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Alternatives to liquid fluorocarbons for detector cooling applications at CERN

Abstract

Many mono-phase convective detector cooling applications at CERN use perfluorohexane C6F14, a greenhouse gas with the GWP of 9300. The purpose of the proposed work package is to identify and conduct initial validation tests of other fluids as sustainable environment-friendly alternatives to C6F14. This activity, initiated by the CERN LHCb group (PH-LBO) and further endorsed by the CERN Detector Cooling Project, requires participation of the CERN chemistry team (TE-VSC-SCC) to perform chemical and radiolytic tests. An example of a possible drop-in replacement of C6F14 is the fluoroketone C6K with GWP of ≈1, recently proposed as a coolant for the SciFi Tracker upgrade in LHCb. The time frame of this project is about one year starting from February 2015. An early work is already ongoing.

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1. Introduction

As part of its general safety policy, CERN is committed to minimize the environmental impact of the research activities [1]. One of concerns in this domain is emissions of PFCs[1], potent green-house gases (GHG) covered by the Kyoto Protocol to the UN Framwork Convention on Climat Changes, which are still being released by CERN in significant quantities. A sizable fraction of these emissions falls to C6F14 used in many detector cooling systems as a heat transfer fluid. For example, in LHCb C6F14 accounts for ~5 $ktCO_2e$, or one third of all GHG emissions by this experiment. A similar situation, even to a larger extent, is observed in other LHC experiments. The programme [2] to monitor and reduce PFC emissions at CERN is ongoing under the supervision of the CERN HSE Unit. In the long run, it implies promoting environment-friendly cooling technologies for new developments, in particular for LHC detectors upgrades, and search for drop-in alternatives to C6F14 for the existing systems with irreducible coolant losses.

These issues are addressed in the LS2 LHCb upgrade project which includes a replacement of the existing Outer Tracker with a new SciFi Tracker [3] requiring a large cooling system for its silicon photo-detectors, to operate them at down to -40°C. After evaluation [4] of several candidate options, a conventional mono-phase liquid cooling technology had been adopted, with the emphasis on using of a new thermal management fluid, fluoroketone 3M™ Novec 649[2] [5], having the GWP, essentially, identical to that of CO2 and, at the same time, the thermo-physical properties very similar to those of C6F14. This solution, reflected in the LHCb Tracker Upgrade TDR [1] and, recently, in the detector cooling proposal [6] for the emittance measurements at the LHC (BGV project), was supported by the thermal mock-up tests performed in 2014 by the CERN LHCb group [7]. As a coolant, C6K turned out to be quite similar to C6F14.

The idea of using C6K was endorsed by the CERN Detector Cooling Project [8] and has attracted attention of the CERN EN-CV group – in the broader context of finding alternative(s) to GHGs in cooling applications at CERN.

2. Purpose

The present work package (WP), earlier discussed at the PH management level [14], is aimed at

- validation of C6K for use in LHCb and other large LHC detectors, as a drop-on replacement of C6F14 in cooling applications at various temperature conditions and radiation environments. The work should include a chemical and radiolytical characterization of C6K, like it was earlier done for C6F14 [9];
- finding and evaluation of other prospective environment-friendly alternatives to C6F14 which appeared on the market during the last decade.
- Выработка предложений по методике очистки новых жидкостей от продуктов воздействия на них радиации и примесе в процессе эксплуатации.

The TS-VCS-SCC group [12] of CERN, which performed C6F14 validation in the past [9], has been contacted [10] to discuss a draft plan of a similar study for C6K. The intent of the present WP is to set up a joint task force with the Detector Cooling Project, LHCb SciFi project and TS-VSC-SCC group as participants.
Given the very small expected radiation damage to the coolant in the SciFi application [11], it is proposed to start with a pilot study of chemical properties of C6K, especially its reactivity with

[1] The acronyms used in the text are explained in Appendix A.1

[2] $C_6F_{12}O$, further referred to as C6K for brevity.

liquid water (reported by the manufacturer, 3M company [13])[3]. A full-scale radiological study of C6K and other prospective liquid coolants, with irradiations at CERN or external facilities, can be anticipated further on.

3. Deliverables

- An up-to-date market survey of different classes of commercial coolants suitable as sustainable alternatives to C6F14 and heavier fluorocarbons for mono-phase liquid cooling applications at CERN.
- In-depth analysis of the published data about prospective fluids, taking into account their core properties as coolants (thermal conductivity, viscosity etc) and secondary aspects important for the intended application in detector cooling systems (possibility of drop-in replacement of existing GHG coolants, electrical insulation properties, radiation resistance, potential long-term chemical effects etc).

