WESTERN POWER DISTRIBUTION

INNOVATION

NEXT GENERATION NETWORKS

SF_6 Alternatives

CLOSEDOWN REPORT

Report Title	:	SF6 Alternatives CLOSEDOWN REPORT
Report Status	:	Final
Project Reference:		WPD_NIA_025
Date	:	05/12/2018

Document Control

	Name	Date
Prepared by:	David Kilpatrick	07/11/2018
Reviewed by:	Paul Edwards, Stavros Saouros	27/11/2018
Approved by:	Roger Hey	05/12/2018

Revision History

Date	Issue	Status
11/10/2018	v0.1	First Draft
07/11/2018	v0.2	Second Draft
27/11/2018	v0.3	Third Draft
05/12/2018	v1.0	Final

Table of Contents

Executive Summary

Sulphur Hexafluoride (SF_6) gas is used throughout the electrical distribution industry as an insulating medium in switchgear. Whilst it provides many benefits, it is a potent greenhouse gas. Western Power Distribution's (WPD) RIIO-ED1 plan promised to reduce SF_6 use on the network while also seeking alternative approaches. Through the Network Innovation Allowance (NIA) SF_6 Alternatives project, we aimed to identify alternative insulating mediums that would be a suitable replacement for SF_6 in High Voltage (HV) distribution switchgear.

The original scope of work is outlined in the list below:

- Development of a comprehensive literature review of SF_6 alternatives and previous projects relating to the subject;
- Identification of suitable alternative insulating mediums to be trialled on no more than three types of 11kV Ring Main Units (RMUs) installed on our network;
- Development of a robust testing methodology for the proposed insulating mediums and evaluation criteria to rank their performance;
- Conduct initial interruption and insulation tests on equipment with the proposed insulating mediums and document the trial outcomes;
- Develop and implement a dissemination strategy which engages external and internal stakeholders.

The project completed a thorough literature review of prior investigation into the use of SF_6 Alternative mediums and identified several potential mediums or technologies that may be used as future alternatives to SF_6 within switchgear. A supporting test methodology was also developed to outline the required industry standards that switchgear utilising these alternatives would be required to comply with. Through correspondence with industry leading experts and technical bodies, additional guidance was created to increase robustness of this procedure, accounting for characteristics that may be introduced through use of alternative mediums.

However, during these phases of the project, it was consistently found that it would be unsuitable to retrofit alternative mediums within pre-existing switchgear, taken from the network. This was due, primarily, to the differing chemical properties of alternative mediums requiring a new circuit breaker housing design. Following a critical analysis of potential future project learnings and expenditure, it was decided to close the project early. This was due to technology readiness of mediums identified, difficultly in the procurement and handling of sufficient gas volumes for testing, the increasing risk of circuit breaker failure during testing with a very low chance of success and knowledge of commercially available products becoming available to market in the near term.

Through the literature review and subsequent communication with vendors, we learned that a small number of switchgear types utilising SF_6 alternatives for insulation, had come to market recently with more expected to follow in the next one to two years. Live network trials of products by several manufacturers are currently underway, with products meeting current IEC regulations. Taking this into consideration and an assumption that other manufacturers will follow, the project explored the cost of

replacing existing 11kV Ground Mounted (GM) SF_6 containing non-primary equipment, predominantly RMUs, with these solutions. An estimated cost for complete overhaul was found to be in excess of £350m. This represents a significant outlay, equivalent to nearly triple the current budget given to all types of 11kV GM switchgear in the current RIIO-ED1 period.

While the project in its current form has been closed down, we intend to monitor this area over the next 18 months, revisiting the project when the technology has matured and been proven suitable for network operations.

1. Project Background

The use of SF_6 is becoming increasingly restricted and regulated following the 2014 EU fluorinated greenhouse gases (F gas) regulations. This presents a significant problem to network operators as SF_6 is an excellent insulating medium which is used extensively in HV and Extra High Voltage (EHV) switchgear.

Our network is fitted with a significant number of assets utilising SF_6. Beginning with a limited number of units installed in the 1970s, steady adoption began in the early 1990s before a marked upturn in use since the mid-2000s. As of 2018 the total number of units in service is around 52,795.

