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### ► To cite this version:

S. Procureur, D. Attié, S. Bouteille, D. Calvet, X. Coppolani, et al.. Why do we flush gas in gaseous detectors?. Nucl.Instrum.Meth.A, 2020, 955, pp.163290. 10.1016/j.nima.2019.163290 . hal-02458764

**HAL Id: hal-02458764**

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Submitted on 7 Mar 2022

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# Why do we flush gas in gaseous detectors?

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## Abstract

The effects and the origin of the gas degradation in a gaseous detector-based tracker are investigated. The study focused on the so-called T2K gas, which turned out to be highly sensitive to pollutants. In particular the H<sub>2</sub>O and O<sub>2</sub> concentrations were monitored online in different conditions to establish their influence on the gain of the detectors. This pollution was first mitigated by a recirculating and accelerating gas system with the use of a turbine and different absorbers. Further measurements revealed that this pollution originates from a continuous permeation process through the different materials of the gas circuit. In particular, polyurethane-based gas pipes or polyester materials largely increase the level of humidity. As a direct consequence of this work, the gas autonomy of the muon telescopes currently deployed inside the Khufu's pyramid have been dramatically improved.

*Keywords:* Micro Pattern Gaseous Detectors, MPGD, Micromegas, Gas purity, Humidity, Muography, ScanPyramids

*PACS:* 29.40.Cs, 29.40.Gx

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## 1. Introduction and context

Gaseous detectors, and in particular Micro-Pattern Gaseous Detectors (MPGDs) [1] have been widely used in particle physics for decades thanks to their outstanding performance and their relatively low price. In contrast with many other detectors, however, their interaction medium often needs to be permanently regenerated, and the gas is usually released in the atmosphere. The environmental cost of these emissions is significant for every

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Preprint submitted to *Nucl. Instrum. Meth. A*

March 6, 2020

19 research center in the world, not to mention the associated gas purchase  
20 budget. Beyond fundamental physics, there are also applications where de-  
21 tectors are installed in nature, in public places or in confined areas, and for  
22 which the delivery, storage, and usage of high pressure gas bottles may be  
23 an issue. Such a situation recently occurred when our team deployed sev-  
24 eral muon telescopes to scrutinize the inside of the Great Pyramid of Khufu,  
25 within the ScanPyramids project [2]. After the first campaigns in 2016 and  
26 2017 where the instruments were placed outside of the pyramid, the tele-  
27 scopes could indeed be installed inside the highly touristic Grand Gallery in  
28 2018, where ventilation is intrinsically limited. The need to minimize the gas  
29 flushing became quite apparent, and encouraged us to study in laboratory  
30 the possibilities to reduce it in a way compatible with the required budget,  
31 transportability and robustness.

## 32 **2. Experimental setups and first measurements**

### 33 *2.1. Detectors*

34 The detectors used in our muography activity are  $50 \times 50 \text{ cm}^2$  bulk Mi-  
35 cromegas [3, 4] called *MG2D*, equipped with a resistive strip layer [5] and  
36 a 2D strip readout connected with genetic multiplexing [6]. The bulk and  
37 the cathode are based on two, 3.2 mm thick PCBs and the resistive layer is  
38 obtained by screen printing on a Kapton film. The gas tightness and the  
39 drift gap are ensured by an Aluminum frame of 8 to 15 mm depending on the  
40 detectors. For the ScanPyramids project, they are flushed with the non flam-  
41 able T2K gas (Ar-iC<sub>4</sub>H<sub>10</sub>-CF<sub>4</sub>, 95%-2%-3% in volume) from 5 or 20 L high  
42 pressure premix bottles. Typically, from 4 to 16 such detectors are flushed  
43 in series, for a total volume between 8 and 50 L depending on the drift gap  
44 (from 8 to 15 mm). For the outside campaigns of 2016-2017, the flushing was  
45 ensured by a manual flowmeter approximately set at 1.2 L/h, resulting in an  
46 autonomy of about 3 weeks with a 5 L bottle filled at 120 bars. Starting from  
47 the second campaign, the high voltages were automatically adjusted through  
48 a feedback using the signal amplitudes recorded in each detector from the  
49 online reconstructed muons [7]. This feedback allowed to keep the gain prac-  
50 tically constant and ensured data taking in stable conditions. It also showed  
51 a very significant HV gradient between the detectors of a single telescope,  
52 with a difference of several tens of Volts between the first and the last in  
53 gas, see Fig. 1. After these observations, it was decided to set a dedicated  
54 test bench in our Saclay laboratory for investigations in a well controlled

environment.