The following information about C6K should be acquired as a result of experimental tests within the framework of the present package[4]:

- Reactivity with water:
  - the hydrolysis reaction kinetics at different water concentrations;
  - its dependence on the fluid temperature;
  - reactivity with water vapour and solid phase (frost, ice);
- appropriate methods of in-line rectification (removal of moisture and the corrosive hydrolysis products from the circulating coolant);
- methods of early detection of hydrolysis products in the coolant, to signal the problem in real time;
- compatibility with metals and their resistivity to the C6K hydrolysis products (PFPA, HF). The current metals of interest (in the order of decreasing relevance) are: titanium "grade 5" alloy, stainless steel, aluminium and copper;
- radiolysis effects under integral ionizing doses of 10, 100, 1000 Gy and neutron fluence of 10^{12} neq/cm^2, with the stress on formation of hazardous or undesirable compounds and methods of their real-time removal from the circulating fluid.

The "radiation resistance" should be evaluated according to the intended use as liquid heat transfer agent for particle detector cooling. The relevant characteristics are viscosity, freezing and boiling points, density, development of solid and gaseous fractions, as well as undesirable (reactive, hazardous) liquid impurities that cannot be easily removed from cooling circuits by filtering.

Contributions are required from different groups involved in this WP, as listed in the table below.

[3] The cooling system design has to take the potential secondary corrosive properties of the coolant into account, like for other coolants exhibiting corrosive behaviour under certain anomalous circumstances, e.g. demineralized water.

[4] Studies of academic interest can be performed in parallel, for sake of a possible scientific publication, but their usefulness should be agreed upon within the framework of this WP.

Group	Contribution/interaction
PH-LBO	- coordination (till December 2015), preparatory work, market survey - procurement of sample fluids (together with EN-CV) - irradiation of the samples at CERN and off-CERN centres (together with TE-VSC-SCC) - physical laboratory tests (heat transfer properties, viscosity etc), together with EN-CV
EN-CV	- construction of test vessels for sample irradiation - interaction with interested CERN groups, via the CERN-wide "Detector Cooling" project - follow-up, coordination as of December 2015
TE-VSC	- pre-irradiation tests of (reactivity of C6K with water, assessment of material compatibility tests performed earlier at PH-LBO, evaluation of the initial sample purity) - study of radiolysis effects in irradiated samples, effects of impurities - assessment of "radiation resistance" of tested fluid(s) with regards to the intended detector cooling application (together with PH-LBO and EN-CV)

4. Planning

The first round of studies, focused on C6K, has to be completed by the end of 2015. It will be coordinated by P. Gorbounov of PH-LBO (SciFi Tracker group). The follow-up studies (as of December 2015) will be coordinated by EN-CV. It is foreseen to perform at least two irradiations of the fluid samples (with charged particles and neutrons at the CHARM facility at CERN). The C6K validation report will be prepared by January 2016. The tentative planning is presented in the table below. A more detailed planning taking into account the availability of TE-VSC-SCC resources and the results of pre-irradiation studies will be available as a separate file in the same EDMS page.

Action	Planning
Work package approval	March 2015
Early material compatibility tests	Ongoing (since December 2014)
Market survey	January–March 2015 (ongoing)
Design and production of test vessels	March-May 2015
Procurement of fluids for pre-irradiation tests	February 2015
Pre-irradiation studies	March-December 2015
First irradiation campaign at CERN	May 2015
Second irradiation campaign	September 2015
Post-irradiation studies	May-December 2015
Physical tests (cooling)	April-November 2015
Summary report	December 2015-January 2015

5. Budget and required resources

The CERN LHCb group (PH-LBO) has already allocated ½ FTE·year to this work (P. Gorbounov, PJAS). The additional required manpower is ~1.5 FTE·year, including

- ½ FTE chemist in TS-VSC-SCC,
- ½ FTE PJAS at PH-LBO (P. Gorbounov, June-November 2015)
- ½ FTE Ph.D. student at EN-CV.

The direct costs of 20-30 kCHF include purchasing of fluid samples and chemicals, manufacturing containers for irradiation tests and, optionally, outsourcing part of the analytical and irradiation tasks. Indirect expenses include the use of CERN irradiation facilities (CHARM, GIF++) and technical services (cleaning etc).