More specifically, as of 2018 there are 36,687 RMUs containing SF_6 recorded on the network as shown in Figure 1-1. Of these 36,007 are RMU Circuit Breaker type and 680 RMU Fuse Switch type.

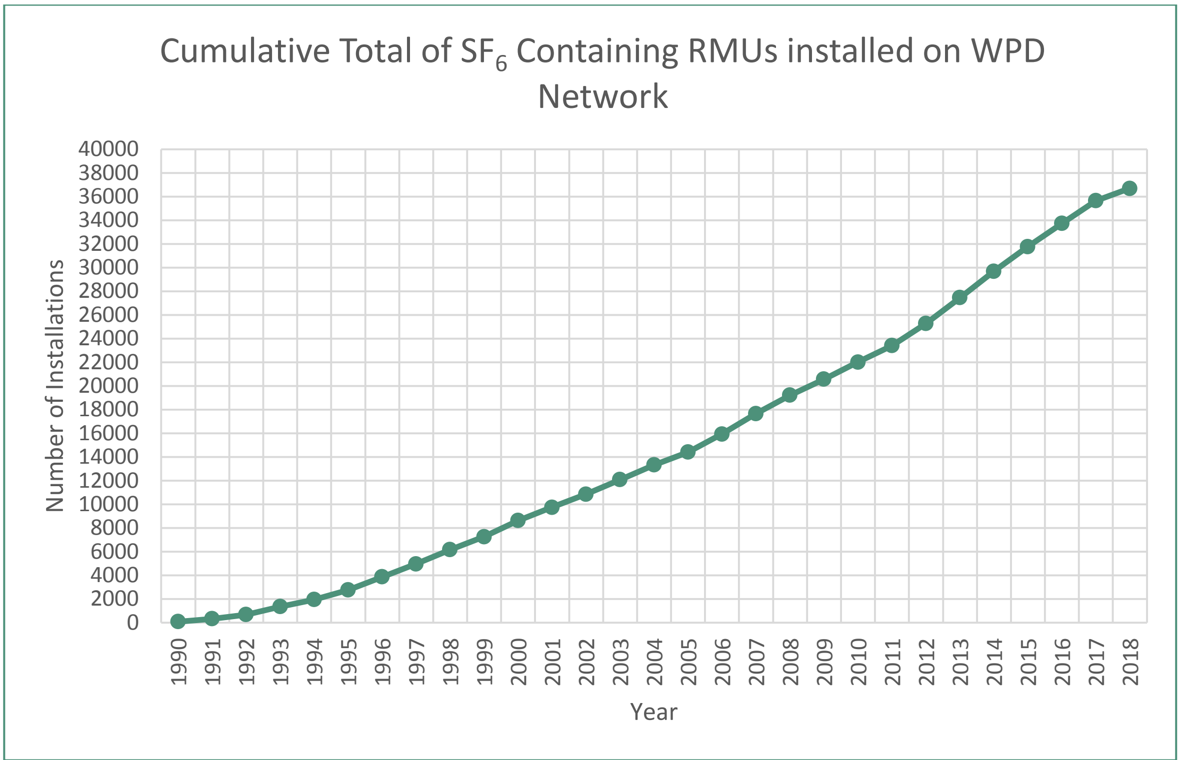

Figure 1-1: Graph of Cumulative Total of RMUs installed on WPD's Network containing SF6

Figure 1-2 shows the breakdown of SF_6 asset emissions by DNO for the year 2016/17. The total measured mass of SF_6 leaked in this period equalled 554 kg.

