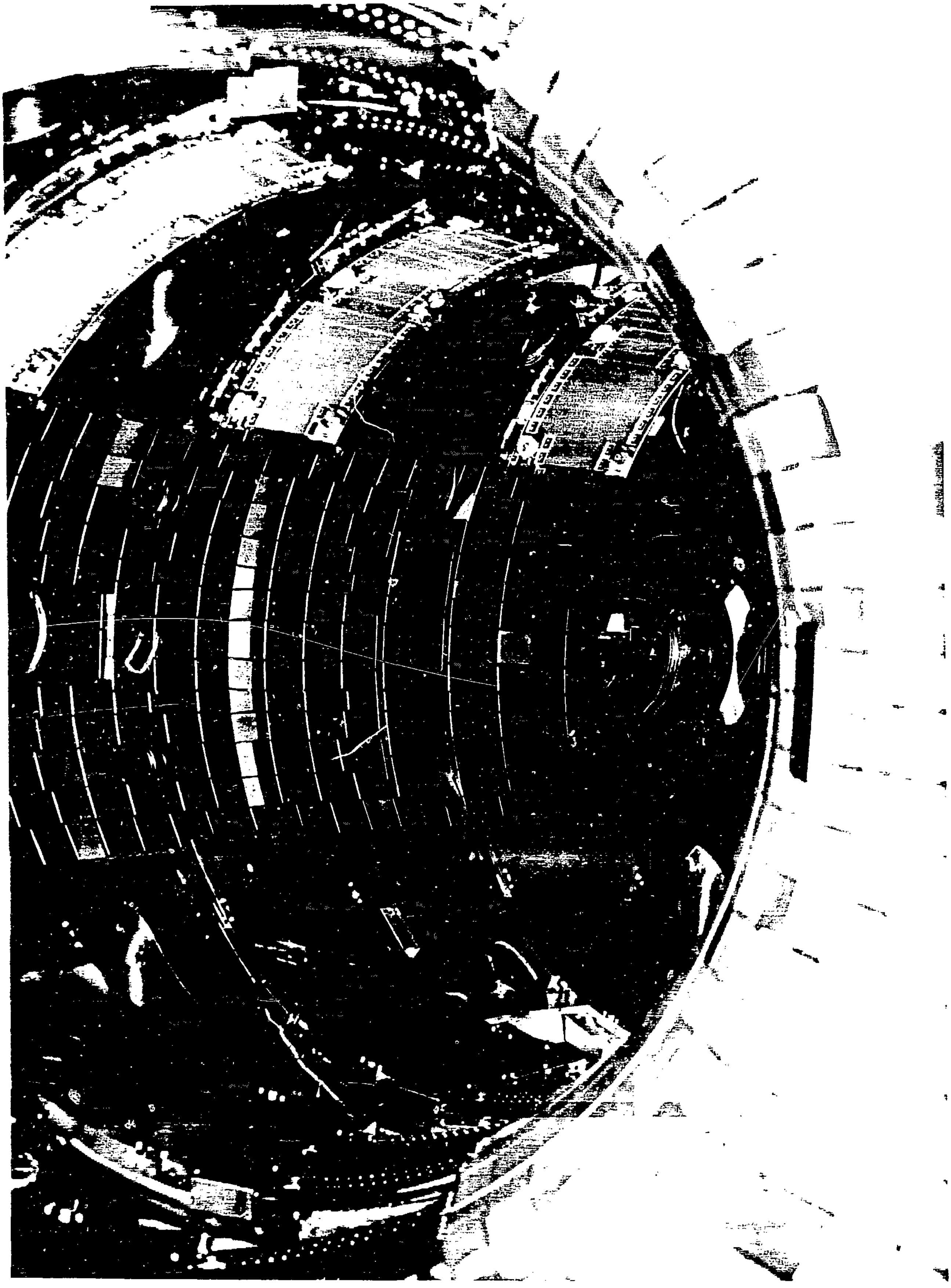


Figure 5

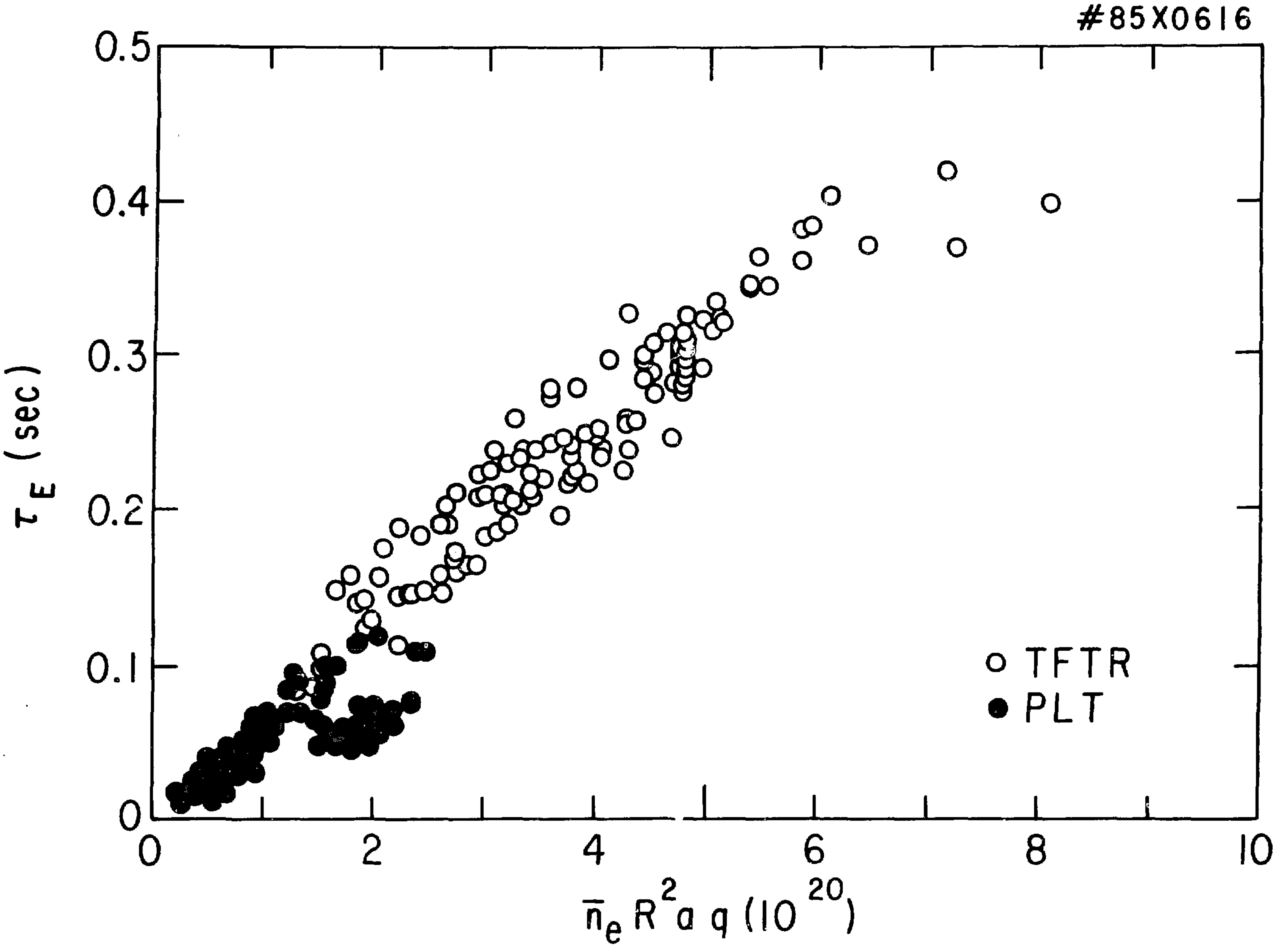

#85X0616
τ_E (sec)
0.5
0.4
0.3
0.2
0.1
0
0
2
4
6
8
10
$\bar{n}_e R^2 a q$ (10^{20})
○ TFTR
● PLT

