Aging Effects in the ATLAS Transition Radiation Tracker and Gas Filtration Studies

The ATLAS TRT collaboration

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Abstract-- **The Transition Radiation Tracker (TRT) is one of three particle tracking detectors now under construction for the ATLAS experiment, whose goal is to exploit the highly exciting new physics potential at CERN's next accelerator, the so called Large Hadron Collider (LHC).**

The TRT consists of 370000 straw proportional tubes of 4 mm diameter with a 30 micron thick anode wire, which will be operated with a $Xe/CO_2/O_2$ gas mixture at a high voltage of approximately 1.5 kV. While the construction of the TRT is now well under way, a number of interesting and challenging questions need to be solved with regard to wire aging phenomena, which are induced by pollution originating from very small amounts of silicon-based vacuum materials in some components of the gas system. Finally a guideline to avoid aging in wire chamber detectors in high luminosity experiments is given.

I. Introduction

The Transition Radiation Tracker (TRT) is based on the use of straw detectors, which can operate at the expected high rates due to their small diameter and the isolation of the sense wires within individual gas volumes. Electron identification capability is added by employing Xenon gas to detect transition radiation photons created in a radiator between the straws.

Fig. 1 shows the layout of the TRT. It has been optimized for the best performance in terms of track reconstruction and electron/pion separation in the extremely harsh operating conditions expected at the LHC. With an active length of 5.5 m and an active diameter of 2 m, the TRT consists of three parts: a central barrel and two end-caps. Each straw is 4 mm in diameter and equipped with a 30 μm diameter gold-plated tungsten wire. The maximum straw length is 144 cm in the barrel, which contains about 50000 straws, each divided in two at the center and read out at both end, to reduce the occupancy. The end-caps contain 320000 radial straws, with the readout at the outer radius. The total number of channels that are read out is 420000. Each channel provides a drift time measurement, giving a spatial resolution of 170 μm per straw, and two independent thresholds. These allow the detector to discriminate between tracking hits, which pass the lower threshold, and transition radiation hits, which pass the higher one.

The barrel section (see Fig. 2) is built of individual modules between 329 and 793 straws each, covering the radial range from 56 to 107 cm. The first six layers are inactive over the central 80 cm of their length to reduce their occupancy. Each end-cap consists of 18 wheels (see Fig. 3). The innermost 14 cover the radial range from 64 to 103 cm, while the last four extend to an inner radius of 48 cm. The production of the last four wheels has been staged. Wheels 7 to 14 have half as many straws per cm in z as the others, to avoid an unnecessary increase of crossed straws and material at medium rapidity. The design and construction of the TRT are described in more detail in reference [1] – [3].

The ionization current density will be 0.15 μA/cm of wire leading to a maximum ionization current per wire of about 10 μA. After 10 years of operation the straws will accumulate a radiation dose of about 10 Mrad, and a neutron fluence of up to $2x10^{14}$ n/cm^2. These numbers include a 50% safety factor for uncertainties in the calculations. The total dose results in unprecedented ionization currents and integrated charges (up to ~10 C/cm of wire) for a large-scale gaseous detector.

The original gas mixture: $Xe(70\%)CF_4(20\%)CO_2(10\%)$ was found (in 2001, after 20% of wires strung) to destroy the glass wire joints. Instead a $Xe(70\%)CO_2(27\%)O_2(3\%)$ gas mixture is used which provides acceptable operational stability and equivalent physics performance [4].

The CF_4 component in the original TRT gas mixture was chosen because of its small diffusion coefficient and large drift velocity. Additionally, the CF_4 radicals created in the gas avalanche prevent hydrocarbon and SiO_2 wire deposits. With the new gas mixture the TRT is much more sensitive to organosilicon impurities because the oxygen radicals which are created in the gas avalanche can prevent hydrocarbon wire deposits but not silicon based ones [5].

Therefore a high level of gas purity is necessary to reach the demanded 10 years lifetime of the TRT. The validation concept for selecting components for the construction of the final closed-loop gas system and possible gas filtration studies are important because already small concentrations of certain gaseous constituents can have very dramatic effects upon the rate of wire aging. These impurities result from outgassing of silicon based materials in contact with the gas. The identification of the origin and the composition of the aging causing impurities is an important precursor to prevent wire aging.