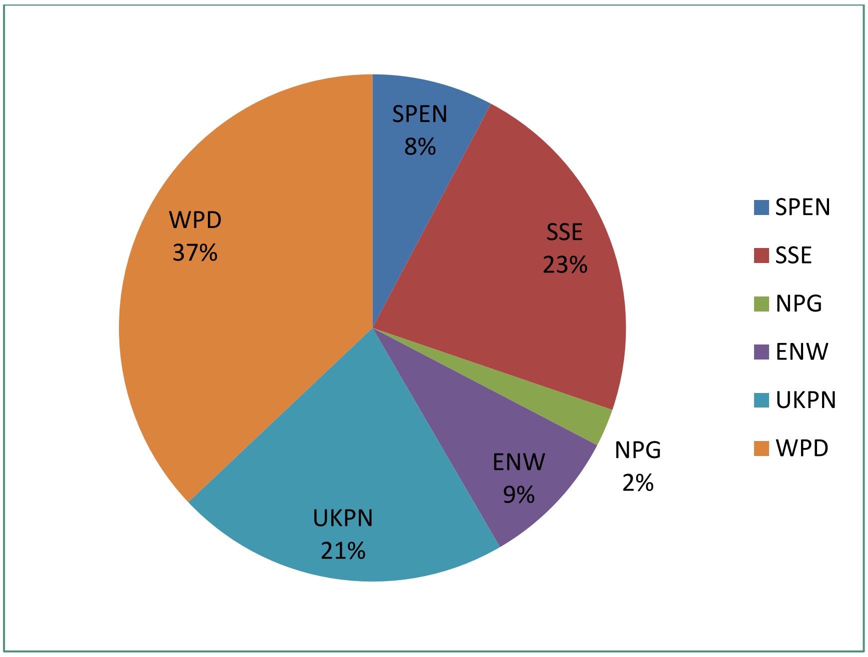

Figure 1-2: UK Leakage of SF_6 from DNO Assets in 2016/17

Responsibility for monitoring SF6 leaked into the atmosphere is held by network operators. A biannual check is currently stipulated in the regulations for switchgear containing more than 6kg of SF_6. If the equipment contains more than 22kg of SF_6 then checks are required to be made every three months. The majority of HV switchgear currently contains less than 5kg of SF_6, therefore checks are not mandatory; however, regulations are constantly changing and the current thresholds could be reduced in the future. The most recent amendment to the regulation now stipulates that from 1st January 2017 all new switchgear with more than 22kg of SF_6 must have an automatic leak detection system fitted.

With SF_6 regulations anticipated to increase further there may be a requirement for every new piece of switchgear to be equipped with leak detection technology in the future. This could result in further expenditure to develop additional systems associated with managing leak detection. The increased expense in complying with future regulations may lead to higher consumer charges for electricity use.

Civil penalties for release and leakage of SF_6 gas have also seen significant increases. For the most serious breaches a maximum fine of £200,000 can be applied. Less serious offences carry fines of up to £100,000 while breaches such as failing to correctly label equipment containing F-gases can incur fines of £50,000. For a DNO, civil penalties are most relevant around infringing the requirements and procedures for emissions/leakage during switchgear maintenance or repair. Without evidence of negligence or malicious activity no civil penalties should currently apply. However, the Environment Agency's stance is clear and the increasing nature of fines suggest a pattern that legislation will become more stringent and cases of careless practice could soon fall within this remit.

The aim of this project was to evaluate the use of alternative insulating mediums when retrofitted into existing switchgear in place of SF_6. It is anticipated that the development of an SF_6 alternative will lead to a more environmentally friendly HV switchgear design.

With a high number of 11kV RMUs containing SF_6 on most DNOs' networks the project focused on these devices with any alternatives tested being applicable as both an interrupting medium in gas-filled RMUs and as an insulating medium for indoor switchgear.

2. Scope and Objectives

This project was to be delivered in three key stages:

1. A comprehensive literature review to capture all previous learning from SF_6 research and investigation;
2. Identifying and presenting the key gases to be assessed through initial trials; and
3. Testing the selected gases using decommissioned 11kV RMUs and proposing recommendations for integrating alternative SF_6 solutions into BaU.

The output deliverables have been captured within reports generated over the lifecycle of the project and summated in this closedown report.

Objective	Status
Conduct a literature review on all previous research considering SF_6 gas alternatives.	✓
Identify alternative gases from the literature review which can be recommended for initial testing.	✓
Conduct initial interruption and insulation tests on the proposed gases and document outcomes.	×
Disseminate the lessons learnt to internal and external stakeholders.	✓

3. Success Criteria

Success Criteria	Status
The production of a document(s) which outlines the current status of SF_6 alternative gases and the identification of potentially suitable gases for further investigation.	✓
The production of a document(s) which shows the method for selecting RMUs for testing, the technical testing specification, the test results and conclusions (even if these simply eliminate the identified gases from being suitable for further study).	×
The implementation of dissemination activities to communicate these findings with relevant stakeholders.	✓

4. Details of Work Carried Out

The initial project task was to conduct a comprehensive literature review to determine:

- Alternative mediums to SF_6 which had been investigated by the Power Networks community; and
- Alternative mediums which would be viable for testing in decommissioned switchgear in a laboratory setting.