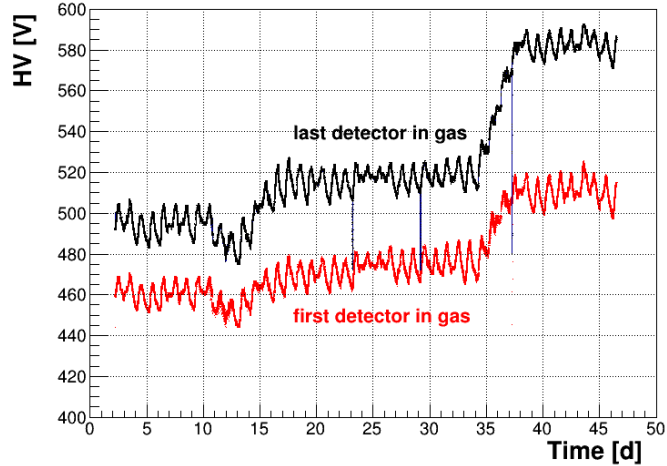


Figure 1: *High voltage evolution of the first and last detectors in gas within a muon telescope during a ScanPyramids outdoor campaign using the online amplitude feedback. The fluctuations mostly originate from temperature variations (daily oscillations) but also from pressure changes. Two 5 L bottles were used for these data, with a gas flow reduction at the end of the campaign to prolongate the data taking.*

55

56

## 57 2.2. The TomoMu test bench

58 The TomoMu cosmic test bench consists of 4 horizontal MG2D detectors  
59 mounted on a vertical axis. It is operated with the same equipment as de-  
60 scribed in [8], except that control is now done by a Nuc mini-PC from Intel,  
61 and our new custom-made high voltage power supply board also controls  
62 two commercial digital flowmeters from Bronkhorst to set the input gas flow  
63 and measure the output flow. The temperature, pressure and humidity of  
64 the gas were continuously measured by Yocto-Meteo sensors from Yoctopuce  
65 placed inside the gas circuit. They were initially embedded in small, 50 mL  
66 polyester-based boxes which were later replaced by aluminum ones and com-  
67 plemented by a Luminox sensor from SST Sensing, as shown in Fig. 2. The  
68 Luminox sensor provides measurements of the temperature, pressure, and  
69 oxygen level. These two sensing devices were read out by an online moni-  
70 toring program running on the Nuc and resulting data files were processed

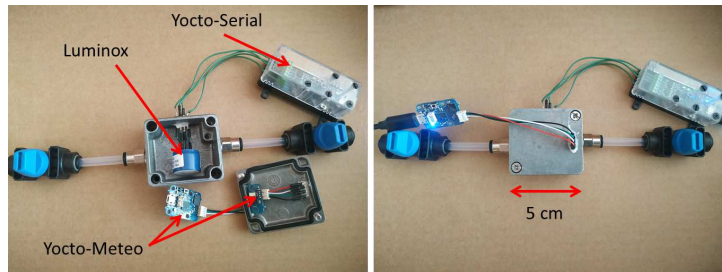


Figure 2: The aluminum probe box containing the Yocto-Meteo ( $T,P,H$  measurement) and the Luminor read by a Yocto-Serial ( $T,P,O_2$ ).

71 offline using the ROOT framework.

72

### 73 2.3. First measurements

74 For the first measurements, the gas was flushed in series in the 4 detec-  
 75 tors, initially at a flow of 4 L/h. The high voltages adjusted automatically  
 76 every 5 minutes with the amplitude feedback based on the online muon re-  
 77 construction. After a few hours, the HV stabilized <sup>1</sup>, and the input flow was  
 78 reduced to 0.4 L/h. The result of the HV evolution afterwards is shown in  
 79 Fig. 3: as was observed before, a large voltage difference appeared, with a  
 80 time scale evolution of several days.

81

## 82 3. Improvements of the gas circuit

83 The above measurements clearly point to an important degradation of  
 84 the gas mixture all along the circuit. A Fluent-based simulation at 0.4 L/h  
 85 revealed that the gas velocity can differ by a factor 50 within the active  
 86 volume of the Micromegas, with velocities down to 0.7 m/day in the vicinity  
 87 of the detector corners. The gas quality thus differs even within a detector,  
 88 leading to gain inhomogeneities and an efficiency loss of a few %. As the  
 89 intrinsic gain inhomogeneities of the detectors are not taken into account  
 90 in the Fluent simulation, a quantitative comparison with real data is not  
 91 straightforward. However, a 5% decrease of the muon rate recorded by the

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<sup>1</sup>apart from the fluctuations due to T,P variations affecting the gain

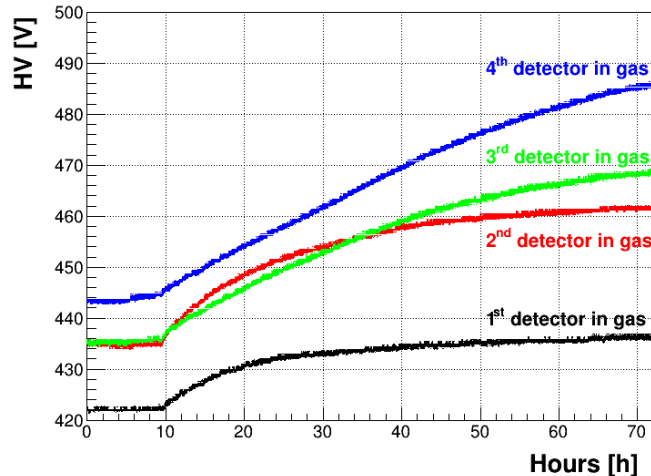


Figure 3: *High voltage evolution (at constant gain) of 4 detectors flushed in series in the TomoMu setup. After a few hours at 4 L/h, the gas flow is reduced down to 0.4 L/h (at  $T=10$  hours on the plot).*

92 telescope has indeed been observed in correlation with a gas flow reduction  
 93 from 1 to 0.4 L/h.

