BNL-64871
CONF-971029--
Abstract No: 410
Program No: VT-WeM3

Measurements of the helium propagation at 4.4 K in a 480 m long stainless steel pipe

H.C. Hseuh, RHIC Project, Brookhaven National Laboratory, Upton, New York, 11973, USA

and E. Wallen, MAX-lab, Box 118, S-22100 Lund, Sweden

RECEIVED
DEC 03 1997
OSTI

Abstract

The Relativistic Heavy Ion Collider (RHIC), with two concentric rings 3.8 km in circumference, uses superconducting magnets to focus the high energy beams. Each sextant of RHIC will have continuous cryostats up to 480 m in length housing the magnets and the cold beam pipes. For an acceptable lifetime of the stored beam, the pressure in the cold beam pipe will be $< 10^{-11}$ Torr. The characteristics of He pressure front propagation due to He leaks will be of importance for beam lifetimes and for vacuum monitoring due to the high vapor pressure of He at 4.4 K, even with small surface coverage. The travel of the He pressure fronts along a 480 m long, 6.9 cm I.D. stainless steel beam pipe cooled to 4.4 K has recently been measured during the RHIC first sextant test. The experiment was carried out over a 12-day period by bleeding in a calibrated He leak of $3X10^{-5}$ Torr·*l*/s (20 C) while measuring the He pressures along this 480 m cold tube at ~30 m intervals. The measured speed of the pressure fronts and the pressure profiles are summarized and compared with the calculated ones.

Electronic Mail: hseuh@bnl.gov

I. Introduction

The relativistic heavy ion collider (RHIC)[1], presently under construction at Brookhaven, is to collide highly relativistic particle beams from proton to gold with energies up to 250 GeV/nucleons for nuclear physics research. The RHIC machine must store two counter-rotating beams for periods of greater than ten hours. There are three distinct vacuum systems in RHIC:[2] the insulating vacuum of the superconducting magnet cryostats; the ambient temperature beam vacuum system; and the UHV cold beam pipes(cold bore) inside the superconducting magnets. The total length of the cold bore in these two 3.8 km interweaving rings is ~ 6.2 km, consisting of 12 arc sections of 480 m each and 12 short insertion sections around the experimental regions. To minimize the beam loss during the acceleration and the 10-hour storage period, the average pressure of the cold bore is to be < 10^{-11} Torr comprising exclusively He and H_2. Helium can leak into the cold bore from the helium filled magnet vessels through metallurgical flaws in the cold beam pipes, or from insulating vacuum due to catastrophic failure of the UHV interconnect piping or bellows.

The travel speed of the He front in cold beam tubes has been studied previously. Edwards and Limon[3] observed that it took ~2.5 min for the pressure front of a large He leak to travel through a 6 cm diameter 20 m long tube cooled to 4.7 K. Based on an adsorption isotherm, Hobson ad Welch[2] modeled the He propagation and the pressure profiles in RHIC with and without cold bore pumps. Wallen[4] measured the time for He to travel in a 4.3 cm diameter 75 m long test tube cooled to 1.9 K and to 4.25 K. His results were in good agreement with the prediction of the model developed by Hobson and Welch.

In the present study, the He propagation at 4.4 K was measured in the 480 m cold bore

over a 12-day period during RHIC first sextant test. The pressures along this cold bore were measured at ~30 m intervals. The results are presented and compared with the calculated ones using the above mentioned model.

II. Measurement of He Propagation in RHIC First Sextant Test

The details of the RHIC vacuum systems have been described previously[2]. In brief, each 480 m arc section consists of a continuous cryostat housing the 64 superconducting magnets. The cold masses of the alternating dipole and quadrupole magnets are approximately 9.5 m and 4.5 m, respectively, in length. The magnet cold bores, made of 316LN stainless steel, have an inner diameter of 6.9 cm and are interconnected with a formed bellows. Either a sorption pump or a gauge conduit is attached to the pullout flange at the neck of the bellows at ~15 m intervals (every other interconnect). The sorption pump contains ~300 gm of activated charcoal and is cooled to a temperature of ~10 K when the magnets are at ~4 K. The helium pumping speed of the sorption pump at the cold bore end of the pullout is ~2.5 *l*/s. The 1.5 m long flexible gauge conduit snakes through the multi-layer insulation, the 55 K heat shield and is then anchored to the ambient temperature cryostat. An inverted magnetron type cold cathode gauge (CCG)[5] is connected to the ambient instrument tree flange at the end of gauge conduit to monitor the pressure of the cold bore.

Prior to cooldown of the magnets, the cold bore beam pipes were pumped down with molecular sieve sorption pumps and turbomolecular pumps to a vacuum of 10^{-4} Torr to 10^{-3} Torr. After the cooldown to 4.4 K, the pressure readings of the CCGs ranged between mid 10^{-10} and low 10^{-9} Torr levels. These readings were due to the localized outgassing of the ambient instrument tree and the gauge conduit. Assuming an unit outgassing rate of 10^{-11} Torr·l/s·cm^2, an area of 10^2 cm^2 for the instrument tree, and a conductance for water through the gauge conduit of ~1 l/s, the background pressure at the CCGs will be 10^{-9} Torr. This localized outgassing limits the minimum detectable pressure change at the CCGs to 10^{-10} Torr. The changes in pressure at CCGs are assumed to be solely contributed by He and H_2 since the vapor pressures of all other gases at 4K are much less than 10^{-11} Torr. With the presence of only He in the cold bore, the real He pressure at the CCG is given by $(Tw/Tc)^{0.5}$ x Pc or ~ 8.2 x Pc, based on the thermal transpiration and assuming no net flow of He between the cold bore and the CCG. The sensitivity of the CCGs for He is ~ 1/7 of that for air, hence the changes in CCG readings equal to ~1.2 times of the true He pressures in the cold bore.

