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BROOKHAVEN NATIONAL LABORATORY
Associated Universities, Inc.
Upton, New York

ACCELERATOR DEPARTMENT
Informal Report

ISABELLE VACUUM SYSTEM

P. Grand

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INTERSECTING STORAGE ACCELERATOR NOTES

ISABELLE VACUUM SYSTEM

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Fabrication and bakeout requirements to establish gas loads and contamination parameters

Introduction: A primary requirement for ISABELLE is the ability to reach ultra-high vacuum conditions in the beam pipe in order to eliminate as much as possible beam-residual gas interactions resulting in beam life decay and noise in the interaction regions. A vacuum of 10^{-10} to 10^{-11} torr is a must but lower pressures are desirable.

Before a system can be designed we have to establish the parameters on which to base the design. In order to achieve ultra-high vacuum $<10^{-10}$ torr and regardless of the pumps used it is clear that we have to reduce as much as possible all sources contributing to gas loads; these include outgassing, leaks, backstreaming from pumps and migration from high pressure regions (e.g. AGS).

This note describes the techniques and establishes parameters to reach very low ultimate gas loads for the pumping system. Desorption of gas by ion bombardment remains a problem as no practical technique is available to clean the walls of strongly bound molecules. However, ion bombardment can be reduced by taking advantage of the cryogenic temperature present to lower the pressure in the system by orders of magnitude if hydrogen and helium gases can be kept out. This makes it desirable to operate the beam pipe at 4°K including the straight sections.

Diffusion of gases through metals: After 6 months of operation the CERN ISR average pressure is $<10^{-10}$ torr and the residual gas consists of 90% H_2 , 5% H_2O and 5% CO and hydrocarbons.⁽¹⁾ The presence of 90% H_2 can be explained if one accepts that H_2 is the main contaminant to the stainless steel vacuum system and slowly eliminates the other gases present by di-

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lution with time. As the partial pressure of H_2 in the atmosphere is 5×10^{-4} torr, it is clear that hydrogen in the system does not come from leaks but from the pipe wall material itself.

All metals are contaminated by gases during the melt and manufacturing processes. Hydrogen is then only one of the contaminants, its source being dissociated H_2O mostly and also cracked ammonia used during the annealing process for stainless steel. It is the most troublesome contaminant as it is highly reactive with most metals at high temperature and once it is in solution in the metal, readily diffuses through in the monoatomic form.^(2,3) Additional H_2 from the atmosphere is negligible because of its small partial pressure (5×10^{-4} torr).

Stainless steel is the most desirable material to use for the beam pipe from the point of view of fabrication; machinability is quite good, welds are reliable and it is hard enough for metal gaskets for vacuum joints. The electrical resistance of stainless steel at $4^\circ K$ is >30 , that of OFHC copper at room temperature.⁽⁴⁾

Commercially produced stainless steel by the air melt method can have a hydrogen contamination of as much as 6 ppm, this is equivalent to 1 std cc-cm⁻³ (~ 1 torr liter cm⁻³). If melted by the consumable electrode or vacuum melt process the maximum can go to 2 ppm. Averages run half that amount.⁽⁵⁾

The one dimensional diffusion equation giving diffusion and outgassing rates is (Fick's second law):

$$D \frac{\partial^2 c}{\partial x^2} = \frac{\partial c}{\partial t} \quad (1)$$

where D = diffusion coefficient

c = concentration of hydrogen

This equation simplified for the practical case if $Dtd^{-2} > 0.025$ leads to⁽⁶⁾:

$$c = 4 c_0 \pi^{-1} \sin(\pi x d^{-1}) \exp(-\pi^2 d^{-2} Dt) \quad (2)$$

and

$$\dot{Q} = 4 c_0 D d^{-1} \exp(-\pi^2 d^{-2} Dt) \quad (3)$$

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where

C_0 = initial concentration of hydrogen

d = thickness of material

$\dot{Q}$ = outgassing rate

Knowing the pipe dimensions, the hydrogen concentration in the material and the diffusion coefficient D for that material, we can then calculate the expected outgassing of the vacuum chamber after a certain history including bakeout.

The diffusion coefficient D has been found experimentally for 304 stainless steel to be about ^(3,6):

$D(\text{cm}^2\text{sec}^{-1})$	Temperature($^{\circ}\text{C}$)
5.0×10^{-14}	20
3.5×10^{-8}	300
3.8×10^{-7}	420
3.0×10^{-8}	570
8.7×10^{-5}	1000

The diffusion coefficient can be calculated for other temperatures as D varies exponentially with T as ⁽⁷⁾:

$$D = D_0 \exp(-E/R^1T^{-1}) \quad (4)$$

where

D_0 = constant ($\sim 3 \times 10^{-2}$)

E = activation energy

(for 304 stainless steel 15,600 cal/mole ⁽³⁾)

R = gas constant

Using equation (4) the diffusion coefficient at 4⁰K is extremely small ($\sim 10^{-800}$). For all practical purposes there is no outgassing of absorbed gas at cryogenic temperatures.