The review was initially conducted through analysing publicly available material and reports to understand the current industry practice and interest. From this research, it was clear that the wider industry sought an alternative solution. Several mediums have been previously investigated and disregarded as they possessed characteristics which made them unsuitable for wider deployment. Furthermore, it was found that there was no identifiable medium which possessed the full range of thermal and electrical properties held by SF_6 while maintaining a low Global Warming Potential (GWP).

However, it was found that a small number of gases had been developed which, while not fully meeting all criteria, were a reasonable improvement over SF_6. Switchgear manufacturers have started development of new products using these alternative mediums which are currently being trialled in field tests.

Following publication of the Literature Review, the next objective outlined within the original proposal was to:

- Conduct initial interruption and insulation tests on the proposed gases and document outcomes.

The first task in this activity was to develop a test methodology for the use of SF_6 alternatives identified within the Literature Review. The overarching specification for switchgear installed on the UK Distribution Network is Energy Networks Association (ENA) Technical Specification (TS) 41-36. Review of this specification and applicable standards within was chosen as the starting point for development of an appropriate test methodology.

The project aimed to use RMUs removed from the network for testing purposes, removing the SF_6 and refilling with the chosen gas or gas mixture. During the review of applicable standards and discussions with internal standards engineers it was determined that making such a fundamental alternation to the switchgear device would result in the invalidation of original type test documentation. Therefore, before installation onto the network a full type test would be required of the RMU.

While this activity would ensure valid testing in accordance with mandatory standards, the ENA standard does not take into consideration the specific needs for testing and validation of gaseous mixtures that are not routinely used in switchgear equipment. To ensure correct validation against this, the project chose to consult with recognised industry experts for further information on testing of SF_6 alternative mixtures.

Industry experts were identified through informal discussions with manufacturers and at CIRED[1] and LCNI[2] technical conferences, where the subject of SF_6 alternative gases was discussed. The consensus view was that the design of existing SF_6 switchgear was unsuitable for alternatives due to the incompatibility in design, reactive nature of some technologies and a failure to match the compact nature of SF_6 as a medium. Therefore, the switchgear equipment required a design overhaul to ensure compliance with the required industry standards.

Through these discussions the project became aware of guidance publications made by T&D Europe, a recognised industry authority on developments within the Transmission and Distribution networks in Europe. Their published guidance *"A Technical Guide to Validate Alternative Gas for SF_6 Equipment"* is compiled by industry leading experts and explores which characteristics of a gas should be considered, specifying the tests, analysis and criteria required to ensure the performance of the electrical equipment throughout its service life. Additionally, it assesses the health and safety risks posed to people who may come into contact with the gases during the equipment's lifecycle.

On assessment, the guidelines laid out within T&D Europe's document were incorporated along with the required type testing as the generalised test methodology for all SF_6 alternatives. Where required more specific focus would be sought from manufacturers and test houses. This information was reflected within a formal Test Methodology document that was reviewed and approved for publication in August 2018.

Throughout the period spent investigating the proposed test methodology, the project continued to investigate the existing work that had been undertaken in this area by recognised manufacturers. By comparing this work to findings of the Literature Review it could be surmised that no alternative mediums were viable for testing in decommissioned switchgear, presently. The technical limitations meant that the project would be unable to successfully complete its aim of implementing an SF_6 alternative medium within existing network switchgear.

With the project discovering that a limited number of technologies were becoming available as a wholesale alternative to SF_6, we chose to perform a cost benefit analysis for the implementation of an entire RMU replacement programme. This could then be used as a base case moving forward, as strategic decisions on the direction of SF_6 replacement and management on the network are made. The analysis assumed that a "like for like" replacement of SF_6 RMUs could be completed at a similar unit cost and without the need for civil modifications to be completed. However, in the short to medium term, as a market equilibrium is established for the use of alternatives and new technologies, it is expected that unit costs will be around 20% greater than current SF_6 equipment.

