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Assessment of the radiation damage to the coolant in SciFi tracker

Abstract: The "back-of-an-envelope" estimates show that the effect of the absorbed radiation on the proposed SiPM coolant (C6K) in SCiFi tracker is negligible. As a consequence, a study of chemical properties of C6K, primarily of its reactivity with water, has a higher priority compared to the radiation resistance study.

1. Introduction, radiation damage in liquids

Liquids lack fixed internal structure, so the effect of radiation for them is limited to radiolysis, the dissociation of molecules by ionizing radiation or neutrons - unlike in solids for which the impact on mechanical or crystalline properties is also relevant. Radiolysis alters the chemical composition of the liquids, primarily through formation of free radicals. This can lead to increased viscosity, polymerization, evolution of gaseous compounds, loss of dielectric strength, increased acidity. In fully fluorinated fluids, like perfluorohexane C_6F_{14} or perfluoroketone $C_6F_{12}O$ (Novec 649 [1], or C6K), the formation of acids from radicals can occur in presence of moisture or hydrogen-containing impurities[1]. All these effects, at elevated radiation doses (a few kGy to hundreds kGy), might cause visible damages to the cooling systems and changes in their performance, especially in 2-phase applications. A comprehensive study [2] of perfluorocarbons (PFC) C_3F_8 and C_6F_{14} at CERN demonstrated a high radiation resistance of purified PFC fluids, characterized by a relatively low radiolysis yield and negligibly small production of hazardous compounds. This can be qualitatively understood as a consequence of the tight molecular structure of these compounds, with the structural C-C bonds reinforced by the presence of multiple very strong C-F bonds [3][2]. On the contrary, the radiolytic properties of perfluoroketones have not been studied at all. It is established that C6K molecules are photolyzed by the UV (with the peak absorption at 307 nm or 4.04 eV) [9]. This property, explaining the very low GWP of C6K, might also result in a lower radiation resistance [4], compared to perfluorocarbons.

2. Estimates for SciFi Tracker application

In the SciFi tracker application [5], C6K is proposed as a coolant in the mono-phase liquid cooling system for silicon photodetectors (SiPMs). The expected radiation dose at the SiPM location is fairly low, <80 Gy, $<10^{12}$ neq/cm^2. Order-of-magnitude estimates, even with exaggerated pessimistic

[1] An organic molecule can be cleaved at its weakest bond in the process of recombination and de-exitation following ionization. In C6K the weakest are the C-C bonds next to the carbonyl C=O group. The fate of the resulting radicals very much depend of the fluid purity. One likely scenario for pure fluids is a recombination. The impurities will cause irreversible chemical transformations. For example, in presence of water, the resulting $(CF_3CF_2CO)^-$ radical can form pentafluoropropionic acid (PFPA) CF_3CF_2COOH. In presence of O2 and water, assuming for the C6K radiolysis the same scenario, as for the photolisys in air [10], the principal products will be CF3C(O)F and COF2 (carbonyl fluoride). CF3C(O)F will further be undergo hydrolysis to give trifluoroacetic acid, while COF2 will hydrolize CO2 and HF.

[2] Another consequences are their chemical inertness of perfluorocarbons and low viscosity of the liquid phase.

assumptions, show that the expected radiation effect on the coolant will be negligible. First, because of the coolant circulation, only a minor fraction of it is exposed to radiation at the detector. Second, the total amount of the coolant that can be transformed by this radiation turns out to be at a ppm level. It is also appropriate to note that the inline rectification of circulating coolant will be constantly removing the radiolysis products.

2.1 The dilution factor

The peak total absorbed ionization dose and neutron fluence quoted in the TDR [5] are calculated for the SiPMs at the periphery of the 5x6 m2 tracking planes. The fluid in the cooling pipes near the middle of the tracker plane will be exposed to the same amount of radiation[3]. However, the fluid in the large connecting line(s) located farther away from the SiPM (say, in 40-50 cm) will get 30-50% less dose. The dose also decreases towards the corners of the tracker planes. We shall conservatively estimate the total dose reduction by factor **1.5**.

