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THE PERFORMANCE OF THE PDX NEUTRAL BEAM WALL ARMOR

By

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ABSTRACT

The PDX wall armor was designed to function as an inner wall thermal armor, a neutral beam diagnostic, and a large area inner toroidal plasma limiter. In this paper we discuss its thermal performance as wall armor during two years of PDX neutral beam heating experiments. During this period it provided sufficient inner wall protection to permit perpendicular heating injections into normal and disruptive plasmas as well as injections in the absence of plasma involving special experiments, calibrations, and tests important for the optimization and development of the PDX neutral beam injection system. Many of the design constraints and performance issues encountered in this work are relevant to the design of larger fusion devices.

1. INTRODUCTION

The PDX wall armor was designed to function as an inner wall thermal armor, a neutral beam diagnostic, and a large area inner toroidal plasma limiter. In this paper we discuss its thermal performance as wall armor during two years of PDX neutral beam heating operations.

The PDX inner wall protective plates were designed to absorb 8 MW of neutral deuterium beam power at maximum power densities of 3 kW/cm^2 for pulse lengths of 0.5 s. The armor consists of arrays of titanium-carbide-coated (20-μm thick) graphite tiles supported on the inner wall of the torus opposite each beam port (Fig. 1). Titanium plates shield the gaps between the graphite units. The graphite tiles are held to stainless steel backing plates by a water-cooled copper dovetail design. Flat springs cause the tiles to float 0.076 cm above the support structures to allow the free expansion and bending of the tiles into the dovetail gap, thereby minimizing thermal stresses while maintaining support at the dovetails. Copper cooling lines between the stainless steel and copper sections provide optional cooling capability (Fig. 2). A detailed description of this armor design and its development is given elsewhere.[1]

2. INITIAL QUALIFICATION

The PDX neutral beam armor was designed so that the front-face material would withstand ~ 10^3 unattenuated beam strikes of 0.5-s duration and ~ 10^4 beam strikes at ~ 20% of full power for each year of its planned five-year life.

Electron beam tests[2] and theoretical studies[1] showed that the selected tile material was suitable to accept power densities of 3 kW/cm^2 for 0.5-s durations. Heat transfer studies were performed by measuring the front-face temperature changes as a function of time with and without cooling water using an infrared (IR) camera. The results of these studies indicated that with water cooling, the prototype would cool down in $\lesssim$ 180-s after a full power, 0.5-s beam strike. It was found that without water cooling, the prototype would cool down in a comparable time after an ~ 10% of full power shot of 0.5-s duration. This cool-down rate was adequate to prevent excessive thermal ratcheting during experimental runs with typical PDX plasma densities and a duty cycle of one pulse every 360-s. The prototype was then subjected to one thousand 40-keV, 2.5-kW/cm^2, 250-ms neutral beam (H°) shots as a test stand target. After this test the prototype showed no visible evidence of beam impact or deleterious effects.

3. OPERATING CONDITIONS

Typically, at the beginning of a daily neutral beam heating run, three to four unattenuated neutral beam shots of ~ 75% of full power and 100-ms duration were injected into PDX in the absence of plasma, usually between normal ohmic heating shots, to outgas the beam ducts and armor. During these beam duct outgassing shots, residual gas analyzer measurements of the PDX vacuum species yielded spectra exhibiting hydrocarbons typical of tokamak vacuum conditions and having intensities which decreased initially by about a factor of two per shot. The behavior of the PDX beam duct outgassing is discussed in detail elsewhere.[3]

During heating experiments, ~ 5-50% of the beam power was transmitted to the armor depending on the beam energy, beam species, and plasma density. Typically, the transmission was 10-15% of full power. Under these conditions, the armor received ~ 80-100 shots per run day at a 360-s duty cycle over a discontinuous period of 28 months. Figures 3 and 4 show the neutral beam operating history during this period.

In addition, special calibrations or experiments were often performed by injecting ~ 75-100% of full power shots of mostly 100-ms duration in the absence of plasma. These experiments involved injection system development,[4] duct outgassing studies,[3] neutral beam computer system development,[5,6] water calorimetry, thermocouple power density profiles,[7] IR camera and pyrometer measurements,[8] species measurements via sample implantation,[9] and species studies using Rutherford backscatter spectrometry.[10] Some of these experiments involved pulses of 200- and 300-ms duration.

In addition to the duct outgassing shots, normal operating modes, special calibrations, and experiments, the inner wall armor has also been used as a beam dump for conditioning ion sources under special circumstances using 50-ms duration pulses of 50-100% of full power at a 60-s duty cycle.

