Residual Gas in the LIGO Beam Tubes: Science, Arts and Recipes

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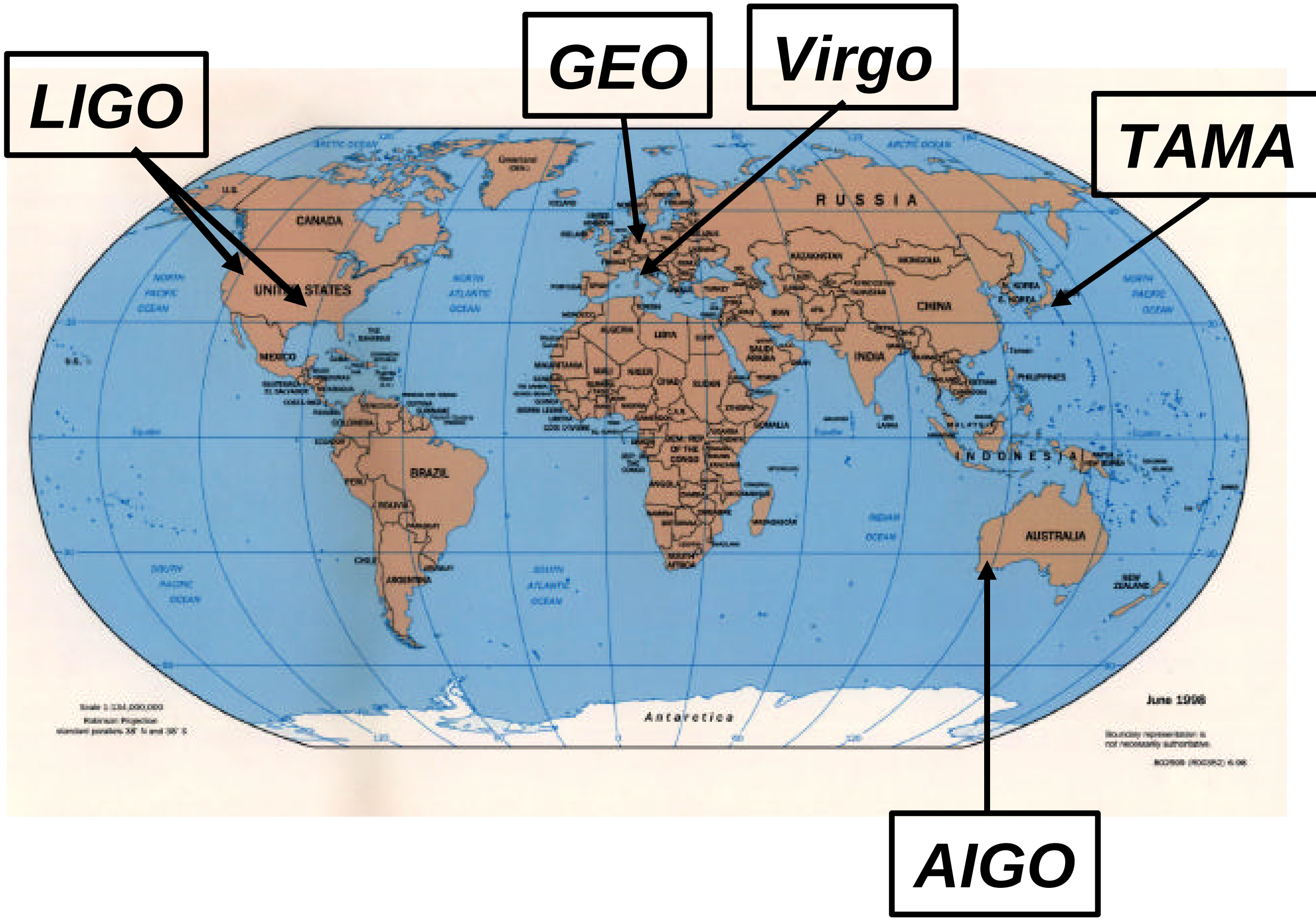
on behalf of the LIGO project and CBI

American Vacuum Society
Baltimore November 5, 2003

LIGO-G030701-00-Z

Interferometers
international network

Simultaneously detect signal (within msec)

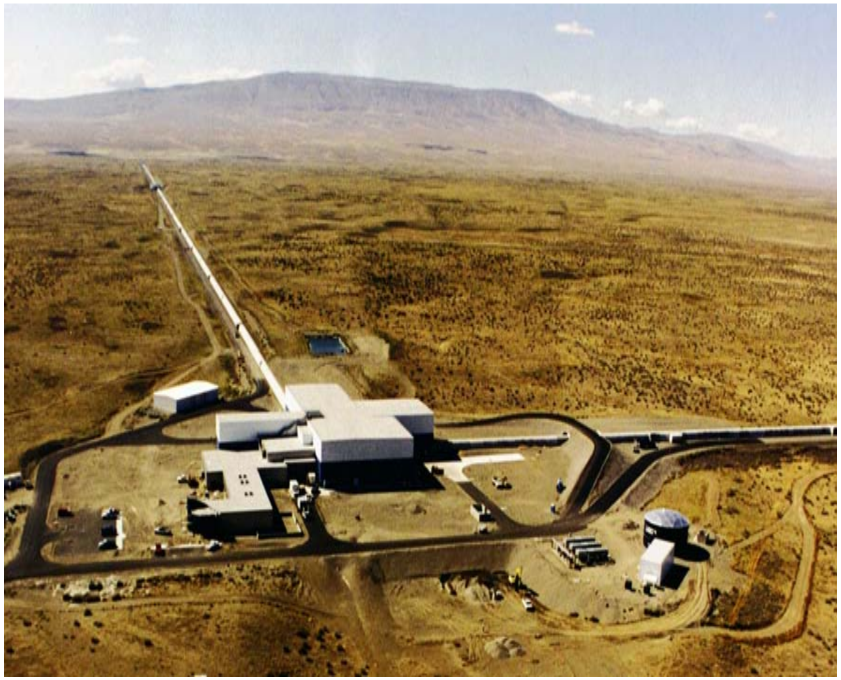


detection confidence

locate the sources

decompose the polarization of gravitational waves

LIGO Observatory Facilities



LIGO Hanford Observatory [LHO]

26 km north of Richland, WA

2 km + 4 km interferometers in same vacuum envelope

LIGO Livingston Observatory [LLO]

42 km east of Baton Rouge, LA

Single 4 km interferometer

Beam Tubes and Enclosures

Precast concrete enclosure

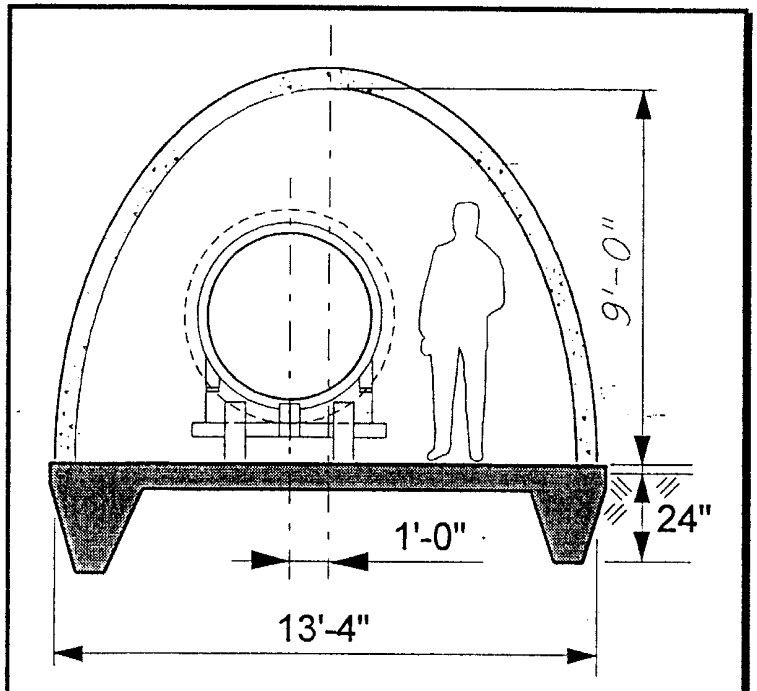
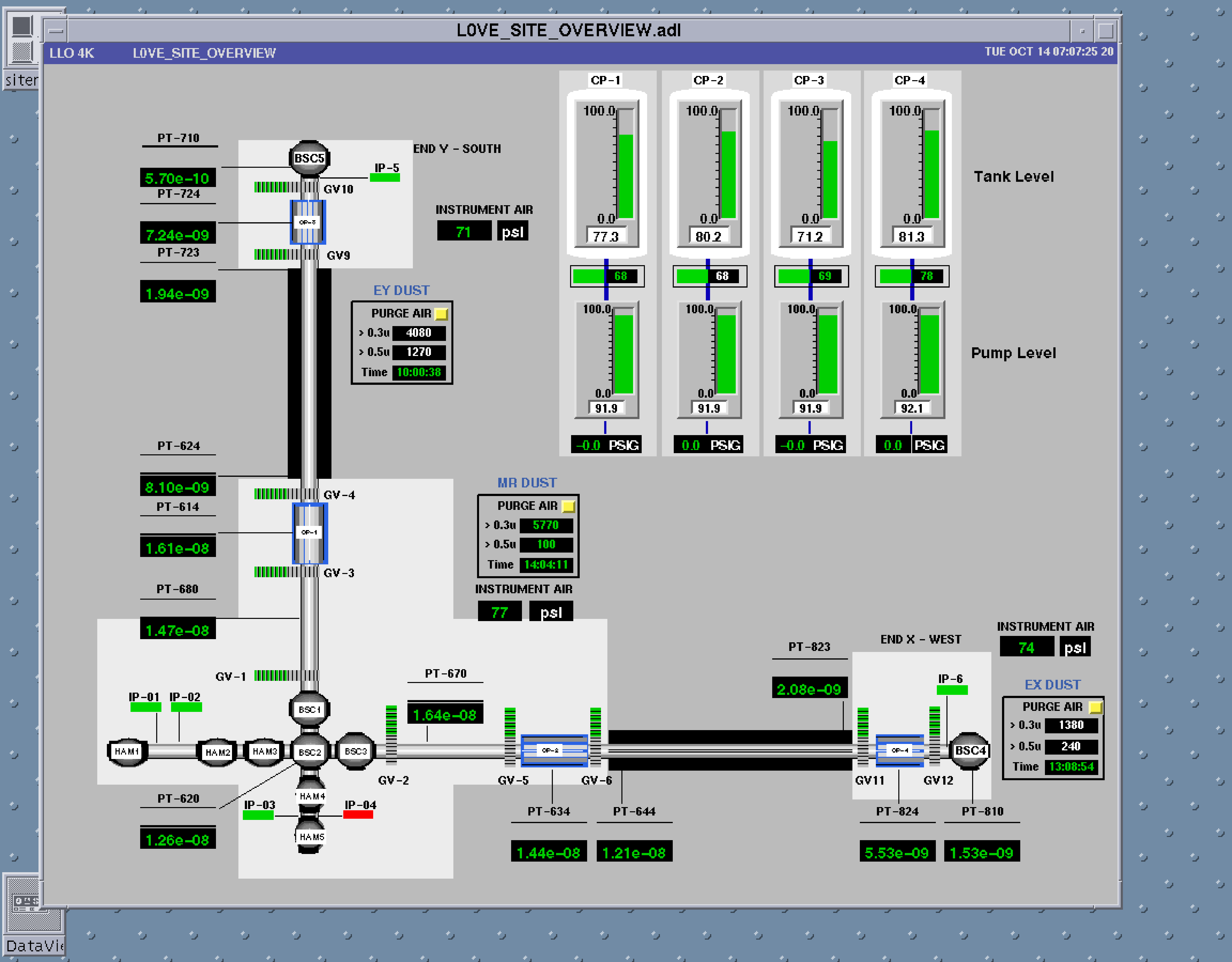


Figure 2.1-1 -- Cross Section of Design Baseline at Hanford

- **Beam Tube**
  - **1.2m diam; 3 mm stainless**
  - **special low-hydrogen steel process**
  - **65 ft spiral weld sections**
  - **50 km of weld (NO LEAKS!)**
  - **In situ 160 C bakeout**
  - **20,000 m^3 @ 10^{-8} to 10^{-9} torr**

LIGO
vacuum equipment



LOVE_SITE_OVERVIEW.adl
LLO 4K
LOVE_SITE_OVERVIEW
TUE OCT 14 07:07:25 20
CP-1
CP-2
CP-3
CP-4
100.0
0.0
77.3
80.2
71.2
81.3
68
68
69
78
91.9
91.9
91.9
92.1
-0.0 PSIG
0.0 PSIG
-0.0 PSIG
0.0 PSIG
Tank Level
Pump Level
PT-710
5.70e-10
PT-724
7.24e-09
PT-723
1.94e-09
BSC5
IP-5
GV10
GV9
END Y - SOUTH
INSTRUMENT AIR
71
psi
EY DUST
PURGE AIR
> 0.3u 4080
> 0.5u 1270
Time 10:00:38
PT-624
8.10e-09
PT-614
1.61e-08
GV-4
GV-3
PT-680
1.47e-08
MR DUST
PURGE AIR
> 0.3u 5770
> 0.5u 100
Time 14:04:11
INSTRUMENT AIR
77
psi
GV-1
IP-01
IP-02
HAM1
HAM2
HAM3
BSC1
BSC2
BSC3
HAM4
HAM5
PT-670
1.64e-08
GV-2
GV-5
GV-6
PT-620
1.26e-08
IP-03
IP-04
PT-634
1.44e-08
PT-644
1.21e-08
PT-823
2.08e-09
END X - WEST
INSTRUMENT AIR
74
psi
IP-6
BSC4
GV11
GV12
EX DUST
PURGE AIR
> 0.3u 1380
> 0.5u 240
Time 13:08:54
PT-824
5.53e-09
PT-810
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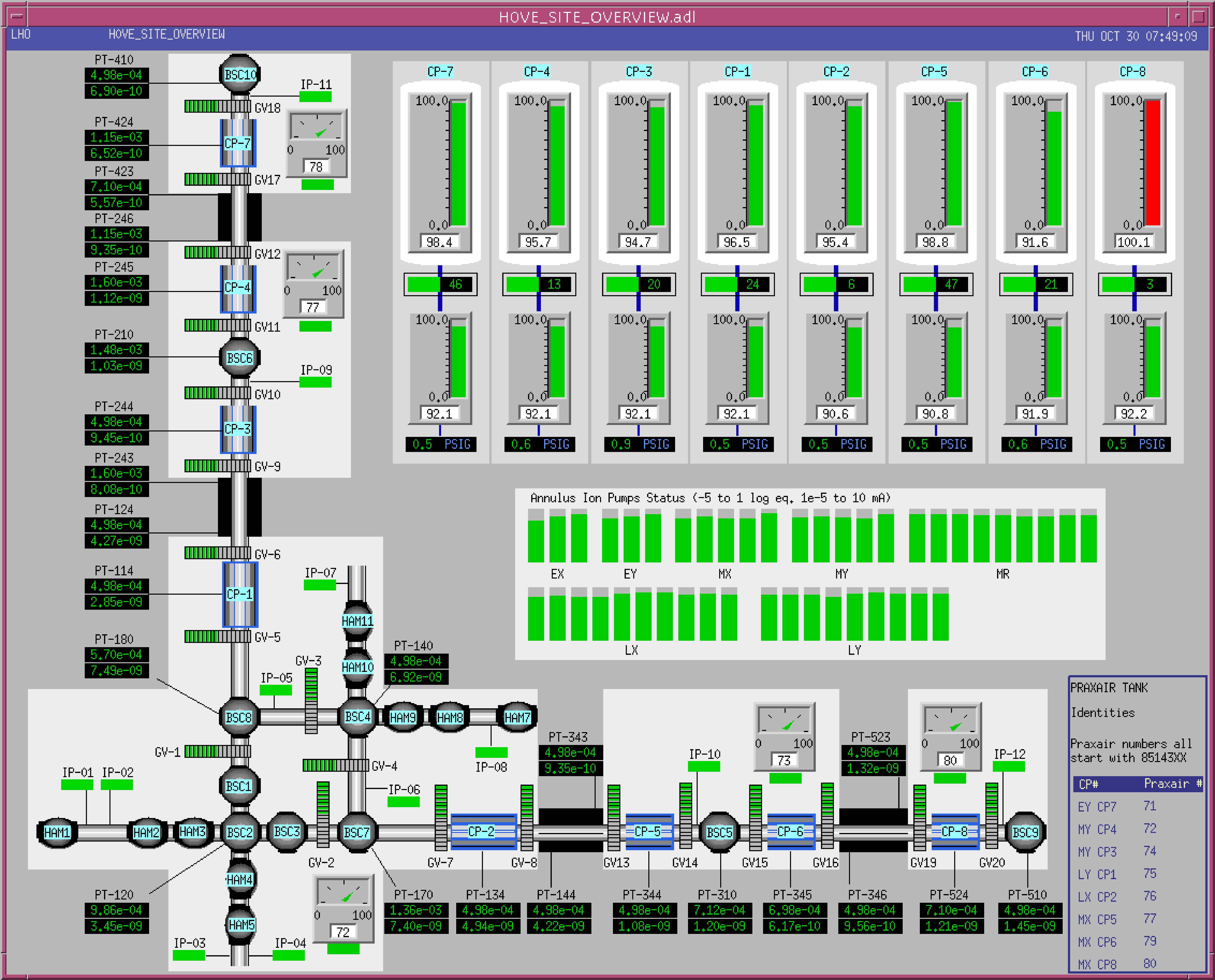
siter
DataVi


