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The ATLAS Vacuum System

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Keywords:vacuum, pressure instability, multipacting, ATLAS vacuum chamber

Summary

The static and dynamic pressures in the ATLAS vacuum chamber have been calculated for both the baked and unbaked case. Parts of the chamber which could show pressure instabilities have been identified and solutions proposed. By modifying the present design of the central Be chamber the dynamic vacuum became stable for all gases when baked but was still unstable for CO and CO_2 when unbaked.

1. Introduction

ATLAS is the proposed high luminosity p-p experiment for the Large Hadron Collider (LHC) and it will be installed at point 1 [1].

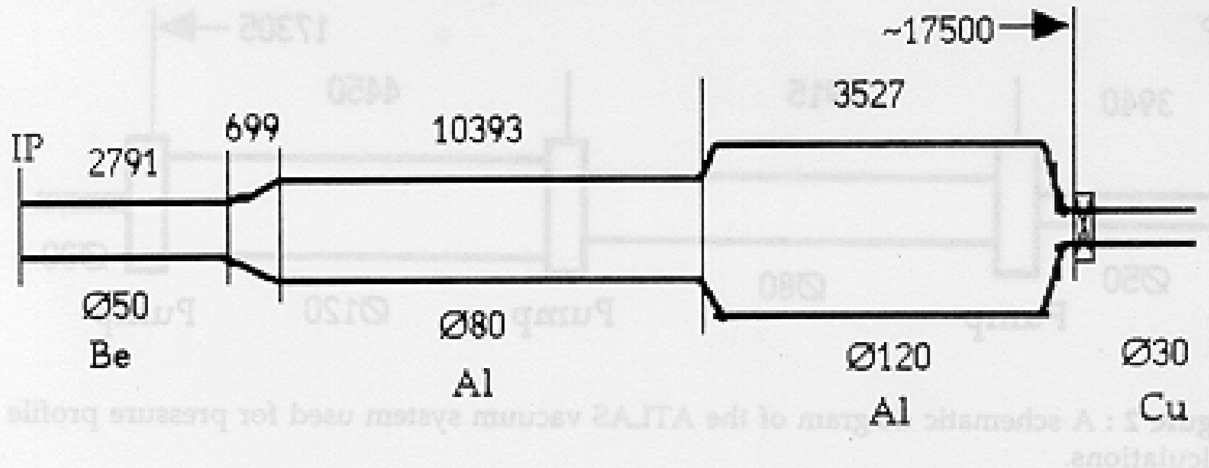

Figure 1 : A schematic diagram of the ATLAS vacuum chamber

The total length of the vacuum chamber is about 35 m between sector valves. The vacuum chamber is shown schematically in Fig. 1 and is divided into three main sections. The first is the central region, covering a distance ± 2.791 m on each side of the interaction point (IP). It is made of Be to provide a good transparency and has an internal diameter of 50 mm. The second two sections are located symmetrically on either side of the IP and are made of circular section Al beam pipes of internal diameter 80 mm joined to the central chamber via conical transitions. The third sections are also located symmetrically on either side of the IP and are made of circular section Al beam pipes of internal diameter 120 mm also joined to the previous chamber via conical transitions. In addition, after the sector valve, on each side, there is a Ø30 mm tube about 3 m long. This tube, for impedance reasons is made of Cu and is buried in a collimator.

2. Pumping System

In order to pump the gases normally found in all-metal ultra high vacuum systems, H_2, CH_4, H_2O, CO and CO_2, the pumping system will consist of a combination of sputter ion pumps and Ti sublimation pumps.

The sputter ion pumps pump all the above gases. The Ti sublimation pumps pump all except CH_4. The pumping speeds required and pumping locations are determined by the required operating pressure and gas composition, the vacuum stability, the constraints of transparency, detector access and the available space.

3. Static Vacuum

No specific pressure requirements have been requested by the ATLAS collaboration. Thus what will be presented here are the pressure profiles and gas composition which can reasonably be expected with and without bakeout for the various gases.

To calculate the pressure profiles in the ATLAS vacuum system it was approximated to a Ø50 central chamber with a Ø80 chamber and a Ø120 chamber on each side with pumps between each as shown in Fig. 2.

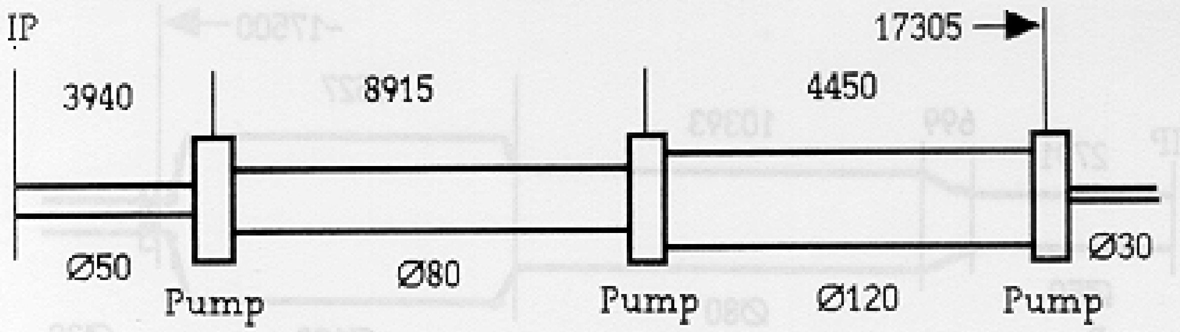

Figure 2 : A schematic diagram of the ATLAS vacuum system used for pressure profile calculations.

In Table 1 are shown the outgassing rates and pumping speeds used in the calculations. The pumping speeds are what can be reasonably installed in the space available and the baked Al outgassing rates are typical of those measured on LEP Al vacuum chambers [2]. As a precaution the baked Be outgassing rates have been taken slightly higher than those of Al since it is not certain that Be can be cleaned as well as Al.

In the unbaked case, the thermal outgassing rates are not well defined quantities since they decrease with pumping time and are dominated by H_2O. In this case we have used outgassing rates measured on an unbaked LEP Al dipole chamber after 100 hours of pumping [2]. After 1000 hours of pumping the values are about a factor of 10 lower. The same outgassing rates were used for unbaked Be.

Table 1

Gas	Pump Speed ($l\ s^{-1}$)	Be Thermal Outgassing Rate ($Torr\ l\ s^{-1}\ cm^{-2}$) Unbaked	Be Baked	Al Thermal Outgassing Rate ($Torr\ l\ s^{-1}\ cm^{-2}$) Unbaked	Al Baked
H_2	200	$7\ 10^{-12}$	$1\ 10^{-12}$	$7\ 10^{-12}$	$5\ 10^{-13}$
CH_4	100	$5\ 10^{-13}$	$1\ 10^{-14}$	$5\ 10^{-13}$	$5\ 10^{-15}$
H_2O	100	$3\ 10^{-10}$	$<1\ 10^{-15}$	$3\ 10^{-10}$	$<1\ 10^{-15}$
CO	100	$5\ 10^{-12}$	$5\ 10^{-14}$	$5\ 10^{-12}$	$1\ 10^{-14}$
CO_2	100	$5\ 10^{-13}$	$5\ 10^{-14}$	$5\ 10^{-13}$	$1\ 10^{-14}$

In Fig. 3, 4, 5, 6 and 7 are shown the pressure profiles for the unbaked system. The average pressures for H_2, CH_4, H_2O, CO and CO_2 were $1.0\ 10^{-9}$ Torr, $1.2\ 10^{-10}$ Torr, $1.1\ 10^{-7}$ Torr, $2.1\ 10^{-9}$ Torr and $2.4\ 10^{-10}$ Torr respectively.

In Fig. 8, 9, 10 and 11 are shown the pressure profiles for the baked system. The average pressures for H_2, CH_4, CO and CO_2 were $1\ 10^{-10}$ Torr, $1.7\ 10^{-12}$ Torr, $9.7\ 10^{-12}$ Torr and $2.4\ 10^{-12}$ Torr respectively.

The results are summarised in Table 2 where, in addition to the pressures, the corresponding gas densities are given for background calculations.

Table 2

Gas	Unbaked Average Pressure (Torr)	Unbaked Average Gas Density (molecules cm-3)	Baked Average Pressure (Torr)	Baked Average Gas Density (molecules cm-3)
H_2	$1.0\ 10^{-9}$	$3.3\ 10^{7}$	$1.0\ 10^{-10}$	$3.3\ 10^{6}$
CH_4	$1.2\ 10^{-10}$	$4.0\ 10^{6}$	$1.7\ 10^{-12}$	$5.6\ 10^{4}$
H_2O	$1.1\ 10^{-7}$	$3.6\ 10^{9}$	$<3\ 10^{-13}$	$<1\ 10^{4}$
CO	$2.1\ 10^{-9}$	$6.9\ 10^{7}$	$9.7\ 10^{-12}$	$3.2\ 10^{5}$
CO_2	$2.4\ 10^{-10}$	$7.9\ 10^{6}$	$1.4\ 10^{-11}$	$4.6\ 10^{5}$

4. Dynamic Vacuum

The possibility of the occurrence of ion induced pressure instability [3] and bunch induced multipactoring [4] has been evaluated when the nominal current of 0.536 mA of protons at 7.0 TeV have been stored in the LHC.

