# Qualification tests of Novec 4170/CO2 mixture

## **Preliminary remark**

Two candidate substitutes for SF6 were identified based on preliminary tests: Novec 4710 (C3F7CN) combined with CO2 and a CO2/N2 combination. The purpose of these preliminary tests was to characterize the behaviour of these gases for particle accelerators.

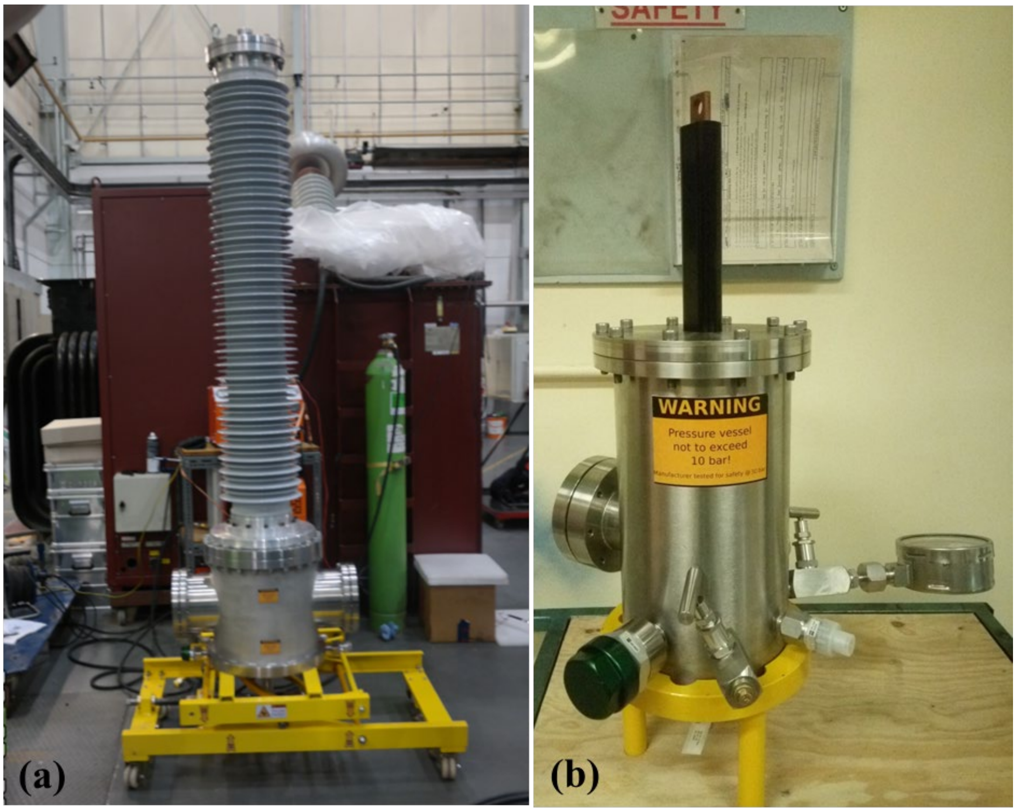
First theoretical analyses quickly lead to put aside the path of CO2/N2 and focus on the Novec4710/CO2 mixture. The fundamental reason is the much higher operating pressure required for the CO2/N2 mix, while the Novec 4710/CO2 mixture allows machine operation at the nominal pressure level of the SF6. This would have prevented the CO2/N2 mix to be used as retrofit on the installed base, as a new design of vessel would have been required. Moreover, the economic advantage versus the Novec 4710 for news sales was jeopardized by higher operational direct and indirect costs.

## **Developed and acquired equipments**

The main aim of this investigation was to identify a suitable Novec 4710/CO2 gas mixture that mimics the electrical performance of SF6 with a significantly lower environmental impact. Comparative study on electrical performance of SF6 and 20/80% Novec 4710/CO2 gas mixture was carried out following defined set of tests. A 20/80% Novec 4710/CO2 gas mixture was chosen for direct comparison with SF6 gas because it was reported in the literature to have similar dielectric strength.

To determine the breakdown characteristics of Novec 4710/$CO_2$ gas mixtures in comparison to $SF_6$, a high-pressure test rig was designed and developed at the University of Manchester.