HOVE_SITE_OVERVIEW.adl
LHO
HOVE_SITE_OVERVIEW
THU OCT 30 07:49:09
PT-410
4.98e-04
6.90e-10
BSC10
IP-11
GV18
PT-424
1.15e-03
6.52e-10
CP-7
0
100
78
PT-423
7.10e-04
5.57e-10
GV17
PT-246
1.15e-03
9.35e-10
GV12
PT-245
1.60e-03
1.12e-09
CP-4
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GV11
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BSC6
IP-09
GV10
PT-244
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GV-6
PT-114
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2.85e-09
CP-1
IP-07
HAM11
GV-5
PT-180
5.70e-04
7.49e-09
HAM10
PT-140
4.98e-04
6.92e-09
GV-3
IP-05
BSC8
BSC4
HAM9
HAM8
HAM7
GV-1
GV-4
IP-08
IP-01
IP-02
BSC1
IP-06
HAM1
HAM2
HAM3
BSC2
BSC3
BSC7
HAM4
GV-2
PT-120
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3.45e-09
HAM5
0
100
72
IP-03
IP-04
PT-170
1.36e-03
7.40e-09
CP-7
100.0
0.0
98.4
46
100.0
0.0
92.1
0.5 PSIG
CP-4
100.0
0.0
95.7
13
100.0
0.0
92.1
0.6 PSIG
CP-3
100.0
0.0
94.7
20
100.0
0.0
92.1
0.9 PSIG
CP-1
100.0
0.0
96.5
24
100.0
0.0
92.1
0.5 PSIG
CP-2
100.0
0.0
95.4
6
100.0
0.0
90.6
0.5 PSIG
CP-5
100.0
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98.8
47
100.0
0.0
90.8
0.5 PSIG
CP-6
100.0
0.0
91.6
21
100.0
0.0
91.9
0.6 PSIG
CP-8
100.0
0.0
100.1
3
100.0
0.0
92.2
0.5 PSIG
Annulus Ion Pumps Status (-5 to 1 log eq. 1e-5 to 10 mA)
EX
EY
MX
MY
MR
LX
LY
PT-343
4.98e-04
9.35e-10
IP-10
0
100
73
PT-523
4.98e-04
1.32e-09
0
100
80
IP-12
CP-2
CP-5
BSC5
CP-6
CP-8
BSC9
GV-7
GV-8
GV13
GV14
GV15
GV16
GV19
GV20
PT-134
4.98e-04
4.94e-09
PT-144
4.98e-04
4.22e-09
PT-344
4.98e-04
1.08e-09
PT-310
7.12e-04
1.20e-09
PT-345
6.98e-04
6.17e-10
PT-346
4.98e-04
9.56e-10
PT-524
7.10e-04
1.21e-09
PT-510
4.98e-04
1.45e-09
PRAXAIR TANK
Identities
Praxair numbers all
start with 85143XX
CP# Praxair #
EY CP7 71
MY CP4 72
MY CP3 74
LY CP1 75
LX CP2 76
MX CP5 77
MX CP6 79
MX CP8 80

LIGO Beam Tubes

- Interaction region between gravitational waves and laser interferometers
  - ›› 16 km of vacuum tubing at two sites
  - ›› initial detectors require 10^{-7} torr
  - ›› ultimate detectors require 10^{-10} torr
  - ›› needs to be economical
    - – minimal pumping, exploit passive nature of system
    - – new welding techniques - continuous spiral weld in 304L
    - – low outgassing materials - air bake to reduce hydrogen outgassing, total low 150C bake to reduce water and heavier molecule outgassing
    - – mass production cleaning
    - – global positioning system alignment

BEAM TUBE SCIENTIFIC REQUIREMENTS

- VACUUM REQUIREMENTS
  - ›› Residual gas
    - – Leak requirements
  - ›› Contamination
  - ›› Operational requirements
    - – Pump down time
    - – Isolation from chambers
    - – Reliability
- MECHANICAL AND OPTICAL REQUIREMENTS
  - ›› Clear Aperture
  - ›› Forward and Backscatter from walls and baffles
  - ›› Motion of tube walls and baffles

BEAM TUBE REQUIREMENTS

- LEAK LIMITS
  - ››Component Level
    - – 1 x 10^{-10} torr liters/sec
  - ››2 km module with 2500 liter/sec end pumps
    - – 1 x 10^{-9} torr liters/sec
- CONTAMINATION ON OPTICS
  - ›› less than 1 monolayer of hydrocarbon/month

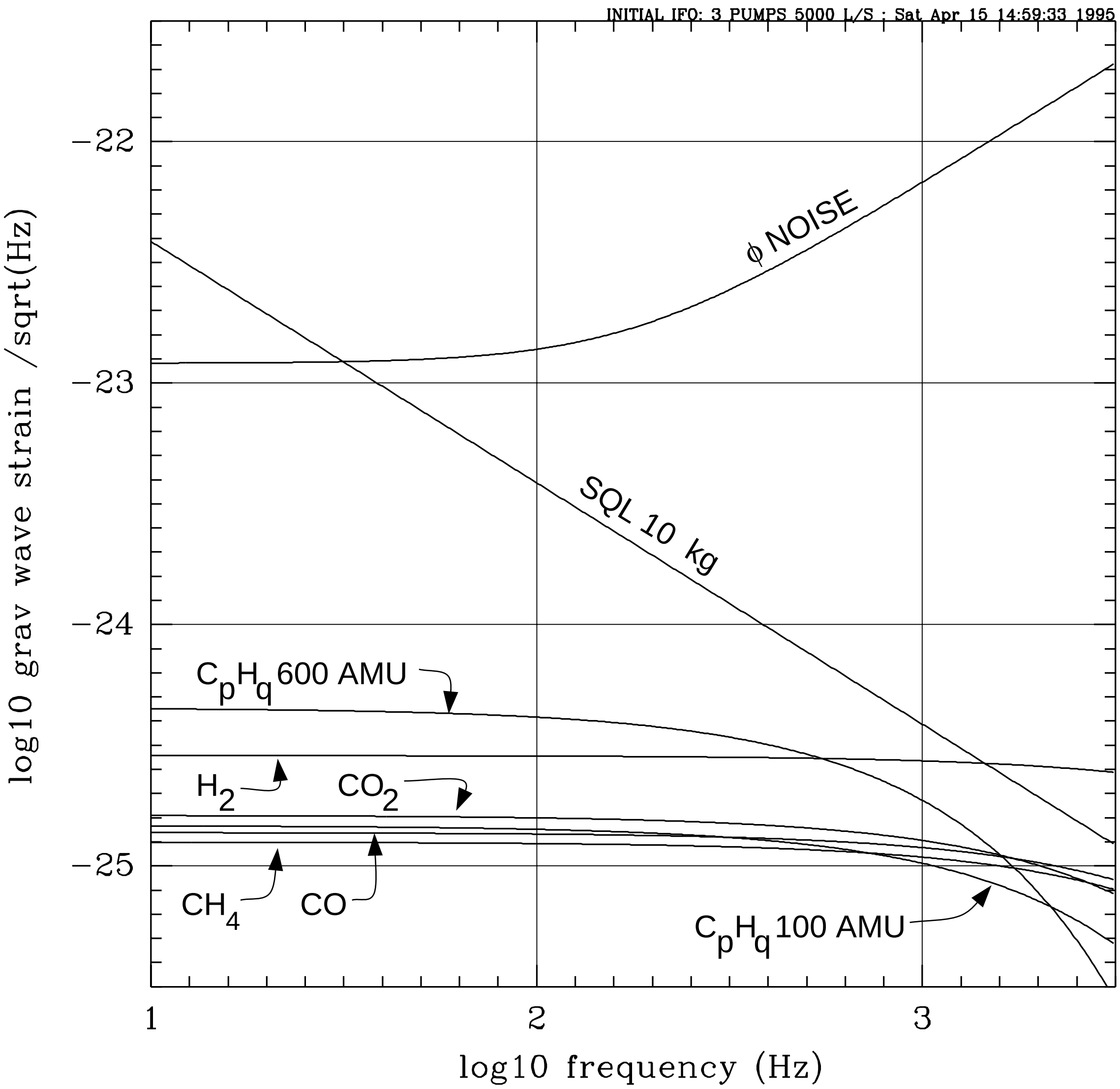
BEAM TUBE REQUIREMENTS

- OPERATIONAL REQUIREMENTS
  - ›› Time to reach required pressure < 2 months
  - ›› Capability to isolate beamtubes from chambers
  - ›› Reliability: leak free state for > 20 years
- MECHANICAL AND OPTICAL REQUIREMENTS
  - ›› Unobstructed aperture 1 meter
  - ›› Backscatter from baffles and tube between 0.5 to 1 micron wavelengths < 2 x 10^{-3} sr^{-1} for angles of incidence greater than 45 degrees
  - ›› Motion of tubes at baffles not to exceed 2 x the ambient seismic noise except in narrow bands

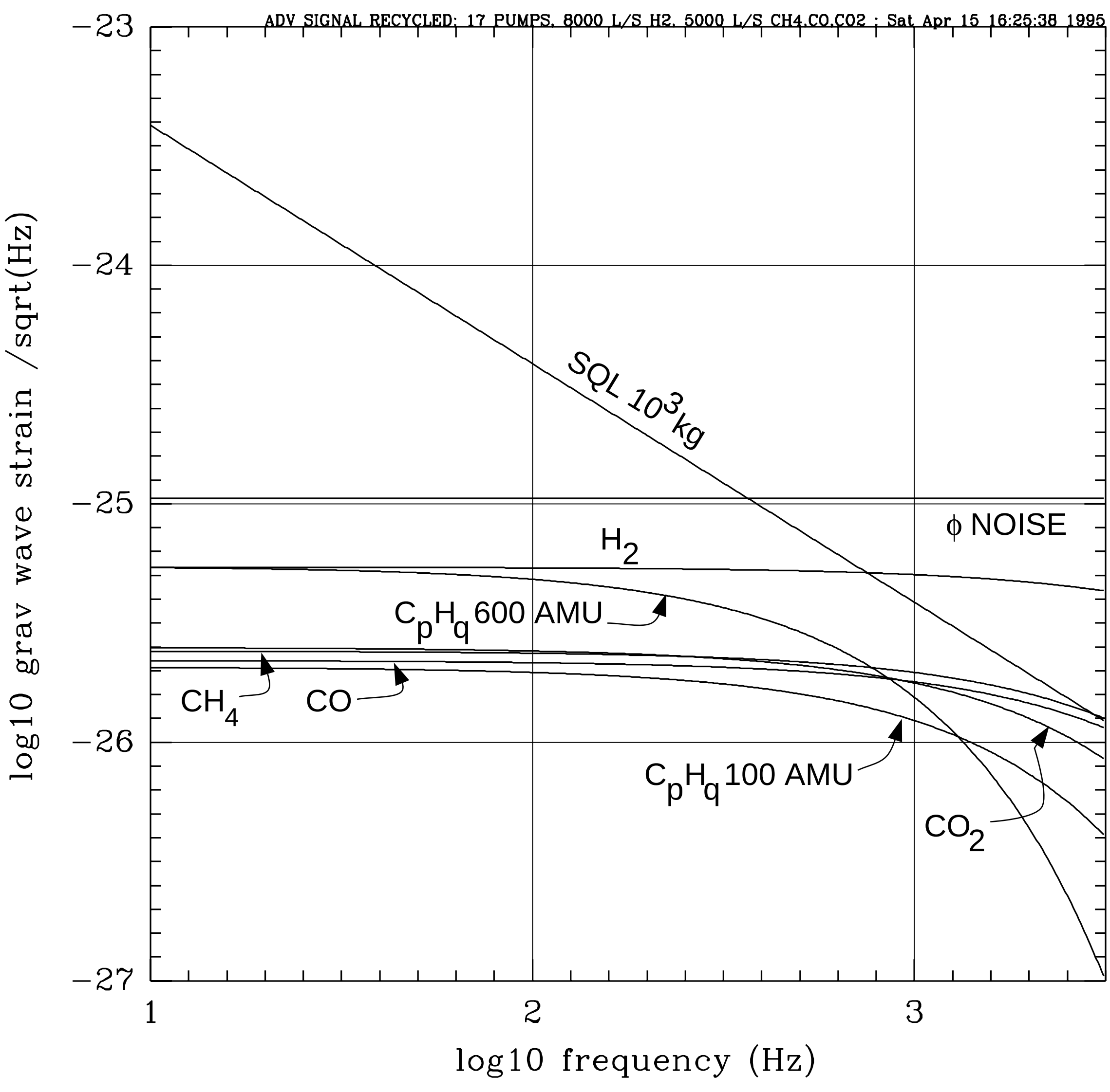
Beam Tube Properties

module length	2 km
25 cm diameter pump ports/module	9
radius of beam tube	62 cm
volume of module	4.831×10^{6} liters
area of module	1.55×10^{8} cm^2
initial pumping speed/surface area	1.94×10^{-5} liters/sec/cm^2
length/short section	1.90×10^{3} cm
wall thickness	3.23×10^{-1} cm
stiffener ring spacing	76 cm
stiffening ring width	4.76×10^{-1} cm
stiffening ring height	4.45 cm
expansion joint wall thickness	2.67×10^{-1} cm
expansion joint convolutions	9
expansion joint longitudinal spring rate	1.5×10^{9} dynes/cm

Initial Interferometer Noise Budget



Advanced Interferometer Noise Budget



Advanced amplitude recycled interferometer parameters:

$A_m = 10^{-5}$

$P_{in} = 100$ W $\qquad P_{circ} \sim 1$ MW

$\varepsilon_{opt} = 0.3$

$\lambda = 1.06\ \mu$

BEAM TUBE BAKEOUT

- Requirements and goals
  - ›› Initial interferometer residual gas phase noise (100Hz)

$$h(f) < 5\times10^{-24}$$

  - ›› Advanced interferometer residual gas phase noise (100Hz)

$$h(f) < 1.5\times10^{-25}$$

  - ›› Relation bewteen pressure and phase noise

$$h(f) \; = \; 4.8\times10^{-21} R\left(\frac{x}{H_2}\right)\sqrt{\langle P(torr)\rangle_L}$$