The quantity of interest in the ion induced pressure instability is the so-called critical current, ηI_c, which is defined as the product of the ion induced gas desorption yield η (molecules /ion) and the beam current I(A). At beam currents greater than the critical current the vacuum is unstable and large runaway pressure increases are produced.

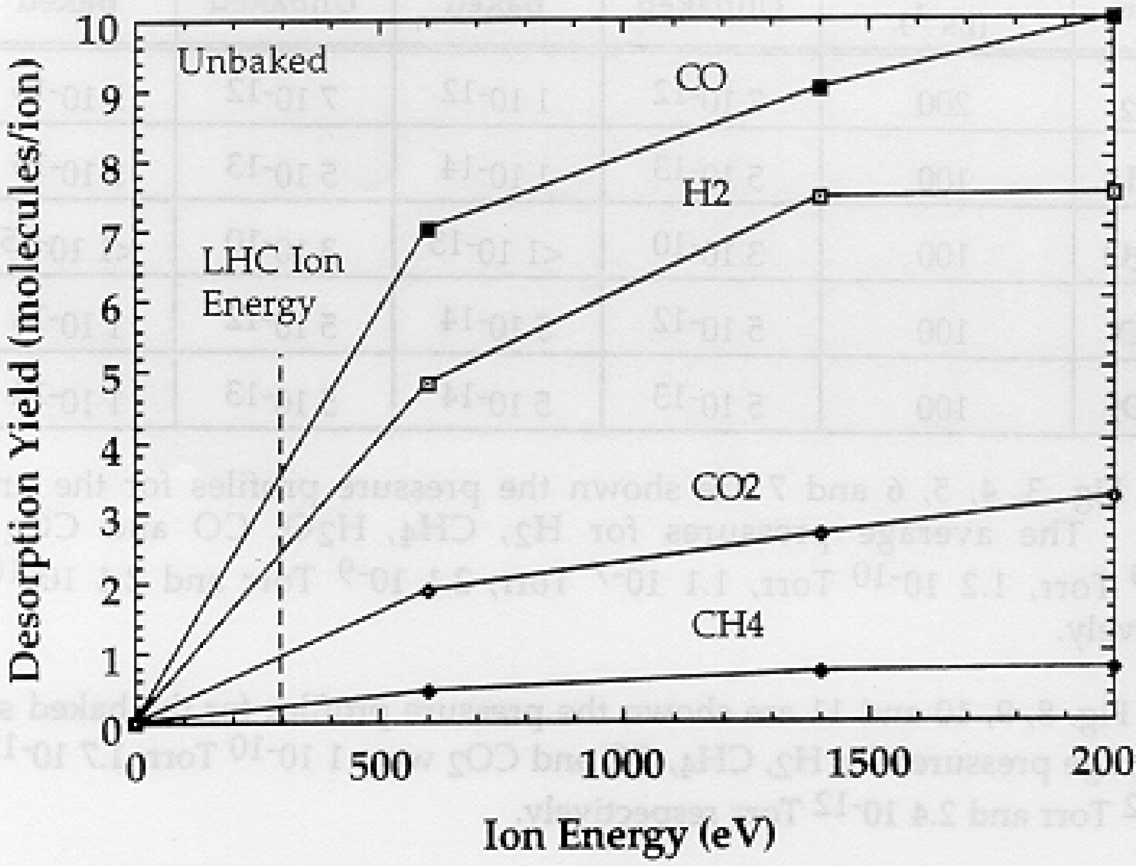

Figure 12 : The ion induced desorption yield for H_2, CH_4, CO and CO_2 for unbaked surfaces.

The ion induced desorption yield η depends on the ion energy which in the LHC is about 300 eV. In Figures 12 and 13 are shown typical ion induced desorption yields for unbaked and baked vacuum chamber material surfaces. There it can be seen that for an unbaked surface at 300 eV the largest yields are for CO (3.6 mol. ion^{-1}), and H_2 (2.4 mol. ion^{-1}) followed by CO_2 (1.0mol. ion^{-1}) and finally CH_4 (0.2 mol. ion^{-1}).

For a baked surface at 300 eV the largest yields are for H_2 (1.2 mol. ion^{-1}), and CO (1.0 mol. ion^{-1}) followed by CH_4 (0.08 mol. ion^{-1}) and finally CO_2 (0.05 mol. ion^{-1}).

These are the values which will be used in verifying the stability of the vacuum system.

In the IP's the two proton beams are in the same chamber therefore the beam current I used in the stability criterion is 1.07 A (2 x 0.536 A).

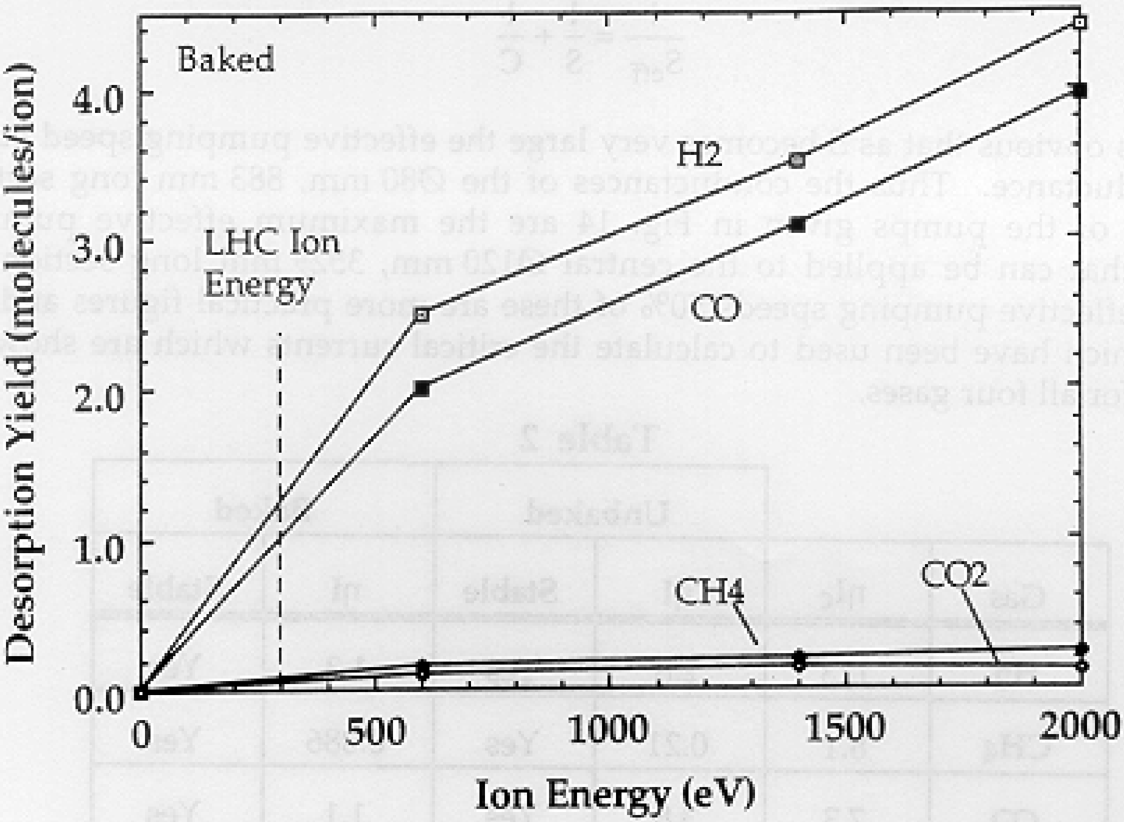

Figure 13 : The ion induced desorption yield for H_2, CH_4, CO and CO_2 for baked surfaces.

For bunch induced multipactoring, where a resonant effect with electrons driven by the positively charged bunched proton beam desorbs gas from the walls of the vacuum chamber, it is the threshold beam current above which the effect may occur which is important.

