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	Draft Pumping Speed Requirements for SPIRE Boxes B. Swinyard	

Introduction

The SPIRE instrument can be represented as three boxes, one inside each other, as shown in figure 1. When the SPIRE instrument is cooled, any residual gas trapped in these boxes will be “cryopumped” onto the cold surfaces. Whether this will cause a problem to the operation or efficiency of the instrument will depend on which surface cools the first and fastest and what the residual gas pressure is when cooling commences.

In this note estimates are made for the required maximum residual pressure inside the “2-K” box; the minimum pumping conductance between the boxes and the time required to pump to a safe pressure.

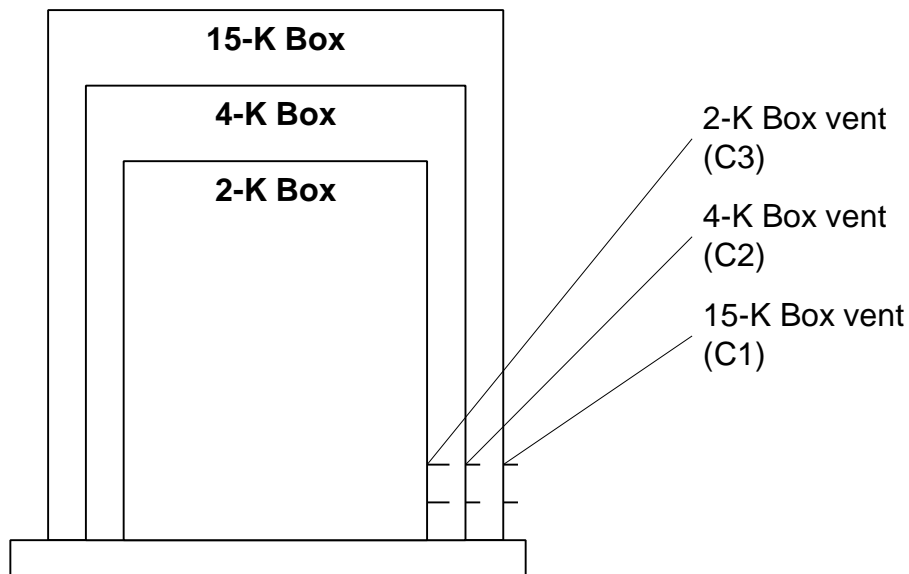


Figure 1: Outline of the SPIRE system for the purposes of pumping speed calculations.

Maximum Residual Pressure in the “2-K” Box

A vacuum system that is not leaking and has not undergone high temperature bake-out will have a residual atmosphere composed of 85% water; 12% CO and CO₂ and the balance hydrogen and trace elements. For the purposes of the following calculations I will assume that the residual gas is composed entirely of water with a molar mass of 18 g/mole; a molecular mass of 3×10^{-23} g and a molecular radius of 0.3 nm.

The volume of the 2-K box will be about 45 litres and the total surface area of the walls and optical elements about 11000 cm². If it is assumed that essentially all the residual gas ends up on the walls or parts of the instrument, then the initial pressure can be estimated assuming a static situation i.e. the cryopumping is the only sink and there are no sources (this ignores the outgassing of the surfaces). I do this for two assumptions 1) the whole area of the 2-K box and optics cools at the same rate 2) the detectors cool first and much faster than any other part, therefore all the gas is pumped onto the detectors.

Case 1:

If we wish to restrict the layer of ice to no more than 1 monolayer then the volume of the layer that is distributed over the whole area will be:

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$$V_1 = 11000 \times 3 \times 10^{-8} = 3.3 \times 10^{-4} \text{ cm}^3$$

If we take the density of the layer to be 1 g cm^{-3} then this is equivalent to:

$$\frac{V_1 \rho N_A}{M} = \frac{3.3 \times 10^{-4} \cdot 1.6 \cdot 0.22 \times 10^{23}}{18} = 1.1 \times 10^{19} \text{ molecules .}$$

Similarly. at gas pressure P, the number of molecules in the 45 l volume will be:

$$\frac{N_A P V_{2K}}{P_{\text{stp}} 22.4} = \frac{6.022 \times 10^{23} P \cdot 45}{1.02 \times 10^5 \cdot 22.4} = 1.19 \times 10^{19} P \text{ molecules,}$$

where P is in Pa. The maximum residual pressure is therefore:

$$P = 0.92 \text{ Pa or } 9.2 \times 10^{-3} \text{ mBar.}$$

This seems high – only just into the molecular flow region and not low enough to allow for decent out-gassing of the surfaces.

Case 2:

The area of the 5 detector arrays is approximately $5 \times 2.5 \times 2.5 = 31.5 \text{ cm}^2$. Using the same calculations as case 1, this gives a maximum residual pressure of

$$P = 2.6 \times 10^{-3} \text{ Pa or } 2.6 \times 10^{-5} \text{ mBar.}$$

This is low enough to allow the surfaces to outgas properly and contains a reasonable safety margin as it is likely to be the worst case.

Could take a further factor of 10 as a safety margin – gives $2.6 \times 10^{-6} \text{ mBar}$ – keep $2.6 \times 10^{-5} \text{ mBar}$ for time being.

If this were a UV experiment a single monolayer would be a disaster, for this waveband I guess it is o.k. (confirmation from the detector folk needed here).