BEAM TUBE BAKEOUT

Table 1: Residual gas phase noise factor and average pressure

Gas Species	$R(x/H_2)$	Requirement (torr)	Goal (torr)
H_2	1.0	1×10^{-6}	1×10^{-9}
H_2O	3.3	1×10^{-7}	1×10^{-10}
N_2	4.2	6×10^{-8}	6×10^{-11}
CO	4.6	5×10^{-8}	5×10^{-11}
CO_2	7.1	2×10^{-8}	2×10^{-11}
CH_4	5.4	3×10^{-8}	3×10^{-11}
AMU 100 hydrocarbon	38.4	7.3×10^{-10}	7×10^{-13}
AMU 200 hydrocarbon	88.8	$1.4x10^{-10}$	$1.4x10^{-13}$
AMU 300 hydrocarbon	146	5×10^{-11}	5×10^{-14}
AMU 400 hydrocarbon	208	$2.5x10^{-11}$	$2.5x10^{-14}$
AMU 500 hydrocarbon	277	1.4×10^{-11}	1.4×10^{-14}
AMU 600 hydrocarbon	345	$9.0x10^{-12}$	$9.0x10^{-15}$

BEAM TUBE BAKEOUT

- Average pressure and outgassing rate

$$\langle p \rangle_L = J\left[\frac{2\pi a L}{nF} + \frac{L^2}{4va^2(n-1)^2}\right]$$

- Outgassing rate vs temperature and time

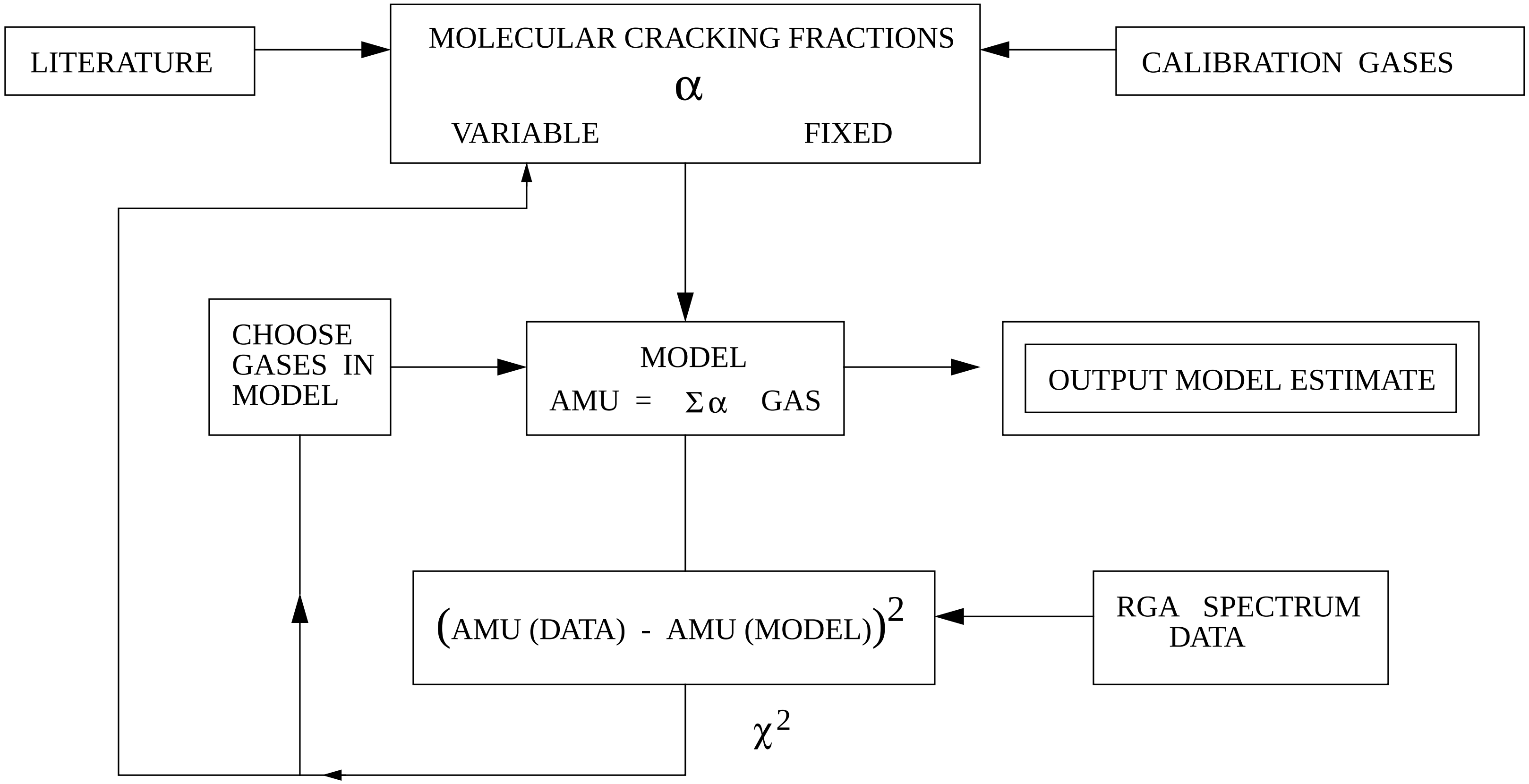
$$J(T) = ae^{-\frac{T_0}{T}}$$

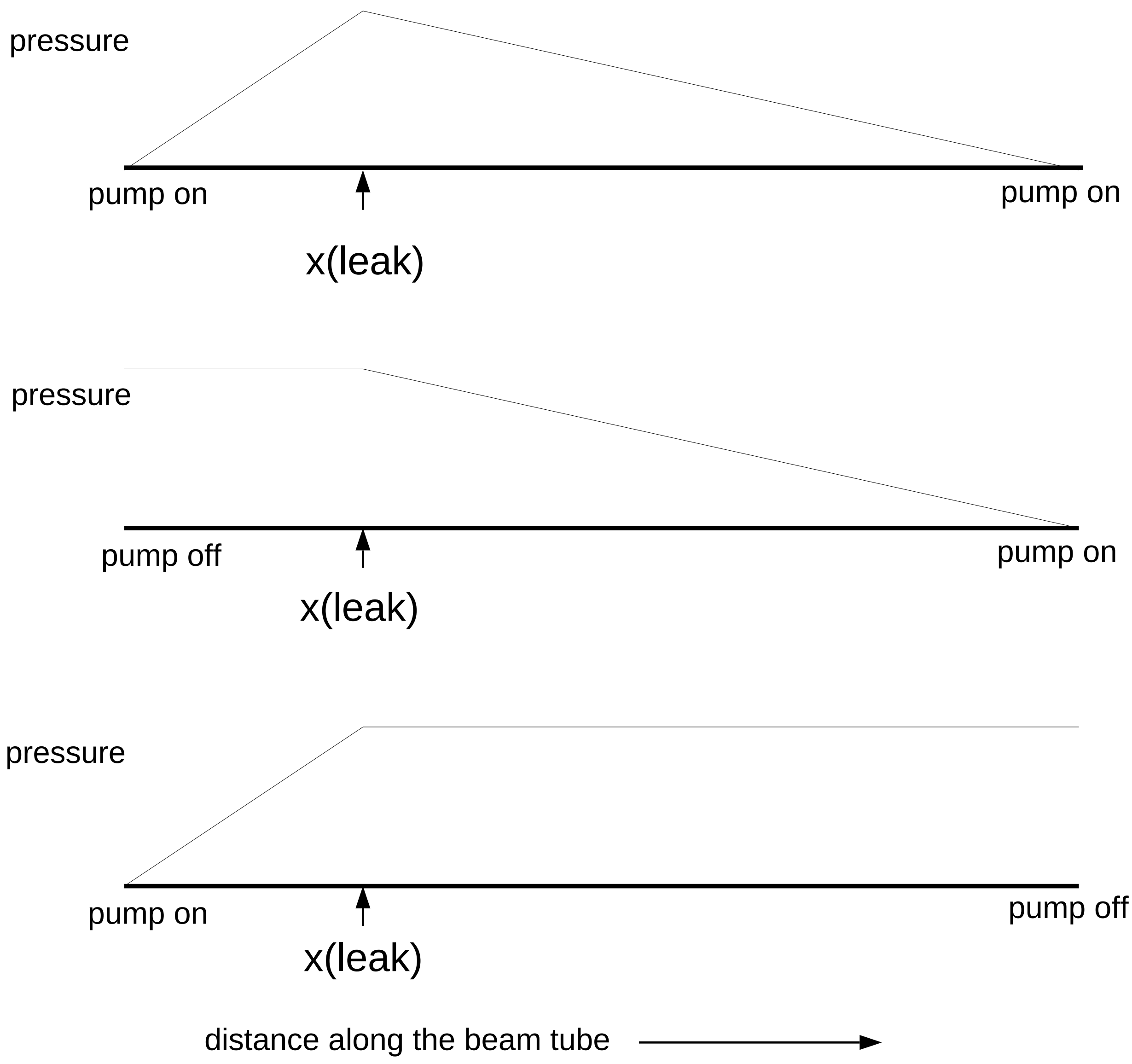
›› Typical: 5000 < T_0 < 10000 K

›› Time dependence

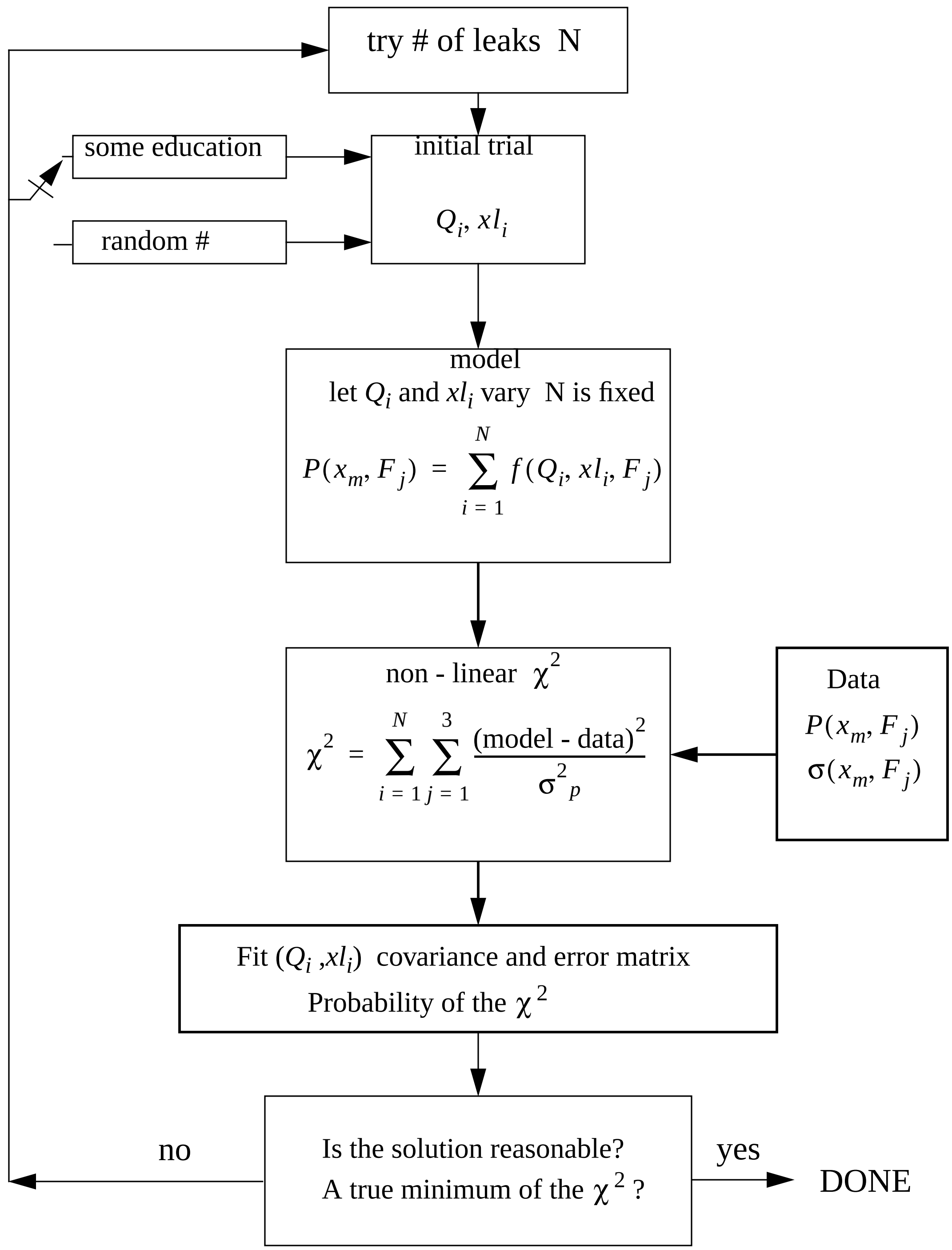
– 1 /t surface adsorption with distribution of binding site energies

– $(1/t)^{0.5}$ diffusion followed by evaporation


LITERATURE
MOLECULAR CRACKING FRACTIONS
α
VARIABLE
FIXED
CALIBRATION GASES
CHOOSE GASES IN MODEL
MODEL
AMU = Σα GAS
OUTPUT MODEL ESTIMATE
(AMU (DATA) - AMU (MODEL))2
RGA SPECTRUM DATA
χ2



Leak pressure profiles in tube



Leak localization algorithm

Beam Tube Cleaning

- Cleaning steps
  - ›› Hot water and detergent - Mirachem 500 spray wash
    - – 30/1 water/Mirachem - 500
    - – 1 cc/ cm^2
  - ›› Steam rinse
    - – 2 cc/ cm^2
    - – 7 - 8.5 atmospheres pressure
    - – 58 - 65 C surface temperature of steel
  - ›› Applied by rotating wand that traverses the tube longitudinally at 20 cm / minute
- Surface analysis
  - ›› Fourier Transform Infrared Spectroscopy FTIR
    - – Sample taken by pouring 2 - isopropanol in strip down tube
    - – Analysis made in professional testing laboratory

Beam Tube Cleaning

›› Auger electron spectroscopy

– Sample strips placed in tube

– Analysis made in surface measurement lab after cleaning

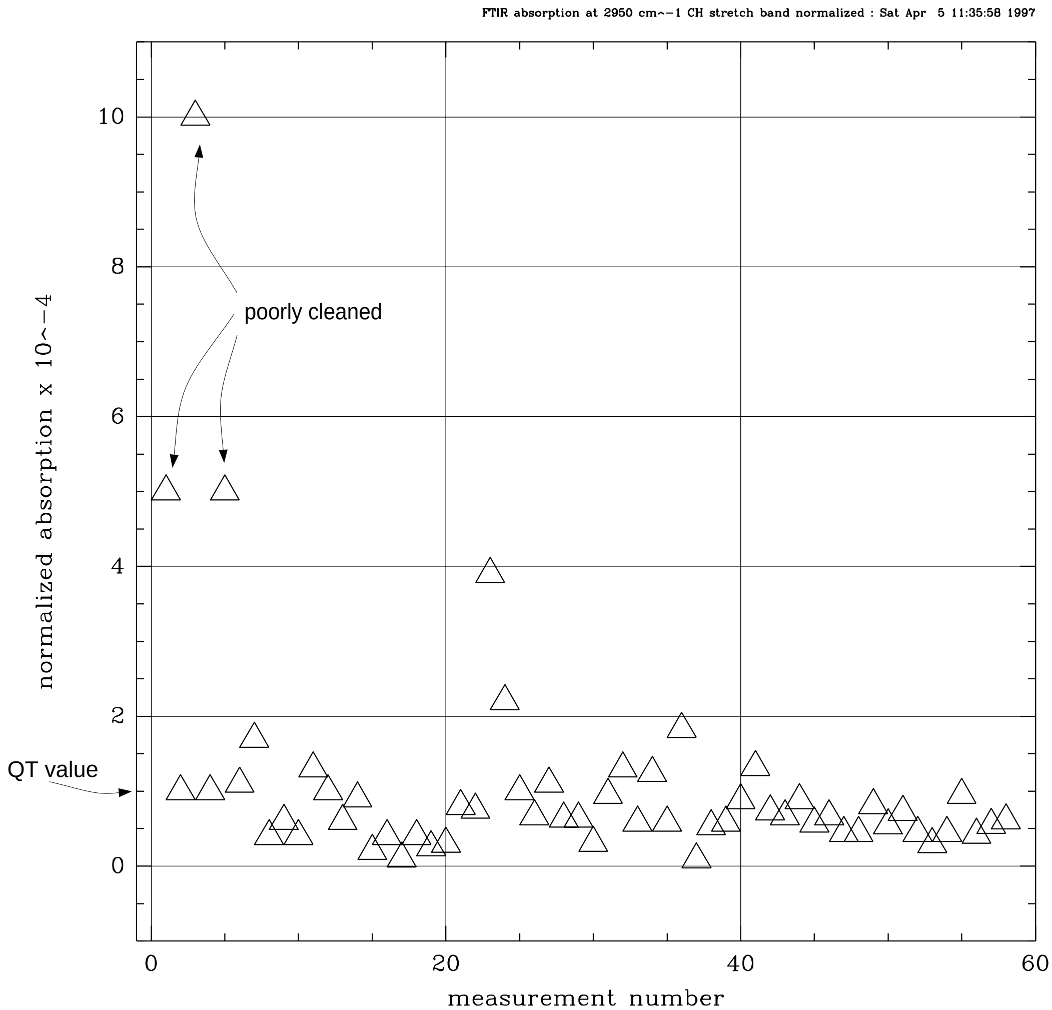
– Sensitive to elemental carbon

– Useful to determine state of rinse by measurement of sodium and calcium

››Water drop adhesion tests

– Qualitative but can be made on location

– Useful in diagnosis of oil layers (poor adhesion) and incomplete rinse of detergent (super adhesion and wetting).