[1] CIRED (Congrès International des Réseaux Electriques de Distribution) technical conference and exhibition held June 2017 in Glasgow, UK.
[2] LCNI (Low Carbon Networks & Innovation) conference and exhibition held December 2017 in Telford, UK

5. Performance Compared to Aims, Objectives and Success Criteria

<table>
<tr><th>Objective</th><th>Performance Review</th></tr>
<tr><td>Conduct a literature review on all previous research considering SF_6 gas alternatives.</td><td rowspan="2">The project successfully delivered a comprehensive literature review which assessed both the present status of SF_6 Alternatives within industry but also those that are the most promising for development. In doing so fulfilling the first two objectives. The Literature Review was published in January 2018.</td></tr>
<tr><td>The production of a document(s) which outlines the current status of SF_6 alternative gases and the identification of potentially suitable gases for further investigation.</td></tr>
<tr><td>The production of a document(s) which shows the method for selecting RMUs for testing, the technical testing specification, the test results and conclusions (even if these simply eliminate the identified gases from being suitable for further study).</td><td>The project successfully delivered a technical testing specification that could be used for all switchgear being used for testing of SF_6 Alternatives. This document was derived from use of ENA TS 41-36 and T&D Europe Guidelines. The document was approved for publication in August 2018 and was made available online in October 2018.</td></tr>
<tr><td>Conduct initial interruption and insulation tests on the proposed gases and document outcomes.</td><td>The project was unable to deliver on this objective as it was found that no proposed gas was suitable for use within existing switchgear.</td></tr>
<tr><td>Disseminate the lessons learnt to internal and external stakeholders.</td><td>The findings and outputs of the project have already been shared with other DNOs who are exploring SF6 alternative innovation projects in the future. One DNO sought further guidance on the subject following review of the Literature Review document in October 2018.

Manufacturers also continue to be engaged with the project. Nuventura, a German company developing an alternative insulating medium, have contacted the project to discuss further partnership.

Moreover, all new learning has been captured in our published reports.</td></tr>
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6. Required Modifications to the Planned Approach during the Project

The original project proposal made the following statements that “this project is to evaluate alternative insulating gases in place of SF_6” and that “A selection of gases will be chosen for initial testing in SF_6 switchgear (such as RMUs which have been removed from the system)”. Through the duration of the project it was found that this approach was not appropriate due to the current Technology Readiness Level (TRL) of SF_6 alternative gases and the associated switchgear housing used for their containment. As a result, the project was unable to deliver on these aims. This led to the project moving to an earlier close down before completion of all aims, resulting in an overall underspend of £341,500 compared to the initial budget.

Until this point the project had followed the predicted path but the high cost and low chance of a successful test meant the project could not ensure value to customers going forward. Instead it was decided that the learnings to this stage be captured and a financial analysis be conducted to determine the cost of replacing existing SF_6 switchgear in the network with alternative solutions. From this project, we will continue to monitor the development, testing and operation of alternative switchgear solutions. There is potential, in the near future, to introduce such equipment for trials within the network.

7. Project Costs

Activity	Budget	Actual	Variance
WPD Project Management	£52,000	£13,607	-73.83%
WSP Project Support	£163,734	£42,893	-73.80%
Other costs (Procurement and Testing)	£146,084	£-*	-100.00%
Contingency (10%)	£36,182	£-*	-100.00%
Total Cost	£398,000	£56,500	-85.80%

Following critical analysis of the technical limitations with retrofitting existing switchgear with currently available SF6 alternative mediums it was decided that in the best interests of project spend and customer exposure the project would proceed to an early closedown. The project scope was therefore narrowed and adapted accordingly, resulting in a total project cost variance of -85.80%.

*Given the project modifications no equipment was procured or tested and no contingency was required.