6. References

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2. ILK review for PFC (2005) EDMS 634952, M.Battistin (2006) EDMS 774749; PFC monitoring and register management procedure, EDMS 774749 v2, M.Battistin (2006) ; E. Thomas (LHCb 2013) EDMS 1311056 (LHCb register 2013) ; all other CERN registers of PFC: EDMS search (greenhouse)
3. Chapter 3 "SciFi Tracker" of LHCb Tracker Upgrade Technical Design Report CERN-LHCC-2014-001; LHCB-TDR-015 https://cds.cern.ch/record/1647400/files/LHCB-TDR-015.pdf
4. a) Joint project "SiPM Cooling" LHCb/EN-CV https://edms.cern.ch/document/1271014/, Issue 181;
   b) SiPM Cooling Workshop, 17 October 2013 https://indico.cern.ch/event/273434/
5. a) 3M Novec 649 Engineered Fluid, Product information;
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6. Detector Cooling for the BGV Demonstrator in the LHC , EDMS 1439028
7. a) P. Gorbounov, E. Thomas, "Thermal measurements with the SciFi read-out box mockups", LHCb Internal Note LHCb-INT-2014-048 , in preparation;
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8. CERN Detector Cooling Project, http://project-detector-cooling.web.cern.ch/project-detector-cooling/
9. M.Battistin, S.Ilie, R.Setnescu, B. Teissandier "Chemical and radiolytical characterization of some perfluorocarbon fluids used as coolants for LHC experiments", TS-Note-2006-010, EDMS 804849 https://edms.cern.ch/file/804849/1/TS-Note-2006-010.pdf
10. Minutes of the 11.11.2014 meeting with TS-VSC-SCC, https://twiki.cern.ch/twiki/pub/LHCb/C6K/04-05.11.2014_Minutes_.pdf
11. P.Gorbounov, Assessment of the radiation damage to the coolant in SciFi tracker, NOvenber 2014, https://twiki.cern.ch/twiki/pub/LHCb/C6K/Memo_on_irradiation_damage_for_C6K.pdf and EDMS 1421023.

12. R. Setnescu (chemistry, radio-chemistry), B. Teissandier (laboratory), M.Taborelli (section leader)
13. From the 3M Product Bulletin "What you need to know about Novec...."
    - *"Novec 1230 reacts with moisture to form HFC-227ea and pentafluoropropionic acid (PFPA).*
    - *"Novec 1230 fluid* ***reacts with water only when dissolved in water and it is only minimally soluble in water****. Accordingly, only a very small amount of acid is formed when Novec 1230 fluid contacts liquid water and* ***no acid is formed when Novec 1230 fluid contacts water vapor.*** *This has been verified through numerous laboratory and full-scale tests in which Novec 1230 fluid was discharged into a humid atmosphere and monitored via methods such as FTIR. No formation of PFPA has been detected."*
14. E. Thomas, GHG: alternative fluid workpackage, EDMS 1479814 v.1

Appendices

A.1 Acronyms and explanation of terms

C6F14 liquid perfluorinated compound C_6F_{14} (CAS 355-42-0); the inert, dielectric and relatively radiation-resistant fluid widely used as a coolant at CERN.

C6K perfluoroketone $C_2F_5C(O)CF(CF_3)_2$ (CAS 756-13-8), the inert fluid historically used, as 3M Novec 1230, for clean fire suppression. Under the trade name Novec 649, it is also sold by 3M as a fluid for thermal applications, like 1- and 2- phase (full immersion) cooling. The radiation resistance of C6K has not been systematically studied, yet. Unlike C6F14, C6K is claimed to be weakly reactive with liquid water, producing an organic acid, but this property requires a quantative study under the typical detector cooling conditions.

GHG greenhouse gas

GHP global warming potential, measured in CO2 equivalent my mass

HF fluoric acid (hydrogen fluoride)

HSE Occupational Health & Safety and Environmental Protection Unit of CERN, formerly the Safety Commission

PFC Perfluorocarbon(s)

PFPA pentafluoropropyonic acid, a perfluorinated carboxil acid, the analog of propionic acid. A relatively strong organic acid (but considerably weaker than strong inorganic acids).

SciFi scintillating fibres, the technology chosen for the LHCb outer tracker upgrade

WP work package

A.2 Test vessels for irradiation of the fluid samples