To measure the travel speed of the He pressure fronts, helium was bled into the cold bore during the RHIC first sextant test in February, 1997. A calibrated He leak of $3X10^{-5}$ Torr·l/s (20 C) was used in this study. The equivalent He leak rate at 4.4 K is proportional to the temperature and is $4.5X10^{-7}$ Torr·l/s. The leak was introduced through an all-metal valve mounted on the ambient instrument tree approximately 120 m from one end of the 480 m cold bore. The locations of the CCGs and the sorption pumps in both directions from the leak are shown in Fig. 1. Due to the placement of special magnets and instrumentation, the CCGs and the sorption pumps toward 'right' are positioned closer to the leak than those toward 'left'. The CCG readings and the magnet temperatures were continuously monitored and recorded by the RHIC data logging system during the measurements. The temperature of the magnets, as measured at ten different locations along the 480 m length, remained within 4.39±0.02 K throughout the experiment, except over a two-hour period when magnet temperature dropped to 4.3 K. Typical plots of the logged CCG readings during the measurement are shown in figures 2 and 3. As mentioned earlier, pressure changes down to 10^{-10} Torr could be observed by the CCGs. The changes in CCG readings were divided by 1.2 to obtain the true cold bore He pressure at 4.4 K. It is important to note that the values of pressure, flow rate, and amount of gas quoted here on, unless specified, will be those at 4.4 K.

Two measurements were conducted in the 12-day period. In the first run, helium was bled in for four hours then valved off for three days. The amount of He bled-in over this 4-hour period is approximately 0.0065 Torr·*l*. The CCG readings returned to the background values a few hours after the calibrated leak was valved off, indicating He removal from the cold bore by the sorption pumps. In the 2nd measurement, helium was continuously bled in for 9 days before being valved off with approximately 0.35 Torr·*l* He bled in. The CCG readings increased sharply when the He fronts reached the particular gauge locations, then levelled off over the whole nine day period. As in the first measurement, the CCG readings decreased rapidly to their original values once the calibrated leak was valved off suggesting the effectiveness of the sorption pumps as perfect sinks for He. The time for the first observable sign of the pressure increase and the time for the readings reaching plateau at the CCGs are listed in Table 1 together with the plateau CCG readings and the corrected He pressure in the cold bore. The He front travelled slower toward 'right' than toward 'left'. The sorption pumps at 'right' are positioned closer to the leak than those at 'left', which reduced the available amount of He progressed down the tube. These results are further discussed and compared with the calculated ones in the next sections.

III. Results and Analysis Using Hobson-Welch Model

In a long cryogenically cooled tube, helium will initially have a limited propagation speed due to the physical adsorption of He on the surface. This phenomenon was first noted by Edwards and Limon.[3] Hobson and Welch[2] developed a model based on a steep adsorption front to describe the phenomenon. This model will be used to calculate the travel speed of the He pressure fronts for the present case and the result compared with the measured values. A few important assumptions of the model and its application to our measurements will be briefly described. Details can be found in the original paper[2] and will not be repeated here.

The model assumes that He has the same probability of moving toward either direction from the leak location (taken as $x = 0$). Initially helium is strongly adsorbed by a narrow band of the cold bore wall at the leak. With the buildup of He on the surface, the adsorption-desorption process will reach an equilibrium and becomes that of the adsorption isotherm. Only then the leading edge of the pressure zone can progress down the tube and adsorbed by the 'fresh' band of the cold bore or pumped by the sorption pump when the foot of the adsorbed layer reaches the pump. When the downstream edge of the front passes the first sorption pump, the flow will be adjusted for the fraction of Q removed by the sorption pump which depends on the location of the front (and the conductance of the cold bore from that location back to the first pump). The pressure at the He front is given by

$$P(x) = Q/Ca \qquad \text{for } x < L$$

$$P(x) = Q/(Ca+Sp) \qquad \text{for } x = L$$

$$P(x) = Q'/Ca \qquad \text{for } x > L$$

with $Ca = 0.91\pi D^2 (T/M)^{0.5}$ the aperture conductance of the pipe, Sp the pumping speed of the sorption pump, L the distance of the first sorption pump to the leak, D the diameter of the pipe, and Q′ the flow Q less the amount removed by the first sorption pump. The pressure at the leak is given by P(0) = Q/Co with Co = Ca / (1+0.75 x / D) for x < L. Therefore the pressure at the leak, at the sorption pump and at the He fronts can be calculated for the selected x using these formulae.