Outgassing, baking requirements: Despite the fact that diffusion and bulk outgassing is non-existent at cryogenic temperature, high temperature baking of the vacuum chamber and associated hardware is still required to:

- a) reduce the gas loads and contamination of the pipe sections operating at room temperature.
- b) reduce the gas loads during initial pumping of the cryogenic temperature sections.

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- c) reduce the overall contamination rate of the system.
- d) remove subsequent contamination (adsorbed gas) during operation if ion bombardment is a problem.

Assuming that we will build the vacuum chamber with 1 mm thick 304 L stainless steel with an average H_2 concentration of 2 ppm (~ 0.3 torr $\mu\text{-cm}^{-3}$) and that we wish to have a maximum outgassing rate of 10^{-13} torr $\mu\text{-sec}^{-1}$ we can estimate the bake requirements from equation (3). At this time it is suggested that the bake be carried out in two steps:

- 1) bake after fabrication and combine with leak checking limited to 450°C (this temperature being the maximum permissible for copper gasket joints).
- 2) bake after assembly in situ combined with the evacuation of the system limited to 300°C (this temperature is arbitrarily chosen as a compromise between a desire for high temperature and what is practical in terms of hardware. The same end results can be achieved at lower temperatures if the bake time is extended).

On that basis we can rewrite equation (3) as:

$$\dot{Q}_{20} = 4 \text{ coD}_{20} \text{ d}^{-1} \exp(-\pi^2 \text{d}^{-2} \text{D}_{450} t_{450}) \exp(-\pi^2 \text{d}^{-2} \text{D}_{300} t_{300}) \exp(-\pi^2 \text{d}^{-2} \text{D}_{20} t_{20}) \quad (5)$$

where the subscripts indicate the determinant temperatures. Since D_{20} is very small (5×10^{-14}) $\exp(-\pi^2 \text{d}^{-2} \text{D}_{20} t_{20}) \approx 1$, hence can be neglected.

Solving now for $\dot{Q} = 10^{-13}$ torr $\mu\text{/sec}^{-1}$ we find that we have to bake:

10 hrs @ 450°C

16 hrs @ 300°C

These numbers are arbitrary and can be changed by trading from the first bake to the second, or vice versa, but not directly since the value of D is different at the two temperatures. It is also clear that the bake times mentioned are tentative as they depend on assumptions made so far. If for instance we buy air-melted, bright-annealed, stainless steel with H_2 concentration of 6 ppm an additional bake in vacuum of the bulk material at high temperature ($\sim 1000^\circ\text{C}$) may be necessary. In addition, the ability to desorb the gas (outgas) diffused from the material is also heavily dependent

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on the surface conditions of the material. Here the assumption is made that the metal has been previously cleaned by e.g. etching, electropolishing or other techniques.

The outgassing rate of the material at 4°K is non-existent and the gas load at that temperature is entirely from leaks, non condensates H_2 and He and desorbed gases due to ion bombardment.

Leaks, leak checking: Leak detection sensitivity can be somewhat enhanced if the leak checking is carried out at high temperature. Since it is desirable to avoid all leaks if possible in the system this procedure is warranted.

Existing leak detectors can be pushed to detection of as little as 10^{-12} std cc-sec $^{-1}$ (standard detectors operate down to 10^{-9} std cc sec $^{-1}$.)

The leak rate for a given leak path varies as:

$$P (T/M)^{\frac{1}{2}} \quad (6)$$

where

P = pressure

T = temperature

M = molecular mass of gas

We can therefore increase the leak detection sensitivity if it is carried out in conjunction with the first bake at 450°C by taking advantage of the temperature dependence of the leak rate and also opening up incipient cracks and defects. Under these conditions leak checking will be carried out with the setup shown on Fig. 1 as follows:

Fig. 1

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- a) The vacuum chamber is cleaned, sealed, inserted in oven and connected to pump and leak detector.
- b) The oven is sealed and evacuated and then pressurized with helium gas.
- c) The vacuum chamber is evacuated and the oven heated to desired temperature.
- d) Leak checking then takes place.

The time the chambers stay at high temperature is determined by the bake requirement (~10 hours), which allows for leaks with long time constants to show up. After showing the chamber to be tight, it is allowed to cool down and be sealed under vacuum until final assembly.

The technique described will give us an overall leak rate $<10^{-12}$ std cc-sec⁻¹ for each subassembled section. Later on each one of these sections will be opened for assembly and have a final joint made (welded) which will be leak checked at room temperature with extreme care to yield leaks hopefully no greater than 10^{-12} std cc-sec⁻¹.

Being conservative for the purpose of establishing gas load parameters we will say that each joint is a potential leak of 10^{-12} std cc-sec⁻¹ and that these are distributed at the rate of one per meter of circumference of ISABELLE.

