Dynamitron® SF_6-FREE Project: The Assessment of Fluoronitrile + CO_2 Applicability

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Abstract— Dynamitron® accelerators produced by IBA are medium energy accelerators used primarily in crosslinking applications and producing electron beam with an energy up to 5 MeV and 160 mA. Dynamitron® accelerators are the most widely used industrial accelerators in the world. SF_6 gas enables the accelerator to sustain up to 5 MV DC voltage but can amount up to 4 tons of SF_6 usage for the biggest equipment. IBA aims to investigate the feasibility of Fluoronitrile + CO_2 to reduce the Dynamitron®'s carbon emissions by 60%. The target is to reduce the equivalent of 40,000 tons of CO_2 emissions by 2024. The SF_6-Free project, funded by LIFE 2017 program from the EU, is a partnership between IBA, General Electric (GE) and the University of Manchester rooted in the common commitment to the environment and the community.

GE performs the materials and components compatibility tests with the gas mixture under representative pressure and temperature conditions. Mechanical and electrical characterizations of metal alloys, polymers, resins and adhesives are performed before and after ageing tests. The gas is analyzed during and following ageing tests with Gas Chromatography and IRTF spectroscopy to ensure the gas quality and approve its applicability with the materials involved in Dynamitron®. The University of Manchester performs the electrical testing of alternative gases. A high-pressure test rig is designed and developed to determine the breakdown characteristics of alternative gases and their mixtures in comparison to SF_6 using representative small-scale prototypes. The test data is used to inform the selection of an optimal gas mix for the design of a full-scale Dynamitron® demonstrator. IBA oversees the global project and defines the key activities to be performed. In order to validate the gas mix determined by the University of Manchester, a full-scale Dynamitron®, equipped with a new gas handling system compatible with Fluoronitrile + CO_2, will be retrofitted to be used as a demonstrator. The compatibility tests carried by GE will impact the materials used within the demonstrator. To validate the proper functioning of the system, beam tests will be carried out and all technical performances will be assessed and compared with standard SF_6 operation.

Keywords—Dynamitron; Accelerator; Alternative gas; Carbon emission reduction; Materials Compatibility; Gas Analysis; Fluoronitrile; Electrical Insulation; SF6-free; GWP Global Warming Potential

I. Dynamitron® Accelerator

The Dynamitron® is an electron beam accelerator, developed by Dr. Marshall Cleland and the company he founded, Radiation Dynamics Inc., in the sixties. RDI was later acquired by Ion Beam Applications in 1999.

A. Principle

The Dynamitron® accelerates electrons in a linear path, from the high DC voltage end of the accelerator to the low DC voltage end. The voltage gradient is thus used as a driving force for the acceleration. The energy of the resulting beam is therefore directly linked to the strength of the high voltage field. The energy range of Dynamitrons® lies typically between 0.5 MeV and 5 MeV. The maximum beam current, for a set energy, depends on the electrical power that is injected in the accelerator to generate the DC voltage.

The Dynamitron® is composed of different subsystems. The global accelerator is built in the pressure vessel, a cylindrical shaped vessel that contains the accelerator itself, and that is pressurized with SF_6 gas. The vessel contains an auto-transformer connected to two large semi-cylindrical electrodes fed with radio frequency (RF) power. The DC voltage is generated by the rectifying stack, a cylindrically shaped rectifier and multiplier which are placed in between both electrodes. The beam itself is accelerated in the beam tube, a vacuum pipe located in the heart of the rectifying stack.

In order to generate the high DC voltage, the grid power is first transformed and amplified to a 100 kHz signal, through the means of a triode coupled to a resonant cavity, forming thus an oscillator. The signal is then amplified inside the Dynamitron® using an auto-transformer, and it oscillates on two semi-cylindrical opposing electrodes. These large electrodes are capacitively coupled to the so-called rectifying stack, a subsystem of the Dynamitron® that transforms the AC voltage to a DC voltage based on the principle of the parallel half wave voltage multiplier. The rectifying stack is terminated by a high voltage dome, also called the high voltage end of the machine. The SF_6 gas is used in the

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machine as a high voltage insulator, to avoid undesired arcing that could degrade the machine.

B. Applications

The Dynamitron® is widely used for different industrial applications with the main application being polymer crosslinking (wires and cables, heat shrink film, heat shrink tubing and tires, etc.), but these accelerators can also be used for sterilization of medical equipment. IBA accounts for over 200 Dynamitrons®, mainly sold in the United States (59%) and Europe (29%).

C. Carbon footprint

The Global Warming Potential (GWP) of SF_6 is 23500 [1], meaning thus that the environmental impact of 1 kg of SF_6 is equivalent to as much as 23500 kg of CO_2.

IBA estimates that each year, on its complete installed base, there are losses of around 12 tons of SF_6 in the atmosphere due to uncontrolled leaks and mishandling of the gas handling system during the accelerators maintenance, which represents the equivalent environmental impact of 282000 tons of CO_2.