The other important assumption of the model is that the pressure profile is a linear function of x between the leak and the front, between the pumps, and between the pump and the front, since the He flow Q or Q′ is constant between them. With the known pressure at the pumps and at the fronts, the pressure profile in each segment then can be calculated. Spreadsheets were set up to calculate the conductance and the pressure profile when the front reaching the first pump by inputting different values of x. In this approach, the pressure profile is constructed without reference to adsorption isotherm or time. Once the pressure profile along the pipe is established, the next step is to integrate the total amount of He entered the cold bore. The amount of He adsorbed σ at any point x is given by the DRK adsorption isotherm equation[6]

$$\ln (\sigma / \sigma_m) = - B (RT \ln P(x) / \ln Po)^2$$

where σ_m being the monolayer coverage, R = 1.986 cal/mol deg, Po = 900 Torr the saturated vapor pressure of He at 4.4 K. Values of 1.27×10^{15} atoms/cm^2 for σ_m and 5.48×10^{-5} mol^2 cal^{-2} for B, the empirical constants as recently reported for stainless steel,[7] are adopted in our calculation. To simplify the task of 'integration', the above equation can be approximated by a power law of

$$\sigma/\sigma_m = k P^n$$

where k and n are temperature dependent empirical constants. The calculated adsorption isotherm for He at 4.4 K using the DRK equation is shown in Fig. 4 together with that by the power law using k = 2.892 and n = 0.2084 which gives the best fit of the two curves for pressure between

10^{-11} and 10^{-4} Torr. Using the power law and the known pressure profile, the quantity adsorbed by the cold bore before passing the first sorption pump is obtained, so is the time to reach that pump by dividing the quantity entered with the leak rate. Expanding the spreadsheet to include the second pump location and using the net conductance of the combined sections and the pump speed, the pressure profile and the quantity adsorbed by both segments of pipes before passing the second pump can then be calculated as well as the amount pumped by the first sorption pump and the time to reach the second pump. Here again, the pressure at the first pump is assumed to be a linear function of time between passing the first pump and reaching the second pump. Using the same approach, the pressure profile passing the successive pumps can be established and the time of reaching successive pumps can be constructed. The pressure and the arrival time at any location, such as at the CCGs, can be derived by changing the value of x between pumps in the spreadsheet.

The calculated travel time for the He pressure front is plotted together with the measured travel time (time with initial pressure rise and time with plateau reading at the CCGs) versus the distance from the leak in Fig. 5. The knees on the calculated curves give the locations of the sorption pumps. Toward the 'right', the pressure increases were very steep and the initial arrival time and the plateau time were both within 40% of the calculated ones. Considering the simplicity of the model and its calculation, and the not-so-well-known surface of the cold bore, the agreement between the measured and the calculated arrival time in 'right' is excellent. Toward the 'left', the measured travel times are shorter than the calculated ones by as much as one decade, if only considering the initial pressure rise time. As shown in figures 2 and 3, the pressure increases at 'left' were also not as steep as compared with those at 'right'. No apparent cause can be attributed to this unexpected observation toward 'left'.

The cold bore He pressures derived from the changes in the plateau CCG readings are also listed in Table 1 and plotted versus the distance in Fig. 6 together with the calculated pressures at time > 100 hours. Again, the knees on the calculated curves give the locations of the sorption pumps. The measured cold bore pressures are in reasonable agreement with the calculated ones in both 'left' and 'right' cases. This result also validates the need and the effectiveness of the sorption pumps in slowing the speed of the He front and in reducing the magnitude of the He pressure zone. In a similar study[4] with a leak of 1×10^{-6} Torr·l/s (4.25 K) and without pumps, the magnitude of the He pressure at x = 75 m was found to be two decades higher and the arrival time one-tenth of those of the present study.

IV. Discussion and Conclusion

The propagation of the helium pressure fronts in a long tube cooled to 4.4 K has been measured in this study over a 12-day period. Using the steep adsorption isotherm model developed by Hobson and Welch,[2] the travel time and the pressure profile in our cold beam pipes have been calculated and compared favorably with the measured values. The effectiveness of the sorption pumps in slowing down the traveling of the helium fronts and in reducing the magnitude of the He pressure zone has been verified.

The present measurements confirm that the He pressure front traveling down the cold tube is indeed front like as can be seen from the steep pressure rise at the CCGs (e.g. see Fig. 2), and from the good agreement between the measured and the calculated results using the steep front model. The model can be used to estimate, with reasonable accuracy, the impact of He leaks into the cold bore in such storage rings as RHIC and the future LHC at CERN. Indeed the model and the spreadsheet used in our calculation also predict arrival times within 17% of those measured by Wallen[4] at 1.9 K and at 4.25 K for LHC.

Several factors affecting the travel speed and the pressure profile have been considered for their effect on the accuracy of the measured values and are discussed below.

(a). The calibrated leak: The calibrated leak used was checked, using AVS recommended procedures,[8] less than a year before the measurment and the estimated decrease in leak rate is ~5%. The leak rate will increase with temperature by a few percent per degreee Celsius, however the ambient temperature of the underground RHIC tunnel was, during our measurments, less than 20 C(the temperature during calibration).

(b). The cold bore surface: The empirical constants σ_m and B used in calculating the isotherm and the power law constants were obtained for a chemically cleaned stainless steel surface.[7] The surface roughness of the RHIC cold bore should not be much different from that of the chemically cleaned one, thus the choice of σ_m. The length of each cold bore segment is taken as the straight length without counting the extra surface area in the rf-shielded bellows at the interconnects, which add ~3% more surface area to the total area and the equivalent length, therefore increasing the arrival time by a similar amount.

(c). The CCG readings: All the CCGs used in RHIC cold bore were installed with Am^{241} source to enhance their ignition at low pressure.[5] The sensitivity variation[9] of the CCGs was estimated to be within 30%, which affects the accuracy of the measured pressure profile but not the travel time. The cold bore He pressure was derived by subtracting the plateau CCG reading with the reading before bleeding in He assuming that the background contribution did not vary over the 12-day period. Changes in the background pressure during the measurement would affect the accuracy of the pressure profile, especially at distance away from the leak where the pressure increase was small. The calculated arrival time agrees better with the measured arrival time based on the plateau CCG readings, especially toward 'left'.