Two stainless steel pressure vessels of different volume (called “small scale”, and “medium scale” vessels) were designed and developed to carry out comparative experimental investigations on $SF_6$ and Novec 4710/$CO_2$ gas mixtures. The medium-scale vessel was designed for carrying out tests using test geometries that require high breakdown voltages (>100 $kV_{DC}$), whereas the small-scale vessel was designed for test geometries that will result in breakdown below 100 $kV_{DC}$. For tests like ageing and humidity, significant contamination can be generated in the test gas or mixture, a small-scale vessel is the preferred option for these tests.




Medium pressure vessel and (b) small pressure vessel.

An existing DC generator capable of delivering DC voltage up to 600 kV with rated current of 200 mA is used to perform all the DC tests proposed in this project. The DC generator is designed for indoor operation and is fixed on a base frame with rollers for easy mobility. The output voltage is measured via a resistive voltage divider (GMR 1200/600) stationed in front of the DC supply. Connections from the DC supply system to the voltage control and monitoring system is through fibre optic cables which eliminate any possibility of having electric shock during operation.


Test set up showing assembly of the 600 kV DC supply.

Also, UoM developed a small-scale design scaled down from the full-scale dimensions of a Dynamitron®, which provides comparison of $SF_6$ with Novec/$CO_2$ under representative electrode configuration for experimental validation.

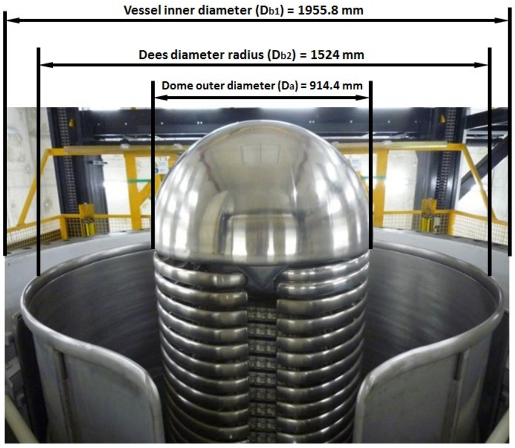
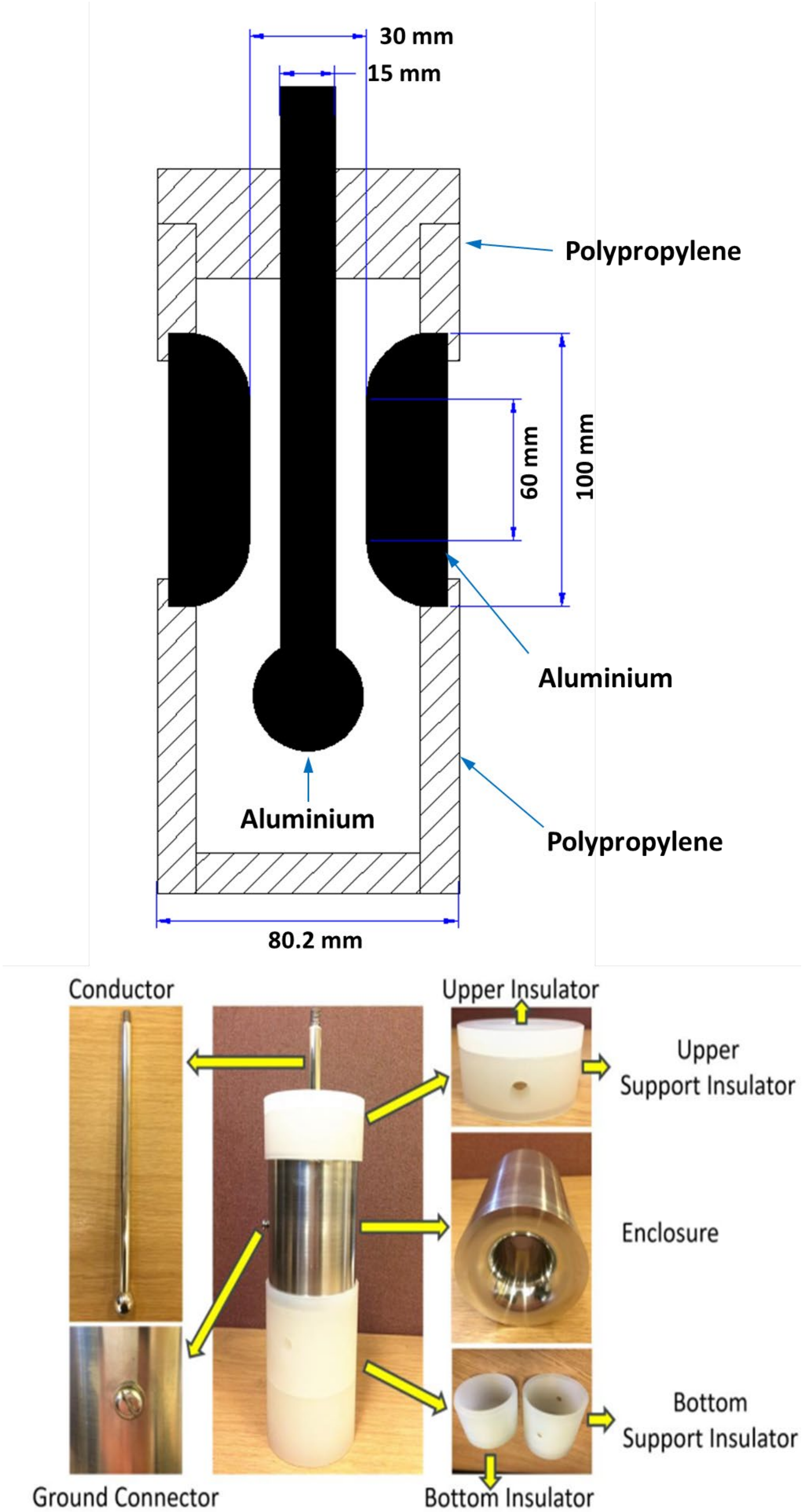