Figure 6a

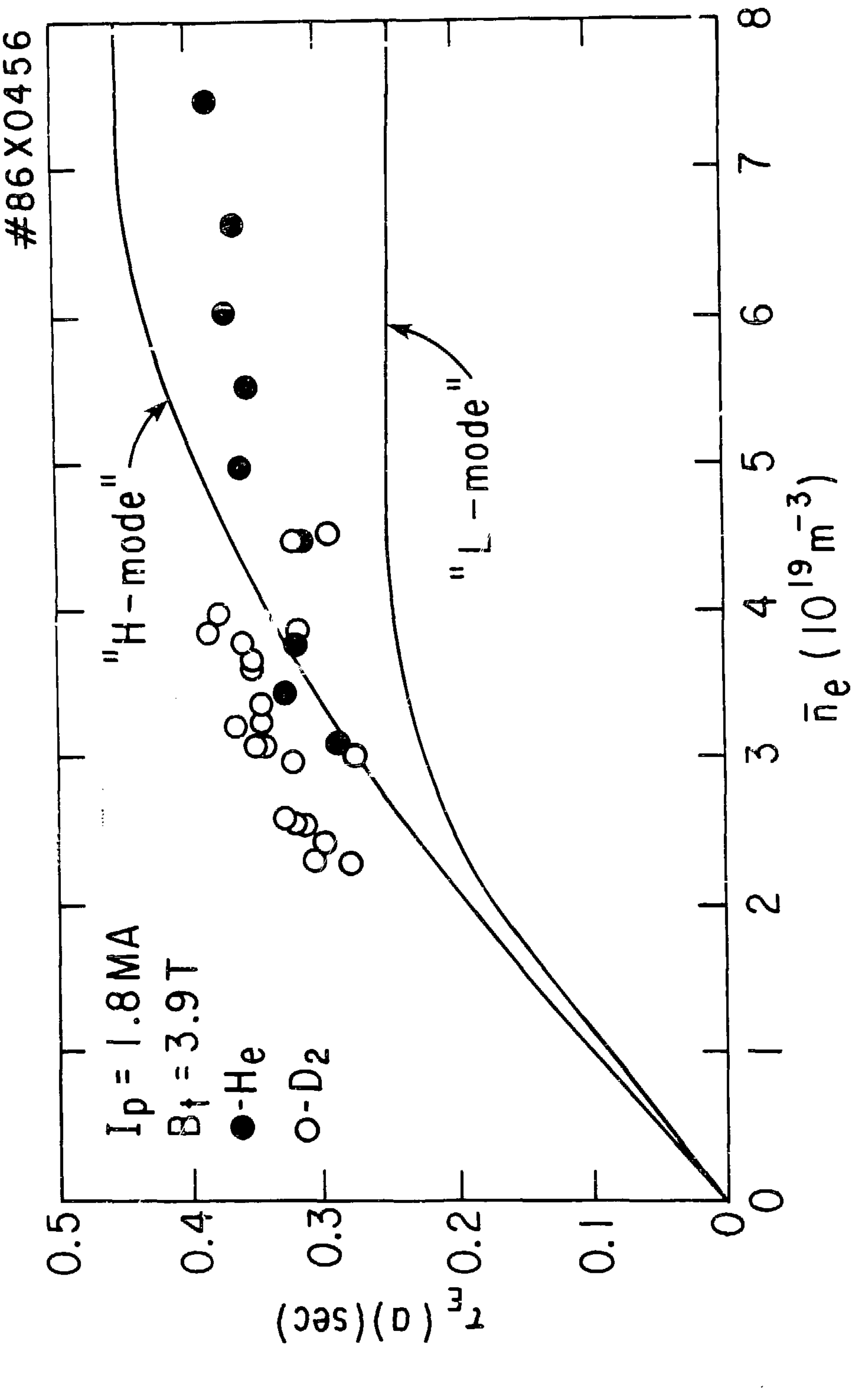

#86X0456
τ_E (a)(sec)
0.5
0.4
0.3
0.2
0.1
0
0
1
2
3
4
5
6
7
8
$\bar{n}_e$ (10^{19}m^{-3})
I_p = 1.8MA
B_t = 3.9T
●-He
○-D_2
"H-mode"
"L-mode"