In short, the uncertainty due to the combination of these three factors should be less than a factor of two. The short initial arrival time and the more gradual pressure increase toward 'left' can not be explained with the present model. With the exception of this discrepancy, the model works reasonably well in predicting the He propagation in the cold tubes.

Further verification of the steep front model for He travel in cold beam pipes will be possible in late 1998 when the construction of RHIC is completed and all the magnets cooled down. With twelve 480 m long cold bores available, accurate measurements on the traveling of the He pressure fronts can be performed using different leak rates and temperatures up to 4.8 K.

Acknowledgments

The model developed by Hobson and Welch[2] makes the comparison of the results between the calculation and the measurement possible. H.C. Hseuh would like to thank the dedication of the RHIC Vacuum Group who completed the RHIC first sextant test in time to allow the present study be carried out. The work is supported by the U.S. Department of Energy under contract no. DE-AC02-76CH00016.

Table 1. Measured arrival time and pressure at the cold cathode gauge locations

CCG Name	Distance to Leak (m)	Initial Arrival Time(hr)	Plateau Arrival Time(hr)	CCG Reading* (Torr, 20 C)	Cold Bore He Pressure** (Torr, 4.4 K)
PC6	85	120		$8.5x10^{-10}$	$1.25x10^{-10}$
PC7	75	62	81.75	$3x10^{-9}$	$1.75x10^{-9}$
PC9	45	8.5	19.75	$1.6x10^{-8}$	$1.12x10^{-8}$
PC10	30	4.5	8.25	$2.1x10^{-8}$	$1.74x10^{-8}$
PC14	30	2.3	7.75	$1.4x10^{-8}$	$1.08x10^{-8}$
PC16	59	8	23.75	$9x10^{-9}$	$6.5x10^{-9}$
PC18	89	13.25	32.75	$3x10^{-9}$	$1.17x10^{-9}$
PC20	119	30.75		$1.7x10^{-9}$	$2.5x10^{-10}$

* flattened readings after the initial steep rise at 20 C

**derived from the CCG reading subtracted by the background reading (before He leak was introduced) and then divided by 1.2 for thermal transpiration and the gauge sensitivity for He

Figure Captions:

Fig. 1. Schematics of the sorption pump and the cold cathode gauge locations in relation to the helium leak during RHIC first sextant test. The magnet cold mass, the interconnecting bellows and the cryostat are not drawn for clarity. The numbers given are the distance from the leak in meters. PCxx are the cold cathode gauge names in the RHIC database. The leak rate 2Q = $4.5x10^{-7}$ Torr·l/s He at 4.4 K.

Fig. 2. Typical plots of the logged cold cathode gauge readings (at 20 C) versus time during measurement for gauges toward 'right'. The gauge locations are given in Fig. 1. Helium leak was introduced at 8:15 on Feb. 9th.

Fig. 3. Typical plots of the logged cold cathode gauge readings (at 20 C) versus time during measurement for gauges toward 'left'. The gauge locations are given in Fig. 1. Helium leak was introduced at 8:15 on Feb. 9th.

Fig. 4. The calculated adsorption isotherms using the DRK equation and using the power law of $\sigma/\sigma_m = k\,P^n$ with k = 2.892 and n = 0.2084 which gives the best fit to that of the DRK equation.

Fig. 5. The travel times of the helium front versus the distance from the leak. The negative values on X axis represent toward 'left' and the positive ones toward 'right'. The 'measured-initial' values are those when 'initial' pressure rises were observed and the 'measured-plateau' are those when the readings flattened at the cold cathode gauge locations.

Fig. 6. The He pressure profile at t > 100 hours versus the distance from the leak. The measured values are derived from the cold cathode gauge readings corrected for background pressure, thermal transpiration and gauge sensitivity. The negative values on X axis represent toward 'left' and the positive ones toward 'right'.

References:

[1]S. Ozaki, Accel. Sci. Technol. 5, 2901(1991).

[2]J.P. Hobson and K.M. Welch, J. Vac. Sci. Technol., A11, 1566 (1993)

[3]D. Edwards, Jr., and P. Limon, J. Vac. Sci. Technol., 15, 1186(1978).

[4]E. Wallen, J. Vac. Sci. Technol., A15 (1997) (in press).

