

TRANSIENT ELECTROMAGNETIC STUDIES
FOR THE TFCX PRE-CONCEPTUAL DESIGN

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1.0 INTRODUCTION

During the pre-conceptual design for TFCX, transient electromagnetic effects were investigated in three main areas; delay in start-up field and flux penetration due to eddy currents induced in the machine structure; disruption induced eddy currents and electromagnetic loads; and requirements for passive and active vertical stabilization elements for the plasma.

Start-up and disruption effects were estimated with a finite element transient em model based on a nominal performance, copper TF coil machine, with superconducting PF coils and an internal vacuum vessel. Several variations on wall thickness and materials were run to develop brackets on the electromagnetic effects due to design options under consideration.

PF coil current profiles for start-up were based on a 60 s ramp time. Model variations were run covering different construction options which resulted in time delays to reach an equivalent flux (plasma loop voltage) level which ranged from 60 ms to 3.2 s. From this set, the most likely design configurations have time lags between 245 ms and 275 ms. This is considered acceptable in view of the long flux swing interval. A more detailed discussion is given in Section 2.0.

The components which are influenced most by the rapid magnetic field change associated with a disruption are the first wall, limiter and vacuum vessel. The plasma was assumed to ramp linearly from ~ 10 MA to zero in 10 ms and the finite element model was used for several construction options in terms of material thickness and toroidal electrical continuity. The disruption induces toroidally directed or saddle type currents

depending on component geometry. These currents interact with the eddy current magnetic fields, toroidal field and poloidal field to develop loads which are in general, normal and tangential to the induced current sheets. In many cases, the loads are non-trivial (eg., - up to ~ 0.3 MPa under certain conditions) and, therefore, require consideration in the structural analysis. A summary of maximum currents and loads is given in Section 3.0 and more detailed load distributions are in Appendices B and C.

The negative field index associated with production of an elongated plasma leads to a condition which is inherently unstable to perturbations in plasma vertical position. The unrestrained growth rate would occur on a very rapid time scale ($\sim 1 \mu s$), but is stabilized through the active and passive elements. The latter carry eddy currents induced by the plasma motion and create a stabilizing field until the control coils can be activated. This reduces the power requirements for the control coils. The analysis during this phase utilized a simplified model of the plasma and structures which led to the following preliminary conclusions.

1. Active control coils are necessary and will require power in the 0.1 to 10 MVA range depending on location;
2. The proximity and electrical continuity of the machine structures is sufficient for passive stabilization without addition of high conductivity elements to augment this effect.

The em transient effects described in this report were performed for the pre-conceptual design of TFCX. They were based on a particular set of machine dimensions, but are appropriate as indicators of trends for minor dimensional variations about the base point.

2.0 START-UP FLUX PENETRATION

A finite element transient electromagnetics code¹ was used to gain an insight into the effects of prospective TFCX shell geometries and wall thicknesses on start-up field and flux penetration to the plasma. Several cases were run with selected changes in features which could effect the eddy current patterns and magnitudes.

2.1 Model Description

The PF coil locations used for this analysis (and for the disruption analysis in Section 3.0) are defined in Table 2.1-1. Field components along the first wall and vacuum vessel due to the PF coils at end of burn are given in figures in Appendix A and used in Section 3.0 to determine part of the wall em loading following disruption. The amp-turn changes used for the start-up cases were based on a linear ramp from the values in the column labelled "start-up" to the values in the column labelled "start of burn" in 60 seconds.

Figure 2.1-1 shows an outline of the regions used in the finite element model together with representative thicknesses, materials, and whether the region is capable of carrying a net current through the rz-plane or whether it is a no-net region. The latter refers to a section capable of carrying current, but which is restricted to return the same

¹ R.D. Pillsbury, "A Two-Dimensional or Axisymmetric Finite Element Program for the Solution of Transient or Steady-State, Linear or Non-Linear, Magnetic Field Problems", COMPUMAG, Chicago, September 1981.

amount of current toroidally (eg., as in sectors where currents can flow toroidally, but which must return in saddle current fashion at the ends of the sector). The model is axially symmetric in all cases. Geometrically, it represents a case with an internal vacuum vessel, a dewar surrounding the central solenoid and inner PF coils, and copper TF coils in stainless steel cases. The plasma was modelled as four nested regions with a specified uniform current density in each region. Figure 2.1-2 shows the field lines produced by the PF coils at start of burn and the boundaries of the finite element plasma region. The close fit of the flux surfaces to the plasma region boundary is a good cross-check on model characteristics and adequate for the purposes of a study of this type.

Table 2.1-2 defines the model materials and thicknesses for the Case 21* baseline. In some instances shell thicknesses have been combined for ease of modelling in this preliminary study. For example, the "bucking cylinder" is shown as 38 cm thick, but is intended to model the combined effect of a 26 cm bucking cylinder plus a 2 cm dewar wall plus 10 cm of outer TF coil case which is toroidally continuous in this region. Similarly, the "15 cm vacuum vessel" on the inboard side models 5 cm of vacuum vessel plus 10 cm of inner TF coil case ring which is toroidally continuous in this region. The port and outboard vacuum vessel are not actually toroidally continuous in an axially symmetric sense, but the latter was

* Case number for authors reference only

treated as a net current region since this was expected to be conservative in estimating the time lag effects under consideration.

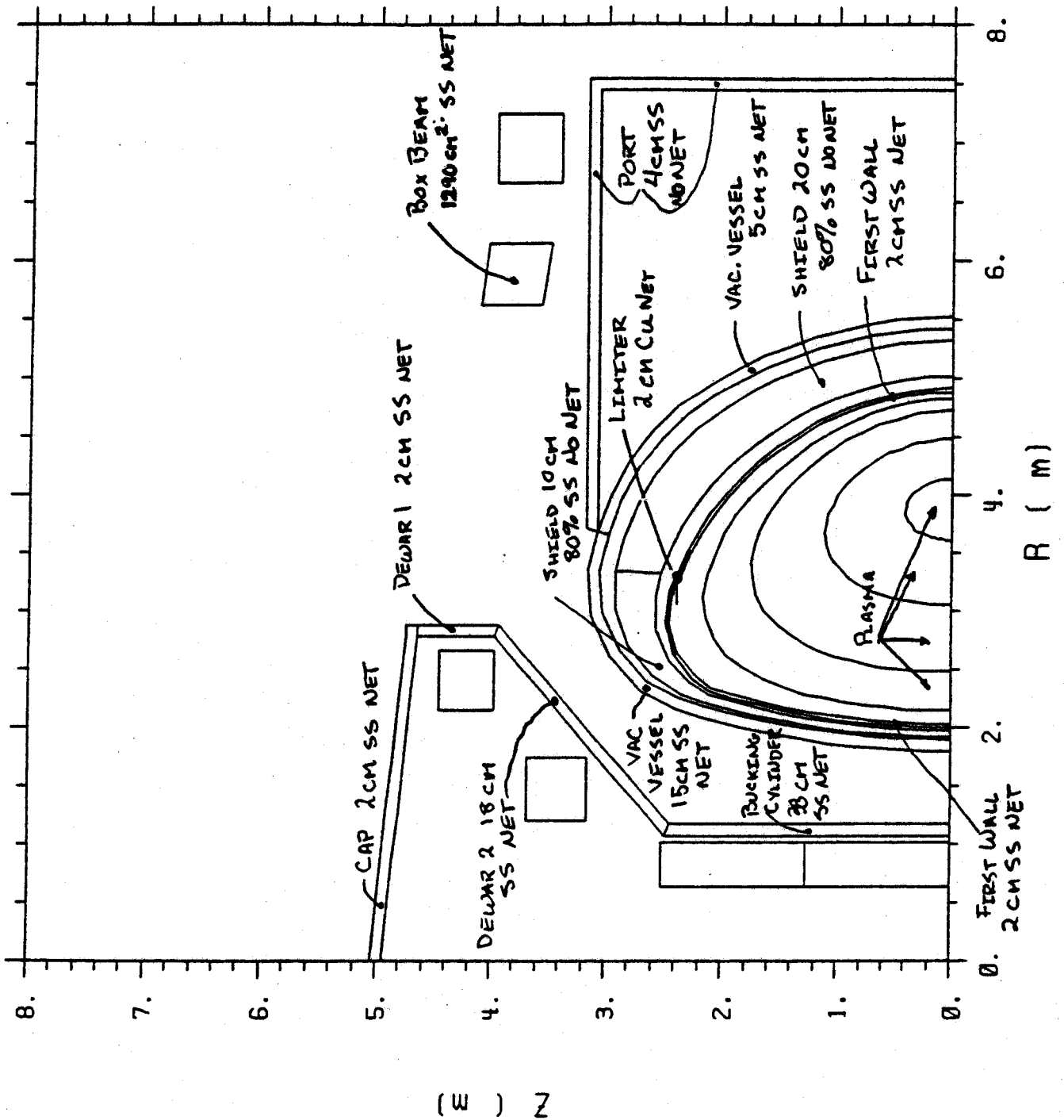
Table 2.1-3 defines the materials and thicknesses for another case used in parametric studies of start-up flux penetration. Results will be discussed in Sections 2.2 and 2.3.

2.2 Flux Penetration Lag

The models described in the previous section were used to calculate the flux produced in the $z = 0$ plane at $r = 3.89$ m, the point of maximum plasma current density, for several variations on wall thickness and toroidal continuity. No plasma was included in these cases.

Figure 2.2-1 shows the flux as a function of time at the point indicated, for the case of "no eddy currents", that is, PF coils only, as well as the results with vessels present. The time lag is defined in this figure as the delay in achieving the desired flux level when the vessels are present and the system has progressed beyond the initial transients and established a "stationary" eddy current pattern.

Table 2.2-1 summarizes the time lags for the cases considered. Cases 14 and 20 are by far the longest at approximately 3 seconds, but are unrealistic extremes since they are dominated by 2 cm thick first walls which are copper. All other cases range from 60 to 275 ms. The most realistic configuration corresponding to designs as of this writing would lie between Cases 21 and 25 which imply a flux lag in the 245 to 275 ms range. Since the start-up flux swing is expected to occur on the 40 to 60 second time scale, this type of lag is probably not significant. However, a plasma MHD analysis which accounts for the current distribution in



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Fig. 2.1-1 Outline of regions used in finite element model.

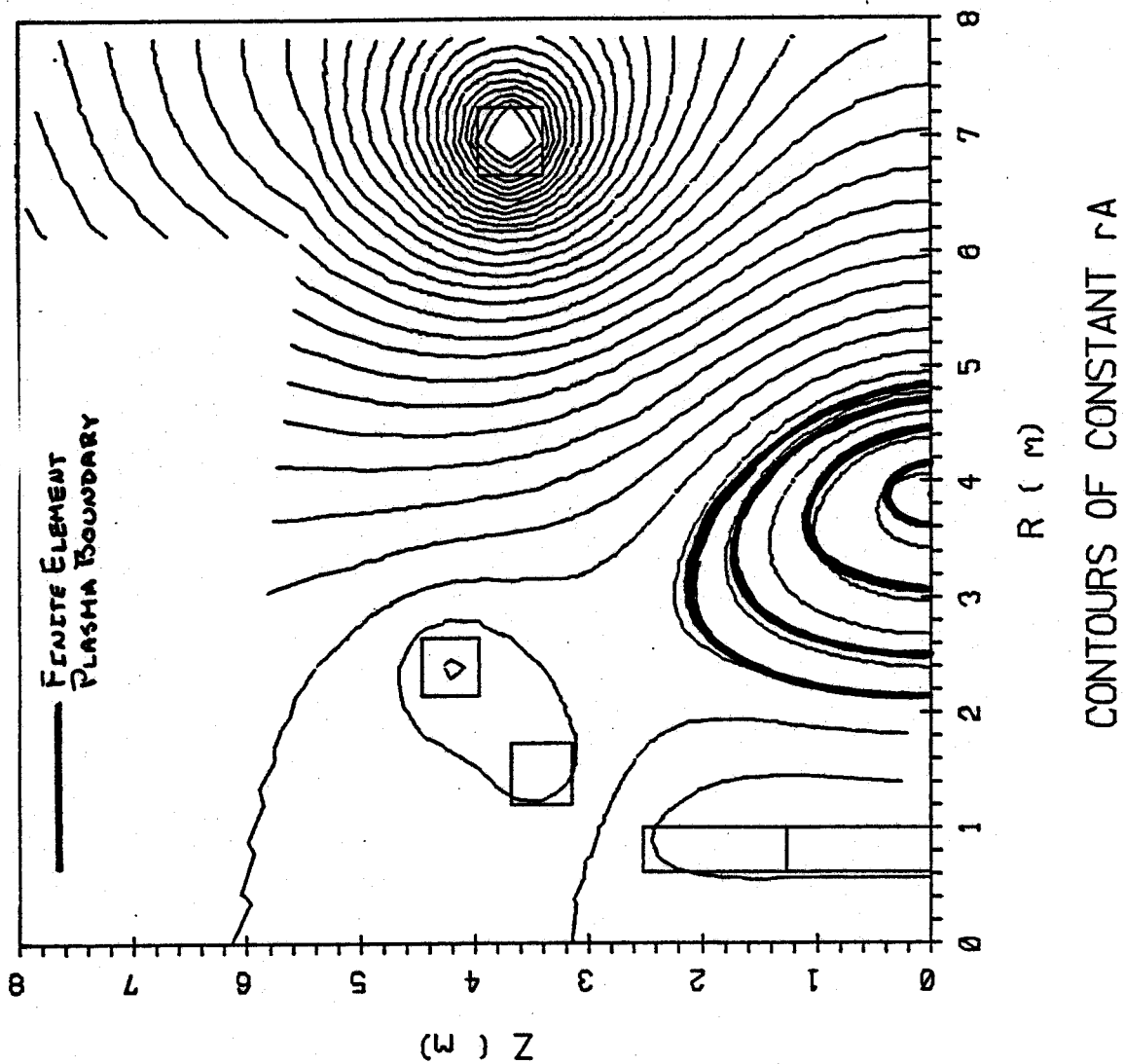


Fig. 2.1-2 Finite element model plasma boundary superimposed on field lines produced by the PF coils at start of burn.

TABLE 2.1-1

TFCX - PF COIL POSITIONS AND CURRENTS

COIL #	$R_c(m)$	$Z_c(m)$	$\Delta r(m)$	$\Delta Z(m)$	NI(MA-T) START-UP	NI(MA-T) START OF BURN	NI(MA-T) END OF BURN
1	0.810	± 0.625	0.390	1.250	6.210	4.076	- 7.411
2	0.810	± 1.875	0.390	1.250	8.776	7.469	- 8.766
3	1.480	± 3.400	0.530	0.530	1.488	5.154	2.389
4	2.400	± 4.200	0.530	0.530	1.488	5.154	2.389
5	6.950	± 3.700	0.600	0.530	0.294	- 6.102	- 6.647

TABLE 2.1-2

TFCX - START-UP LAG MODEL - CASE 21* BASELINE

COMPONENT NAME	MATERIAL	THICKNESS (cm)	NET CURRENT	NET CURRENT
BUCKING CYLINDER	SS	38.0	✓	
DEWAR 1	SS	18.0	✓	
DEWAR 2	SS	2.0	✓	
CAP	SS	2.0	✓	
PORT	SS	4.0		✓
VACUUM VESSEL INBOARD	SS	15.0	✓	
VACUUM VESSEL OUTBOARD	SS	5.0	✓	
SHIELD INBOARD	80% SS	10.0		✓
SHIELD OUTBOARD	80% SS	20.0		✓
FIRST WALL INBOARD	SS	2.0	✓	
FIRST WALL OUTBOARD	SS	2.0	✓	
BOX BEAM	SS	200 in ²	✓	

* For authors reference only

TABLE 2.1-3
TFCX - START-UP LAG MODEL - CASE 12* BASELINE

COMPONENT NAME	MATERIAL	THICKNESS (cm)	NET CURRENT	NO NET CURRENT
BUCKING CYLINDER	SS	15.3	✓	
DEWAR 1	SS	2.0	✓	
DEWAR 2	SS	2.0	✓	
CAP	SS	2.0	✓	
PORT	SS	4.0	✓	
VACUUM VESSEL INBOARD	SS	2.0	✓	
VACUUM VESSEL OUTBOARD	SS	2.0	✓	
SHIELD INBOARD	80% SS	10.0		✓
SHIELD OUTBOARD	80% SS	20.0		✓
FIRST WALL INBOARD	SS	1.0		✓
FIRST WALL OUTBOARD	SS	1.0		✓

* For authors reference only

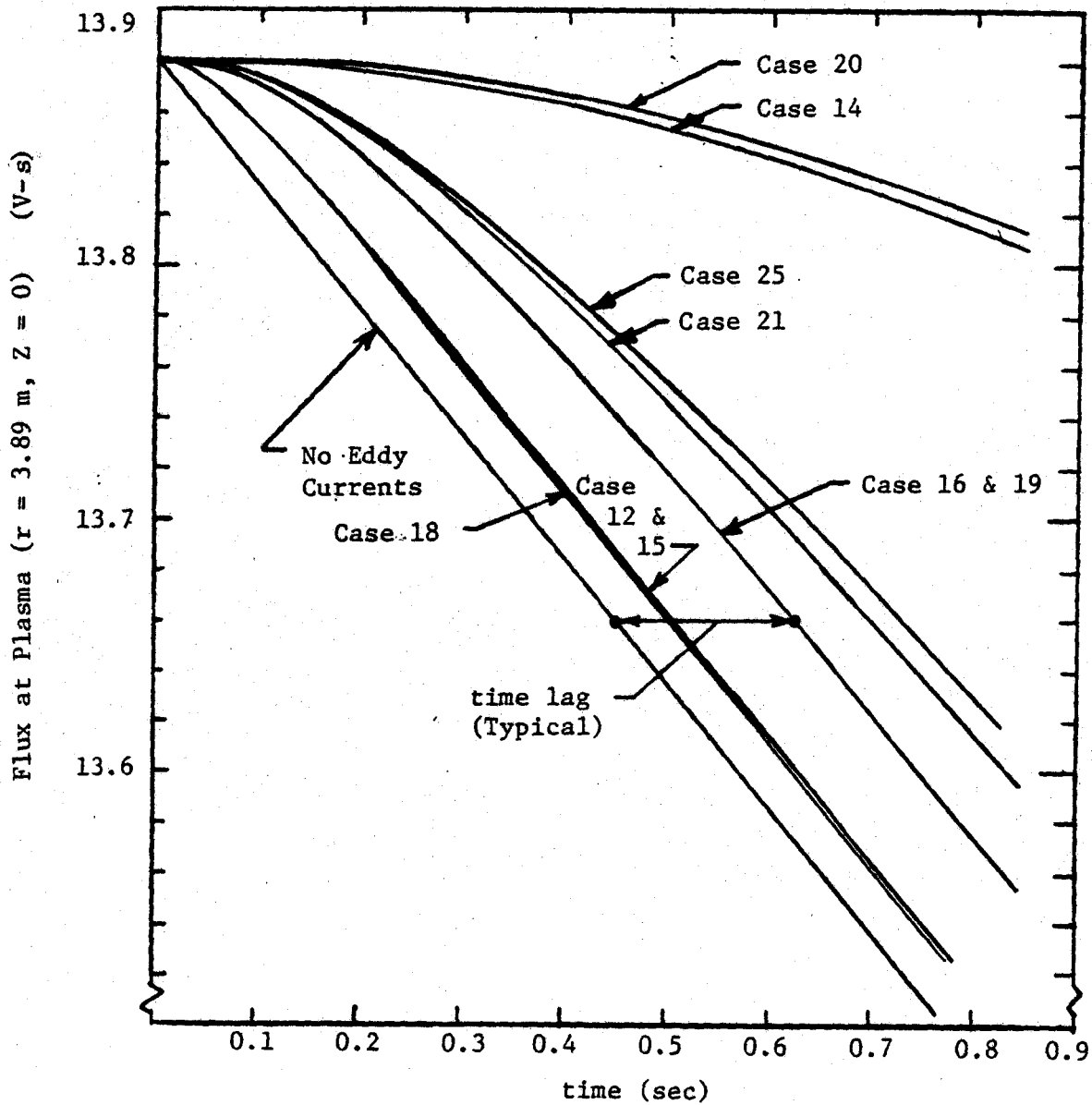


Fig. 2.2-1 Flux at plasma ($r = 3.89 \text{ m}$) vs time for selected TFCX shell characteristics.

TABLE 2.2-1

START-UP FLUX LAG AT $(3.89, 0)$; $\dot{\phi} = 0.5$ VOLT-SEC
 No EC -----
 SEC

CASE *	SS VACUUM VESSEL (cm)	(cm)	(mat'l.)	FIRST WALL (Inboard)	(Outboard)	TIME LAG (s)	NOTES
21	15/5	2	ss	Net	Net	0.245	Case 21 (See Table 2.1-1)
25	15/5	2	ss	Net	Net	0.275	Case 21 Plus 2 cm Cu Net Limiter (See Fig. 2.0-1)
12	2	1	ss	No Net	No Net	0.065	Case 12 (See Table 2.1-2)
14	2	2	cu	Net	No Net	~ 3.2	" " with FW variations
15	2	2	cu	No Net	No Net	0.065	" " " "
16	2	2	ss	Net	No Net	0.180	" " " "
18	2	ALL OTHER REGIONS			$\rho \rightarrow \infty$	0.060	" " " "
19	5	2	ss	Net	Net	0.180	" " " "
20	5	2	cu	Net	Net	~ 3.2	" " " "

* For authors reference only

the plasma and variations in the fields over the plasma cross-section remains to be done to verify this conclusion.

2.3 Component Eddy Currents

In a system with a complex geometry and many components and materials, the eigenvalues which govern the transients are combinations of time constants for individual elements in the conducting regions. There is no single "time constant" for the system. Although the current patterns will shift within and between components during the transient, it is useful to plot the total current in each component as a function of time to gain insight into the relative importance of the different components.

Figure 2.3-1 shows the total current in the net current carrying components in Case 21 (see Table 2.2-1 and Fig. 2.0-1) and illustrates the initial dominance of the box beam, and dewar section near the inner PF coil (dewar 1). These are followed by the bucking cylinder which becomes the dominant component eventually. For this case, the port, shield outboard, and shield inboard are no net current carrying regions. They carry currents toroidally which must return toroidally within their section. The net current in one direction must turn in the saddle direction in order to return toroidally in the opposite direction. The total saddle current magnitudes for this case are shown in Fig. 2.3-2.

In Case 25, the effects of a limiter were evaluated by modeling a section of the first wall as being copper (see Fig. 2.0-1). To maximize the influence of the limiter, it was assumed to be a net current carrying region and, therefore, toroidally continuous. Component currents versus time for this case are shown in Figs. 2.3-3 and 2.3-4 in a format similar

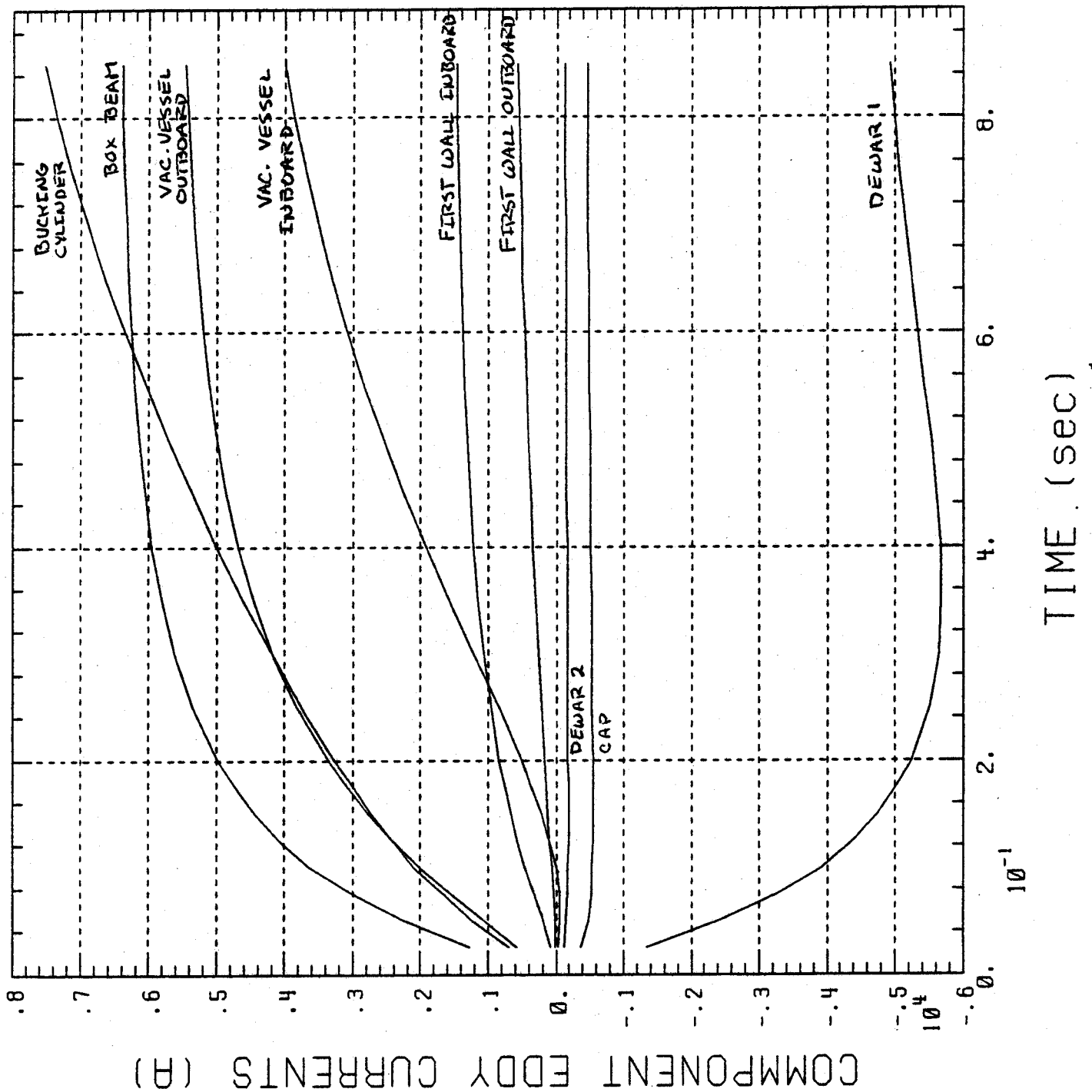


Fig. 2.3-1 Component eddy currents vs time for the Case 21 Baseline. Currents are for the components above the midplane. Component names correspond to those in Fig. 2.1-1.

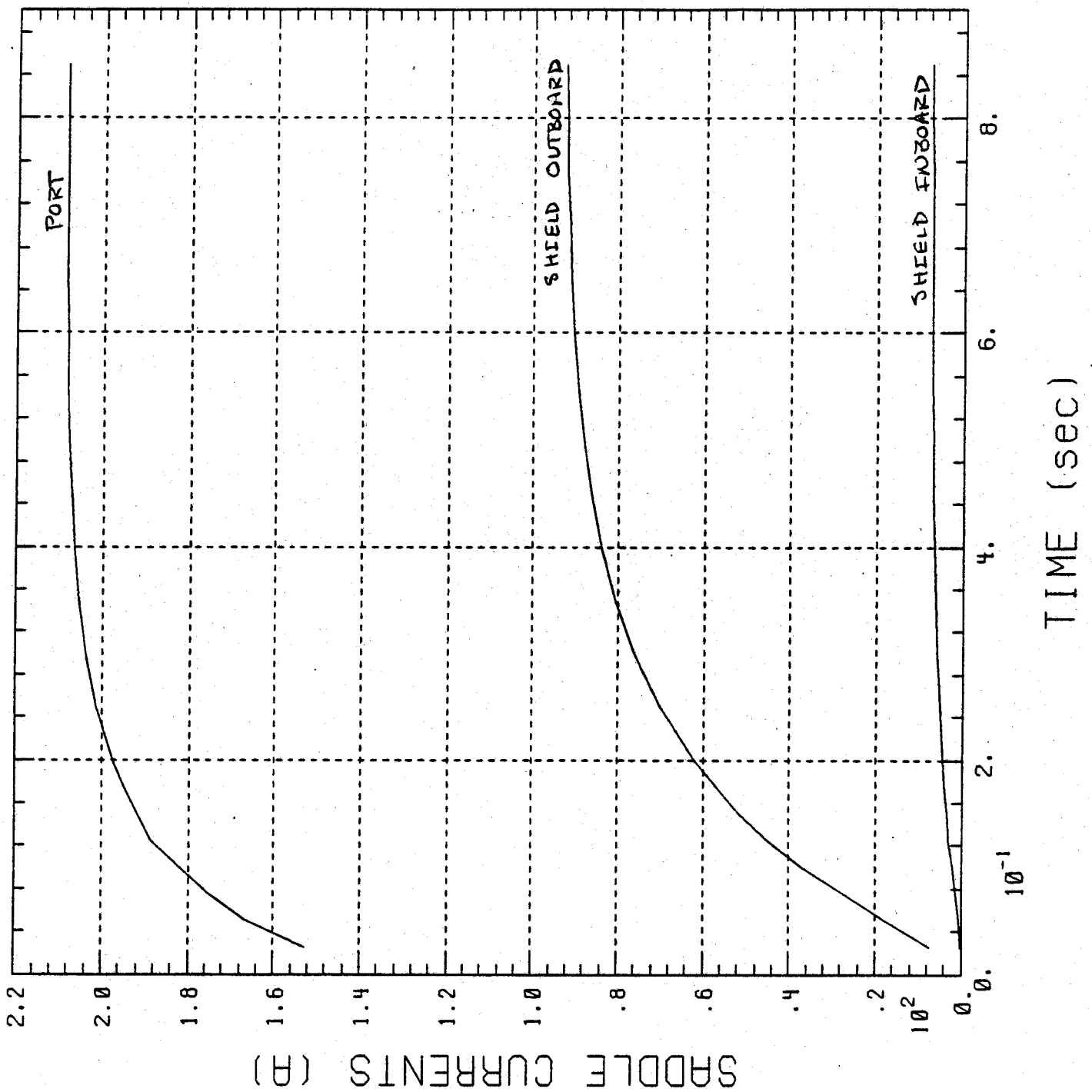


Fig. 2.3-2 Component saddle currents vs time for the Case 21 baseline. Saddle currents occur only in no net regions. Region names correspond to those in Fig. 2.1-1.

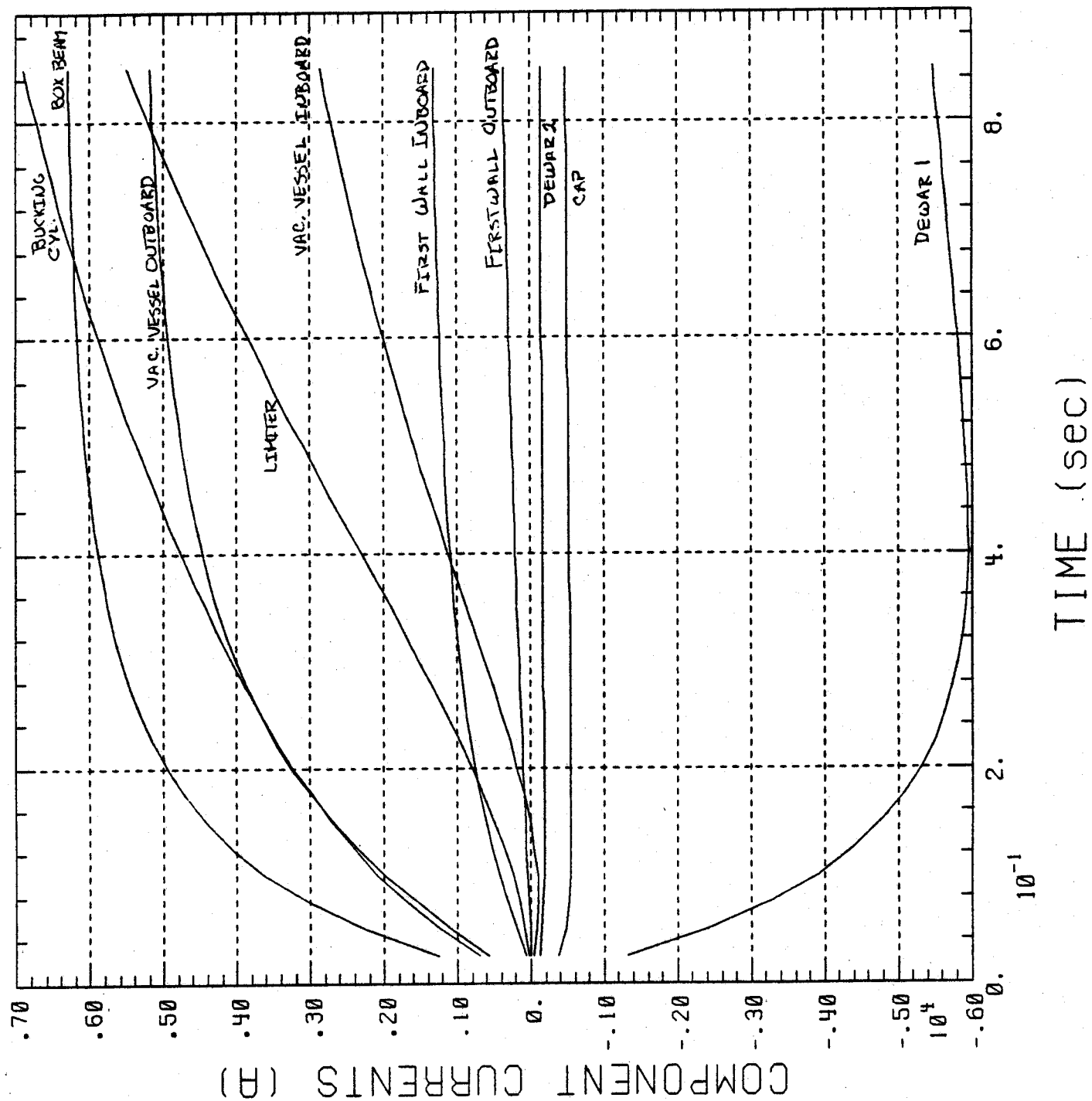


Fig. 2.3-3 Component eddy currents vs time for Case 25. Currents are for the components above the midplane. Component names correspond to those in Fig. 2.1-1.

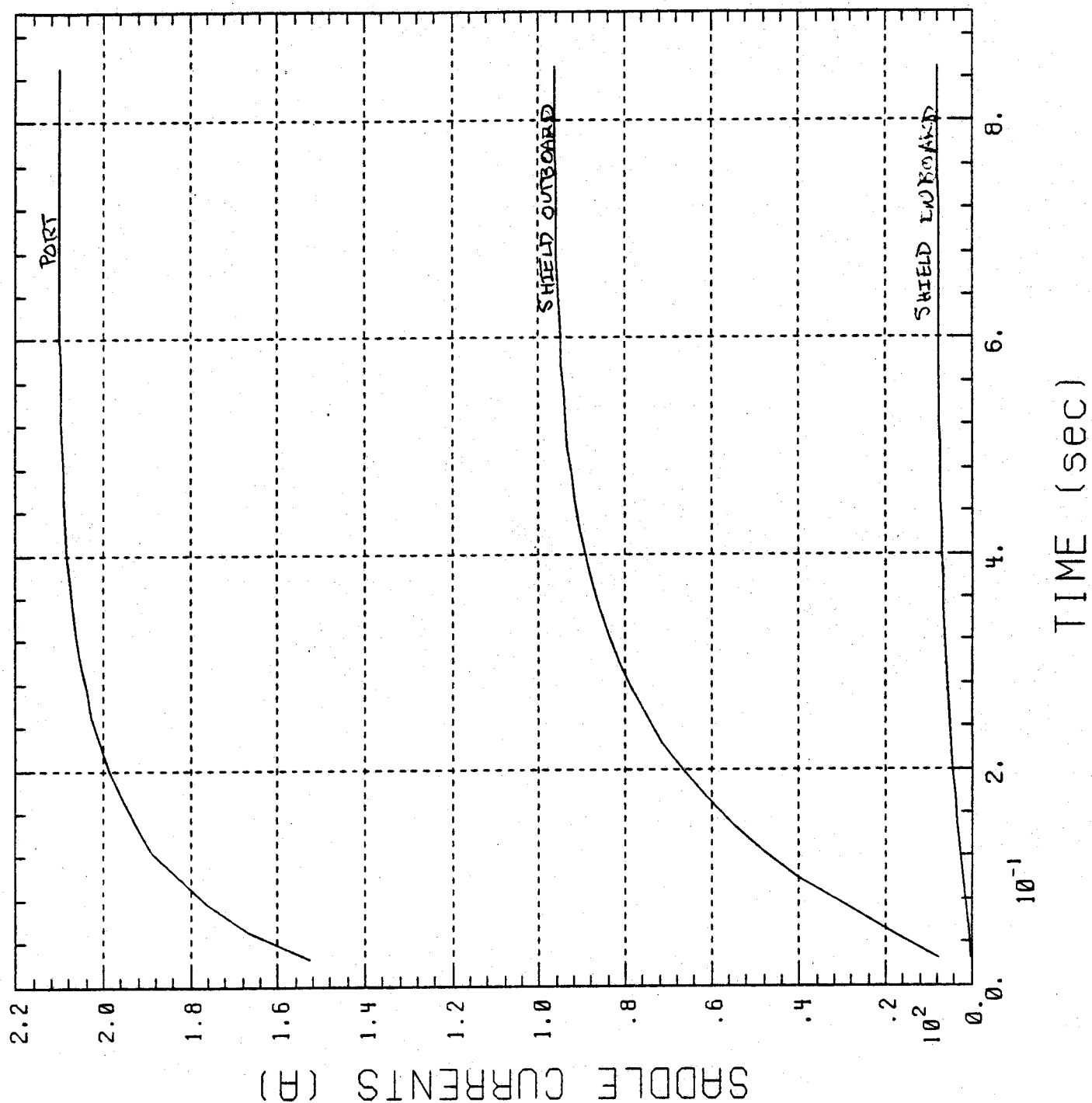


Fig. 2.3-4 Component saddle currents vs time for Case 25. Saddle currents occur only in no net regions. Region names correspond to those in Fig. 2.1-1.

to that used previously. Note that even though the limiter is toroidally continuous in the model and copper, it is not initially dominant because, during start-up, the field penetration occurs from the outside of the vessel inward.

The previous cases were run without any plasma current present. Figures 2.3-5 and 2.3-6 are a repeat of Case 25 but with a plasma current ramping up to 10.3 MA during the start up PF swing. The current density was uniform and restricted to the innermost region in Fig. 2.0-1. A comparison with the previous two figures indicates that the primary impact is to reduce the current induced in the limiter.

The start-up cases which have been run in this preliminary analysis imply that flux penetration to the plasma is acceptable and are useful as an indicator of the dominant components during this part of the operating scenario.

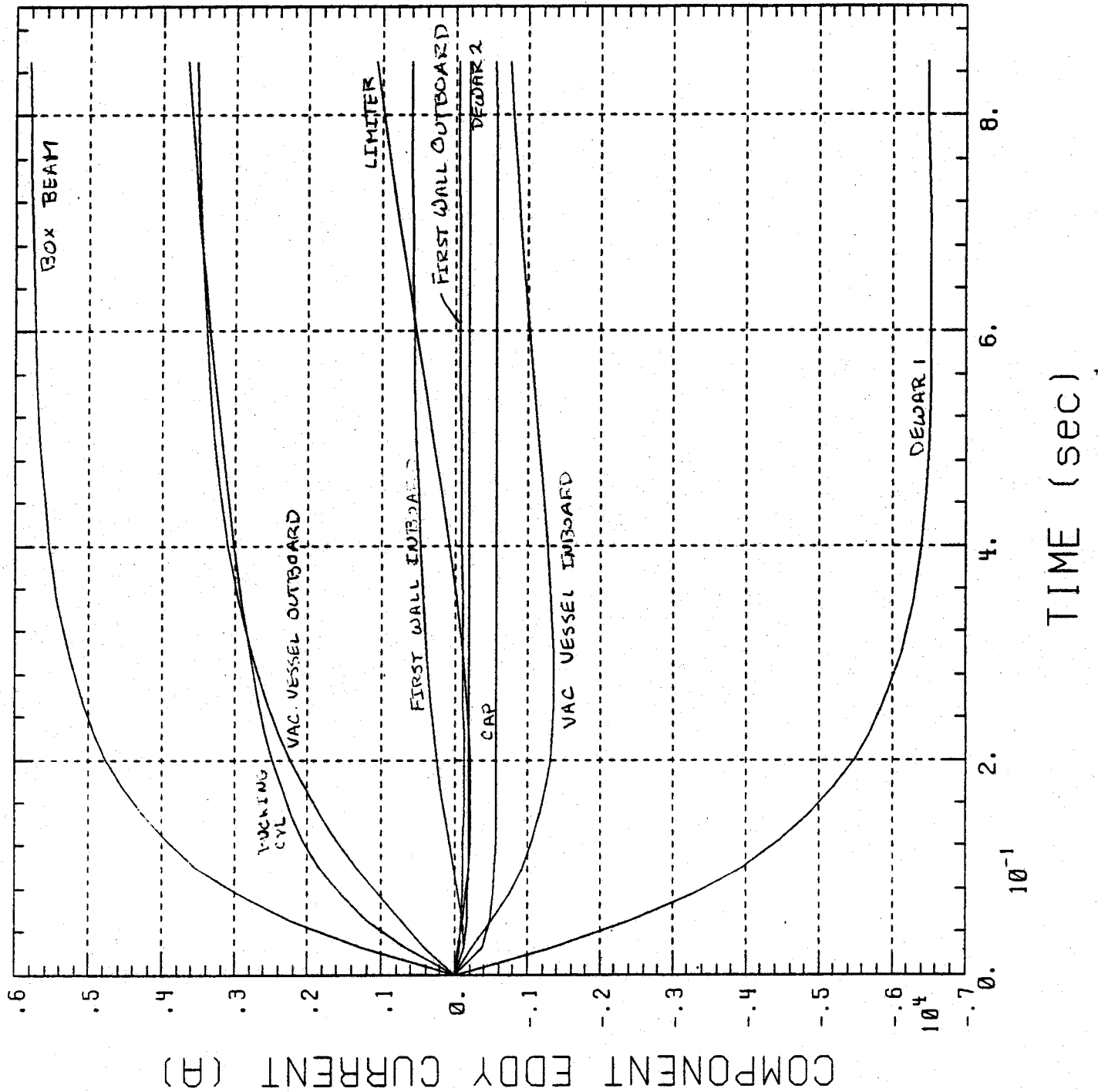


Fig. 2.3-5 Component eddy currents vs time for Case 26. Currents are for the components above the midplane. Component names correspond to those in Fig. 2.1-1.

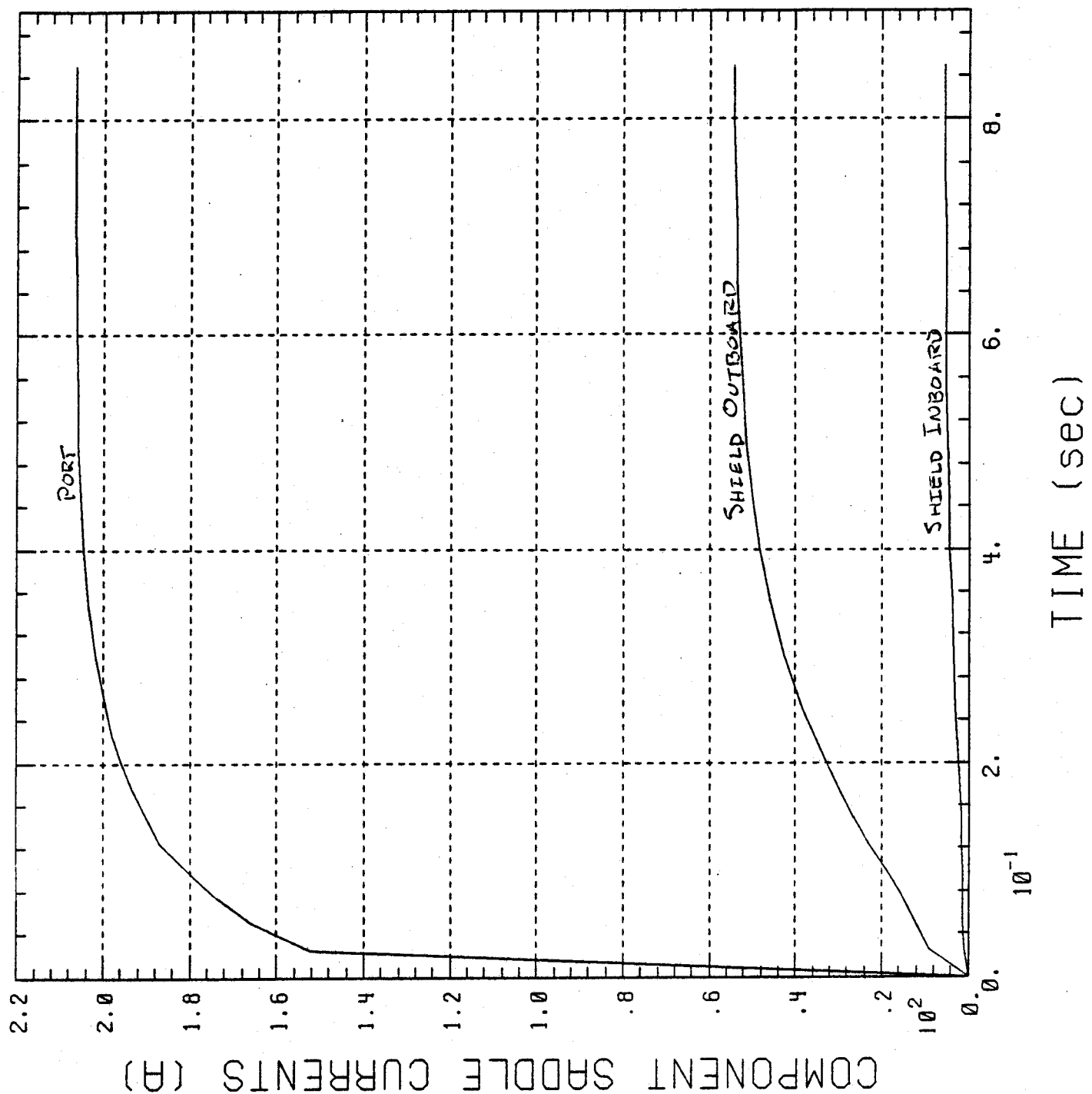


Fig. 2.3-6 Component saddle currents vs time for Case 26. Saddle currents occur only in no net regions. Region names correspond to those in Fig. 2.1-1.