### 94 3.1. Recirculation

95 One way to reduce these inhomogeneities is to increase the gas flow in  
 96 the circuit by decorrelating it from the input gas flow. This can be achieved  
 97 using a recirculation system which accelerates the gas and reinjects it at  
 98 the entrance, as depicted in Fig. 4. In particular, it makes use of a turbine  
 99 developed within the HARPO project [9] for the reinjection. In this setup, the  
 100 gas velocity can therefore be maintained at a high value independently on the  
 101 input gas flow. Using the same setup and the same detectors as before, the  
 102 implementation of this modified circuit provides a good homogeneity between  
 103 the detectors, as shown in Fig. 5. In this case, the HV are essentially equal<sup>2</sup>  
 104 and close to the mean HV value from the initial setup, as the recirculation  
 105 simply mixes the gas without changing the pollution level.

106

107 We open here a parenthesis to briefly discuss the question of the gas flow in

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<sup>2</sup>up to small intrinsic differences due to the detector manufacturing

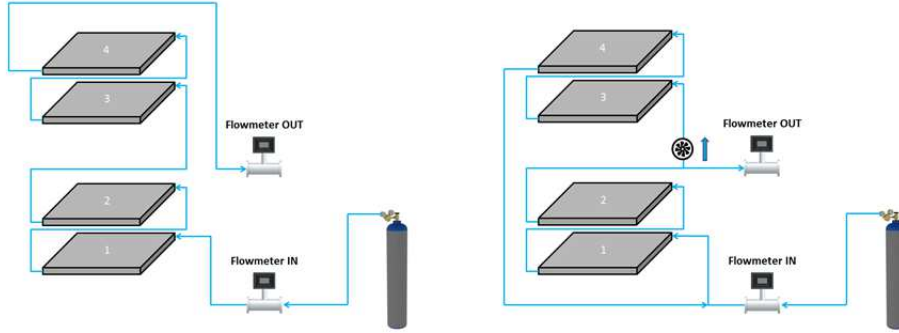


Figure 4: *Standard (left) and recirculation (right) gas circuits.*

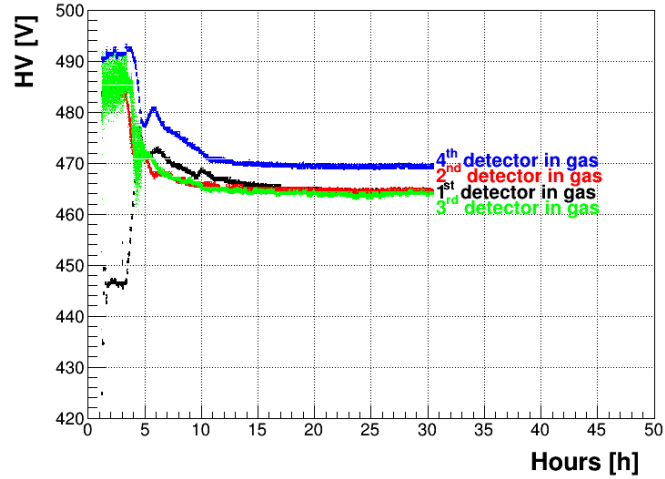


Figure 5: *High voltage evolution of 4 detectors flushed with the recirculation mode in the TomoMu setup using the amplitude feedback as before. The recirculation starts at  $T=2$  hours. Both vertical and horizontal scales are identical to Fig. 3 for easier comparison.*

108 such a circuit. Its actual value indeed cannot be accessed by inserting another  
 109 flowmeter, as such a device introduces some inertia which slows down the gas.  
 110 Instead, we made use of the Darcy-Weisbach equation relating the pressure  
 111 drop  $\Delta P$  in a circuit flushed with a given gas at a velocity  $v$ :

$$\Delta P = f \frac{L}{D} \frac{\rho v^2}{2}, \quad (1)$$

112 where  $L$  is the pipe length,  $D$  its diameter,  $\rho$  the volumic mass of the gas  
 113 and  $f$  is a dimensionless pressure drop coefficient. In our case, the flow is  
 114 completely laminar <sup>3</sup>, providing the following expression for  $f$ :

$$f = \frac{64}{Re}, \quad (2)$$

115 where the Reynolds number  $Re$  writes:

$$Re = \frac{\rho v D}{\mu}, \quad (3)$$

116 and  $\mu$  is the gas dynamic viscosity. Introducing the gas flow  $F$  one finally  
 117 gets:

$$\Delta P = \frac{128}{\pi} \frac{\mu L F}{D^4}, \quad (4)$$

118 This relation was checked separately with a Bronkhorst flowmeter related to  
 119 2 Yocto-Meteo sensors measuring the pressure drop through a 31 m pipe of  
 120 3 mm inner diameter. As can be seen in the Table 1 the agreement is very  
 121 good, which allows in turn to get the flow in an open circuit containing the  
 122 turbine through the measurement of the pressure drop. This measurement  
 123 was performed for different values of the turbine power supply, and for two  
 124 different engines, yielding values up to 5 L/h (see Fig. 6), *i.e.* 12 times the  
 125 input gas flow.