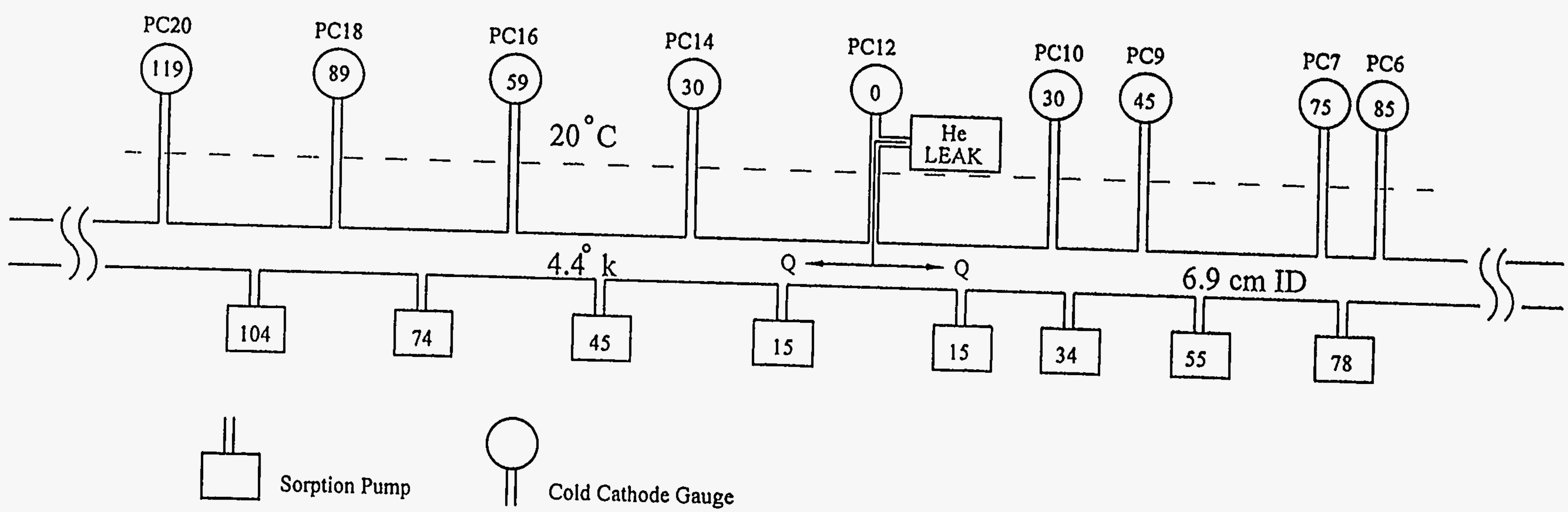
[5]L. Smart, K.M. Welch and R.J. Todd, J. Vac. Sci. Technol., A14(1996).

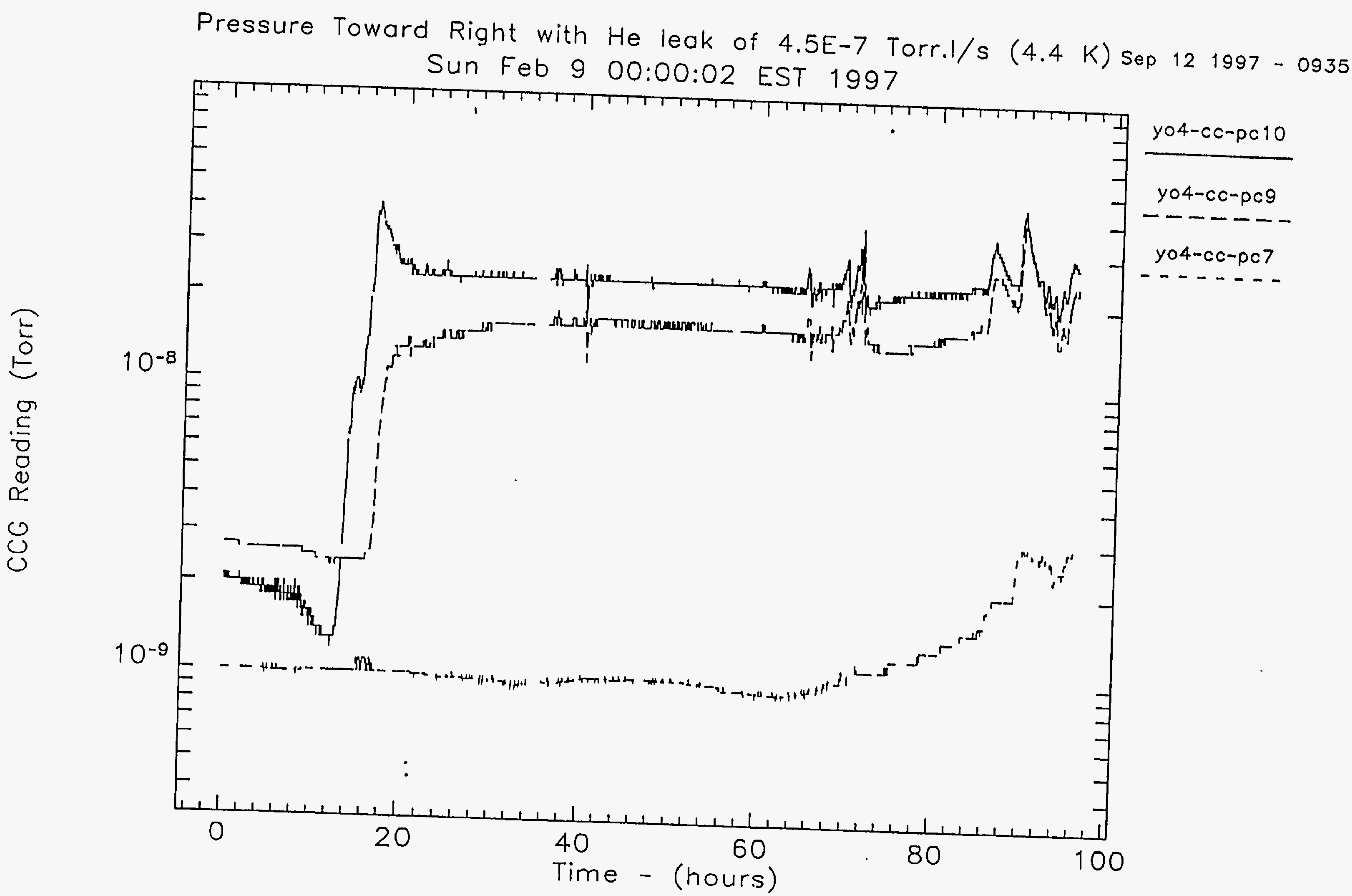
[6]P.A. Redhead, J.P. Hobson and E.V. Kornelson, the Physical Basis of Ultrahigh Vacuum (Chapman and Hall, London, 1968), p 46.