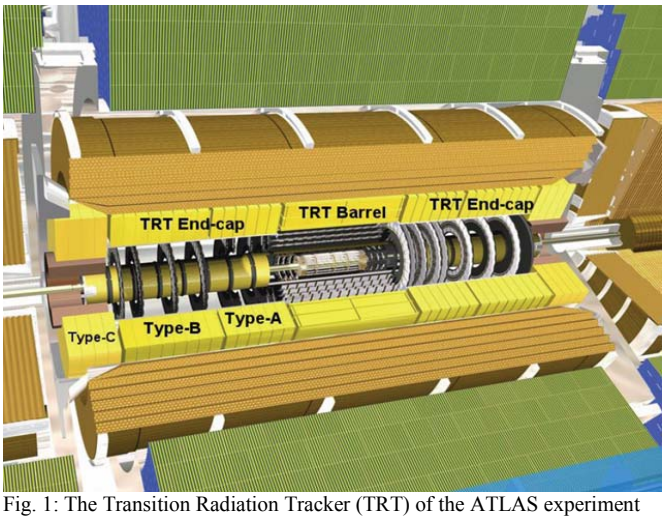


Fig. 1: The Transition Radiation Tracker (TRT) of the ATLAS experiment

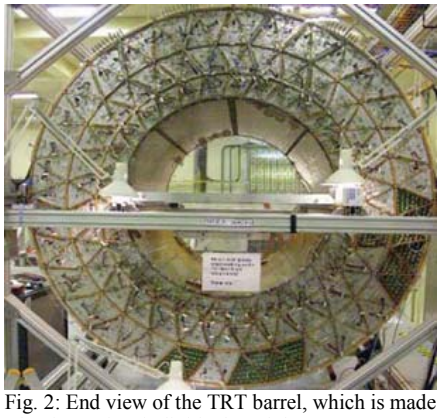


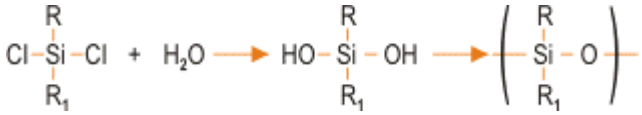
Fig. 2: End view of the TRT barrel, which is made of 3 rings of 32 individual modules

Fig. 3: End-Cap wheel of the TRT

II. Organosilicon Compounds

Silicones are synthetic polymers and are therefore not found naturally. They have a linear repeating silicon-oxygen backbone with organic groups attached directly to the silicon atoms by carbon-silicon bonds. These types of compounds are also known as polyorganosiloxanes. Certain organic groups can be used to link two or more of these silicon-oxygen backbones and the nature and extent of crosslinking enables a wide variety of products to be manufactured.

The starting materials for the manufacture of silicones are alkyl or aryl substituted chlorosilanes [6]. The most common method for preparing silicones is the reaction of a chlorosilane with water. This produces a hydroxyl intermediate, which condenses to form a polymer-type structure. The basic reaction sequence is represented as:



This is the favored route although other raw materials such as alkoxysilanes can be used.

The resulting structure of the chain (straight, ramified, crosslinked) determines the thermodynamic properties. A linear polymer gives silicon oils and lubricants, where crosslinked versions are important rubbery sealants, caulkings, coatings and tubing materials. These materials have a wide variety of applications in vacuum systems. Through their low vapor pressure they can easily pollute an initially clean gas mixture through outgassing processes.

III. Aging Process

In the thin tube of plasma surrounding the anode wire, many complex physical and chemical phenomena are occurring simultaneously. Dissociation of polyorganosilixanes in this plasma leads to the deposition of SiO_2 films on the anode wire. Dissociation and deposition are not understood clearly, however a general model of the deposition mechanism can be specified.

In the gas phase, collisions of neutral molecules with high energy electrons and heavy particles (ions or neutrals) or photon absorption results in the generation of molecular fragments. "Generic" reactions for these processes are indicated in equation (1) → (6), where X_2 represents any molecular chemical species, and B represents an ion, molecule or atom [7].