4. NET THERMAL LOAD

Figure 5 shows a histogram of the approximate number of shots of various durations and intensities impacted on the east neutral beam armor in the absence of plasma during the experimental period. These shots were typically 100-300 ms in duration, of 50-100% of full power with maximum on-axis power densities at the armor of 1.5-3 kW/cm^2 using H° and D° beams. Figure 6 shows a histogram of the approximate total net kJ absorbed by the armor during the experimental period. Figure 7 shows a calculated plot of front-face temperature versus pulse duration for a 500-ms pulse with a power density of 3 kW/cm^2 incident on a 1.27-cm thick graphite tile. It is seen that during full power shots with durations of 100 to 300 ms, the peak front-face tile temperatures varied from about 950°C to 1550°C. Typical equilibrium tile temperatures observed during or after runs using the armor thermocouples were in the range of ~ 50 to 250°C.

5. OUTGASSING AND IMPURITIES

Prior to installation, measurements of the outgassing from an unbaked armor titanium-carbide-coated graphite tile were performed up to 800°C using a residual gas analyzer. The results indicated the presence of typical hydrocarbons at levels acceptable to the PDX environments.[11] Prior to installation in the backing plates, the armor tiles were baked in a vacuum furnace at 600°C for 8 hours. Residual gas analyzer measurements of the PDX vacuum constituents made after duct outgassing shots in the absence of plasma, as discussed above, or measurements made after normal heating injections into PDX plasmas yielded spectra exhibiting hydrocarbons typical of tokamak vacuum conditions. During neutral beam heating injections into either circular C-rail limited, circular inner bumper limited, or Dee-diverted plasmas, the plasma cleanliness was monitored extensively and the main intrinsic impurities were found to be usually C, O, and Ti with intensities typical of Ti-gettered tokamaks.[12] There has been no significant impurity production attributable to the heating of the armor tiles under clean machine conditions. The behavior of Z_{eff} versus injected beam power for C-rail limited, inner bumper limited, and Dee-diverted plasmas is discussed in detail elsewhere.[12]

6. SURFACE CHANGES

The tile surfaces initially exhibited a uniform metallic appearance which gradually changed over large regions of the armor due to titanium deposits from dome and midplane gettering in PDX. These regions are darker, less specular, and exhibit multiple colors characteristic of thin films. In general, this film became easier to remove with light brushing after several weeks of exposure to the atmosphere. However, over the beam impact regions that received maximum power densities, the surface chemistry appeared to be more complex, exhibiting an apparent alloying of the titanium film with the tile surface due to beam heating. The texture is smooth and constant across these regions and there is no tactile evidence of a break or discontinuity in the surface smoothness.

In general, with the exception of the alloying effect described above, a visual inspection of the armor using fluorescent light after open machine conditions for several weeks found no indication of beam impact on the armor units. Although the beam power density profiles are approximately axially symmetric gaussians in shape, there is no visual evidence of concentric rings of different color or texture on any armor unit. There is no visual evidence that beam impact has chipped, melted, or removed titanium carbide coating from the tile surfaces.

Some tiles outside of the beam impact regions exhibit surface arcing streaks predominantly in the vertical direction relative to the toroidal plane. In some regions of the armor, at the graphite/titanium interfaces (see Fig. 1), there are several gaps for inner wall diagnostics such as laser dumps, for example. Some of the tiles at the edges of these gaps have exposed graphite edges or corners indicating that sufficient power was deposited from the plasma to remove a small amount of titanium carbide coating. This type of surface edge damage appears to be more prevalent on edges that received power depositions from the ion-direction of the plasma current. Perhaps this type of minimal edge damage could be controlled by more rounded edges at the armor gaps, minimizing the width of armor gaps, or appropriate shielding.

Preliminary microscopic surface measurements have been performed on a tile from the center of the east armor unit.[13] Elemental distributions were measured using energy dispersive X-ray spectroscopy (EDX), and surface topology was examined using a scanning electron microscope (SEM). The elemental distributions found in thin surface films and surface droplets were characteristic of PDX materials (i.e., Ti, Fe, Cr, Ni, and Aℓ). The surface topology exhibited several interesting phenomena including enhanced sputtering at grain boundaries, 2 to 3 -μ diameter blisters, micro-projections, and oriented "wedge-shaped pits." The investigation of these effects is still in progress and may yield a deeper understanding of neutral beam/plasma armor requirements.[13]

7. SAFETY INTERLOCKS

The primary safety interlock was a signal supplied by the plasma-current sensing circuits which permitted acceleration voltage across the ion sources when plasma current was present. This system never failed to inhibit heating injections during plasma-current disruptions. This interlock was manually removed during special injections in the absence of plasma or to allow the continuation of injecting pulses following disruptions in plasma current for the calibrations and special experiments discussed above.

A secondary interlock was provided by the thermocouple control circuitry which disconnected the thermocouples from the vessel prior to each shot in order to maintain electrical isolation of the vessel. Prior to disconnecting the thermocouples, this circuit also scanned each thermocouple and measured the resistance across its junction and the resistance between the thermocouple and the vessel. A high resistance was taken as indication of a cracked or missing tile or a thermocouple malfunction, which alerted the operator until manually returned to normal.