[7]E. Wallen, J. Vac. Sci. Technol., A15, 265(1997).

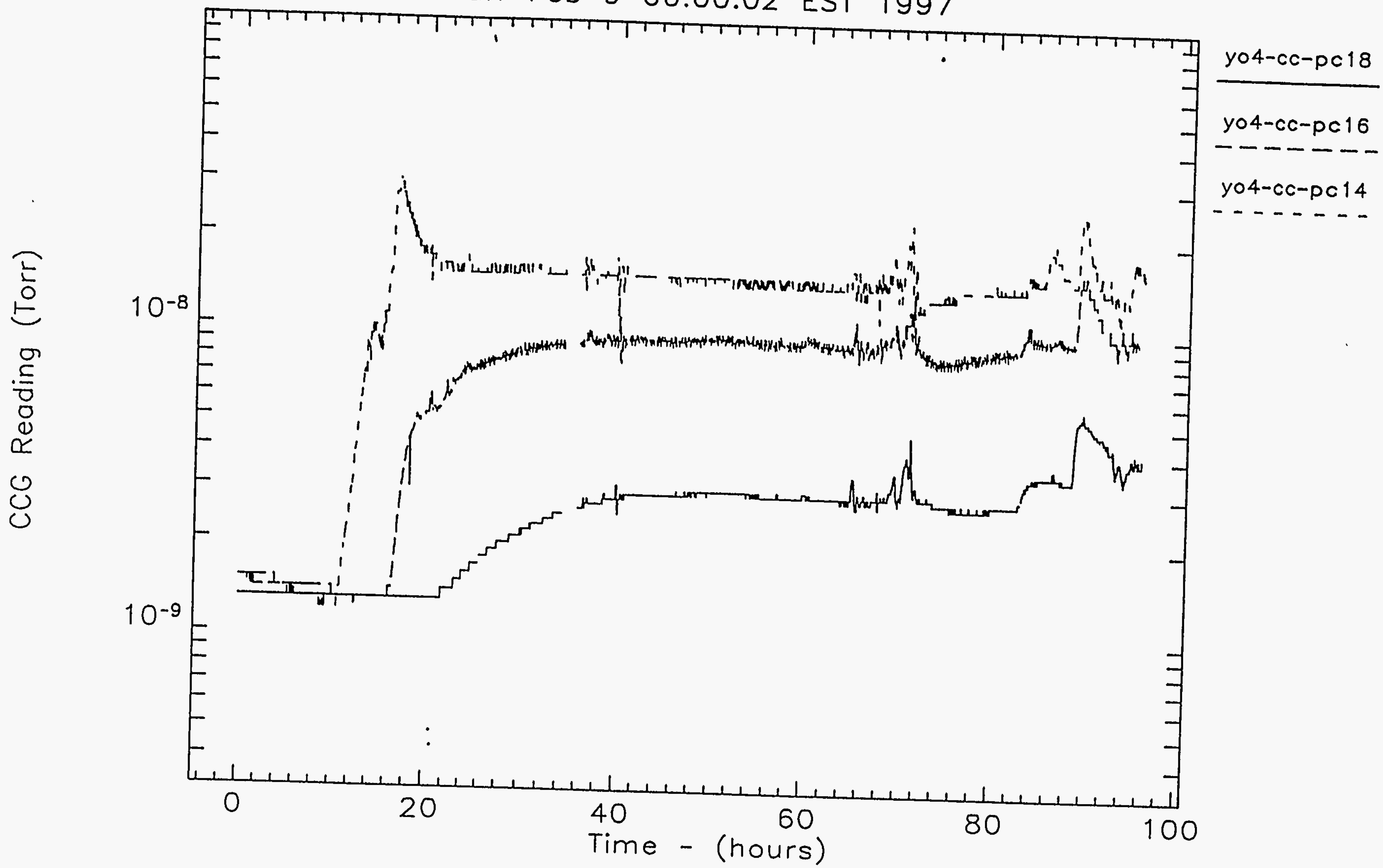
[8]C.D. Ehrich and J.A. Basford, J. Vac. Sci. Technol., A10, 1(1992).