4.1 The Ø120 mm Al Chambers

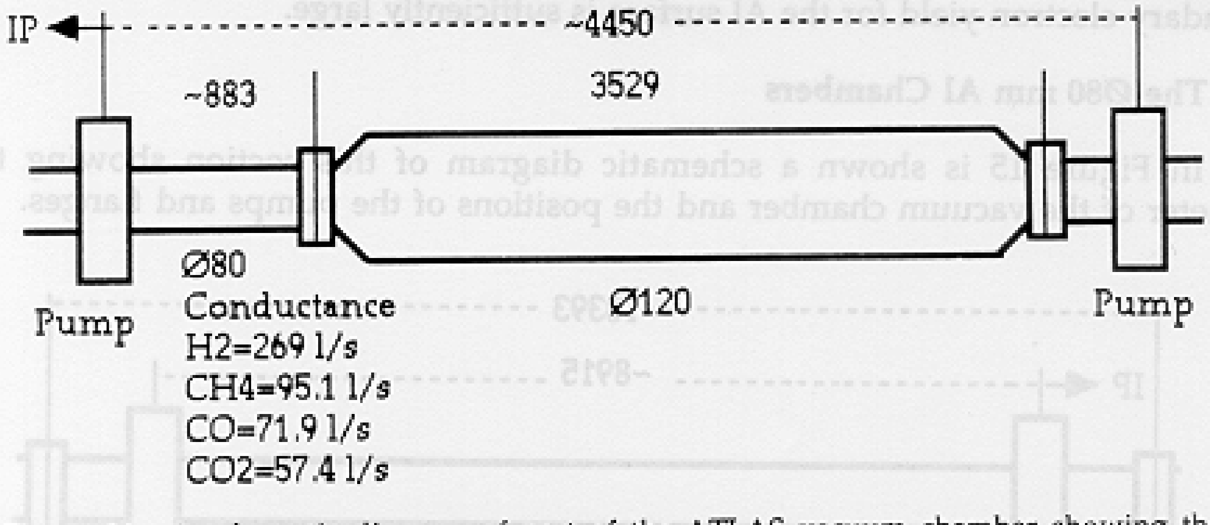

Figure 14 : A schematic diagram of part of the ATLAS vacuum chamber showing the chamber diameters and the positions of the pumps.

In Figure 14 is shown a schematic diagram of this section showing the positions of the pumps and flanges.

The system in Fig. 14 is somewhat complicated in that the chamber between the pumps changes cross-section making an exact calculation of the ηI_c difficult.

For a pumping speed S (ls-1) and a conductance C (ls-1) connected in series, as is the case here, the effective pumping speed S_{eff} (ls-1) is given by:

$$\frac{1}{S_{eff}} = \frac{1}{S} + \frac{1}{C}$$

It is obvious that as S becomes very large the effective pumping speed equals the conductance. Thus the conductances of the Ø80 mm, 883 mm long sections in front of the pumps given in Fig. 14 are the maximum effective pumping speeds that can be applied to the central Ø120 mm, 3529 mm long section. In reality, effective pumping speeds 50% of these are more practical figures and it is these which have been used to calculate the critical currents which are shown in Table 2 for all four gases.

Table 2

		Unbaked		Baked	
Gas	ηI_c	ηI	Stable	ηI	Stable
H_2	173	2.6	Yes	1.3	Yes
CH_4	8.1	0.21	Yes	0.086	Yes
CO	7.3	3.8	Yes	1.1	Yes
CO_2	4.0	1.07	Yes	0.05	Yes

There it can be seen that this section is always stable for all gases in both the unbaked and baked states with a reasonable margin of security.

The current threshold for bunch induced multipacting in the Ø120 mm chamber was calculated to be 87 mA and therefore could be a problem if the secondary electron yield for the Al surface is sufficiently large.

4.2 The Ø80 mm Al Chambers

In Figure 15 is shown a schematic diagram of this section showing the diameter of the vacuum chamber and the positions of the pumps and flanges.

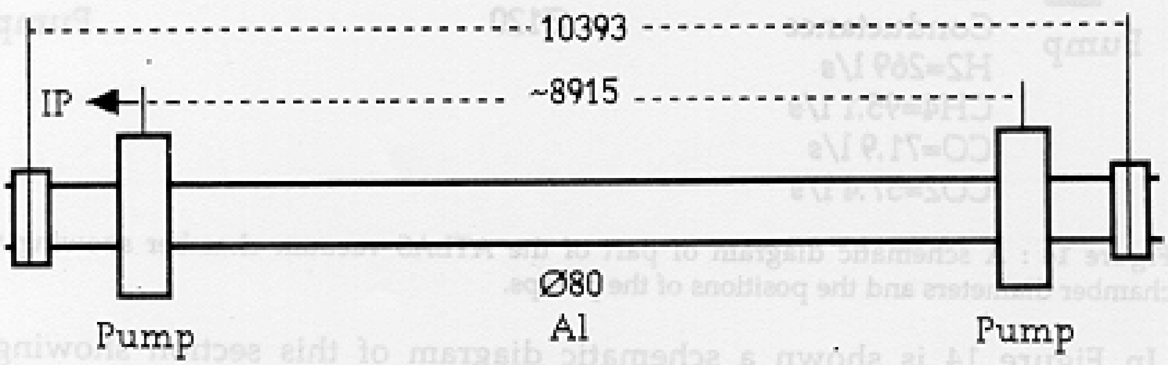

Figure 15 : A schematic diagram of part of the ATLAS vacuum chamber showing the chamber diameter and the positions of the pumps.

The results of the calculations of the vacuum stability are shown in Table 3 where a pumping speed of 200 ls^{-1}, a reasonable upper limit of what can be installed in practice, was used.

There it can be seen that, in the unbaked situation, at 7.0 TeV and 0.536 A, the vacuum is unstable for CO and just stable for CO_2 with almost no reserve.

For the baked case the system is stable for all gases.

Table 3

Gas	ηI_c	Unbaked ηI	Unbaked Stable	Baked ηI	Baked Stable
H_2	33.6	2.6	Yes	1.3	Yes
CH_4	2.5	0.21	Yes	0.086	Yes
CO	2.4	3.8	No	1.1	Yes
CO_2	1.4	1.07	Just	0.05	Yes

The dependence of the calculated critical current ηI_c for CO in this section on the distance between pumps for various pumping speeds is shown in Fig. 16. There it can be seen that increasing the pumping speed does little to improve the situation. To get a reasonable safety margin some extra pumping would have to be installed between the two existing pumps giving a distance of about 4.5 m between pumps.

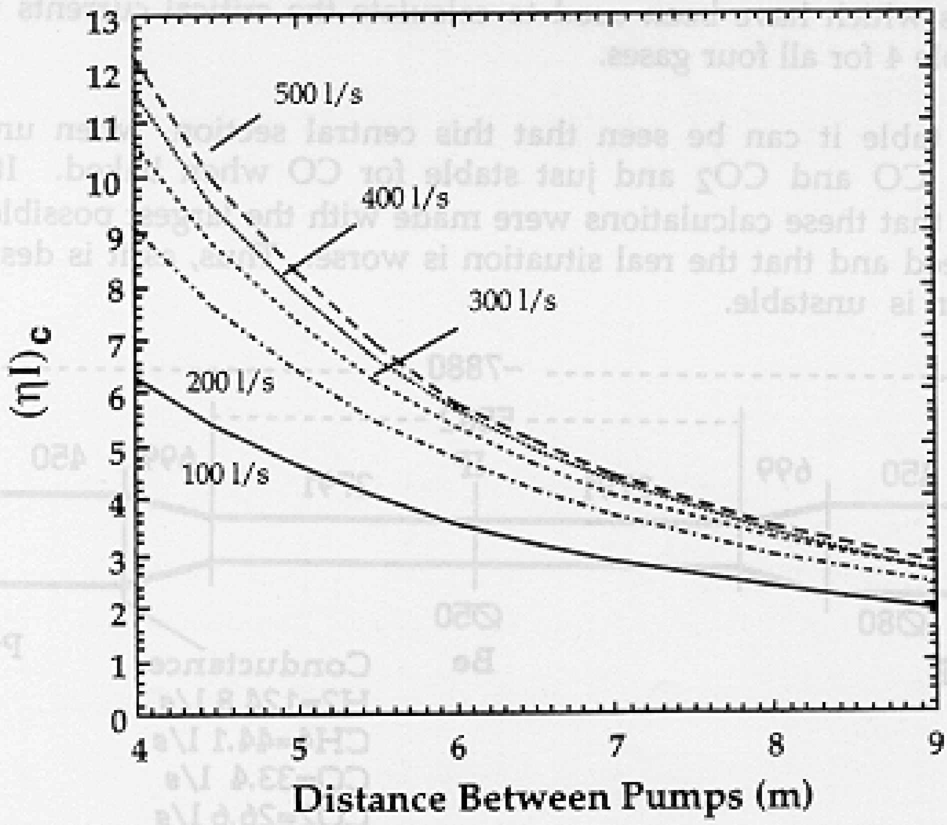

Figure 16 : The dependence of the critical current for CO on the pumping speed and distance between pumps.

If the chamber were not in Al but stainless steel, an elegant solution to the problem would be to fix some St 707 Non Evaporable Getter (NEG) ribbon on the inside surface of the chamber and activate it by baking the chamber via heating jackets on the outside [5]. NEG is an alloy of Zr, V and Fe (70, 24.6, 5.4 % by weight) in the form of powder which is cold sintered onto a constantan (Cu 55 Ni 45) ribbon 30 mm wide and 0.04 mm thick. One metre of this ribbon, when activated in vacuum to 300°C has an initial pumping speed of at least 350 ls^{-1} for H_2, CO and CO_2. Unfortunately the chamber is in Al which cannot be baked above about 150°C but, if a short section were in stainless steel, this idea could be used.

Another alternative would be to increase the diameter of the vacuum chamber to at least Ø100 mm where the ηI_c for CO increases from 2.4 to 3.8 and the ηI_c for CO_2 increases from 1.4 to 2.3.