In addition, a prototype IR pyrometer interlock was demonstrated to inhibit effectively a beam when the armor front face temperature exceeded a selected threshold.[8] This was demonstrated for injections in the absence of plasma, injections into circular C-rail limited plasma, and injections into circular plasmas inner limited by the armor.

8. CONCLUSIONS

The thermal loads, electromagnetic forces, mechanical vibrations, duty cycle, plasma control requirements, and ultra clean environment of PDX imposed many difficult conflicting constraints on the design of the wall armor. The overall thermal performance of the PDX wall armor has provided sufficient inner wall protection to permit perpendicular heating injections during normal and disruptive plasma conditions. In addition, it has permitted short pulse length, full power shots in the absence of plasma for special experiments, calibrations, and tests important for the optimization and development of the PDX neutral beam injection system. There has been no significant impurity production attributable to the heating of the armor tiles under clean machine conditions. Many of the design constraints and performance issues encountered in this work are relevant to the design of larger fusion devices.

ACKNOWLEDGMENTS

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Johnson, R. Hulse, R. Kaita, S. Kaye, R.J. Knize, H. Kugel, D. Manos, D. Mansfield, K. McGuire, D. Mueller, K. Oasa, M. Okabayashi, D.K. Owens, J. Ramette, R. Reeves, M. Reusch, G. Schmidt, S. Sesnic, S. Suckewer, H. Takahashi, F. Tenney, P. Thomas, M. Ulrickson and R. Yelle, "Impurity Levels and Power Loading in the PDX Tokamak With High Power Neutral Beam Injection," J. Nucl. Mater 111 & 112, 343 (1982).

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FIGURE CAPTIONS

FIG. 1. A partial schematic top view showing the location and injection angles of the PDX neutral beam injection system, and the location of the coated graphite wall armor.

FIG. 2. Partial schematic cross-sectional end view of the armor graphite tile and backing plate arrangement.

FIG. 3. PDX neutral beam operating history. Shown is the neutral beam heating injections per month during the experimental period. The variations in total injections per month were due primarily to the PDX experimental schedule.

FIG. 4. PDX neutral beam ion sources fault history. Shown are the percentage of neutral beam ion source faults per injecting ion source during the experimental period.

FIG. 5. A histogram of the approximate number of shots of various durations and intensities impacted on the east armor unit in the absence of plasma during the experimental period.

FIG. 6. A histogram of the cumulative energy (kilojoules) absorbed by the armor during the experimental period.

FIG. 7. Calculated plot of front-face temperature versus pulse duration for a 500-ms pulse with a power density of 3 kW/cm^2 incident on a 1.27-cm thick graphite tile.