Estimate of the Required Conductance.

Each box will have a pumping conductance in l/s given by the size of the port through which the volume is vented. These are shown as C_1 , C_2 and C_3 respectively in figure 1. The total effective conductance of ports in series is given by:

$$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \dots\dots$$

And the throughput is given by CP where P is the pressure at the port.

We wish to balance the outgassing rate from each of the boxes against the pumping speed to that box. Starting from the inside out. The outgas rate for aluminium at room temperature is $6.3 \times 10^{-9} \text{ mbar l/s cm}^{-2}$ after a few hours pumping. So for the 2-K cover we require

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$$11000.6.3 \times 10^{-9} = 6.9 \times 10^{-5} = C_{T2K}P \text{ mbar l/s}$$

If P is 2.5×10^{-5} mBar, this gives $C_{T2K} \sim 2.7$ l/s. The next box has to be able to clear both its own outgassing and that from the inner box so (given the areas are about the same):

$$C_{T4K}P = 2.6.9 \times 10^{-5} \text{ mbar l/s}$$

And

$$C_1P = 3.6.9 \times 10^{-5} \text{ mbar l/s}$$

So $C_1 = 7.8$ l/s and $C_{T4K} = 5.2$ l/s. C_2 is calculated as 15.6 l/s and C_3 as 5.6 l/s.

In fact it makes more sense to have the ports going from biggest to smallest through the boxes so we can set:

$$\begin{aligned} C_1 &= 15.6 \text{ l/s} \\ C_2 &= 7.8 \text{ l/s} \\ C_3 &= 5.6 \text{ l/s} \end{aligned}$$

In the molecular flow regime the conductance of a port is given approximately by $11.6A$, where A is the area in cm^2 . The equivalent radii of the ports required in each cover are therefore: 2-K 0.4 cm; 4-K 0.5 cm; 15-K 0.65 cm. These ports will have to be carefully designed to avoid any problems with straylight.

Time to pump the 2-K box

The time taken to pump a volume V from P_1 to P_2 is given by:

$$t = 2.3 (V/S_e) \text{Log}_{10}(P_1/P_2)$$

Where S_e is the effective pumping speed – this will be totally dominated by the port conductance through the boxes. We must treat the viscous and molecular regions separately. In the viscous region the conductance of a circular orifice is approximately $20A$. The viscous conductance to the 2-K box is therefore 4.9 l/s. If we start at atmospheric pressure and assume that the molecular flow regime starts at 1×10^{-2} mBar then this will take ~ 2 minutes. This implies that the speed of pump down of the vacuum vessel will dominate in the viscous regime. To pump from 1×10^{-2} mBar to 2.5×10^{-5} mBar will take another two minutes. In fact the outgassing rate will dominate the pump out speed of the box in the molecular regime and to be safe the instrument should be pumped for some hours before cooldown commences to ensure that the surfaces have outgassed.

The rate at which the vacuum vessel around the instrument can be pumped will depend on the pressure differential across critical items such as filters within the instrument. This will have to be calculated separately once the detailed design of the instrument is established.

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Addendum:

What happens when the cool down commences?

As the temperature is reduced the residual atmosphere in the boxes will be pumped onto the surfaces and the pressure will fall. At some point the pressure will stabilise again as the rate of pumping is balanced either by the outgassing rate from the surfaces or by any direct sources. In fact the efficiency of the pumping will also reduce because there will be so few gas molecules that they won't hit the walls very often. The gas balance equation can be written as:

$$\frac{d(PV)}{dt} = Q_{\text{pump}} + Q_{\text{cryo}} + Q_{\text{outgas}} + Q_{\text{inlet}}$$

We assume that the 2-K box cools faster than any other, i.e. it is a cryopump. We assume the conductance between the 2-K and 4-K boxes is small enough that the pressure in the 4-K box essentially stays at the pressure as before cooling commences. Therefore, there will be no additional pumping ($Q_{\text{pump}} = 0$) and the 4-K box will act as a source of with throughput of C_3P_o . We can then write:

$$\frac{d(PV)}{dt} = C_3P_o - kTA \frac{dN}{dt} + AR_{\text{outgas}} \quad (1)$$

Where R_{outgas} is the outgassing rate for the walls of the box. The rate of impact per unit area at pressure P and temperature T is given by:

$$\frac{dN}{dt} = \frac{P}{(2\pi mkT)^{1/2}} \quad (2)$$

and the pumping rate will be this times the coefficient of absorption at this temperature, S .

When equilibrium is reached, $d(PV)/dt = 0$ and equations (1) and (2) (combined with the absorption coefficient) can be rearranged to give:

$$C_3P_o = \frac{SAP (kT)^{1/2}}{(2\pi m)^{1/2}} - AR_{\text{outgas}}$$

As the temperature falls then S will, initially at least, be 1. If we take the point at which pumping begins to be 273 K (*check this at not STP*) then we can write:

$$P = (C_3P_o + 6.9 \times 10^{-5}) / 155 \text{ mbar}$$

$$P = 9 \times 10^{-7} \text{ mBar}$$

This equates to 3% of the residual atmosphere before cooldown commenced. In fact the outgas rate will fall with the temperature and the 4-K box will stop acting as a source as it too begins to cool. The final pressure will therefore be somewhat lower than this.