The current threshold for bunch induced multipacting in the Ø80 mm chamber was calculated to be 39 mA and therefore could be a problem if the secondary electron yield for the Al surface is sufficiently large.

4.3 The Central Ø50 mm Be Chamber

A schematic diagram of the Ø50 mm, 5582 mm long Be central section is shown in Figure 17. The distance between pumps is ~7880 mm and a conical transition 699 mm long connects the Be chamber to the 450 mm long Ø80 mm chamber in front of each pump. The conductance of this conical plus cylindrical section for each gas is also shown in the figure. It is these optimistic pumping speed figures which have been used to calculate the critical currents which are shown in Table 4 for all four gases.

In this table it can be seen that this central section, when unbaked, is unstable for CO and CO_2 and just stable for CO when baked. It must be remembered that these calculations were made with the largest possible effective pumping speed and that the real situation is worse. Thus, as it is designed, the central section is unstable.

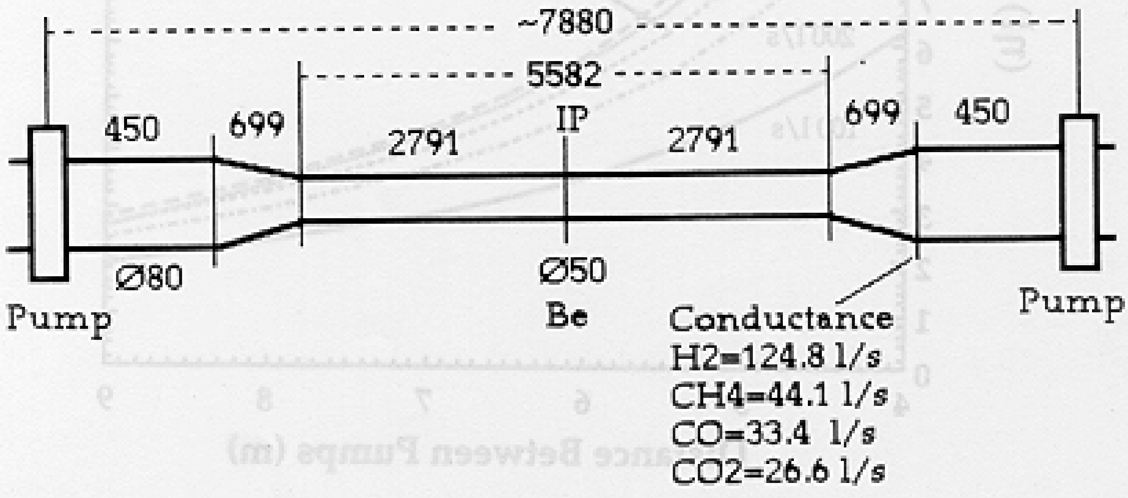

Figure 17 : A schematic diagram of the Ø50 mm, 5582 mm long Be central chamber with pumps 7880 mm apart.

Table 4

		Unbaked		Baked	
Gas	ηI_c	ηI	Stable	ηI	Stable
H_2	34.1	2.6	Yes	1.3	Yes
CH_4	1.6	0.21	Yes	0.086	Yes
CO	1.4	3.8	No	1.1	Just
CO_2	0.8	1.07	No	0.05	Yes

In an attempt to increase the vacuum stability it was proposed [6] to limit the length of the central chamber to 2000 mm (+/- 1000 mm) and to connect the pumps to it via a conical section. This is shown schematically in Fig. 18. The conical section enables the maximum effective pumping speed to be applied to the central chamber. The conductances of this 2940 mm long cone are also shown on the figure.

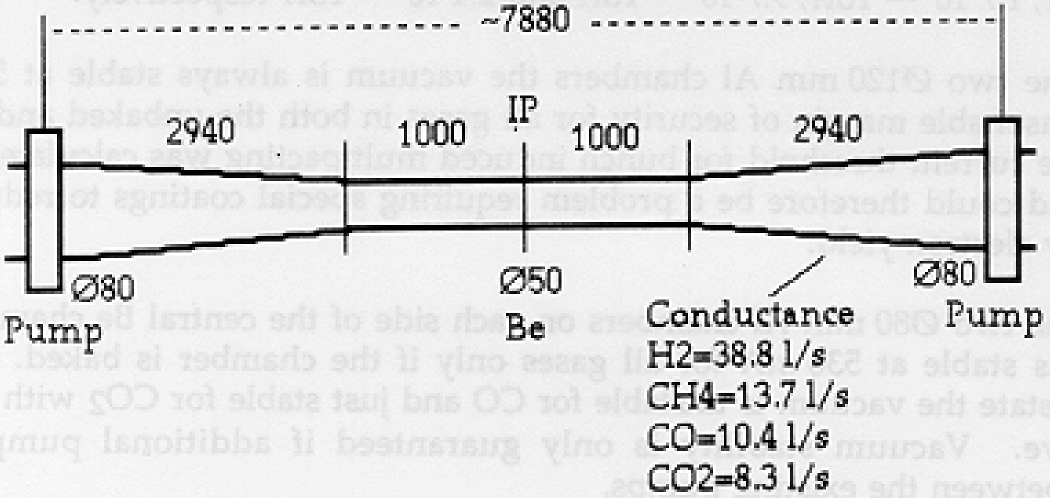

Figure 18 : A schematic diagram of the Ø50 mm, 2000 mm long Be central chamber with pumps 7880 mm apart.

The results of the calculation are shown in Table 5 where effective pumping speeds equal to 50% of the maximum have been used in the calculation There it can be seen that the situation is somewhat better in that the system is stable for all gases when baked, H_2 and CH_4 when unbaked but still unstable for CO and CO_2 when unbaked.

Even using the impracticable maximum effective pumping speeds does little to improve the situation in that CO when unbaked remained unstable and CO_2 became just stable with almost no safety margin.

If the cone could be made of stainless steel with NEG ribbons on the inside then the effective pumping speed at the entrance to the Be chamber could be much larger. For example if the effective pumping speed were only 50 ls^{-1} the ηI_c for CO increases from 1.8 to 6.2 and for CO_2 from 1.0 to 3.9 giving a good margin of security.

Table 5

Gas	ηI_c	Unbaked ηI	Unbaked Stable	Baked ηI	Baked Stable
H_2	43.6	2.6	Yes	1.3	Yes
CH_4	2.0	0.21	Yes	0.086	Yes
CO	1.8	3.8	No	1.1	Yes
CO_2	1.0	1.07	No	0.05	Yes

5. Conclusions

In the unbaked system the average pressures for H_2, CH_4, H_2O, CO and CO_2 were 1.0 10^{-9} Torr, 1.2 10^{-10} Torr, 1.1 10^{-7} Torr, 2.1 10^{-9} Torr and 2.4 10^{-10} Torr respectively.

For the baked system the average pressures for H_2, CH_4, CO and CO_2 were 1 10^{-10} Torr, 1.7 10^{-12} Torr, 9.7 10^{-12} Torr and 2.4 10^{-12} Torr respectively.

In the two Ø120 mm Al chambers the vacuum is always stable at 536 mA with a reasonable margin of security for all gases in both the unbaked and baked state. The current threshold for bunch induced multipacting was calculated to be 87 mA and could therefore be a problem requiring special coatings to reduce the secondary electron yield.

In the two Ø80 mm Al chambers on each side of the central Be chamber the vacuum is stable at 536 mA for all gases only if the chamber is baked. In the unbaked state the vacuum is unstable for CO and just stable for CO_2 with almost no reserve. Vacuum stability is only guaranteed if additional pumping is inserted between the existing pumps.

A solution involving a low mass NEG ribbon inside the chamber and activated by baking the outside to 250°C could work if that part of the chamber were in stainless steel. The current threshold for bunch induced multipacting was calculated to be 39 mA and could therefore be a problem requiring special coatings to reduce the secondary electron yield.

In the central Be chamber, when baked, the vacuum was stable at 536 mA for H_2, CH_4 and CO_2 but just stable for CO with very little margin. When unbaked it was unstable for both CO and CO_2.

Modifying the design to decrease the length of the Be chamber from 5582 mm to 2000 mm and improve the pumping helped somewhat. In the baked state, the vacuum was stable at 536 mA for all gases but was still unstable for CO and CO_2 when unbaked.

Making the conical transition in stainless steel and installing some NEG ribbon could give the required vacuum stability with a good safety margin.