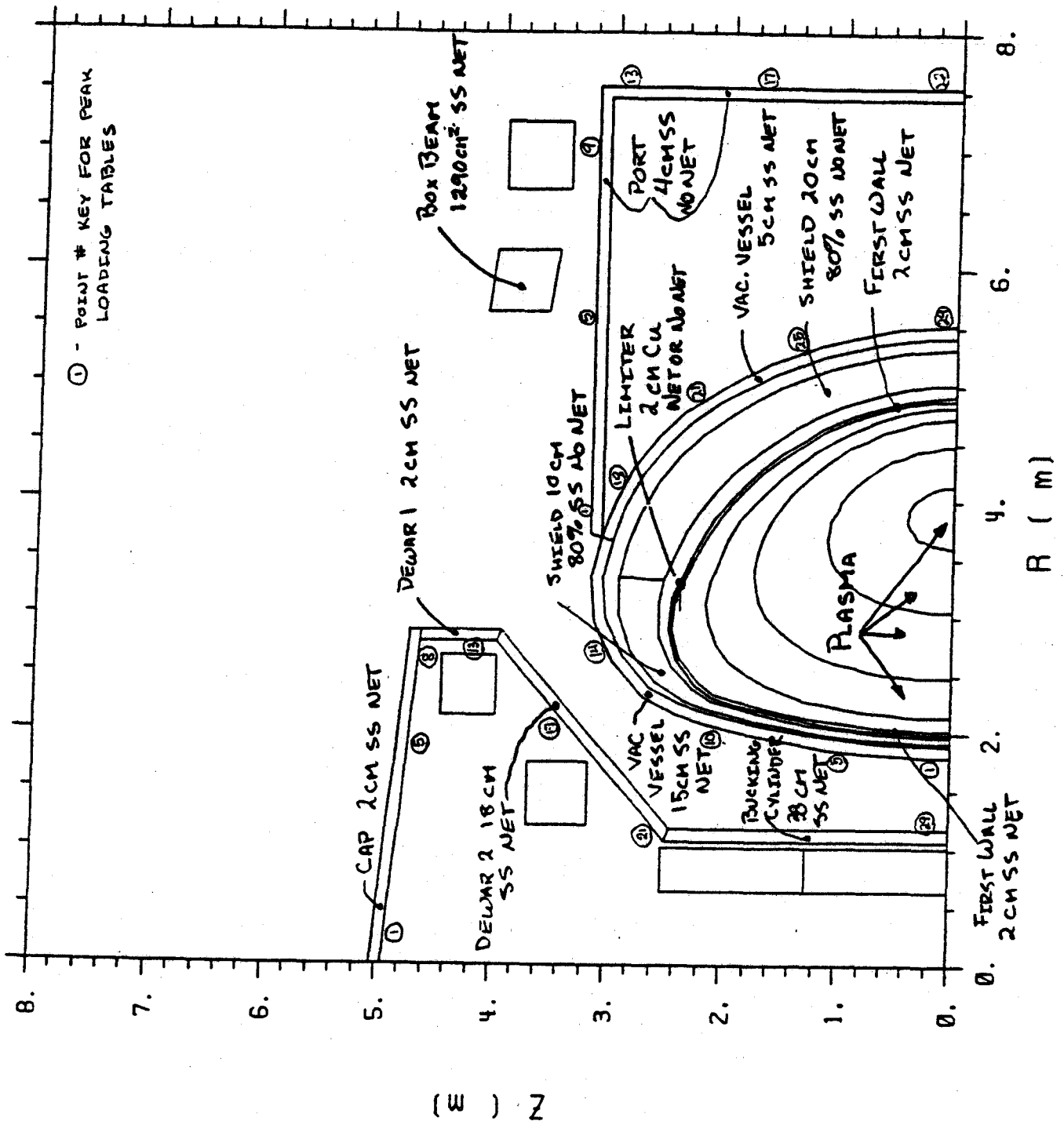
3.0 DISRUPTION EDDY CURRENTS

The axially symmetric transient electromagnetics code was used with several variations on the models used in the start-up analysis to produce preliminary estimates of the loads produced on selected components as a result of a disruption. In particular, induced current and em load distributions were estimated for the first wall, vacuum vessel and limiter. The latter was considered for cases which were either toroidally continuous or segmented to prevent net current flow. Current distributions and maximum load results are given in this section to summarize the study. Appendices B and C contain load distributions along the first wall and vacuum vessel throughout the transients.

3.1 Model Description

An outline of the finite element regions used in this study is shown in Fig. 3.1-1. Attention was focused on currents and loads on the first wall, the section of the first wall which modeled the limiter, and the vacuum vessel. The numbered points in Fig. 3.1-1 will be useful in identifying peak load locations when used with some of the tables which follow. Note that the outboard vacuum vessel was modeled as a net current carrying region and the port as a no net region. Neither are actually axially symmetric as assumed in the model. This will be rectified in future models using the SPARK¹ code, but is not expected to be a major influence on the trends indicated in this study.

¹ D.W. Weisenburger, "SPARK Version One: Reference Manual", PPPL-2040, Princeton Plasma Physics Laboratory, Princeton, NJ, October 1983.



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Fig. 3.1-1 Finite element model for disruption used a stationary plasma ramped to zero current in 10 ms and a limiter which had either "net" or "no net" current carrying ability.

The plasma carried 10.3 MA before disruption. The plasma current was distributed over each of four regions and was motionless as the current was ramped to zero in 10 ms. Throughout the transient the PF coil currents were held constant at levels corresponding to end-of-burn (see last column in Table 2.1-1). The characteristics of each region in the model are defined in Table 3.1-1. Figure 3.1-2 illustrates the steady-state ($t < 0$) field line distribution produced by the plasma alone.

Figure 3.1-3 is a sketch showing typical current and load directions on both net and no-net current carrying passive components. The top sketch shows a section of a toroidally continuous shell segment capable of carrying a net current through an rz-plane. The induced currents in this type of section as a result of a disruption will be in the toroidal direction and will interact with fields from the plasma, the PF coil system and other eddy current fields. The result will be em loads per unit shell surface area which have components normal and tangential to the shell surface. In the figures which follow these will be referred to as normal and tangential pressures and have the dimensions of force per unit shell surface area. Normal pressures are defined positive outward and tangential pressures are defined positive clockwise in the rz - plane.

The lower sketch in Fig. 3.1-3 shows a no-net current carrying shell segment. This is also subject to the type of loads described above. In addition, however, the toroidally directed currents must return within the same shell, hence, there must be saddle components of current. The model

TABLE 3.1-1

TFCX - PLASMA DISRUPTION MODEL

COMPONENT NAME	MATERIAL	THICKNESS (cm)	NET CURRENT	NO NET CURRENT
BUCKING CYLINDER	SS	38	✓	
DEWAR 1	SS	18	✓	
DEWAR 2	SS	2	✓	
CAP	SS	2	✓	
PORT	SS	4		✓
VACUUM VESSEL INBOARD	SS	15	✓	
VACUUM VESSEL OUTBOARD	SS	5	✓	
SHIELD INBOARD	80% SS	10		✓
SHIELD OUTBOARD	80% SS	20		✓
FIRST WALL INBOARD	SS	2	✓	
FIRST WALL OUTBOARD	SS	2	✓	
LIMITER	Cu	2	✓	or ✓
BOX BEAM	SS	1290 cm ²	✓	

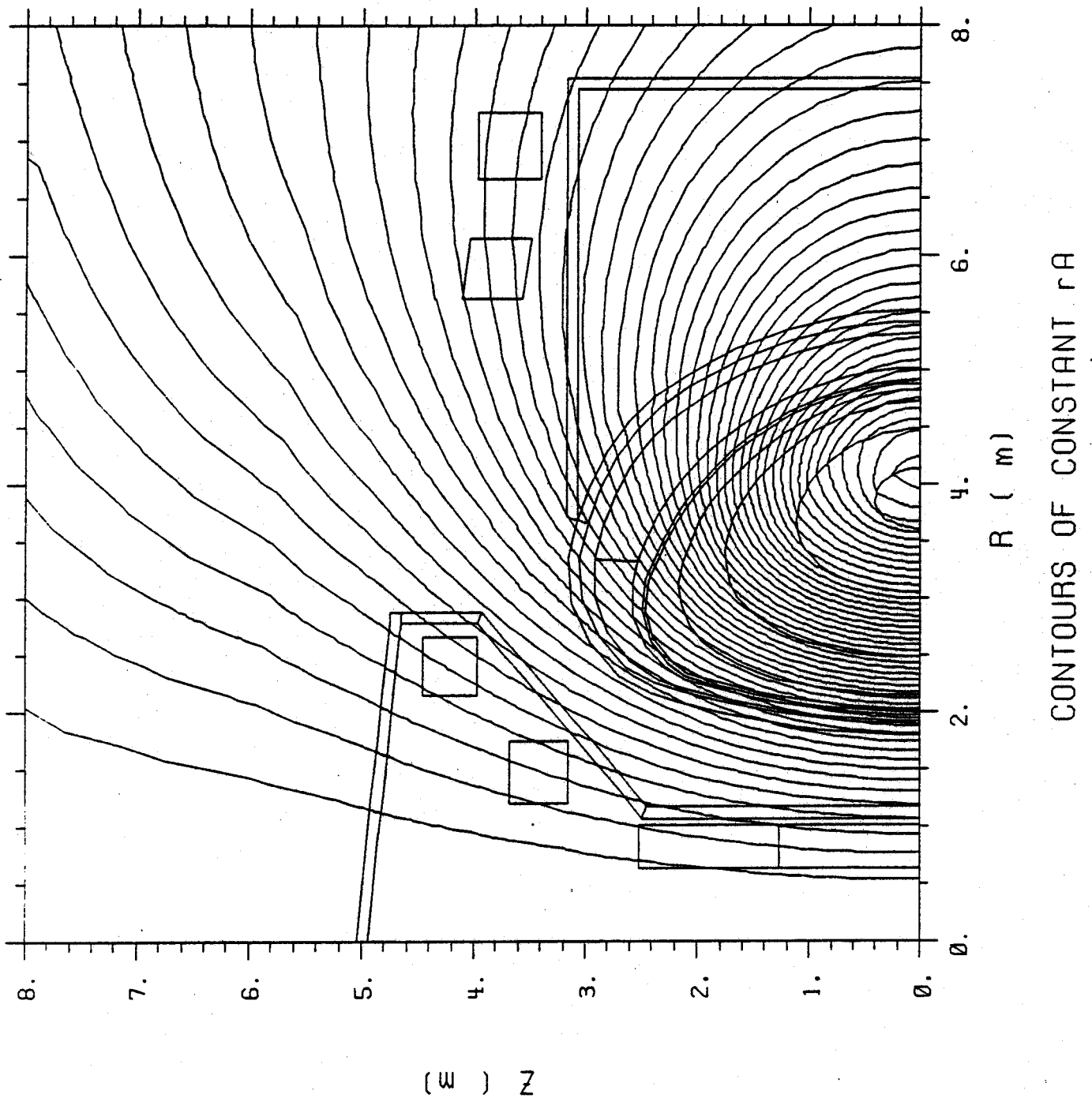
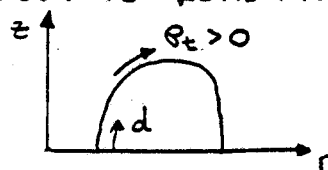
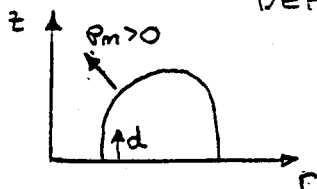


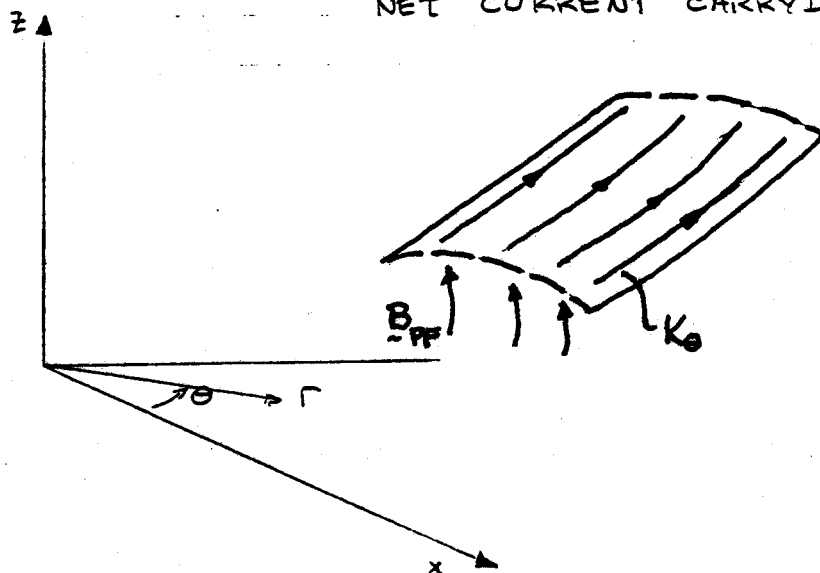
Fig. 3.1-2 Steady state ($t < 0$) field line distribution produced by the plasma alone.

DEFINITION OF POSITIVE LOADING

-26-



NET CURRENT CARRYING REGION



$$\underline{P} = \underline{K} \times (\underline{B}_{PF} + \underline{B}_{EDDY})$$

NO NET CURRENT CARRYING REGION

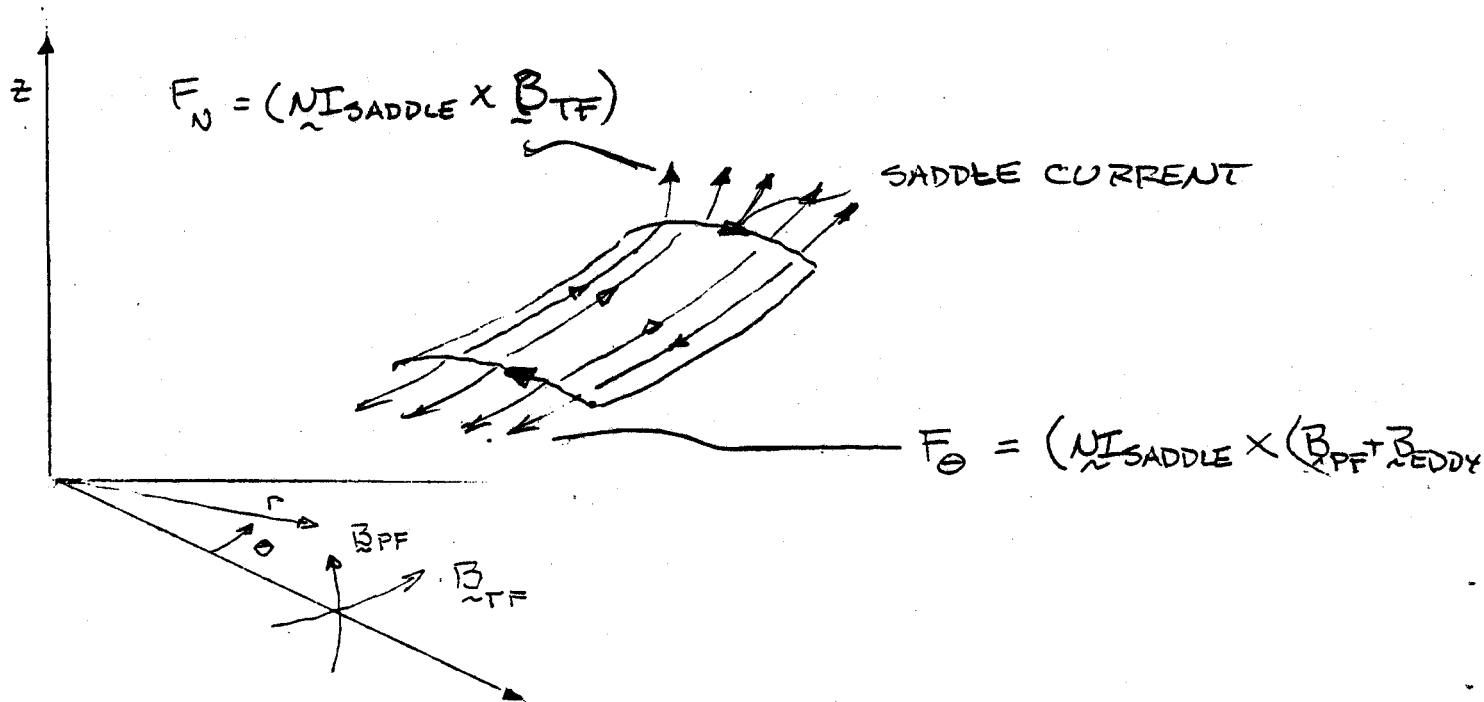


Fig. 3.1-3 Definition of positive current and load directions for disruption eddy current analysis.

is axially symmetric so the saddle current distribution cannot be determined. However, the magnitude of the total saddle current for a no net region must be equal to the total toroidal current flow in one direction and are important since they interact with the toroidal field to produce equal and opposite loads on each end of the shell with the loads lying in rz-planes. The same saddle currents interact with the poloidal field and the eddy current fields to produce equal and opposite loads in the toroidal direction on each end of the segment.

3.2 Limiter Carrying Net Current

This case is based on the configuration in Fig. 3.1-1 and the assumption that the limiter can carry net current in the toroidal direction. The latter may be expected to produce the maximum possible current in the limiter.

The plasma current decays linearly to zero in 10 ms and the steady-state field pattern from the plasma which is shown in Fig. 3.1-2 changes as shown in Figs. 3.2-1 to 3.2-4 which correspond to times of 10, 30, 50, and 100 ms, respectively. The presence of eddy currents is indicated in the figures by "kinks" in the field lines because the currents in the shells are essentially toroidally directed current sheets which cause local discontinuities in the tangential components of poloidal magnetic field. The strong influence of the net current carrying limiter is evident.

The flux through the $z=0$ plane is shown in Fig. 3.2-5 for selected instants of time. The $t<0$ curve is due to the steady-state plasma alone.

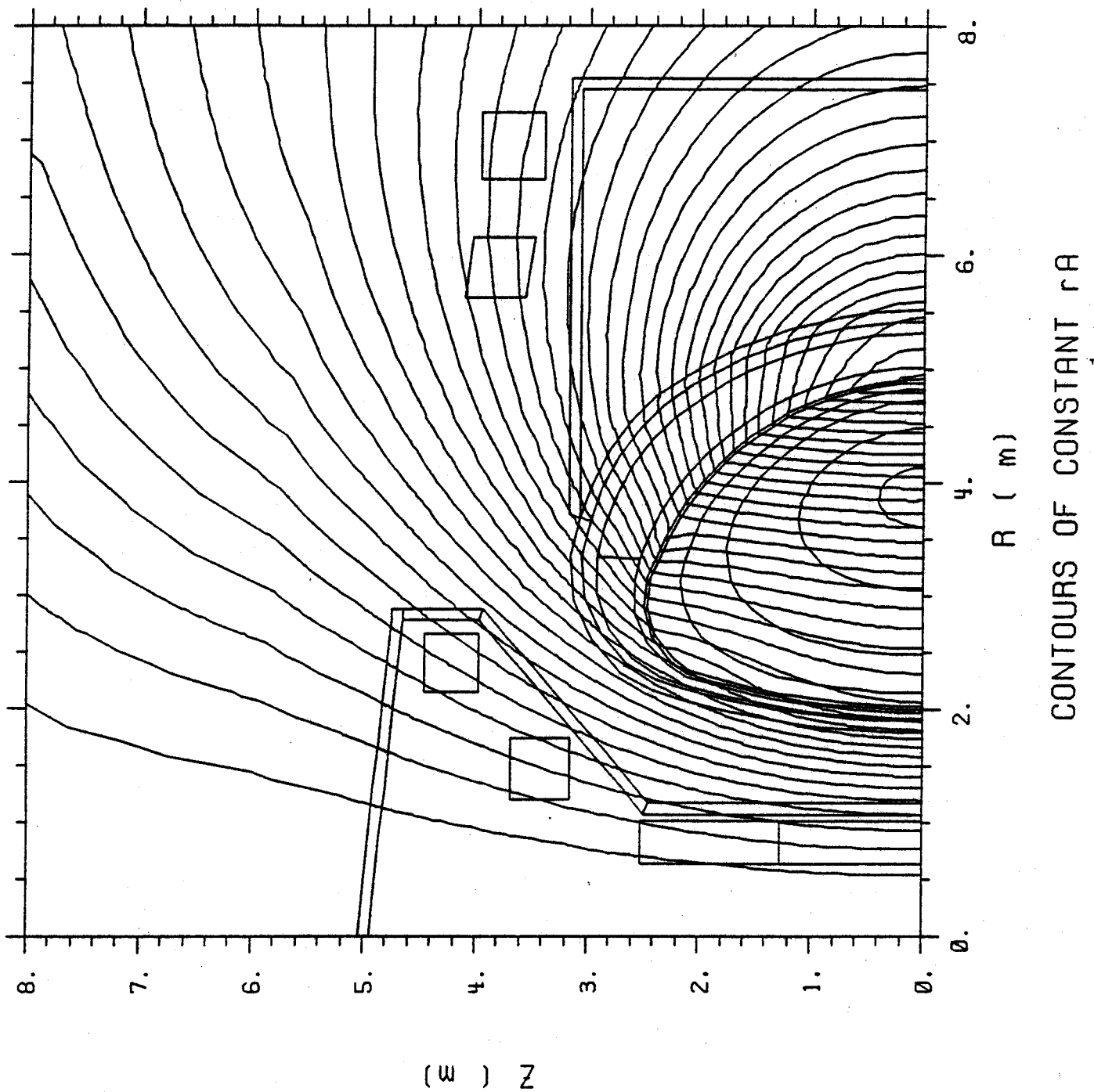


Fig. 3.2-1 Fieldline distribution at 10 ms for a 10 ms plasma disruption with a net current carrying limiter.

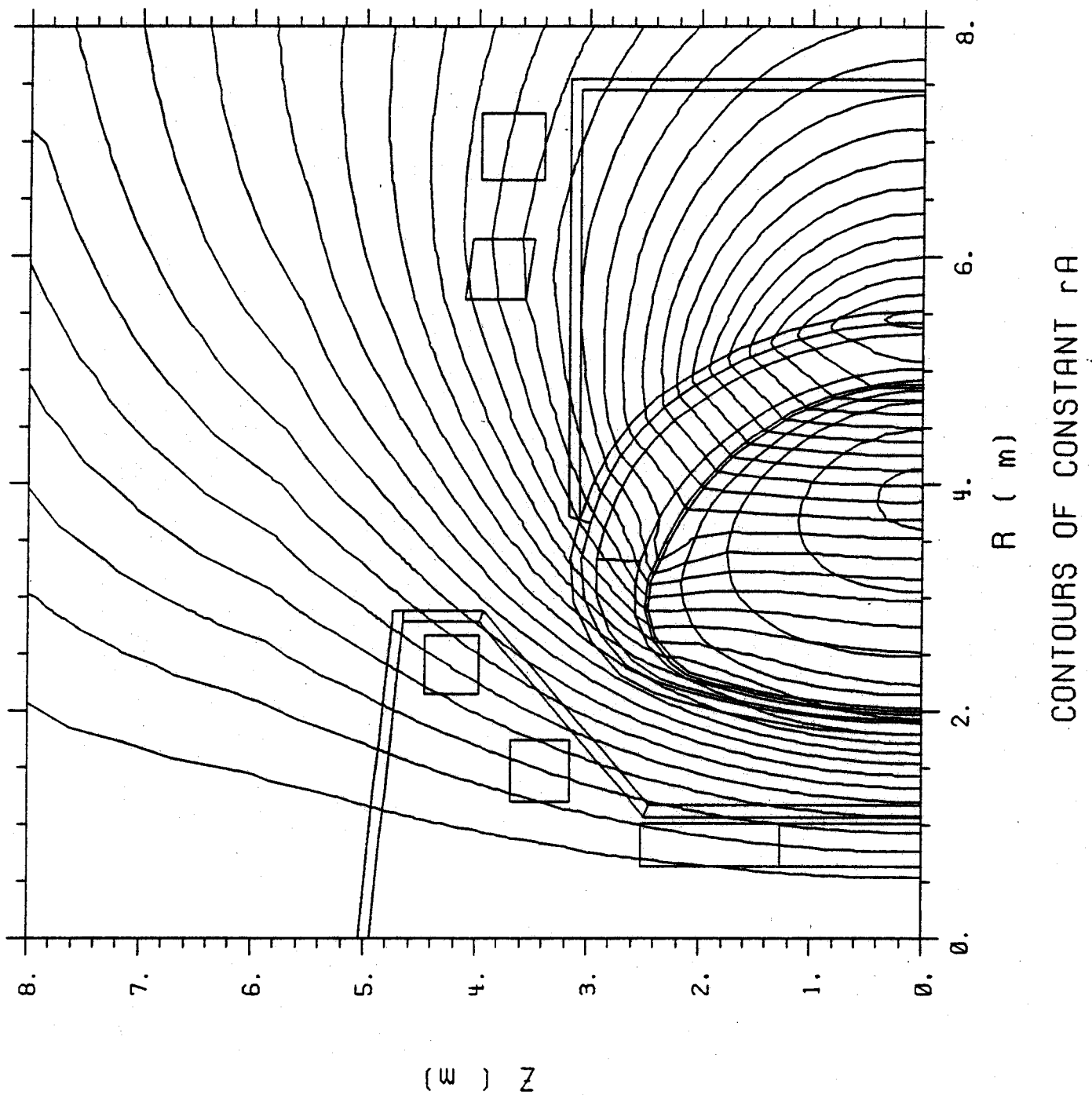


Fig. 3.2-2 Fieldline distribution at 30 ms for a 10 ms plasma disruption with a net current carrying limiter.

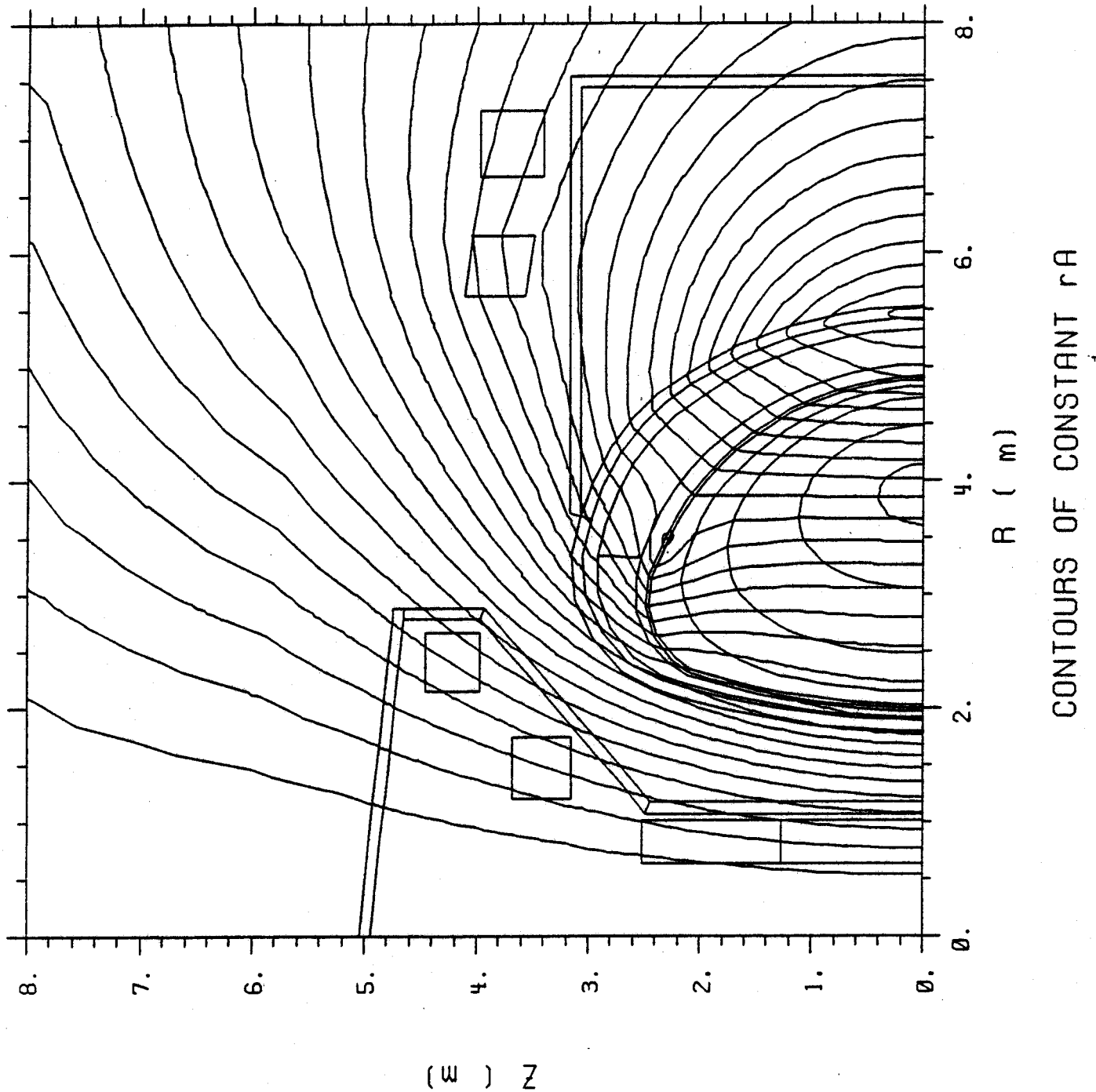


Fig. 3.2-3 Fieldline distribution at 50 ms for a 10 ms plasma disruption with a net current carrying limiter.

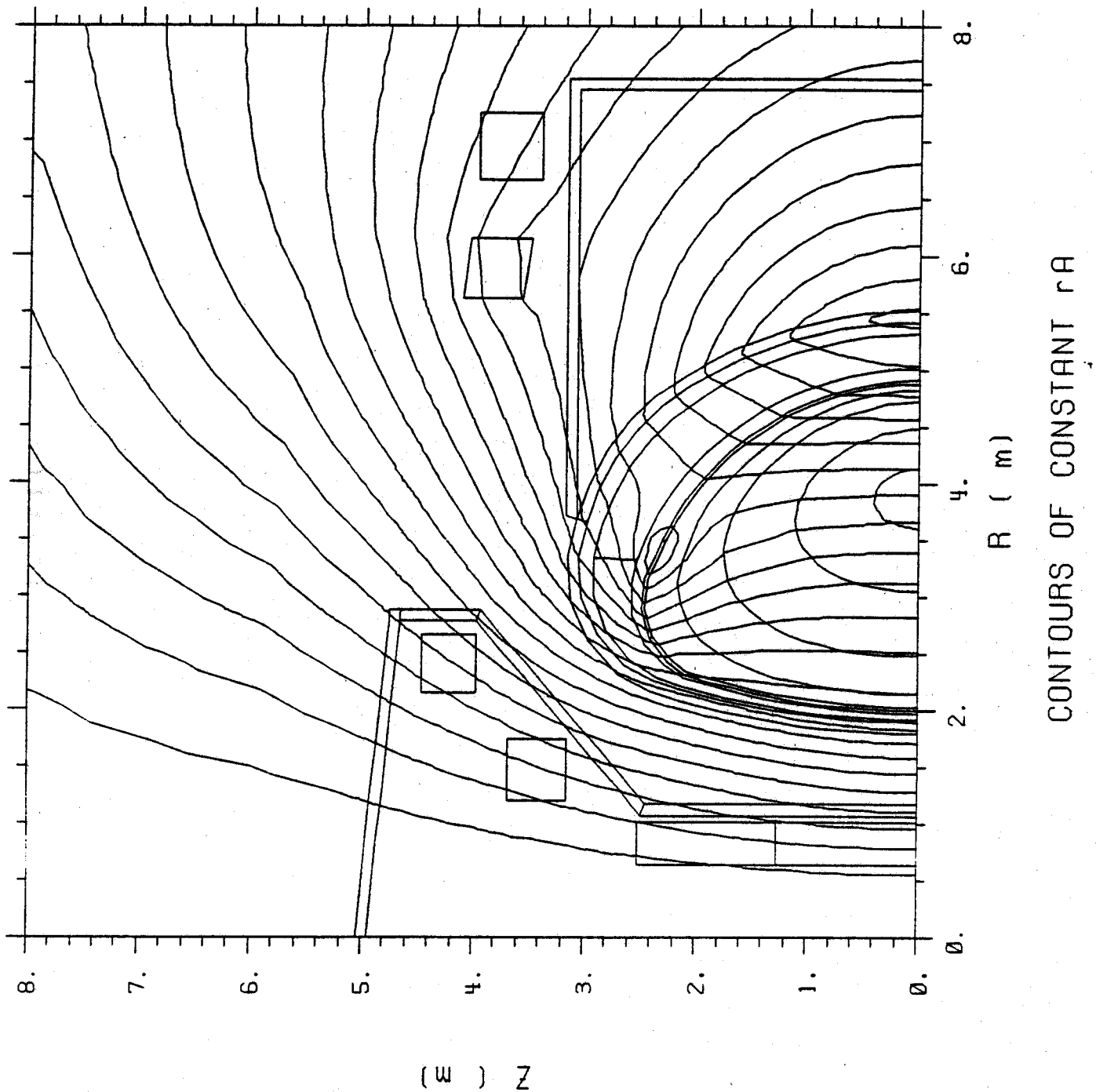


Fig. 3.2-4 Fieldline distribution at 100 ms for a 10 ms plasma disruption with a net current carrying limiter.

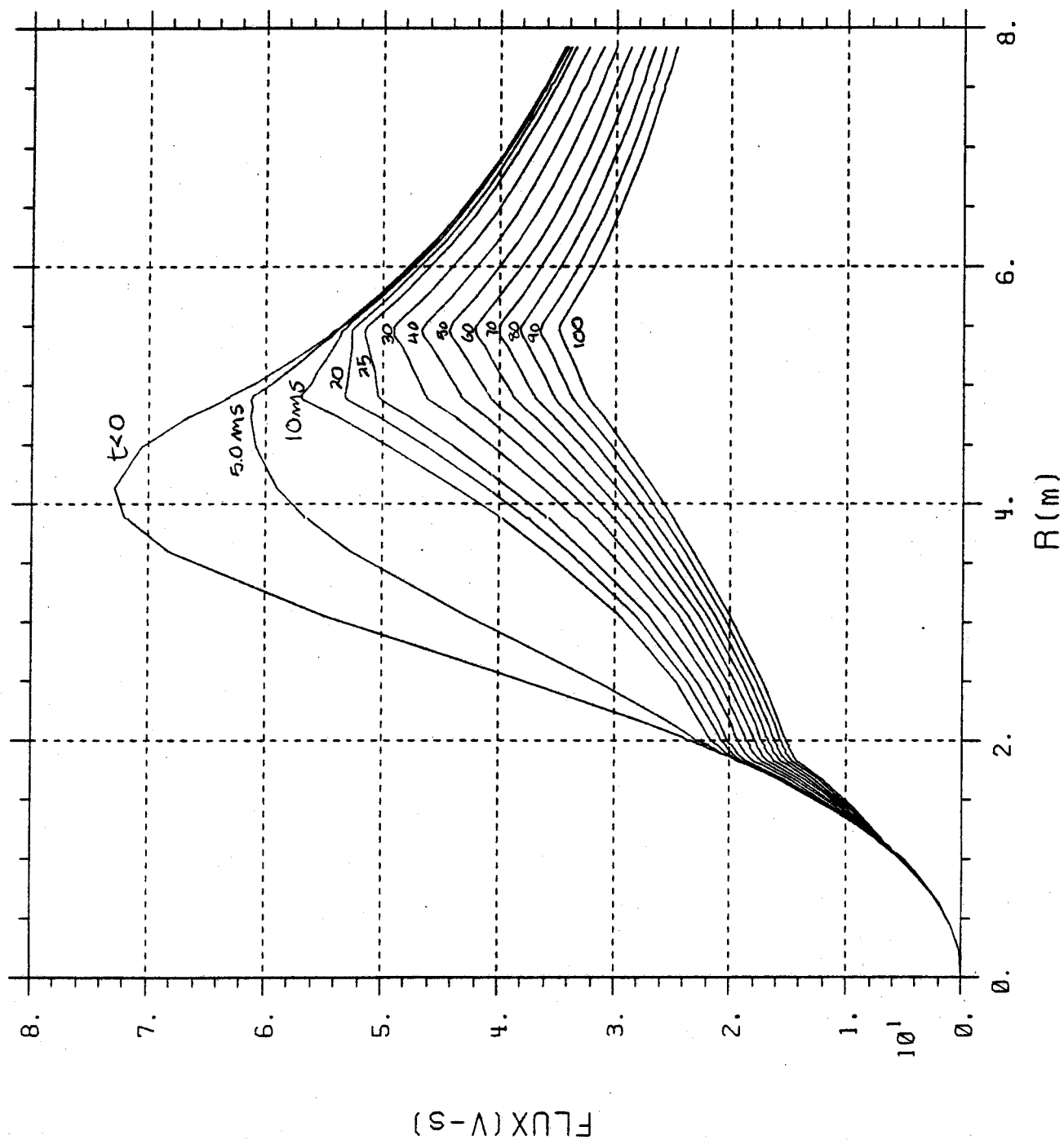


Fig. 3.2-5 Flux vs radial position along the midplane ($Z = 0$) for various times during and after a 10 ms plasma disruption for a net current carrying limiter.

The plasma decays in 10 ms which leads to a collapse of the center of the pattern on the same time scale since the major portion of this part of the flux corresponds to those field lines which were totally within the nearest conducting wall and did not link any conducting material (e.g., see Fig. 3.1-2). For $t > 10$ ms, the decay of the flux pattern is much slower because of the eddy currents induced in the vessel walls.

The total currents in the individual regions in the model are given in Figs. 3.2-6 and 3.2-7. Comparison of the latter with the former shows that the net current regions carry substantially higher current levels. Furthermore, Fig. 3.2-6 shows that the components nearest the plasma (i.e., the first wall inboard and outboard) respond first, but have a relatively rapid decay rate because they are thin compared with the vacuum vessel inboard which is further from the plasma, thicker and eventually becomes dominant. Note that the vacuum vessel outboard is not actually toroidally continuous as assumed in the model, hence, it will be less influential and somewhat higher currents will probably result in the inboard vessel and limiter. Furthermore, if the first wall inboard and outboard are not net current carriers as assumed then the other components can be expected to respond faster than shown.

The current sheet amplitude is shown in Fig. 3.2-8 as a function of distance along the first wall measured from the inboard side in the $z=0$ plane. The plot is for the instant at 10 ms when the plasma current has just reached zero and shows relatively high currents along the first wall and a concentration of current in the limiter. A similar plot at 100 ms

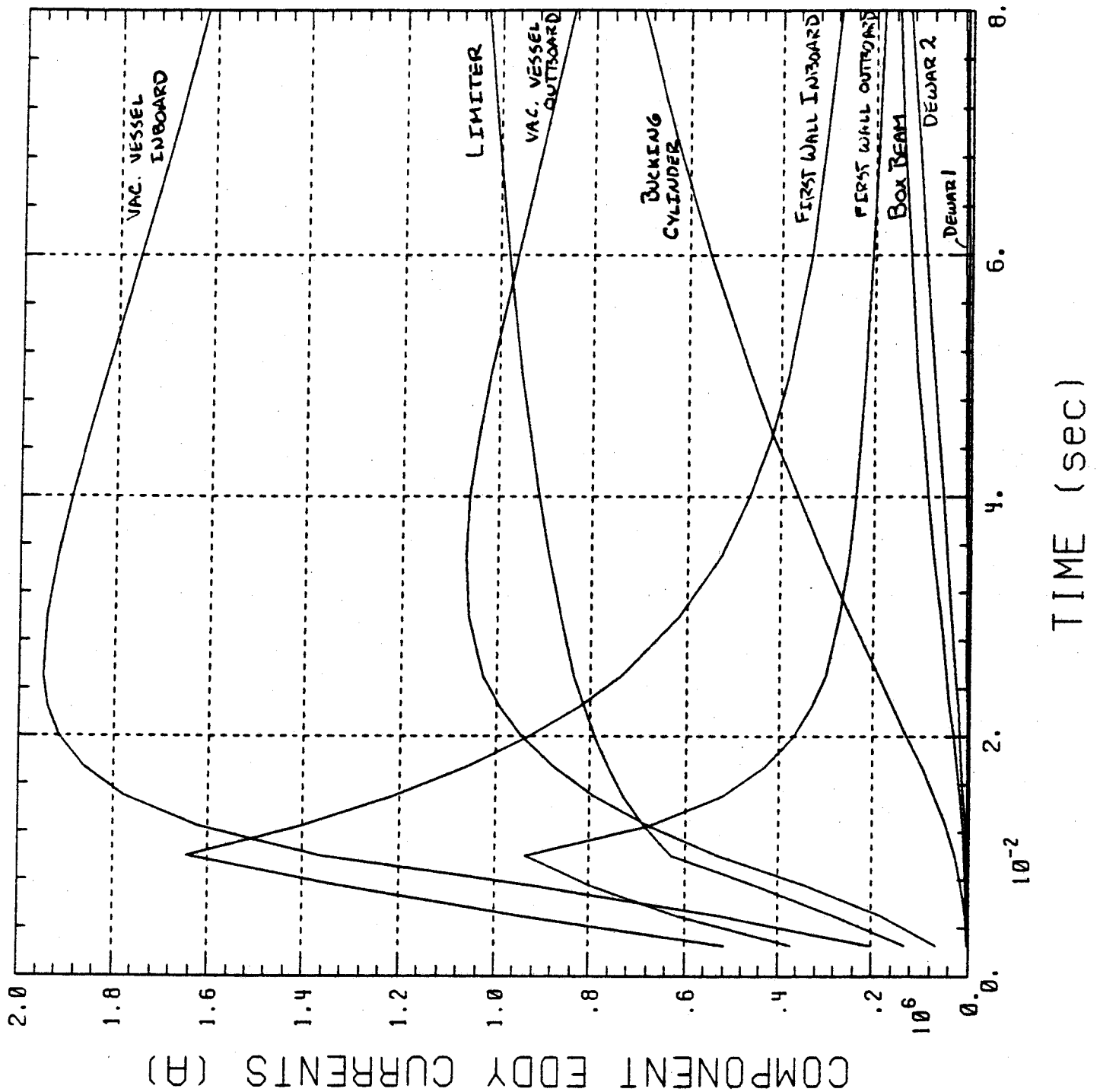


Fig. 3.2-6 Component eddy currents vs time for a 10 ms plasma disruption and a net current carrying limiter. Currents are for the components above the midplane. Component names correspond to those in Fig. 3.1.1.

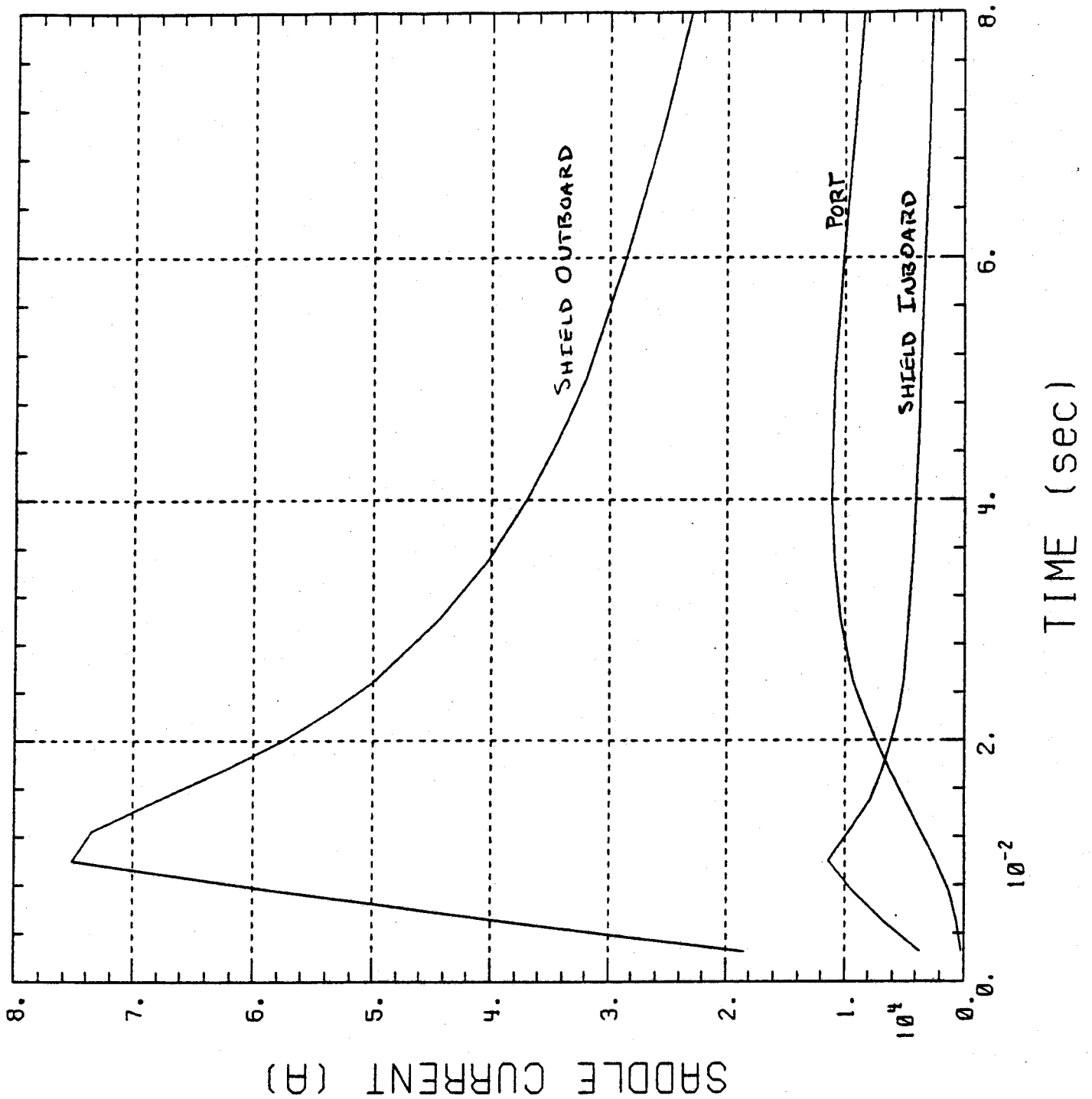


Fig. 3.2-7 Component saddle currents vs time for a 10 ms plasma disruption and a net current carrying limiter. Currents occur only in no net regions. Region names correspond to those in Fig. 3.2-1.