F [L/h]	0.1	0.2	0.3	0.5	1.0	2.0	3.0	4.0	5.0
$\Delta P_{calc}$ [mbar]	0.10	0.19	0.29	0.48	0.96	1.92	2.88	3.84	4.80
$\Delta P_{mes}$ [mbar]	0.09	0.20	0.32	0.50	0.93	1.94	2.91	3.88	5.01

Table 1: Pressure drop calculated from Eq. 4 and measured, as a function of the input gas flow.

126

127

### 128 3.2. Effects of humidity and oxygen absorbers

129 As stated in the previous section, the turbine only provides a better mix-  
 130 ing of the gas in the circuit, but does not change the contamination level.

---

<sup>3</sup>The Reynolds number numerically yields less than 10 times the gas flow in L/h.



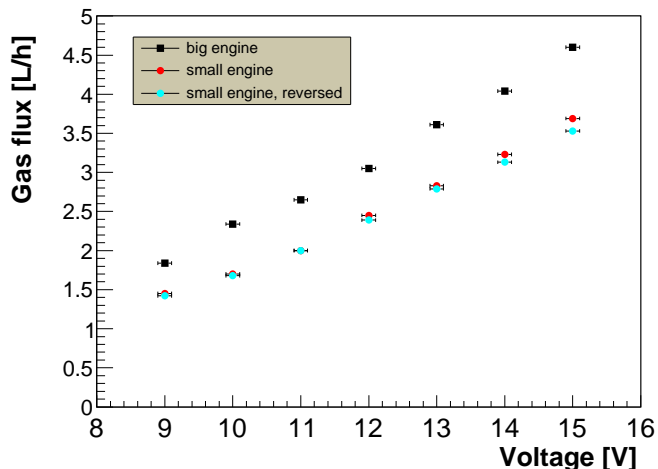


Figure 6: Gas flow obtained from the pressure drop measurement using a turbine with different configurations of engines, as a function of the turbine supply voltage.

131 An easy way to reduce this contamination is to add specific absorbers in the  
 132 circuit, as can be seen in Fig. 7. In this measurement, the TomoMu setup was  
 133 supplied with a constant 0.3 L/h input gas flow, using the recirculation mode.  
 134 The high voltages were monitored, as well as environmental parameters, hu-  
 135 midity and oxygen levels. As can be seen from the upper right of Fig. 7,  
 136 the atmospheric pressure underwent large variations during the first 2 days,  
 137 leading to similar variations of the high voltage (adjusted for constant gain).  
 138 When the pressure finally stabilized, a stainless steel capsule containing hu-  
 139 midity absorbers was introduced. Within a few hours, and thanks to the fast  
 140 gas circulation from the turbine, the humidity dramatically decreased from  
 141 4.5 to 1 g/m<sup>3</sup>. Because of the better gas purity, all the high voltages dropped  
 142 by a considerable amount, about 18 V. After one day, all the parameters were  
 143 stable, so the oxygen absorber was introduced in a second stainless steel cap-  
 144 sule. It consists of small iron-based bags initially developed by ATCO for  
 145 food industry. As for the humidity, the oxygen concentration rapidly de-  
 146 creased from 1.2 to 0.4%, and was accompanied by another 18 V drop of the  
 147 high voltages. The amplitude of the HV drops are not yet understood. A  
 148 Garfield simulation showed a 0.5% increase of the level of H<sub>2</sub>O would require  
 149 to increase by less than 5 V the HV of the detector to keep the gain con-  
 150 stant. However, the required HV increase was measured to be about 18 V in

151 our test. Such a discrepancy is not understood, and in general the extreme  
 152 sensitivity observed with this specific gas mixture to temperature, pressure  
 153 and pollutants is a mystery.

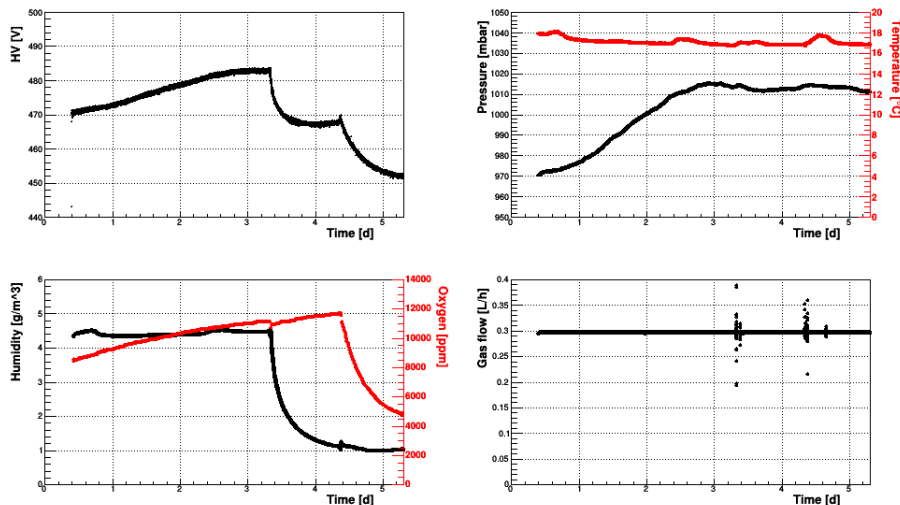


Figure 7: Measurements of the mean high voltage of the four detectors (upper left), environmental parameters (temperature and pressure, upper right), humidity and oxygen contamination in the gas (bottom left) and input gas flow (bottom right) in the setup with the turbine. The humidity and oxygen absorbers are introduced 3.4 and 4.4 days respectively. See text for details.