Figure 6b

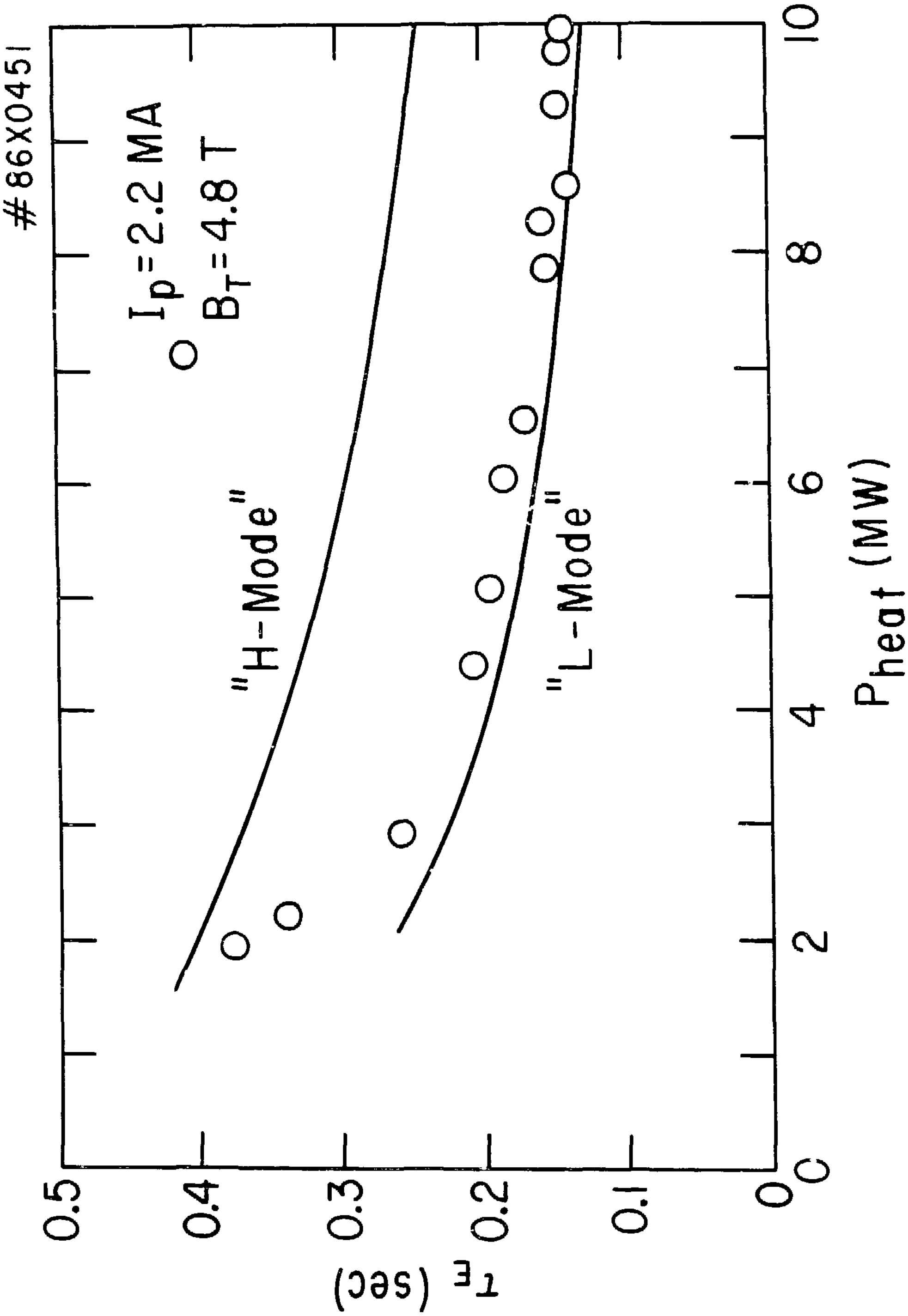
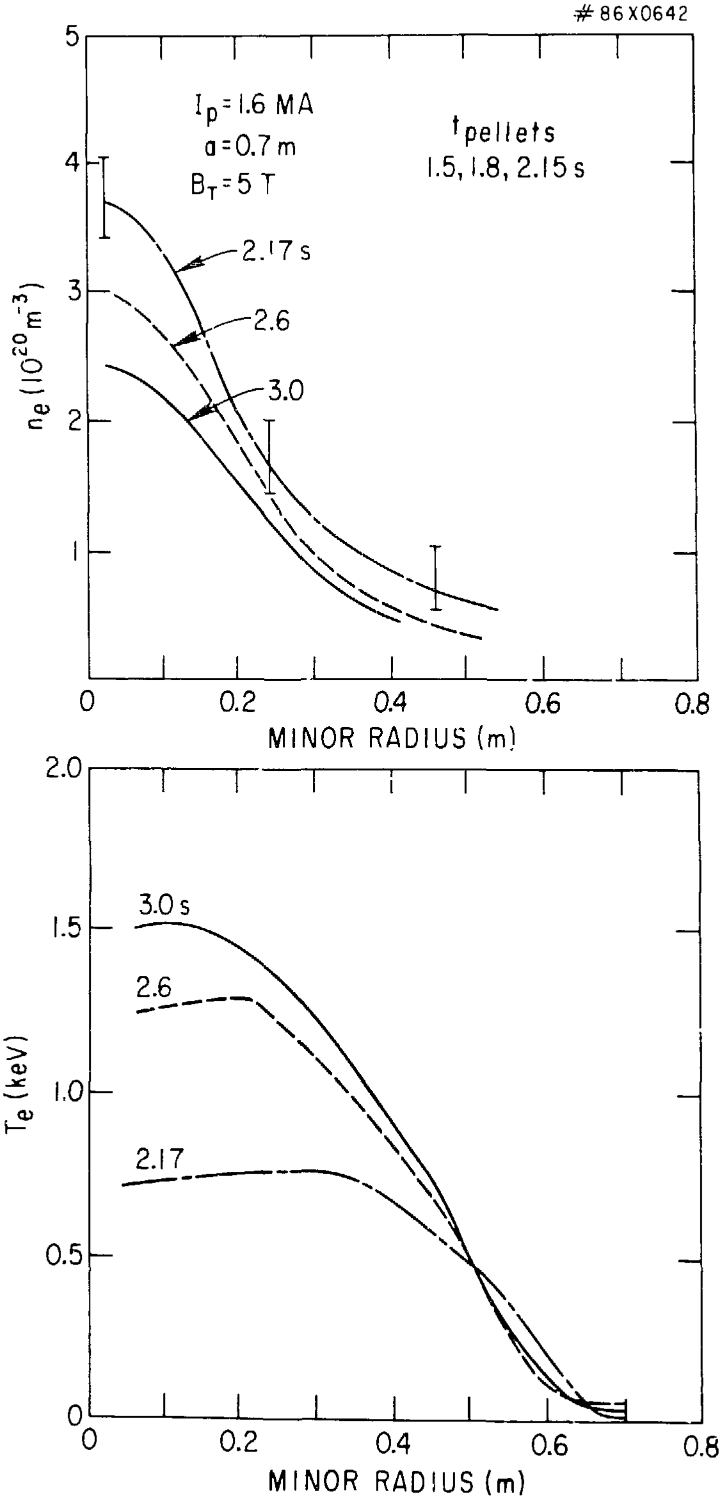

#86X0451
$I_p = 2.2$ MA
$B_T = 4.8$ T
"H-Mode"
"L-Mode"
τ_E (sec)
0.5
0.4
0.3
0.2
0.1
0
0
2
4
6
8
10
P_{heat} (MW)