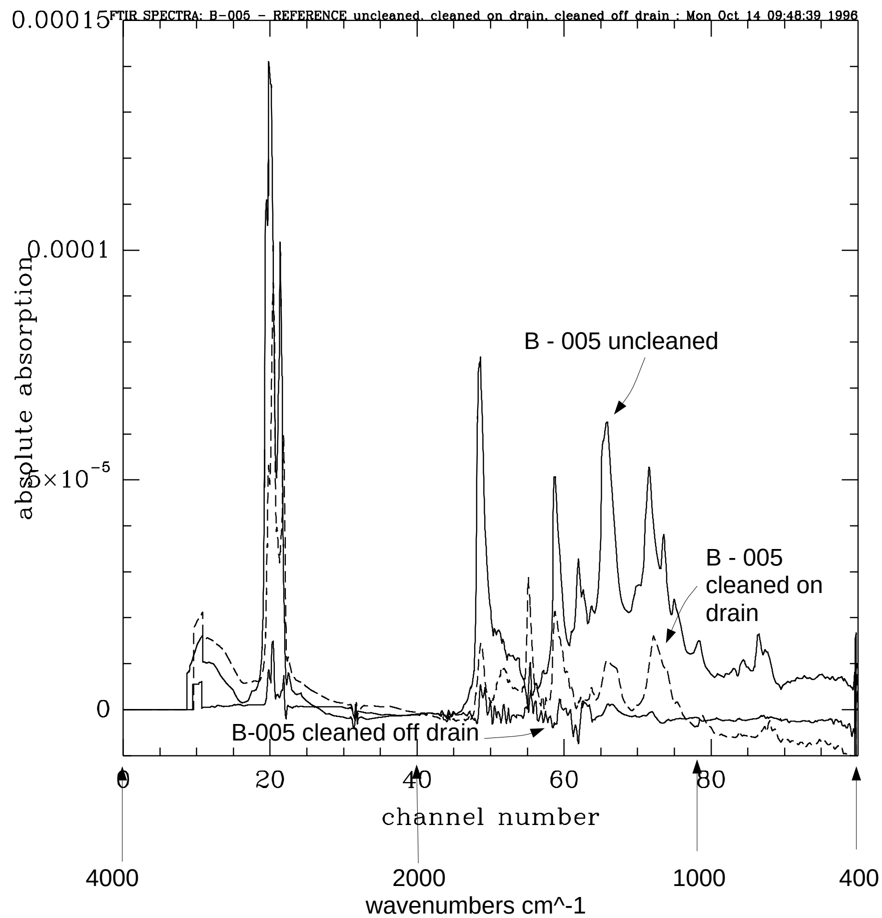
Normalized absorption z at 2950 cm^{-1}

$$z = \frac{(\ln(I/I_0)_{\text{sample}} - \ln(I/I_0)_{\text{reference}}) \times \text{KBr area} \times \text{sample volume in tube}}{\text{sample volume evaporated on KBr} \times \text{area of tube exposed}}$$

Typical values:

Area of tube exposed = 2 x 10^4 cm^2
Sample volume in tube = 2 liters
Sample evaporated = 200 cc
KBr area = 0.6 cm^2

$z \approx 1 \times 10^{-4}$ corresponds to 0.1 monolayer of 100 amu hydrocarbon



Spectra of tube B-005 uncleaned, and cleaned with sample taken along and off the drain line. The off drain sample is more characteristic of the average wall condition. The spectra have had the reference spectrum of the isopropanol subtracted, hence the negative values of the absorption.

Table 1: Auger analysis 270 ev Carbon line given in terms of 10^3 counts in 1.64 minutes vs A^+ milling time

tube # or surface	*condition*	*0 min*	*1 min*	*2 min*	*3 min*	*4 min*
22B	uncl	57.4	24.3	16.5	11.8	10.8
22B	cl	26.1	8.1	6.5	4.4	5.1
B-005	uncl	59.5	17.6	10.6	8.3	7.1±1.0
B-005	cl 1	24.3	5.2	2.3	1.0±1.0	0.0±1.0
B-005	cl 2	21.9	6.7	2.1	1.0±1.0	0.0±1.0
Oxidized	super cl	35.1	22.1	3.0	2.7±1.0	2.4±1.0
smooth	super cl	27.9	2.9	0.0±1.0		
rough	oily	61.9	64.9	63.2	62.3	62.3

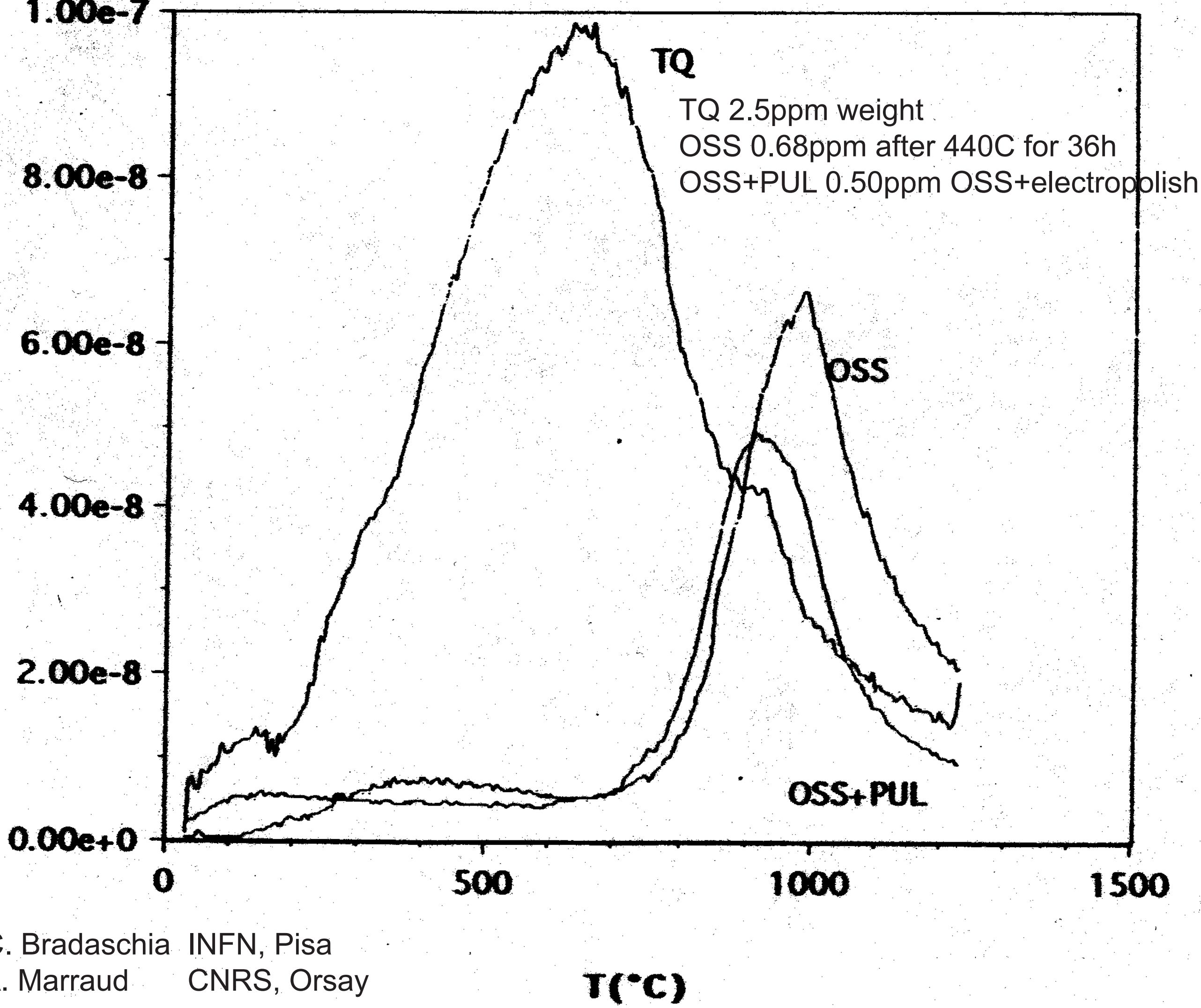
Conditions:

Incident electron energy = 5kV
Incident electron current = 100nA
Ion milling energy = 2kV
Ion current density = 10µ A/cm^2

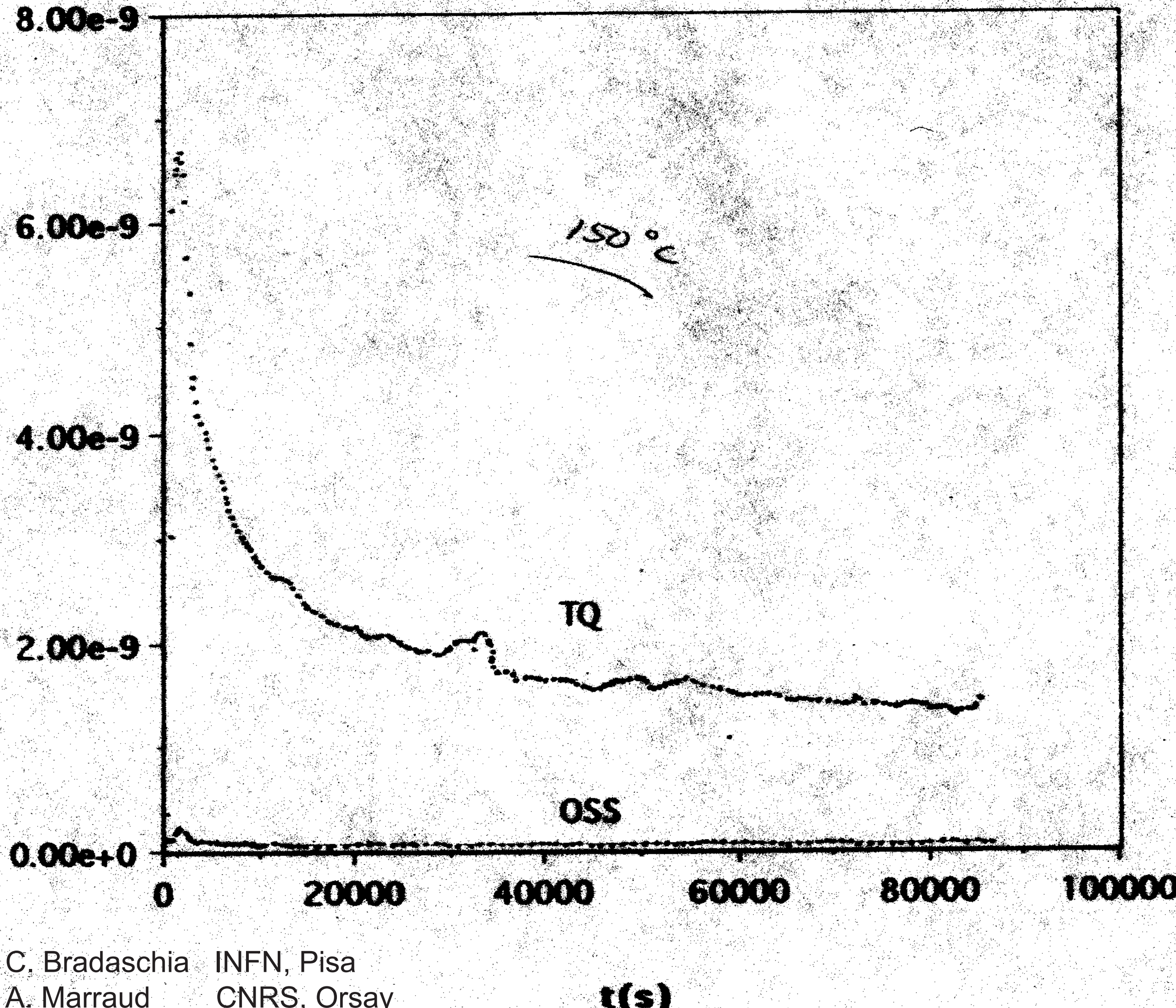
5 x 10^4 counts of 270 ev electrons in 1.64 sec of acquisition time corresponds to 1 monolayer of carbon bearing molecule

Hydrogen Reduction

- Dry air bake at 454C for 36 hours
  - Reduced 1 micron reflectivity of 304 L
  - Max temperature to minimize Carbide formation
- Mechanism:
  - tight (20000K) and loose (5000K) H binding sites
  - reduce density of loosely bound H and J(300K)
  - surface important for recombination (Myers)
  - Oxide layer not a significant factor
- Avoid reintroduction in welding
  - Dry purge gas until weld is cool
  - Clean weld rod