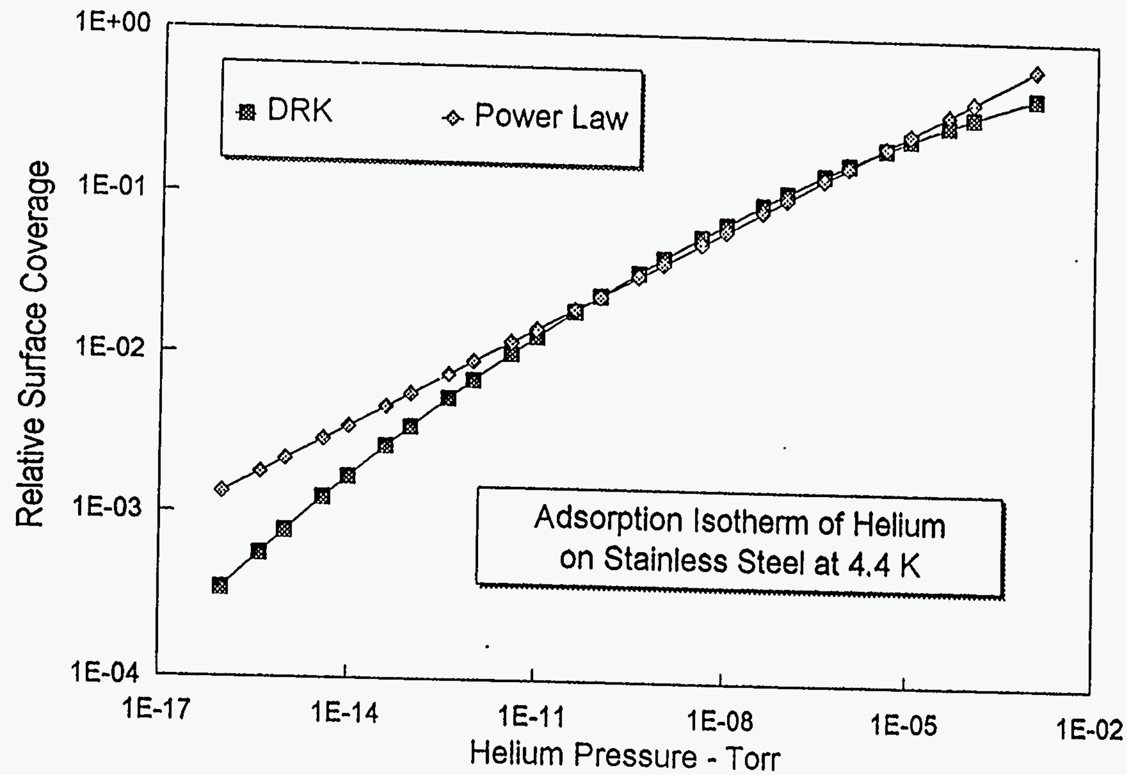
[9]B.R.F. Kendall and E. Drubetsky, J. Vac. Sci. Technol., A15, 740(1997).

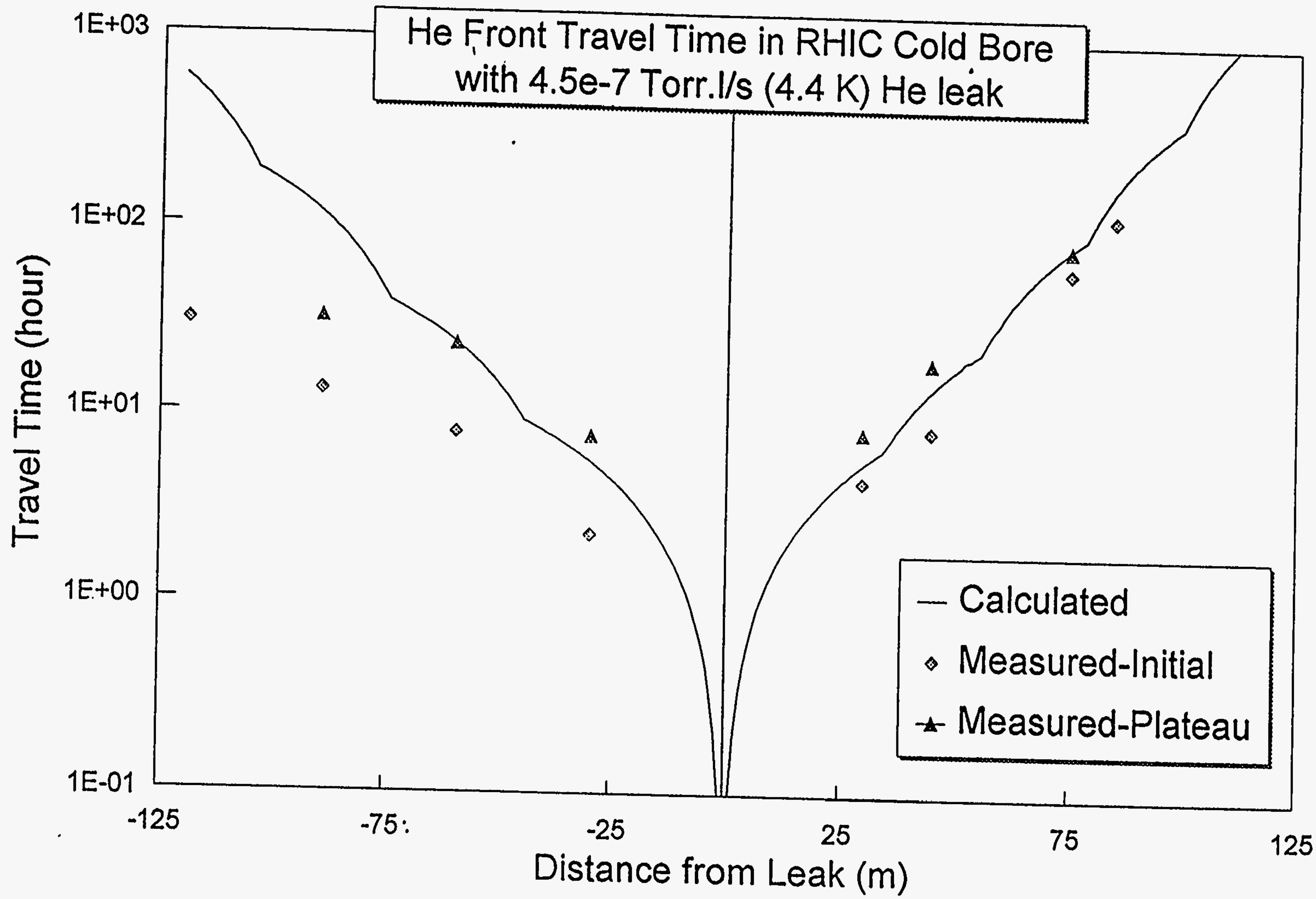

PC20
119
PC18
89
PC16
59
PC14
30
PC12
0
He
LEAK
PC10
30
PC9
45
PC7
75
PC6
85
20°C
4.4° k
Q
Q
6.9 cm ID
104
74
45
15
15
34
55
78
Sorption Pump
Cold Cathode Gauge