Figure 7



86X0642
I_p = 1.6 MA
a = 0.7 m
B_T = 5 T
$t_{pellets}$
1.5, 1.8, 2.15 s
2.17 s
2.6
3.0
n_e (10^{20} m^{-3})
0
1
2
3
4
5
0
0.2
0.4
0.6
0.8
MINOR RADIUS (m)
3.0 s
2.6
2.17
T_e (keV)
0
0.5
1.0
1.5
2.0
0
0.2
0.4
0.6
0.8
MINOR RADIUS (m)

Figure 8

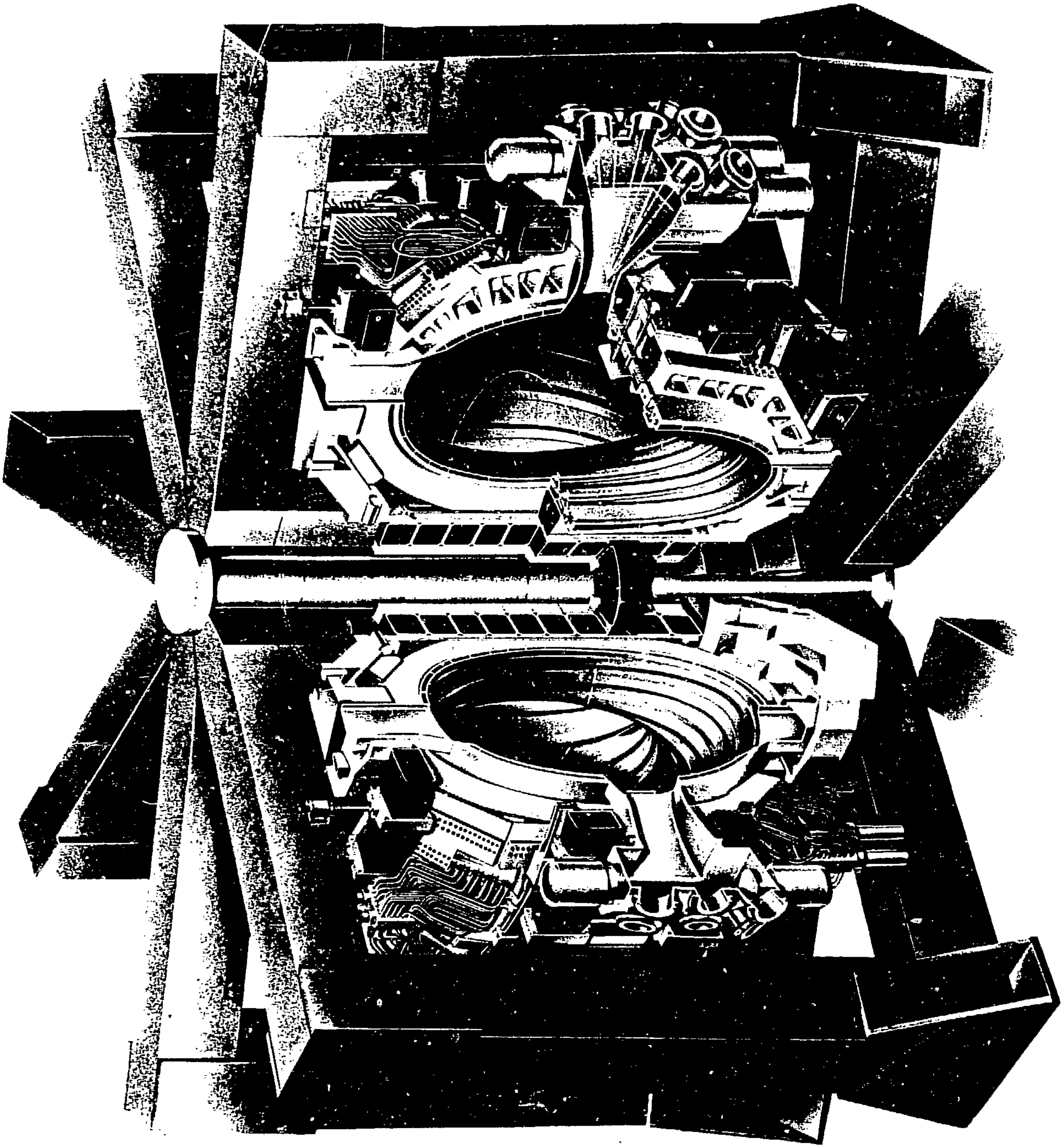


Figure 9

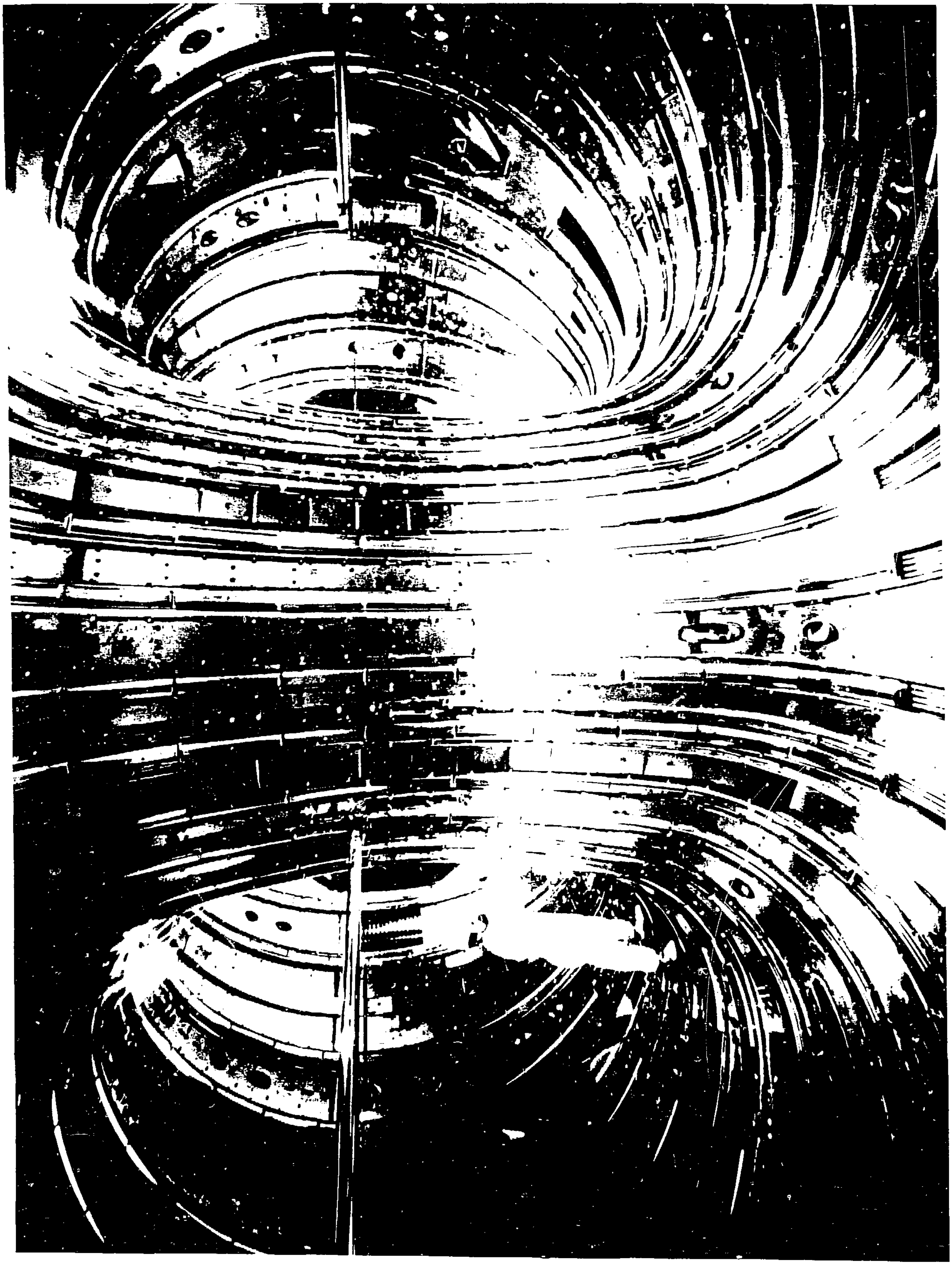
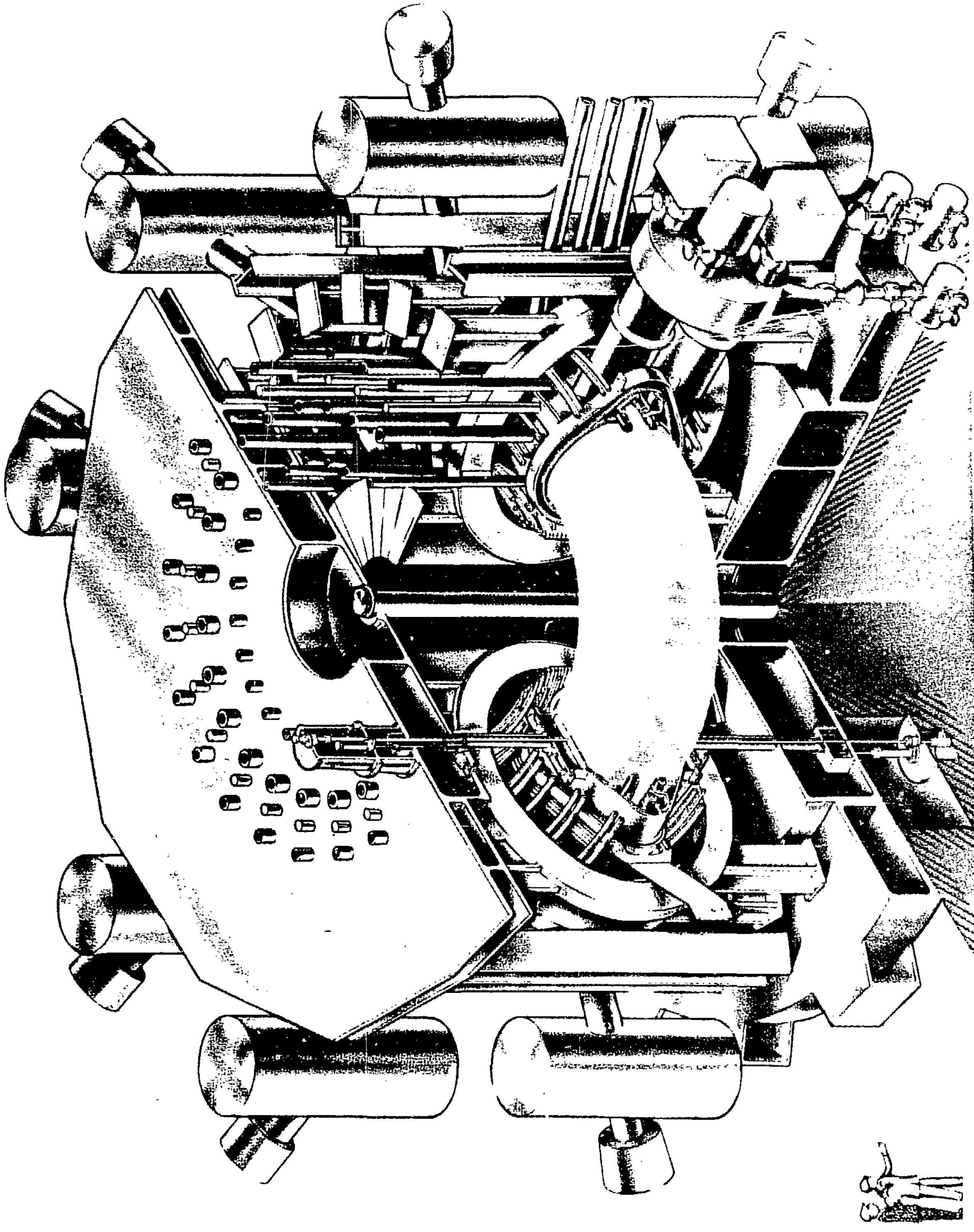