C. Bradaschia INFN, Pisa
A. Marraud CNRS, Orsay



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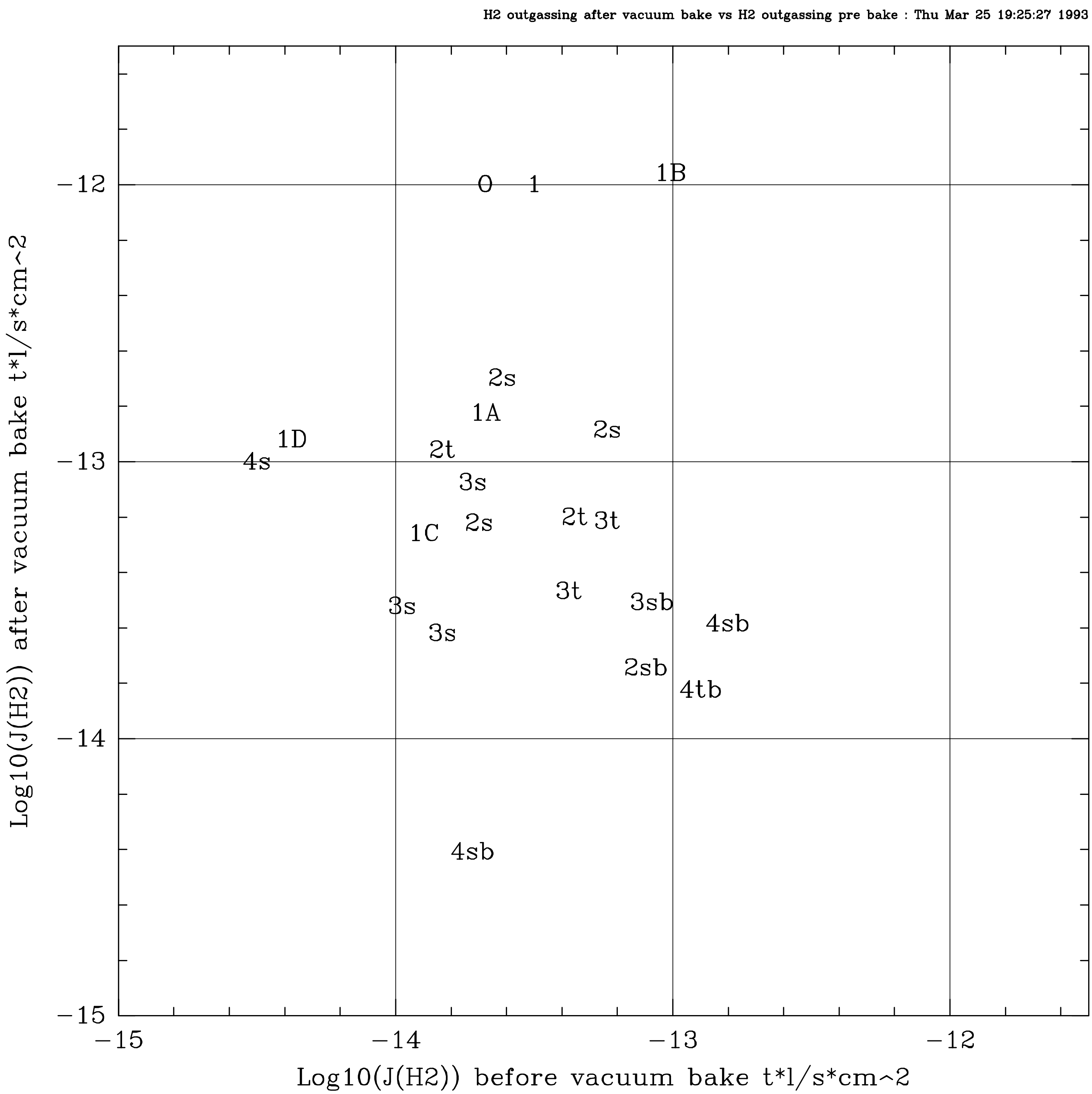
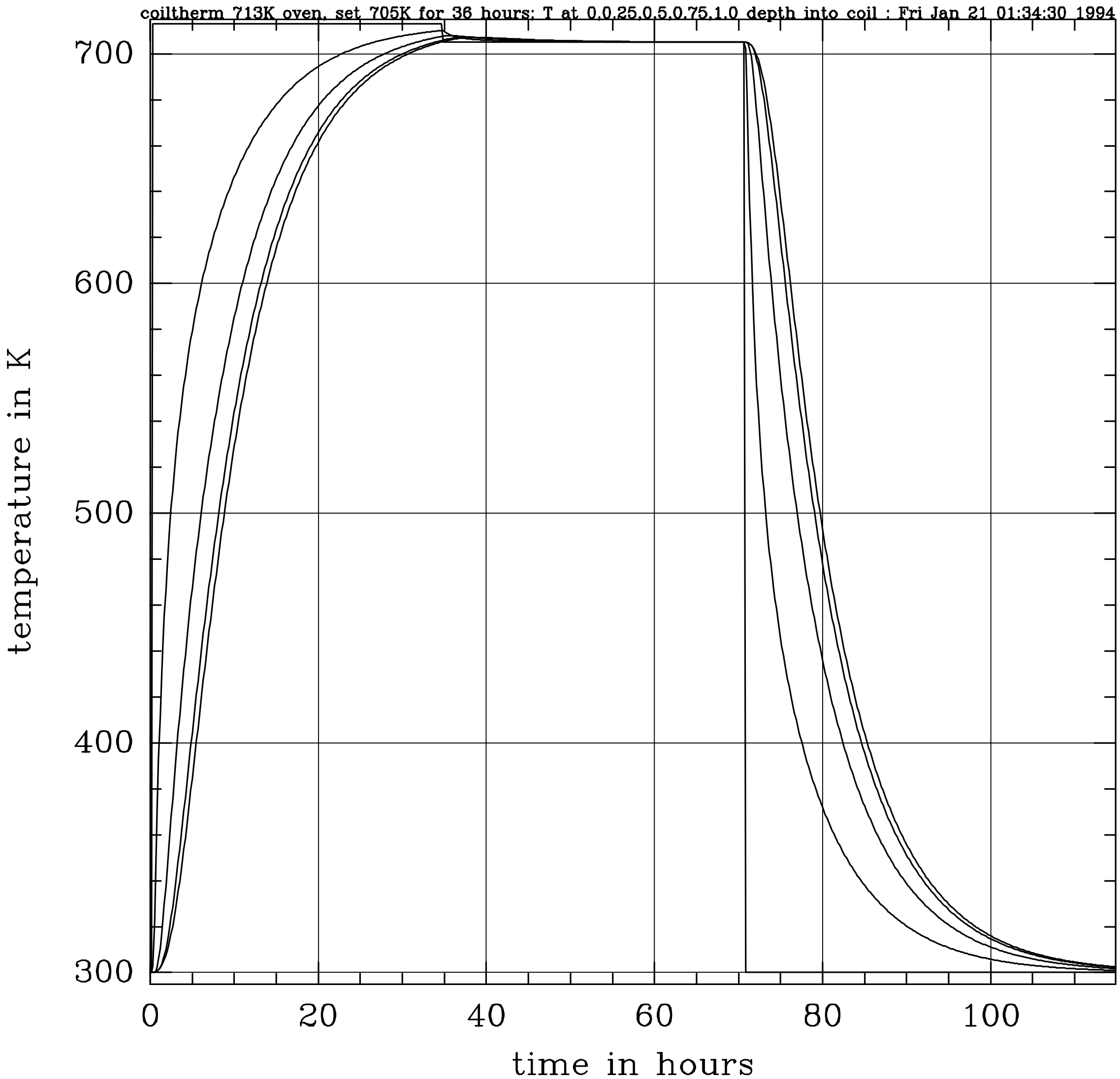
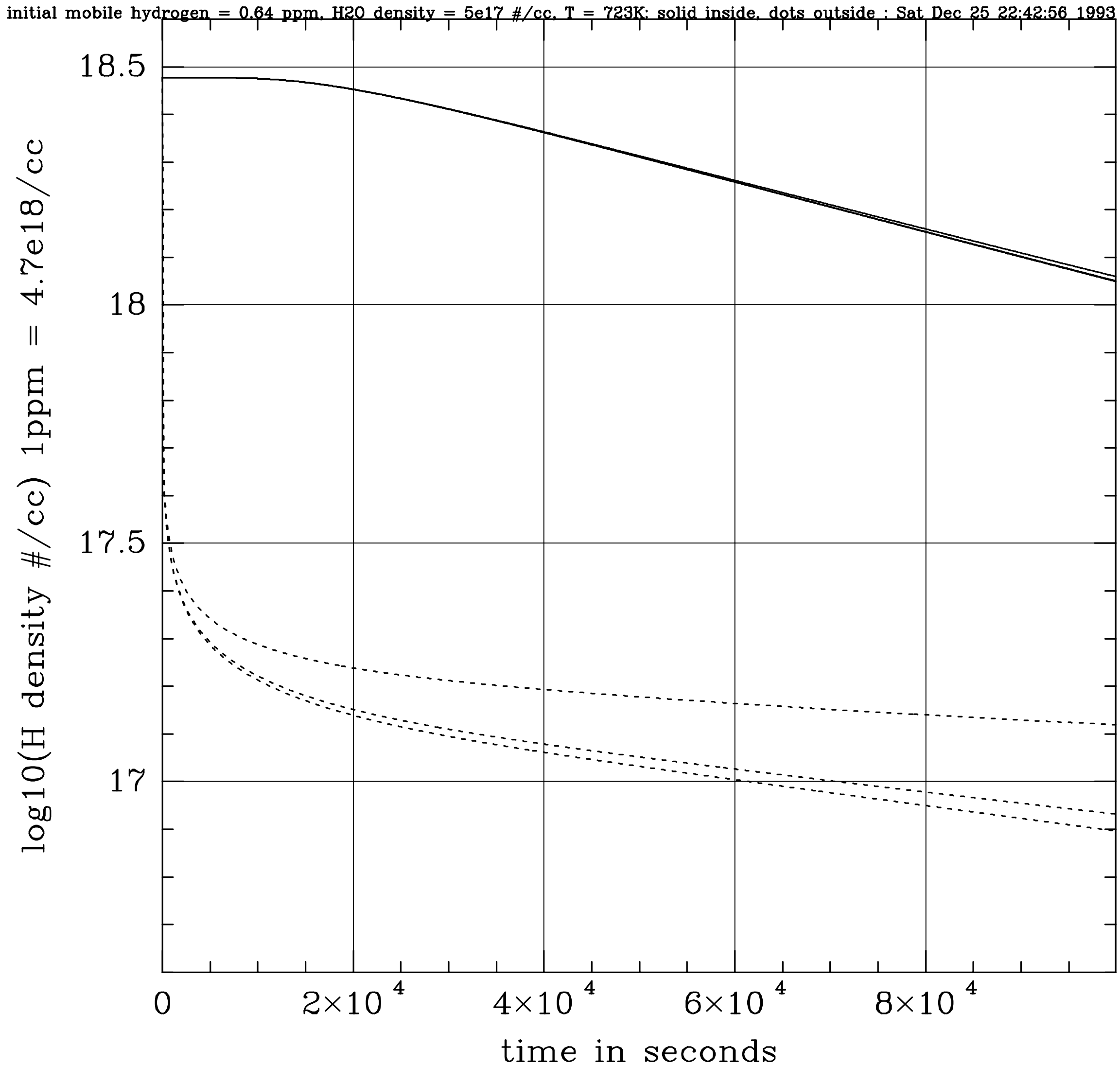
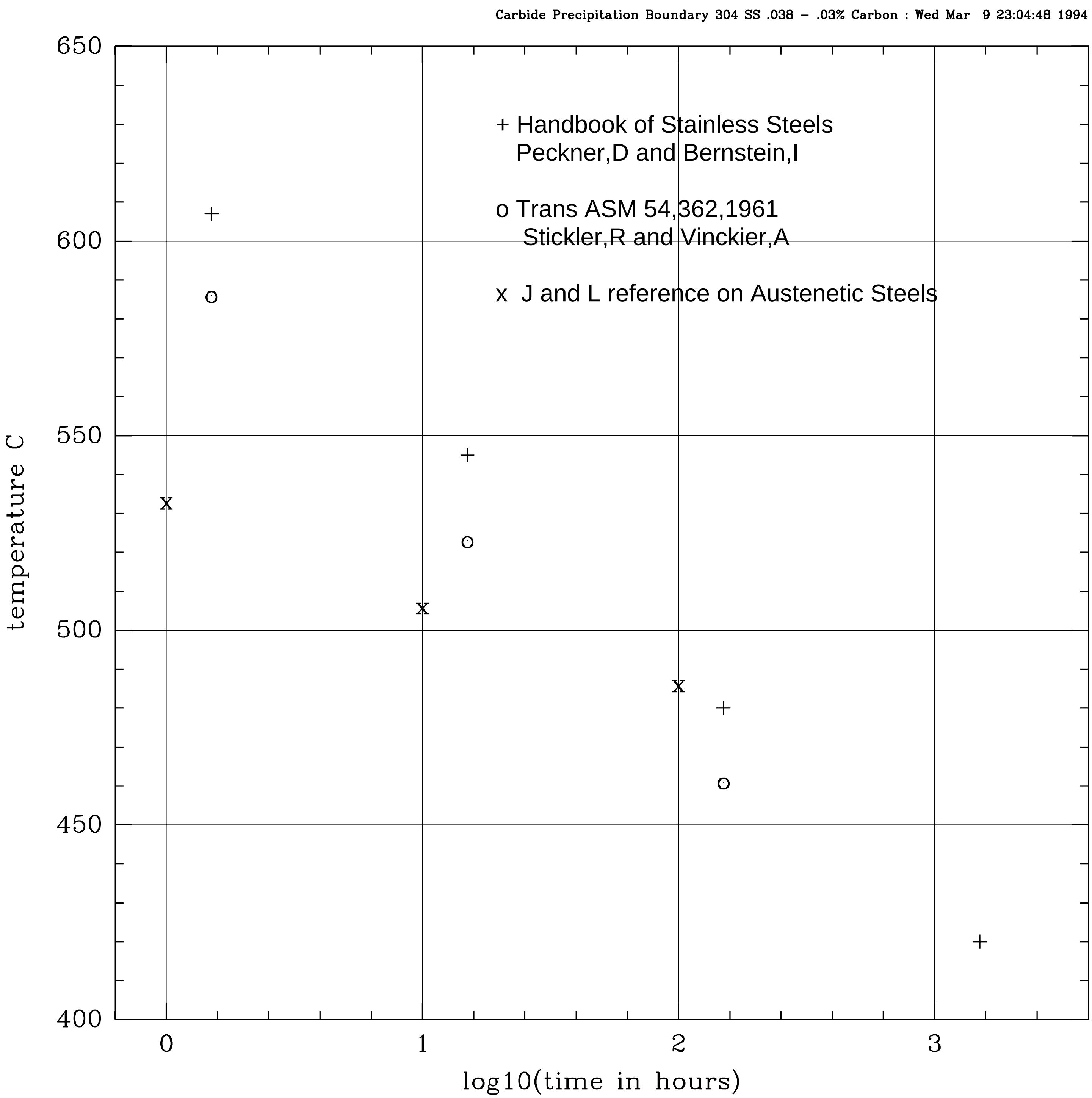

H2 outgassing after vacuum bake vs H2 outgassing pre bake : Thu Mar 25 19:25:27 1993
Log10(J(H2)) after vacuum bake t*l/s*cm^2
Log10(J(H2)) before vacuum bake t*l/s*cm^2
−15
−14
−13
−12
0
1
1B
2s
1A
1D
4s
2t
2s
3s
2t
3t
2s
1C
3t
3sb
3s
4sb
3s
2sb
4tb
4sb


coiltherm 713K oven, set 705K for 36 hours: T at 0,0.25,0.5,0.75,1.0 depth into coil : Fri Jan 21 01:34:30 1994
700
600
500
400
300
temperature in K
0
20
40
60
80
100
time in hours


initial mobile hydrogen = 0.64 ppm, H2O density = 5e17 #/cc, T = 723K: solid inside, dots outside : Sat Dec 25 22:42:56 1993
log10(H density #/cc) 1ppm = 4.7e18/cc
18.5
18
17.5
17
0
2×10 4
4×10 4
6×10 4
8×10 4
time in seconds

Chromium Carbide formation boundary temperature vs time at temperature
From several sources



Heuristic Statistical Mechanics Model

Dubinin-Radushkevich (DR) equilibrium surface coverage:

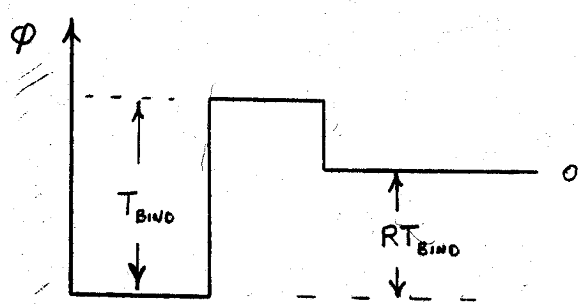
$$\frac{\sigma}{\sigma_m} = e^{-(T/T_0)^2 ln^2(P/P_0)}$$

DR site distribution function:

$$\theta(T_{bind}) = \left(2T_{bind}/T_0{}^2\right) e^{-(T_{bind}/T_0)^2}$$

$$\int_0^\infty \theta(T_{bind}) \delta T_{bind} = 1$$

Heuristic surface potential:



Emission time:

$$\tau_{emit}(T_{bind}) = \tau_0 e^{T_{bind}/T}$$

Adsorption time:

$$\tau_{ads} = \frac{4n\sigma_0}{\alpha\rho v_{th}(1 + (1-R)T_{bind}/T)e^{-(1-R)T_{bind}/T}}$$

Detailed balance per site:

$$\frac{dP(T_{bind}, t)}{dt} = -\frac{P(T_{bind}, t)}{\tau_{emit}} + \frac{(1 - P(T_{bind}, t))}{\tau_{ads}}$$

Integration:

$$P(T_{bind}, t) \ = \ P(T_{bind}, 0)e^{-t/\tau} \ + \ P_{equil}(T_{bind})(1 \ - \ e^{-t/\tau})$$

where

$$\tau = \frac{\tau_{emit}\tau_{ads}}{(\tau_{emit} \ + \ \tau_{ads})}$$

and

$$P_{equil}(T_{bind}) \ = \ \frac{\tau_{emit}}{(\tau_{emit} \ + \ \tau_{ads})}.$$

Incremental outgassing rate of band of sites:

$$dJ_{out}(t) = n\sigma_0 \ \theta(T_{bind})(\frac{dP(T_{bind}, t)}{dt}) \ \delta T_{bind}$$

Aside: for $P(T_{bind}, 0) \ = \ 1$ and $\tau_{ads} \rightarrow \infty$

$$J_{out}(t, T) = \left(\frac{2n\sigma_0 T}{tT_0}\right) \int_0^a bln(y/a)e^{-(bln(y/a))^2} e^{-y} dy$$

where

$$b = T/T_0 \qquad a = t/\tau_0$$

Computational algorithm (waterbakesm.f)

Step time:

$$\Delta t/\tau_s \;=\; f \quad \tau_s \;=\; V/F$$

Probability computation over 1024 binding energies $0 \rightarrow 3T_0$

$$P(T_{bind}, t_{j+1}) \;=\; P(T_{bind}, t_j)\, e^{-f\tau_s/\tau_j} + P_{equil}(T_{bind}, t_j)\,(1 - e^{-f\tau_s/\tau_j})$$

Surface coverage:

$$\sigma(t_{j+1}) \;=\; n\sigma_0 \sum_{0}^{3T_0} \theta(T_{bind}) P(T_{bind}, t_{j+1}).$$

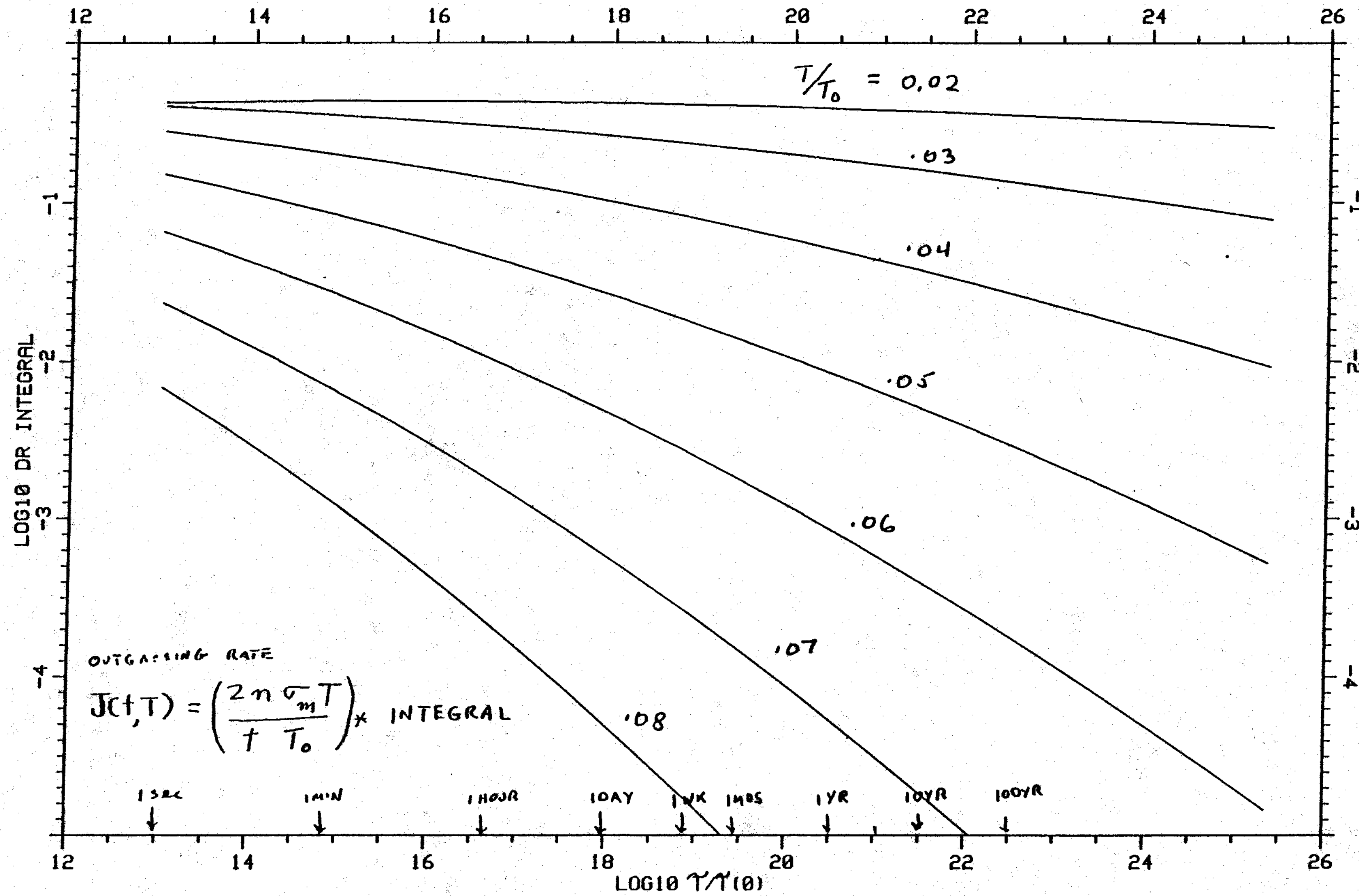
Outgassing rate:

$$J(t_{j+1}) \;=\; \frac{(\sigma(t_{j+1}) \;-\; \sigma(t_j))}{f\tau_s}$$

Pressure:

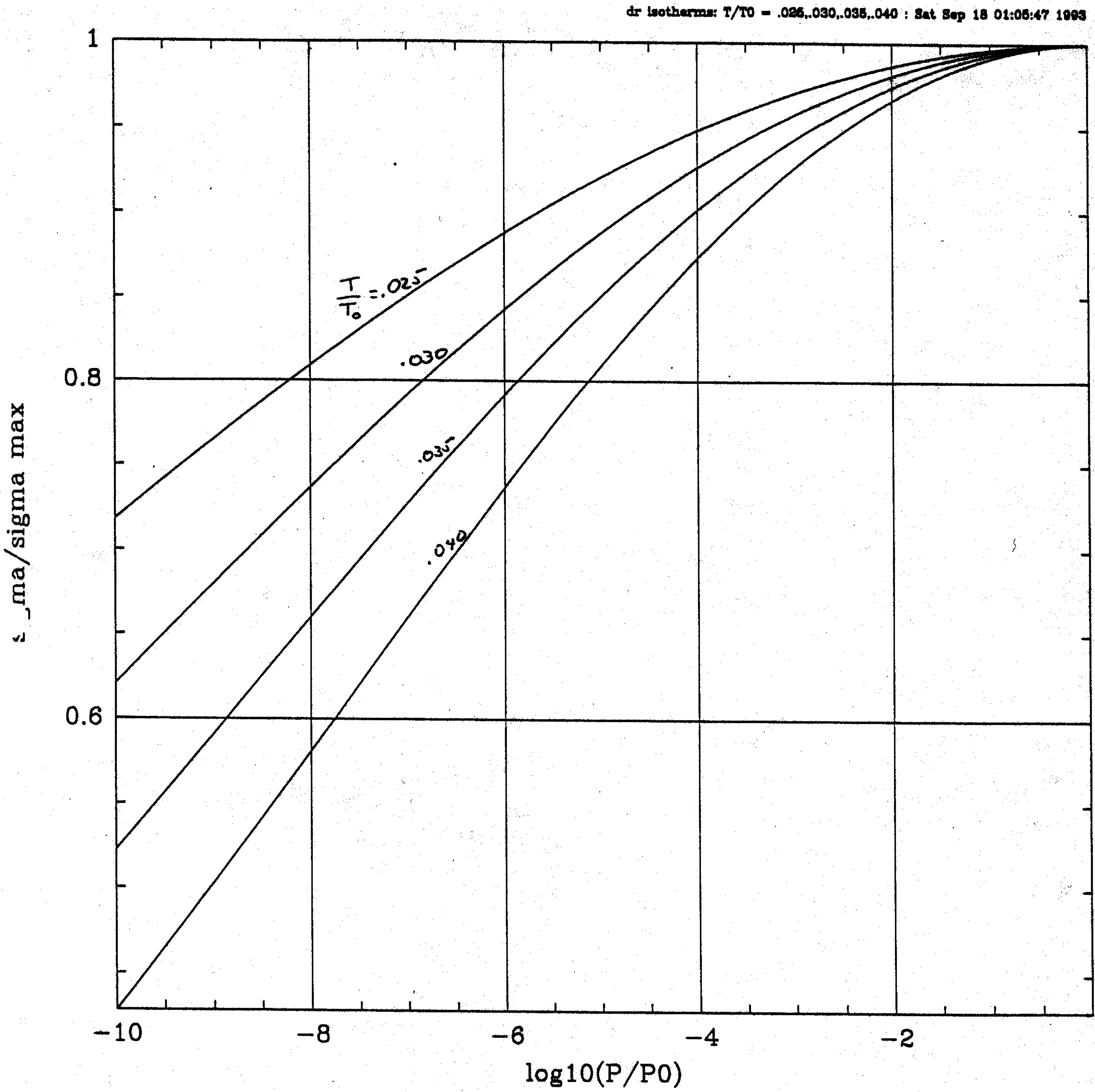
$$p(t_{j+1}) \;=\; p(t_j)\, e^{-f} \;+\; (\frac{J(t_j)A}{F})(1 \;-\; e^{-f})$$

GO BACK AND DO IT AGAIN (new time and temperatures)