References

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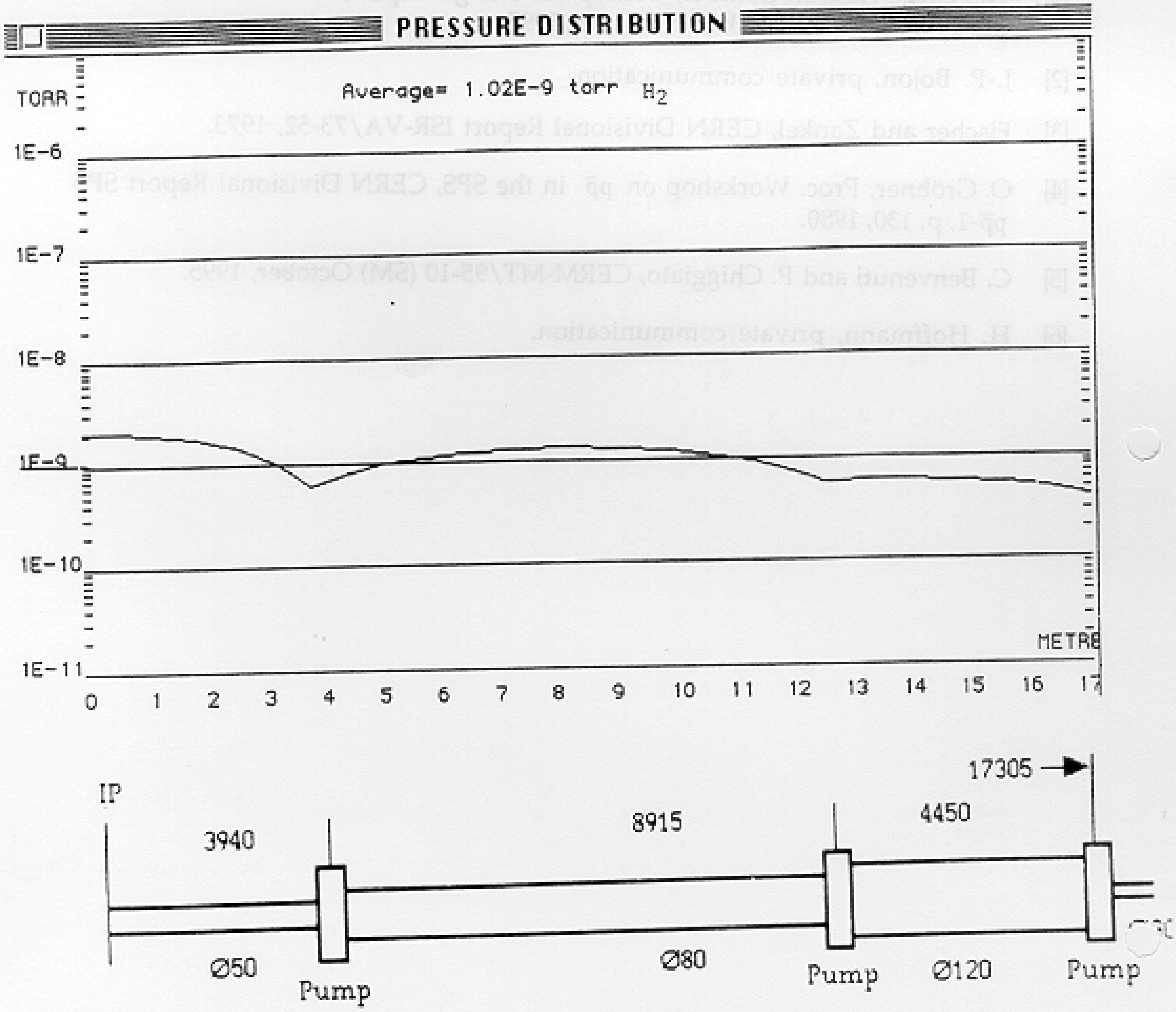
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TORR
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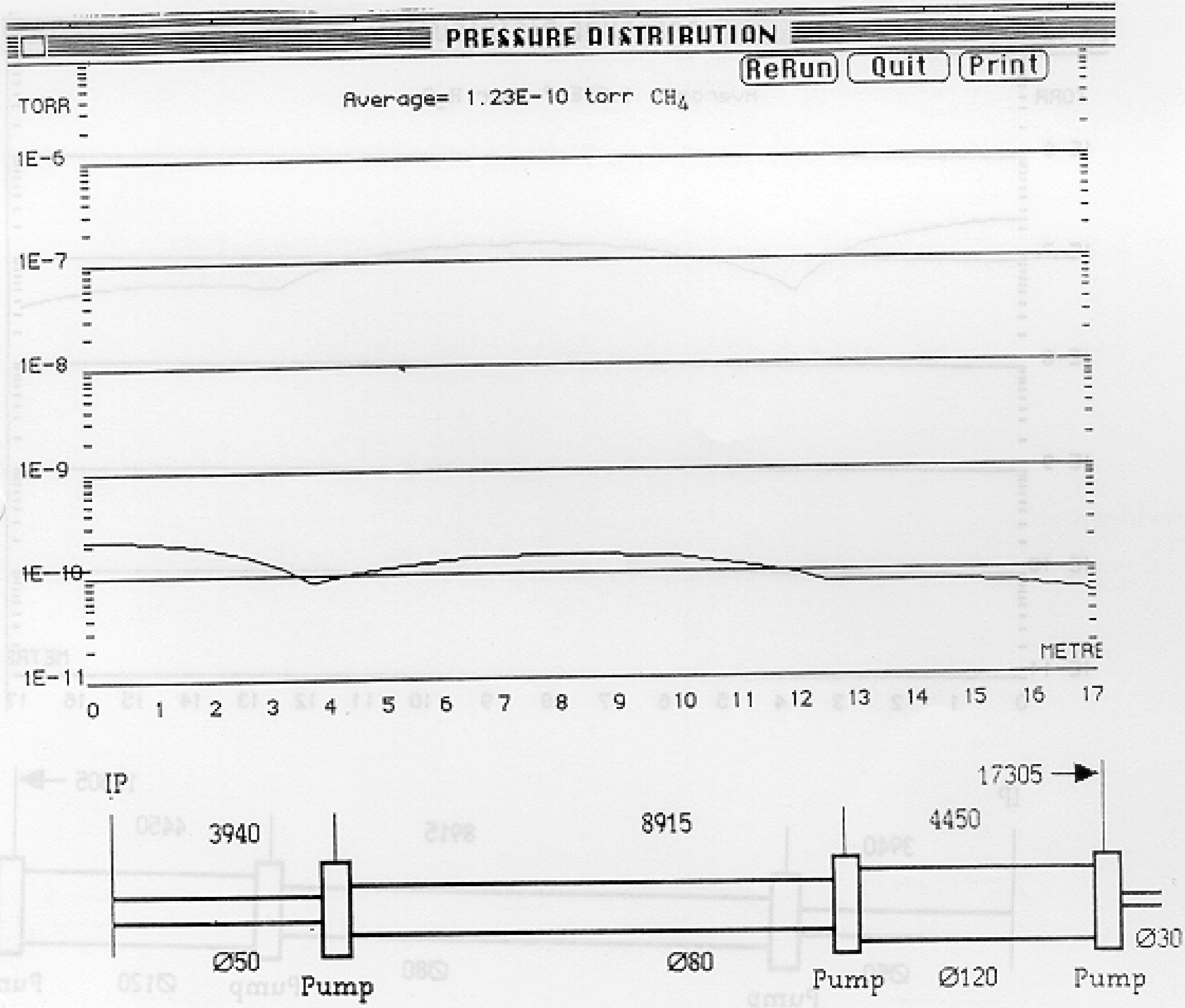
1E-6
1E-7
1E-8
1E-9
1E-10
1E-11
METRE
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
IP
3940
8915
4450
17305
Ø50
Ø80
Ø120
Pump
Pump
Pump