Figure 10



臨界プラズマ試験装置（JT-60)

Figure 11

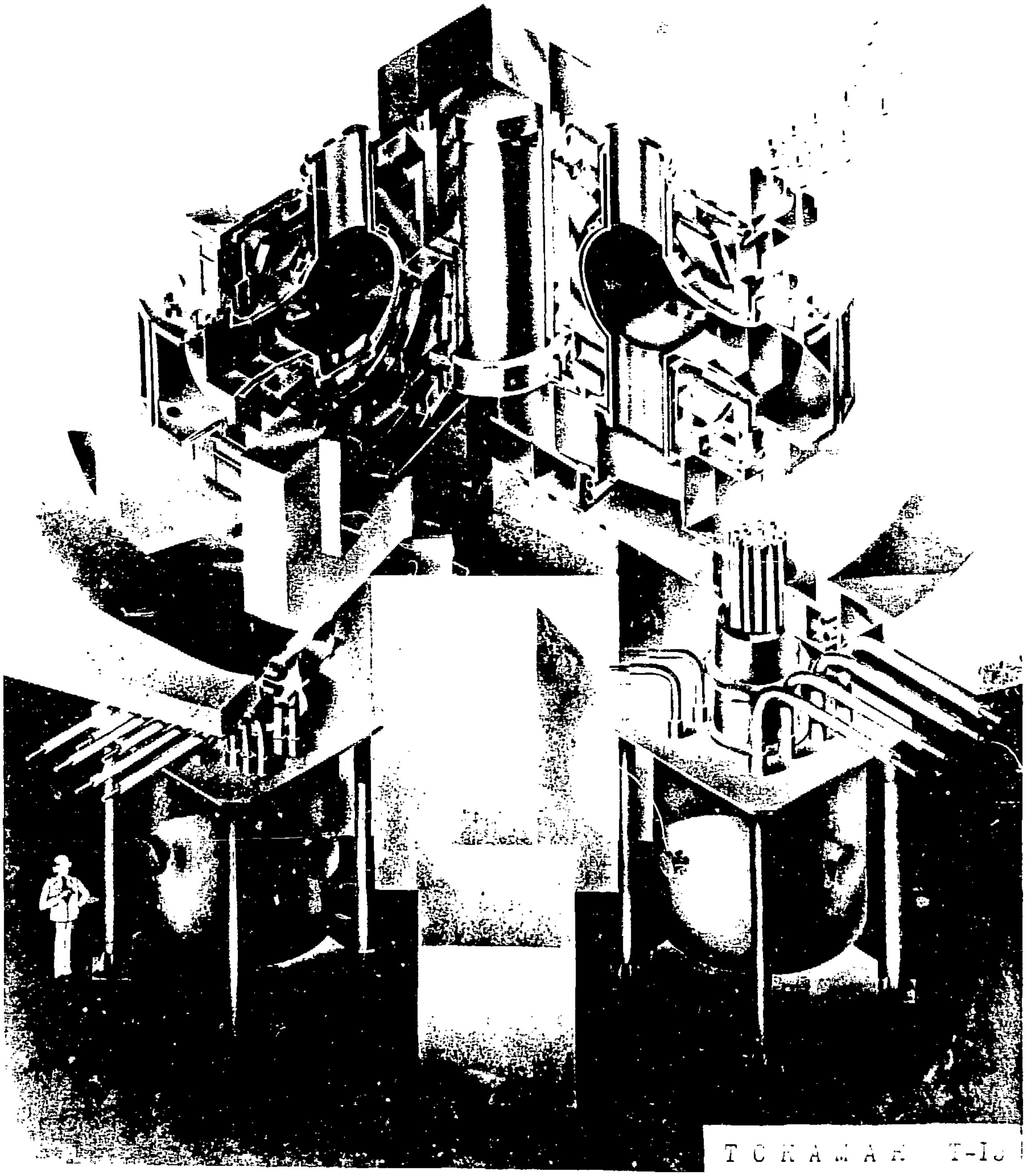