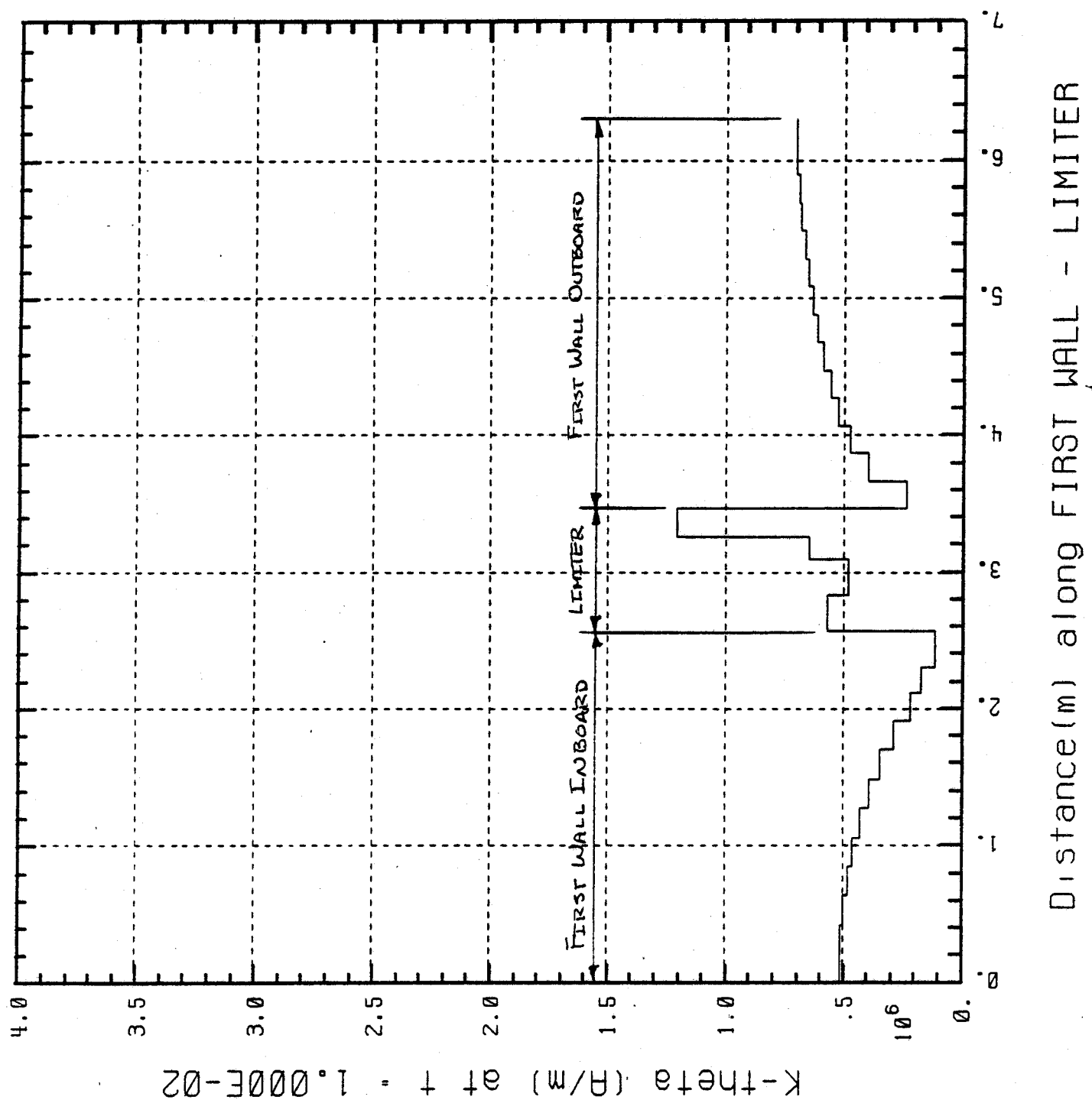


Fig. 3.2-8 Toroidal current sheet amplitude vs position along the first wall and limiter at 10 ms for a 10 ms plasma disruption and a net current carrying limiter.

is shown in Fig. 3.2-9 and indicates that the currents in the first wall sections have decayed, but the current in the limiter has increased substantially. Plots of this type for the vacuum vessel are shown in Figs. 3.2-10 and 3.2-11 which are for 10 and 25 ms, respectively. The time of 100 ms was selected for the first wall example and 25 ms for the vacuum vessel since these are close to the time for maximum currents in the limiter and vessel, respectively.

Tables 3.2-1 and 3.2-2 summarizes the maximum currents and loads for this case, together with the times at which they occur, and their locations keyed to the points identified in Fig. 3.1-1. In general, the loads are extreme in the components away from the plasma at later times (~ 10 ms). The extreme loads on the first wall/limiter occur on the limiter at 100 ms. The peak shield loading occurs at 10 ms (consistent with the much shorter time constant of the no-net region). All components have both positive and negative pressures indicative of a non-uniform loading.

More detailed distributions may be found in Appendix B which gives the loads plotted along the first wall and vacuum vessel peripheries at selected instants of time.

3.3 Limiter Carrying No Net Current

This case is based on the configuration in Fig. 3.1-1 and the assumption that the limiter can not carry net current in the toroidal direction. The latter may be expected to produce much lower toroidal currents in the limiter than the previous case, but will result in saddle currents which are necessary to satisfy the no net restriction.

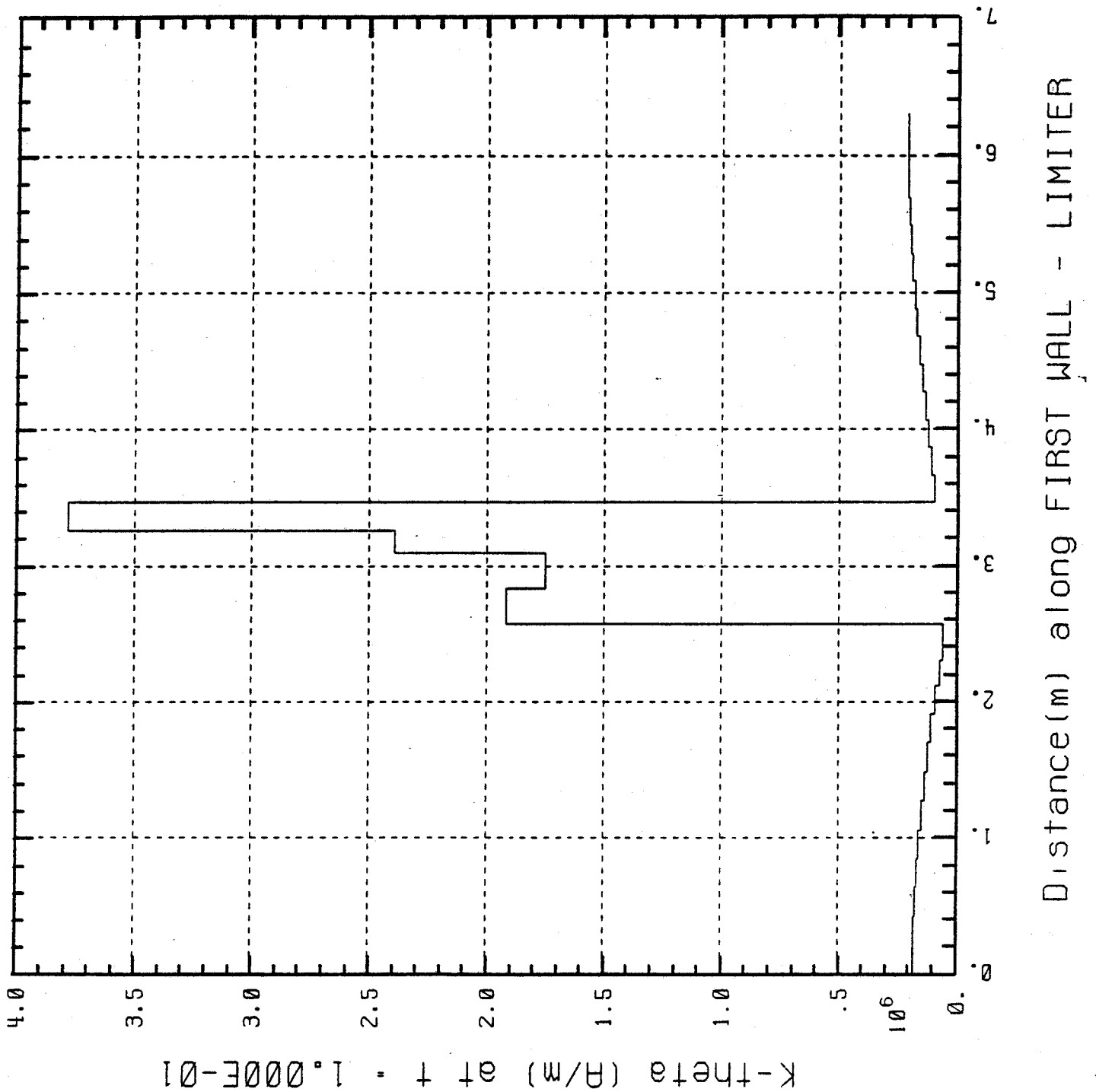


Fig. 3.2-9 Toroidal current sheet amplitude vs position along the first wall and limiter at 100 ms for a 10 ms plasma disruption and a net current carrying limiter.

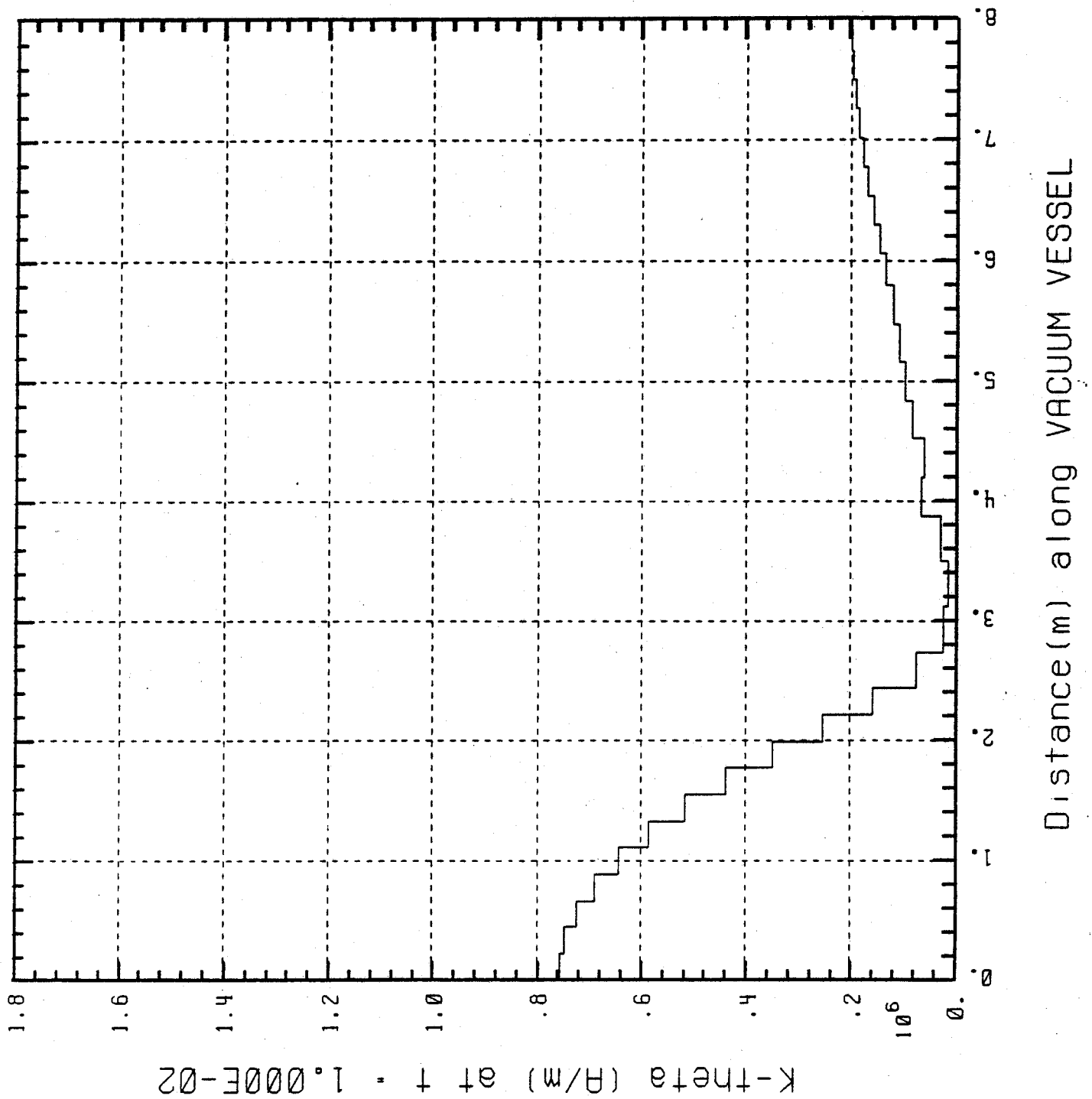


Fig. 3.2-10 Toroidal current sheet amplitude vs position along the vacuum vessel at 10 ms for a 10 ms plasma disruption and a net current carrying limiter.

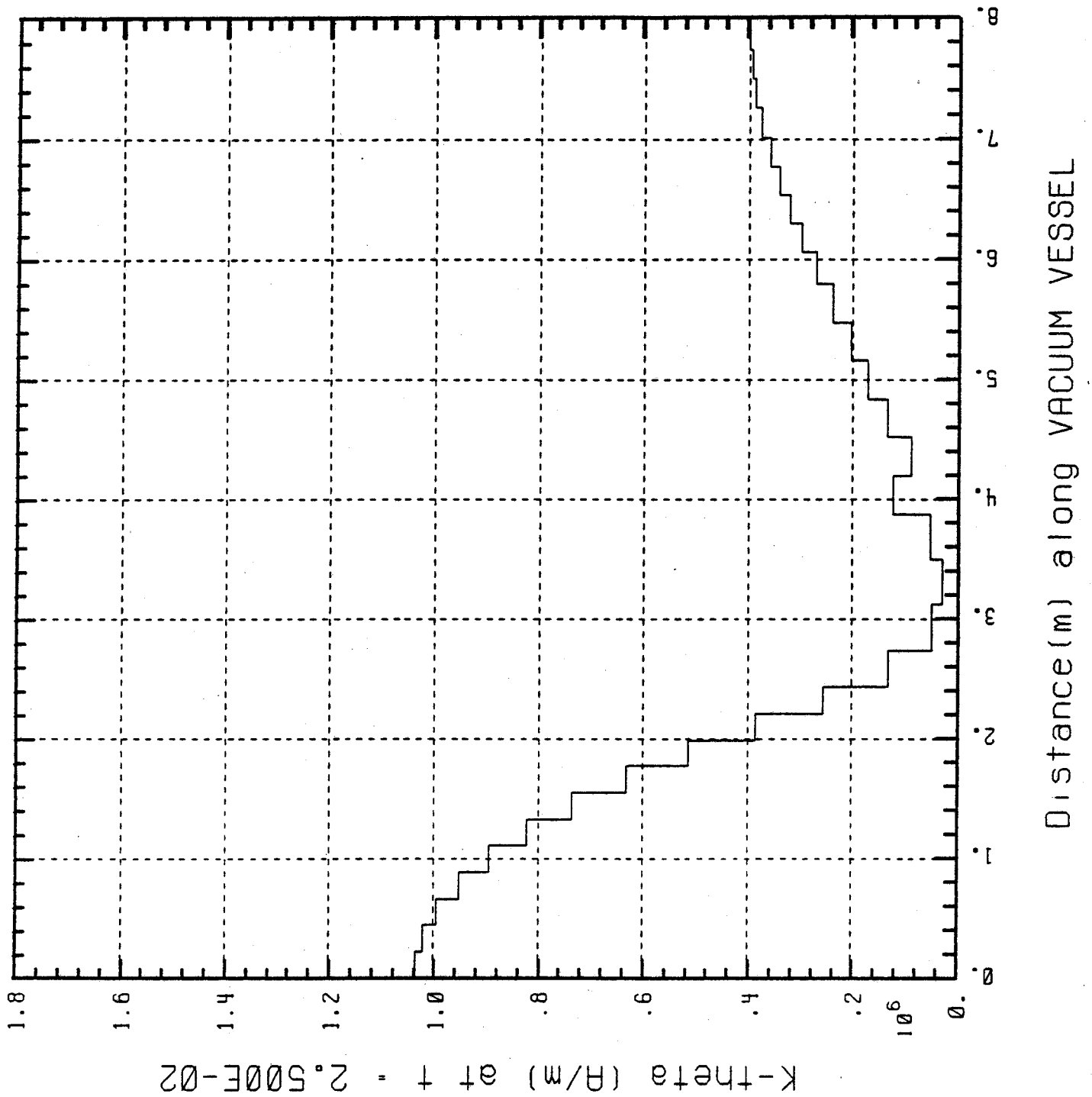


Fig. 3.2-11 Toroidal current sheet amplitude vs position along the vacuum vessel at 25 ms for a 10 ms plasma disruption and a net current carrying limiter.

TFCX - 10 ms PLASMA DISRUPTION - NET LIMITER - CASE 23

Extrema In The Current Sheet Magnitude

Region	point #	Minimum K-theta (MA/m)	time (ms)	point #	Maximum K-theta (MA/m)	time (ms)
DEWAR	1	0	0	29	0.946	100
FIRST WALL - LIMITER	1	0	0	16	3.830	70
SHIELD	16	-0.103	10	30	0.063	60
VACUUM VESSEL	1	0	0	1	1.711	60
PORT	1	-0.009	45	22	0.020	60

Extrema For The Normal Pressure Magnitude

Region	point #	Minimum Normal Pressure (MPa)	time (ms)	point #	Maximum Normal Pressure (MPa)	time (ms)
DEWAR	15	-0.185	100	29	0.987	100
FIRST WALL - LIMITER	16	-0.625	60	13	0.468	100
SHIELD	30	-0.033	10	16	0.051	10
VACUUM VESSEL	1	-0.881	60	13	0.051	100
PORT	8	-0.017	60	12	0.005	60

Extrema For The Tangential Pressure Magnitude

Region	point #	Minimum Tangential Pressure (MPa)	time (ms)	point #	Maximum Tangential Pressure (MPa)	time (ms)
DEWAR	22	-0.414	100	15	0.071	100
FIRST WALL - LIMITER	16	-3.386	100	13	0.247	100
SHIELD	20	-0.012	60	16	0.046	10
VACUUM VESSEL	16	-0.318	100	9	0.275	90
PORT	7	-0.014	80	13	0.009	60

Table 3.2-1 Net Current Carrying Limiter — Summary of maximum induced currents, normal pressures and tangential pressures.

TFCX - 10 ms PLASMA DISRUPTION - NET LIMITER - CASE 23

Extrema In The Saddle Current Magnitude

Region	point #	Minimum Current (kA)	time (ms)	point #	Maximum Current (kA)	time (ms)
SHIELD INBOARD	15	0.00	0	12	11.49	60
SHIELD OUTBOARD	5	-66.33	10	15	128.0	60
PORT	13	-11.07	40	22	76.64	60

Extrema In The Toroidal Force Magnitude

Region	point #	Minimum F-theta (kN/m)	time (ms)	point #	Maximum F-theta (kN/m)	time (ms)
SHIELD INBOARD	14	-6.34	80	15	6.34	60
SHIELD OUTBOARD	3	-24.95	15	7	5.53	100
PORT	13	-31.85	60	7	35.99	80

Extrema In The Normal Force Magnitude

Region	point #	Minimum F-normal (MN/m)	time (ms)	point #	Maximum F-Normal (MN/m)	time (ms)
SHIELD INBOARD	9	-0.072	10	15	0.0	0
SHIELD OUTBOARD	15	-0.347	60	4	0.218	10

Table 3.2-2 Net Current Carrying Limiter — Summary of maximum saddle currents and saddle current loads on the no net current carriers.

The plasma current decays linearly to zero in 10 ms and the steady-state field pattern from the plasma which is shown in Fig. 3.1-2 changes as shown in Figs. 3.3-1 to 3.3-3 which correspond to times of 10, 30, and 50 ms, respectively. The presence of eddy currents is indicated in the figures by "kinks" in the field lines because the currents in the shells are essentially current sheets which cause local discontinuities in the tangential components of magnetic field. The influence of the limiter is not as strong as in the previous case because its induced current cannot link the main flux through the center of the machine due to the no net restriction.

The flux through the $z=0$ plane is shown in Fig. 3.3-4 for selected instants of time. The $t < 0$ curve is due to the steady-state plasma alone. The plasma decays in 10 ms which leads to a collapse of the center of the pattern on the same time scale since the major portion of this part of the flux corresponds to those field lines which were totally within the nearest conducting wall and did not link any conducting material. For $t > 10$ ms, the decay of the flux pattern is much slower because of the eddy currents induced in the vessel walls. The two abrupt changes in slope on the outboard side are primarily due to the first wall and outboard vacuum vessel which are net current carrying regions in the model. If the first wall is actually designed as a no net region, then the inner "kink" would essentially disappear.

The total currents in the individual regions in the model are given in Figs. 3.3-5 and 3.3-6. Comparison of the latter with the former shows that the net current regions carry substantially higher current levels.

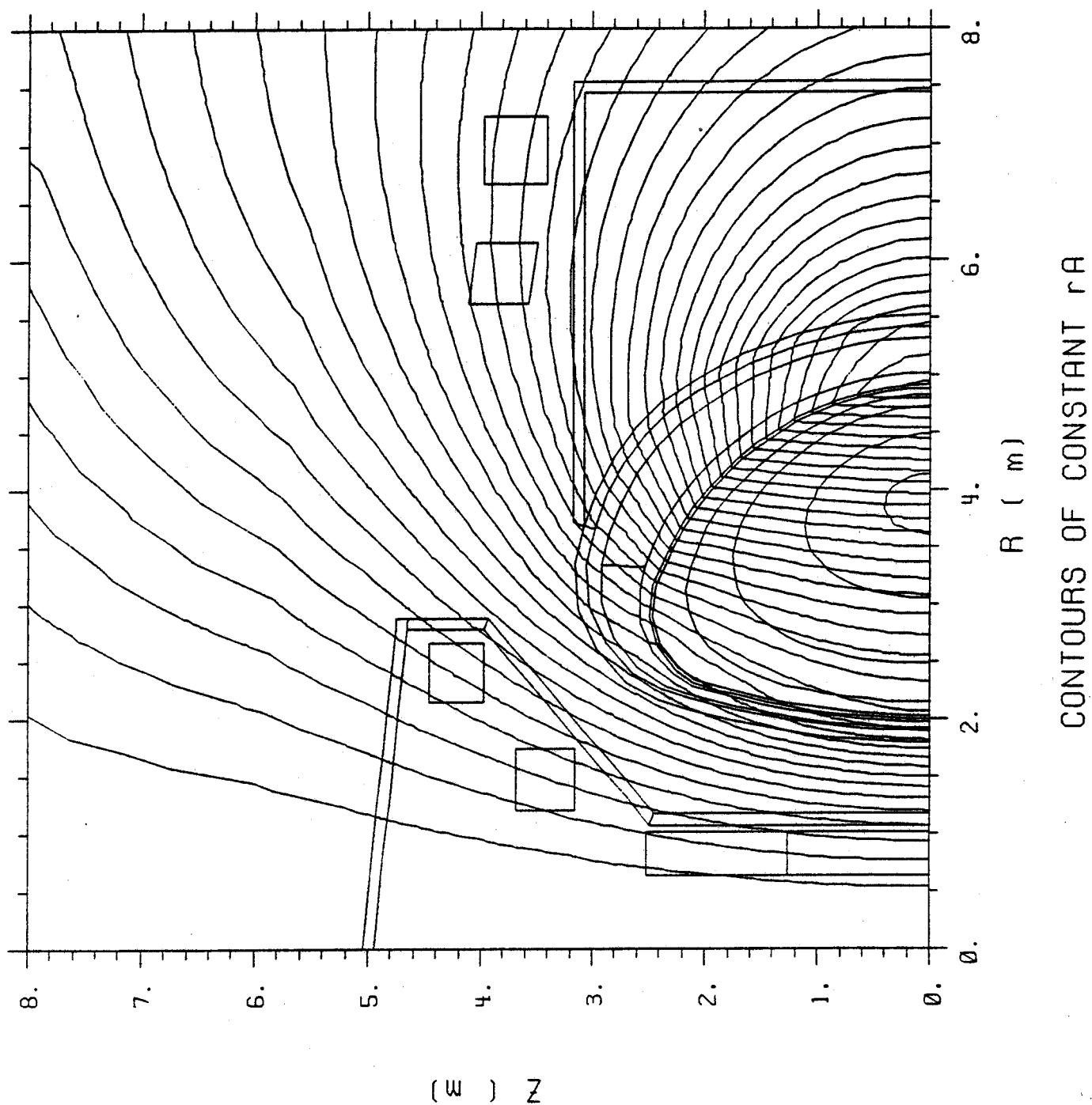


Fig. 3.3-1 Fieldline distribution at 10 ms for a 10 ms plasma disruption with a no net current carrying limiter.

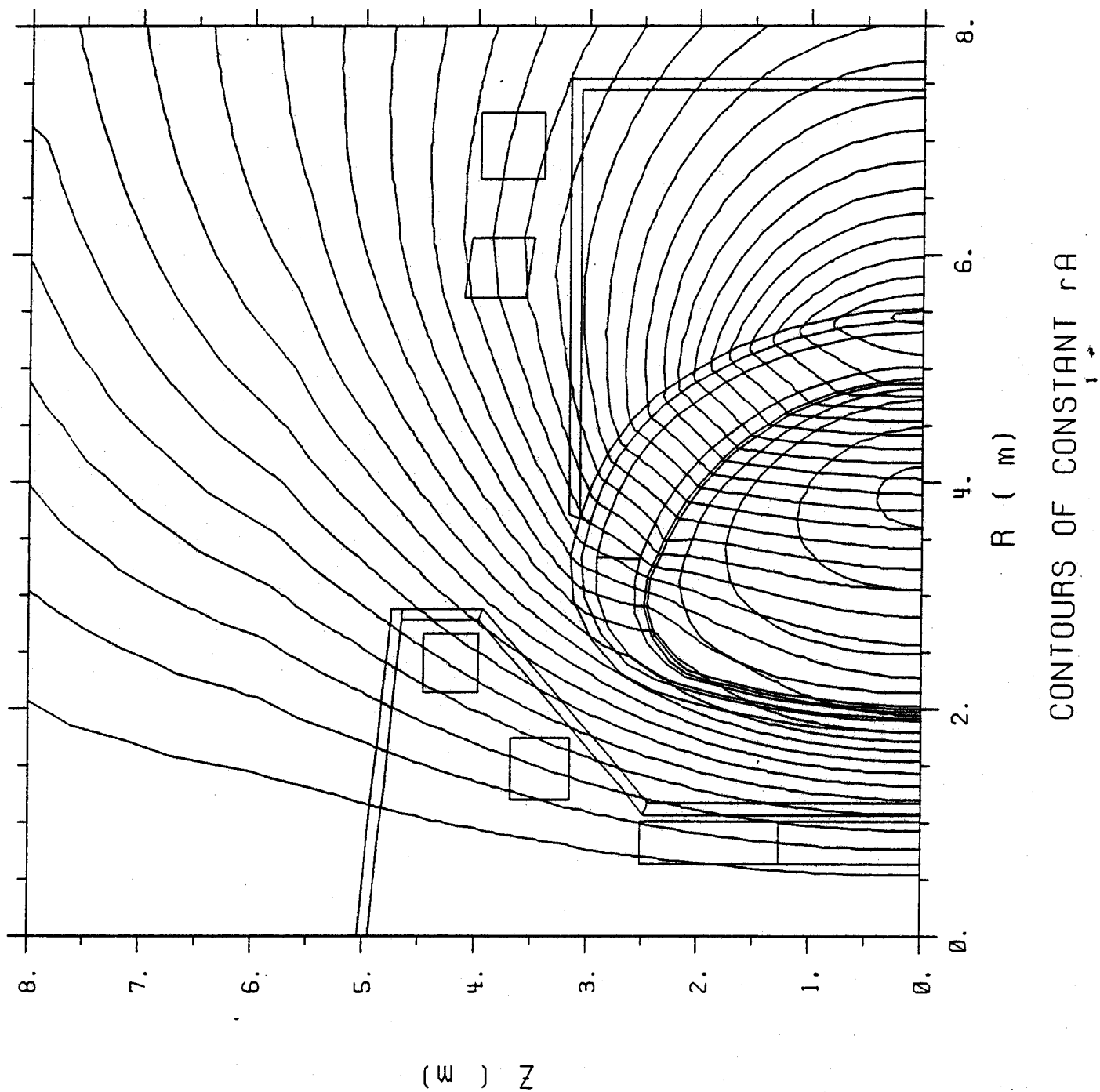


Fig. 3.3.2 Fieldline distribution at 30 ms for a 10 ms plasma disruption with a no net current carrying limiter.

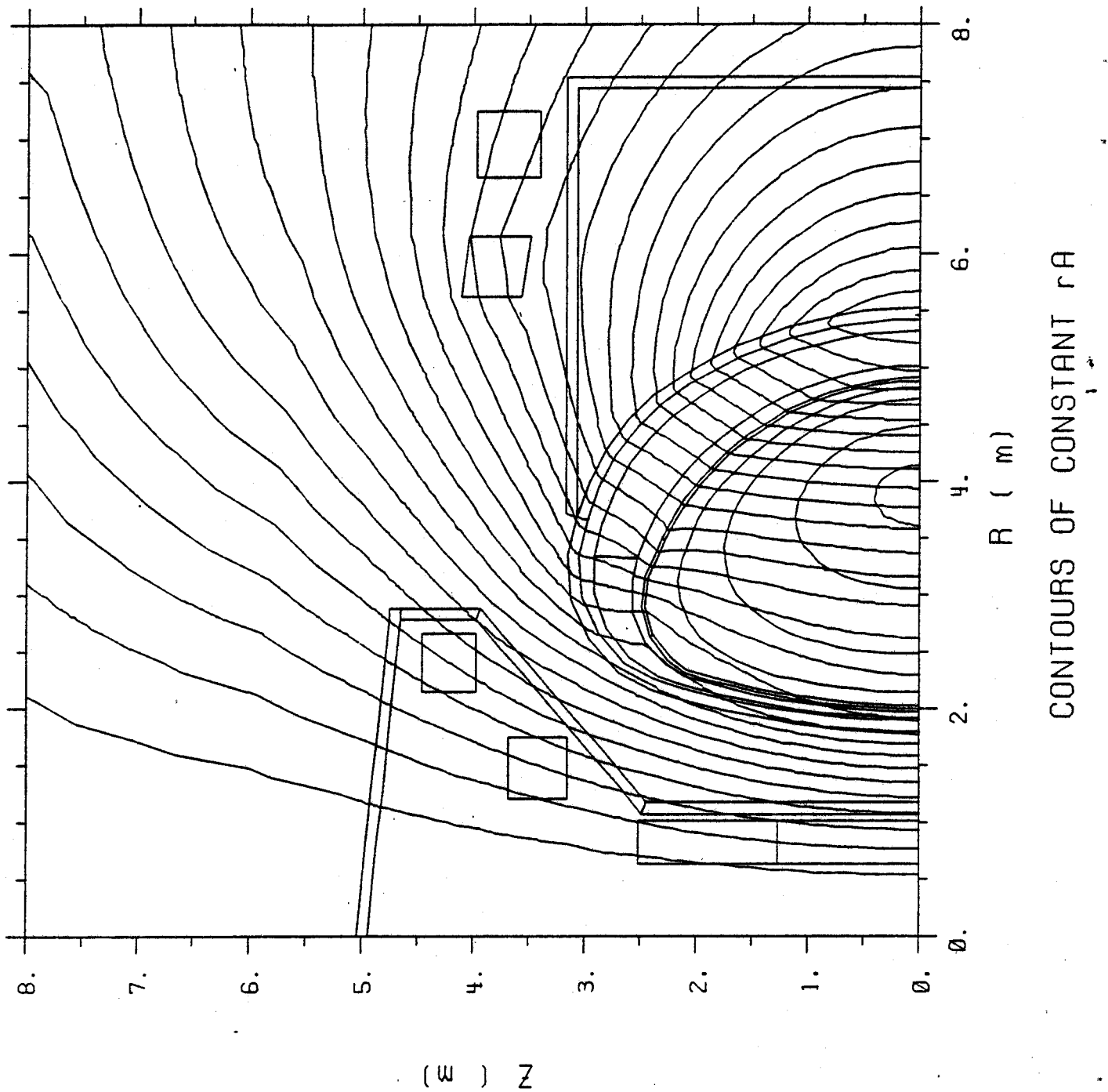


Fig. 3.3-3 Fieldline distribution at 50 ms for a 10 ms plasma disruption with a no net current carrying limiter.

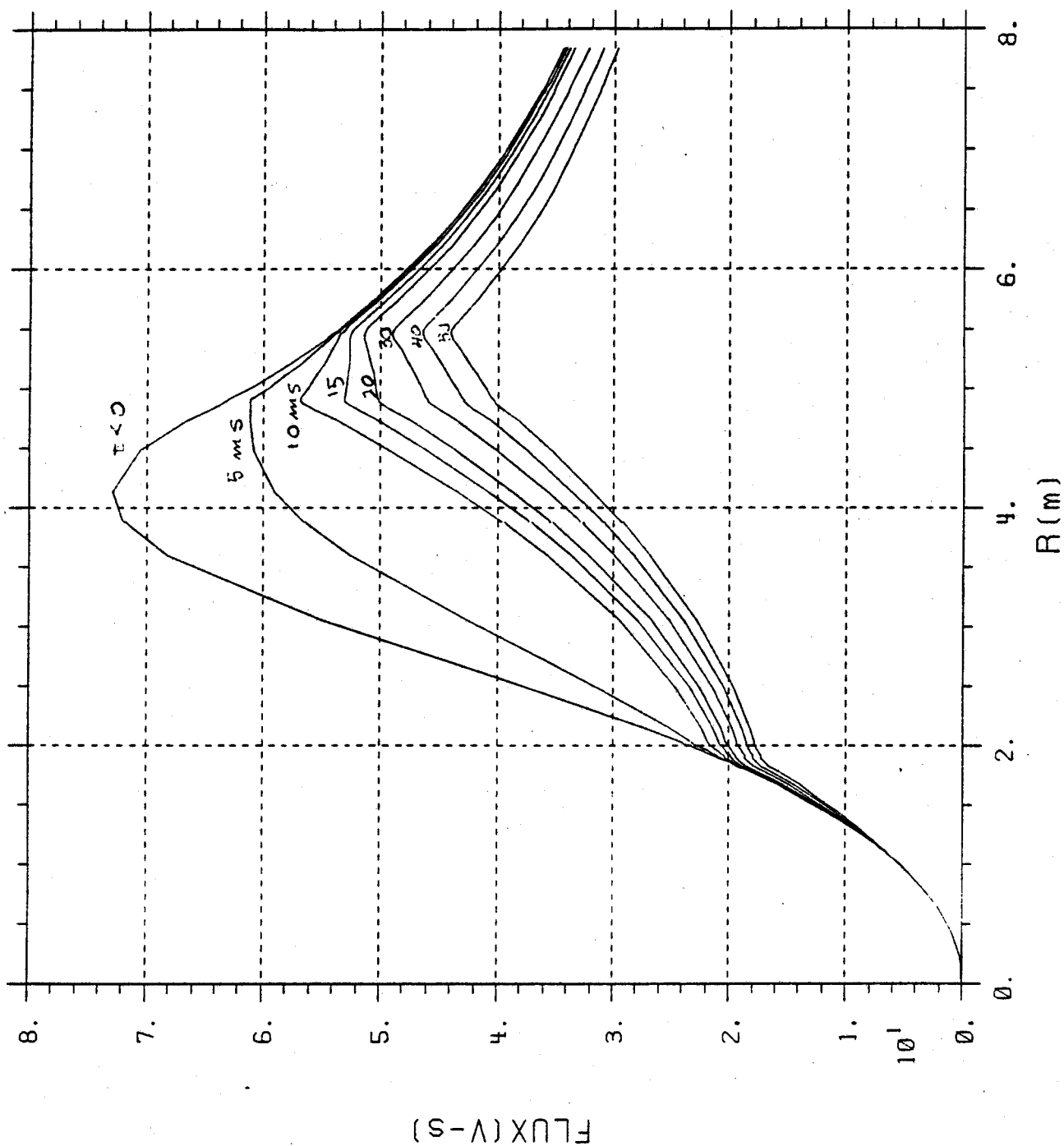


Fig. 3.3-4 Flux vs radial position along the midplane ($Z = 0$) for various times during and after a 10 ms plasma disruption for a no net current carrying limiter.

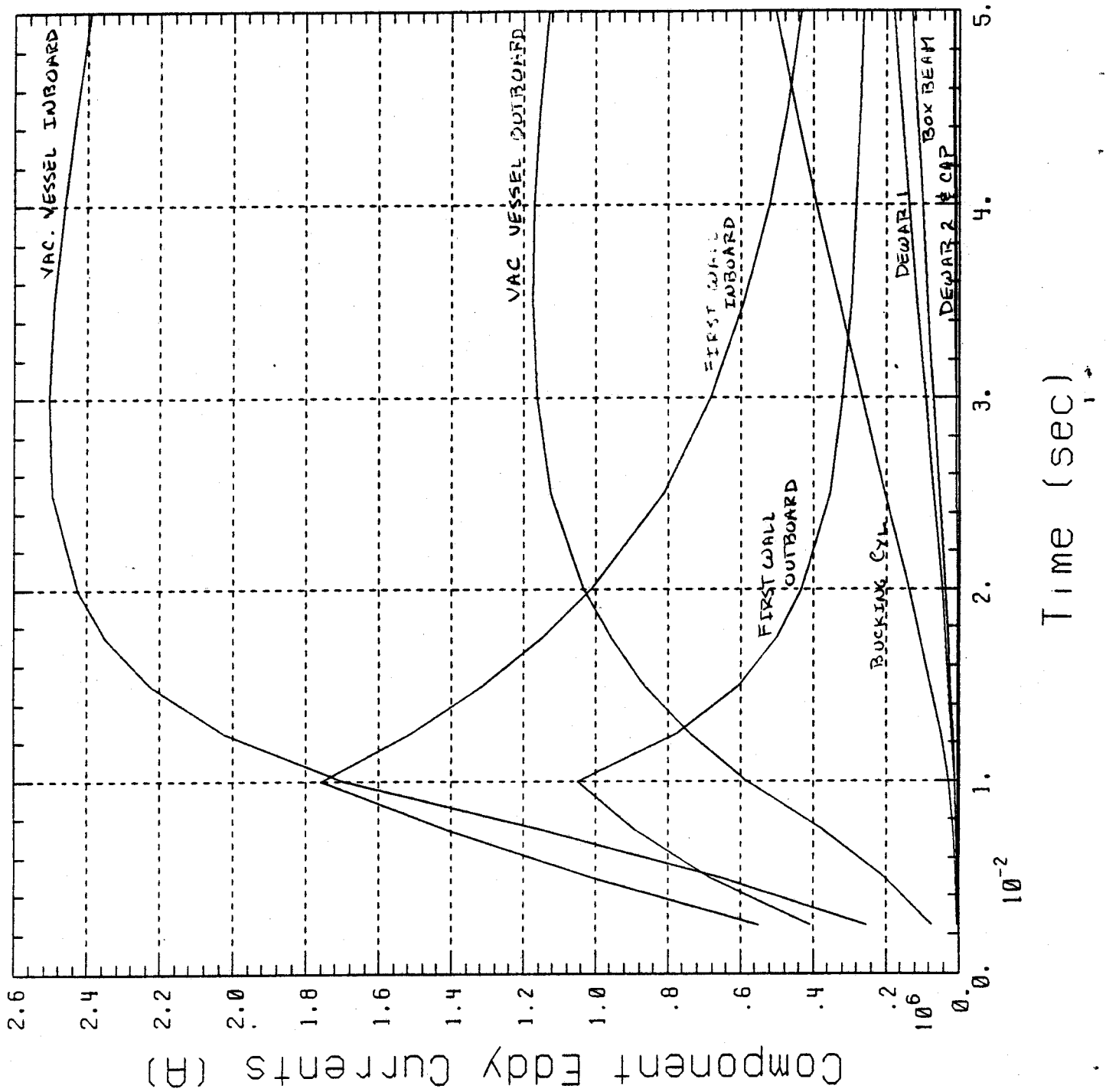


Fig. 3.3-5 Component eddy currents vs time for a 10 ms plasma disruption and a no net current carrying limiter. Currents are for the components above the midplane. Component names correspond to those in Fig. 3.1-1.

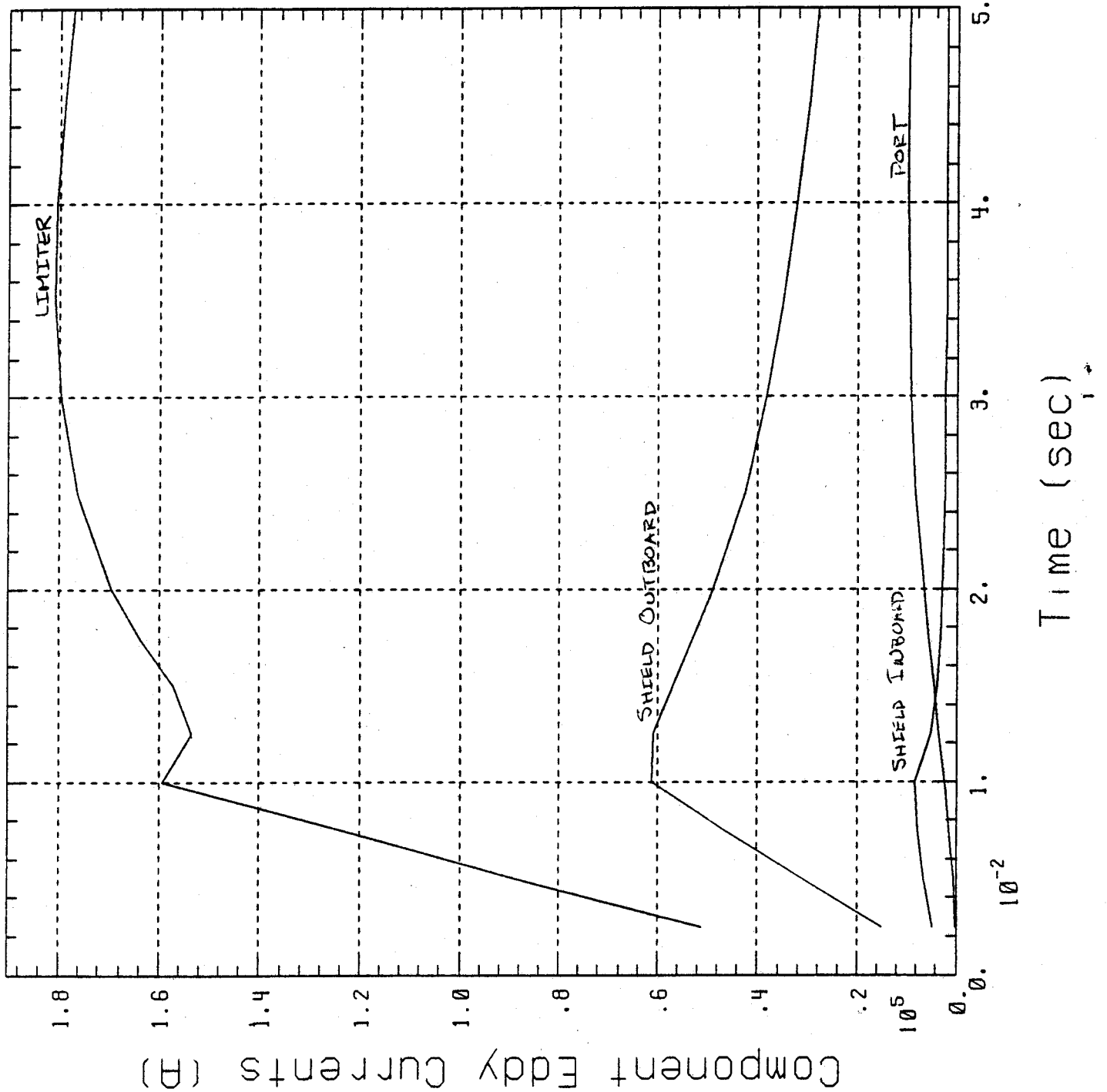


Fig. 3.3-6 Component saddle currents vs time for a 10 ms plasma disruption and a no net current carrying limiter. Currents occur only in no net regions. Region names correspond to those in Fig. 3.2-1.

Furthermore, Fig. 3.3-5 shows that components nearest the plasma (i.e., the first wall inboard and outboard) respond first, but have a relatively rapid decay rate because they are thin compared with the vacuum vessel inboard which eventually becomes dominant. Note that the vacuum vessel outboard is not actually toroidally continuous as assumed in the model, hence, it will be less influential and higher currents will result in the inboard vessel. If the first wall inboard and outboard are not net current carriers as assumed then the other components can be expected to respond faster than shown. Note that the limiter carries substantially less current than in the previous case (e.g., compare Fig. 3.3-6 with Fig. 3.2-6).

The current sheet amplitude is shown in Fig. 3.3-7 as a function of distance along the first wall measured from the inboard side in the $z=0$ plane. The plot is for the instant at 10 ms when the plasma current has just reached zero and shows relatively high currents along the first wall. The shaded region illustrates the current carried by the no net limiter. A similar plot at 30 ms is shown in Fig. 3.3-8 and indicates that the current in the limiter has increased somewhat. Plots of this type for the vacuum vessel are shown in Figs. 3.3-9 and 3.3-10 which are for 10 and 30 ms, respectively.

Tables 3.3-1 and 3.3-2 summarize the maximum currents and loads for this case together with the times at which they occur and their locations keyed to the points identified in Fig. 3.1-1. In general, the peak

loads are uniformly lower for the no net limiter than for the net limiter (See Table 3.2-1). Similarly times at which the extrema occur are smaller. The point at which the peak loadings occur does not change significantly for the dewar, shield, and vacuum vessel.

More detailed distributions may be found in Appendix C which gives the loads plotted along the first wall and vacuum vessel peripheries at selected instants of time.

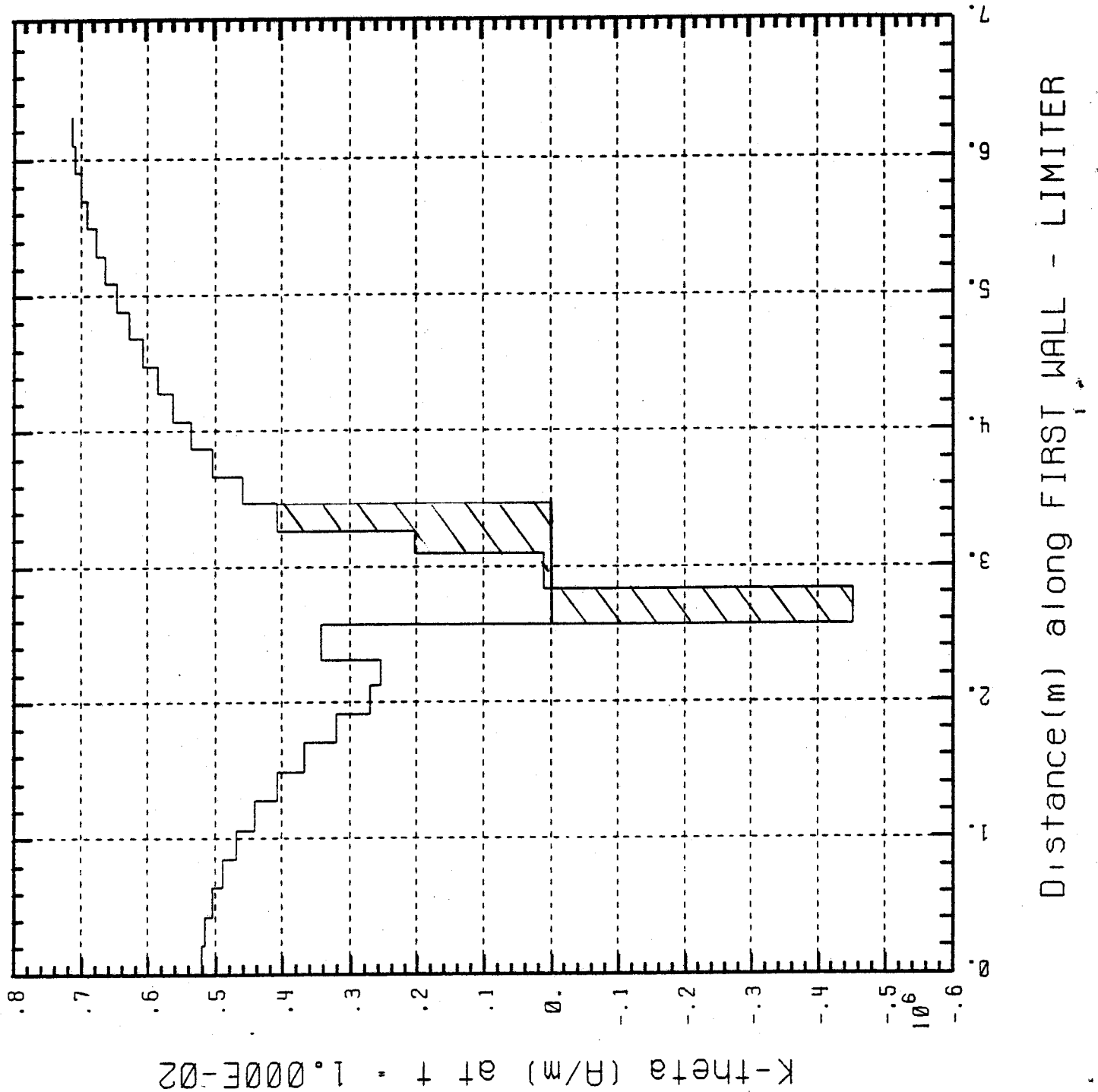


Fig. 3.3-7 Toroidal current sheet amplitude vs position along the first wall and limiter at 10 ms for a 10 ms plasma disruption and a no net current carrying limiter.