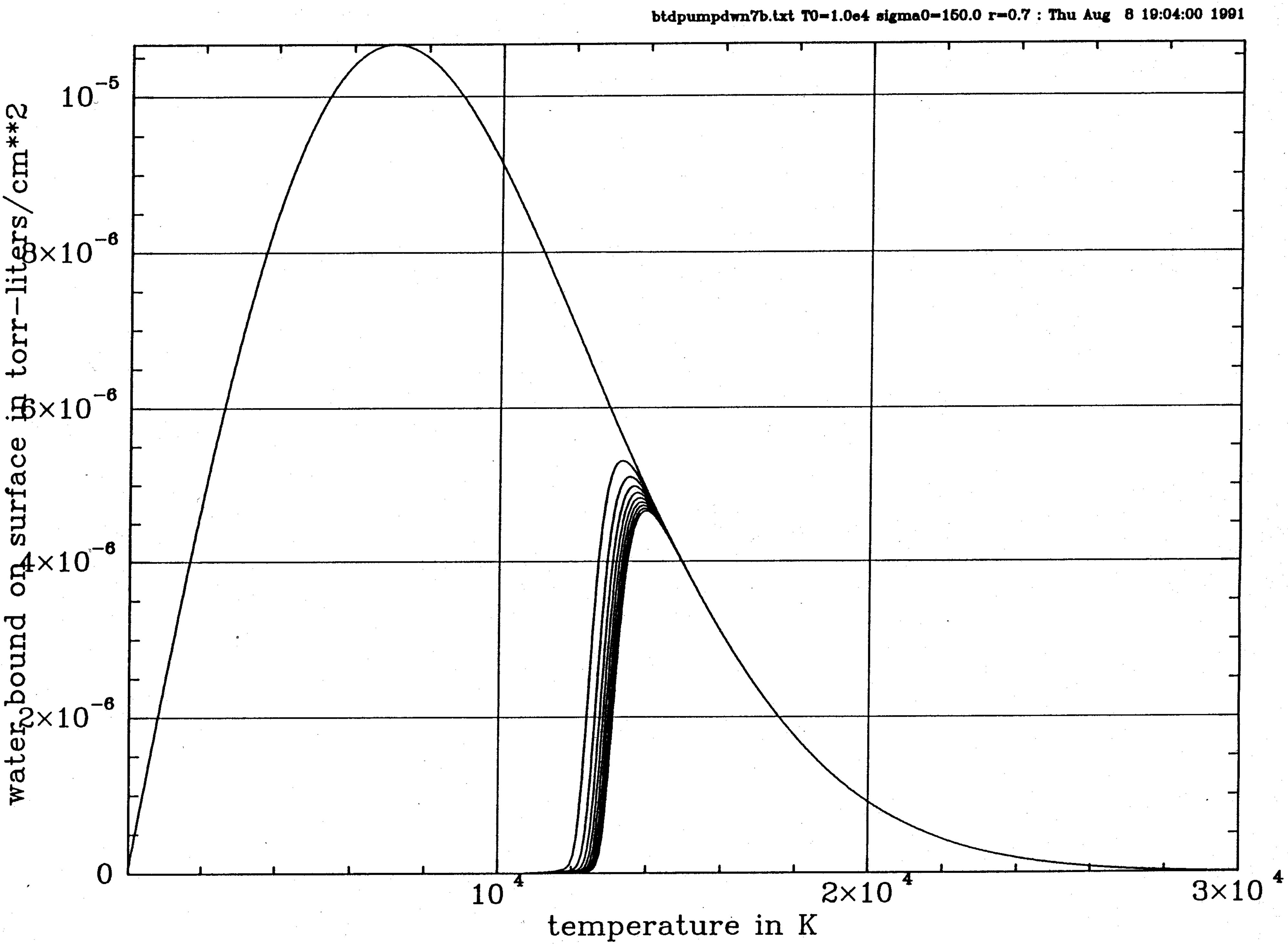
DR INTEGRAL VS NORMALIZED PUMPING TIME

ASSUME $\tau_0 = 10^{-13}$ sec

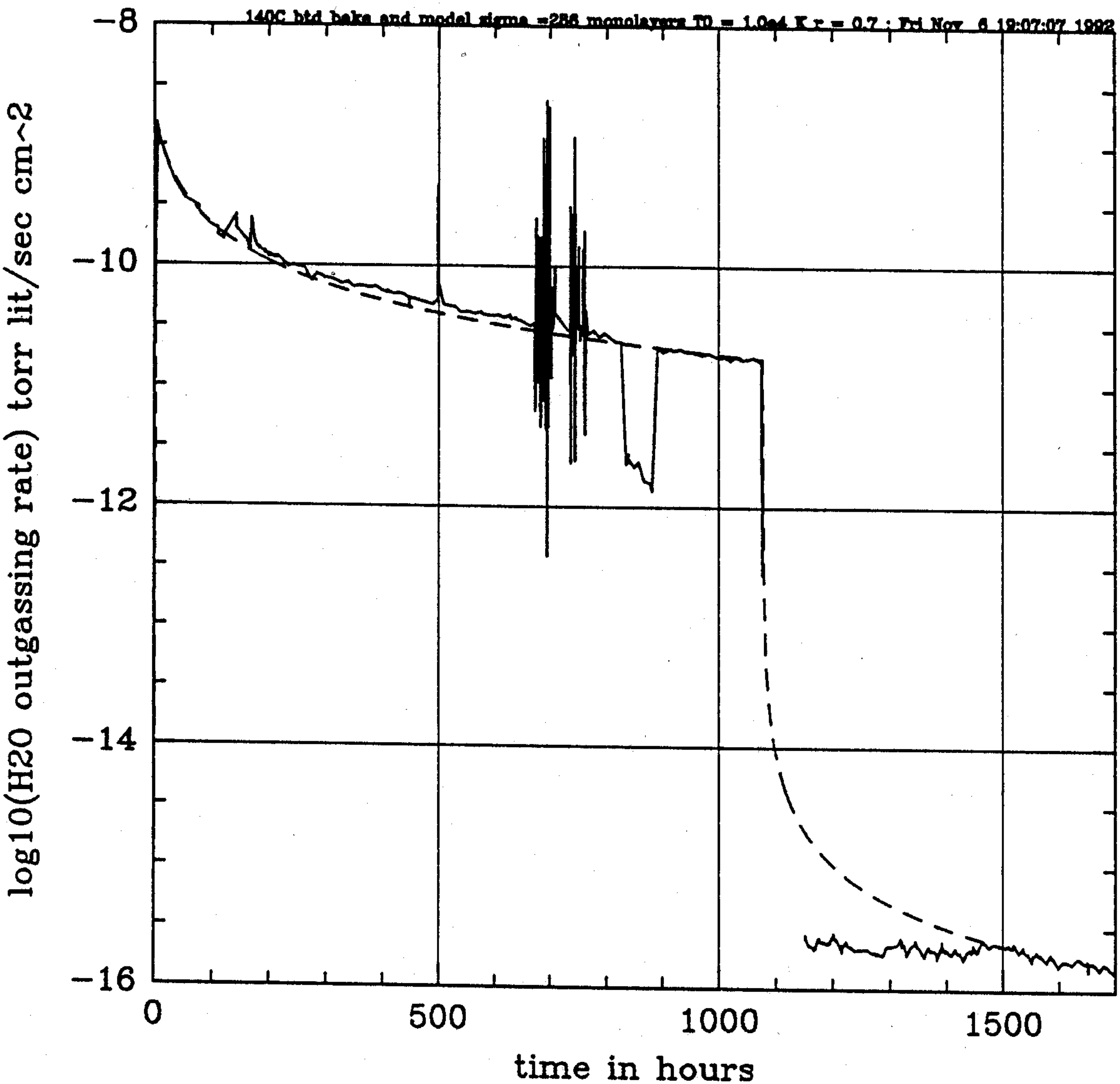


$$\frac{\sigma}{\sigma_m} = e^{-\left(\frac{T}{T_0}\right)^2 \ln^2\left(P/P_0\right)}$$

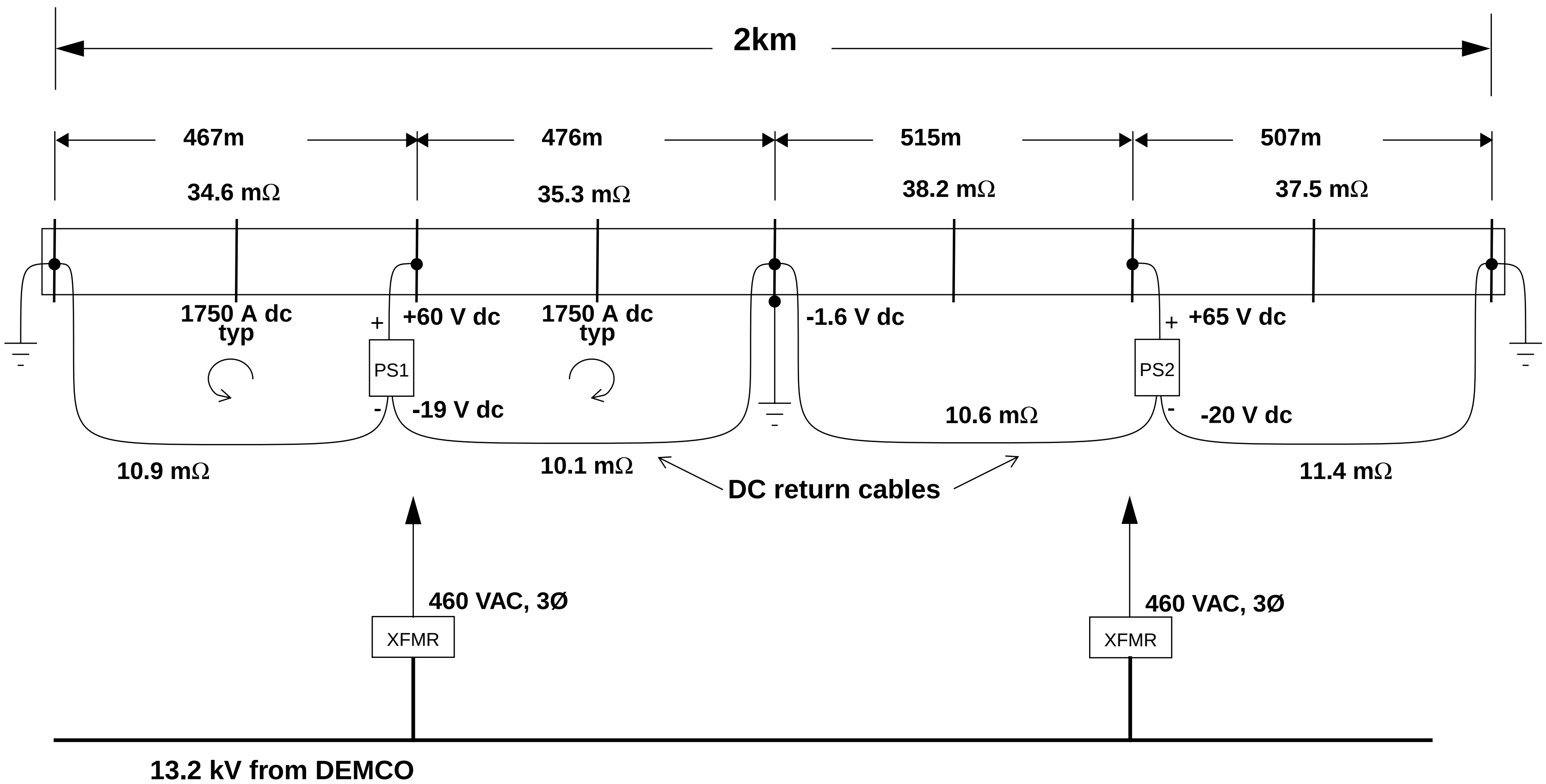
EQUILIBRIUM WITH SURFACE



btdpumpdwn7b.txt T0=1.0e4 sigma0=150.0 r=0.7 : Thu Aug 8 19:04:00 1991
water bound on surface in torr-liters/cm**2
10^{-5}
8×10^{-6}
6×10^{-6}
4×10^{-6}
2×10^{-6}
0
10^4
2×10^4
3×10^4
temperature in K

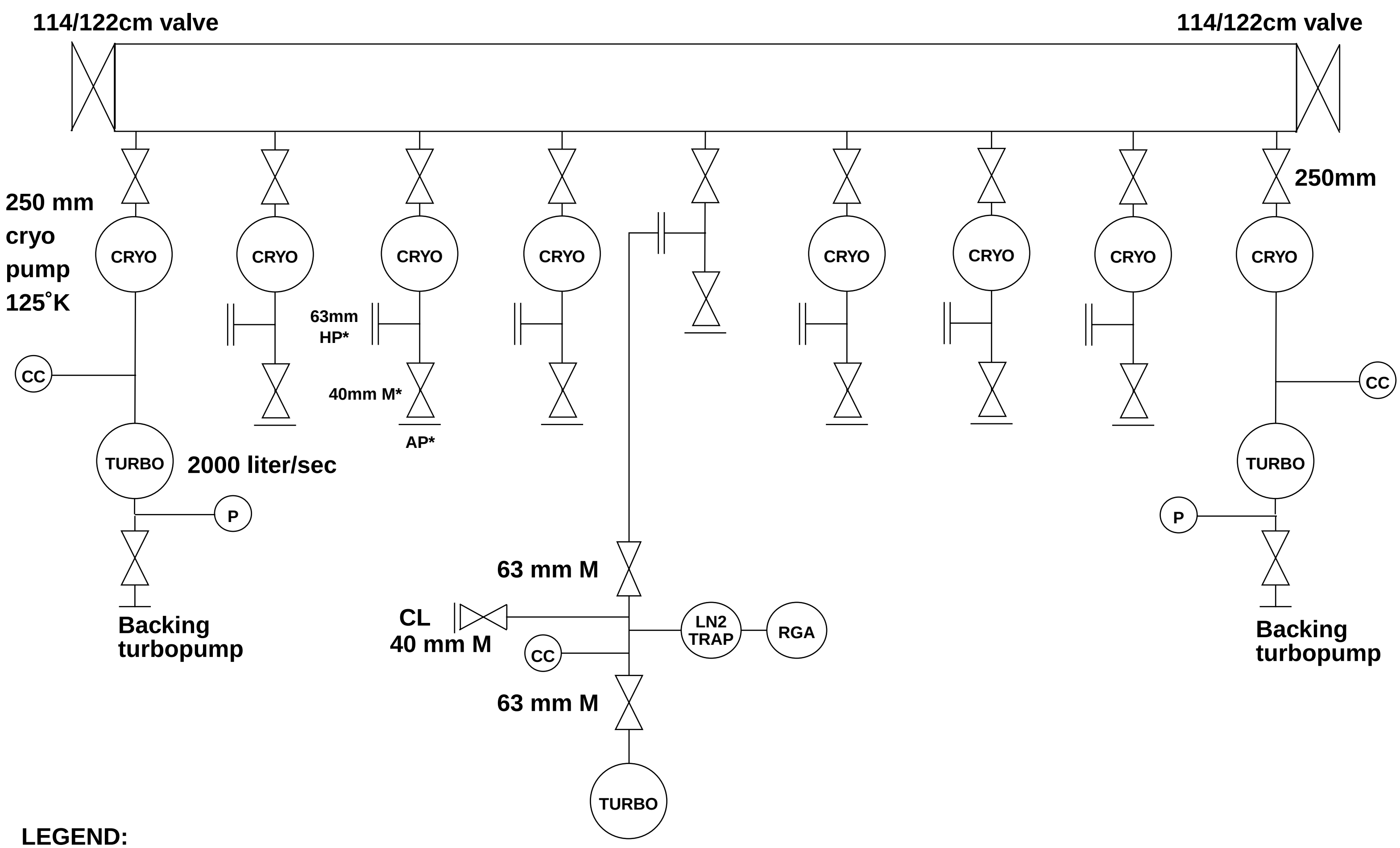

140C btd bake and model sigma =286 monolayers T0 = 1.0e4 K r = 0.7 : Fri Nov 6 19:07:07 1992
log10(H20 outgassing rate) torr lit/sec cm^2
-8
-10
-12
-14
-16
0
500
1000
1500
time in hours

BEAM TUBE BAKEOUT ELECTRICAL HEATING POWER



Legend: XFMR Power Transformer PS Low voltage, high current DC power supply

SCHEMATIC OF PUMPS AND RGA DURING BAKEOUT



LEGEND:

AP Port for auxiliary pump

CC Cold Cathode gauge

CL Port for calibration leaks

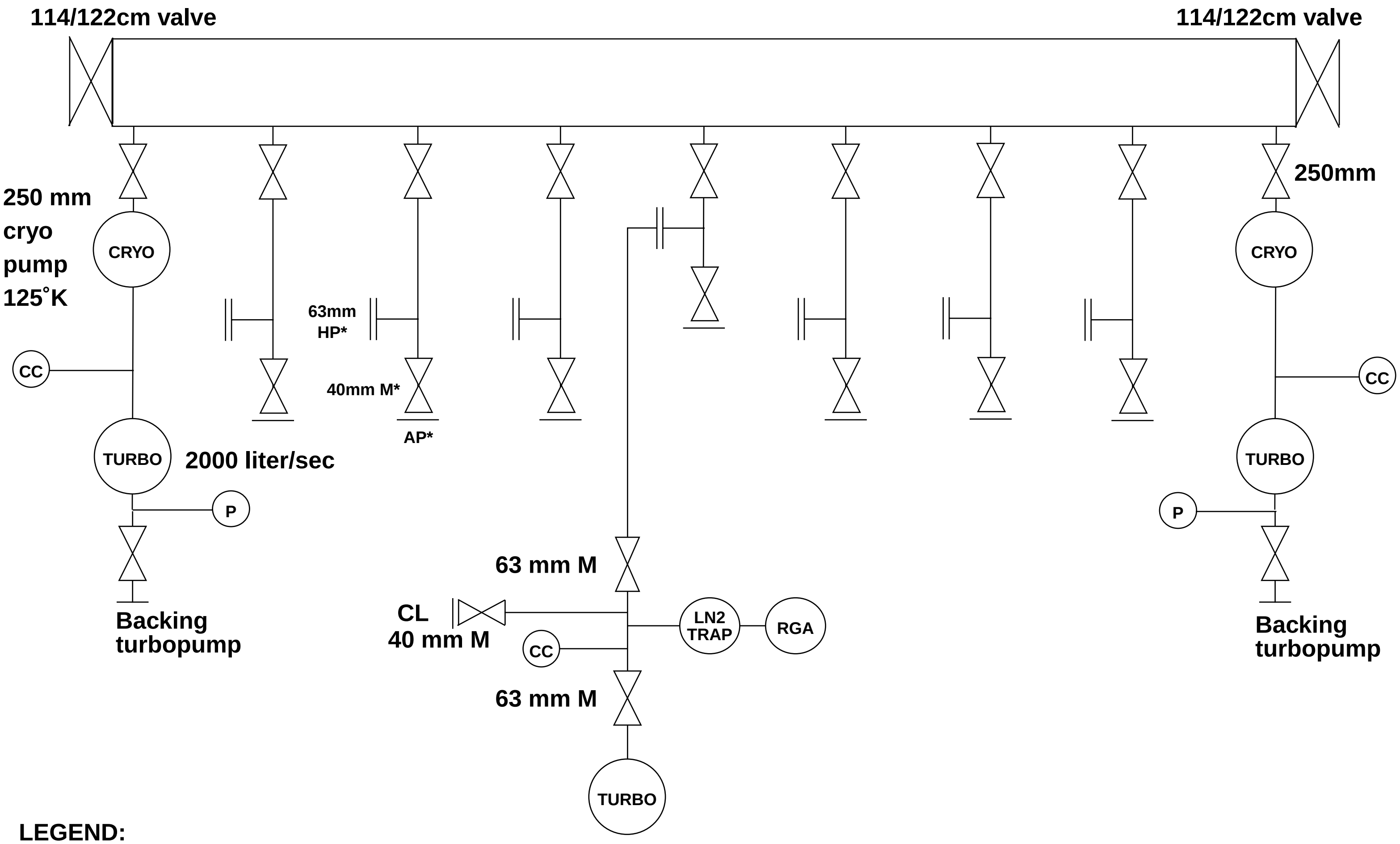
HP Port for RGA head installation

M Metal sealed valve

P Pirani gauge

*** Type H Pump Port Hardware furnished by CBI**

POST-BAKE TEST CONFIGURATION



LEGEND:

AP Port for auxiliary pump

CC Cold Cathode gauge

CL Port for calibration leaks

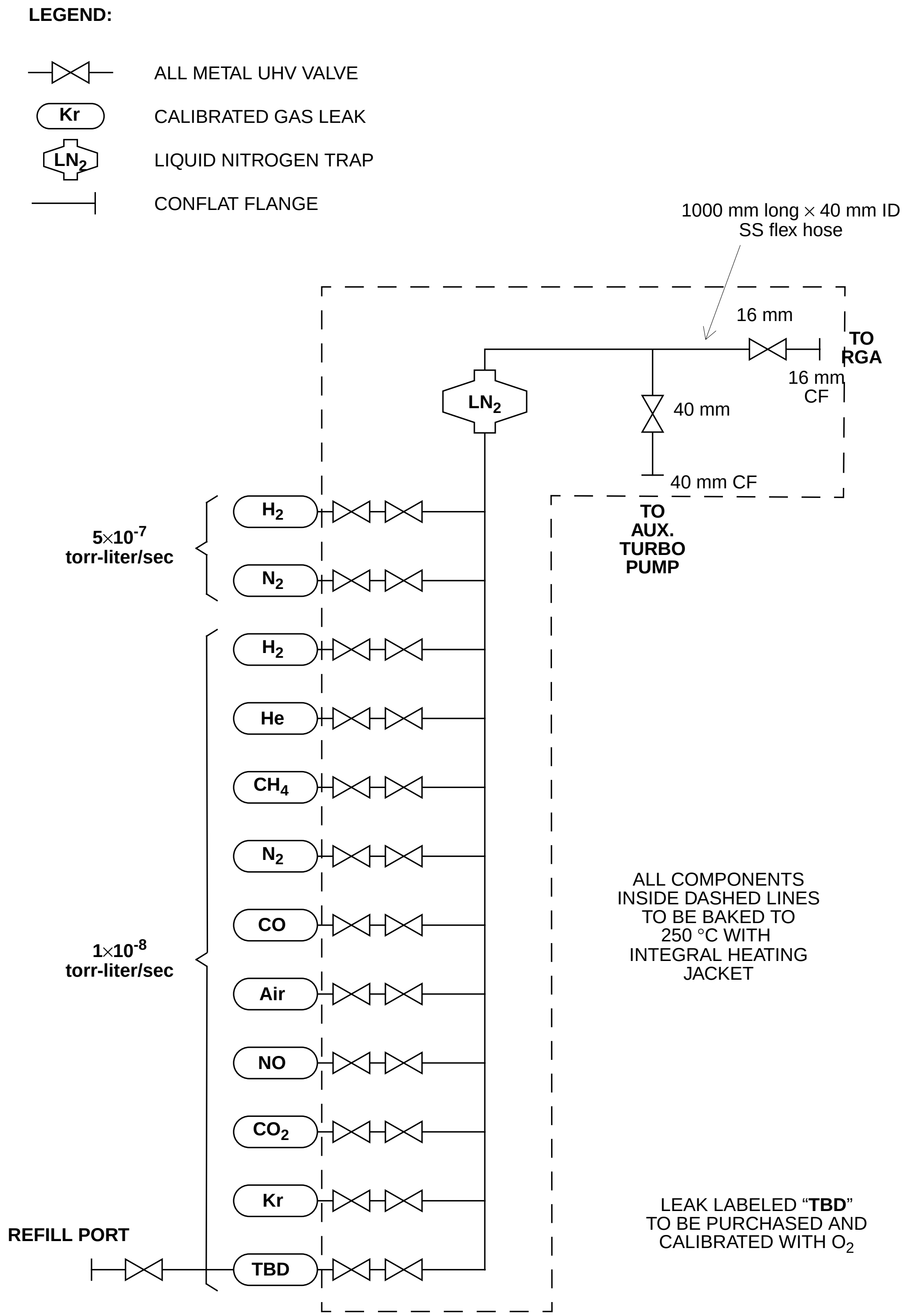
HP Port for RGA head installation

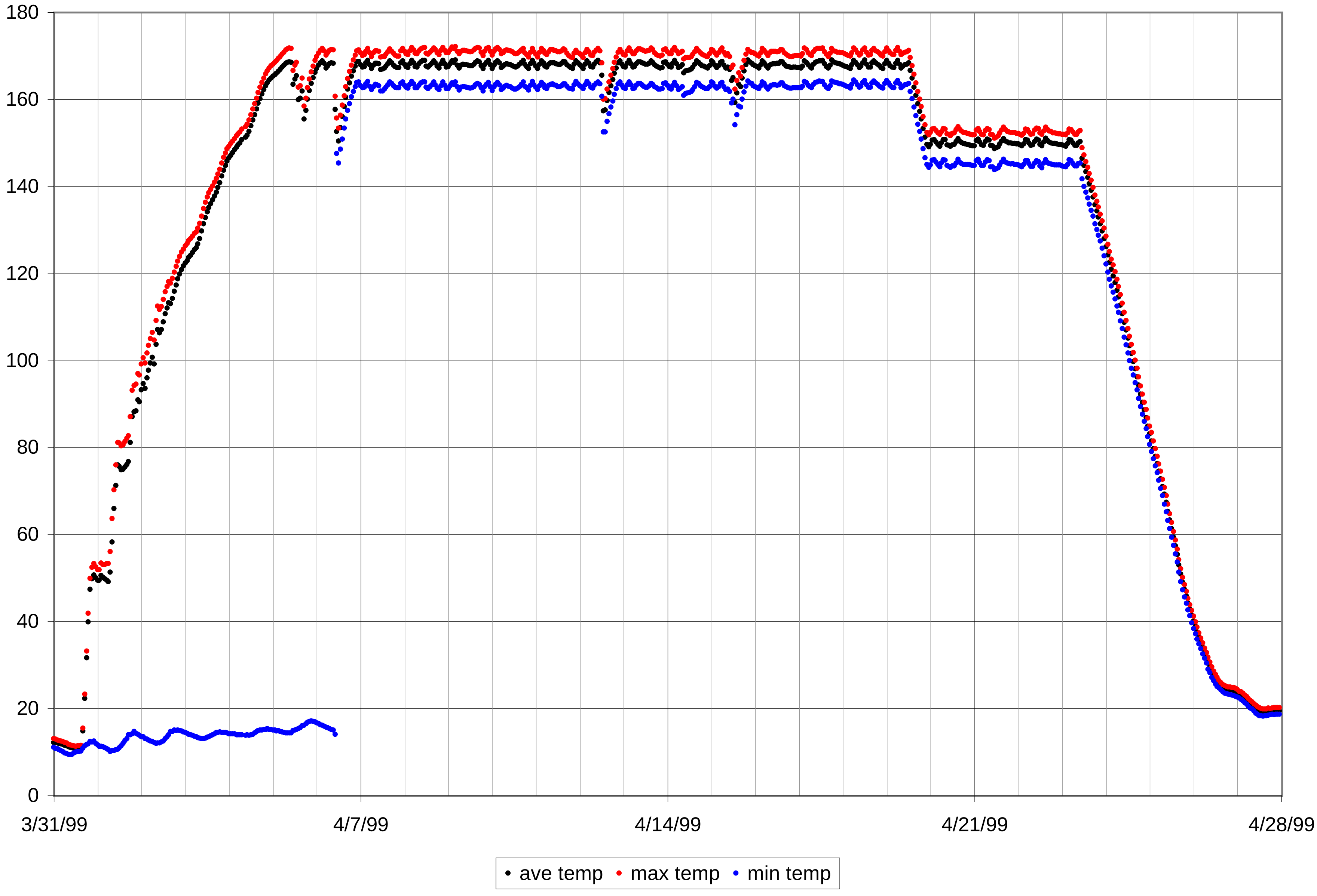
M Metal sealed valve

P Pirani gauge

* Type H Pump Port Hardware furnished by CBI

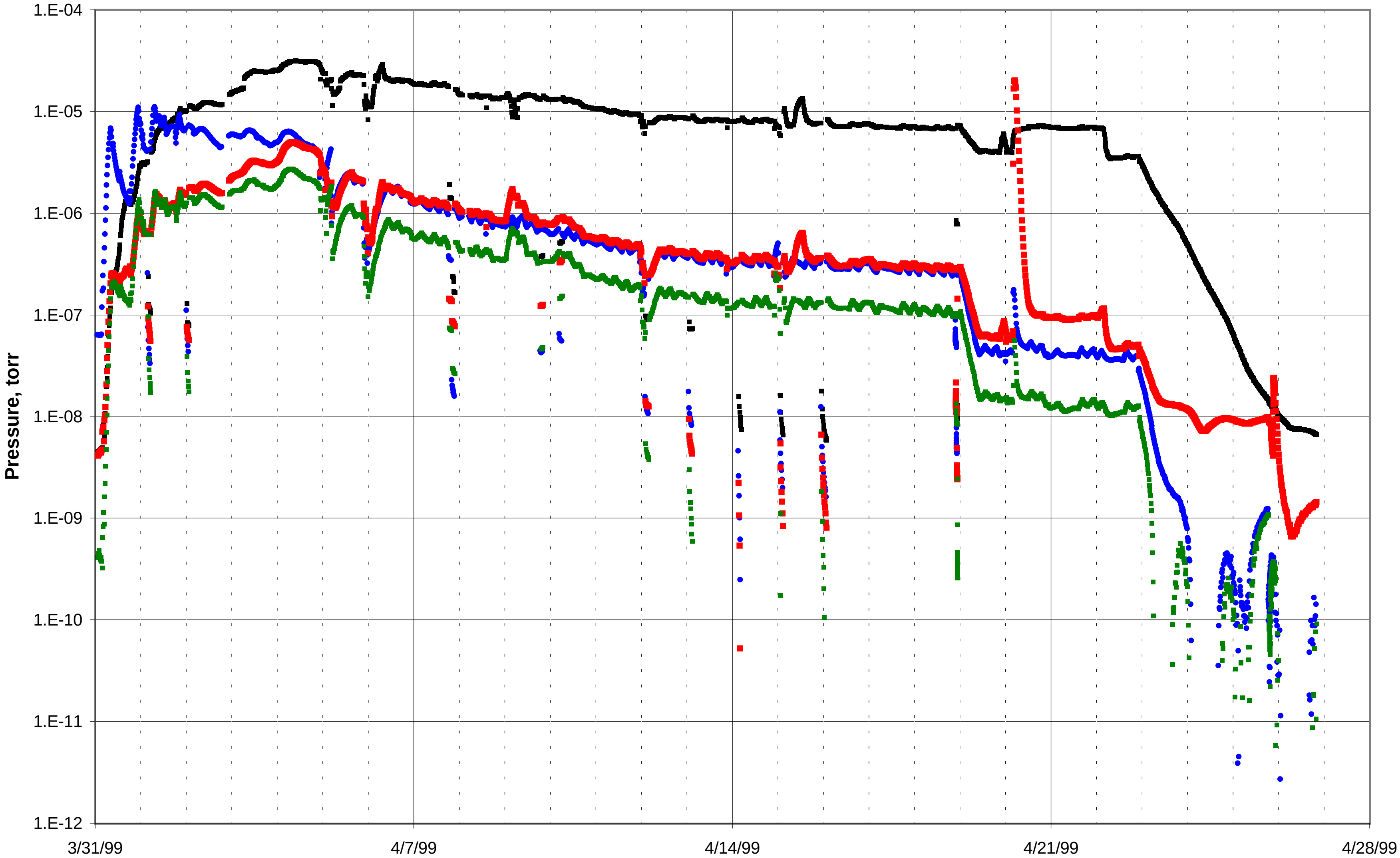
CALIBRATION ASSEMBLY





180
160
140
120
100
80
60
40
20
0
3/31/99
4/7/99
4/14/99
4/21/99
4/28/99
ave temp
max temp
min temp

HX2 RGA PRESSURE, AMU 2 (blk), AMU 18 (blu), AMU 28 (red), AMU 44 (green)



Postbake measurements of module X1 at Hanford

March 11-12, 1999

Table 1: Results from gas model solution of 16.9 hour postbake accumulation ending March 12, 1999 at 10:00AM .

molecule	Outgassing rate @ 10C	pressure@ 10C	outgassing rate @ 23C	pressure@ 23C
	torr liters/sec/cm^2	torr	torr liters/sec/cm^2	torr
H_2	1.6×10^{-14}	1.0×10^{-9}	5.2×10^{-14}	3.4×10^{-9}
CH_4	$< 2 \times 10^{-20}$	$< 3.4 \times 10^{-13}$	$< 8.8 \times 10^{-20}$	$< 1.5 \times 10^{-12}$
H_2O	$< 3 \times 10^{-19}$	$< 5.2 \times 10^{-13}$	$< 1.3 \times 10^{-18}$	$< 2.3 \times 10^{-12}$
N_2	$< 9 \times 10^{-19}$ **	$< 1.5 \times 10^{-13}$		
CO	$< 1.3 \times 10^{-18}$	$< 1.7 \times 10^{-13}$	$< 5.7 \times 10^{-18}$	$< 7 \times 10^{-13}$
O_2	$< 1.2 \times 10^{-20}$	$< 2.3 \times 10^{-14}$		
A	$< 2.5 \times 10^{-20}$	$< 3.6 \times 10^{-14}$		
CO_2	$< 6.5 \times 10^{-20}$	$< 1.2 \times 10^{-13}$	$< 2.9 \times 10^{-19}$	$< 5.2 \times 10^{-13}$
$NO+C_2H_6$	$< 1.5 \times 10^{-19}$	$< 1.6 \times 10^{-13}$	$< 6.6 \times 10^{-19}$	$< 7.2 \times 10^{-13}$
$H_nC_pO_q$	$\sum$amu41,43,55,57 $< 1.2 \times 10^{-19}$	$< 2.2 \times 10^{-13}$	$\sum$amu41,43,55,57 $< 5.3 \times 10^{-19}$	$< 9.7 \times 10^{-13}$

Volume = 2.4×10^6 liters and Area = 7.8×10^7 cm^2

** The equivalent air leak into the module Q < 3.5×10^{-11} torr liters/sec from amu 28.

Correction from 10C to 23C uses a binding temperature of 8000K for hydrogen and 10000K for all other molecules

The data shows the outgassing rates of the tube are acceptable. The higher temperature bake at 168C for a shorter time has accomplished a better result than the longer bakes at 150C.

Beam Tube Bakeout Results

	Outgassing Rate corrected to 23 °C torr liters/sec/cm^2 (All except H_2 are upper limits)					
molecule	**Goal***	**HY2**	**HY1**	**HX1**	**HX2**	
H_2	4.7	4.8	6.3	5.2	4.6	$\times 10^{-14}$
CH_4	48000	< 900	< 220	< 8.8	< 95	$\times 10^{-20}$
H_2O	1500	< 4	< 20	< 1.8	< 0.8	$\times 10^{-18}$
CO	650	< 14	< 9	< 5.7	< 2	$\times 10^{-18}$
CO_2	2200	< 40	< 18	< 2.9	< 8.5	$\times 10^{-19}$
$NO+C_2H_6$	7000	< 2	< 14	< 6.6	< 1.0	$\times 10^{-19}$
$H_nC_pO_q$	50–2†	< 15	< 8.5	< 5.3	< 0.4	$\times 10^{-19}$

air leak	1000	< 20	< 10	< 3.5	< 16	$\times 10^{-11}$ torr liter/sec

*Goal: maximum outgassing to achieve pressure equivalent to 10^{-9} torr H_2 using only pumps at stations

†Goal for hydrocarbons depends on weight of parent molecule; range given corresponds with 100–300 AMU

5/24/99 wea