154

155 To better emphasize the correlation between humidity and high voltages for  
 156 a constant gain, we analyzed cosmic ray data taken during August 2019.  
 157 During this time, all the conditions were particularly stable (constant atmo-  
 158 spheric pressure within 7 mbar, constant temperature within 1.2 °C, constant  
 159 oxygen level in the gaz within 0.25%) except for the humidity in the gas which  
 160 slowly increased due to the saturation of humidity absorbers. Fig. 8 shows  
 161 the remarkable correlation between the HV and the humidity level, with a  
 162 slope close to  $4 \text{ V}/(\text{g}/\text{m}^3)$ .

163

### 164 3.3. Effects of preliminary pumping and heating

165 Another usual way to lower the gas contamination is to force outgassing  
 166 by pumping and heating the gas inside [10]. We tested this method with

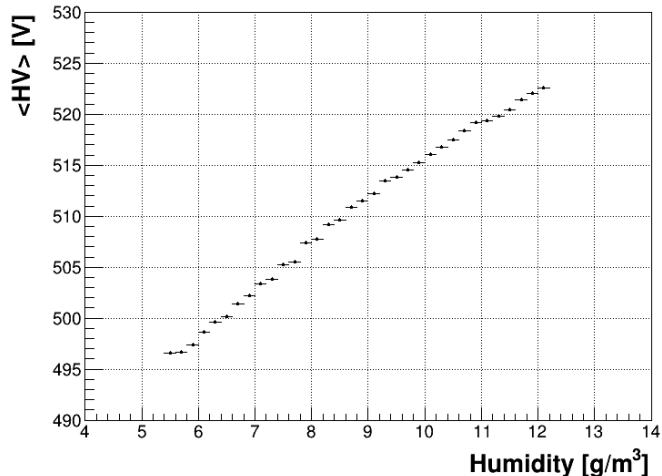


Figure 8: *Correlation between the mean high voltage (at a constant gain) of a telescope and the humidity level in the gas.*

167 the 50 mL, polyester boxes containing the Yocto-Meteo, after gluing the box  
 168 cover to ensure the sealing. Though the Yocto documentation stated that  
 169 the probes should not be used in vacuum, it turned out they survived all the  
 170 pumping cycles without any degradation. The box first underwent a short  
 171 pumping at 54 °C, then it was filled with pure Argon with an overpressure  
 172 of 50 mbars. The humidity evolution was then measured by the Yocto-  
 173 Meteo. This operation was repeated several times, with 4, 2.5 and 2.5 days  
 174 of additional pumping/heating. Because of the glue, the heating temperature  
 175 could not exceed 60 °C. The primary pump used provided a modest vacuum  
 176 slightly below  $10^{-1}$  mbar. The humidity measurements are shown in Fig. 9,  
 177 and reveal as expected a progressive drying of the box, though 9 days seem  
 178 still not enough to evacuate completely the humidity.

179

180 All these improvements allowed for a stable operation of the TomoMu setup  
 181 with an input gas flow below 0.2 L/h, *i.e.* 6 times smaller than during 2016  
 182 measurements. In spite of our efforts, it was however not possible to operate  
 183 TomoMu in a stable mode without any gas input. Indeed, a further reduction  
 184 of the input gas flow generated a new increase of the high voltages which this  
 185 time was not correlated with the humidity and oxygen levels. It is likely this  
 186 contamination is due to Nitrogen, but a mass spectrometer would be needed

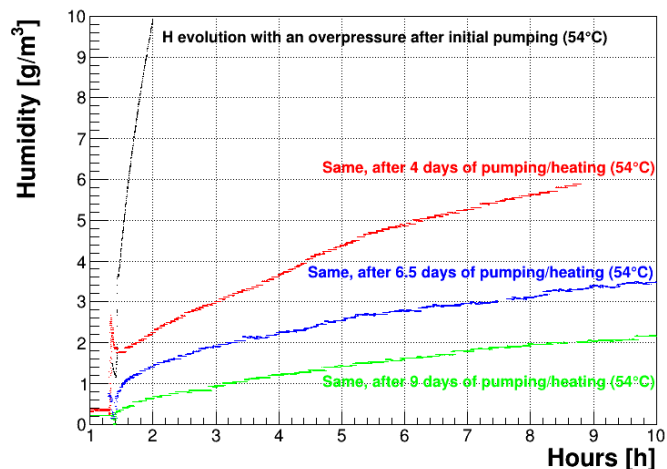


Figure 9: Humidity measurements inside the sealed Rose, polyester box after successive cycles of pumping/heating and Argon filling.

187 to confirm this assumption.