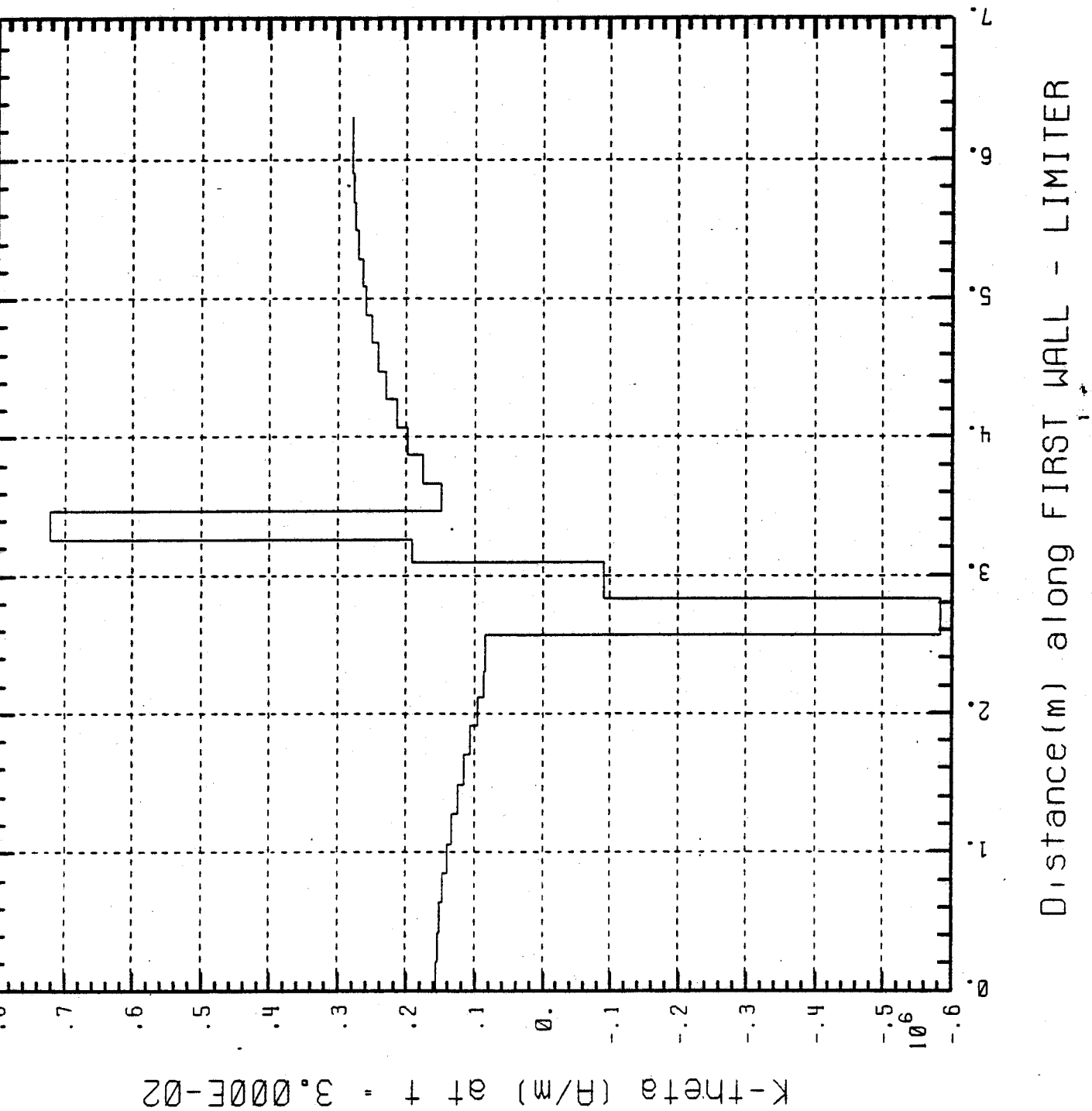


fig. 3.3-8 Toroidal current sheet amplitude vs position along the first wall and limiter at 30 ms for a 10 ms plasma disruption and a no net current carrying limiter.

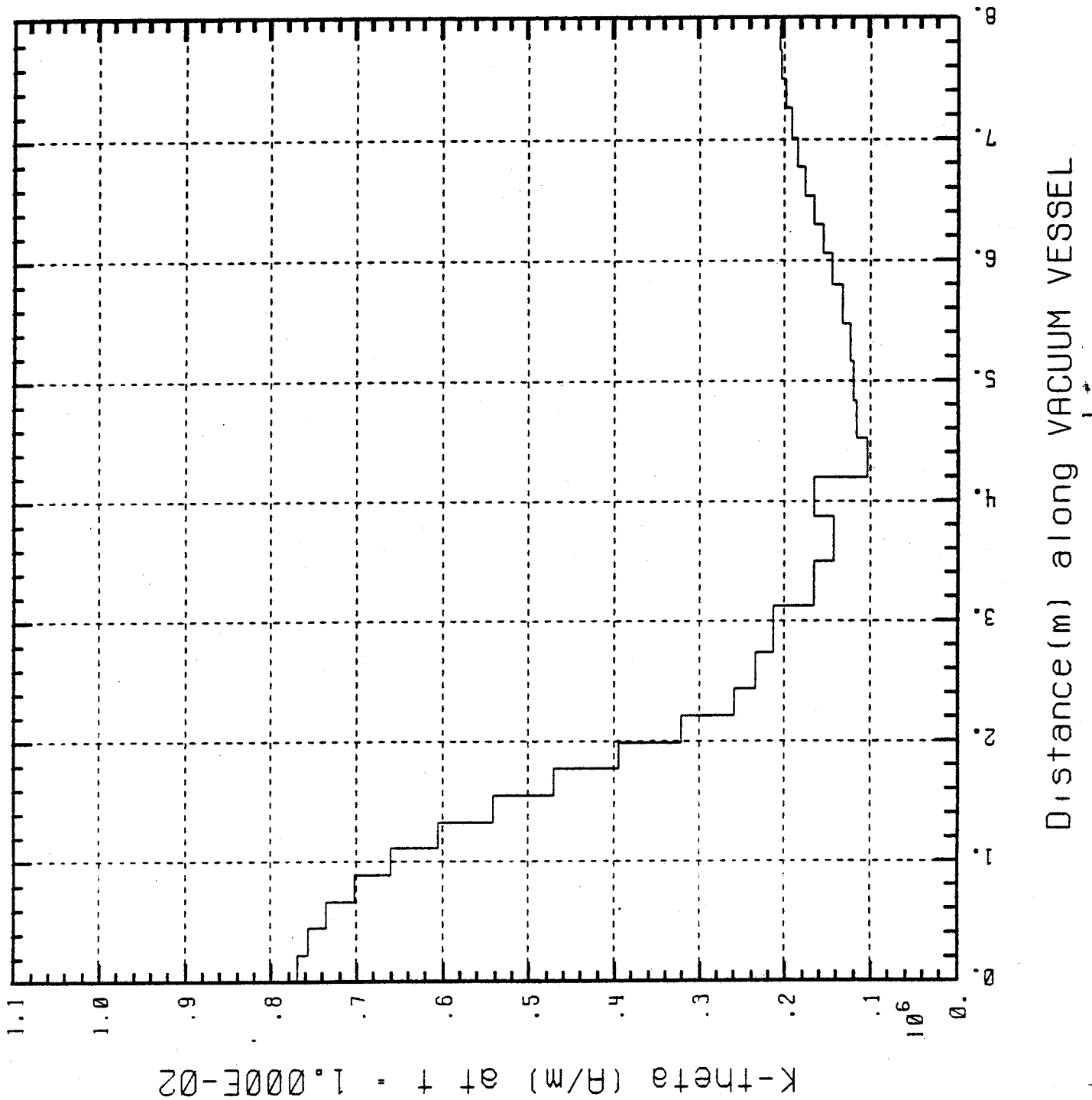


Fig. 3.3-9 Toroidal current sheet amplitude vs position along the vacuum vessel at 10 ms for a 10 ms plasma disruption and a no net current carrying limiter.

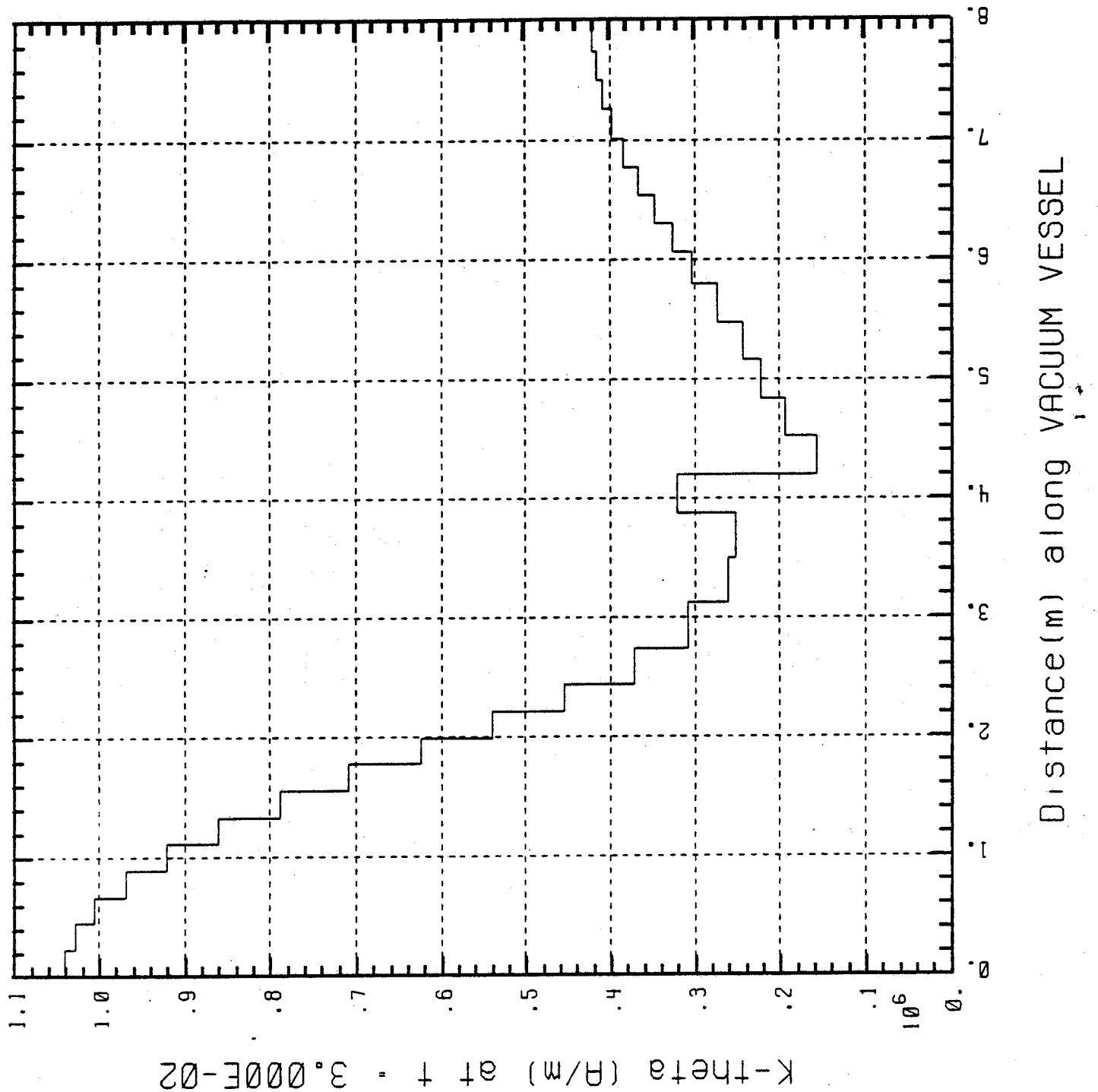


Fig. 3.3-10 Toroidal current sheet amplitude vs position along the vacuum vessel at 30 ms for a 10 ms plasma disruption and a no net current carrying limiter.

TFCX - 10 ms PLASMA DISRUPTION - NO NET LIMITER - CASE 24

Extrema In The Current Sheet Magnitude

Region	point #	Minimum K-theta (MA/m)	time (ms)	point #	Maximum K-theta (MA/m)	time (ms)
DEWAR	1	0	0	29	0.287	50
FIRST WALL - LIMITER	13	-0.586	30	16	0.727	35
SHIELD	16	-0.072	15	30	0.034	12.5
VACUUM VESSEL	17	0.041	5	1	1.057	22.5
PORT	1	-0.006	50	22	0.006	40

Extrema For The Normal Pressure Magnitude

Region	point #	Minimum Normal Pressure (MPa)	time (ms)	point #	Maximum Normal Pressure (MPa)	time (ms)
DEWAR	15	-0.102	50	29	0.356	50
FIRST WALL - LIMITER	30	-0.356	5	12	0.067	10
SHIELD	30	-0.026	10	17	0.024	12.5
VACUUM VESSEL	1	-0.853	15	13	0.142	50
PORT	22	-0.002	40	8	0.004	30

Extrema For The Tangential Pressure Magnitude

Region	point #	Minimum Tangential Pressure (MPa)	time (ms)	point #	Maximum Tangential Pressure (MPa)	time (ms)
DEWAR	22	-0.133	50	15	0.037	50
FIRST WALL - LIMITER	16	-0.310	50	13	0.184	50
SHIELD	15	-0.002	10	16	0.032	15
VACUUM VESSEL	16	-0.258	50	10	0.143	50
PORT	12	-0.002	30	1	0.005	50

Table 3.3-1 No Net Current Carrying Limiter — Summary of maximum induced currents, normal pressures and tangential pressures.

TFCX - 10 ms PLASMA DISRUPTION - NO NET LIMITER - CASE 24

Extrema In The Saddle Current Magnitude

Region	point #	Minimum Current (kA)	time (ms)	point #	Maximum Current (kA)	time (ms)
LIMITER	2	-180.0	40	4	0.07	22.5
SHIELD INBOARD	12	-4.06	5	7	2.09	15
SHIELD OUTBOARD	5	-51.09	12.5	15	0.00	15
PORT	13	-9.89	40	3	0.12	5

Extrema In The Toroidal Force Magnitude

Region	point #	Minimum F-theta (kN/m)	time (ms)	point #	Maximum F-theta (kN/m)	time (ms)
LIMITER	1	-48.48	50	4	0.02	22.5
SHIELD INBOARD	14	-0.44	5	14	1.36	12.5
SHIELD OUTBOARD	6	-18.57	10	6	326.0	12.5
PORT	7	-13.54	45	12	10.67	40

Extrema In The Normal Force Magnitude

Region	point #	Minimum F-normal (MN/m)	time (ms)	point #	Maximum F-Normal (MN/m)	time (ms)
LIMITER	4	-0.000	22.5	2	0.834	40
SHIELD INBOARD	7	-0.014	15	12	0.023	5
SHIELD OUTBOARD	15	0.000	15	5	0.165	12.5

Table 3.3-2 No Net Current Carrying Limiter — Summary of maximum saddle currents and saddle current loads on the no net current carriers.

4.0 PLASMA VERTICAL STABILITY

The negative field index associated with the poloidal field necessary to create an elongated plasma produces a configuration which is inherently unstable vertically since a small displacement leads to a net force on the plasma in a direction tending to increase the displacement. The growth rate would occur on a fast time scale ($\sim 10^{-6}$ s.) if unconstrained. However, the rapid displacement is initially stabilized by eddy currents induced in passive conducting elements which restrain the growth rate until an active coil system can be actuated to produce the radial field required to stabilize the plasma position.

The inherent passive stabilization characteristics of the TFCX configuration and preliminary estimates of the active coil power requirements as a function of location were carried out with a simplified model. The plasma consists of a rigid circular filament carrying a constant current. The plasma can move vertically and is inductively coupled to any number of passive or active lumped parameter circuits of specified geometry.

The most effective locations for passive stabilization elements can be determined by first assuming that they are a pair of conducting loops symmetrically located relative to the $z = 0$ plane. Contours of constant effectiveness* for loop locations can then be superimposed on the normalized geometry of TFCX as illustrated in Fig. 4.0-1. This shows the most useful locations and the rapid degradation in passive stabilization ability with distance from the plasma. For this type of system it may be

* R.J. Thome, R.D. Pillsbury, Jr., D.B. Montgomery, et al., "Passive and Active Circuits for Vertical Plasma Stabilization", PFC/RR-83-32, December 1983.

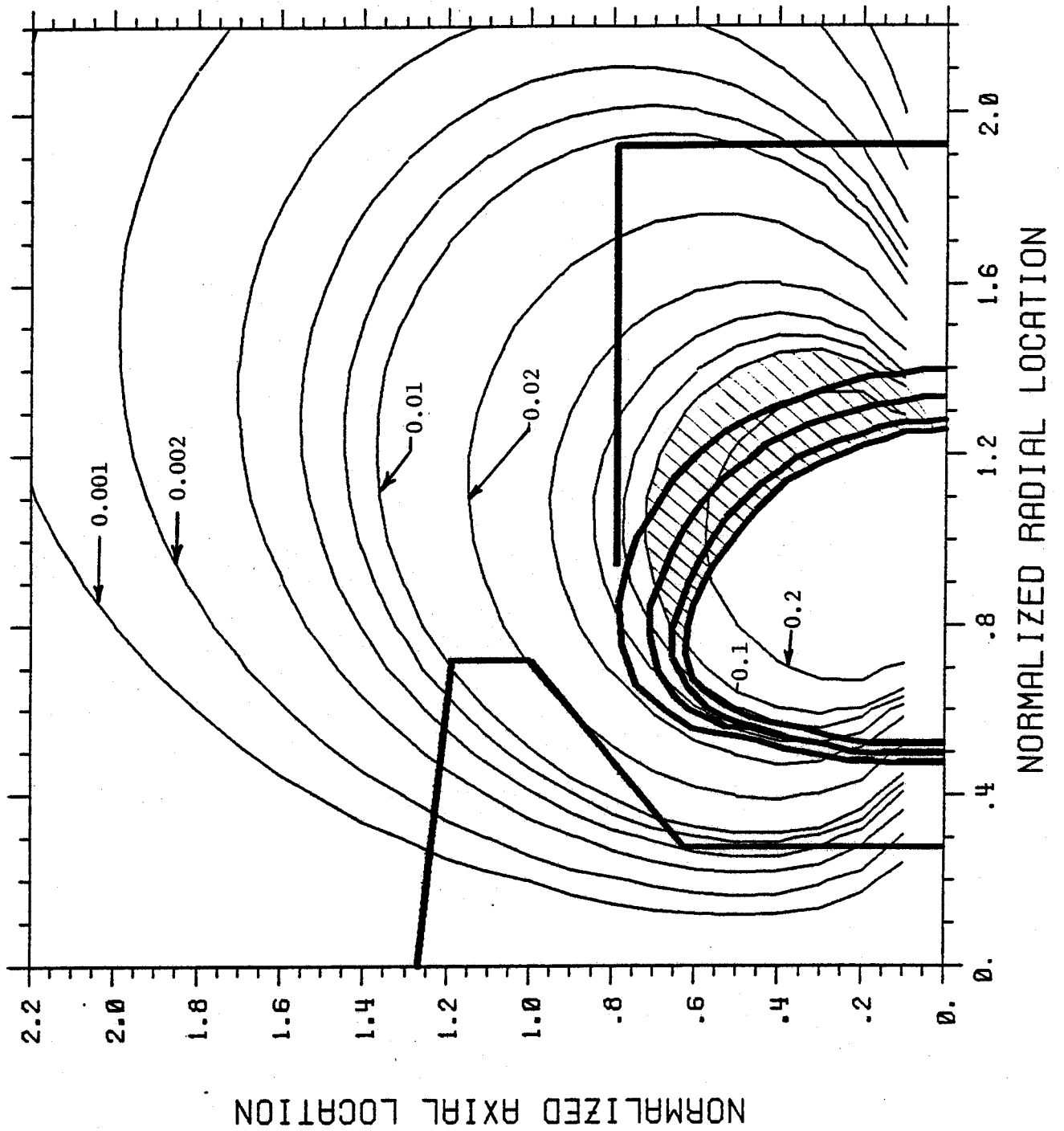


Fig. 4.0-1 - Contours of Constant Passive Element Effectiveness
Superimposed on TFCX ($r_o = 3.9$ m).

shown that a necessary but not sufficient condition for stabilization is:

$$\frac{\mu_0 I_p}{(-B_z)r_0} G(r/r_0, z/r_0) > -\eta_f \quad (4.1)$$

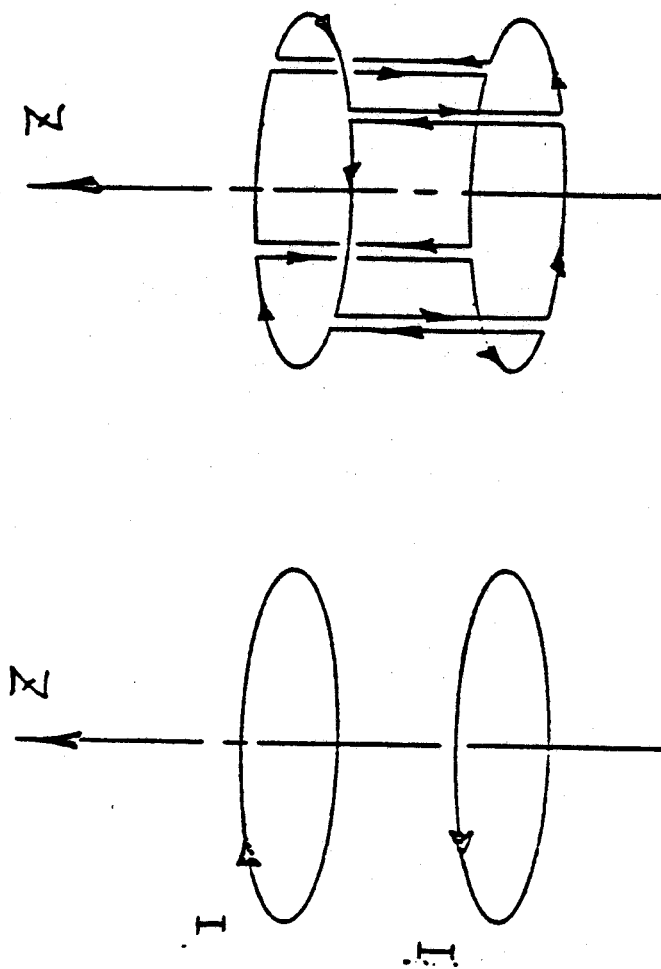
where:

- μ_0 = $4\pi \times 10^{-7}$ [H/m]
- B_z = vertical field
- r_0 = plasma radius
- η_f = field index
- G = a function of passive element normalized location

In TFCX, the plasma current is 10.3 MA, the vertical field is -0.64 T, the field index is -0.5, and the radius to the current center is about 3.9 m. With these parameters Eq. (4.1) implies that passive loops must lie on G contours with values of ≈ 0.1 or greater to be effective. The shaded region in Fig. 4.0-1 includes contours with the desired values which simultaneously lie outside the first wall. They imply that substantial sections of the first wall and shield may be expected to be effective.

The contours were based on the use of a single pair of passive loops. They need not be toroidally continuous because of the up-down asymmetry of the required stabilization currents. Hence, saddle type currents (as shown in Fig. 4.0-2 which are induced in sectors which are not toroidally continuous may be expected to perform the same function to first order.

The previous plot implies that we need only model conducting sections relatively close to the plasma to gain insight into the passive stabilization characteristics of the system although other conducting sections may



TWO DISCRETE
LOOPS WITH
TOROIDAL CONTINUITY

TWO LOOPS FORMED
FROM SADDLE TYPE
CURRENTS

Fig. 4.0-2 Vertical stabilizing coils may have toroidal continuity (ie - complete loops) or may be segmented (ie - saddle coils).

influence the performance (i.e., prevent field penetration) from the active coil system.

A filament type model consisting of the plasma, 24 passive elements, and a pair of control coils located at one of three locations was constructed to investigate vertical stability. The top half of the model is illustrated in Fig. 4.0-3 with an outline of selected features of TFCX for clarity. Passive coils are labelled P1, P2, .. and the active coils are either A4, A5, or A6 depending on the case under consideration. Note that A4, A5 and some of the passive elements are saddle shaped.

The procedure used by the computer program is outlined in Table 4.0-1. After input of the circuit, plasma, stationary field, and feedback characteristics, the system eigenvalues are found. The system is stable if the real part of all eigenvalues is negative. If initial conditions are then specified, output variables such as coil currents, voltages, plasma displacement, and active coil power can be determined.

Cases were studied with element resistances as indicated in Table 4.0-2. These correspond to the equivalent resistances of the first wall, vacuum vessel and box beam cross-sections as indicated in Fig. 4.0-3. In order to bracket the power requirements, the shield was considered for two extremes: toroidally continuous and 80% stainless steel/20% water or no shield. The active coil power requirements for these cases are shown in Figs. 4.0-4 and 4.0-5 as a function of the time required to return the plasma to 10% of its initial displacement (assumed to be 0.01 m in all cases). The figures indicate:

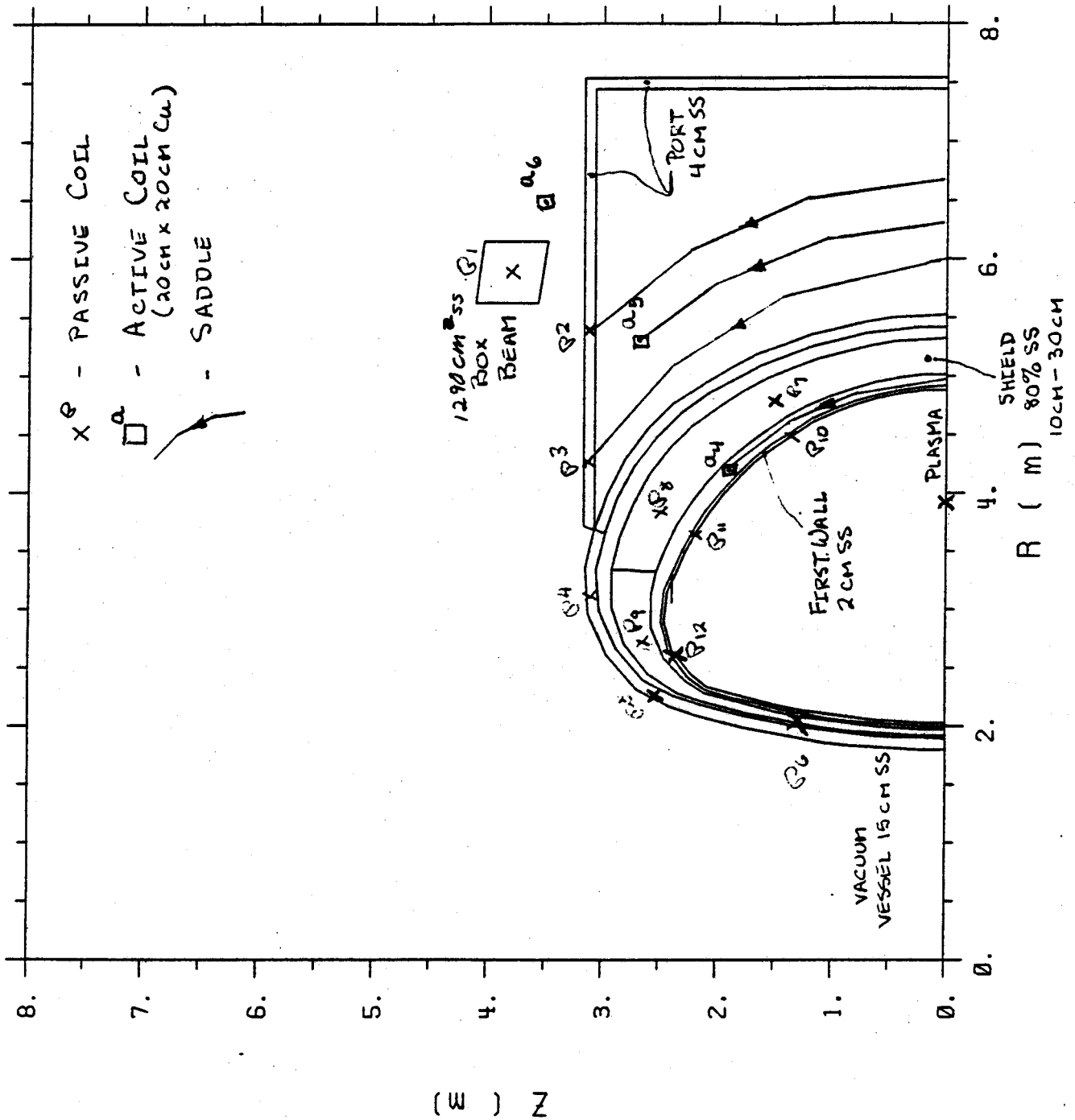


Fig. 4.0-3 Passive and active elements for preliminary vertical stability study of TFCX.

TABLE 4.0-1
COMPUTATIONAL PROCEDURE USED IN COMPUTER PROGRAM

----- INPUT: $[M_{ij}], [R_{ij}], B_{rk};$	CIRCUIT CHARACTERISTICS (Inductance, Resistance, Radial Field Per Unit Current)
r_o, I_p	PLASMA CHARACTERISTICS (Plasma Radius, Plasma Current)
η_f, B_z	STATIONARY FIELD CHARACTERISTICS (Field Index, Vertical Field)
$t_{ai}, t_{bi}, t_{ci}, \alpha_i;$	FEEDBACK CHARACTERISTICS (Lead, Lag Delay, Gain) $V + (t_b + t_c) \dot{V} + t_b t_c \ddot{V} =$ $- \alpha (Z + t_a \dot{Z})$
----- DETERMINE EIGENVALUES, $\lambda_i;$	NOTE: STABILITY REQUIRES $R_e[\lambda_i] < 0 \text{ FOR ALL } i$
----- DETERMINE: $I_i(t)$	CURRENT
$V_i(t)$	NOTE: $V = 0$ IF COIL IS PASSIVE
$Z(t)$	DISPLACEMENT
$P(t)$	POWER

TABLE 4.0-2
ELEMENT RESISTANCES FOR MODEL IN FIGURE 4.0-3

ELEMENT	REGION MODELED	R(Ω)
P 1	Box Beam	5.04 E - 04
P 2	Port	5.12 E - 03
P 3	Port	4.98 E - 03
P 4	Vacuum Vessel	6.72 E - 04
P 5	Vacuum Vessel	1.44 E - 04
P 6	Vacuum Vessel, Shield & F.W.	6.65 E - 05
P 7	Shield	2.32 E - 04
P 8	Shield	2.16 E - 04
P 9	Shield	1.63 E - 04
P10	F.W.	2.03 E - 03
P11	F.W.	1.79 E - 03
P12	F.W.	1.41 E - 03

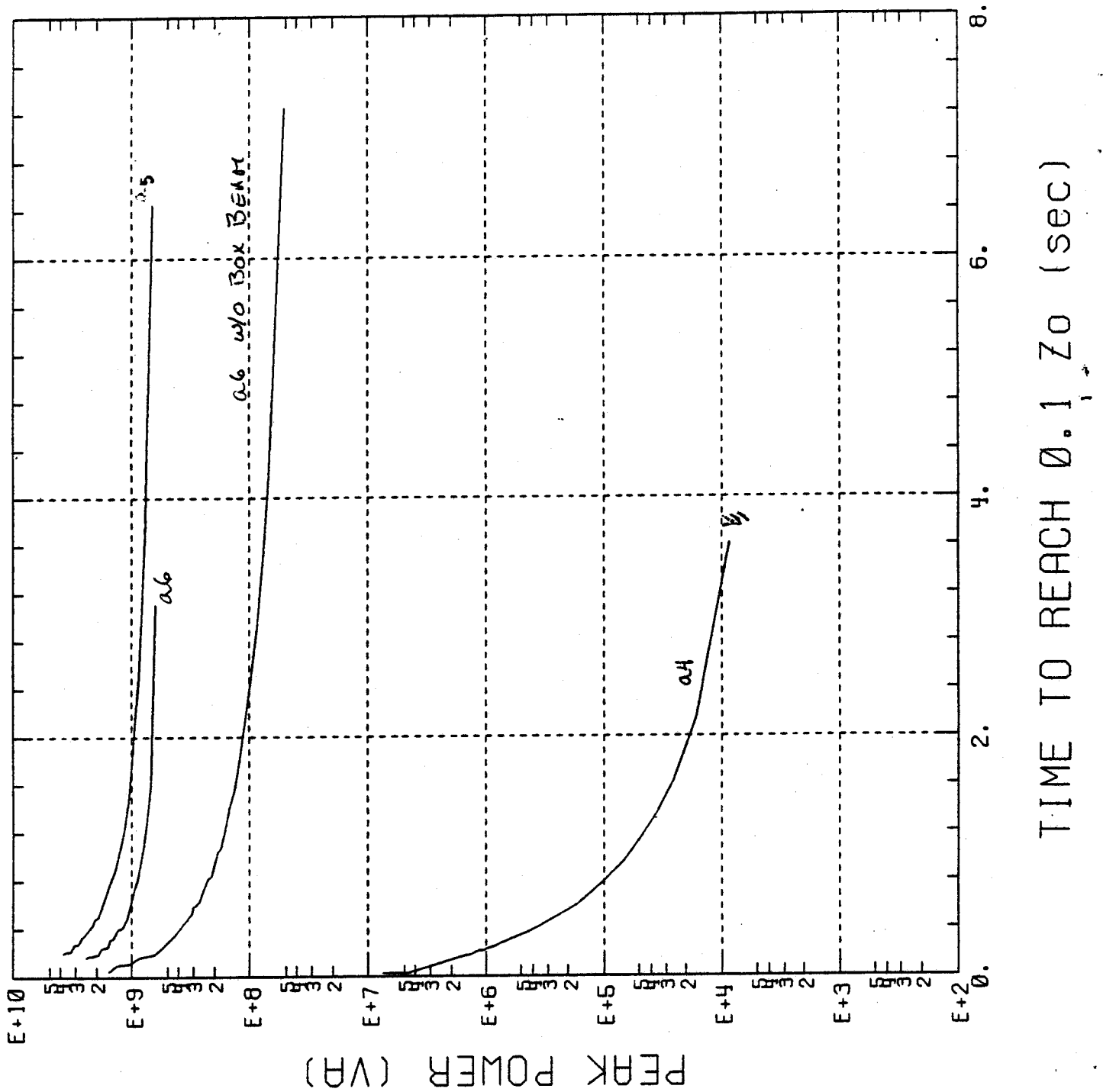


Fig. 4.0-4 Peak control coil power as a function of time to return the plasma to 10% of its initial displacement for the extreme case of a toroidally continuous shield.

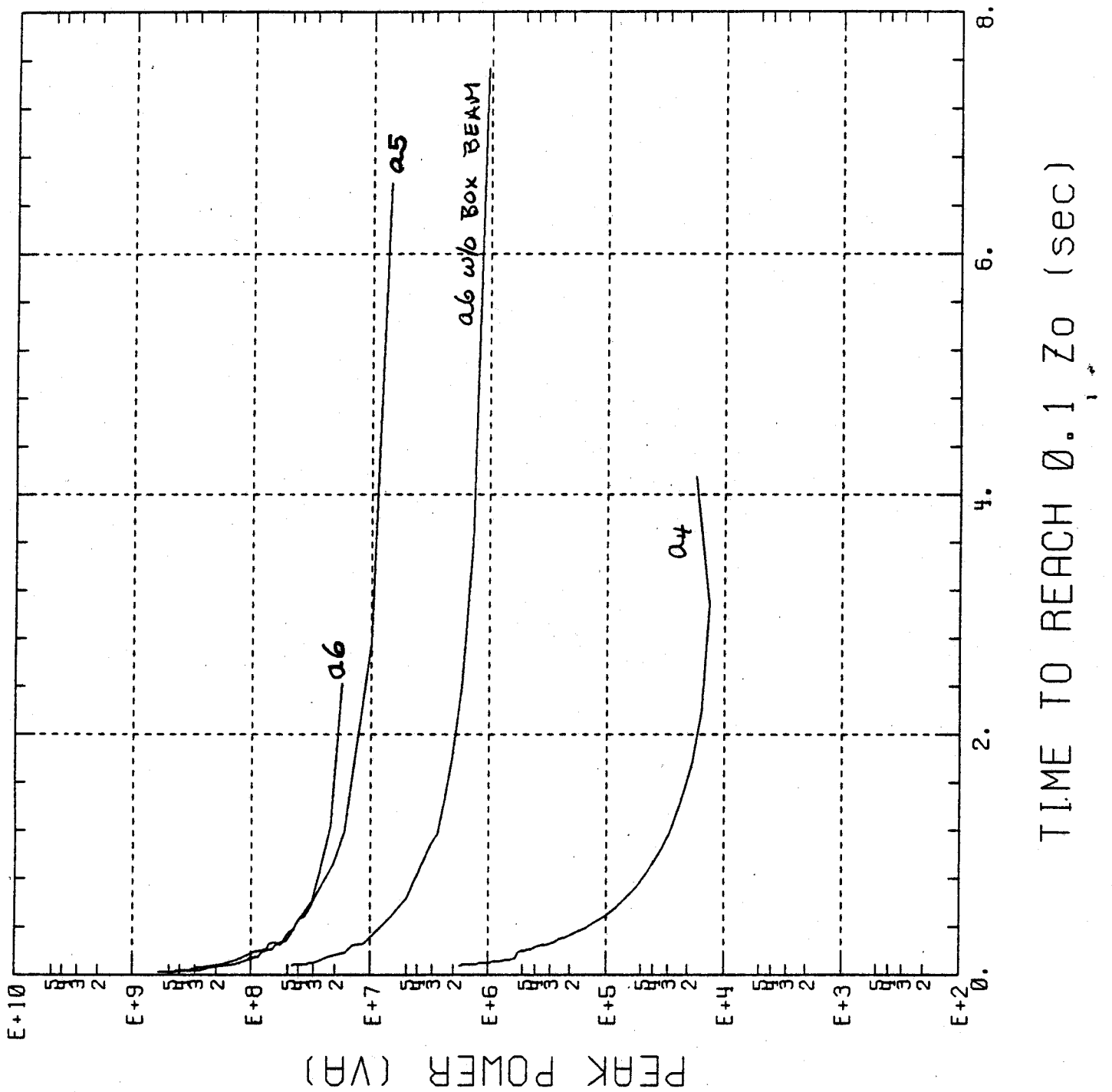


Fig. 4.0-5 Peak control coil power vs time to return the plasma to 10% of its initial displacement for the extreme case of no shield.

- (1) An active coil location on the face of a removable sector, but behind the first wall has a power requirement in the .01 to 1.0 MVA range unless return times faster than 0.1 seconds are desired in which case the power requirement would be higher.
- (2) Active coil locations further out from the plasma have power requirements which increase rapidly for equivalent plasma position return times. Coils at locations like A6 may have prohibitive power requirements depending on structural characteristics (e.g., presence of the box beam) or shield electrical conductivity.

The figures show that A5 requires more power than A6 which seems inconsistent with its relative position. However, subsequent cases shown in Fig. 4.0-6, which assumes no shield and no passive elements at P2 or P3, implies that it is effectively shielded by these elements.

The controller time constants for all cases were chosen to be $t_a = t_c = 3$ ms and $t_b = 0$. When the value of $t_a = t_c$ was varied between 0 and 10 ms the required gain and power to return the plasma to 10% of its initial displacement in 1 second did not change significantly. Similarly for $t_a = t_c = 3$ ms and varying t_b from 0 to 6 ms also had little impact on power for a return of 1 second. However, when the required time to return was lowered to 10 ms, the choice of controller time constants had significant effect. For example, $t_a = t_c = 3$ ms and $t_b = 0$ required 74 kVa, when t_b was 3 ms the power was 190 kVa.

A typical set of output curves for plasma displacement, active coil current, active coil voltage, and active coil power as functions of time are shown in Figs. 4.0-7 to 4.0-10, respectively.

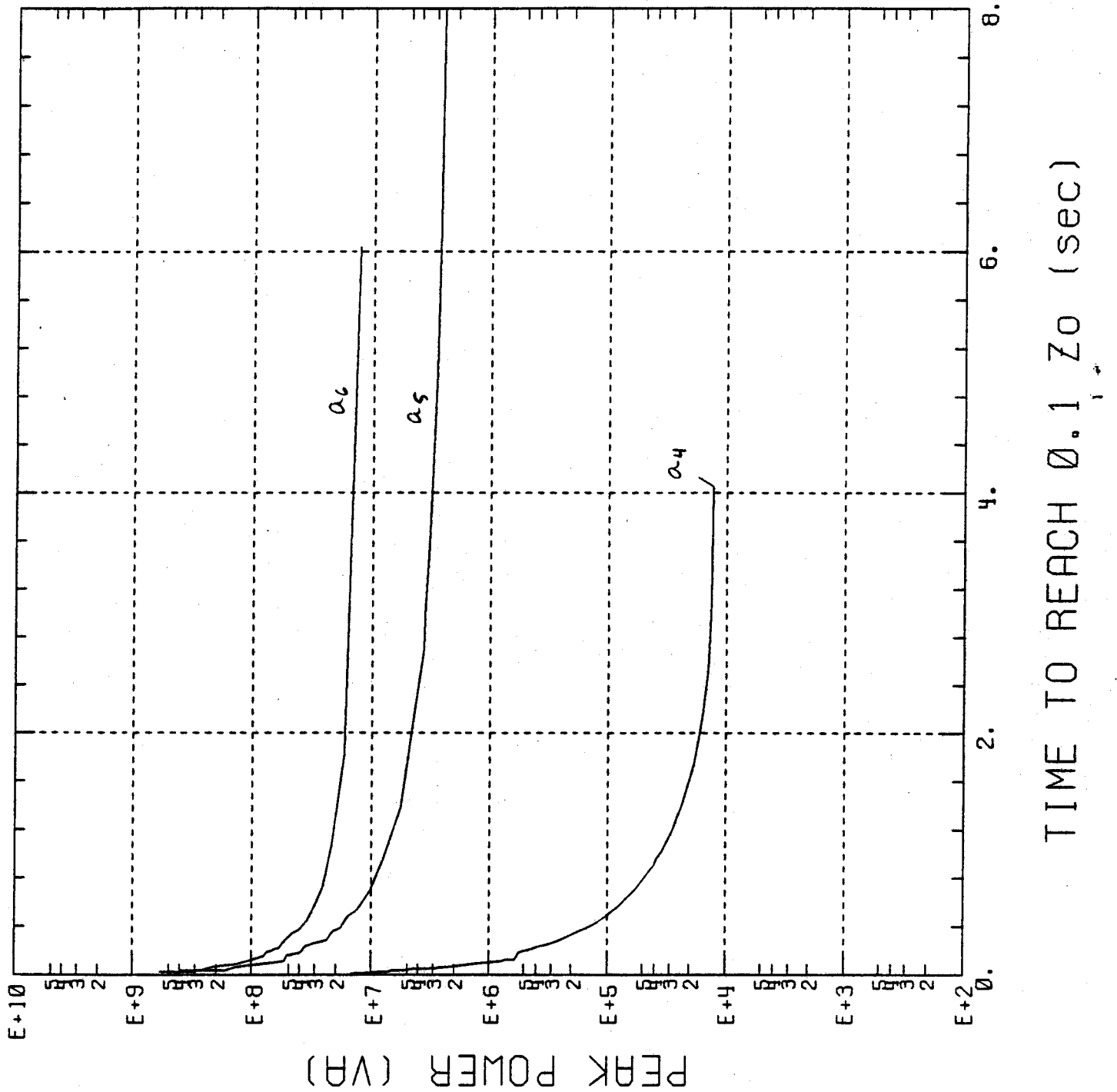


Fig. 4.0-6 Peak control coil power for the case without shield and without passive elements P2 and P3 which, when present, effectively shield A5.

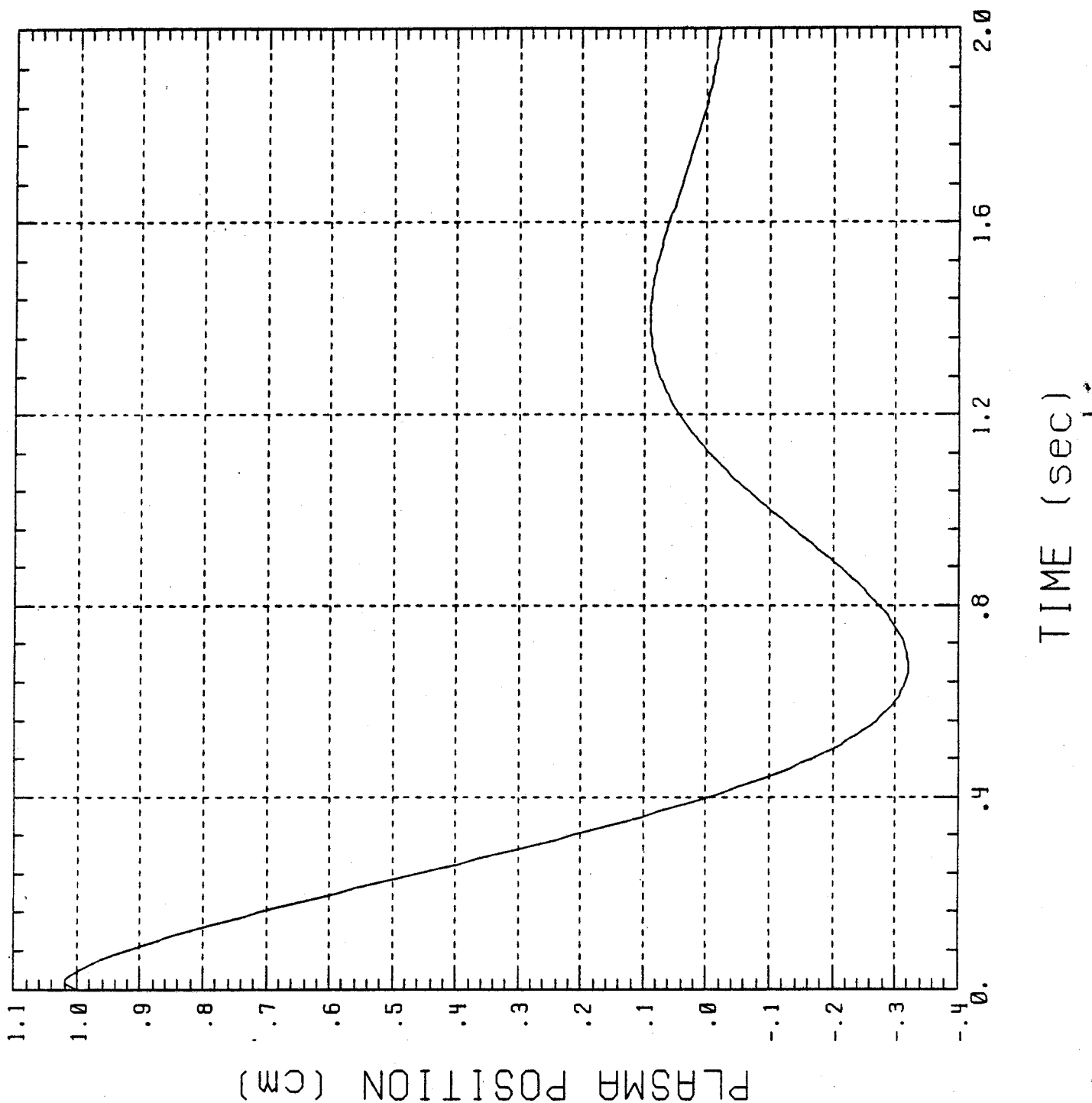


Fig. 4.0-7 Plasma position vs time for A4 driven with $t_a = t_c = 3$ ms, $t_b = 0$ and $G = 650$ V/m. The shield was assumed to be 80% stainless steel and the initial displacement is 1 cm.