PDX INSTALLATION, PARTIAL TOP VIEW

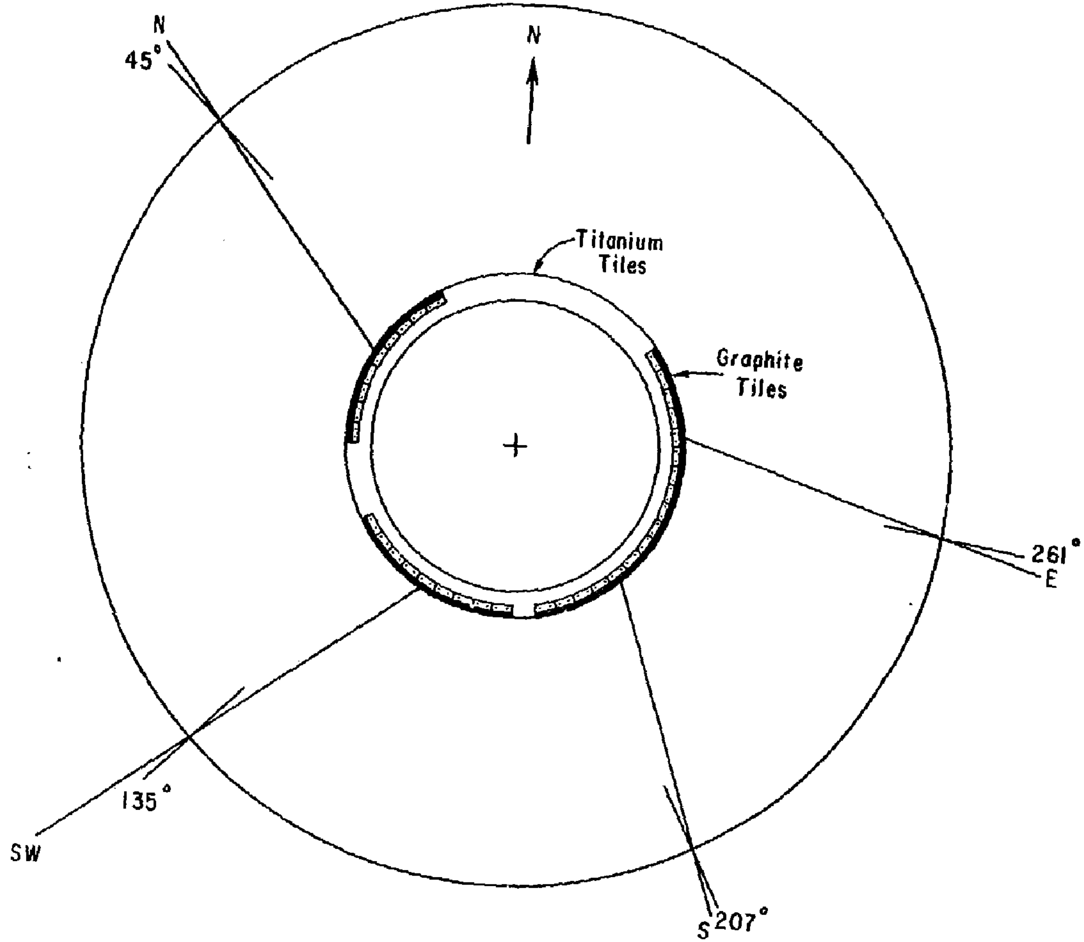


Fig. 1

GRAPHITE-SLAT ALIGNMENT

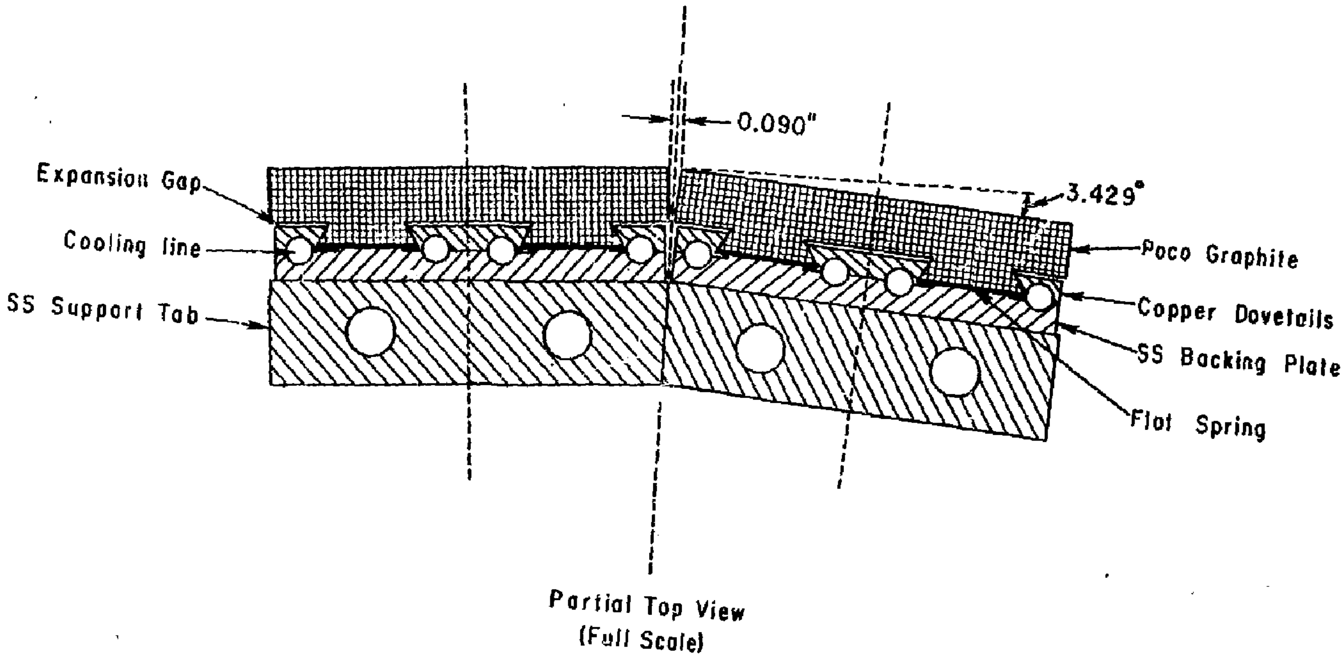


Fig. 2

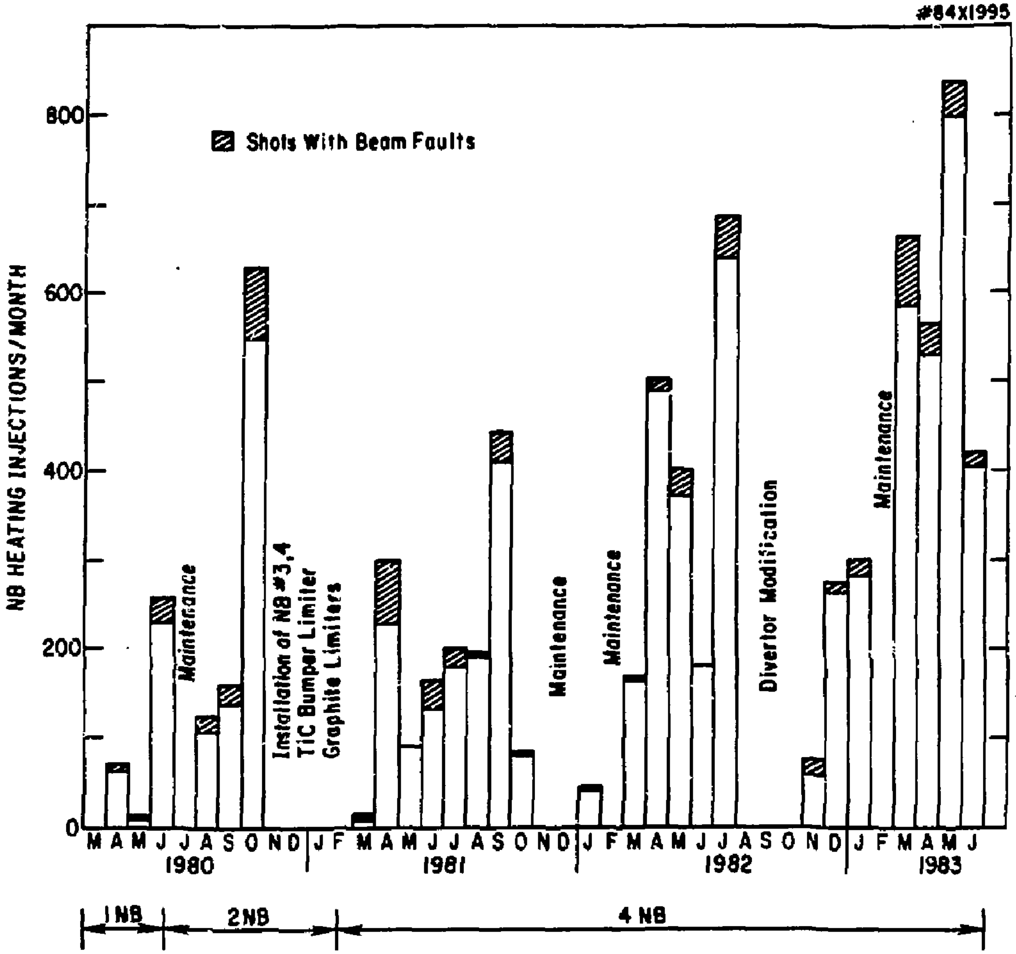

#84X1995
Shots With Beam Faults
NB HEATING INJECTIONS/MONTH
0
200
400
600
800
Maintenance
Installation of NB #3,4
TiC Bumper Limiter
Graphite Limiters
Maintenance
Maintenance
Divertor Modification
Maintenance
M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J
1980
1981
1982
1983
1 NB
2 NB
4 NB