II. Fluoronitrile + CO_2 Gas Alternative

A. Use in HV Substations

Based on Kyoto Protocol requirements [1] and as a SF_6-free gaseous environmentally friendly solution, GE Grid Solutions, in partnership with the 3M™ Company, has developed an environmentally gas mixture, based on heptafluoro-iso-butyronitrile $(CF_3)_2$-CF-CN (or fluoronitrile [2] and mixed with carbon dioxide and oxygen. Gas mixtures of this fluoronitrile with CO_2 and O_2 were found to be an optimal solution for disconnector and circuit breaker applications. It has been proved to be the most technically and economically promising solution with the advantage of meeting requirements of minimum outdoor temperatures as defined in international standards (like -25°C or -30°C) [3, 4] and has shown a decrease by more than 99% the GWP compared to SF_6. Several high voltage equipment with Fluoronitrile + CO_2 have been installed in Switzerland (145 kV GIS) [5], England (420 kV GIL) [6] and Scotland (420 kV GIL), and 245 kV Instrument transformers in Germany.

B. Applicability in Dynamitron®

The characteristics and behavior of Fluoronitrile + CO_2 gas mixture have been investigated over the last few years by GE Grid Solutions and are fully known and controlled. From onsite gas handling management, gas behavior in circuit breakers and analysis of gas and solid by-products, to gas ageing and compatibility with the materials involved in high voltage equipment. Based on this knowledge and gained experience, GE Grid Solutions performs for IBA the materials and components compatibility tests with the selected gas mixture and under representative pressure and temperature conditions.

C. Materials Compatibility Tests

- Ageing Tests

The materials and parts listed in table 1, undergo the ageing test in direct contact with the gas (pure Fluoronitrile in to simulate and accelerate the ageing process). Pressure is 2 bar abs. and temperature is 50°C. Ageing test of the same materials is done in SF_6 under 7 bar abs. and 50°C. The mechanical and electrical properties are measured before and after the ageing tests.

TABLE I. Materials and parts involved with ageing tests

Materials Family	**Plastics Polymers**	Acrylic Plexiglas Polyamide Delrin© Polycarbonate
	Metals Alloys	Stainless Steel 304 Brass Copper Bronze
	Adhesives Glues Greases	Sealant threadlocker Epoxy adhesive Silicone adhesive High Vacuum Grease Compound Sealant Rtv
	Parts	Wires, cables, wraps, tubings, valves, gaskets, rubbers, flexibles, chokes RF, resistors, spark plugs, pressure actuators…

- Experimental Set-up and Specification

The materials and parts are loaded inside the vessels which undergo a specific gas vacuuming and filling procedures to reach very low amounts of humidity and air impurities in the target gas. The ageing test is maintained 2000 hours. Gas sampling is performed meanwhile at 500 and 1000 hours for gas analysis using GC-MS. Here, the concentration of Fluoronitrile and eventually gas by-products is qualified. The setup GC 7890A from Agilent is used coupled to 5975 Inert MSD spectrometer.

On raw metallic and plastic materials, mechanical properties as elongation under constant load and yield strength are the key parameters. Tensile tests are performed on standard specimens following international standards such as DIN 51220 and NF A 03-501.

Few polymeric materials undergo Differential Scanning Calorimetry (DSC) tests to measure the thermochemical behavior before and after ageing tests.

Volume and surface electrical resistivity of insulating materials are measured before and after ageing to check if the gas has a direct influence on the electrical insulation characteristics of the materials. Tests and specifications are based on standards IEC 93 (1980) and IEC 212 (1971).

Resistance is also measured on metallic material test specimens. The target is to understand the eventual influence of ageing with gas on the surface conductivity of the materials. Measurements are based on IEC 694 (6.4).

After dismantling the vessels assembly, observations do not show any specific degradation or aspect's alteration of the raw materials (metals and polymers) in contact with Fluoronitrile.

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The physico-chemical, mechanical and electrical characteristics are also stable.

III. Electrical Testing of Alternative Gases

To achieve the aim of replacing SF_6 with an environmentally friendly alternative in Dynamitron® and to reduce the carbon emissions of Dynamitron® to about 60% by 2024, electrical tests have been defined and to be carried out by the University of Manchester. The defined tests are as follows:

1. Standard tests: *determine a range of mixture concentrations of Fluoronitrile + CO_2 that best mimics SF_6 gas performance using uniform, non-uniform and quasi-uniform test configurations (Figure 1).*
2. Ageing test: *determine by-products generated after extensive sparking events using a selected Fluoronitrile + CO_2 gas mixture.*
3. Specific test: *develop small-scale prototypes that replicate the electric field as found in Dynamitron® equipment for experimental validation.*

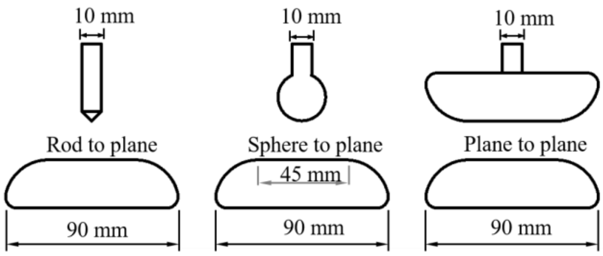

Figure 1. Electrodes geometries used for standard tests.