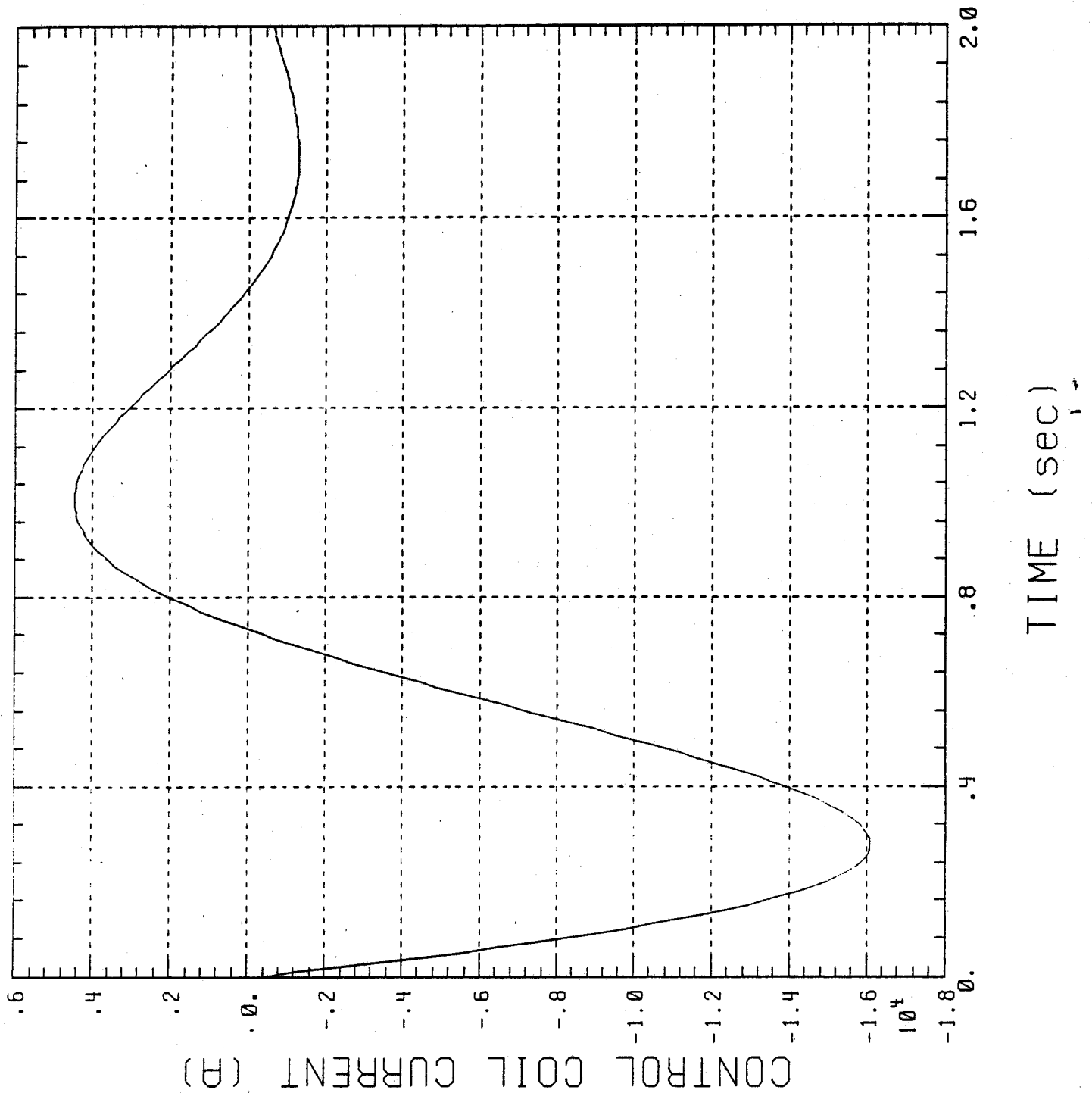


Fig. 4.0-8 Control coil current vs time for A4 with $t_a = t_c = 3$ ms, $t_b = 0$ and $G = 650$ V/m. The shield was assumed to be 80% stainless steel and the initial displacement was 1 cm.

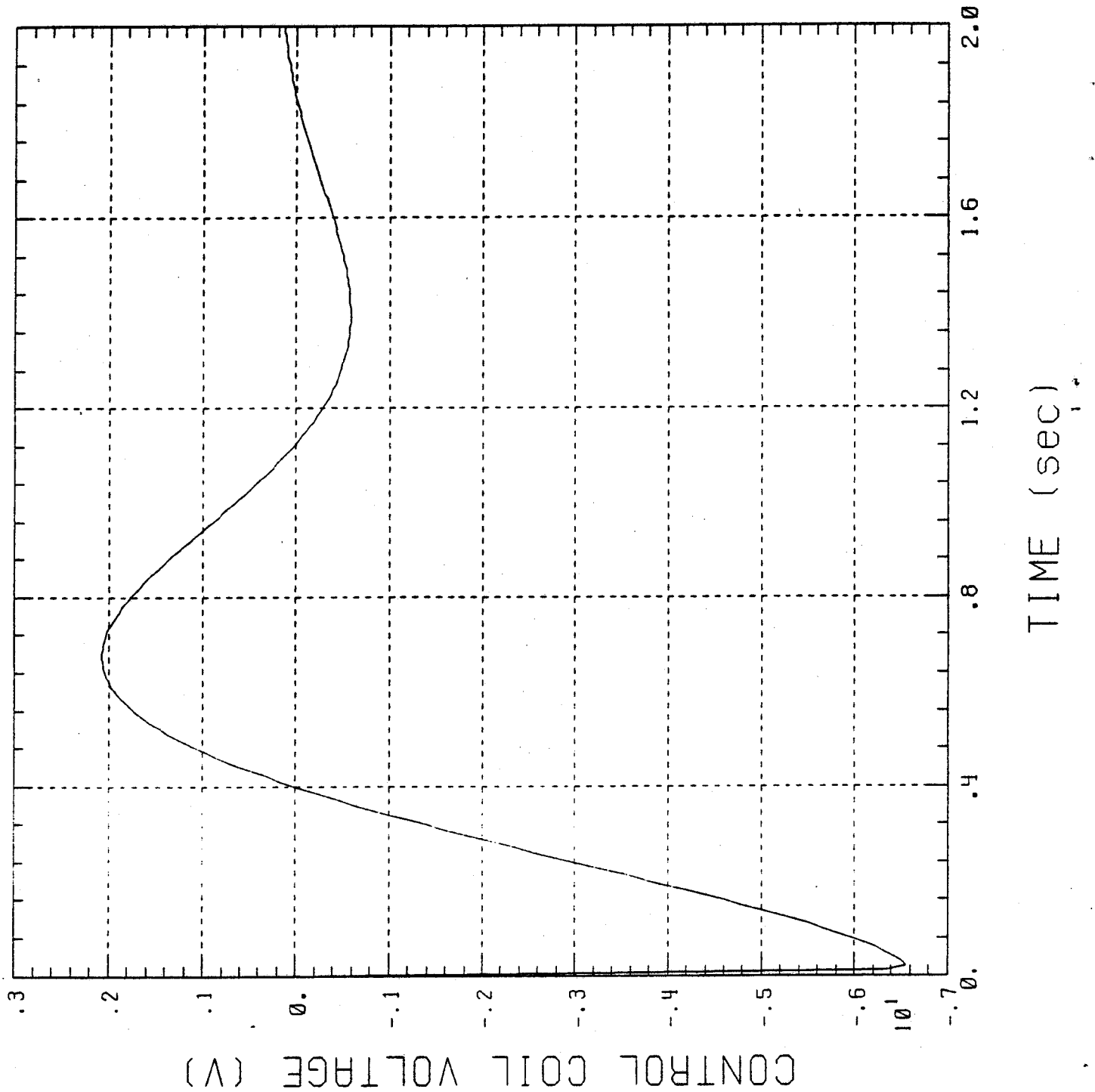


Fig. 4.0-9 Control coil voltage vs time for A4 with $t_a = t_c = 3$ ms, $t_b = 0$ and $G=650$ V/m. The shield was assumed to be 80% stainless steel and the initial displacement was 1 cm.

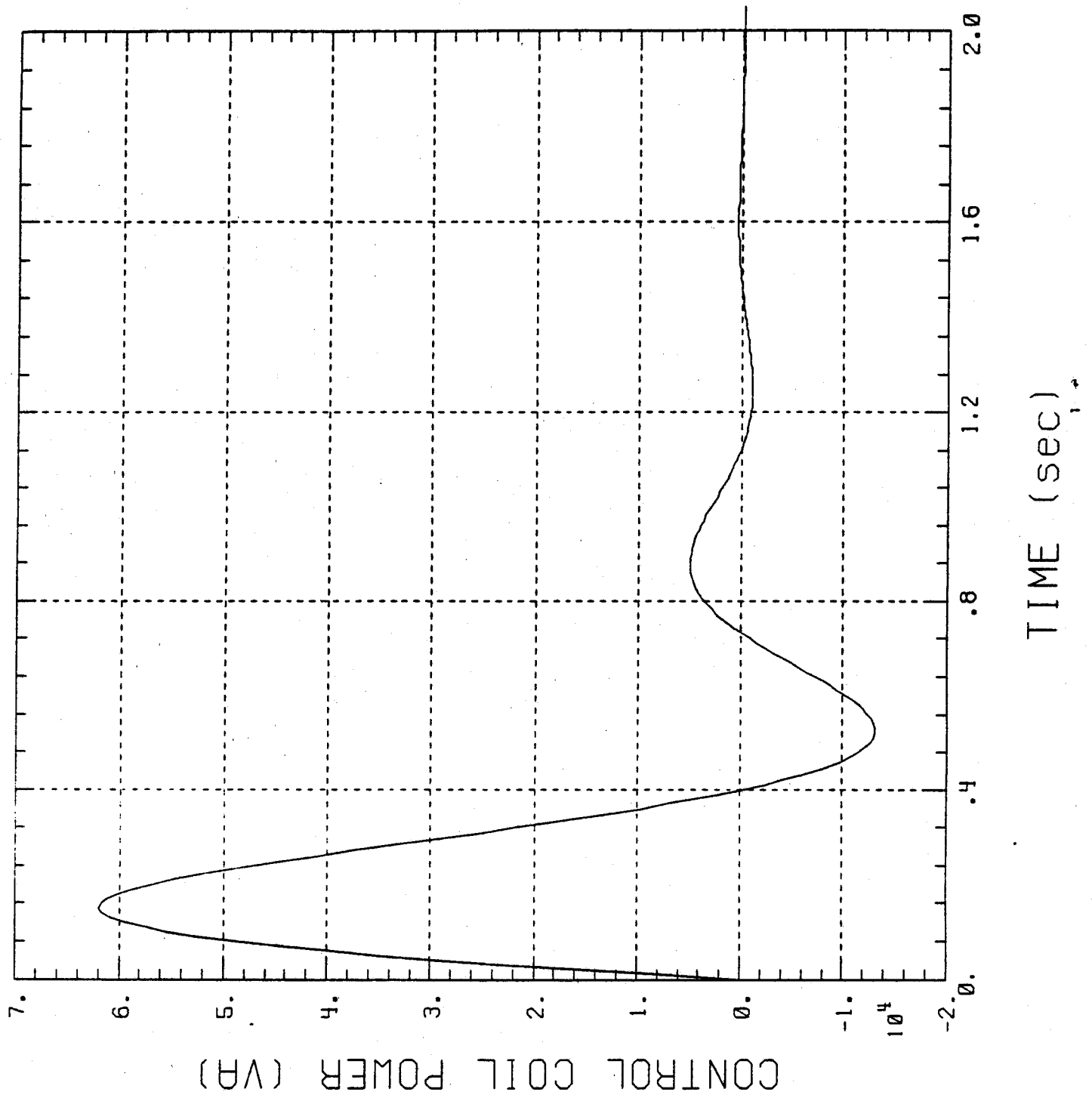


Fig. 4.0-10 Control coil power vs time for A4 with $t_a = t_c = 3$ ms, $t_b = 0$ and $G = 650$ V/cm. The shield was assumed to be 80% stainless steel and the initial displacement was 1 cm.

The model is useful as a preliminary indicator that:

- (1) Active control coils are necessary;
- (2) The passive stabilizing character of typical components in TFCX is likely to be sufficient without addition of high conductivity passive elements;
- (3) Active coils are likely to have reasonable power requirements provided they are located sufficiently close to the plasma and not excessively shielded by other components.

The model is preliminary in nature and requires the addition of considerably more elements as well as further study of the feedback character and other system constraints. In addition, studies must be performed with models utilizing a distributed plasma current.

APPENDIX A - PF COIL FIELDS AT THE FIRST WALL AND VACUUM VESSEL

Figures A-1 and A-2 give the components of the fields from the PF coils as a function of distance along the first wall periphery in an rz-plane. The coil currents correspond to the end of burn condition in Table 2.1-1. Fields have been resolved into components which are locally normal or tangent to the wall. In Sections 3.0 and in Appendices B and C these fields were assumed constant during the disruption, combined with the induced fields, and used to find the em load distributions discussed in those sections.

Figures A-3 and A-4 are similar to those discussed above, but are calculated along the vacuum vessel.

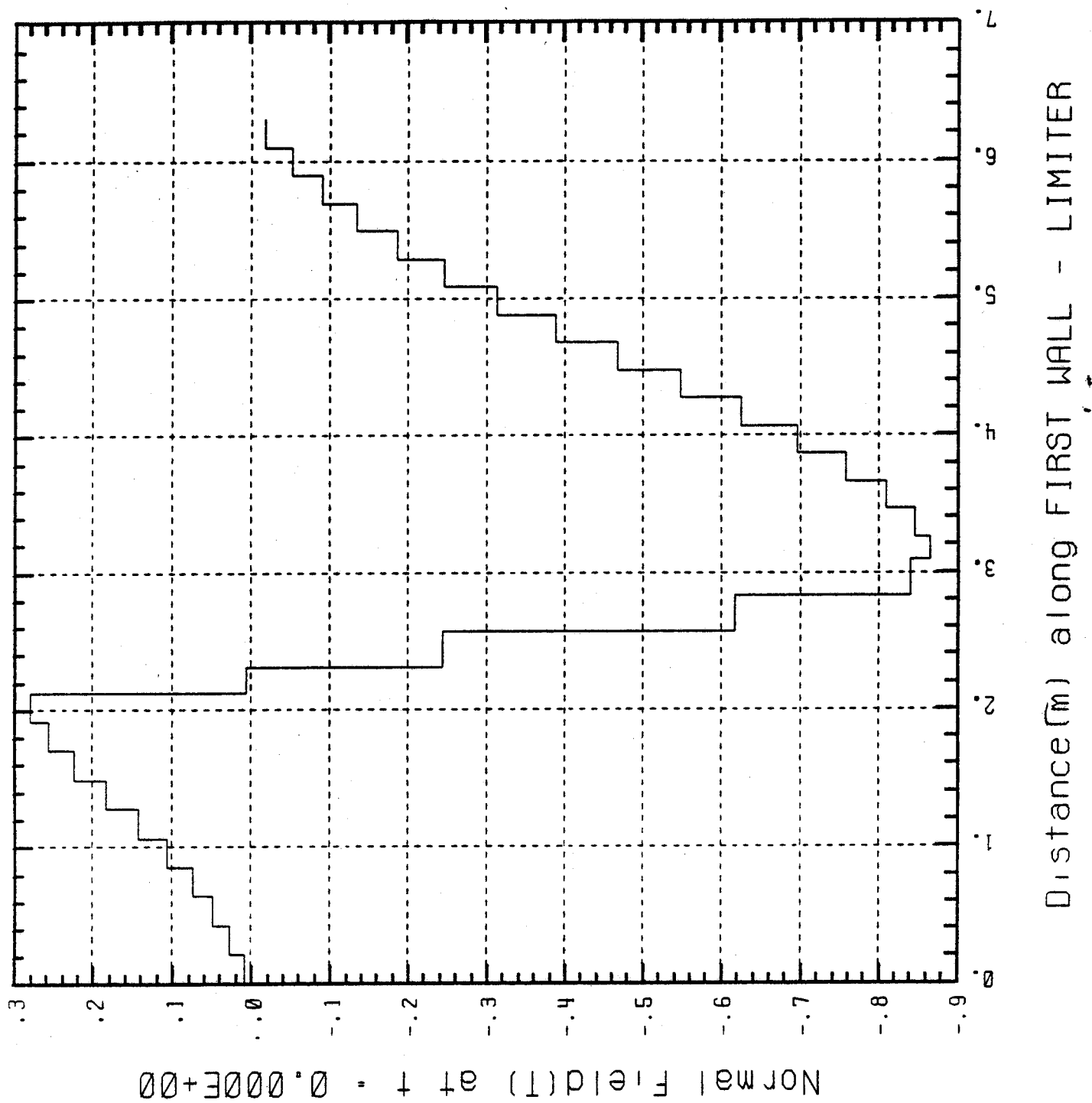


Fig. A-1 Normal component of the "end of burn" poloidal fields along the first wall and limiter.

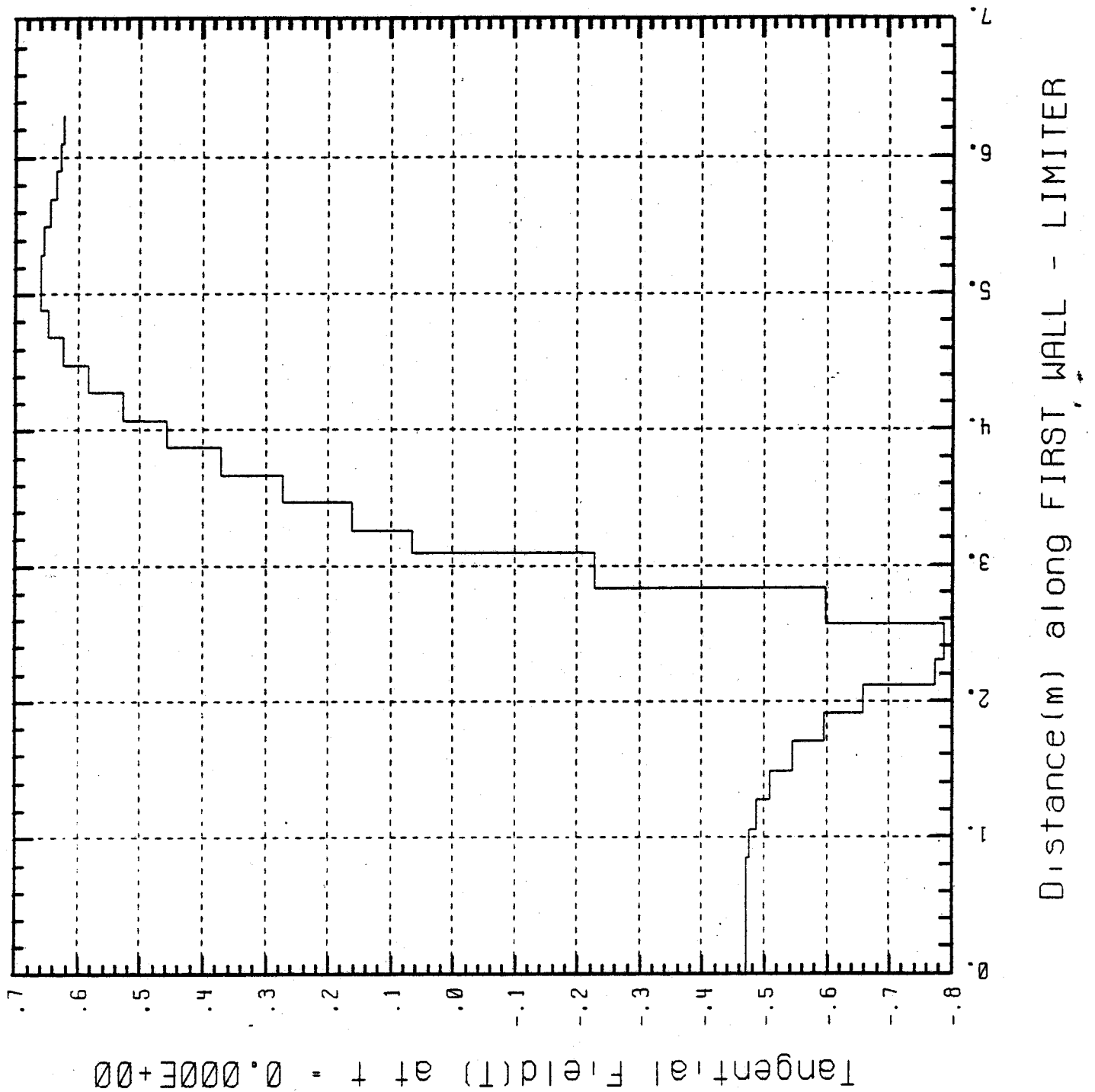


Fig. A-2 Tangential component of the "end of burn" poloidal fields along the first wall and limiter.

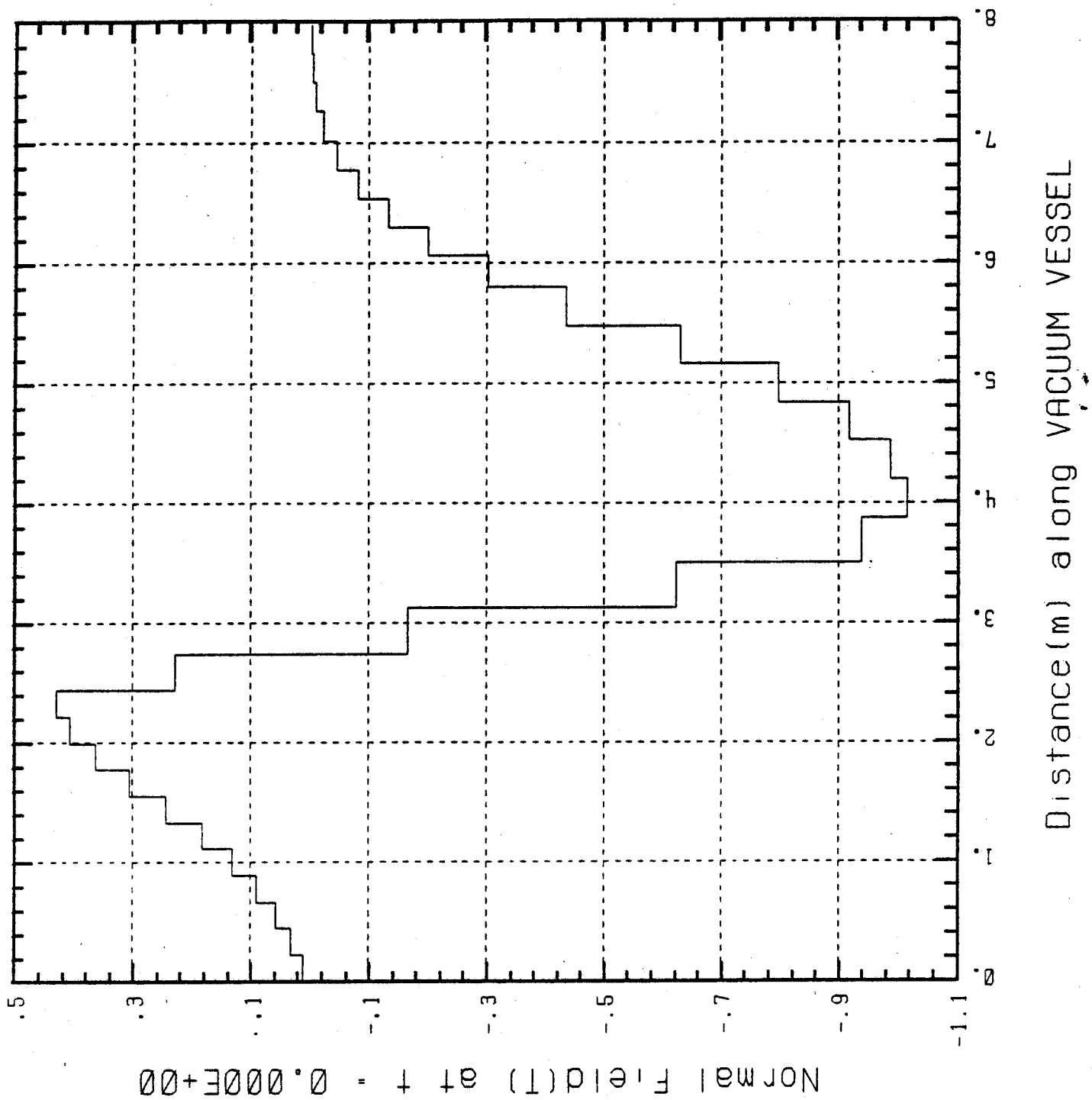


Fig. A-3 Normal component of the "end of burn" poloidal fields along the vacuum vessel.

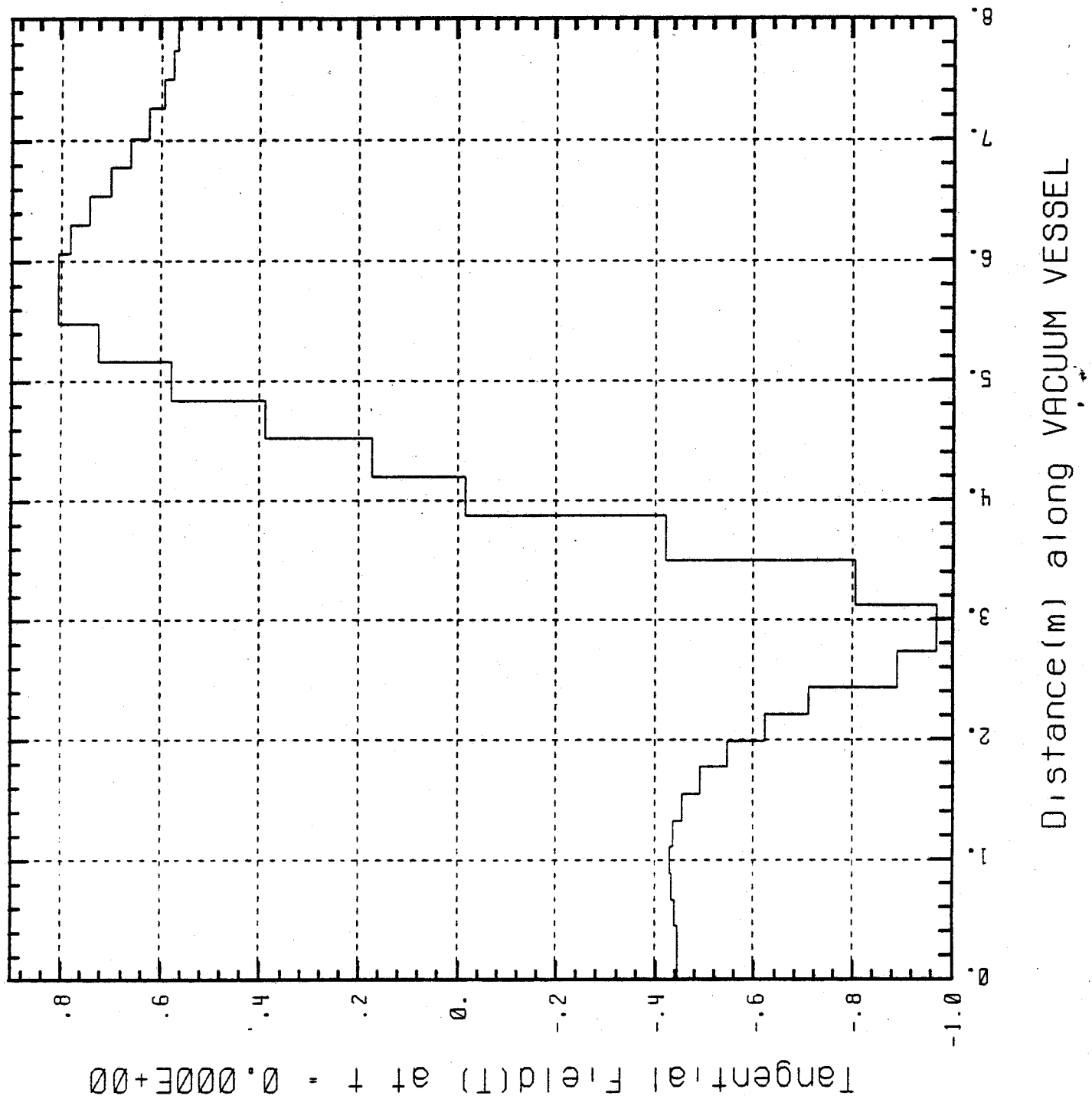


Fig. A-4 Tangential component of the "end of burn" poloidal fields along the vacuum vessel.

APPENDIX B - NORMAL AND TANGENTIAL PRESSURE DISTRIBUTIONS FOR THE
FIRST WALL AND LIMITER; NET CURRENT CARRYING LIMITER

Section 3.2 contained the induced current distributions in the first wall and vacuum vessel at selected instants of time for the case of the net current carrying limiter. Tables were also included to summarize the peak pressure amplitudes, locations and times. These points were determined by evaluating the current and pressure distributions at selected times throughout the transients. This Appendix contains a selection of those distributions to allow an insight to be gained into the development of the pressure profiles along the first wall and vacuum vessel and the manner in which the profiles change with time.

Figures are numbered in this Appendix according to the following outline. Each figure corresponds to a specific instant of time and they are grouped in sets giving profiles at $t=10, 20, 40, 60, 80$, and 100 ms. Captions are not included on the figures since the required information is contained in the axis labels on each plot.