Fig. 3

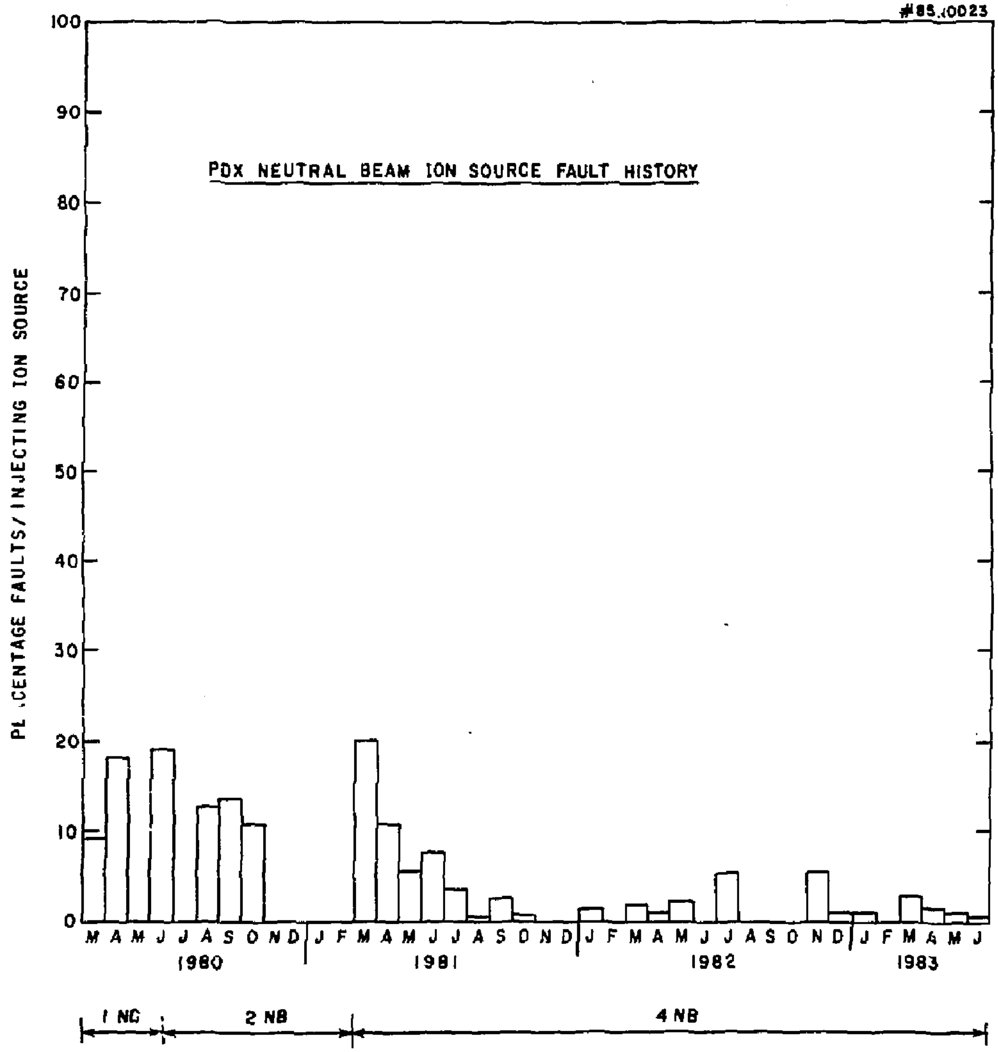
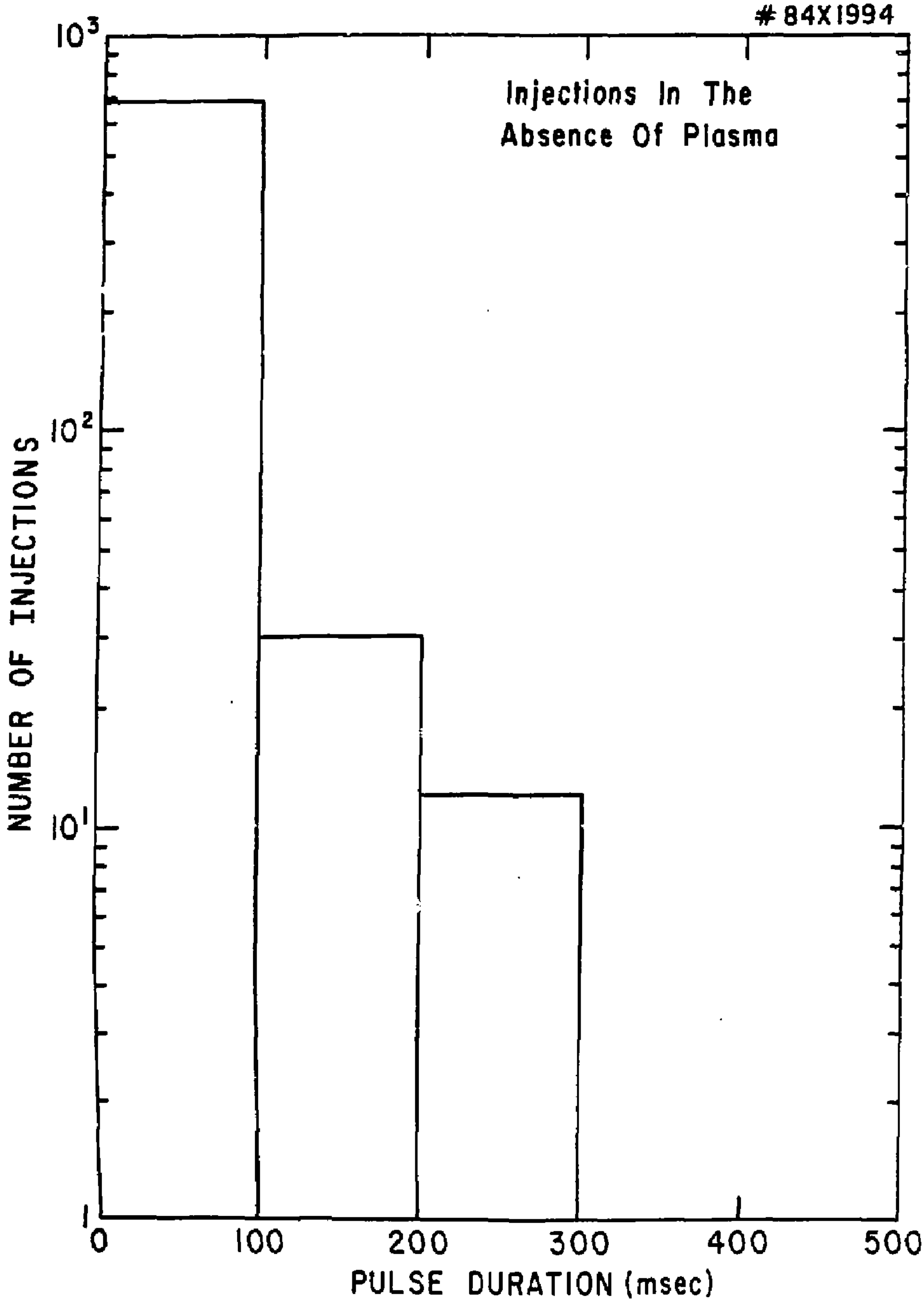