Figure 3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ReRun
Quit
Print
TORR
Average= 1.23E-10 torr CH4
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1E-7
1E-8
1E-9
1E-10
1E-11
METRE
0
1
2
3
4
5
6
7
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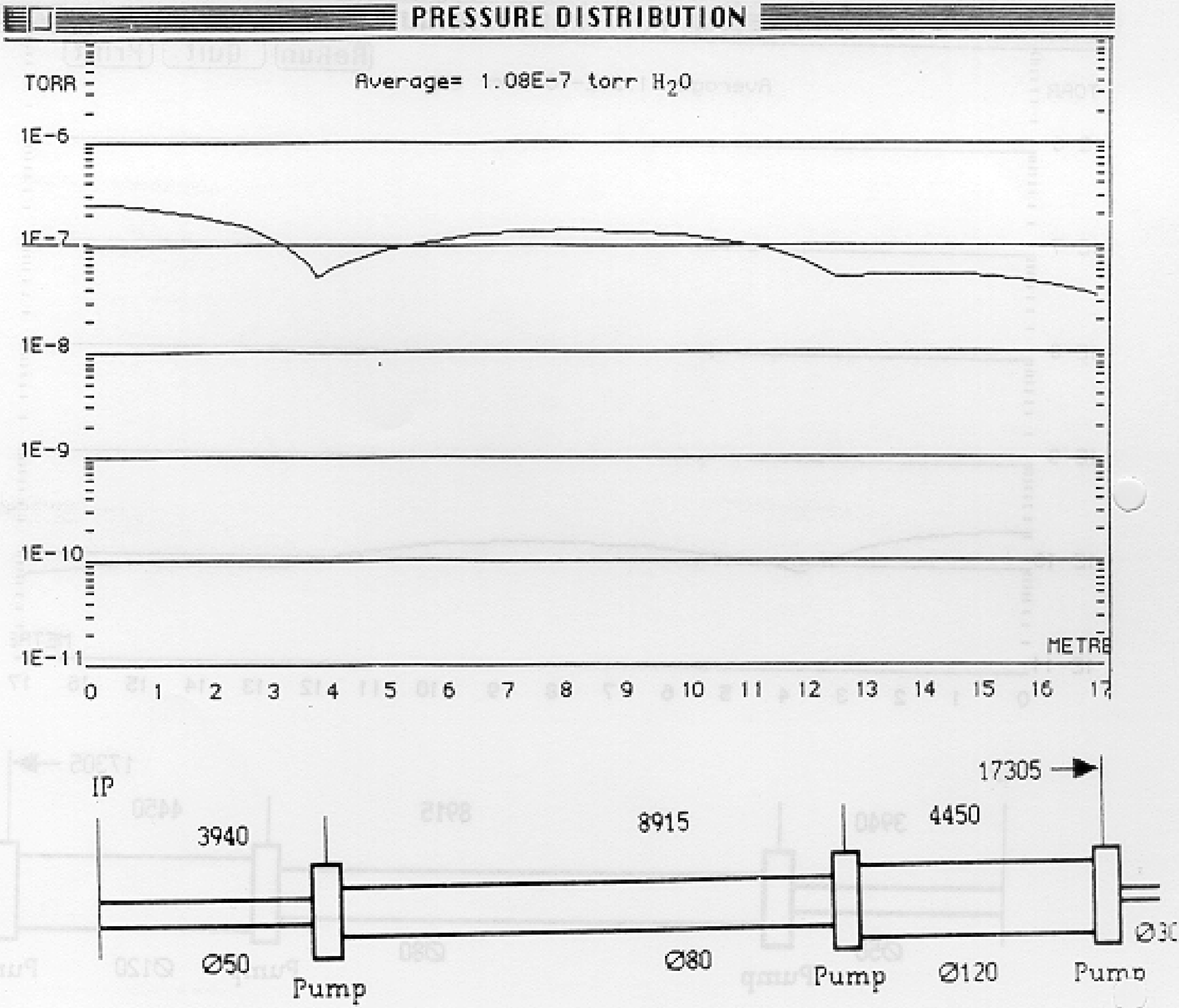
Figure 4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Average= 1.08E-7 torr H2O
1E-6
1E-7
1E-8
1E-9
1E-10
1E-11
METRE
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
17305
IP
3940
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Pump
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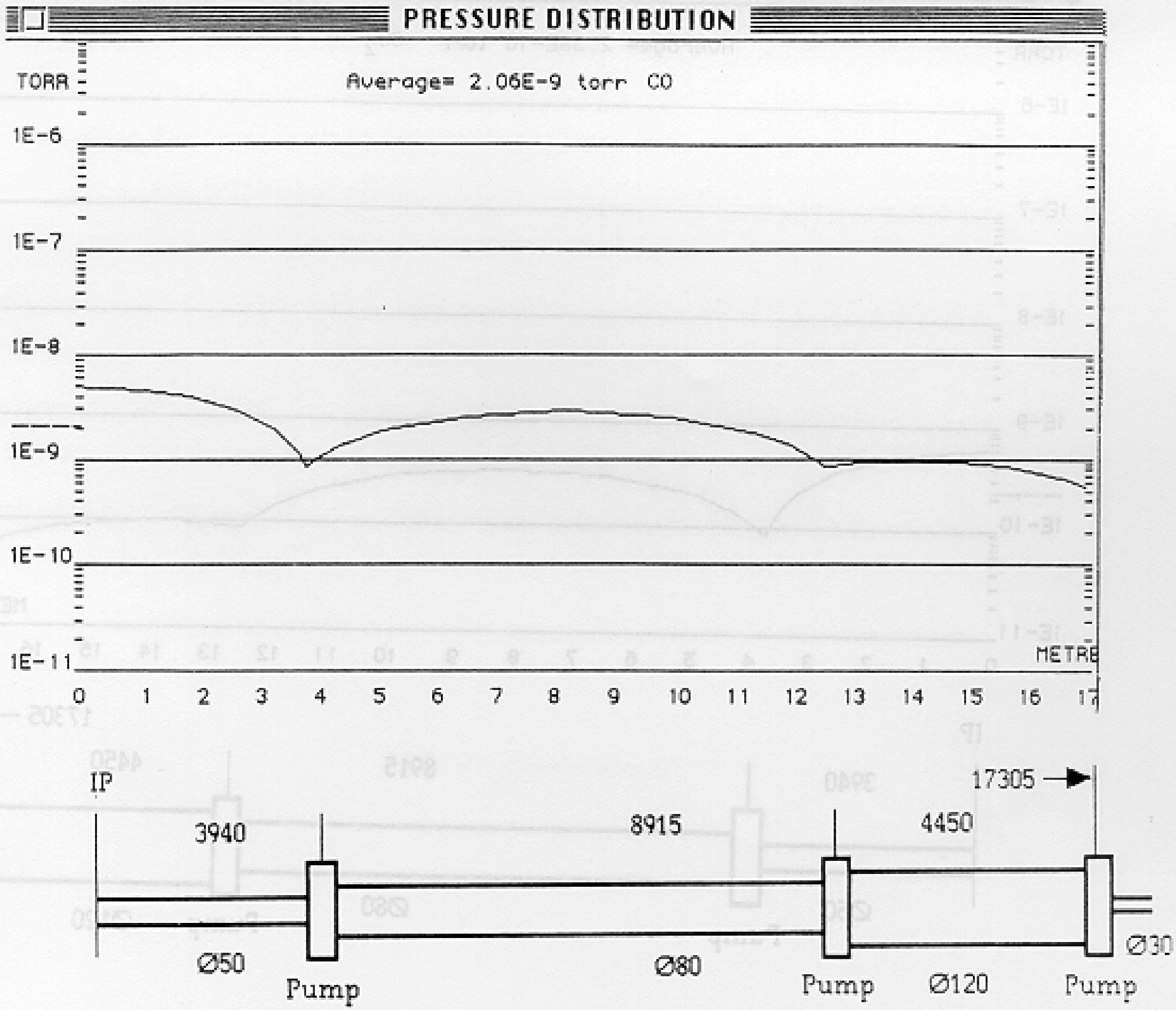
Pump
Ø120
Pump

Figure 5



PRESSURE DISTRIBUTION
TORR
Average= 2.06E-9 torr CO
1E-6
1E-7
1E-8
1E-9
1E-10
1E-11
METRE
0
1
2
3
4
5
6
7
8
9
10
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12
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IP
3940
8915
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17305
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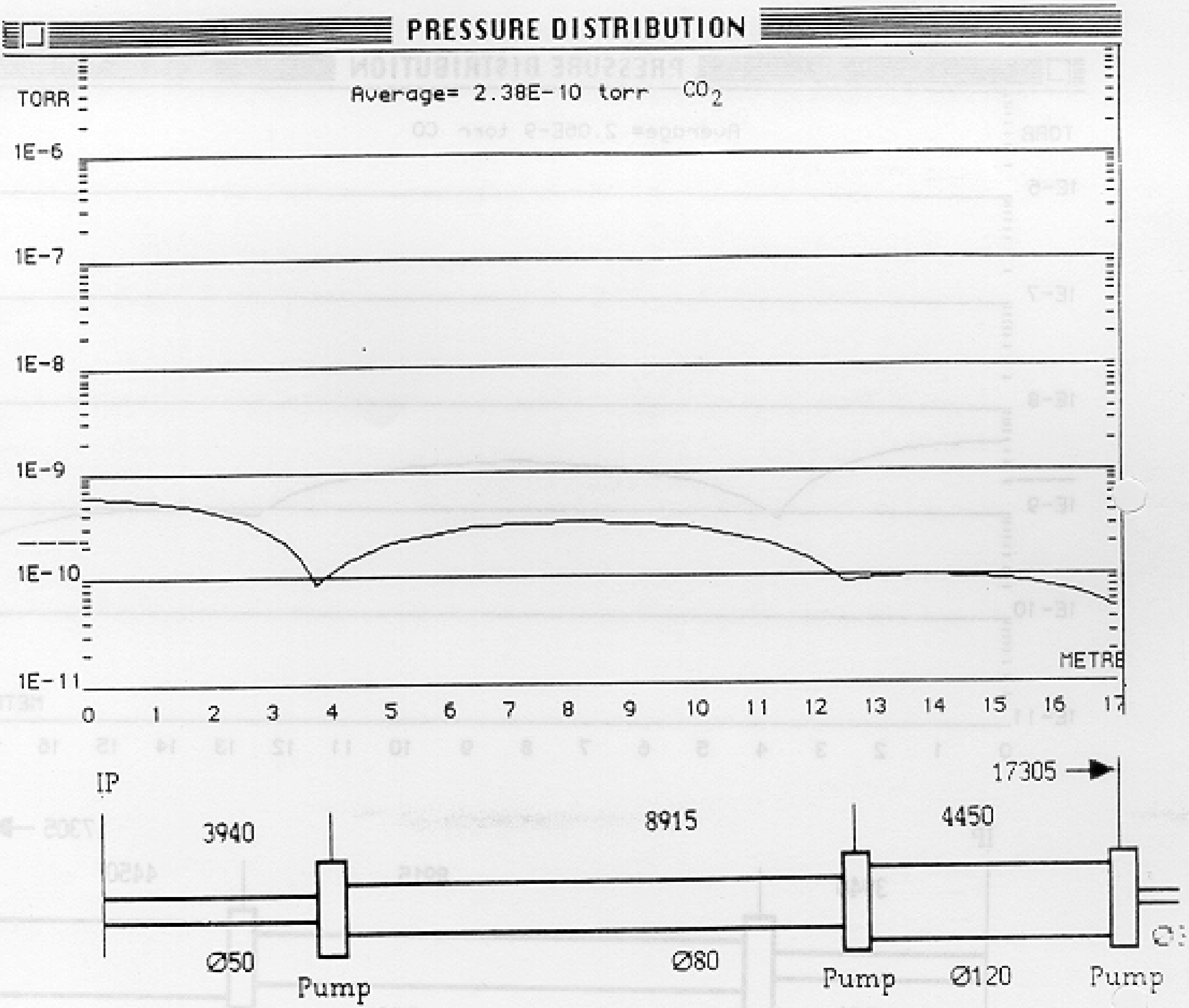
Pump
Ø80
Pump
Ø120
Pump
Ø30