Figures B-1 to B-6: Normal Pressure Along First Wall

Figures B-7 to B-12: Tangential Pressure Along First Wall

Figures B-13 to B-18: Normal Pressure Along Vacuum Vessel

Figures B-19 to B-24: Tangential Pressure Along Vacuum Vessel

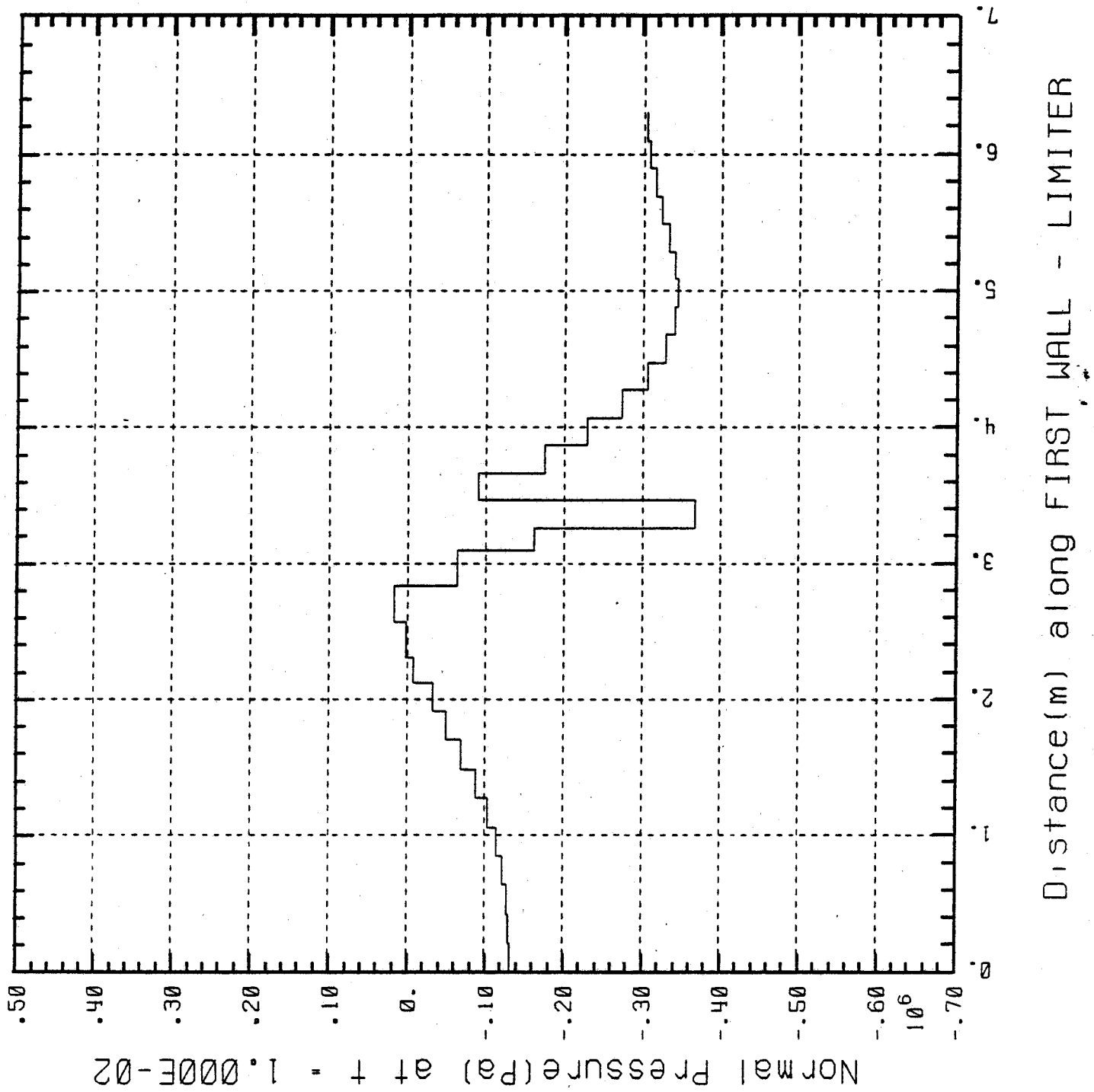


Fig. B-1

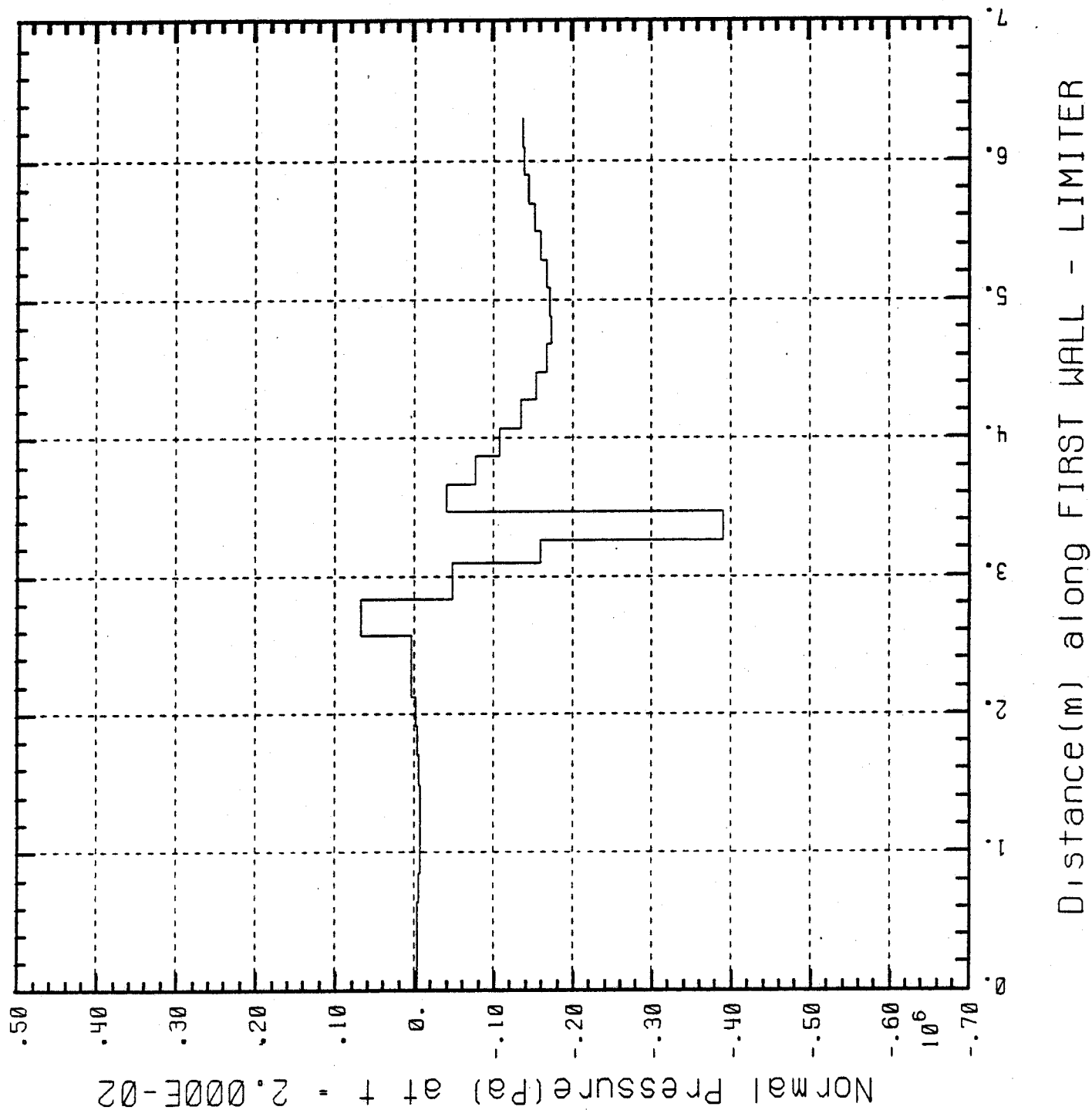


Fig. B-2

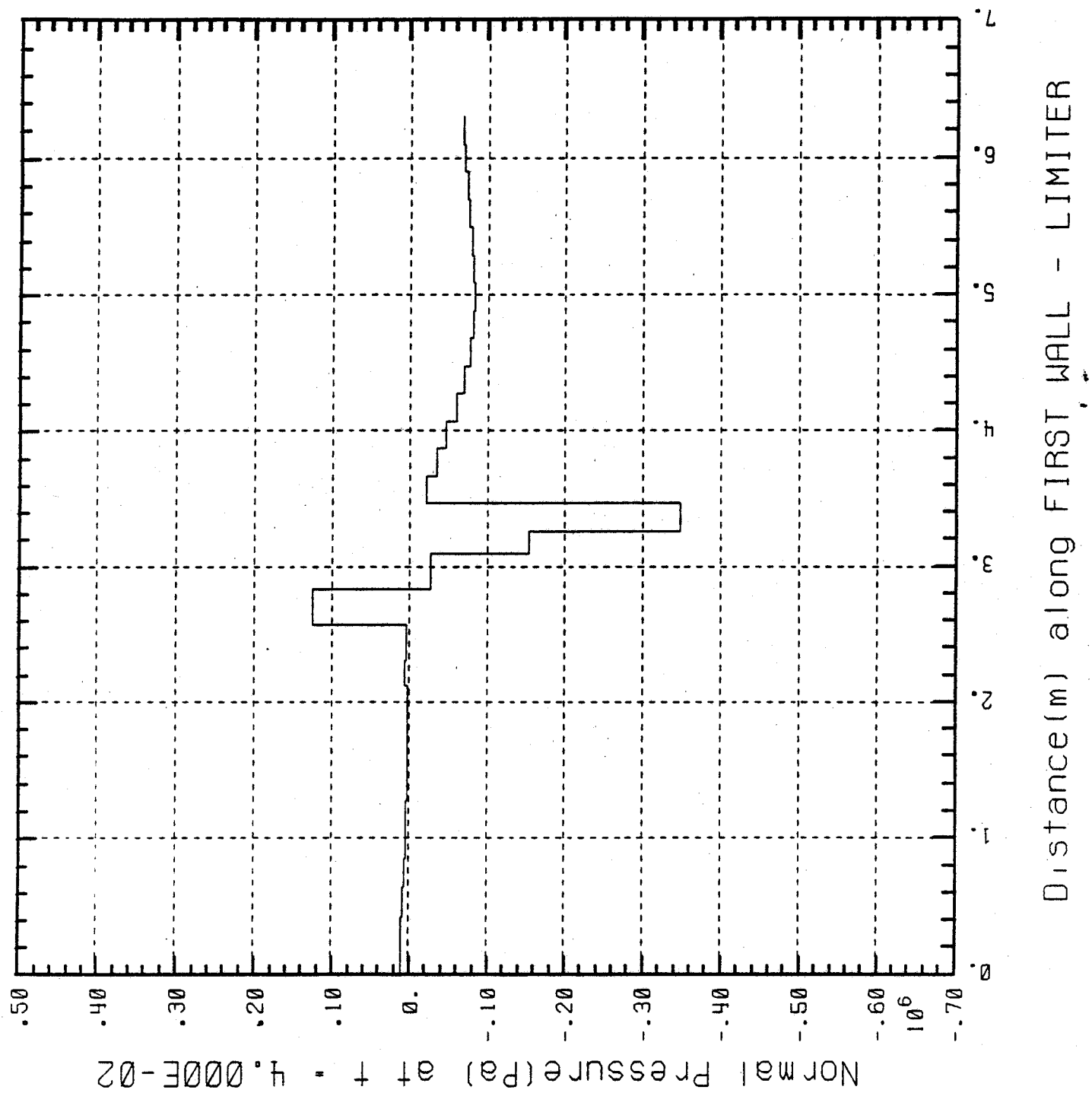


Fig. B-3

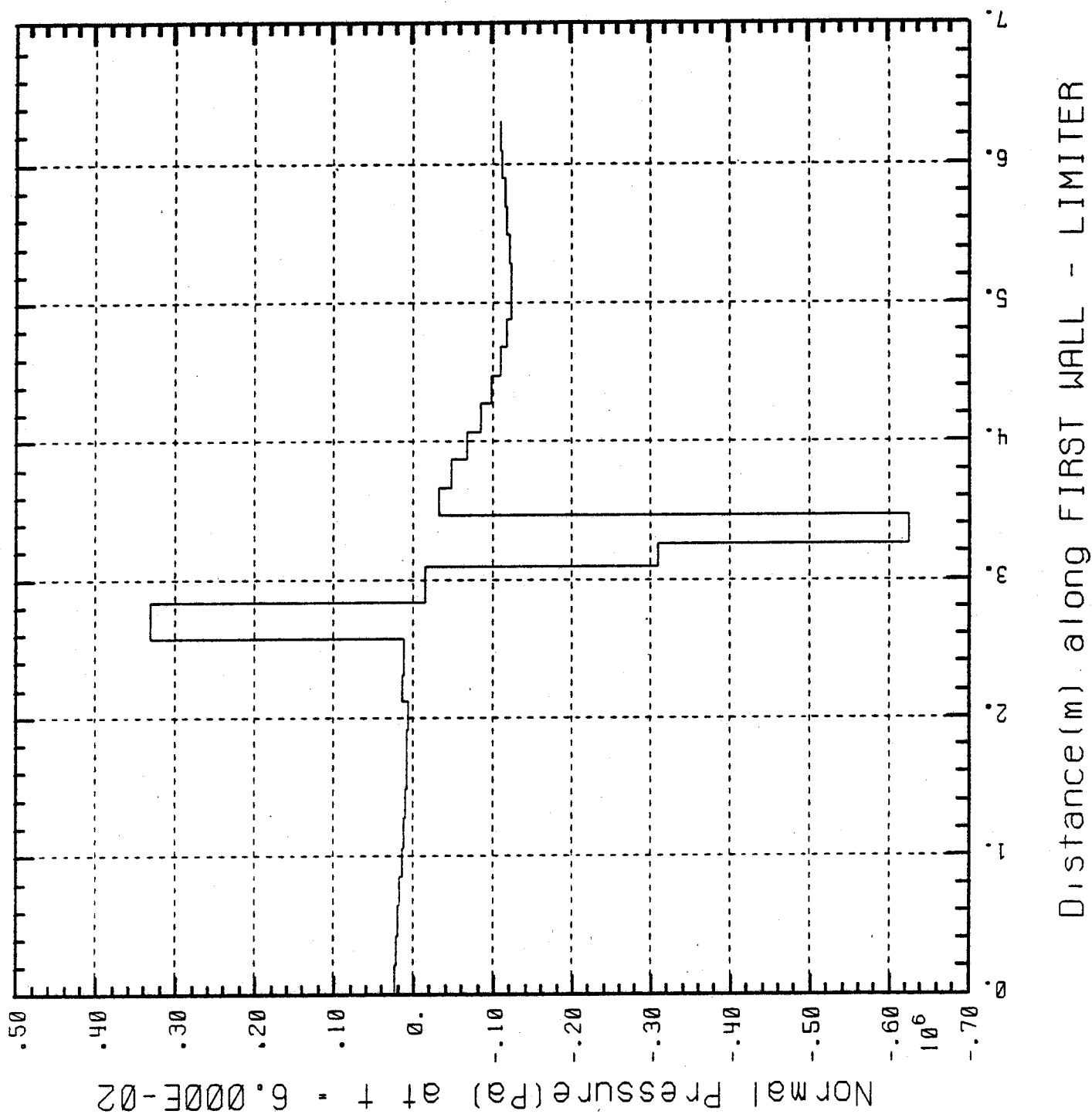


Fig. B-4

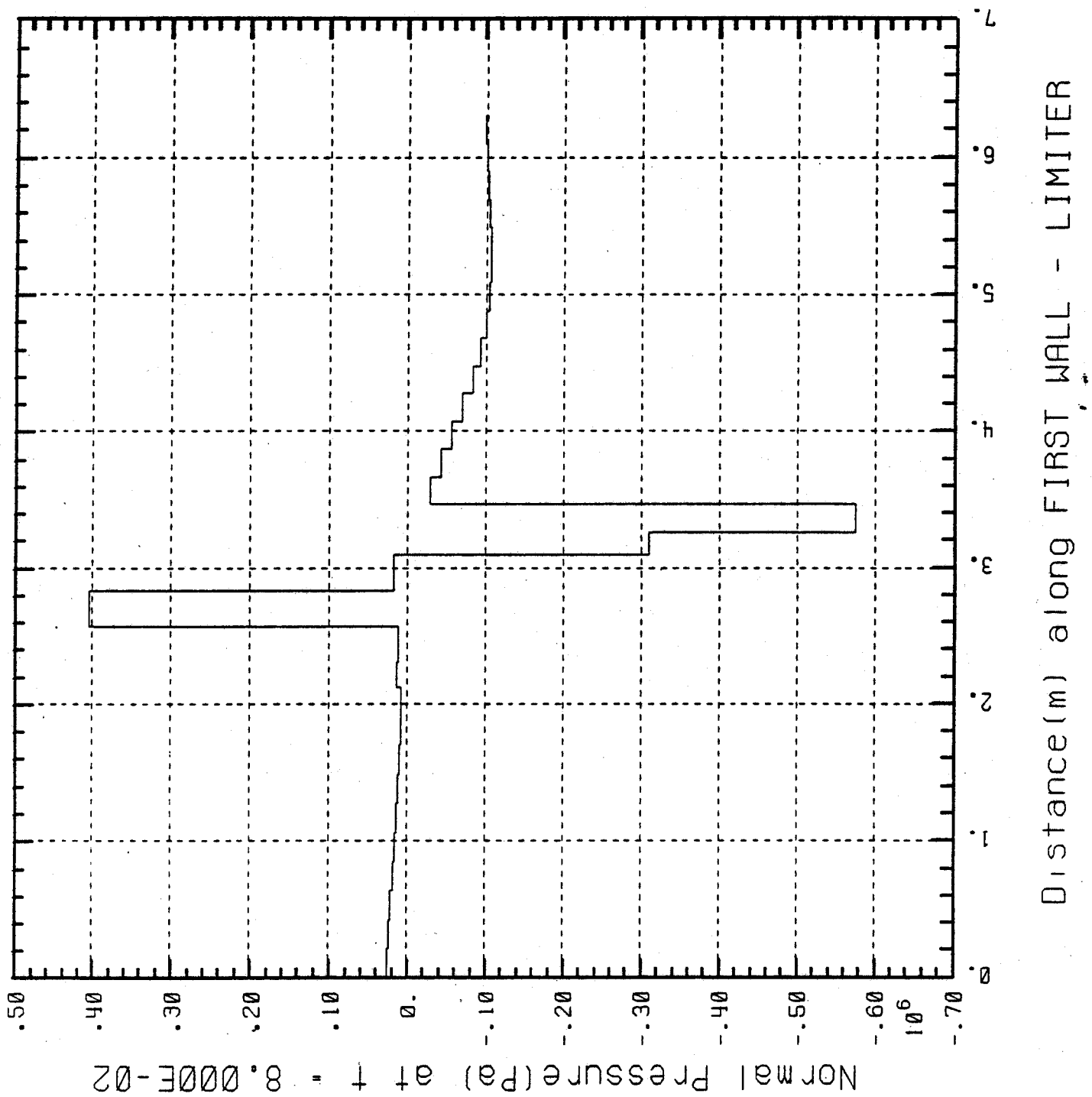


Fig. B-5

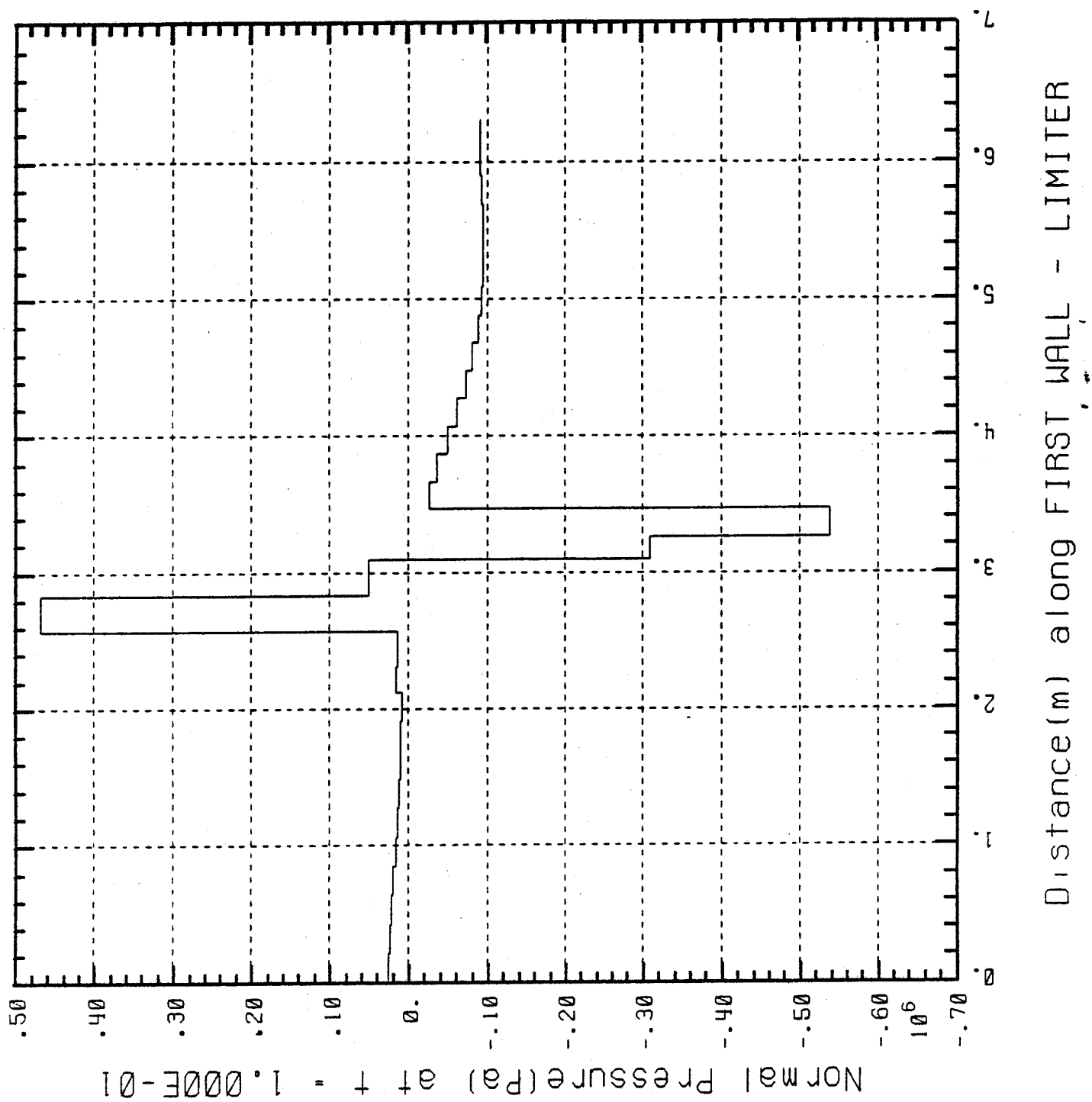


Fig. B-6

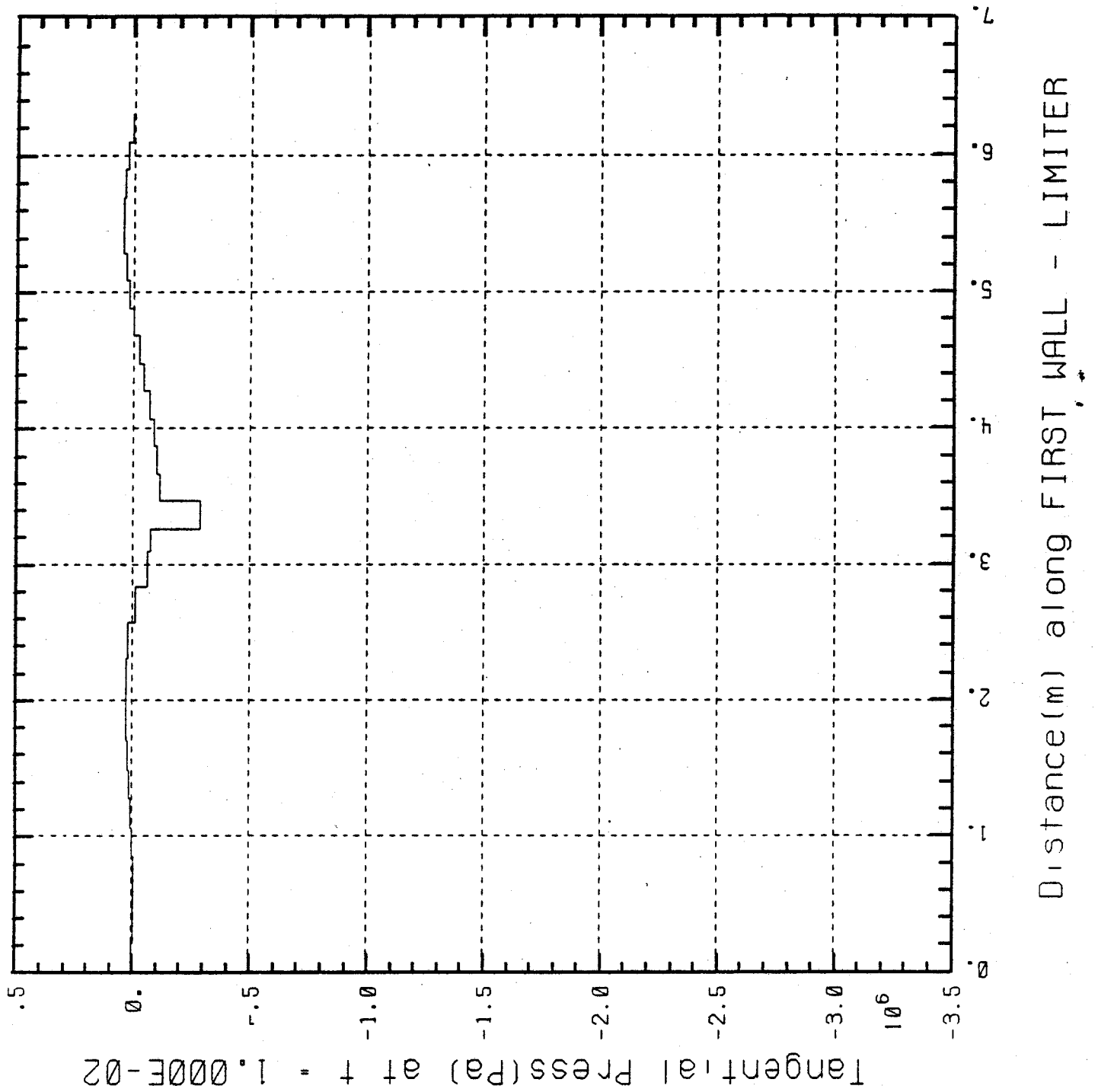


Fig. B-7

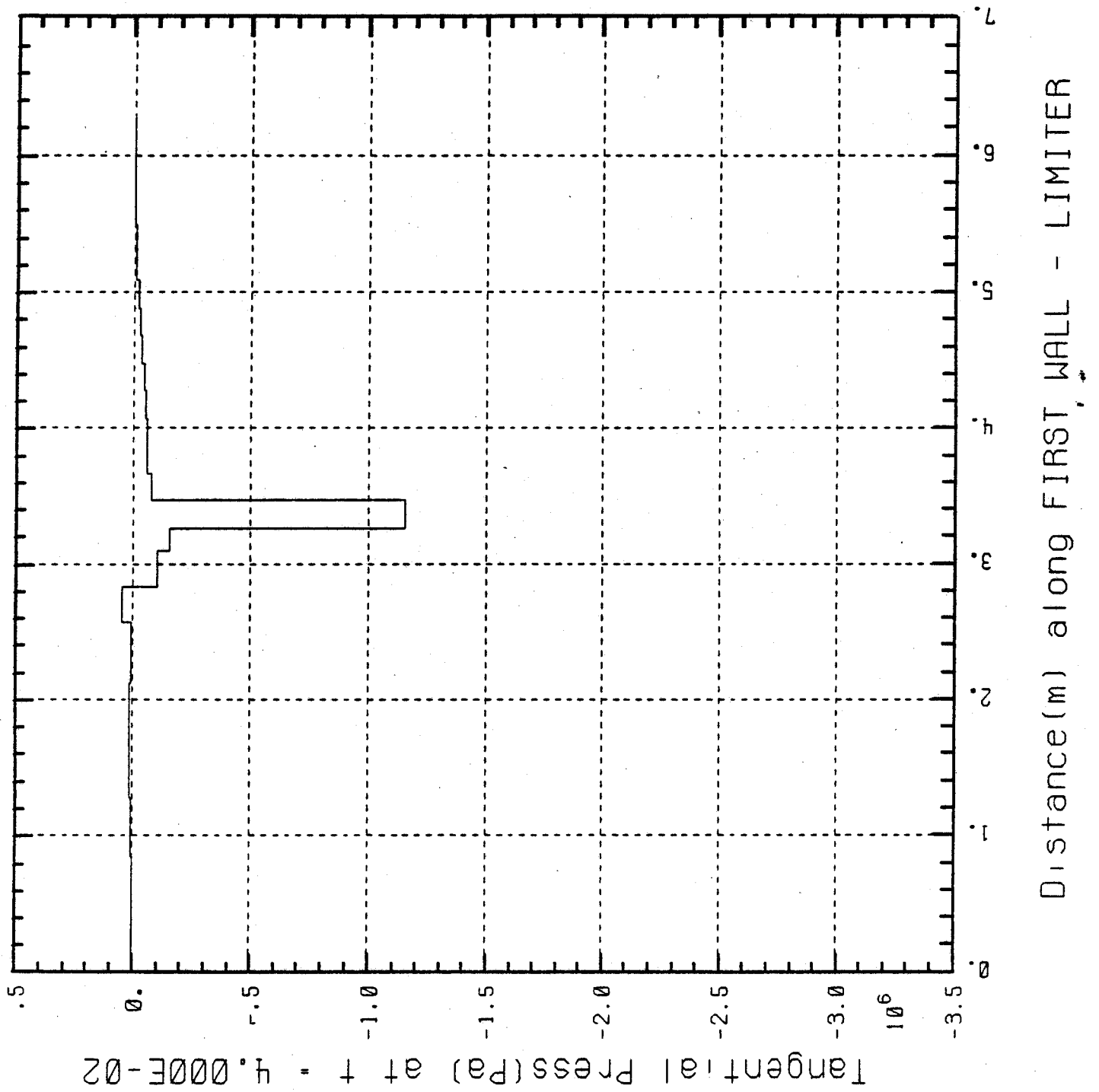


Fig. B-9

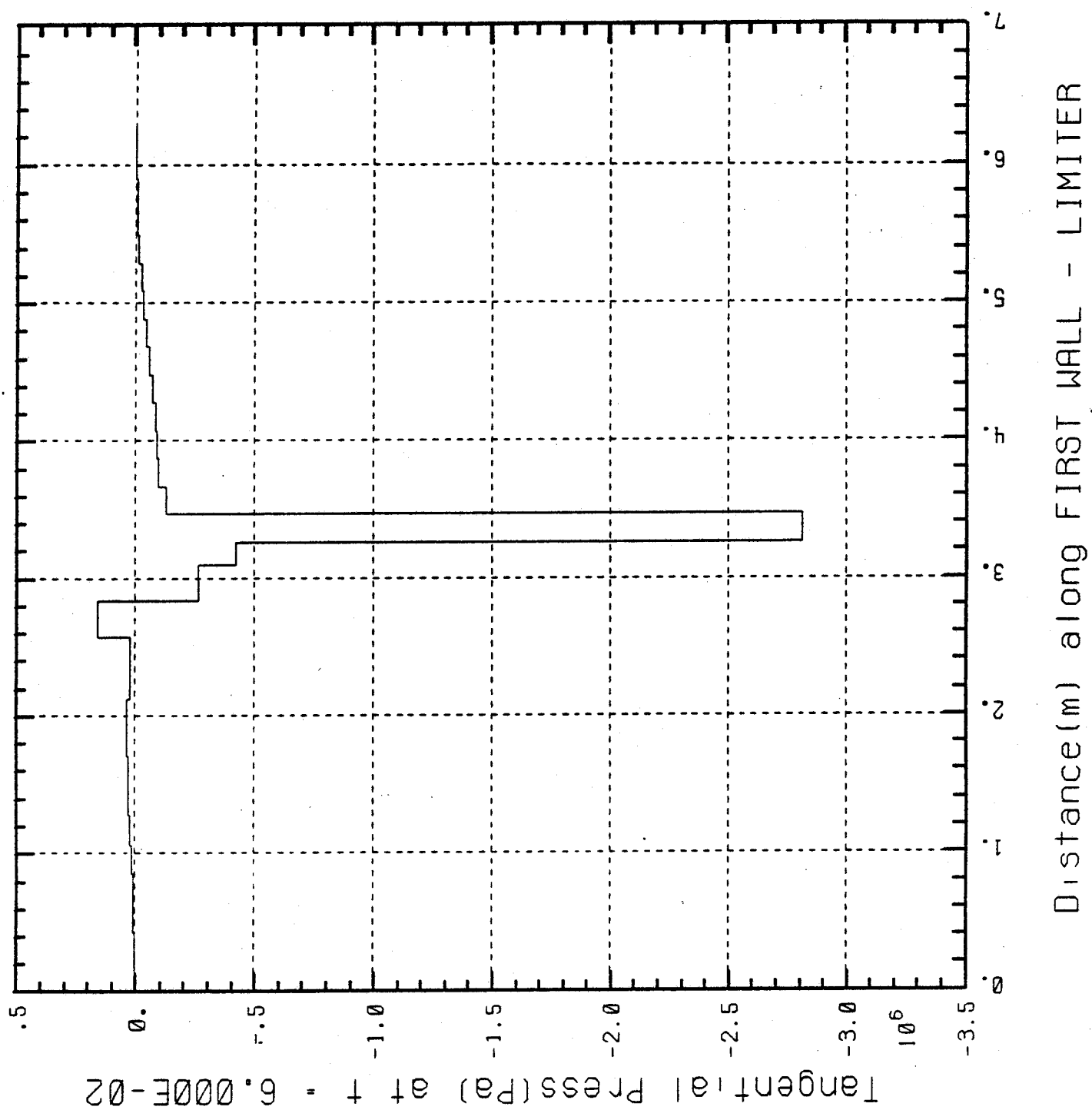


Fig. B-10

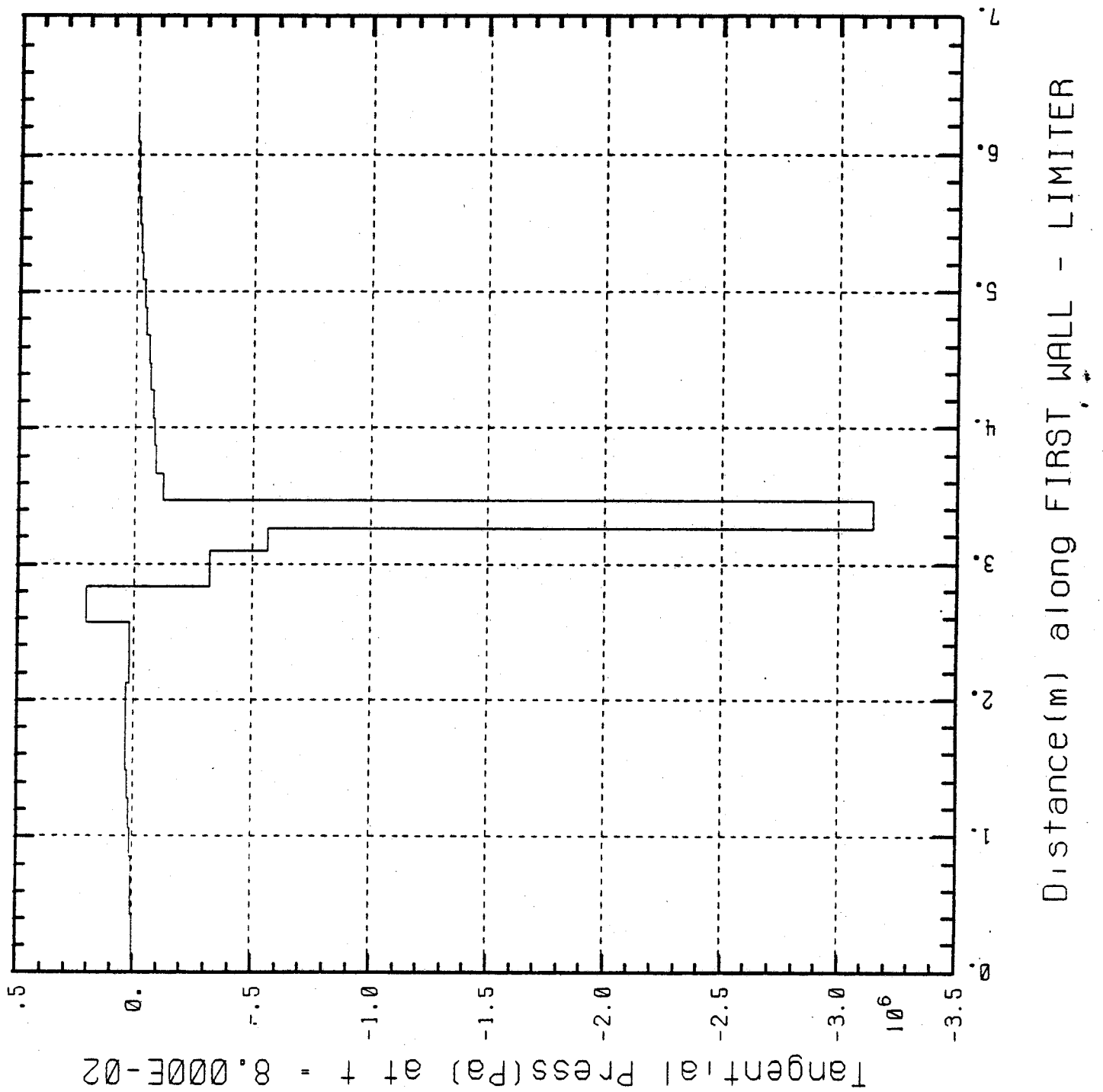


Fig. B-11

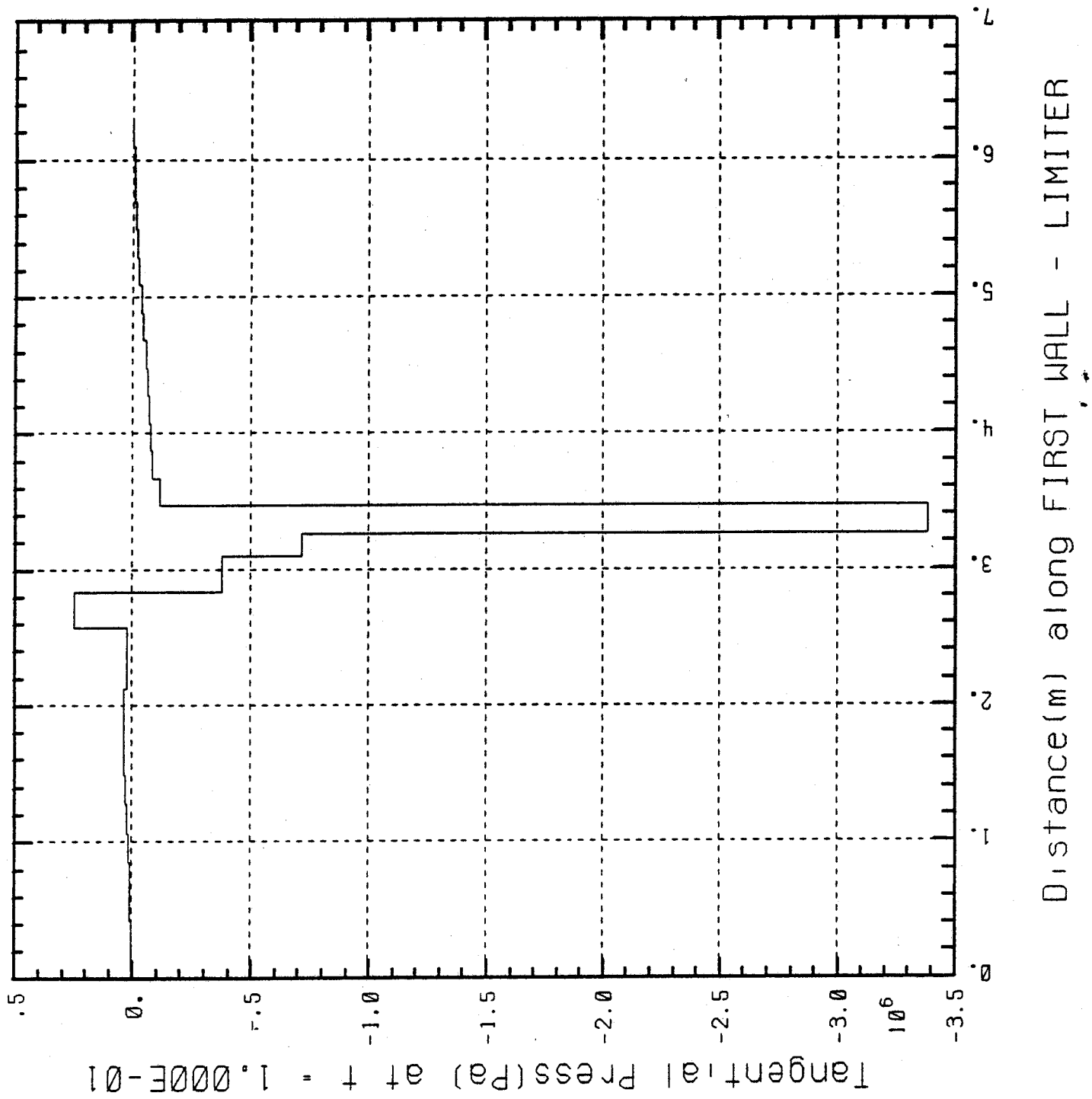


Fig. B-12

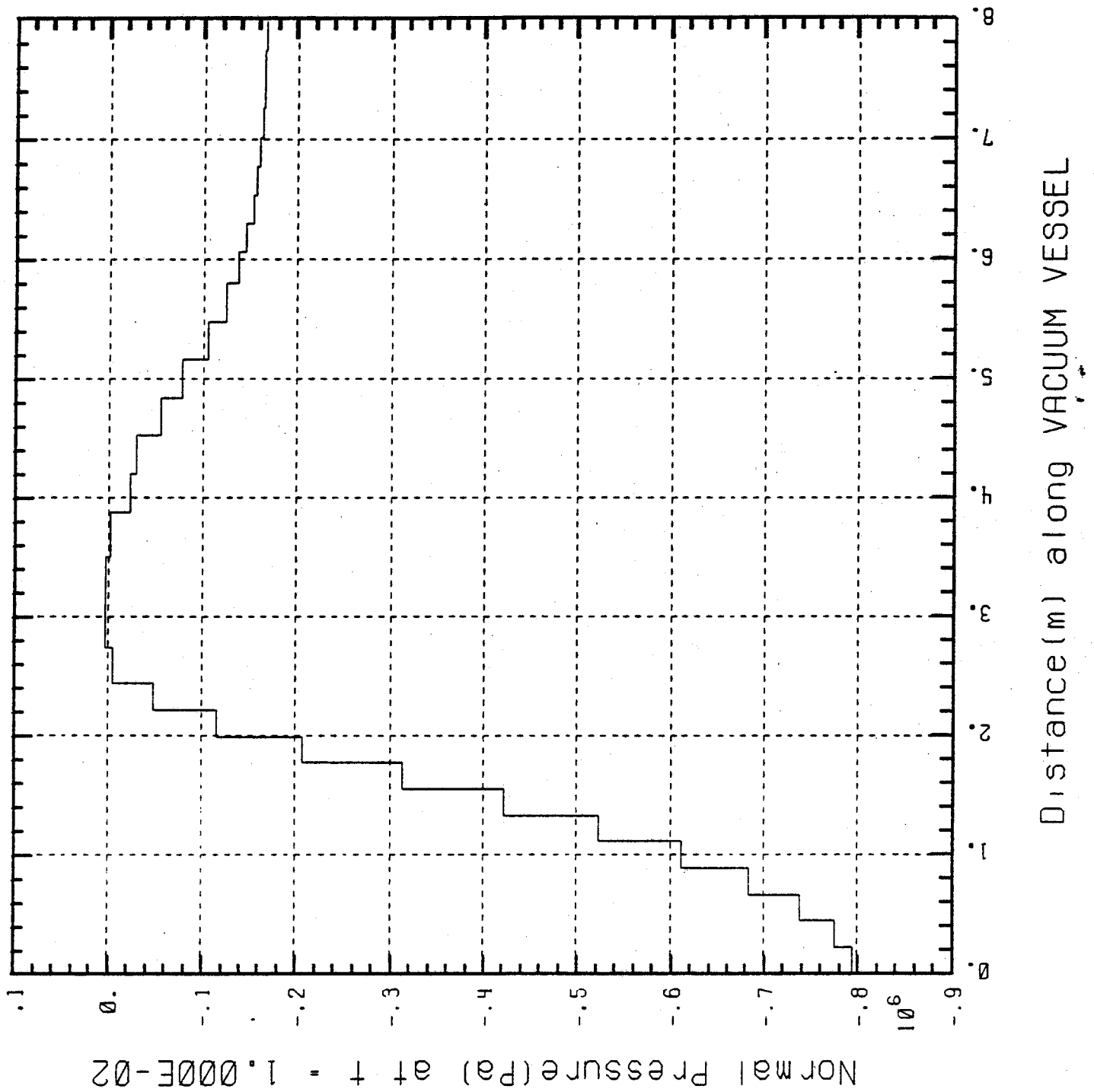


Fig. B-13

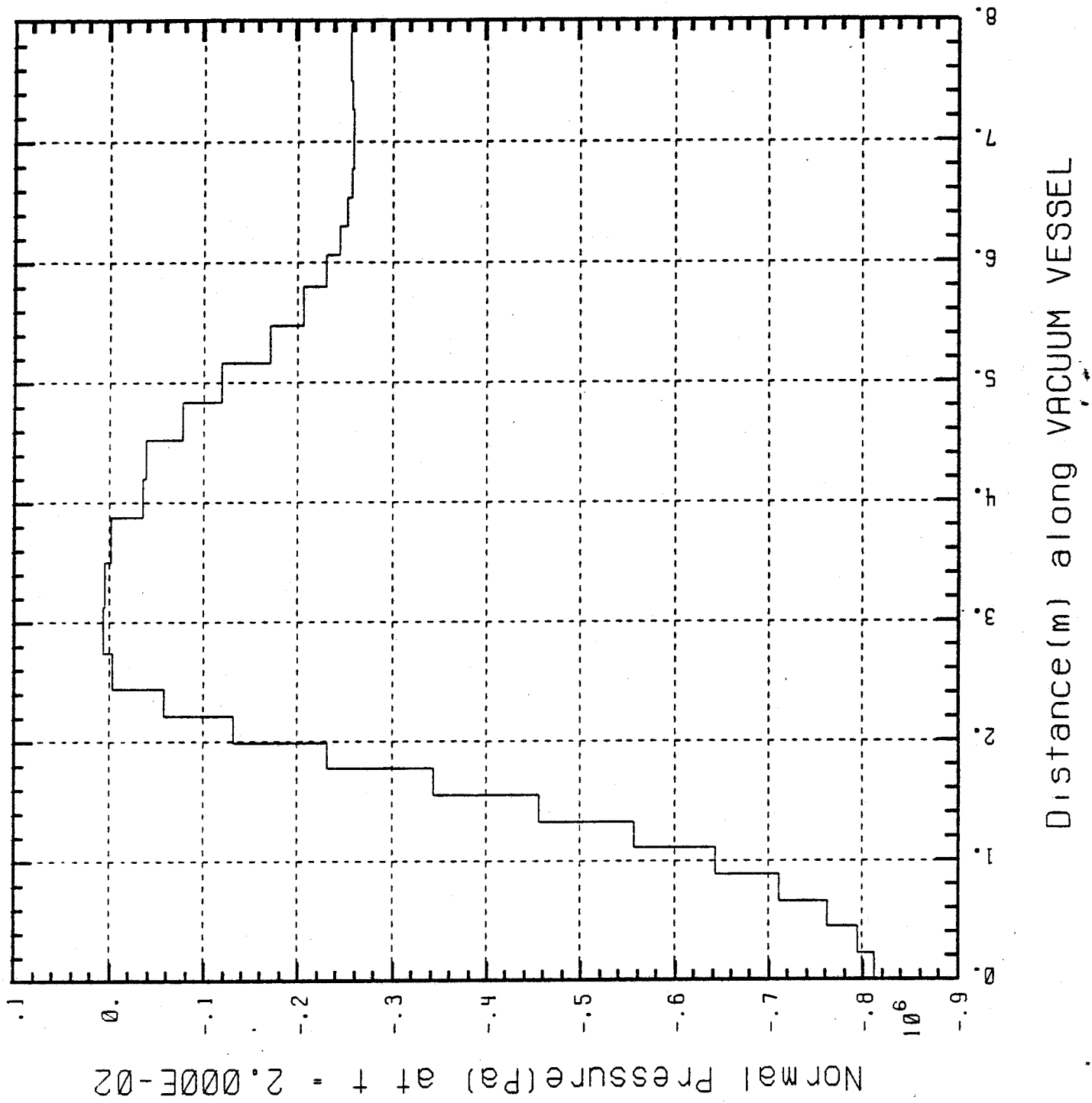


Fig. B-14

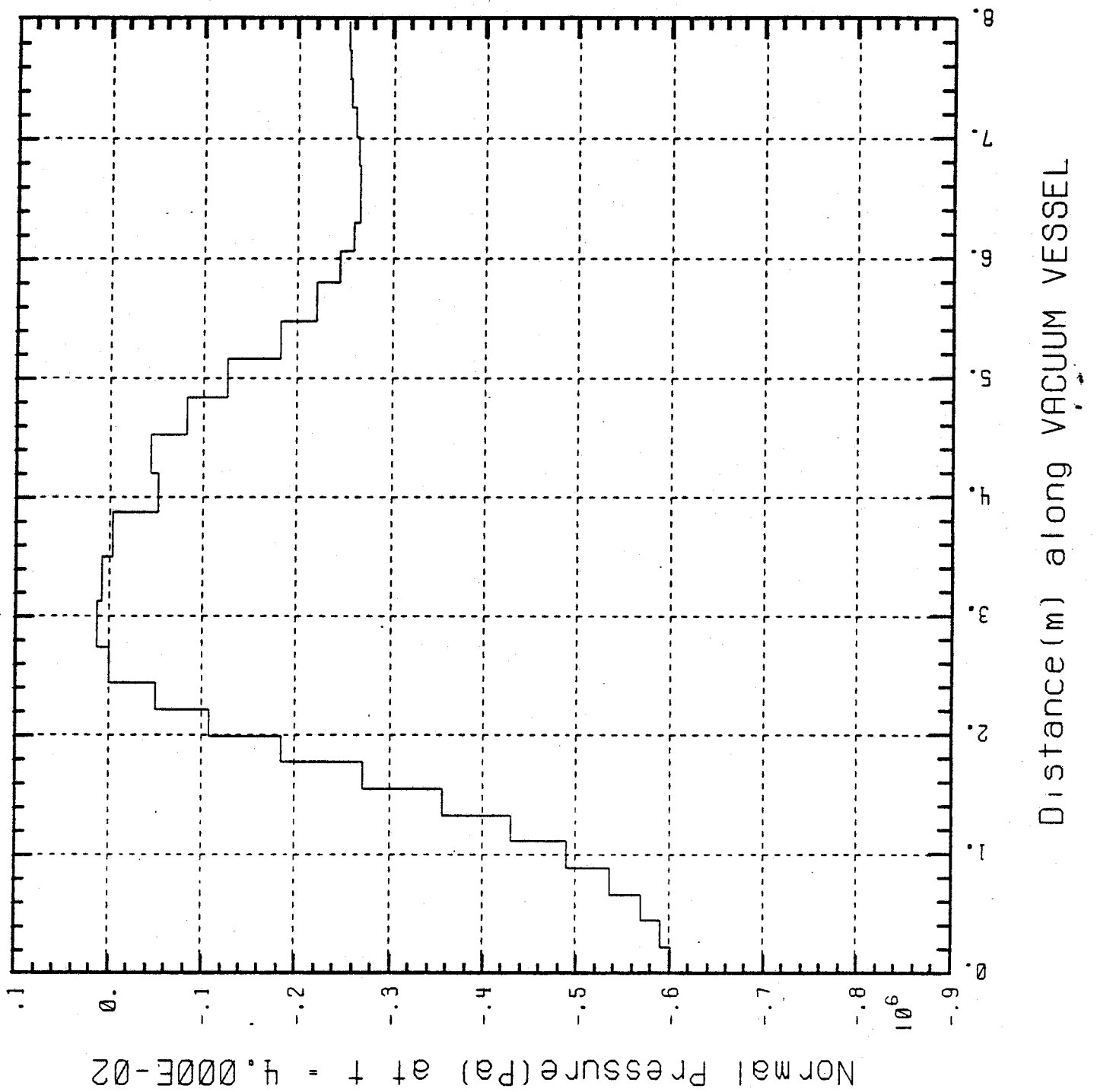


Fig. B-15

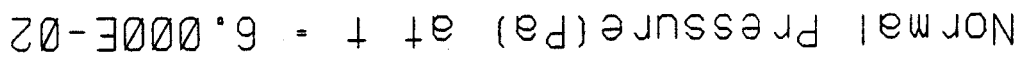


Fig. B-16

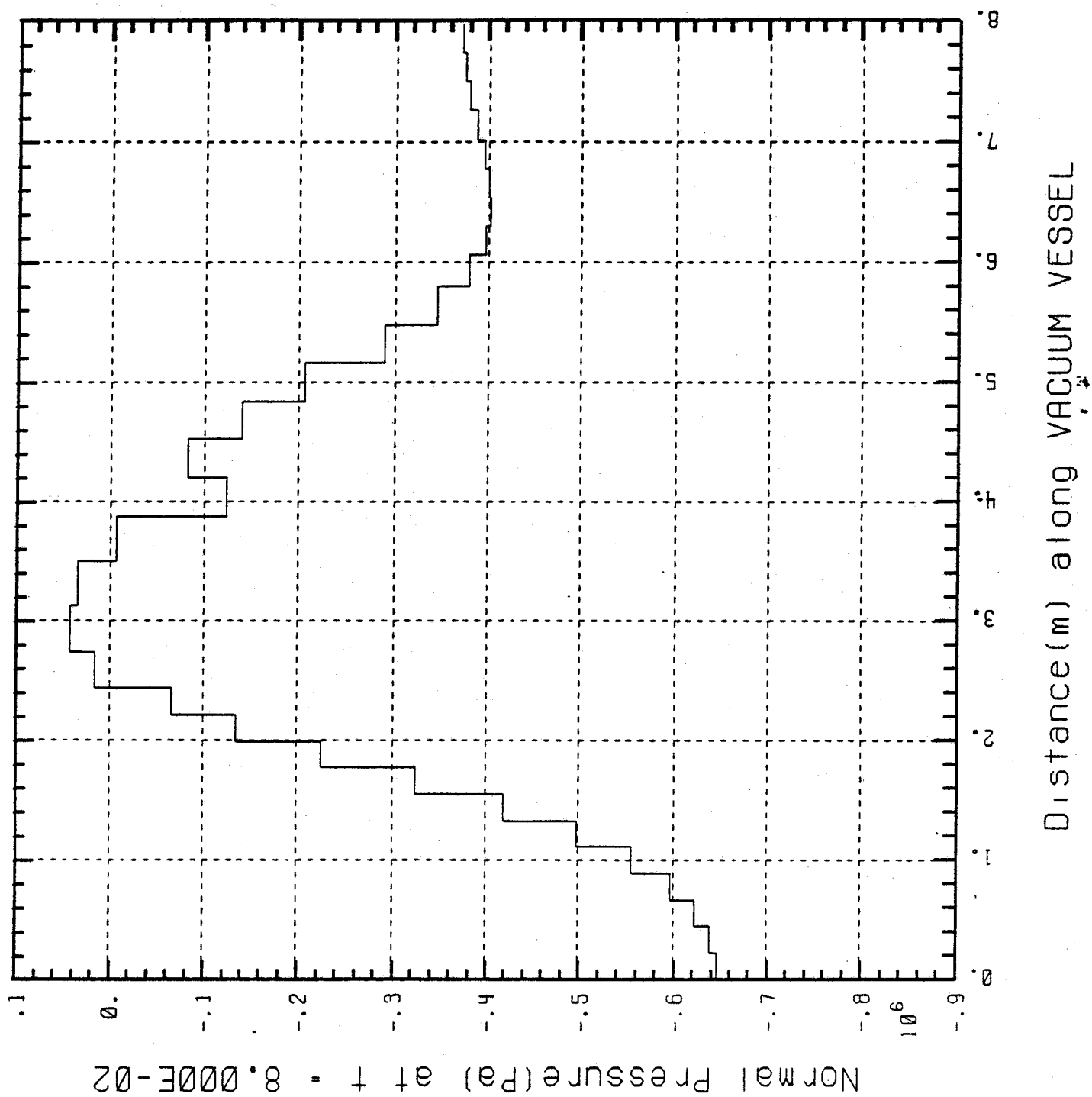


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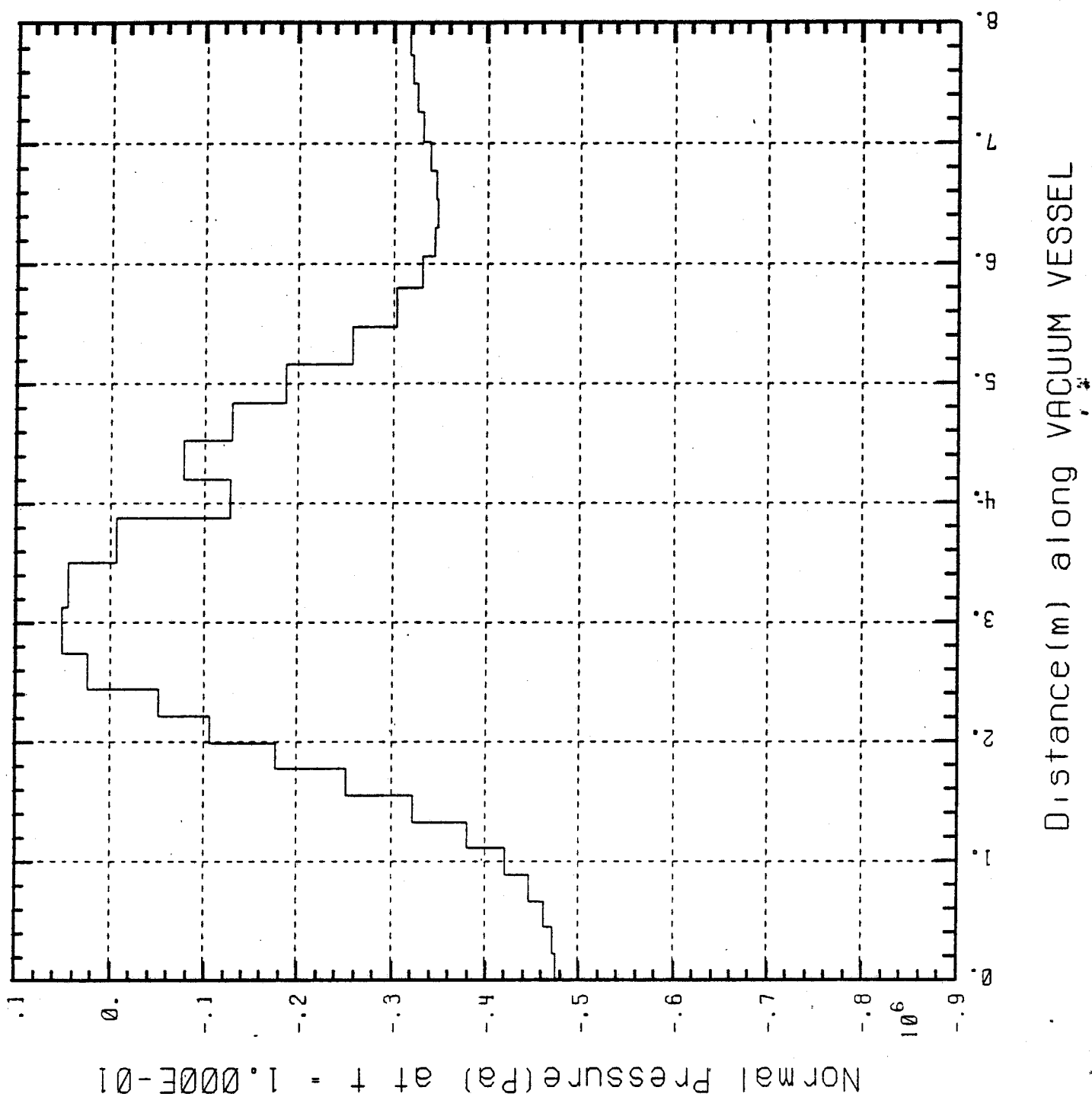