Electron impact collisions

$$e + X_2 \rightarrow 2X + e \quad (1)$$
$$e + X_2 \rightarrow X^+ + X^- + e \quad (2)$$

Photon exposure

$$h\nu + X_2 \rightarrow 2X \quad (3)$$
$$h\nu + X_2 \rightarrow X^+ + X^- \quad (4)$$

Heavy particle collisions

$$B + X_2 \rightarrow 2X + B \quad (5)$$
$$B + X_2 \rightarrow X^+ + X^- + B \quad (6)$$

Obviously, the chemistry occurring in plasmas is extremely complex, and thus virtually impossible to define completely. In the plasma around the anode wire, intermediate products which are mainly produced by electron impact collisions react with the present O atoms or O_2. As the result of such oxygen in the vapor phase, there is a possibility that a part of silicon arrives at the wire surface as relatively low molecular compounds such as SiO or SiO_2. The present O_2 converts the eliminated hydrocarbon gases into the oxides H_2O and CO_2 which are leaving the straw with the gas flow.

As specified in section II, the aging causing impurities are polyorganosiloxanes, most common a polymethylsiloxane. Fig. 4 shows the reaction mechanism for a pentamethyldisiloxane in the deposition process. The composition of the deposit on the wire surface depends strongly on the O_2 content in the gas mixture, on the exposure time and on the current density. Higher O_2 concentrations, longer exposure times and higher current densities are leading to purer SiO_2 deposits. In general the deposit resulting from polyorganosiloxanes impurities are a mixture of SiO_2, R-SiO and Si-OH [8].

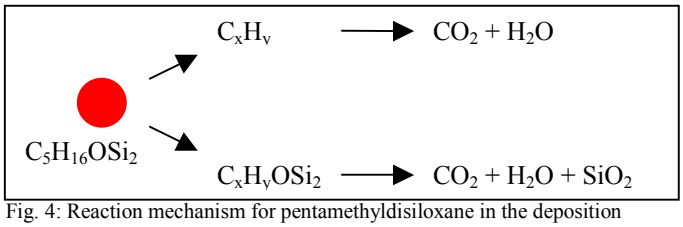


Fig. 4: Reaction mechanism for pentamethyldisiloxane in the deposition process

IV. Systematic Component Validation

A complex issue for the safe operation of gaseous detectors is the cleanliness of the gas supply system. The components used to build the gas system have to be selected with care to avoid pollution of an initially clean gas mixture.

The TRT consistently has followed a strict validation policy for all components used in the gas system. A component is considered validated if, after performing an aging test with TRT straws in a clean gas system where the component under test has been introduced, no aging is detected after ~500 hours of irradiation at the nominal gas flow and current density, of one volume exchange per hour and 100 nA/cm respectively. The aging rate does not depend on the gas mixture for Ar-CO_2, Ar-CO_2-O_2 and Xe-CO_2-O_2, because Ar and Xe are inert gases and O radicals are produced in all these mixtures through the dissociation of CO_2 under irradiation. Therefore the cheaper Ar(70%)CO_2(30%) mixture is used for the validation process. A typical validation run for a component under test will be performed at 1.5 cm^3/min/straw, which corresponds to 10 times the nominal flow, at nominal gas gain and at a current density of 100 nA/cm. The straw will be irradiated over a length not more than 1 cm. A gas flow of 10 times the nominal rate accelerates the aging test, thus a test can be performed in 200 hours instead of 500 hours at the nominal rate. This test doesn't guarantee a complete clean gas system but it guarantees that the gas gain drop will be less than 5 % per year of TRT operation. 1 cm of wire irradiation during the validation test is enough, because aging is observed at the beginning (in terms of gas flow) of the irradiated area. Fig. 5 shows the setup for the aging tests with straw prototypes and Fig. 6 the validation test of an aging causing rotameter. The gain drops by ~20% in 250 hours of irradiation, invalidating the use of this component in any of the gas systems used during production, quality tests and operation of TRT modules. Many other components, such as stainless steel pipes, electronic and mechanical flowmeters, valves, etc, have been checked and validated in aging tests. Only components which have been validated as "CLEAN" have been used for the assembly of the TRT gas system.