Figure 6


PRESSURE DISTRIBUTION
TORR
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1E-7
1E-8
1E-9
1E-10
1E-11
METRE
0
1
2
3
4
5
6
7
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17305
IP
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4450
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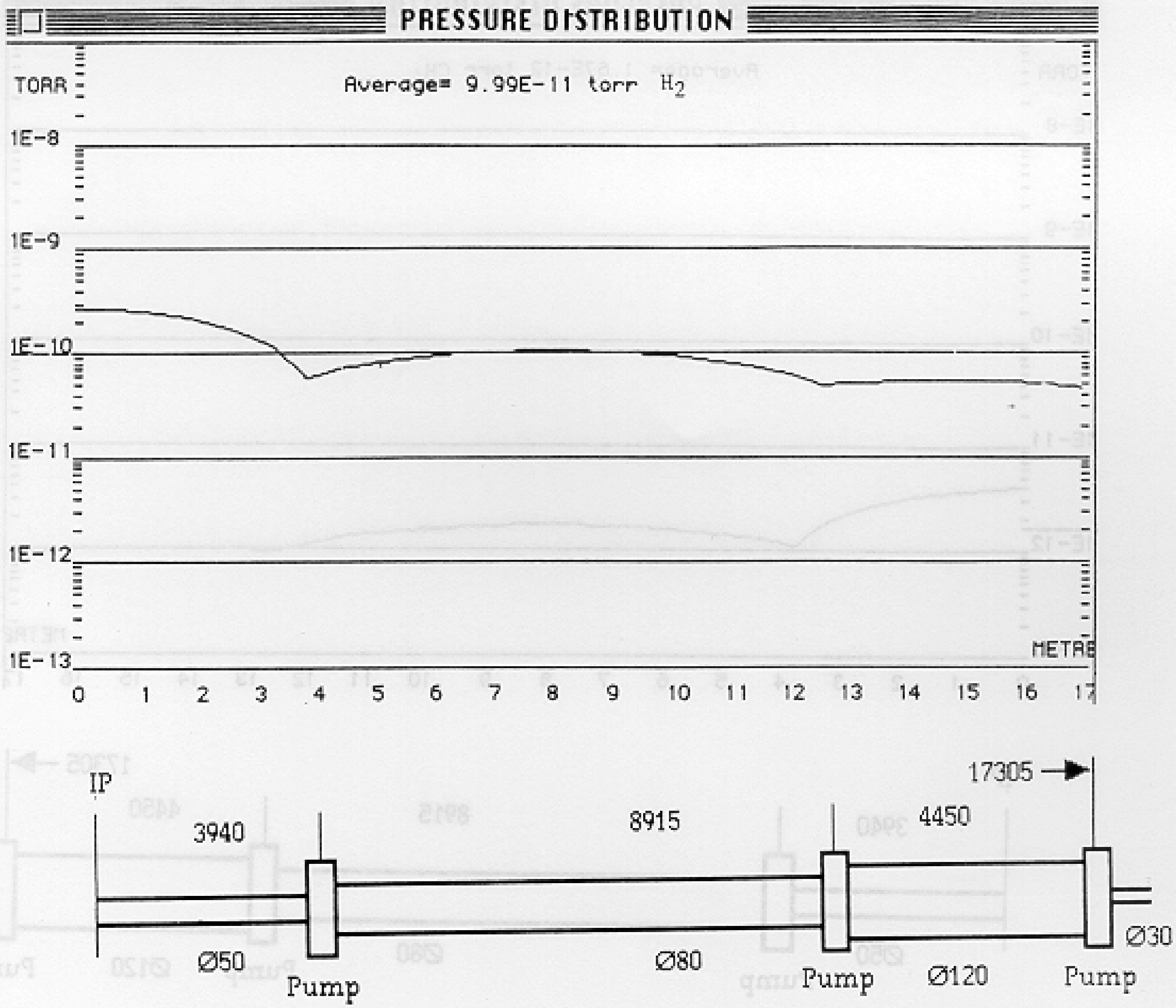
Pump
Ø80
Pump
Ø120
Pump

Figure 7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TORR
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1E-9
1E-10
1E-11
1E-12
1E-13
METRE
0
1
2
3
4
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4450
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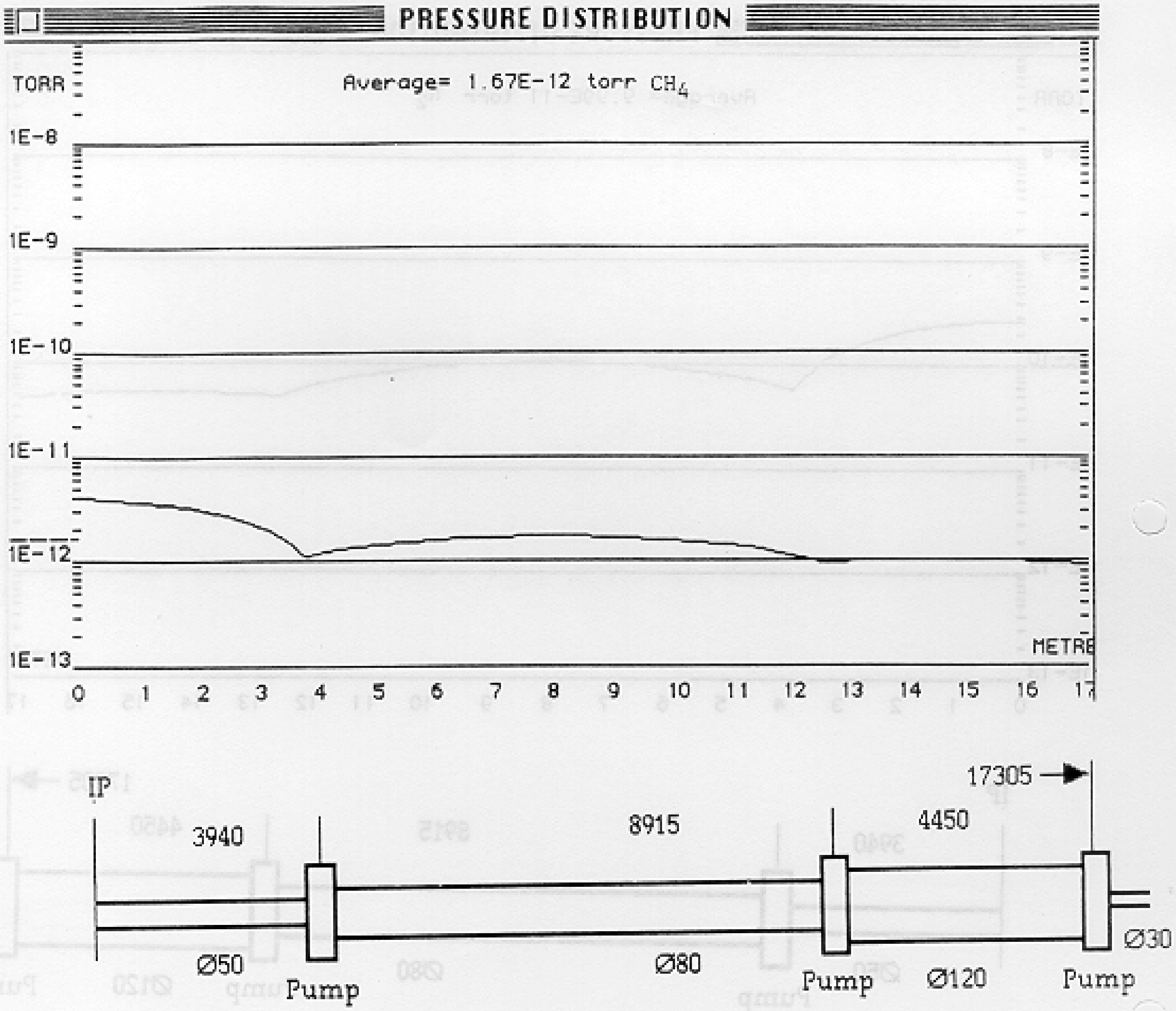
Pump
Pump
Pump