Image of a Dynamitron® accelerator.

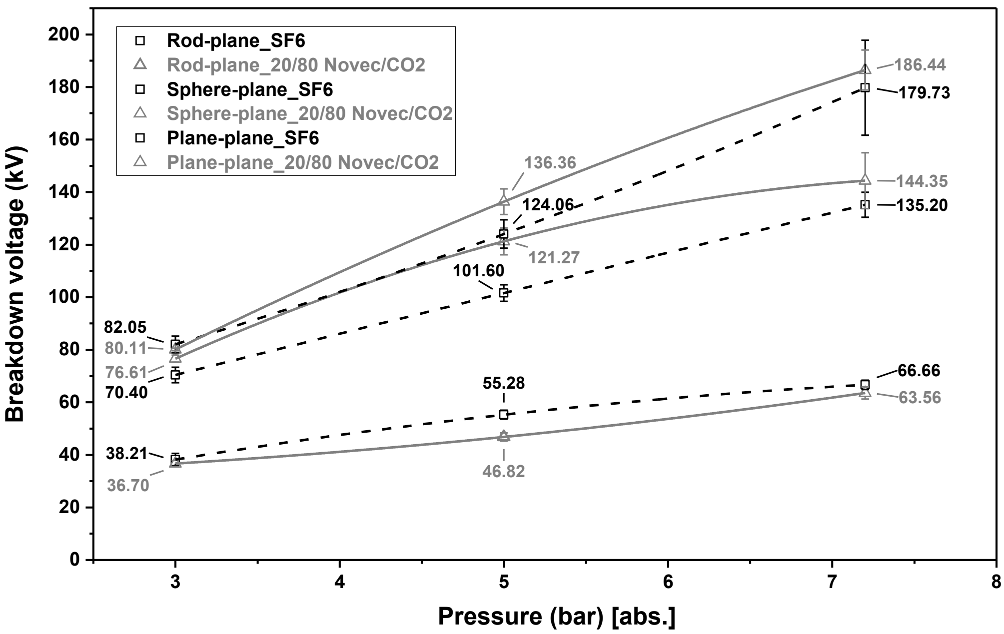



Design and construction of the reduced scale prototype.