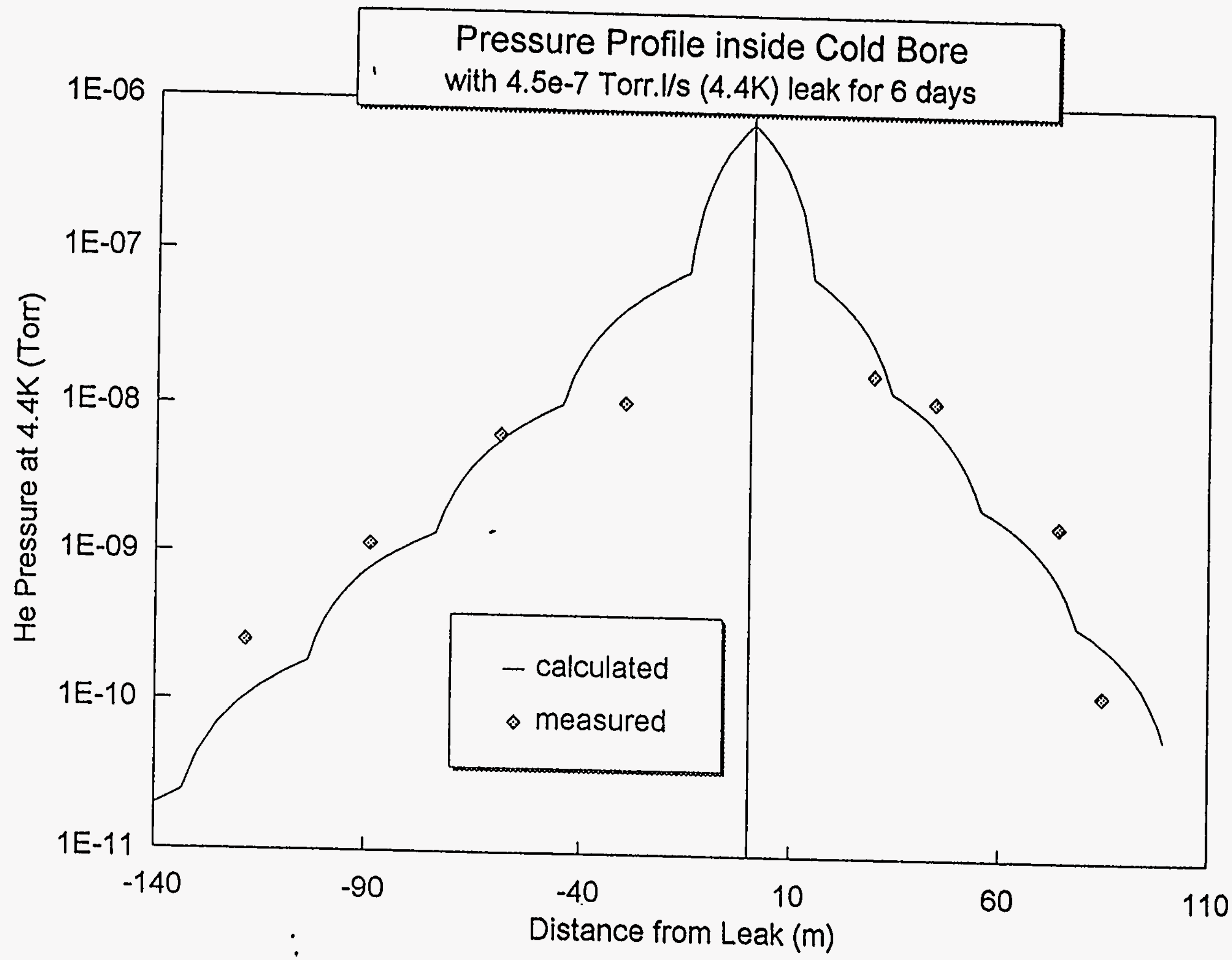

Pressure Toward Right with He leak of 4.5E-7 Torr.l/s (4.4 K) Sep 12 1997 - 0935
Sun Feb 9 00:00:02 EST 1997
CCG Reading (Torr)
10-8
10-9
0
20
40
60
80
100
Time - (hours)
yo4-cc-pc10
yo4-cc-pc9
yo4-cc-pc7

Pressure Toward Left with He leak of 4.5E-7 Torr.l/s (4.4 K) Sep 12 1997 - 1000
Sun Feb 9 00:00:02 EST 1997




DRK
Power Law
Adsorption Isotherm of Helium
on Stainless Steel at 4.4 K
1E+00
1E-01
1E-02
1E-03
1E-04
Relative Surface Coverage
1E-17
1E-14
1E-11
1E-08
1E-05
1E-02
Helium Pressure - Torr


He Front Travel Time in RHIC Cold Bore
with 4.5e-7 Torr.l/s (4.4 K) He leak
Travel Time (hour)
1E+03
1E+02
1E+01
1E+00
1E-01
-125
-75
-25
25
75
125
Distance from Leak (m)
Calculated
Measured-Initial
Measured-Plateau



Pressure Profile inside Cold Bore
with 4.5e-7 Torr.l/s (4.4K) leak for 6 days
He Pressure at 4.4K (Torr)
1E-06
1E-07
1E-08
1E-09
1E-10
1E-11
-140
-90
-40
10
60
110
Distance from Leak (m)
calculated
measured