#85.10023
PDX NEUTRAL BEAM ION SOURCE FAULT HISTORY
PERCENTAGE FAULTS/INJECTING ION SOURCE
100
90
80
70
60
50
40
30
20
10
0
M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J
1980
1981
1982
1983
1 NC
2 NB
4 NB

Fig. 4



84X1994
Injections In The Absence Of Plasma
NUMBER OF INJECTIONS
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10^2
10^1
1
0
100
200
300
400
500
PULSE DURATION (msec)

Fig. 5

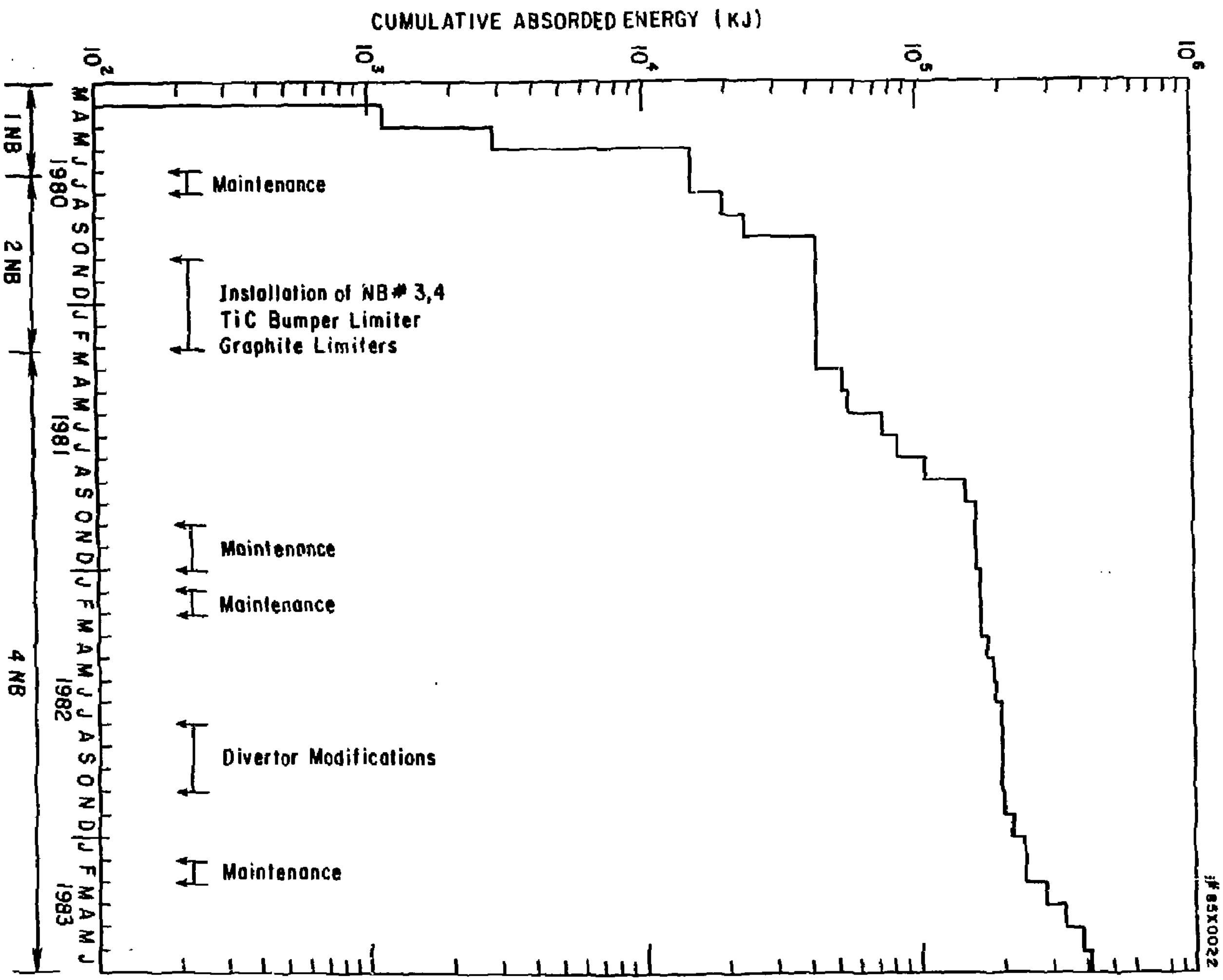
CUMULATIVE ABSORDED ENERGY (KJ)
10^2
10^3
10^4
10^5
10^6
1 NB
2 NB
4 NB
M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J
1980
1981
1982
1983
Maintenance
Installation of NB # 3,4
TiC Bumper Limiter
Graphite Limiters
Maintenance
Maintenance
Divertor Modifications
Maintenance
85X0022