5% gas gain drop per year of the TRT detector can be accepted as the initial gas mixture Ar(70%)CO_2(26%)CF_4(4%) can be used for up to 30 days of TRT operation to restore the gas gain. This is because fluorine based radicals issued from the avalanche process are able to etch away wire deposits. Thus, one cleaning run per year, if needed, seems to be realistic.

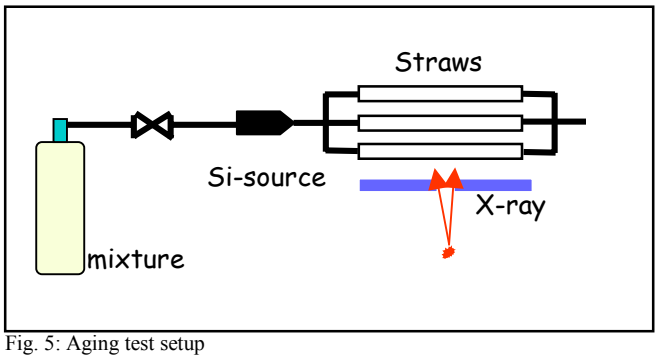


Fig. 5: Aging test setup

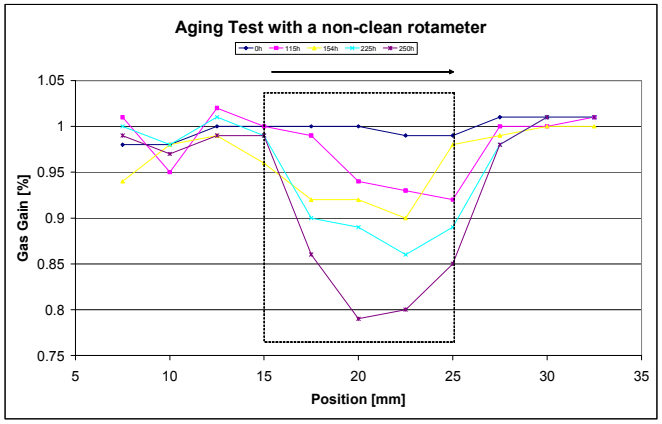


Fig. 6: Aging test with a non-clean rotameter

V. Gas Cleaning by Adsorption Processes

Since we know that silicon containing VOC's (volatile organic compounds) are causing anode wire degradation and taking into account that the construction of an absolute clean gas supply is almost impossible we were looking for a feasible gas cleaning procedure.

Separation and purification of gas mixtures by selective adsorption of one or more of its components on a micro- or mesoporous solid is a widely used application in the chemical industry. Adsorption of VOC's is most generally performed using fixed beds of adsorbents [9]. The advantage of fixed bed adsorption is that the working temperature is ambient and that no heat or power is required for the operation.

Fig. 8 shows the principle of a fixed bed adsorber [10]. Mechanical sieves at the inlet and outlet of the adsorber holds the sorbens in the reactor. The outlet sieve is also used to keep fines and dust back, which are resulting from ablation processes of the sorbens. The polluted gas stream enters the adsorber and gas separation occurs by producing a saturated zone, followed by a MTZ (mass transfer zone) and fresh sorbens. For good filtration efficiency it is important that the MTZ is as small as possible. As soon as the MTZ reaches the outlet of the adsorber, breakthrough of the pollutants appears and regeneration has to be started. The sorbens can be used in form of powder, pellets, spheres or beads (Zeolite UY8 beads are shown in Fig. 7 [10]). The advantages of beads are their high bulk density, their low formation of fines and dust and their minimized pressure drop.

The adsorption capacity of different sorbens can be found in Table 1. This adsorption capacity has been examined at CERN in several breakthrough tests with hexamethyldisiloxane. It appears to be a good representative for the real impurities in the TRT gas system, as the main component of the outgassing materials is polymethysiloxane (see section II).

The adsorption measurements have been performed at 10ppm. The maximum expected impurity level in the TRT active gas system should be around 10ppb, for this impurity concentration filters with a lifetime of ~100 years can be produced. The volume of these filters for the 3 m^3/h gas flow in the TRT gas system is ~5 kg with sorbens prizes of about 10 Eur/kg. Regeneration is possible (see Table 1) and has been tested at CERN for various sorbens, but will be most likely not performed as the adsorption capacity is very high and the prize of the material is very low.