#### 188 4. Origin of humidity and oxygen contaminations

189 We now turn to the question of the origin of the observed gas contami-  
 190 nation. It can proceed *a priori* through only 2 mechanisms:

- 191 • leakage
- 192 • outgassing

193 The effect of direct leakage can be minimized with special care on the gas  
 194 tightness, and also by setting an overpressure in the detectors. Many mea-  
 195 surements were performed over the last 2 years on the gas tightness, and  
 196 values well below 1 mL/h per detector were routinely achieved. Still, resid-  
 197 ual leakage can contaminate the gas even in the presence of an overpressure,  
 198 as the gas concentration inside and outside the circuit homogenized at the  
 199 interface. This phenomenon was evaluated with detectors with different leak-  
 200 age values, and no significant effect was observed on the humidity and oxygen  
 201 level.

202 The outgassing can be separated in two processes: desorption and perme-  
 203 ation. The first one refers to a contamination from the inner surface of the

204 circuit elements, while the second corresponds to a migration of molecules in  
205 the volume of the materials. They fundamentally differ on their duration, as  
206 the former is limited in time and can be suppressed by initial pumping, while  
207 the latter is by nature a continuous process. We decided to focus on specific  
208 measurements with the probe boxes and with the gas pipes to determine the  
209 true origin of this contamination.

#### 210 *4.1. Measurements on the probe boxes*

211 The short term measurements shown in Fig. 9 could point to a pollu-  
212 tion from desorption only. However, a couple of polyester boxes was then  
213 prepared with different, long pumping/heating cycles, filled with Argon and  
214 left for 3 months with an overpressure to study their long term evolution.  
215 With sufficiently long pumping, it was possible to obtain a humidity below  
216 the detectable level of the Yocto-Meteo, *i.e.*  $0.01 \text{ g/m}^3$ , during several days.  
217 However, the humidity reappeared after that time, and later increased at a  
218 nearly constant rate, as shown in Fig. 10. This continuous increase is per-  
219 fectly compatible with a permeation from the outside, especially since the two  
220 boxes experienced exactly the same increase, though outgassed during differ-  
221 ent times. The period with undetectable humidity level can be understood  
222 as a complete drying of the box, followed by a progressive rehumidification  
223 by the permeation.

224 A similar measurement was performed on oxygen, with a dramatic increase  
225 in only a few weeks with the polyester box, as shown in Fig. 11. A stainless  
226 steel box in the same conditions yields an oxygen contamination 100 times  
227 smaller. For this reason, the polyester boxes were then replaced in the gas  
228 circuit by aluminum and stainless steel ones.

#### 229 *4.2. Effects of gas pipes*

230 Another element which can contribute to the mixture degradation are  
231 the gas pipes. In practice a large number of different pipes can be used in  
232 test installations. In our building, more than 10 were identified, and several  
233 are often combined in a given setup. Flexible pipes are mostly used, and  
234 in this case polyurethane-based ones (labelled PU or PUN) are frequently  
235 recommended in research centers for their fire resistance. Other flexible  
236 pipes include polyamide (PA12), Teflon-like materials - polytetrafluoroethy-  
237 lene (PTFE), fluoropolymer (FEP) - or aluminum.

238 To investigate their influence, we monitored their humidity and oxygen dur-  
239 ing Argon flushing, before and after an outgassing procedure. We first col-

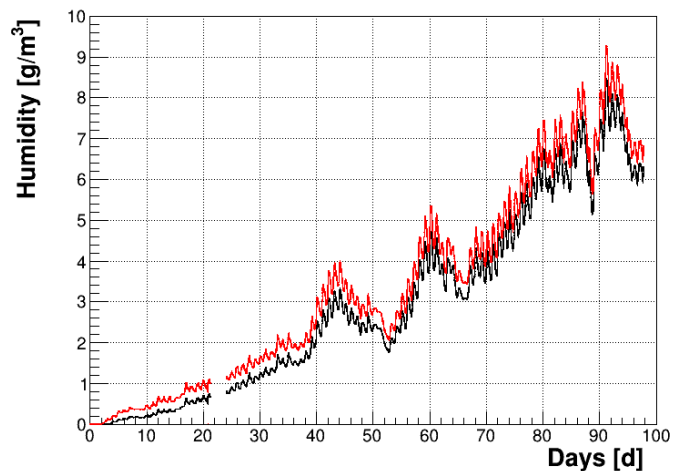


Figure 10: Long term humidity monitoring inside two polyester, probe boxes after intensive outgassing.

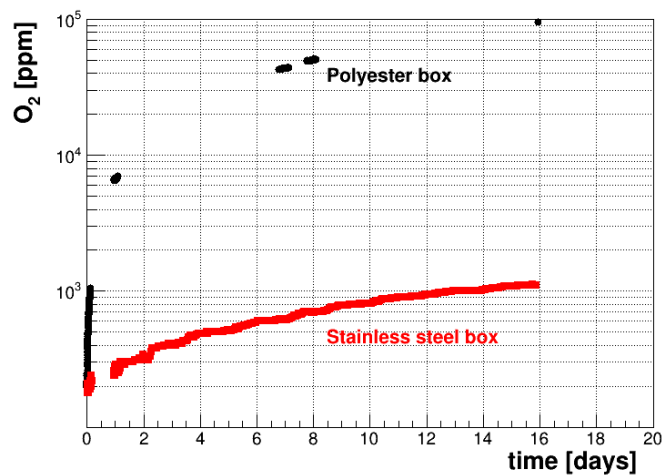


Figure 11: Oxygen monitoring inside a polyester and a stainless steel probe boxes after outgassing.