One factor not to be overlooked and underestimated is the effect of temperature cycling on in-pient leaks. Although the system may be tight at room temperature, leaks may open up at 4°K and these may be extremely difficult to locate. For that reason we will strive to avoid having any joint in contact with helium and we will also use the secondary cryogenic vacuum insulation system to reduce the pressure differential across leak paths by 10^5 which will reduce the potential leak rates by the same amount.

Wall cleanliness: The final bake after assembly (in situ) at 300°C for about 24 hours is necessary to desorb the gases adsorbed during the construction period thus reducing the outgassing of adsorbed gas during operation and removing wall contaminants.

It is clear that the methods proposed to reduce the gas load of the vacuum chamber do not necessarily make the chamber walls free of contaminants. A final 24 hours bake at 300°C will desorb non-activated gas with heats of desorption of about 45 K cal/mole (2 ev) binding energy. Although degassing the materials and subsequent cleaning and baking make for a "clean" system

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in terms of vacuum technology, it still leaves us then with all contaminants with binding energies >2 ev ready to be desorbed by sputtering or energy transfer >2 ev resulting from possible ion bombardment or grazing high energy protons^(7,8,9)

I believe however, that in ISABELLE the problem of desorption by ion bombardment may not be serious if we utilize the cryogenic aspect of the machine to provide additional pumping to reach operating pressures $<10^{-11}$ torr. This low pressure is realizable if:

- a) Hydrogen and helium are kept out of the system by proper degassing and fabrication control.
- b) After the final bake a pressure of 10^{-10} torr is reached at room temperature prior to cool down. Typically at that time the residual gas composition will consist of H_2, CO, H_2O, CO_2, N_2 and noble gases and the average gas density will be $\sim 5 \times 10^8$ molecules/cm³.
- c) The design of the beam pipe provides cryogenic cooling for as much of the pipe as possible, including the straight sections. This has the three-fold effect of condensating gases on the walls, stopping outgassing and lowering leak rates for given leaks by a factor of ~ 10 (unless the leaks open up instead.)
- d) Special care is taken in the room temperature regions to achieve lower leak and outgassing rates and to provide enough pumping capacity to slow the migration of contaminants.
- e) The beam transfer lines with poor vacuum are differentially pumped and valved off when not in use (e.g. AGS line.)

Contamination buildup: Assuming we start off with a "clean system" and having one leak per meter circumference of 10^{-12} std cc-sec⁻¹, the time to accumulate one monomolecular layer of gas on the geometric surface in the 5 cm pipe⁽¹⁰⁾ will be $\sim 10^3$ years. We do not know what the critical coverage is. At the CERN ISR with 10^{-10} torr operating pressure they estimated the coverage to be 0.01 monomolecular layer when the pressure rises occurred at 6.5A beam current⁽¹¹⁾. At the above leak rate this coverage will be reached in 10 years with the system kept at 4°K.

The leak rate quoted is conservative since most joints will see the dewar vacuum on the pressure side and hopefully there will be fewer joints than 1/meter.

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A potentially more serious problem will be the leaks and outgassing of the hardware operating at room temperature. These gases will eventually migrate to the cold regions. Due to the different diffusion and permeation coefficients for various gases, the main contaminants will be H_2 which at $4^{\circ}K$ has a vapor pressure of 10^{-7} torr and the helium whose concentration in the atmosphere is likely to be large because of the cryogenic system present. These two gases will not freeze on the pipe walls but will tend to increase the pressure of the system since they are only being pumped by the getter pumps.

It is then possible that in the case of a cryogenic accelerator and considering the ion bombardment effect we should not speak of critical wall contamination but of critical pressure.

The above discussion is somewhat academic at this time but gives a rough idea of what can be expected. Much work needs to be done on this subject and better approximations can be made when a physical design is available.

Conclusions: In order to reach the ultra-high vacuum desirable at room temperature of 10^{-10} torr prior to cool down, we can establish the following parameters for the vacuum chamber and the associated hardware:

- a) Care must be taken to choose all the materials exposed to vacuum with the view that they should be degassed at high temperature and reduce their gas concentration to obtain outgassing rates $<10^{-13}$ torr $\mu\text{-sec}^{-1}$ after the final bake.
- b) Assuming the beam pipe to be 304 L stainless steel, an acceptable limit of H_2 concentration to be set at <2 ppm max. prior to fabrication. This can be accomplished by high temperature degassing ($>1000^{\circ}C$) in a vacuum furnace at the Vendor's plant.
- c) Leak checking should be carried out on preassembled sections as long as practical at a temperature of $450^{\circ}C$ to yield final total leak rates $<10^{-12}$ torr $\mu\text{-sec}^{-1}$.
- d) The final assembly of the sections in place should have the fewest joints possible and each should be leak checked to yield leaks $<10^{-12}$ torr $\mu\text{-sec}^{-1}$ per joint.

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- e) The final bake should be carried out at 300°C for 24 hours to achieve the cleanest walls practically possible while arriving at the low outgassing rate mentioned.

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