Table 1: Adsorption capacity of various porous materials

Filter	Conc.	Cap.	Cap.	Reg.	Comment
	[ppm]	[l_{gas}/g]	[$g_{Si}/kg_{Sorbens}$]		
Zeolite UY8	10	1600	116	OK	particle size (0.4-0.5mm)
TIMIS Catalyst	10	1100	80	OK	pellets (d=1.0mm; l=2-4mm)
Aeronex Standard Filter	10	700	51	OK	type 35KF 1slpm
Zeolite ZSM 5	10	600	44	OK	particle size (0.25-0.5mm)

Figure 7: Zeolite Beads UY8

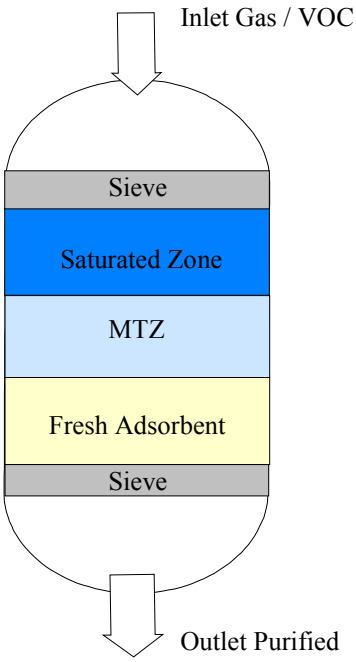


Figure 8: Fixed Bed Adsorber

VI. Principle And Guidelines

In this section we will give useful guidelines in order to avoid aging problems in wire chambers. The guidelines are based on experiments made in laboratory tests. Table 2 shows a list of "BAD and GOOD" materials or procedures, which are reasonably well established in context with aging problems [11]. This list relates to materials commonly used for the TRT assembly and is therefore not complete. It should be noted that a clean gas system together with a supply of a very pure gas can reduce aging to small or negligible levels. Another approach is to place a filter upstream of the chamber, so only materials of the chamber itself can cause aging problems, and these can be more easily controlled.

Avoiding pollution during the assembly process requires the establishment of clean and safe methods for assembly and operation of the system. These principles should be used to assemble, not only the final gas system, but also any system supplying gas during the production of modules at the various sites. Below the cleanness specification for the TRT gas system components is listed:

General

1.) All pipes, fittings and components used in the gas systems have to be cleaned and degreased before installation. Cleaning must always happen before any assembly (even for tests). Cleaning has to be done in ultrasonic baths.
2.) Gas system components must tolerate the presence of ozone in the system (100-200 ppm of O_3).
3.) Some parts of the system will be exposed to CF_4 for a maximum of 30 days and the distribution system might be exposed to CF_4 disintegration products for the same period of time.

Components

1.) The components must be free from any traces of lubricant, particularly any silicon containing products.
2.) Silicon containing O-rings, seals or joints must not be used.

Table 2: Recommendations for materials and procedures

Materials		
Elastomers (Gas Seals)	preferred	EPDM, Viton, Teflon (not in contact with CF_4)
	forbidden	any type of rubber, NBR, RTV
Metals	preferred	Stainless Steel, Copper, Brass
	forbidden	Al in the distribution system
Plastics	preferred	ULTEM, PEEK+
	forbidden	
Thread Tightening	preferred	Teflon-Band
	forbidden	Si-Joint Loctite
Glues	preferred	Araldite AW103, Tra-Bond 2115
	forbidden	Araldite AW106
Bubbler Oils	preferred	none, water if needed
	forbidden	all Si containing and low pressure organic oils
Lubricants	preferred	to be avoided, if ever use Kryotox or Apiezon
	forbidden	any other

VII. Summary and Conclusions

Recent progress made in understanding the processes leading to aging effects in wire chambers has been reported. These effects are largely due to wire coatings resulting from dissociation processes of polyorganosiloxanes. A reasonable explanation is given, which, when correlated with results from plasma chemistry, seems to offer some qualitative explanations for aging processes.

The present state of knowledge allows one to formulate a clear set of procedures to follow in order to avoid wire aging.

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