## Summary of tests and results

Four categories of tests have been performed:

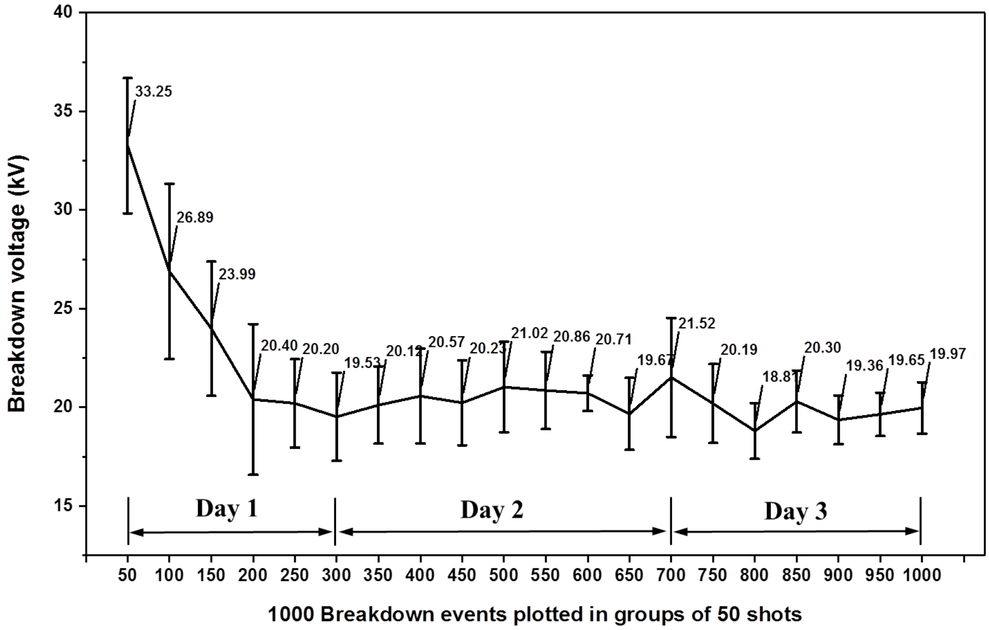
1. Standard tests: to compare the breakdown strength of 20/80% Novec 4710/CO2 gas mixture and that of SF6 gas using uniform, non-uniform and quasi-uniform electrode configurations. The results from the test can be summarised as:
    a. It can be seen that 20/80% Novec 4710/CO2 gas mixture has comparatively higher breakdown results than SF6 gas for electrode configurations that are more uniform (plane-plane and sphere-plane configurations).
    b. Under non-uniform (rod-plane) electric field, SF6 outperforms the 20/80% Novec 4710/CO2 gas mixture.




Comparison of negative DC breakdown characteristics of $SF_6$ and 20/80% Novec 4710/$CO_2$ gas mixture tested for non-uniform, quasi-uniform and uniform field configurations with a fixed gap spacing of 3 mm and at pressures of 3, 5 and 7.2 bar (abs.).

2. Ageing test: to determine the gas stability of 20/80% Novec 4710/CO2 gas mixture after extensive breakdown events and to determine by-products generated post-breakdown. The results are summarised as follows:
    a. A sharp reduction in breakdown voltage has been observed after first 200 breakdown events on Day 1 of testing, which stabilises afterwards for Days 2&3 resulting in a long L-shaped curve.
    b. A whitish layer was observed to coat around the electrodes during the ageing test (visually observed from the viewing window). The gas was collected into

pressure bottles and electrodes removed, bagged and sent to GE for by-product analysis.




A curve showing decreasing average breakdown voltage value from 3 days data collated from ageing test plotted in groups of 50 data points.

3. Spark gap tests: to determine the breakdown characteristics of 20/80% Novec 4710/CO2 gas mixture in comparison to SF6 using spark gap electrodes (4-40 acorn nuts and ¼-20 acorn nuts) which are currently used in Dynamitron®. Using 4-40 acorn nuts (5.8 mm spherical diameter), SF6 outperforms 20/80% Novec 4710/CO2 gas mixture. However, for ¼-20 acorn nut with a bigger spherical diameter (~10 mm) tested under similar test conditions, 20/80% Novec 4710/CO2 gas mixture performs better than SF6. It seemed that for highly non-uniform electrodes systems, SF6 performs better than 20/80% Novec 4710/CO2 gas mixture as observed with rod-plane test under standard test and the result from 4-40 acorn nut due to smaller gaps and sphere diameter of ~5.8 mm used in the test.