240 lected 9 different pipes in the neighbouring laboratories (5 PU, 2 PUN, 2  
 241 PA12, differing only by their colours), and bought FEP, PTFE and aluminum  
 242 pieces. Each of them were tested with a 1 m long sample, first flushed one

243 by one during 15 minutes in a 4 L/h Argon flux, *i.e.* equivalent to a 80 times  
 244 renewal of the pipe inner volume. The pipes were then closed with gastight  
 245 valves, and left for 50 days in the lab. After that time, they were again  
 246 flushed during 10 minutes at the same Argon flux, and the humidity and  
 247 oxygen levels at the exit of the pipes were monitored. The measured humid-  
 248 ity levels are shown in Fig. 12 (left) for the 6 different types (pipes of the  
 249 same material showed nearly identical behaviour). PU and PUN yield the  
 250 highest humidity values, and still suffered from high humidity after the 10  
 251 minutes flushing. PA12 was found better than PU, but still at a high level.  
 252 PTFE, FEP and aluminum were found to be very similar, and much better  
 253 than PU and PA12. The same operation was repeated after outgassing: each  
 254 pipe was placed in a vacuum chamber, heated and periodically flushed with  
 255 Argon. After less than a week, the chamber vacuum stabilized, suggesting  
 256 that the outgassing was over. Pipes were than again filled with Argon, left  
 257 for 30 days in the lab, and the same measurements were done, see Fig. 12  
 258 (right). Considering the pipes were at rest during only 30 days instead of 50  
 259 for the first tests, these results convincingly prove that the gas degradation  
 did not change significantly after the outgassing.

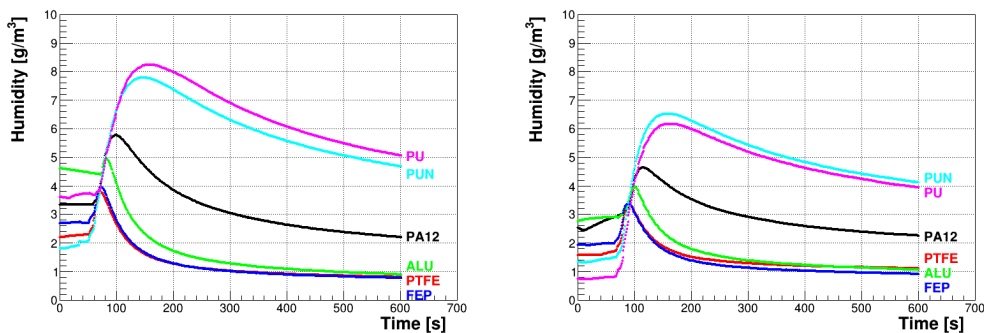


Figure 12: *Humidity monitoring during a 4 L/h Argon flushing in 1 m long pipes of different nature, before (left) and after (right) the outgassing procedure. In the left (resp. right) case, pipes were left at rest during 50 (resp. 30) days, which explains the relative humidity difference between the 2 plots.*

260

261 Oxygen levels were monitored in parallel both before and after outgassing, as  
 262 shown in Fig. 13, with quite different conclusions. In this case the aluminum  
 263 pipe is by far the best one, whereas FEP and PTFE seem to have a large  
 264 permeability to Oxygen, even higher than PU, PUN and PA12.

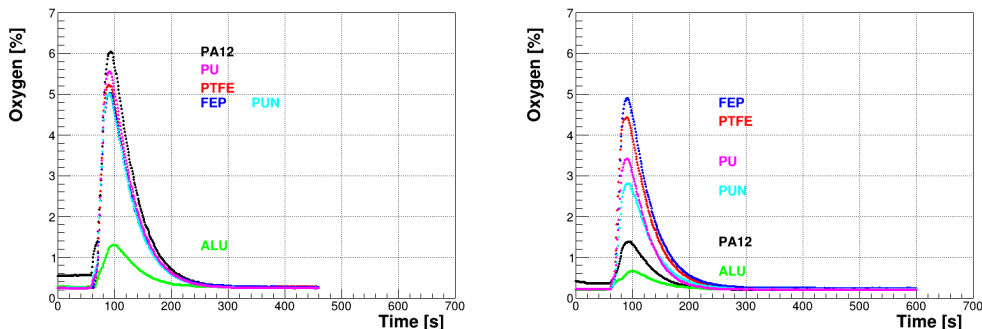


Figure 13: *Oxygen monitoring during a 4 L/h Argon flushing in 1 m long pipes of different nature, before (left) and after (right) the outgassing procedure. In the left (resp. right) case, pipes were left at rest during 50 (resp. 30) days.*