8. Lessons Learnt for Future Projects

Topic / Area	Learning generated
Equipment	SF_6 alternatives must meet the following criteria: • High dielectric strength; • High heat dissipation; • Low boiling point; • Low toxicity; • Fast arc-quenching capability; • No Ozone Depletion (ODP); • Non-flammability; • Compatible with switchgear materials (Non-Corrosive); • Chemically inert; • Similar footprint to SF_6 units; • High stability; • Market availability; and • Easy to handle during maintenance work.
Market Interrogation	Manufacturers appear to be bringing products to market in the near term. ABB and GE have developed alternative insulating mediums for use within other product ranges. It can be expected that this will progress to RMUs.
Equipment	The maintenance regime will need to be assessed for any alternative solutions. Current switchgear products are advertised as either maintenance free or low maintenance, it would be ideal to have products with the same intention. However, new products will require much more testing and product validation before market trust can be developed.
Equipment	Vacuum interrupters are likely the most plausible replacement for gas filled equipment. Insulation mediums can be paired with this to provide a complete solution.
Equipment	Fluoroketones and Fluoronitriles offer potential solutions through collaboration with switchgear manufacturers. These have the highest TRL of investigated alternatives. One point for concern is that data sheets for both note that they may not be compatible with some components such as compounds used to produce gaskets and O-rings.

Market Interrogation	Literature suggests many pure gases are unsuitable for use. Many gases do not possess all the key criteria (high GWP & dielectric strength, low GWP & toxicity etc.). However, by mixing with other substances/compounds this issue can be managed. It is likely that a solution will be found by taking this approach. Air, CO_2 and N_2 have all been explored in this context.
Equipment	Ability to match physical dimensions of the existing switchgear is a key factor in producing a successful alternative to SF_6. Ideally the solution would be 'plug and play' as would avoid extra costs of wide-scale retrofitting. Developing mediums that can match and better the chemical properties of SF_6 may be the easier task. Ability to match the physical properties as to have the least commercial impact for DNOs could be the greater challenge.
Equipment	The process of combining an alternative product within existing switchgear is very complex. There are several factors which add to this complexity including the need to account for practical handling of the separate gases, as well as the risk of derating a breaker due to the alternative gas not being able to dissipate heat as well as SF_6. Furthermore, some existing products have experienced failures in the field which may prevent their use as a basis for testing alternative solutions.
Market Interrogation	The challenge of introducing new products is overcoming a series of technical and economic challenges. An example of this is the clearance gap in vacuum interrupters which are very small and could subsequently be perceived as unsafe.
Equipment	Most commercially available products are currently for indoor RMUs or front panels. Development of the technologies and techniques may extend the findings to outdoor applications but ambient effects will have a determining factor.
Market Interrogation	Through conversations with vendors it has been found that compatibility between existing switchgear/ RMU enclosures is poor. In most cases redesign of equipment was required to accommodate the new medium being used.

Equipment	Solid insulation has been investigated thoroughly. However, levels of insulation offered are not equivalent to that provided by SF_6. Additionally solid insulation requires a greater physical footprint compared to that made possible when using SF_6 gas. This is an issue when faced with retrofitting devices as additional labour and cost will be involved to make compatible.
Market Interrogation	Nuventura have a RMU product which uses dry air at atmospheric pressure as an insulator without compromising on the size of an SF_6 RMU. No technical information has yet been made available, and this technology is still under investigation. Capital and operational expenditure for use of this equipment may be significantly lower due to removal of handling requirements.
Testing	The replacement of SF_6 gas within a switchgear/RMU is recognised as a material change in the properties of the equipment. This means the whole device needs to be recertified in accordance with applicable type tests.
Equipment	The following characteristics must be known to validate alternative gases for SF_6 equipment: • Boiling point at 1 bar • Buffer gas if mixture • GWP of gas or mixture • Ozone Depletion Potential of gas or mixture • Flammability • Toxicity (LC50 on mice and TWA) • By-product analysis after long duration test under electrical field • By-products analysis after internal arc test

Testing	The behaviour of the gas and the materials to be used in the electrical equipment need to be known when exposed to internal arc fault. The electrical energy supplied and the increase of pressure throughout the test should be measured. The results should be used for adequate design of electrical equipment and pressure release device(s). By-products after the internal arc fault testing should be evaluated. The gas must not be explosive in the when operating (filling, temperature rise test, partial discharge, making of disconnector, internal arc fault test, leakage). This is particularly relevant for especially when the gas containing oxygen atoms. In the case of mixed gases, flammability should be checked at different temperatures given the relationship to pressure.
Testing	In addition to dielectric type testing it is recommended to make dielectric tests at minimum ambient operating temperature and maximum gas temperature. These tests should be performed at the gas or gas mixtures minimum functional density.
Testing	Making/breaking tests should be conducted throughout the temperature range of the new gas or gas mixture. Values of total pressure must be recorded before and after making/breaking tests to consider the temperature increase of the gas and/or waiting time to recover the ambient temperature of the equipment. Once making/breaking tests are completed, a gas sample should be taken for analysis.
Testing	As with any new technology long term performance is an area that holds question. To give best guess at the performance of alternative gases in SF_6 equipment long term performance testing should be conducted in line with the guidance from T&D Europe.