A. Experimental Setup and Test Protocol

A purpose-built pressure vessel rated up to 10 bar (abs.) was developed. The vessel is complimented with a linear actuator setup capable of precise adjustment of electrode gaps under high pressure. A state-of-the-art 600 kV DC test set was used to perform the defined tests. The automatic voltage ramp control and data logging system ensure an accurate testing procedure. The overall setup can be seen in Figure 2 including the DC test set and the pressure vessel.

Through preliminary investigations, a continuous rising DC voltage method based on IEC 60060-1 was adopted [9]. Gas Breakdown characteristics of an insulating gas is dependent on its intrinsic properties as well as other factors like the voltage ramp rate, critical electric field strength and electrode geometry. It is noteworthy that there is no significant difference in breakdown results when adopting different voltage ramp rates (0.2 kV/s, 1 kV/s and 5 kV/s). Considering the volume of tests and experimental time, a voltage ramp rate of 5 kV/s was chosen for the defined tests.

B. Gas Handling Procedures

A strict gas handling procedure which involves vacuuming, filling gas and extracting gas after test was enforced to minimize the likelihood of moisture ingress and air impurity. Two separate gas handling systems were used for SF_6 and Fluoronitrile/CO_2 mixtures to avoid cross-contamination. Prior to filling any gas, hoses and pressure vessel were vacuumed down to 1 mbar. The vessel is then purged with dry CO_2 gas for minimum of 1 hour to absorb any residue moisture. The vessel is then vacuumed again down to 1 mbar before filling the vessel with any test gas or mixture.

Figure 2. Assembly of the DC test set with the pressure vessel positioned adjacently for high voltage connection. The red arrow indicates the connecting point of the divider to the bushing.

C. Electrical Test Results and Analysis

Figure 3 shows the comparison of breakdown results of Fluoronitrile + CO_2 verses SF_6 under uniform electric field. A fixed 3 mm gap was maintained between a pair of plane electrodes made of stainless steels and dimensions can be seen in Figure 1. Each data point on the graph is a statistical average of 30 DC breakdowns.

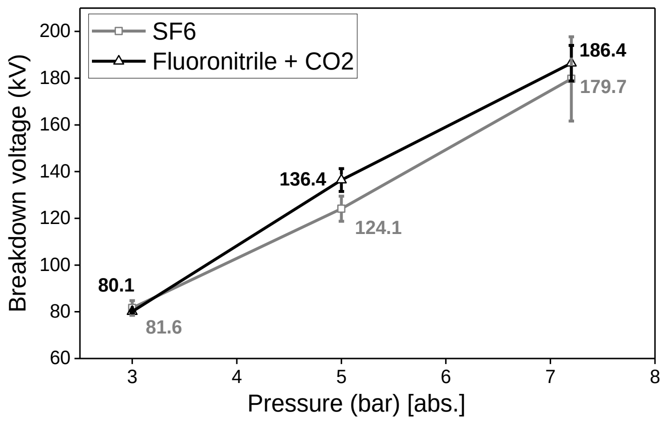

Figure 3. Comparative electrical tests for Fluoronitrile + CO_2 and SF_6 for a plane-plane configuration and a fixed gap of 3 mm over a range of pressures.

As expected, the breakdown voltage increases with increasing pressure for both Fluoronitrile + CO_2 mixture and SF_6. At higher pressures, Fluoronitrile + CO_2 gas mixture can be seen to outperform their SF_6 counterpart. This is the first

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step in characterizing the electrical performance of a new gas candidate. The results shown in Figure 3 are a promising indication of adopting Fluoronitrile + CO_2 gas mixture as a more environmentally friendly solution in Dynamitrons®.

IV. Conclusions

On the one hand, materials compatibility tests in pure fluoronitrile do not show major degradation of the aspects or the properties of the raw materials or the parts used in the Dynamitron®. This test campaign provides a first insight of the compatibility of materials and parts with pure Fluoronitrile. On the other hand, the initial DC breakdown results in this paper have shown that a Fluoronitrile + CO_2 gas mixture has slightly better breakdown strength than SF_6 in a uniform field configuration. Further electrical and material compatibility investigations are planned to fully characterize the proposed Fluoronitrile candidate as a more environmentally friendly solution in high voltage accelerator applications.

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