The volume V_d of the coolant exposed to radiation in all pipes around the tracker (including the connecting pipes) is only a fraction of the total coolant volume V_t circulating in the system. Therefore, the dose absorbed by the coolant will be further "diluted" by the factor $f=V_d/V_t$.

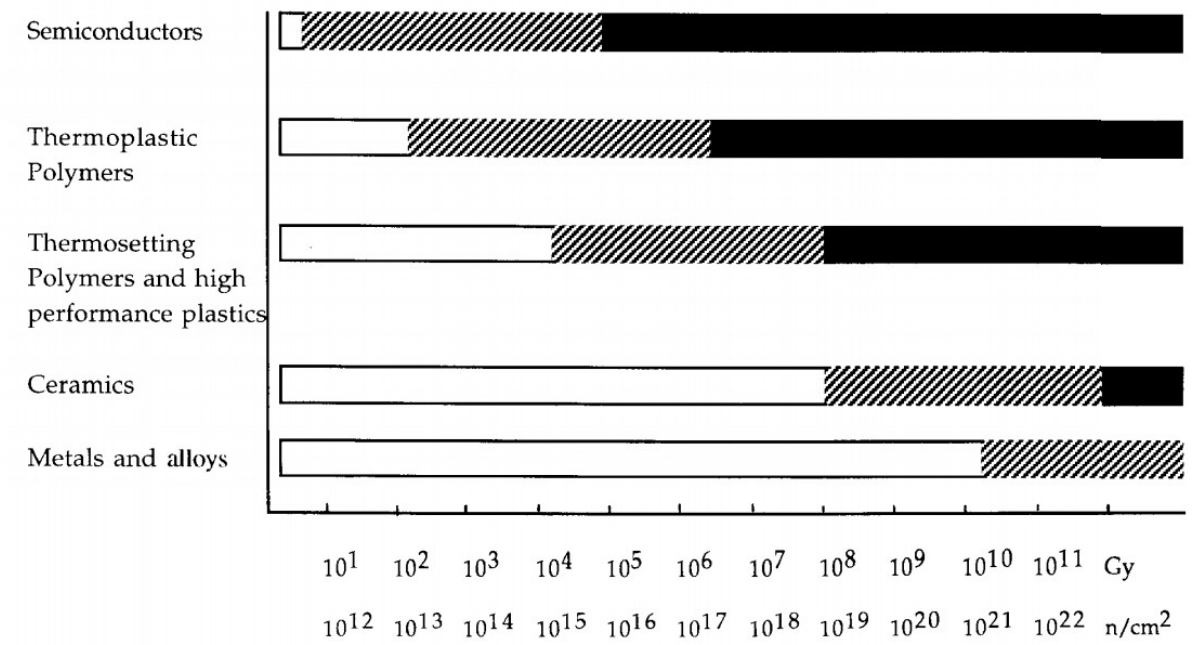
Both V_t and V_d depend on the manifolding scheme (serial or parallel). The TDR [5] refers to the serial connection scheme, with m_c=330 kg of Novec 649 or C_6F_{14}. The parallel connection will require a bigger volume of all connecting pipes, because a) they will transport (~6 times) higher fluid flow and b) in addition to one feeding pipe per branch, there will be a return line of the same cross-section.