4. Reduced scale prototype tests in the reduced-scale coaxial prototype that has similar electric field as found in Dynamitron® equipment. UoM performed investigation on the breakdown characteristics of SF6 gas and 20/80% Novec 4710/CO2 gas mixture under more representative electrode configuration. SF6 gas outperforms 20/80% Novec/CO2 gas mixture for coaxial prototype. The maximum breakdown strength of a coaxial geometry is achieved based on a trade-off between gap spacing and field uniformity. Despite the field uniformity being relatively uniform (~0.69), the proposed coaxial design will not behave in the same way as a typical plane-plane configuration.

| Fixed gap of 3 mm at 7.2 bar (abs.) pressure |
|---|

| Electrode geometry | | Experimental | | | Calculated | |
|---|---|---|---|---|---|---|
| | | Point-plane | Sphere - plane | Plane-plane | 4-40 nut | 1/4-20 nut |
| Utilization factor 'f' | | 0.399 | 0.856 | 0.979 | 0.718 | [0.73] |
| Breakdown voltage (kV) | $SF_6$ | 66.66 | 135.2 | 179.73 | 173.65 | 117.21 |
| | Novec/CO2 | 63.56 | 144.35 | 186.44 | 150.07 | 149.82 |

Comparison of utilization factor and breakdown voltages at fixed 3 mm gap distance for $SF_6$ and 20/80% Novec/$CO_2$ gas test at 7.2 bar (abs.) for each electrode geometry.

## Recommendations

- Electrical: Breakdown results clearly indicate that the field uniformity versus breakdown voltage is different for SF6 and Novec/CO2 mixture. When the field is more uniform, a 20/80% Novec/CO2 mixture is comparable or better than SF6. However, when the uniformity decreases, a higher concentration of Novec 4710 is required in the mixture to match the performance of SF6.

- Operational: using a high concentration of Novec 4710 (20-25%), the gas mixture is likely to liquefy at 0°C operating temperature and under typical operating pressures of 7.2 and 9.2 bar (abs.) within the Dynamitron®. It is recommended that temperature control must be incorporated and the table below presents the minimum operating temperatures required to prevent liquefaction to the Novec 4710 mixtures at 7.2 and 9.2 bar (abs.). It is acknowledged that gas storage tank could be placed outdoor and could lead to liquefaction of Novec4710/CO2 mixtures. However, storage tank heating mechanism can be deployed to pre-heat the mixture and ensure it is homogeneous prior to gas handling activities.

- Next Step: The design margin of SF6 used within Dynamitron® is unknown and this could potentially allow IBA to use a lower concentration of Novec 4710 due to the large initial design margin. However, based on the existing breakdown results, it is clearly advisable for the consortium to use a higher concentration of Novec 4710 (25%). If this performs successfully, we can over-fill additional CO2 content to create a 20/80% mixture for further explore the safe operational margin.

| T (deg °C) | T (K) | SVP (bar) [abs.] | | |
|---|---|---|---|---|
| | | 20/80% $C_3F_7CN/CO_2$ | 22/78% $C_3F_7CN/CO_2$ | 25/75% $C_3F_7CN/CO_2$ |
| 15 | 288.15 | 9.86 | 8.978 | 7.912 |
| 10 | 283.15 | 8.129 | 7.408 | 6.535 |
| 5 | 278.15 | 6.667 | 6.079 | 5.367 |
| 0 | 273.15 | 5.433 | 4.956 | 4.378 |

Saturated vapour pressure (SVP) of Novec 4710/CO2 at different concentrations.

| Pressure (bar) [abs.] | Liquefaction Temperature (deg ℃) | | |
|---|---|---|---|
| | 20/80% Novec 4710/$CO_2$ | 22/78% Novec 4710/$CO_2$ | 25/75% Novec 4710/$CO_2$ |
| 7.2 | 6.9 | 9.24 | 12.49 |
| 9.2 | 13.16 | 15.61 | 19.01 |

Liquefaction Temperatures of Novec 4710/$CO_2$ at different concentrations.