Figure 8



PRESSURE DISTRIBUTION
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1E-9
1E-10
1E-11
1E-12
1E-13
METRE
0
1
2
3
4
5
6
7
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9
10
11
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IP
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17305
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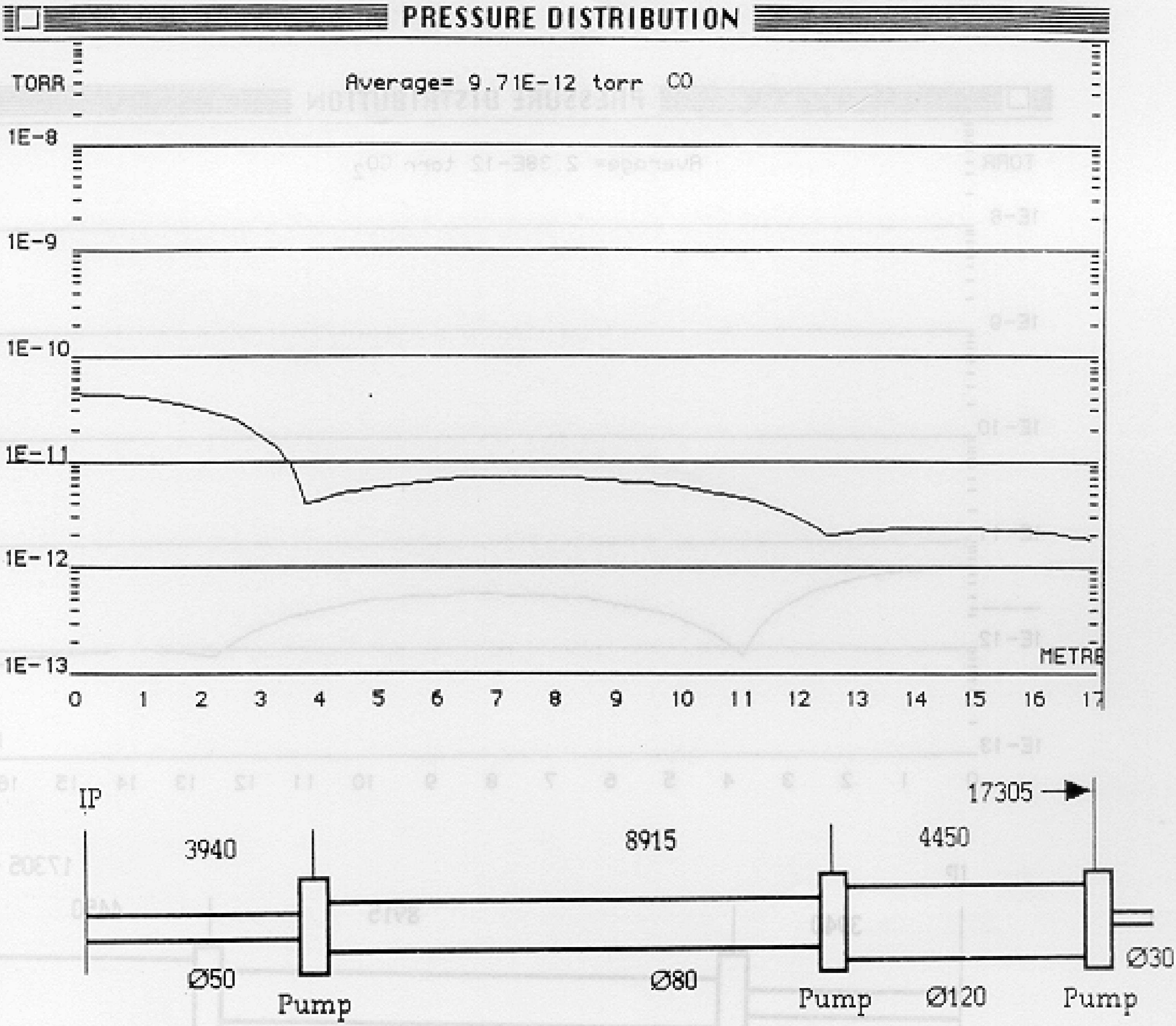
Ø120
Ø30
Pump
Pump
Pump

Figure 9



PRESSURE DISTRIBUTION
TORR
Average= 9.71E-12 torr CO
1E-8
1E-9
1E-10
1E-11
1E-12
1E-13
METRE
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
IP
3940
8915
4450
17305
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Pump
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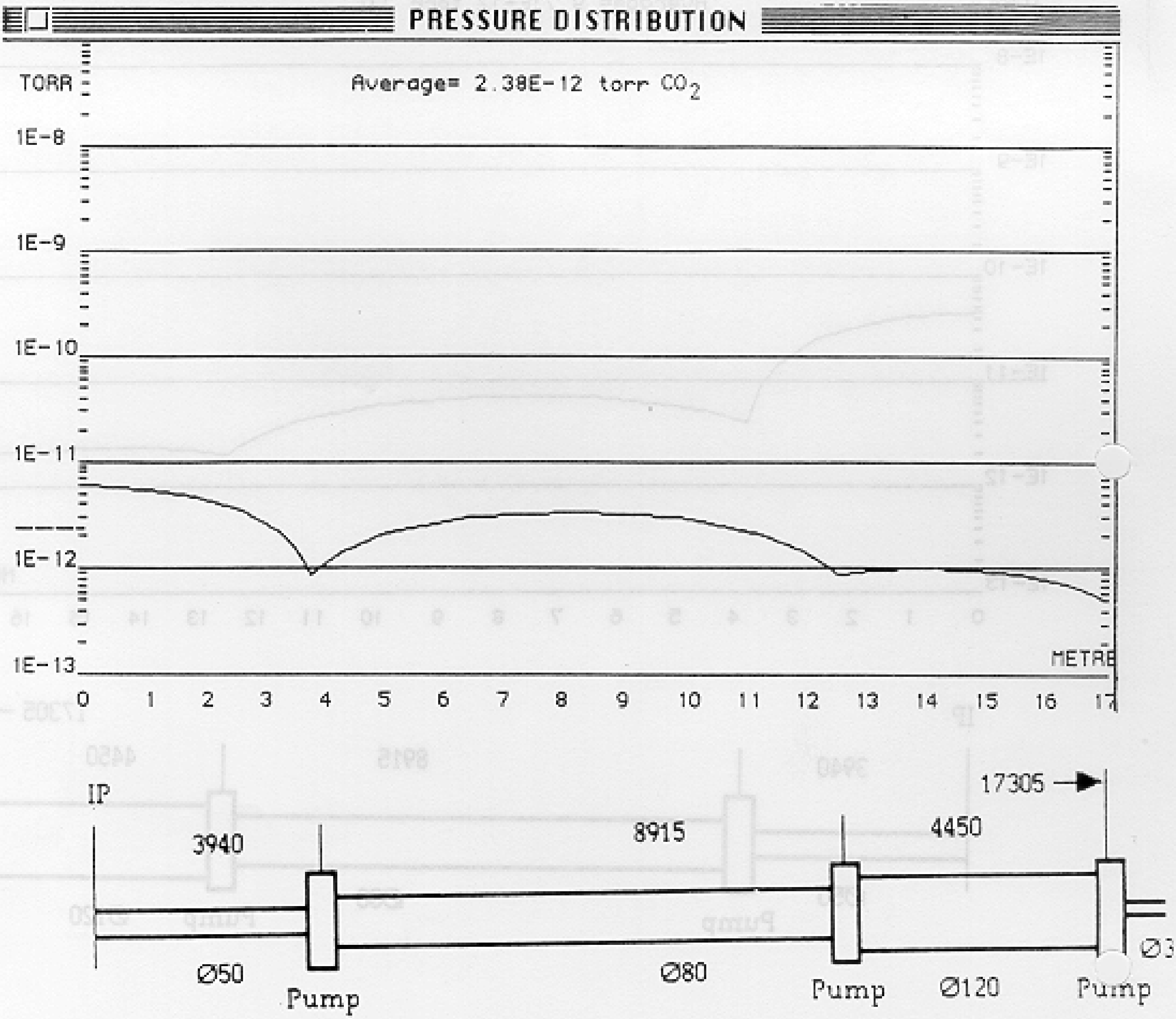
Pump
Ø120
Pump
Ø30

Figure 10


PRESSURE DISTRIBUTION
TORR
Average= 2.38E-12 torr CO_2
1E-8
1E-9
1E-10
1E-11
1E-12
1E-13
METRE
0
1
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IP
3940
8915
4450
17305
Ø50
Pump
Ø80
Pump
Ø120
Pump

Figure 11