- *Serial connection*. Branch length is L_b=6*53=318 cm. Cooling pipe radius r_c is 2 mm, its cross-section is S_c=0.126 cm2. The cooling pipe volume, including U-bends (10%) is $6 \cdot S_c \cdot L_b \approx 44$ ml per branch of 6 modules. A ~2 times thicker horizontal feed pipe has the cross-section S_f= 0.5 cm2 and V_f= 159 ml. Total per branch: V_b=44+159=203 ml. Total per detector = 203*48 ≈ 10 l. The vertical connection/manifolding lines will have a comparable volume, so the total volume Vd of the coolant at the detector is ≈20 l. At -40°C, the coolant density is ~1.8 kg/l, so the total coolant volume will be 330 kg/1.8 kg/l = 183 l and the dilution factor will be f_{serial}=20/183≈0.11

- *Parallel connection*. Cooling pipe volume, assuming the same S_c as for the serial case and including two 40 cm-long in/out connections per module, is roughly 110 ml. Two identical feed and return lines with the 6 times larger cross-section S_f=6*0.126=0.76 cm2 have the volume $V_f=S_f$*318*2=480 ml. Total per branch is V_b=110+480=590 ml, the total per detector is 0.59*48=28 l. Including similar vertical side connections we obtain V_d ≈ 60 l. The total volume of the infrastructure pipework (transfer lines, chiller, pump) will have to be significantly larger than for the serial case, to support the ~6 times higher flow rate. My guesstimate is minimum ~240 l. We arrive to the dilution factor $f_{parallel}$=60/(240+60)=0.2, for the total coolant mass m_c=300*1.8=540 kg.

For further estimates I assume the second, more pessimistic, scenario, that is f=0.2 (and m_c=540 kg). Including the above mentioned factor 1.5, we arrive to the overall downscale factor 0.2/1.5=0.13 for

[3] Note that ionization losses in fluorocarbons are close to that of Si (1.664 MeV cm^2/g). For example PTFE has dE/dX = 1.671 MeV cm^2/g [PDG].



the dose and the integrated neutron fluence for the coolant. This gives **11 Gy** and **~0.13·10^{12} neq/cm^2**, respectively. By all measures, these are very small values for most of materials (see Fig. 1).

Figure 1: General appreciation of radiation damage to materials (from [6]). No damage (blank), mild to sever (shaded) or destruction (black). The horizontal axis shows the ionizing dose in Gy and the approximate equivalent neutron fluence (note that the effect of 1 Gy roughly corresponds to 10^{11} neq/cm2).

2.2 The upper limit for the radiolysis yield

The efficiency of the chemical effect of radiation (further referred to as a radiolysis yield) for chemical compounds is usually characterized by the G-value, the number of molecules, radicals or ions produced or transformed per 100 eV of absorbed ionizing radiation, at the final (chemical) stage of the particle track[4]. In particular, G(-M)-values represent the number of starting molecules permanently changed [7]. The G_{tot} value for all products is, typically, about 2-3 for aliphatic ketones and for the perfluorocarbon C6F14 [7,8]. For further estimates, I assume a grossly exaggerated value G(-M)=25 for C6K which corresponds to the physical upper limit given by the energy 4 eV of the α-cleavage of the C6K molecule[5].

Under this assumption, the dose of 1 Gy can dissociate $G \cdot 6.24 \cdot 10^{18}$ (eV/kg)/100 eV $\approx 1.6 \cdot 10^{18}$ molecules per kilogram of C6K. 1 kg of this compound contains 1000 g$\cdot N_A / M_W \approx 19 \cdot 10^{23}$ molecules. The estimated total radiolysis yield is, therefore, $1.6 \cdot 10^{18}/19 \cdot 10^{23} \approx$ **0.82 ppm/Gy** or, for the expected dose of 11 Gy, **9 ppm**. In other words, not more than ~540 kg$\cdot 10^3 \cdot 9 \cdot 10^{-6} \approx$ **4.9 g** (or about 2.7-3 ml, less than a teaspoon) of the coolant will be transformed during the entire lifetime of the project.

[4] The "chemical" stage starts after ~10-6 s, after recombinations, de-excitations and all other fast secondary effects have occurred.

[5] The unknown real value can be only less than that – by up to factor ~10.