Fig. B-18

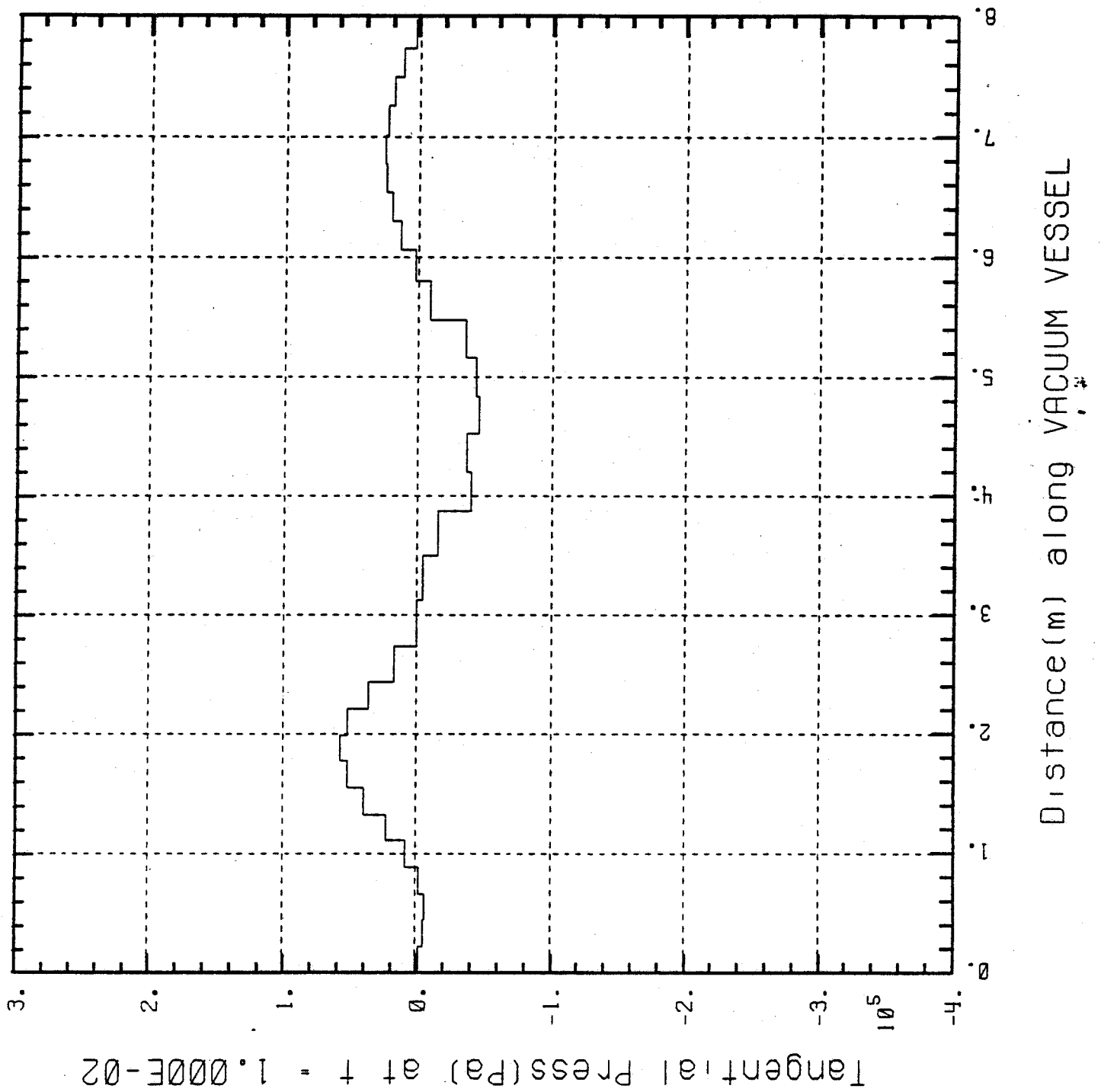


Fig. B-19

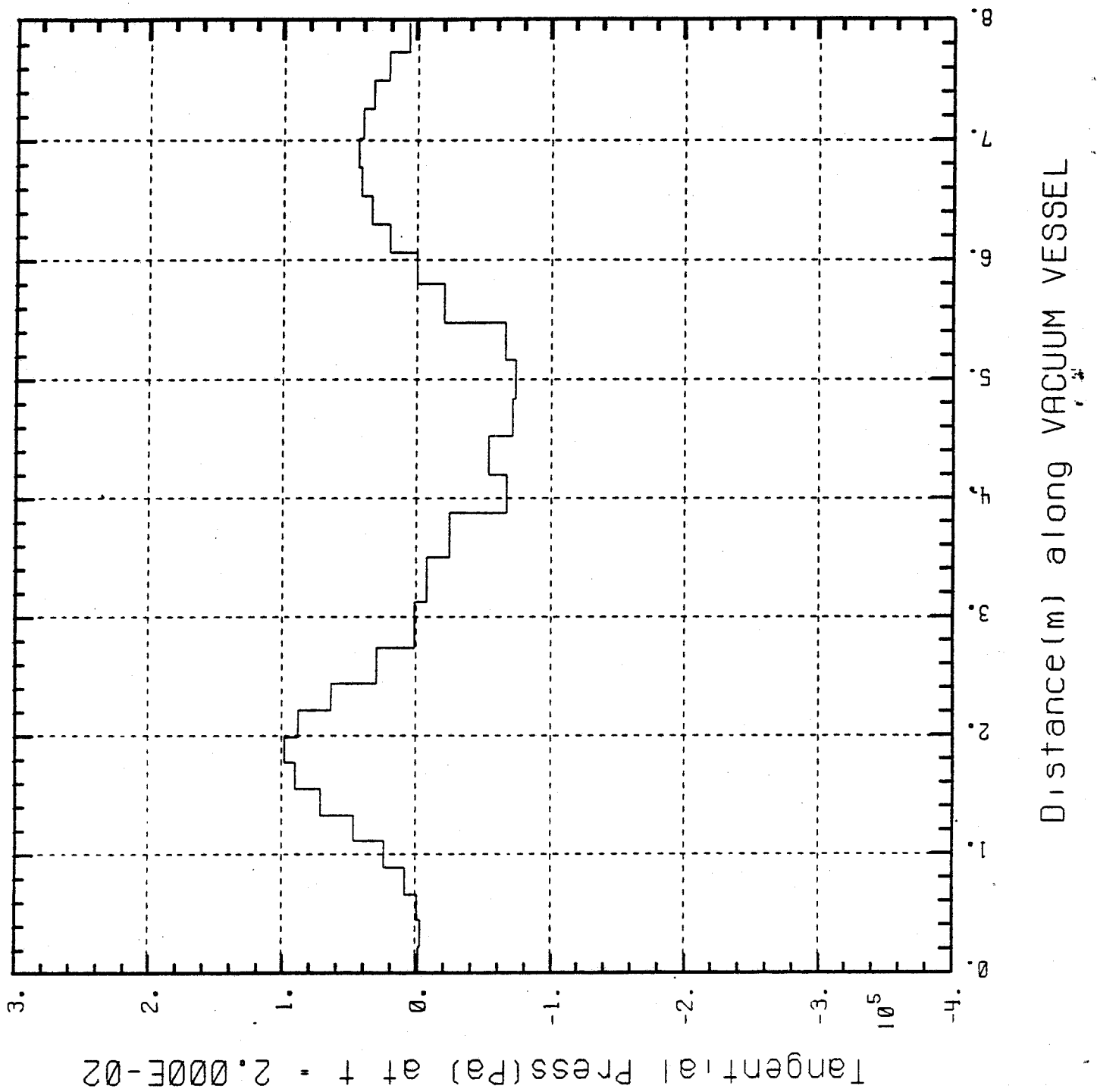


Fig. B-20

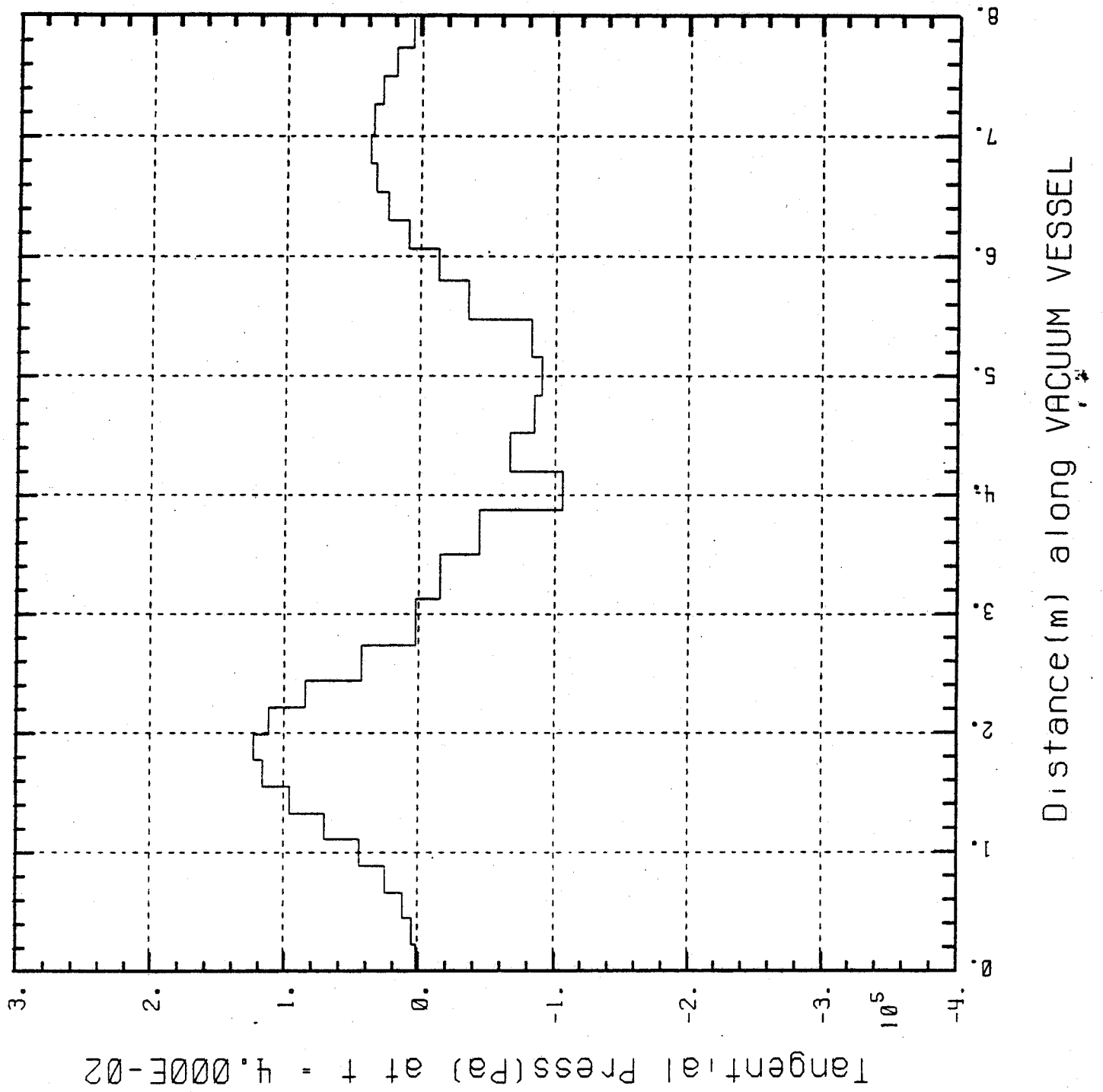


Fig. B-21

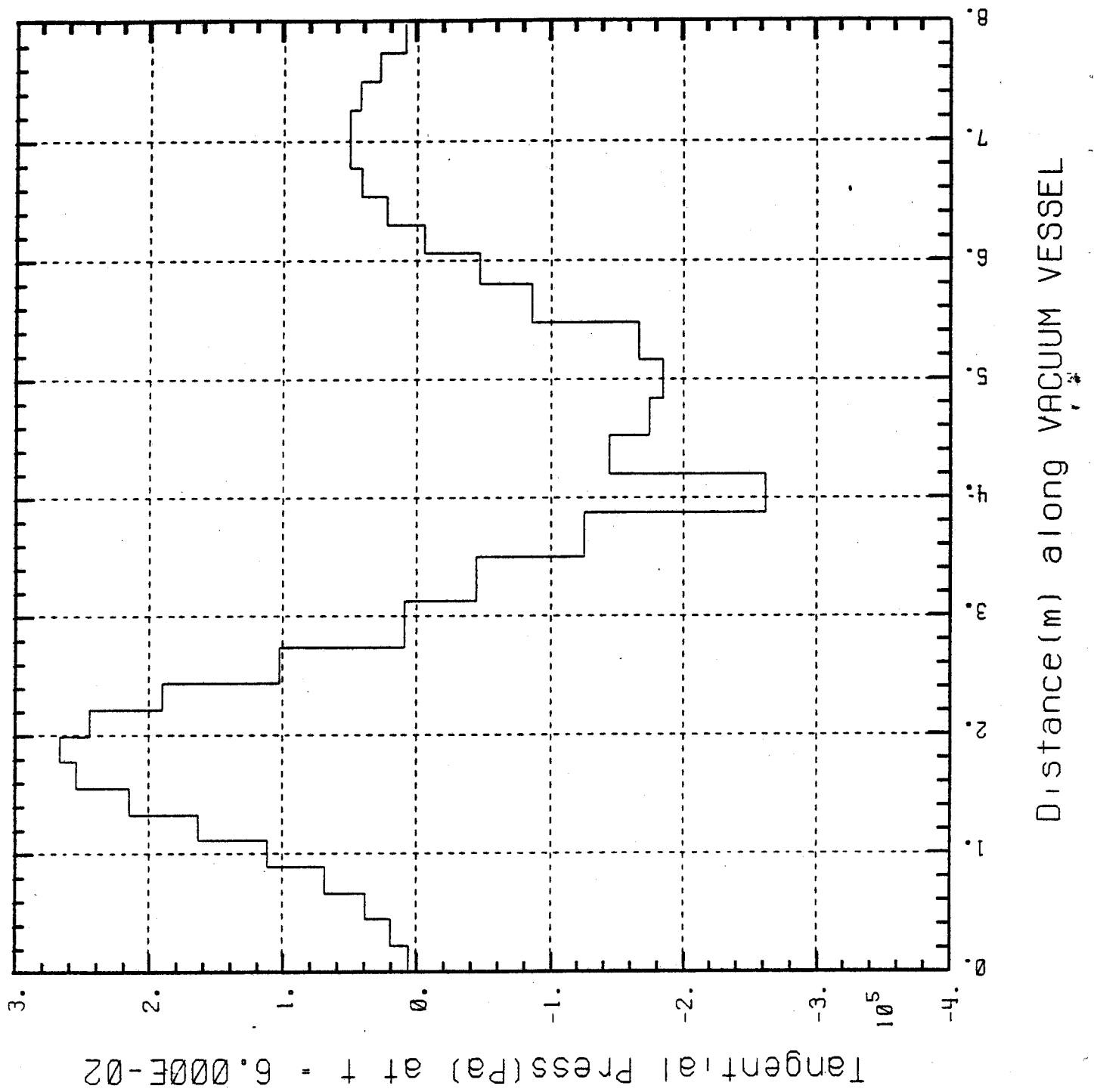


Fig. B-22

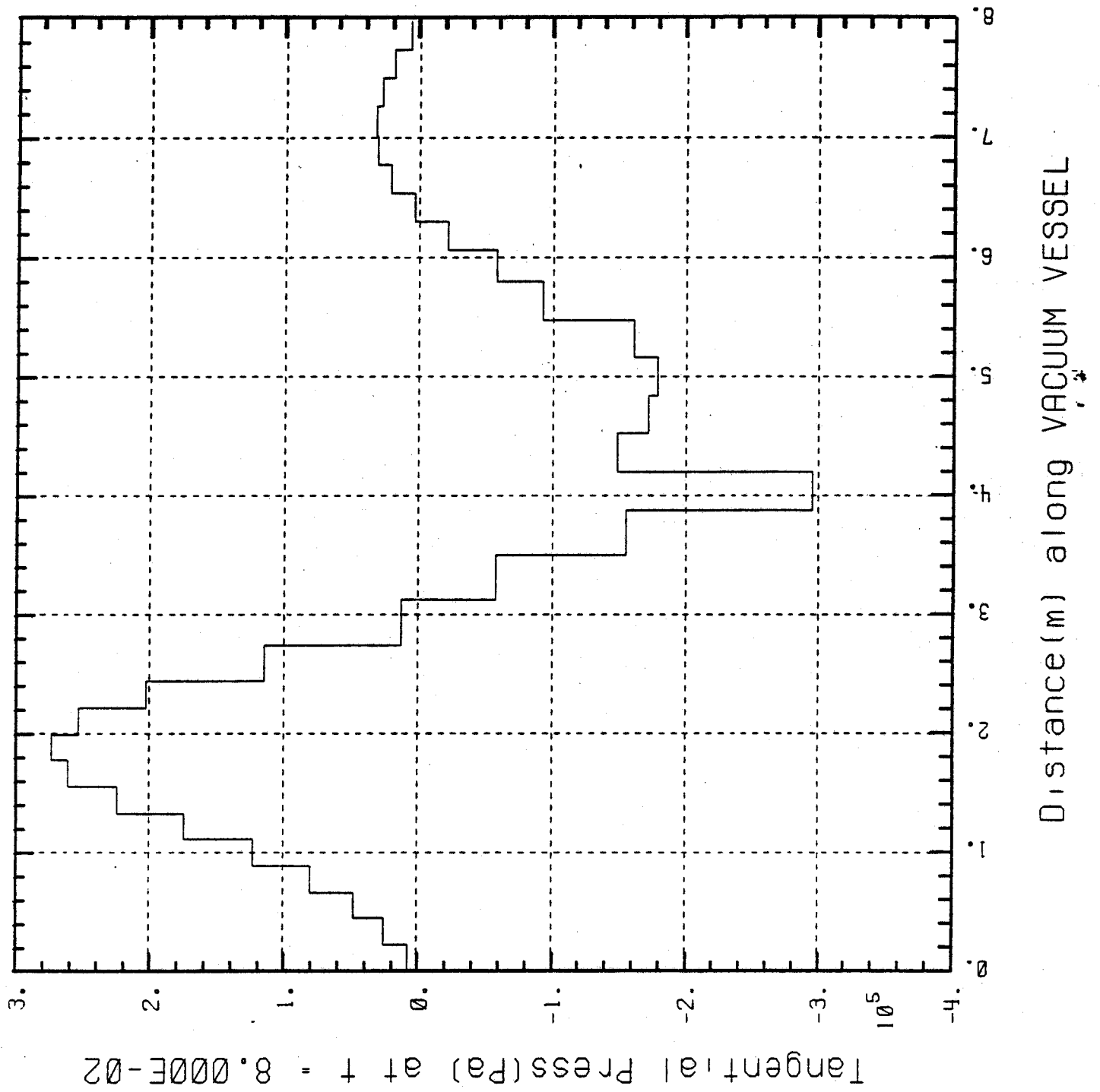


Fig. B-23

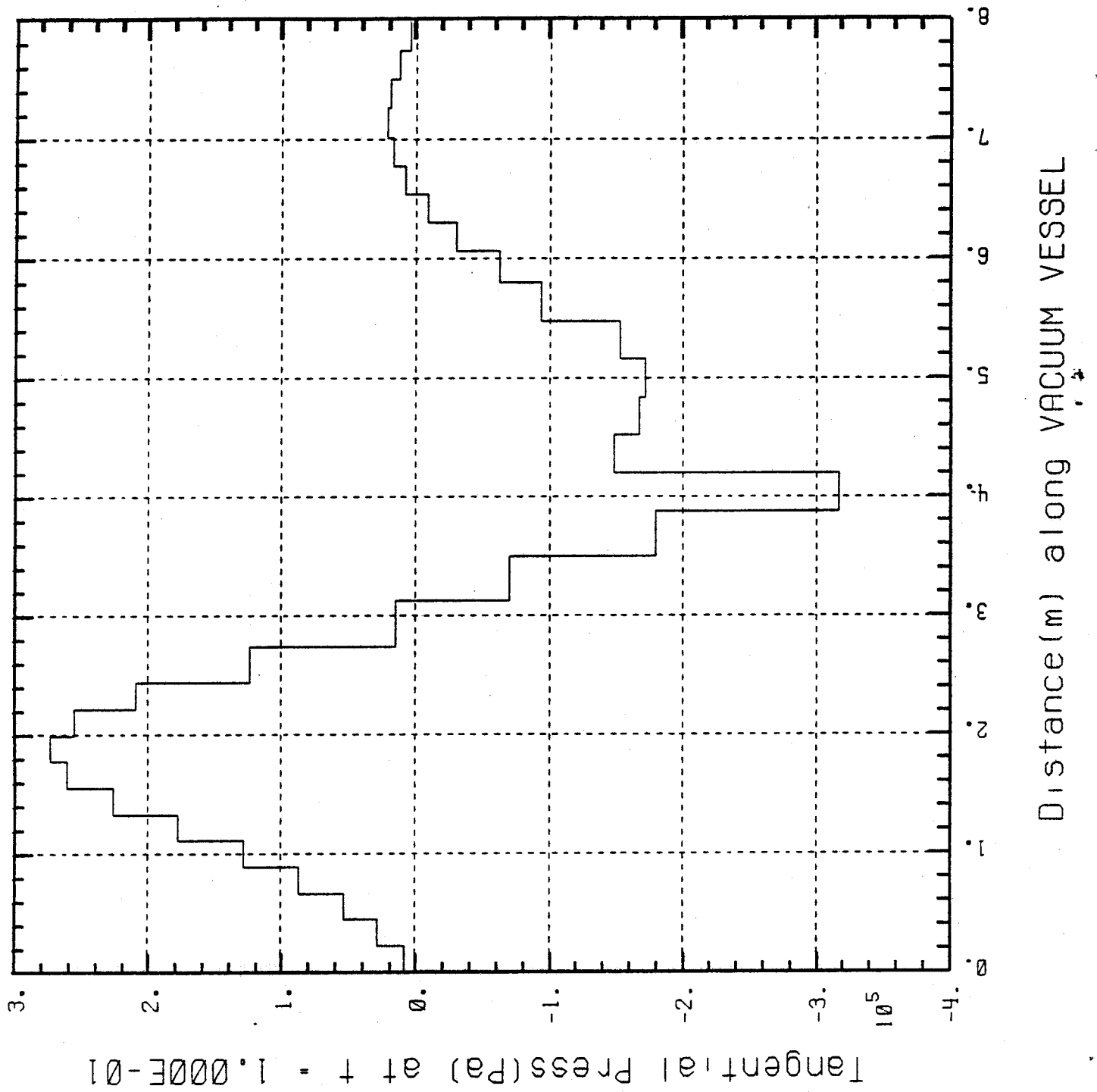


Fig. B-24

APPENDIX C - NORMAL AND TANGENTIAL PRESSURE DISTRIBUTIONS FOR THE
FIRST WALL AND LIMITER; NO NET CURRENT CARRYING LIMITER

Section 3.3 contained the induced current distributions in the first wall and vacuum vessel at selected instants of time for the case of the net current carrying limiter. Tables were also included to summarize the peak pressure amplitudes, locations and times. These points were determined by evaluating the current and pressure distributions at selected times throughout the transients. This Appendix contains a selection of those distributions to allow an insight to be gained into the development of the pressure profiles along the first wall and vacuum vessel and the manner in which the profiles change with time.

Figures are numbered in this Appendix according to the following outline. Each figure corresponds to a specific instant of time and they are grouped in sets giving profiles at $t=10, 20, 30, 40,$ and 50 ms. Captions are not included on the figures since the required information is contained in the axis labels on each plot.