265

266 All the previous measurements suggest that permeation effects are already  
 267 significant after only a few days in the pipes, a particularly rapid time scale  
 268 compared to typical operations of the instruments. As a final test to show  
 269 the rapidity of the migration process, we placed one of the PU pipes in a  
 270 sealed chamber, and connected its extremities to 2 gas holes in the walls  
 271 of the chamber. The inner and outer volumes of the pipe were thus sepa-  
 272 rated, and the pipe was continuously flushed with a 0.5 L/h Argon flux. The  
 273 humidity level was monitored at its entrance and exit, and the difference  
 274 is shown in Fig. 14. Digital flowmeters were also plugged at the entrance  
 275 and exit, to check the absence of any direct leakage and to set an overpres-  
 276 sure of 15 mbar in the pipe. During the first 3 days, the chamber was open,  
 277 and thus filled with air. Once the pipe humidity stabilized, the chamber  
 278 was sealed and flushed with a 10 L/h Argon flux. After only 3 hours, the  
 279 pipe humidity started to decrease dramatically, proving that the humidity  
 280 migration within the pipe is primarily determined by the water vapor par-  
 281 tial pressure difference. After 2 days, the humidity difference stabilized very  
 282 close to zero, and the Argon atmosphere within the chamber was replaced  
 283 by a vacuum around 0.1 mbar. As expected, the humidity difference did not  
 284 change. After an additional day the chamber was re-filled with air at the end  
 285 of the measurement, and as can be seen the humidity difference re-increased  
 286 within 3 hours. The humidity difference in air provides a measurement of  
 287 the water contamination in the gas in the laboratory conditions (28°C and



288 a humidity around 10 mg/L) with this PU pipe, *i.e.* 1150  $\mu\text{g}/\text{h}$  per meter  
 289 of pipe. Similar measurements with 50 m long PTFE and aluminum pipes  
 290 showed permeation rates of respectively 20 and 0.62  $\mu\text{g}/\text{h}$  per meter of pipe.  
 291 In the same conditions, the oxygen permeation yields 90  $\mu\text{L}/\text{h}$  per meter of  
 292 pipe for PTFE, and less than 1.4  $\mu\text{L}/\text{h}$  per meter of pipe for aluminum. Last  
 293 but not least, the oxygen permeation timescale was found to be about 30  
 times faster than for humidity.

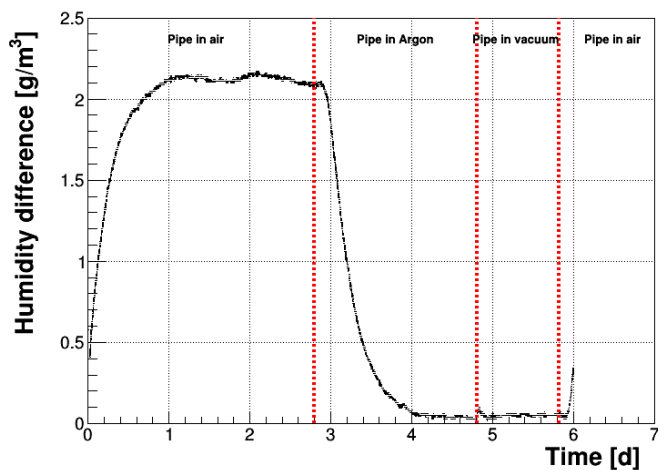


Figure 14: *Evolution of the humidity difference between both extremities of a 0.9 m PU pipe placed in a sealed chamber. The pipe is flushed continuously with Argon at 0.5 L/h with a 15 mbar overpressure. The sealed chamber is first open and filled with air. After 2.8 days (left vertical line), the sealed chamber is closed and rapidly flushed with Argon. After 2 more days (middle vertical line) the chamber is pumped down to 0.1 mbar. Finally the chamber is opened at the end of the measurement and re-filled with air (right vertical line).*

294  
 295

## 296 5. Conclusion

297 The degradation of the gas mixture in gaseous detectors have been stud-  
 298 ied in some details, showing its large impact on the detector gain. The effects  
 299 of humidity and oxygen have been quantified and turned out to have a pri-  
 300 mary and similar importance in this degradation. If this can be mitigated  
 301 by the use of specific absorbers and by a faster homogeneization of the gas,

302 other contaminants seem to participate to the gas degradation at very low  
303 flushing. This work also revealed the importance of the gas pipe material,  
304 generating large differences of the contamination level. This contamination  
305 could never be stopped by a preliminary outgassing procedure, and the mea-  
306 surements unambiguously show that a continuous permeation process is at  
307 work. Polyurethane-based pipes are found to be the worst choice in terms  
308 of humidity, though often recommended for their fire resistance capabilities.  
309 FEP and PTFE are good candidates to lower humidity, but exhibit a larger  
310 oxygen permeability. Not surprisingly, the aluminum pipe appears as the  
311 best choice, of course at a cost of a lower flexibility. More studies are now  
312 planned to measure the permeation rate of different gases in several materials  
313 using a mass spectrometer, and to investigate anti-permeation coatings.

## 314 6. Acknowledgments

315 We are very grateful to the ELVIA company, and particularly to C. Guine-  
316 folleau, for the main production of the detectors. We also thank H. Alves  
317 and C. Filosa for their help during the integration of the detectors.

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