The expected effect of neutron irradiation is even smaller. If we assume, following [6] (Fig. 1), that the effect of 10^{11} neq/cm2 is roughly equivalent to 1 Gy, then the expected radiolysis yield of the total fluence of ~$0.13 \cdot 10^{12}$ neq/cm2 will be equivalent to the effect of 1.3 Gy, that is 1.3Gy·0.82 ppm/Gy≈**1 ppm**.

We can try to obtain an upper limit for the neutron effect differently, by computing the total effective surface S_c of the coolant exposed to the neutron flux and taking an exaggerated assumption that all neutrons crossing this surface will be absorbed in the coolant. The biggest pipes (the feed, or return, or vertical connection pipes, see the previous Section) in the exposed area will each have the effective square inner cross-section of $(0.87\ cm)^2$. The two pipes will have the combined width of <2 cm. For safety, we take 5 cm and obtain S_c=0.05m·2·(5m(H)+6m(W))·12 planes ≈13 m2. Assuming 1 MeV/n, the total "guesstimated" deposited energy will be $13 \cdot 10^4 \cdot 0.15 \cdot 10^{11} \cdot 10^6 \approx 2 \cdot 10^{21}$ eV which will dissociate $G \cdot 2 \cdot 10^{21}/100 \approx 5 \cdot 10^{20}$ molecules out the total of $540 \cdot 19 \cdot 10^{23} \approx 10^{27}$ molecules of the coolant. This corresponds to **0.5 ppm,** which qualitatively agrees with the above estimate.

Thus, the expected combined radiolysis effect on the SiPM coolant will be microscopic. Furthermore, only a fraction of the radiolysis products will represent a potential hazard (e.g., acids), especially taking into account that most of such products will be removed by inline coolant rectification facilities (filters, ad/absorbers). ~~In addition, one can speculate that a significant part of non-acid C6K radiolysis products will be similar to those of C_6F_{14} radiolysis considered to be harmless or tolerable.~~

The above estimates refer to a hypothetical pure compound in vacuum. A presence of dissolved gases and, especially, water will increase the chemical impact of the radiation due to the high chemical activity of the radicals and, especially, the important role of oxygen in their fate[1]. ~~However, these effects should be largely similar for C6K and C_6F_{14}.~~

For C6K, the hydrolysis effect of liquid water, which is soluble in C6K at the level of **20 ppm** by weight [1] and with which C6K can directly react producing PFPA, *appears to be more important than the radiolysis at the doses expected at SciFi.*

3. Conclusion

Simple estimates, under most pessimistic assumptions, show that the effect of irradiation of the C6K with the doses expected in the SCiFi application will be negligibly small, with the total radiolysis yield of 1 to 10 ppm by weight. Given that only a fraction of the radiolysis product will represent potential hazards (e.g., PFPA), it seems that the pilot validation study should mainly focus on the chemical reactivity of C6K with expected contaminants (first of all, with water) and methods of inline rectification. However, using C6K in other applications, with orders of magnitude higher expected doses, will certainly require a detailed radiolysis study.

References

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    a. The yield of radiolytic decomposition of organic molecules is largely determined by the relation between the 1st excitation exergy and the energy of th chemical bond: when the excitation energy is much higher than the bond energy, decomposition is highly probably. In alkanes, all ionized and excited molecules undergo chemical decomposition. In aromatics it is the opposite, the decomposition yield is very low.
    b. G-value (is) defined as the number of product molecules formed (or initial molecules changed).
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Appendix: Trivia

Gy = 1 J/kg	1 J = 6.24 ·10^{18} eV	1 eV = 1.6 ·10^{-19} J	1 eV/ion = 96 kJ/mol
1 R = 0.00877 Gy	Average C-C bond energy =3.6 eV [1]		C6K = $C_6F_{12}O$ (M_W = 316)
$N_A = 6 \cdot 10^{23}$	E = hc/λ ≈ 1242 (eV)/λ(nm)		

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