Figures C-1 to C-5: Normal Pressure Along First Wall

Figures C-6 to C-10: Tangential Pressure Along First Wall

Figures C-11 to C-15: Normal Pressure Along Vacuum Vessel

Figures C-16 to C-20: Tangential Pressure Along Vacuum Vessel

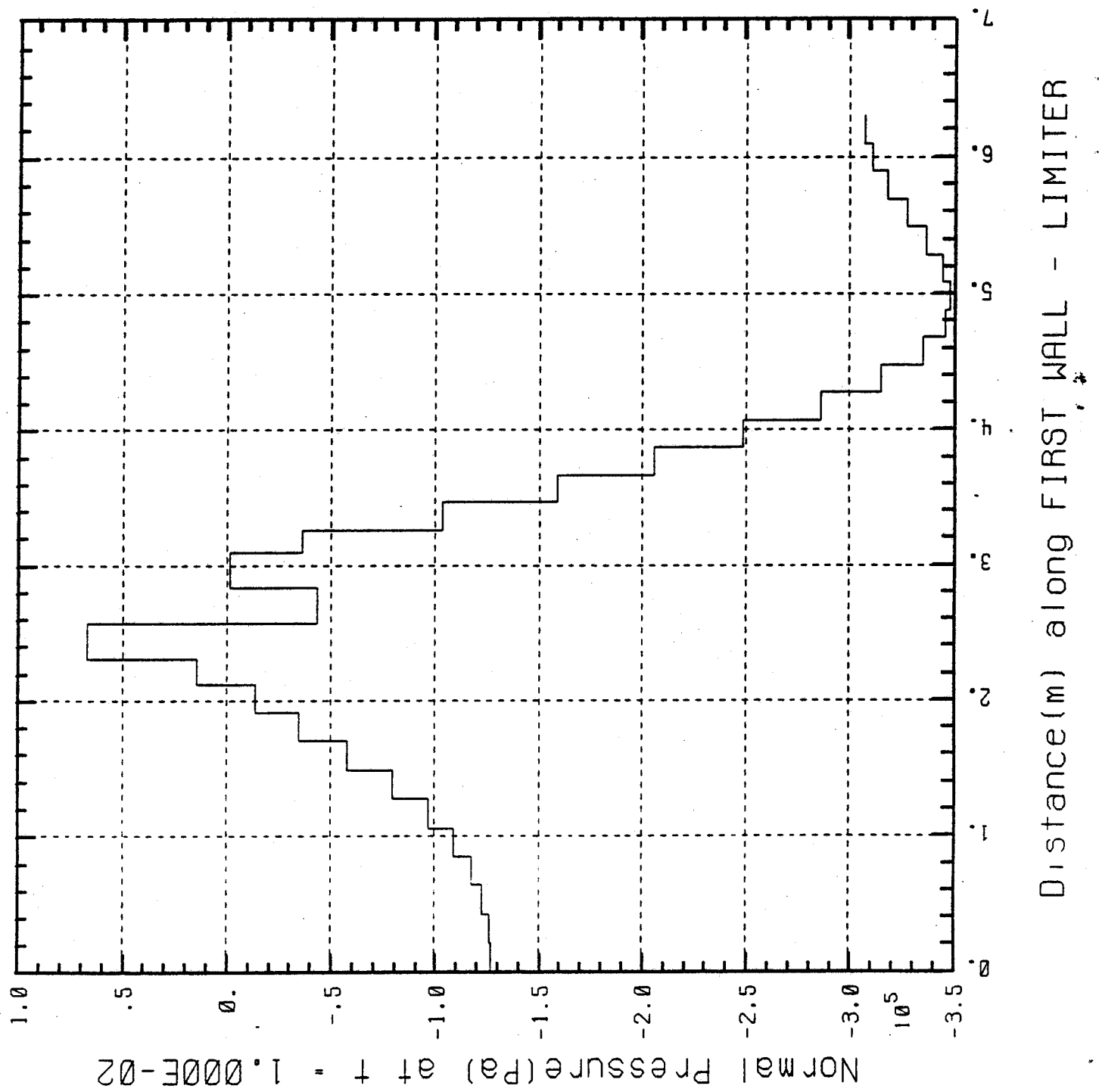


Fig. C-1

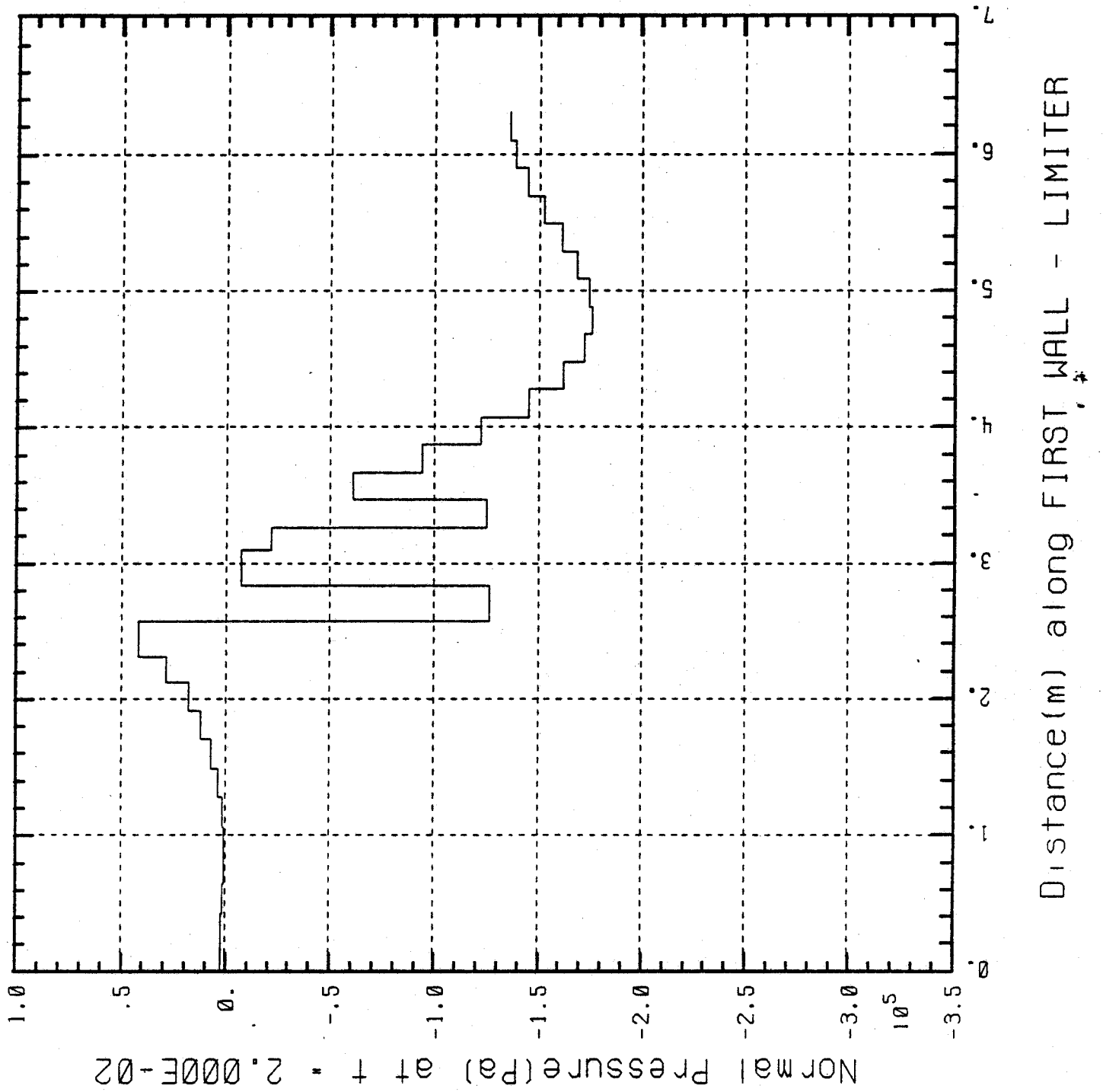


Fig. C-2

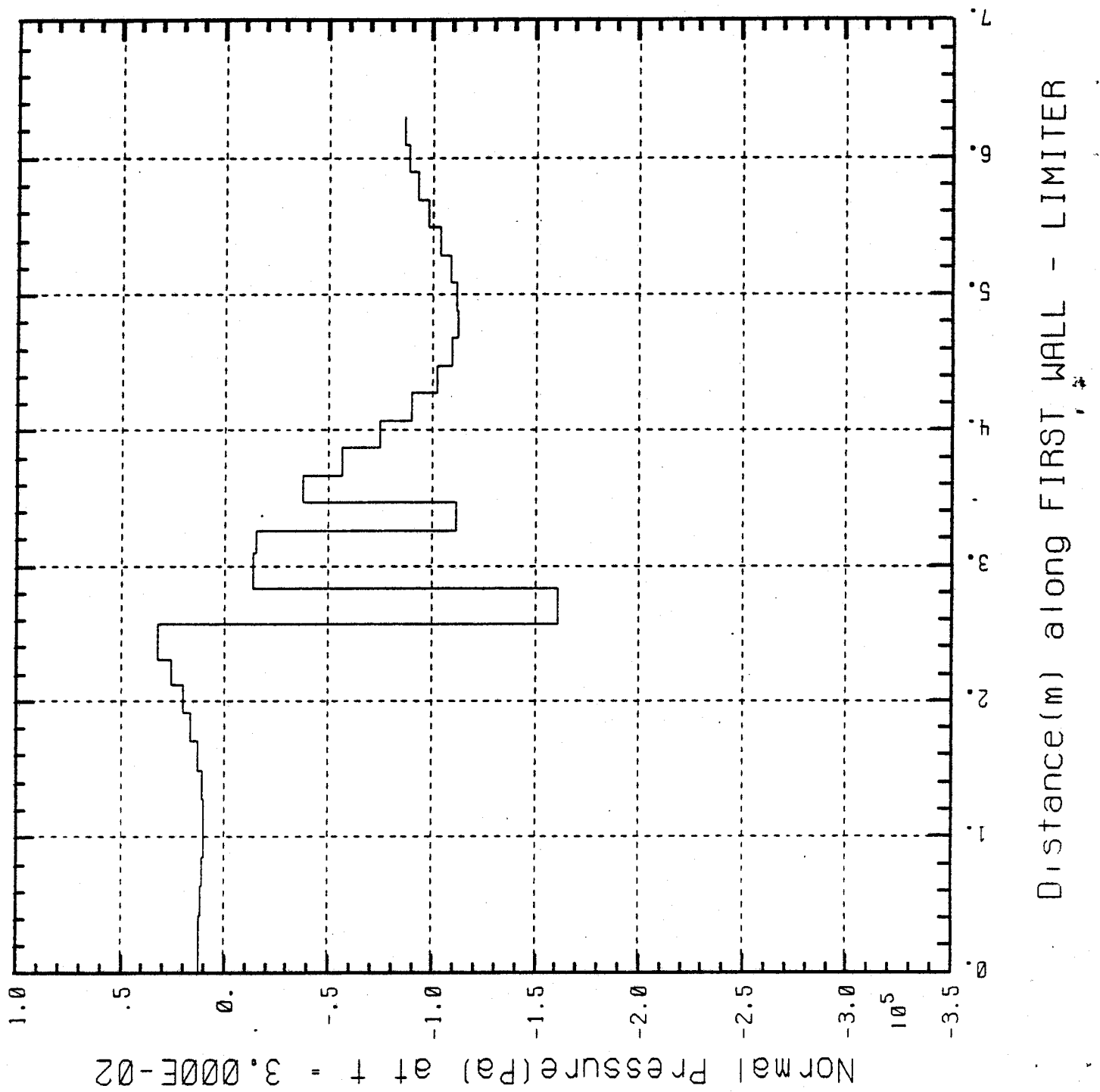


Fig. C-3

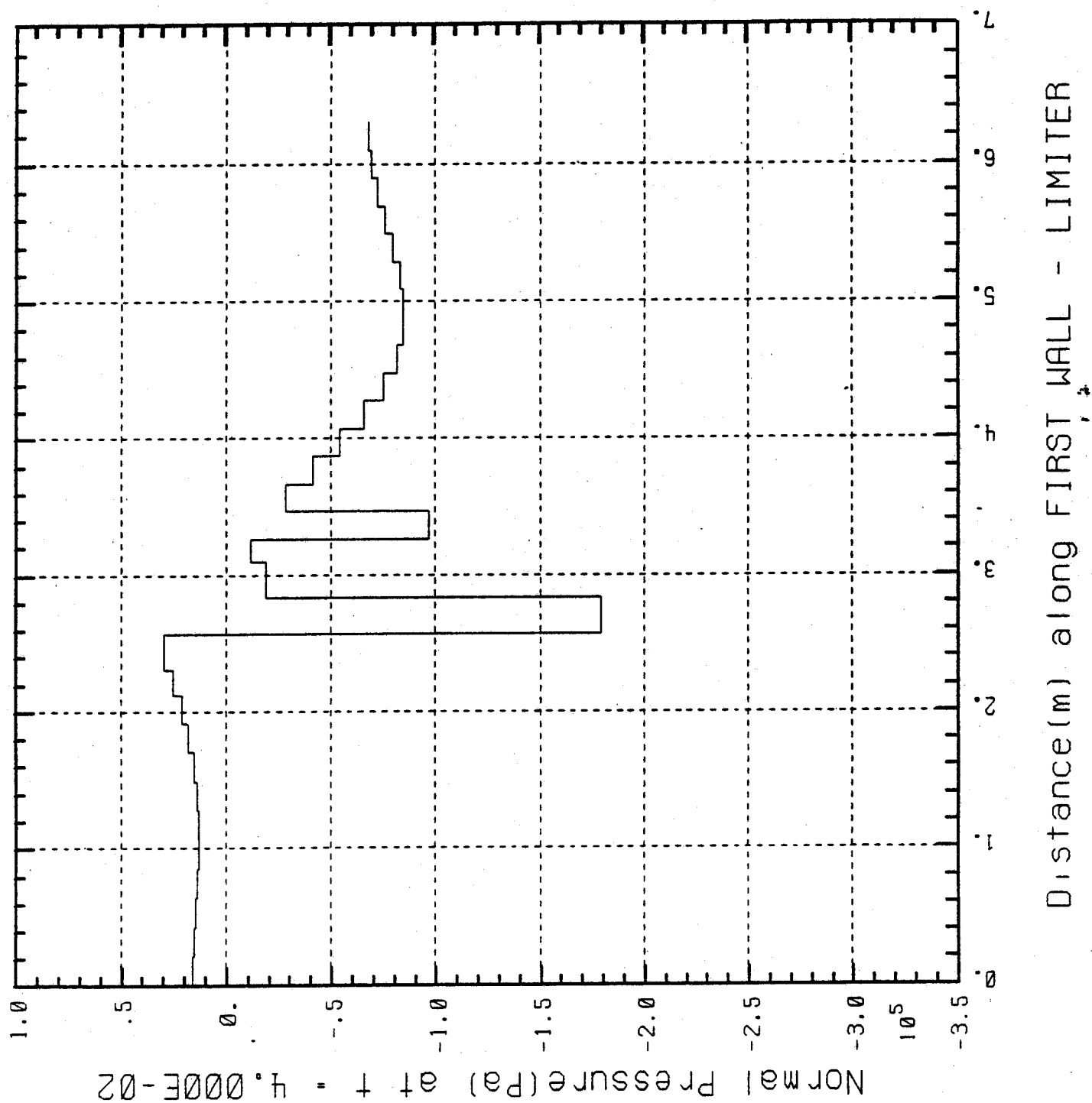


Fig. C-4

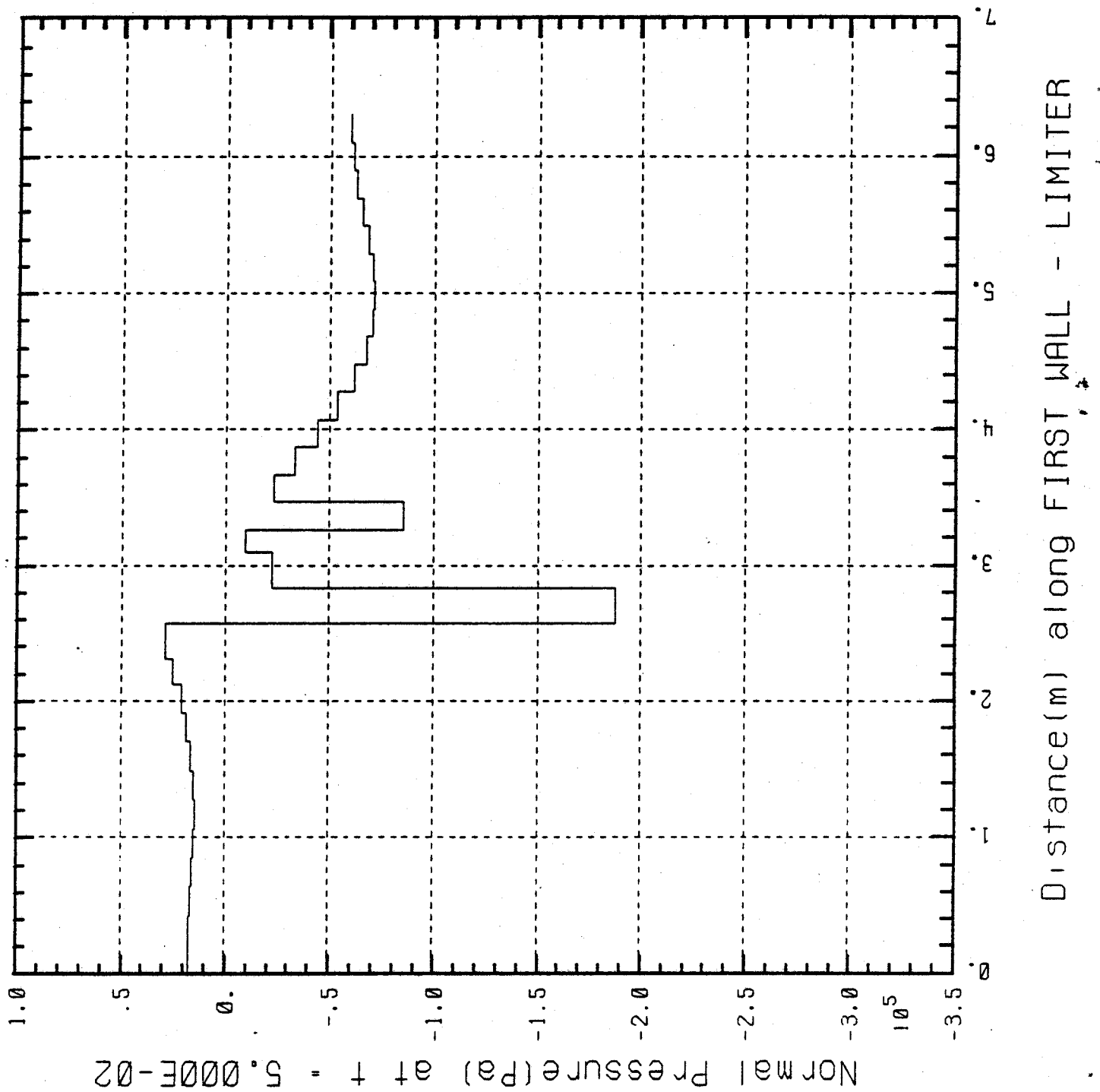


Fig. C-5

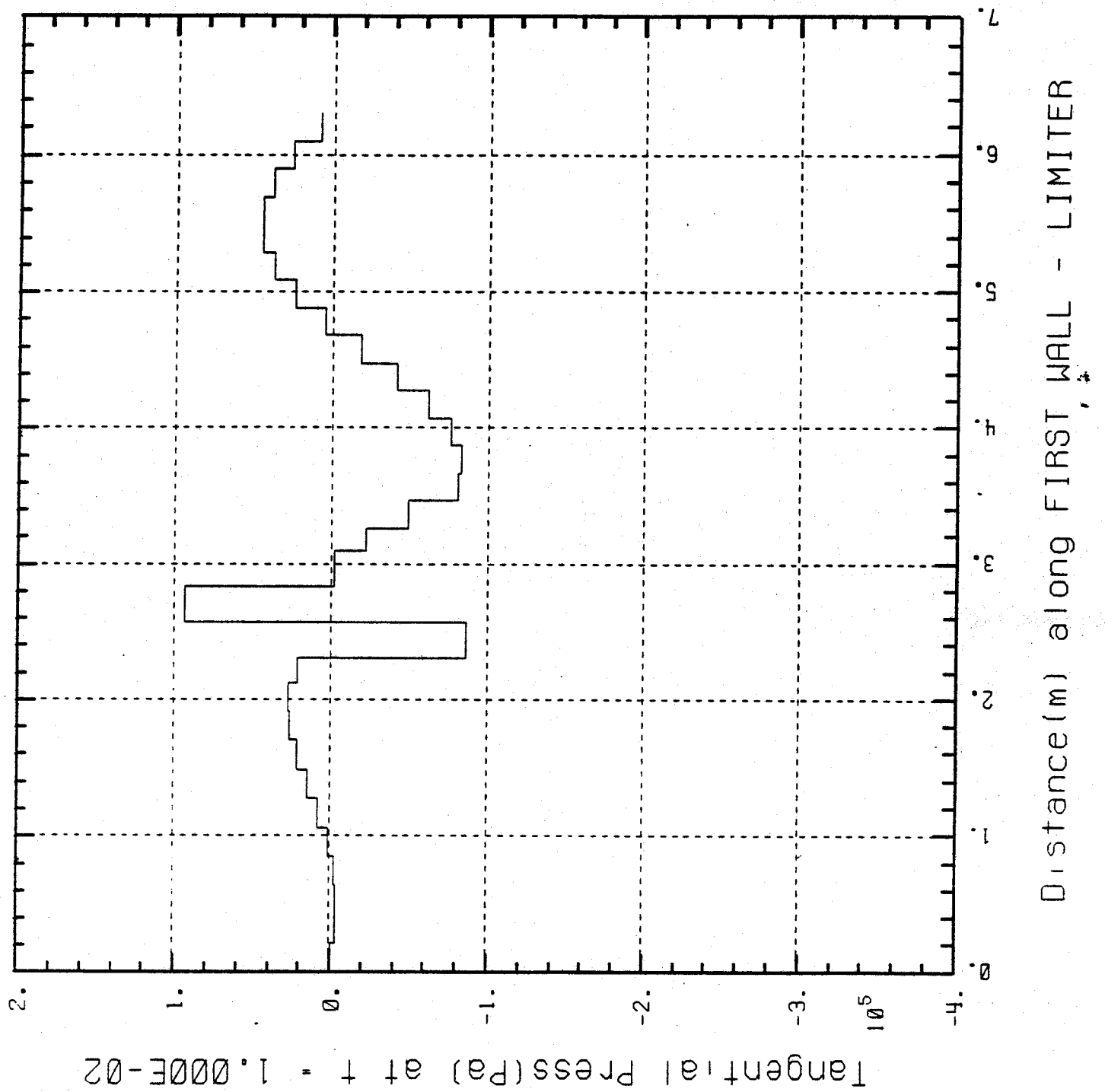


Fig. C-6

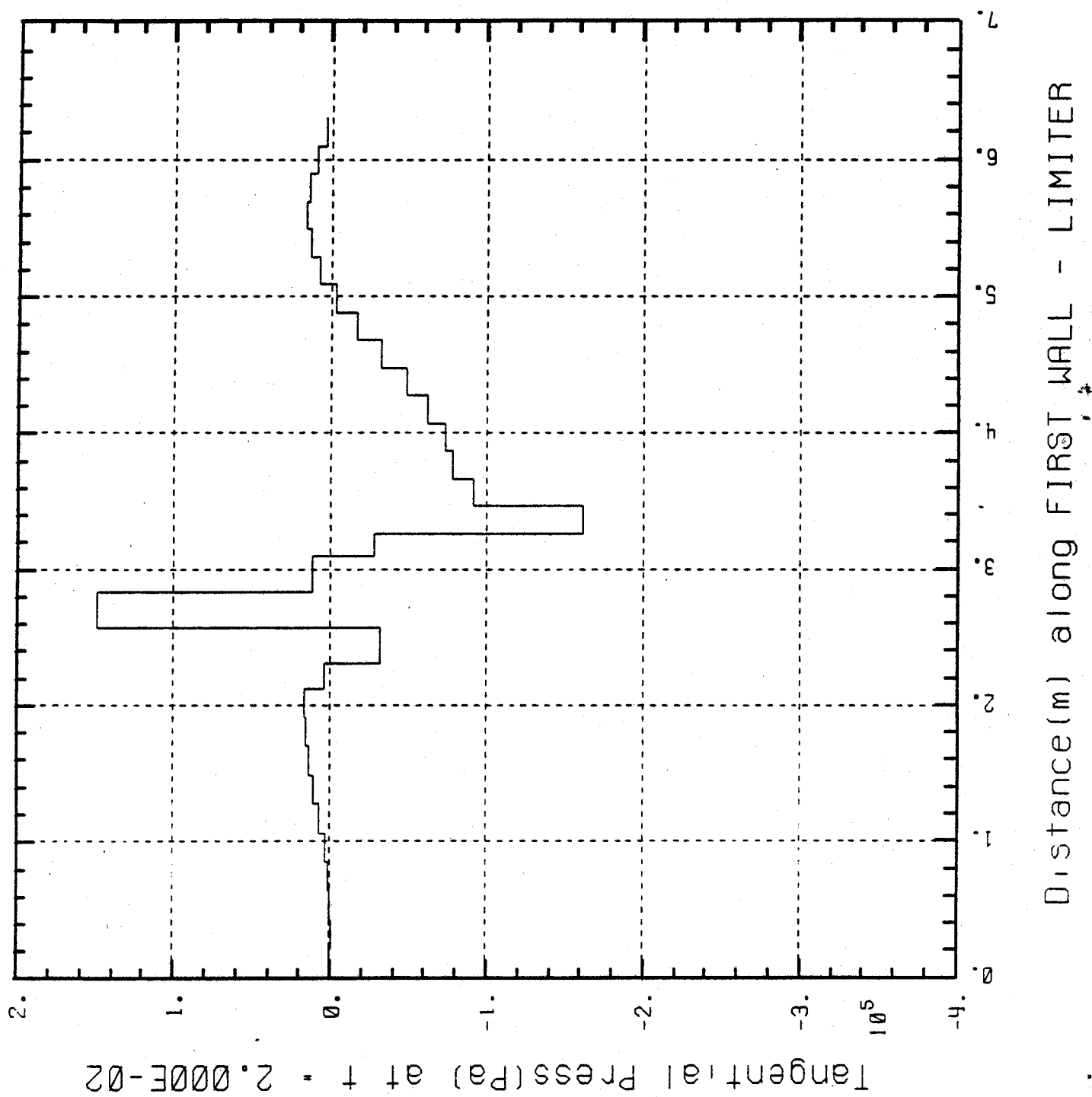


Fig. C-7

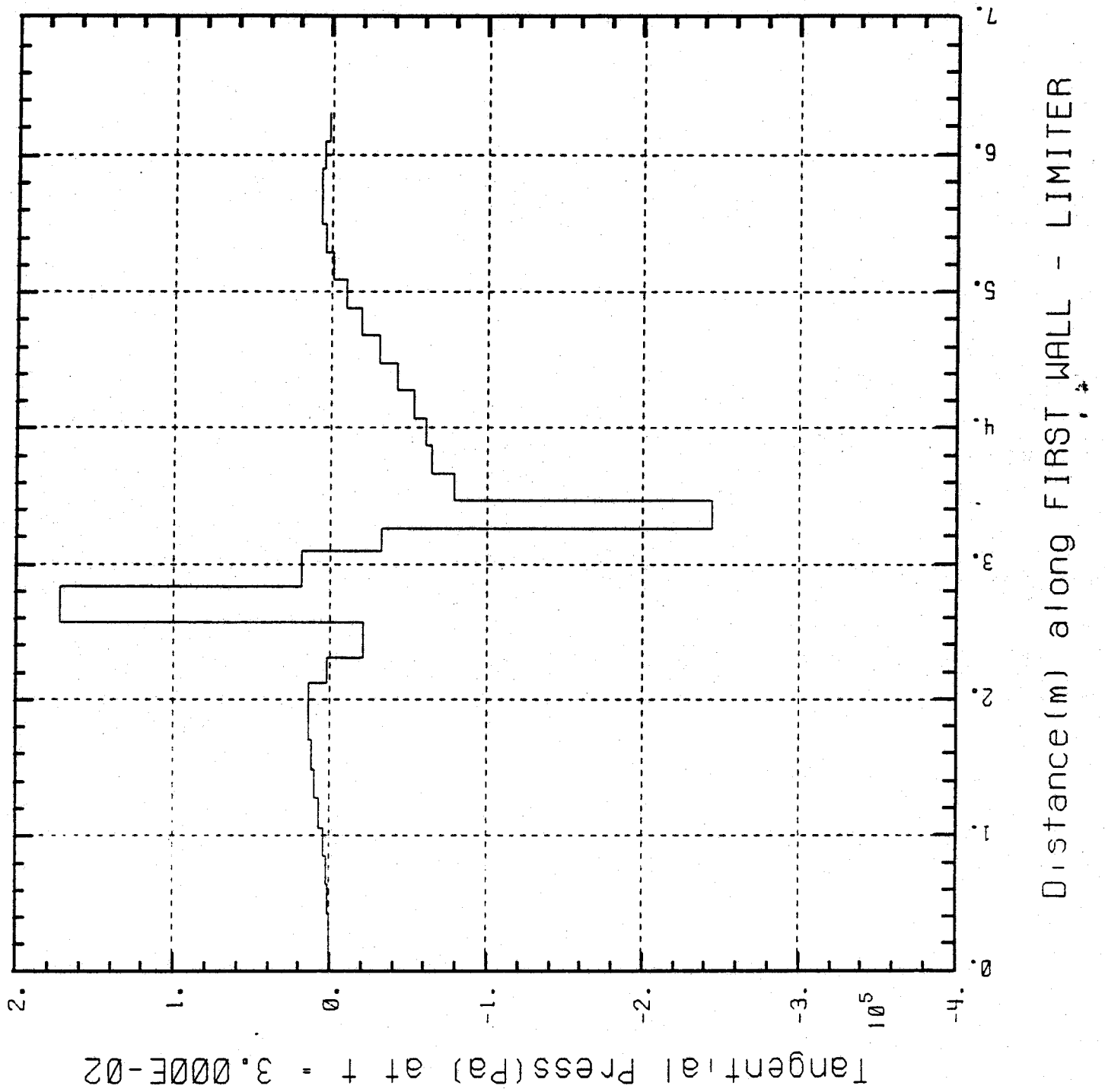


Fig. C-8

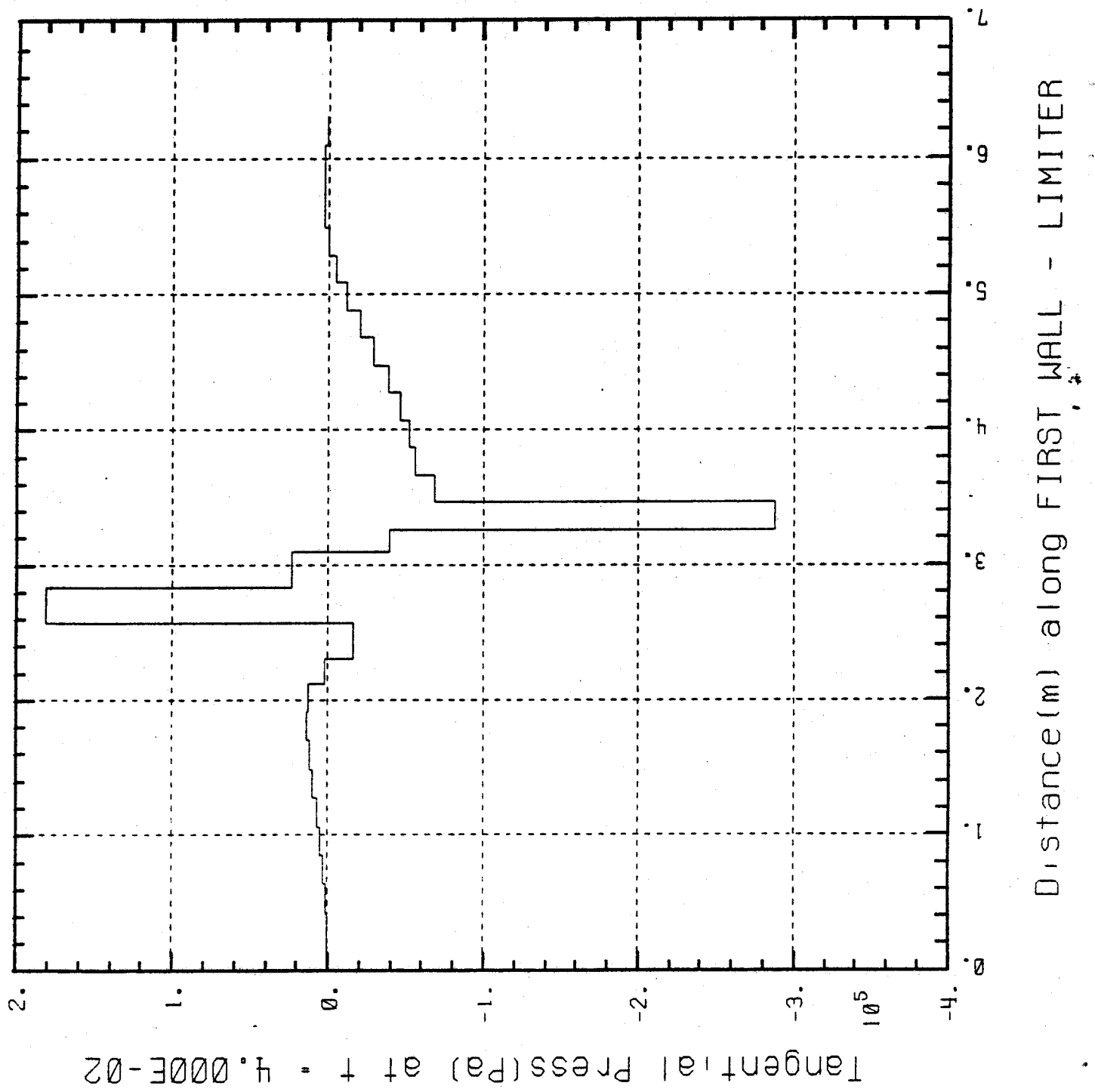


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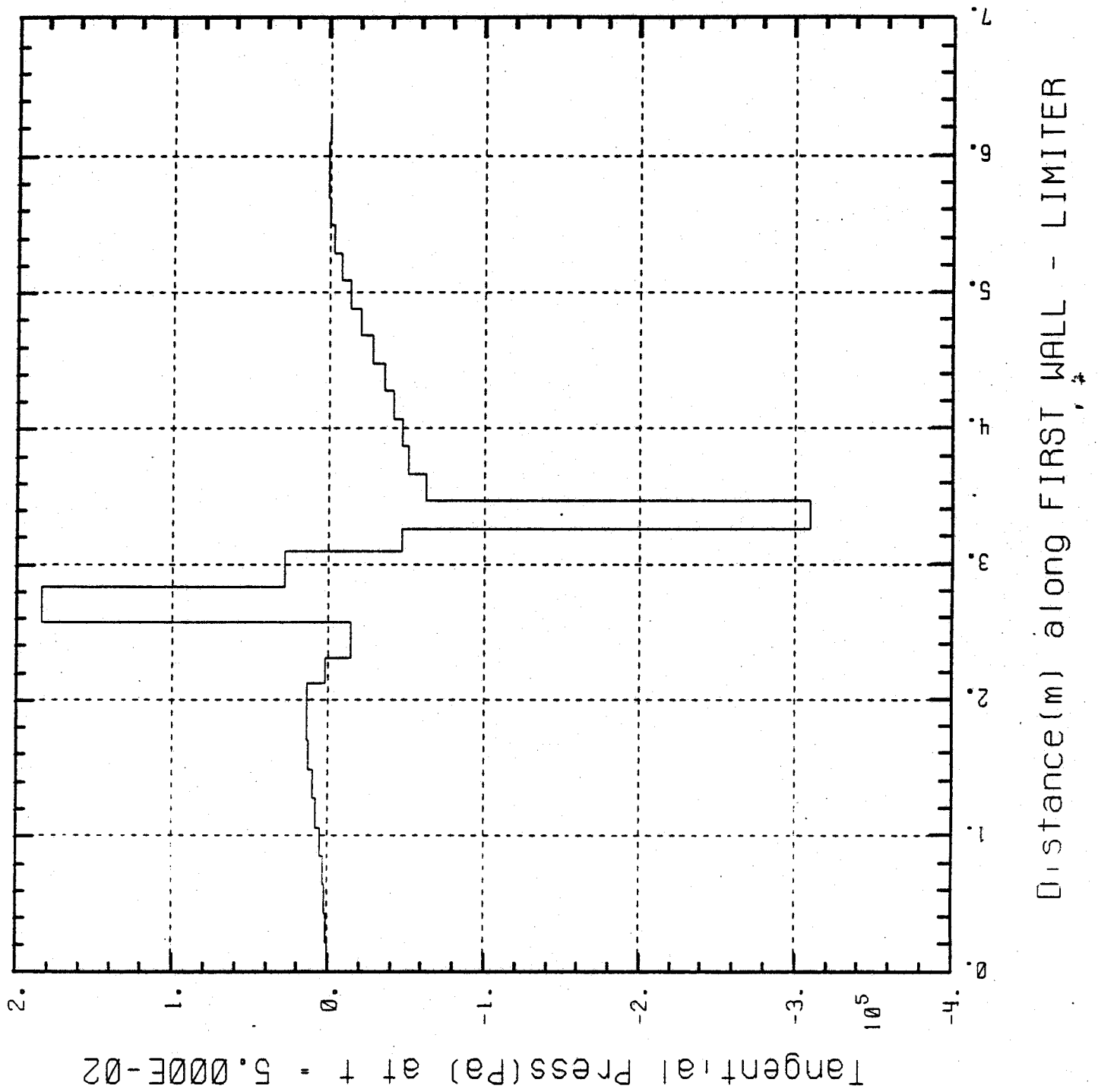


Fig. C-10

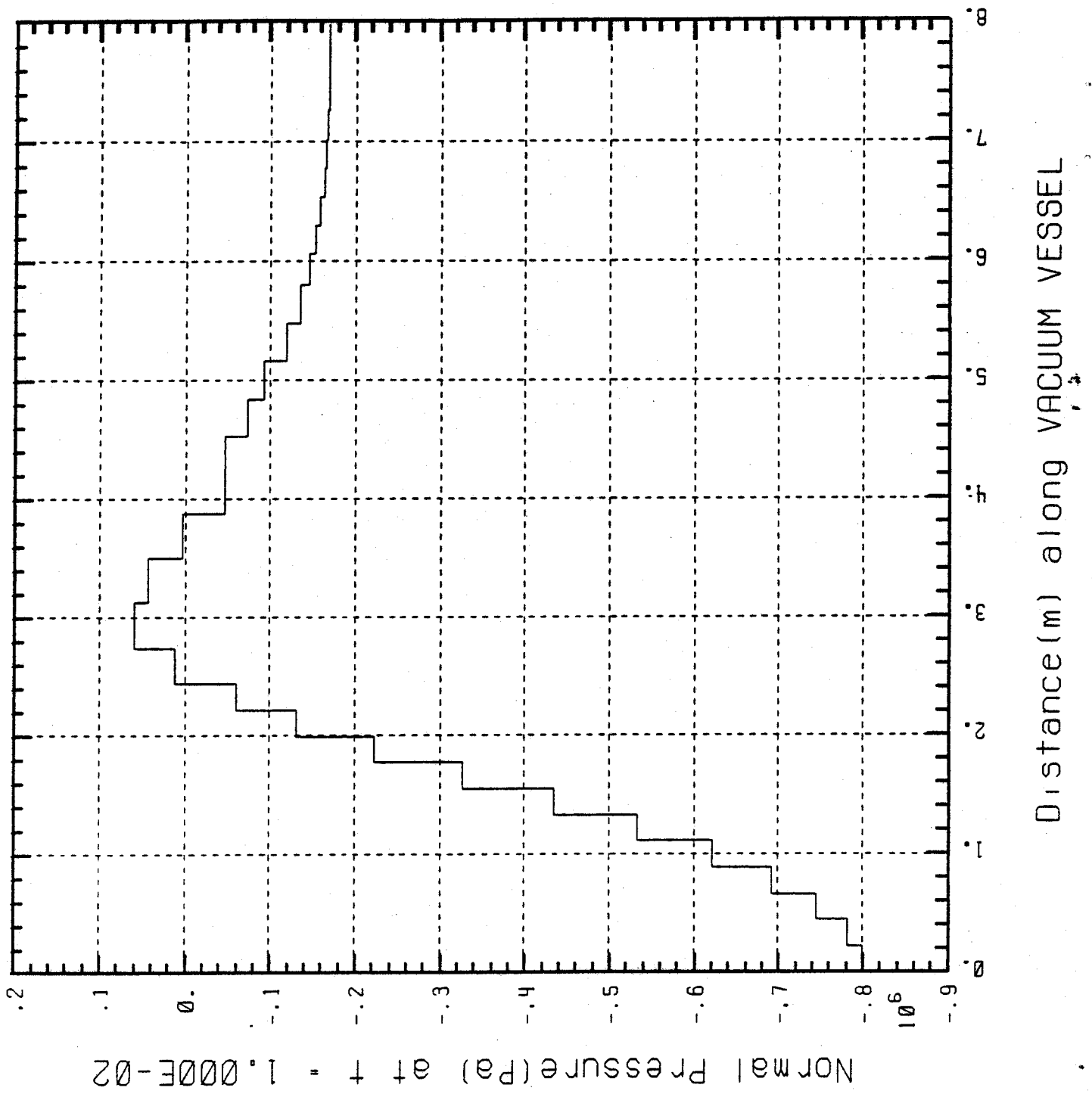


Fig. C-11

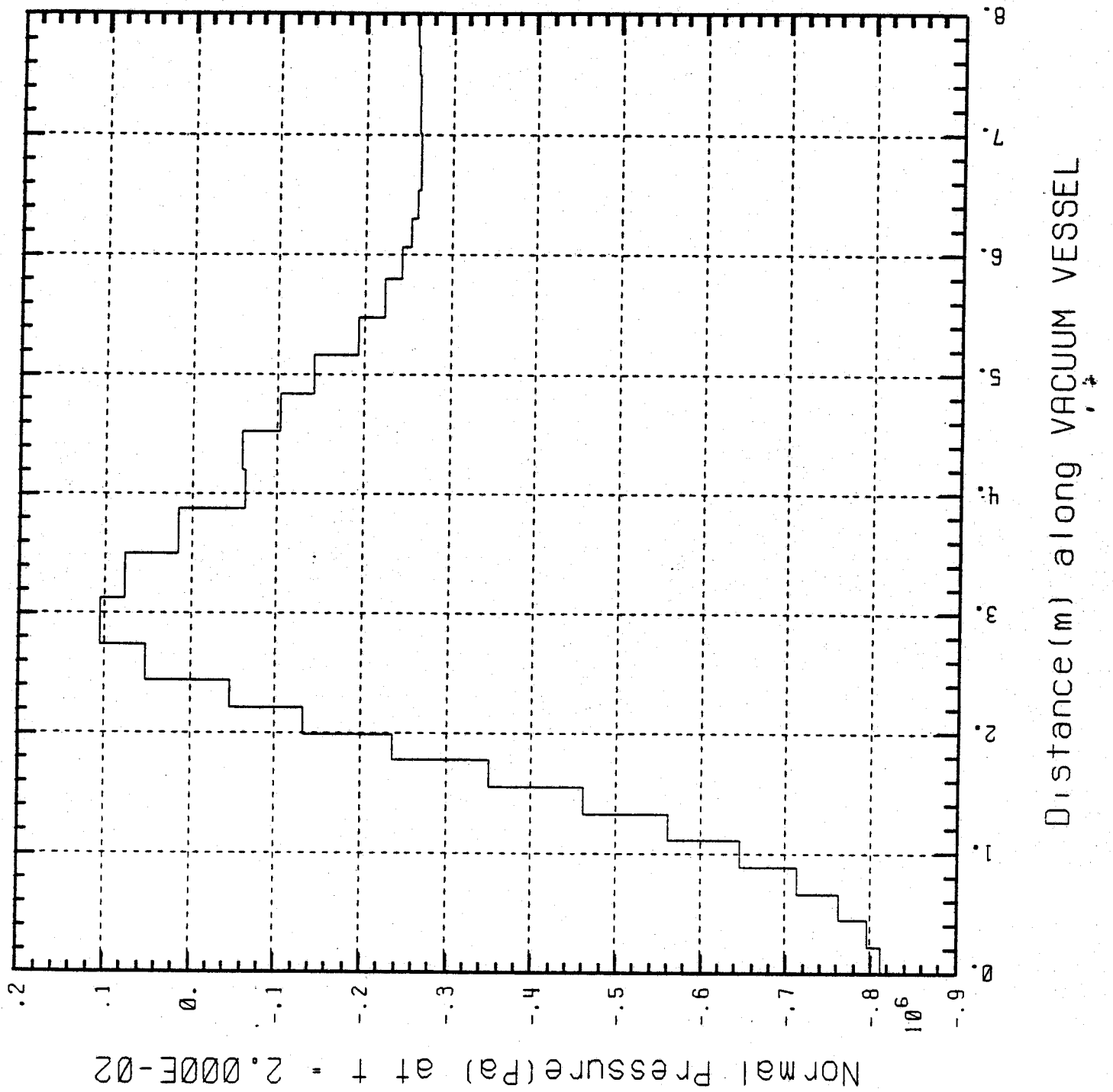


Fig. C-12

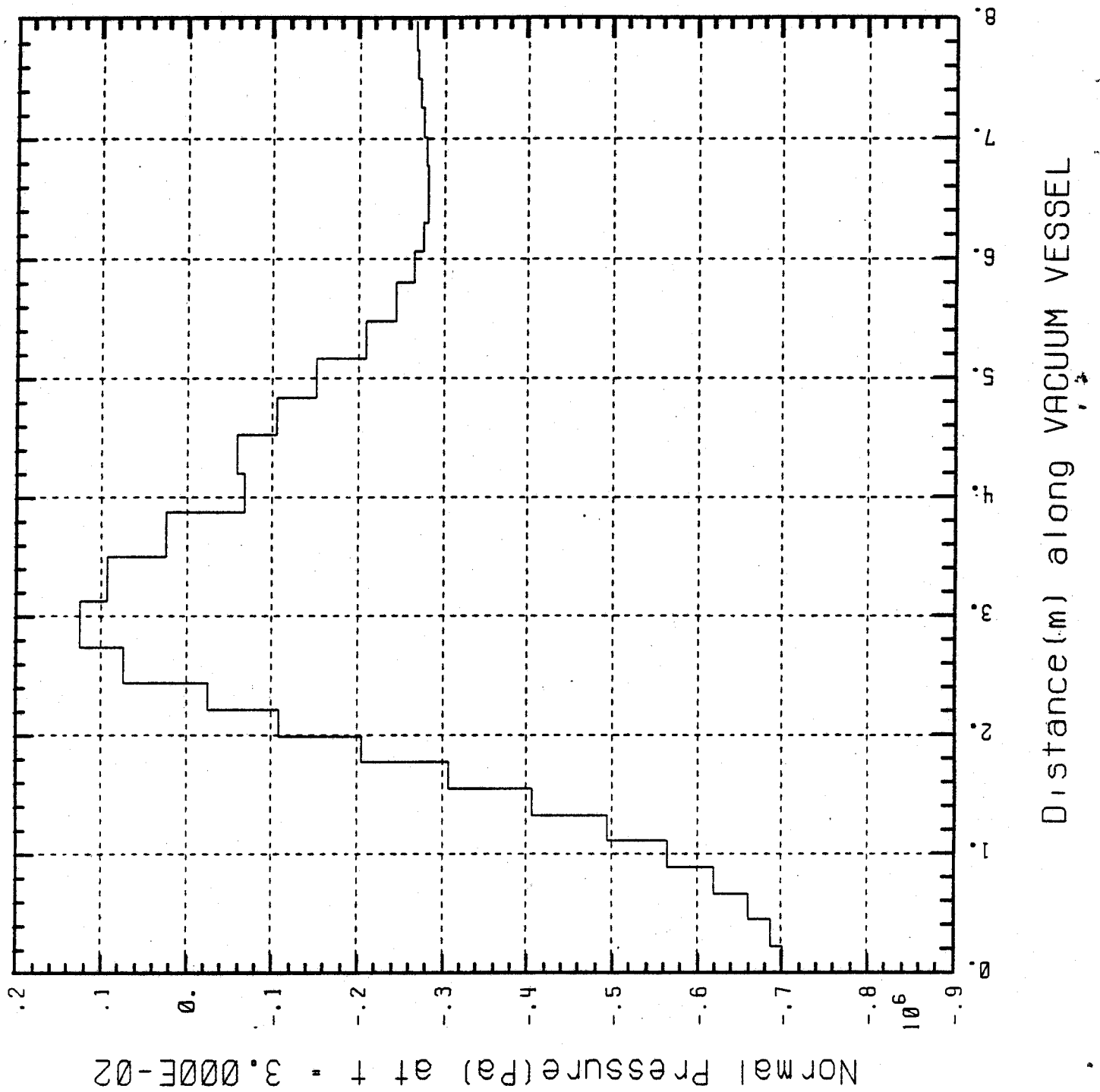


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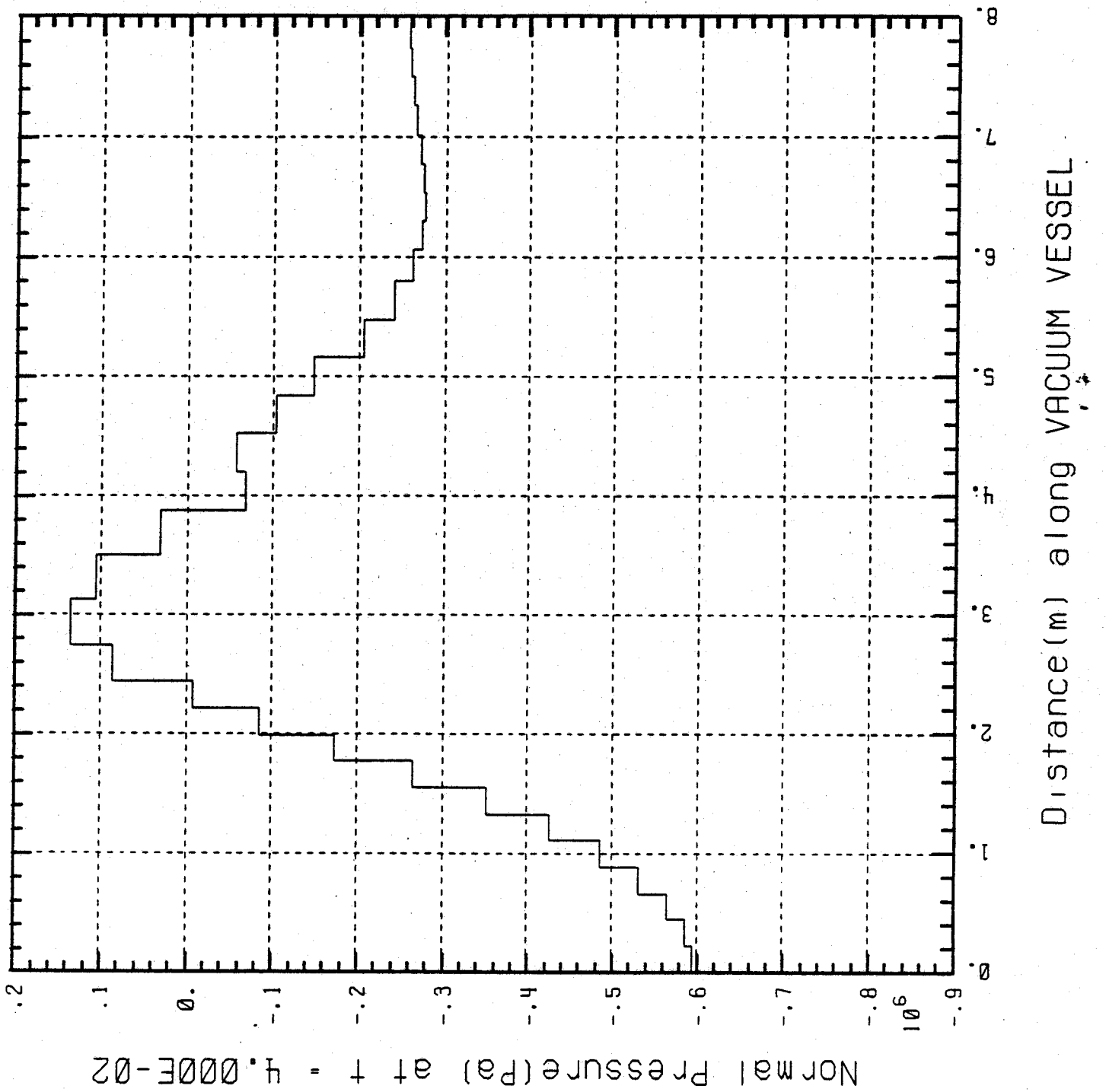


Fig. C-14

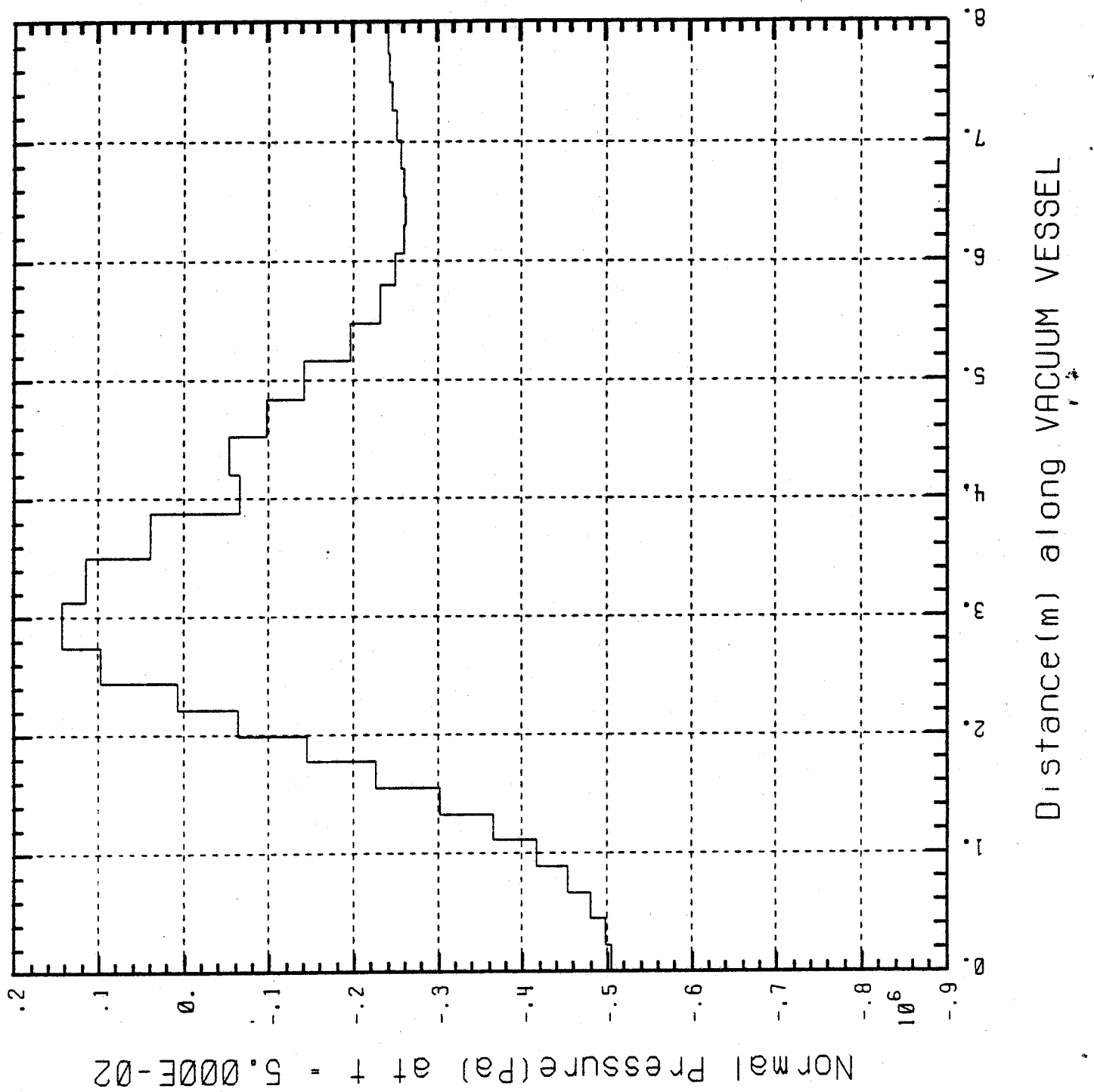


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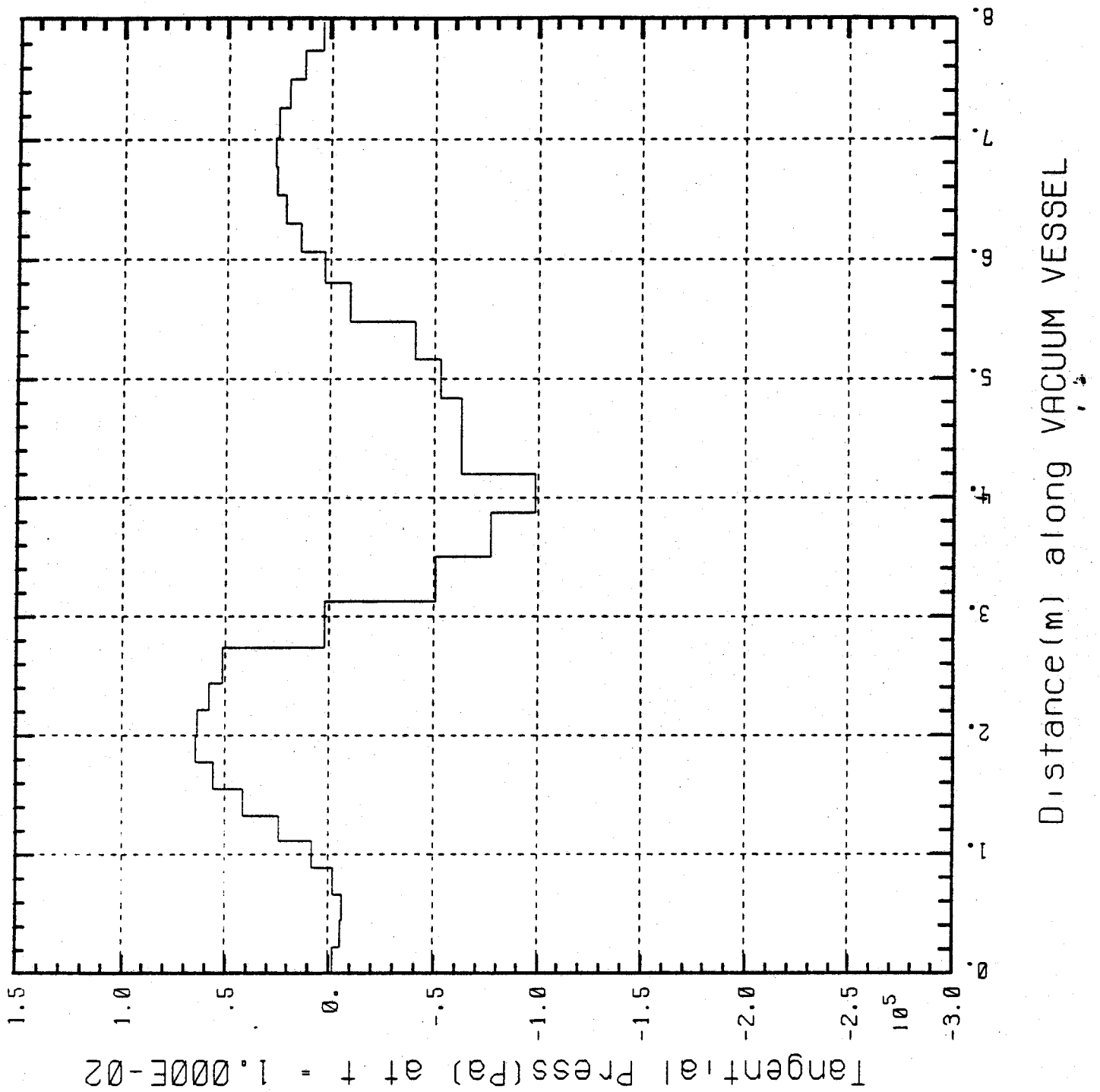


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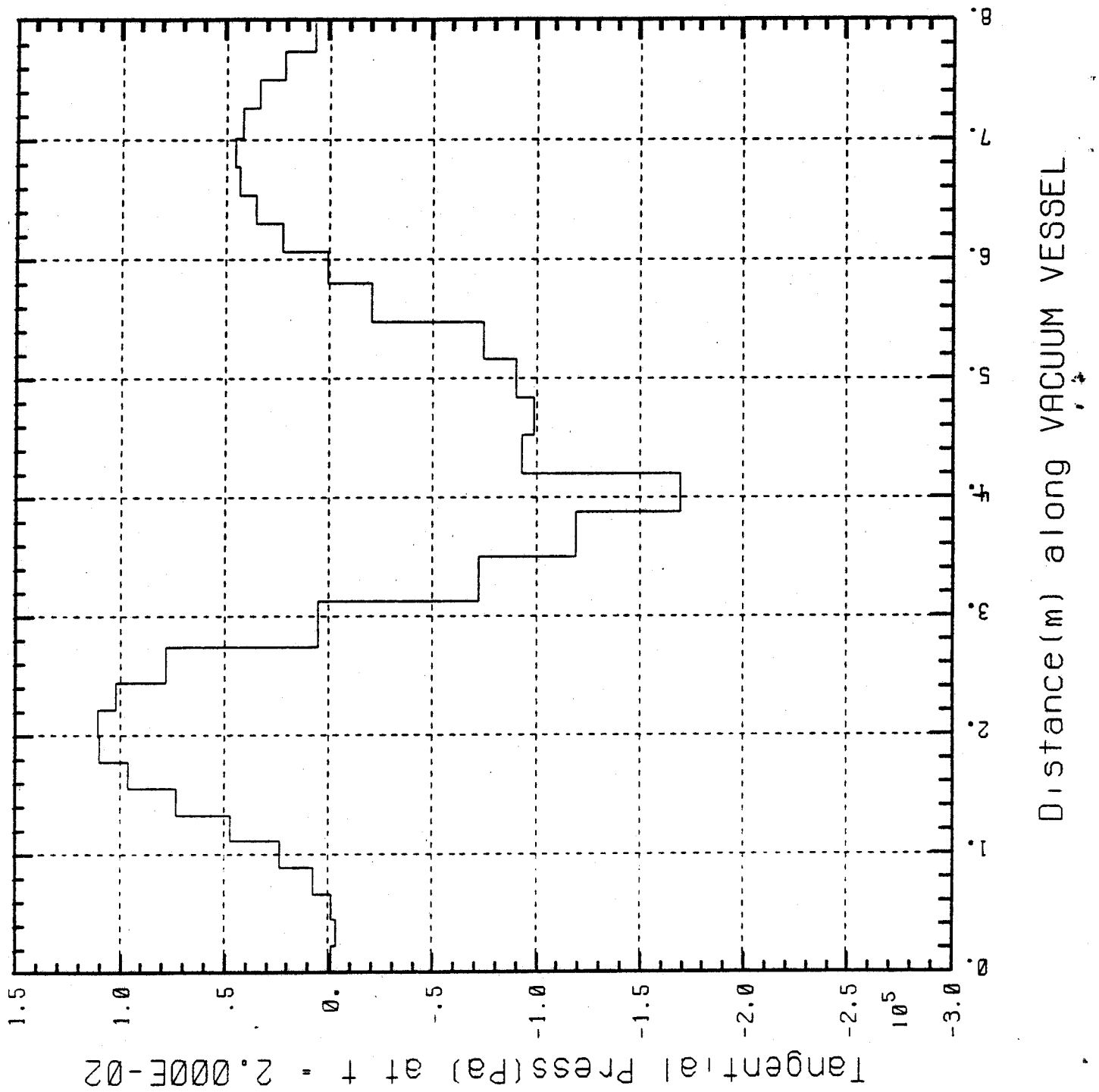


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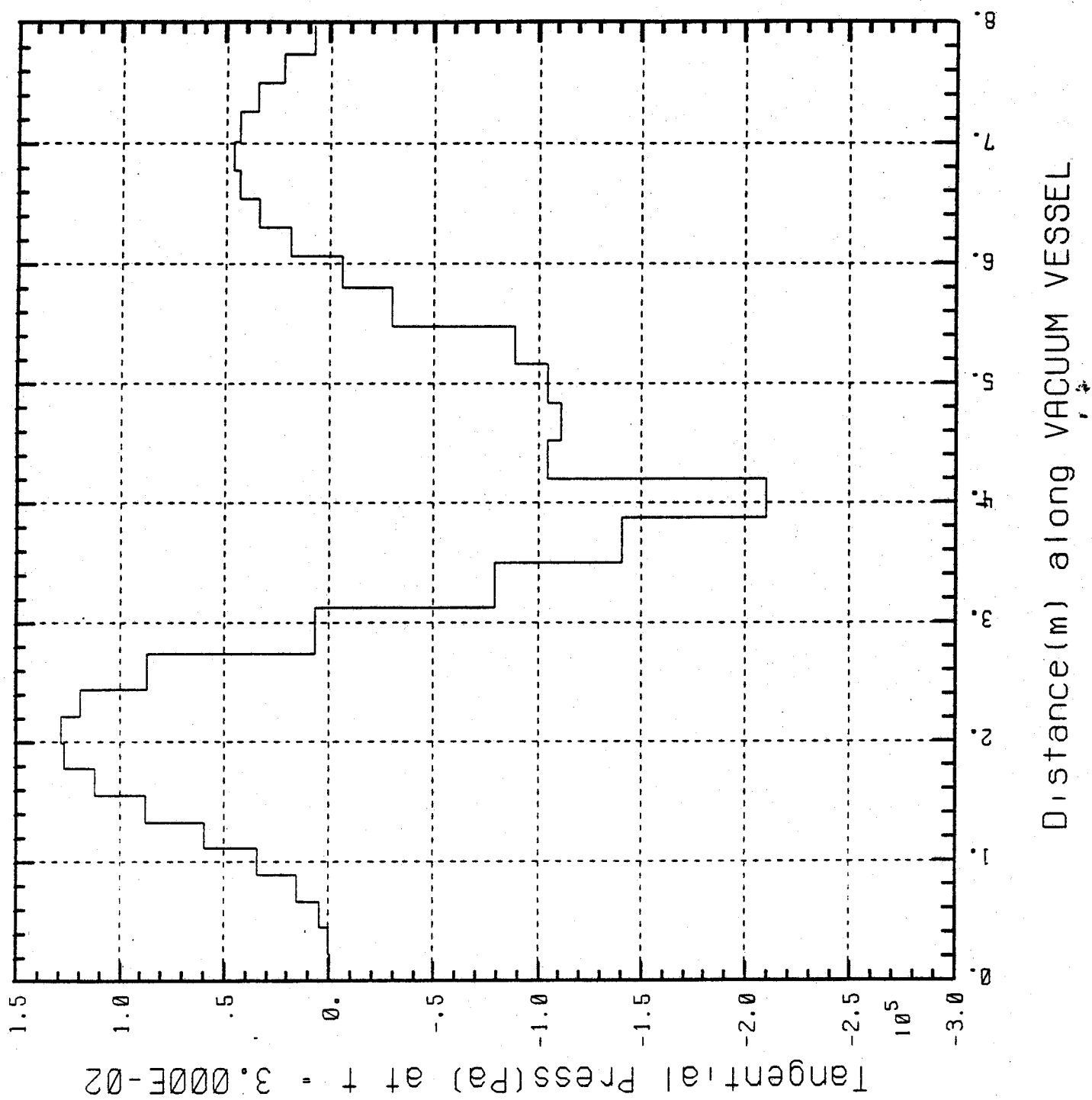


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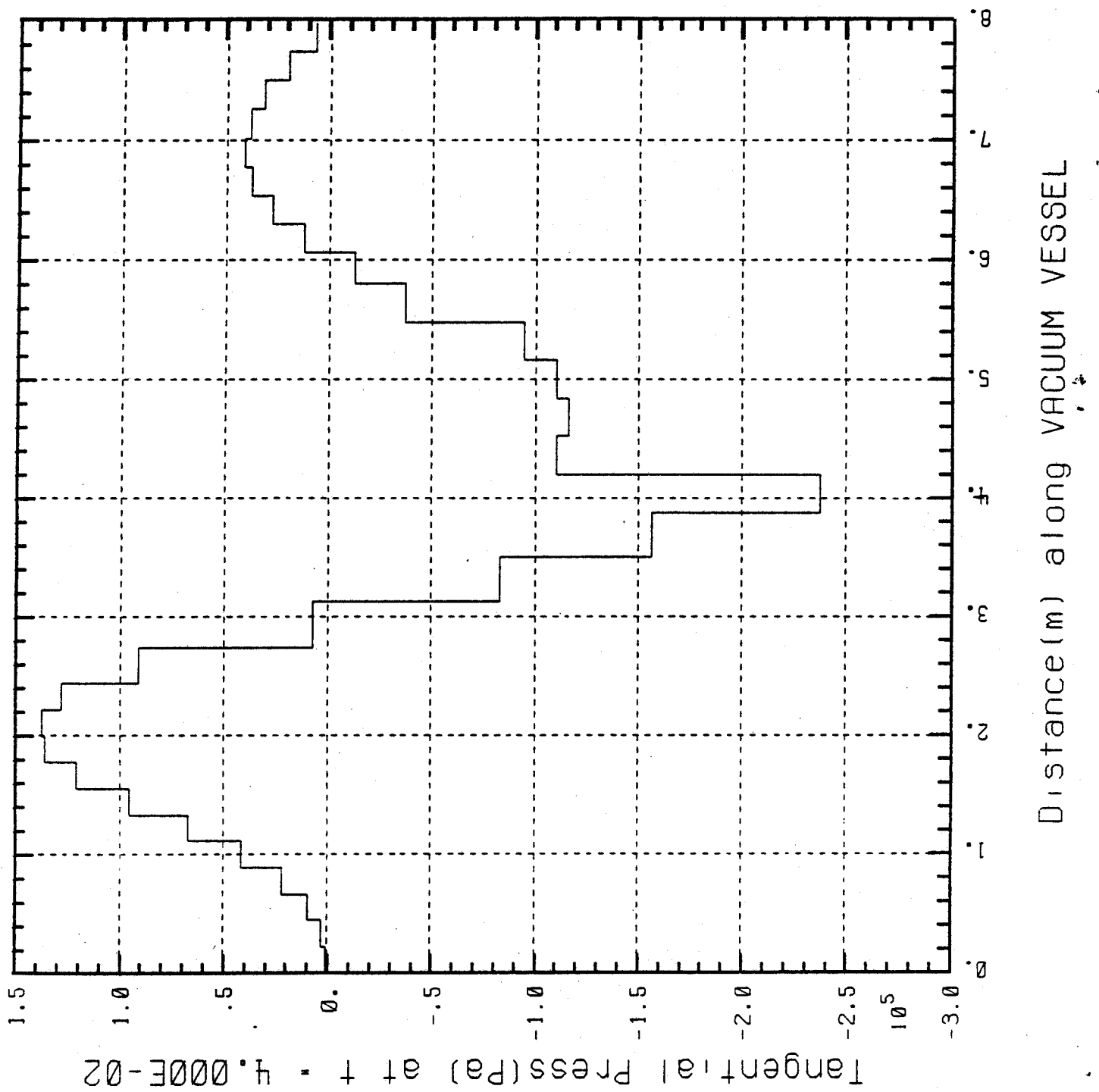


Fig. C-19

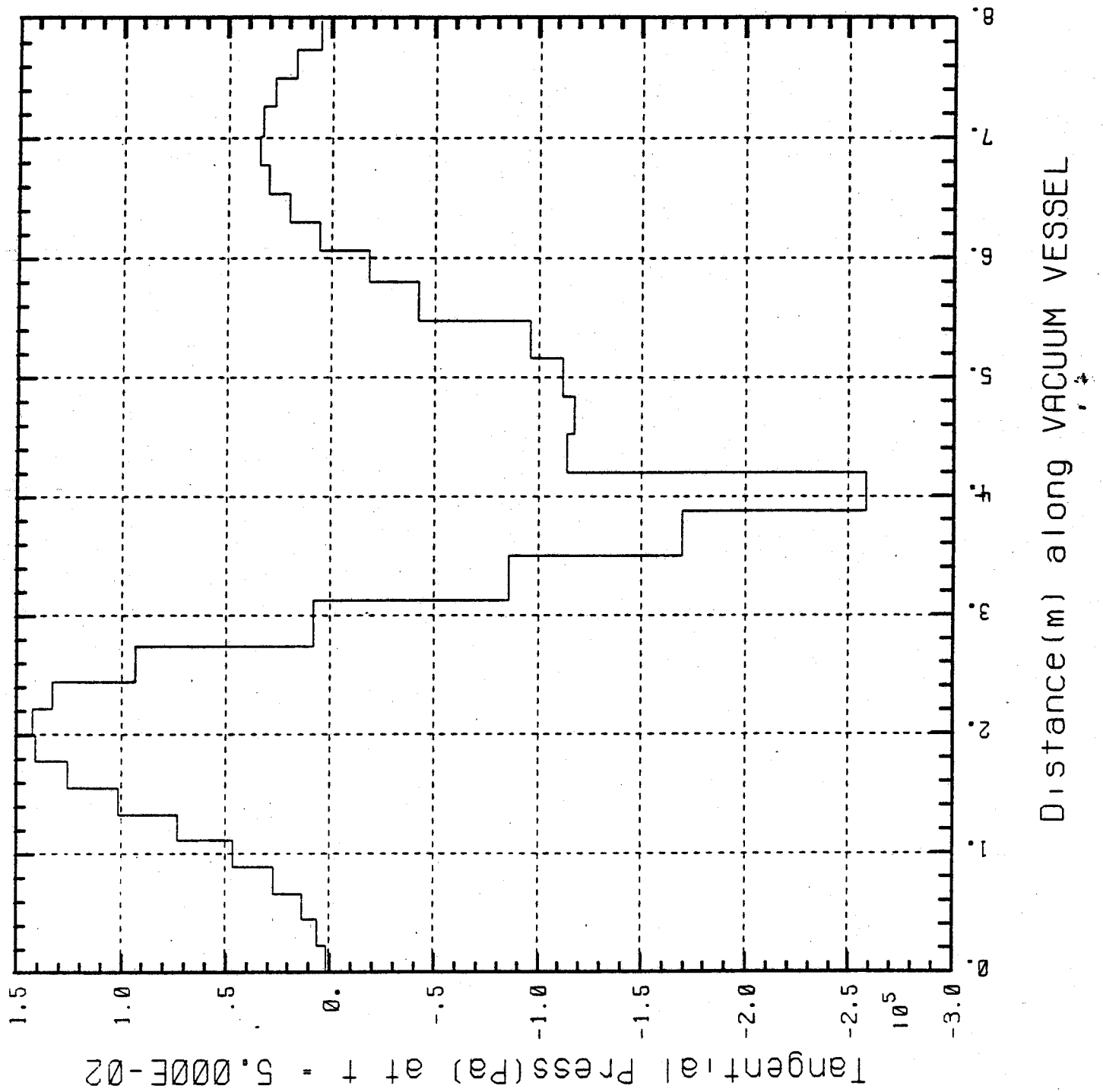


Fig. C-20