Figure 12

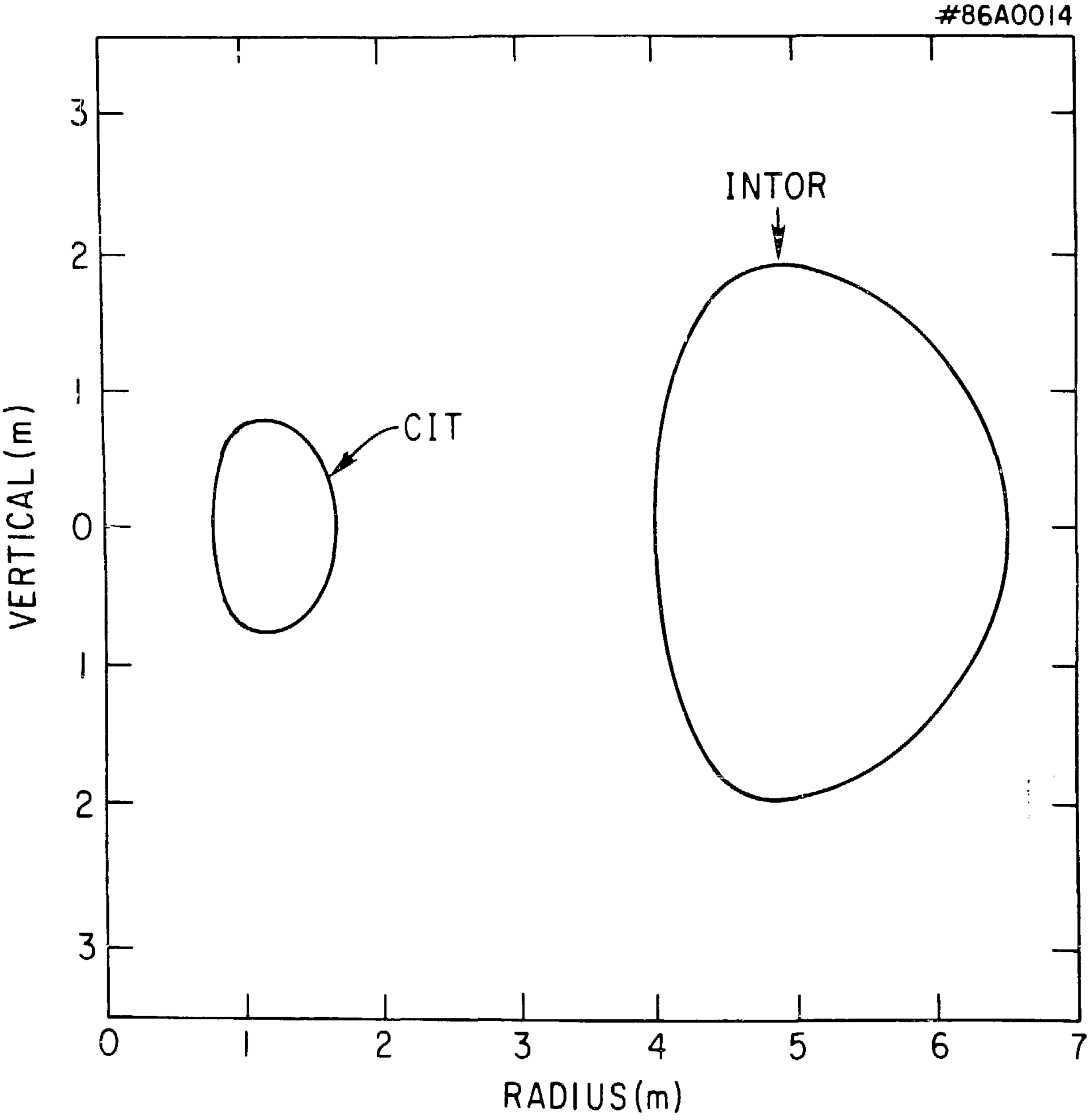


Figure 13