Fig. 6

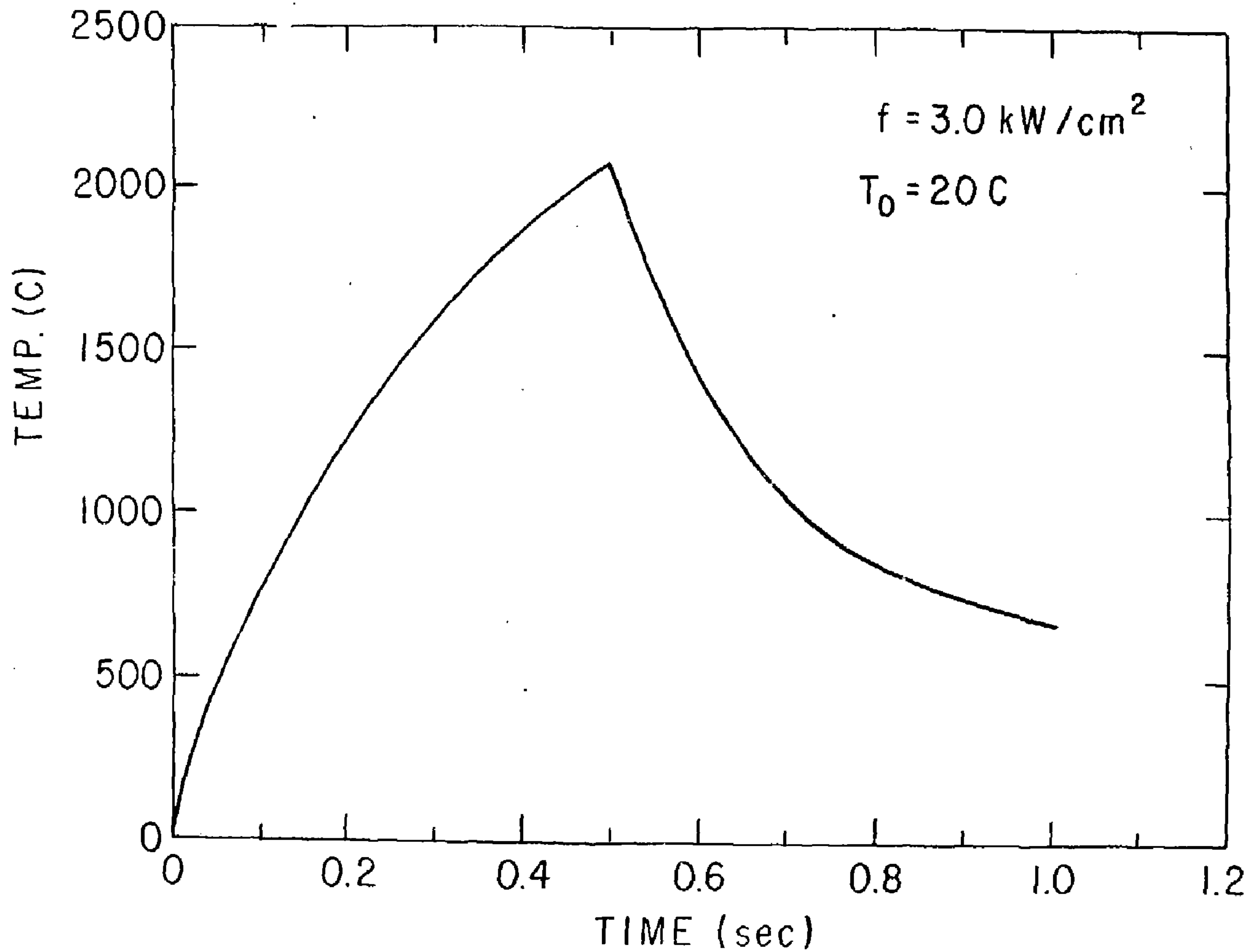
f = 3.0 kW/cm²
T0 = 20 C
TEMP. (C)
TIME (sec)
2500
2000
1500
1000
500
0
0
0.2
0.4
0.6
0.8
1.0
1.2

Fig. 7

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Nuclear Res Estab, Julich Ltd, W. GERMANY
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