Equipment	Information/ Policy is readily available on the handling of SF_6 during the "normal" lifecycle process but very limited in cases applicable to this project. Removal of SF_6 gas is usually covered by end of life cycle procedures which also include the destruction of gas housing. This does not align with initial project intent to retrofit a new medium within an enclosure previously used to house SF_6.
Equipment	Having spoken with a senior figure at an internationally recognised Vendor, with experience in the assessment of SF_6 alternatives, it has become clear that injecting a new gas into existing RMU devices is not a viable solution. To perform a valid test a new enclosure must be designed for the alternative medium.
Equipment	Initial project scope will require work far outside usual business practice and this will introduce significant risk. Given the work currently being undertaken by vendors, it would be more advantageous to reassess project in a period of 12-18 months.
Other	Estimated cost of replacement for all SF_6 HV GM RMUs in the network ranges from £312m to £420m dependent upon strategy taken. Timescales associated to these costs also vary greatly, from 40+ years to 20 years. This is an indicative assessment of the overall cost of replacement using equipment costs as known today and assuming replacement does not require significant alteration to infrastructure.
Other	Civil penalties have substantially increased for the release/leakage of F-gases with different levels of fine according to the seriousness of the breach. Fines of up to £100,000 exist for infringing requirements and procedures for minimising emissions or leakage and recovery of F-gases from equipment. This is most relevant to DNOs when repairing and maintaining electrical switchgear. At this stage unless there is evidence of negligence or malicious activity no civil penalties should apply. Failing to correctly label equipment containing F-gas, or not keeping records of F-gas equipment can incur a fine up to £50,000.

Market Interrogation	Clear challenges exist in developing alternative product which will be accepted by the market, but also in developing a switchgear product using the proposed mediums. The industry has been focused on SF_6 switchgear for a significant period of time and to change the culture from this will be a significant challenge regardless of regulatory change.

9. The Outcomes of the Project

The literature review showed that multiple technologies have the potential to replace SF_6 in the future. Fluoroketones such as Novec 5110 ($CF_3C(O)CF(CF_3)$) show promise as alternatives for insulation within switchgear. The Dielectric properties exceed that of SF_6, it has a GWP of less than one and is compatible with a wide range of equipment components. However, the boiling point is too high as a pure gas and mixing with other gases is required. Equally, Fluoronitriles including Novec 4710 have been developed as both an interrupting and insulating medium with a dielectric strength double that of $SF_{6.}$ Similar issues to that of Fluoroketones persist and there are issues of compatibility with some components. However, recognised manufacturers are developing products using both these technologies. ABB's Fluoroketone compound, is currently being trialled in the Netherlands with results expected at the end of 2018. GE have developed a Fluoronitrile compound, however no commercially available product currently exists at medium voltage level.

Other solutions have a broad spectrum of TRLs and are being applied at different voltage levels and in different switchgear types. There are instances of RMUs suitable for indoor use whereas the project investigated the viability of retro-fitting outdoor RMUs. This of course does not rule out the progression to outdoor applications but the effect of variance in ambient conditions on the equipment would have significant effects that need consideration.

Deployment of alternatives in other forms of switchgear also shows that progress is being made. However, the techniques or technologies involved are not currently fitted within RMUs. These options could be deployed as part of a replacement programme for similar switchgear types (circuit breakers and switches) but this would incur additional labour and cost. It could also be assumed that many breakers and switches will be replaced by RMUs, combining their functionality. It would not prove good value for the consumer to change a large quantity of assets twice if in allowing technology to mature two initiatives could be achieved by one intervention.

With many technologies only able to support insulating capabilities a common theme uncovered is the use of vacuum interruption alongside many of these technologies. It is well researched and many commercial products are available. It would be recommended that where there is a need to replace only SF_6 for interruption, the solution would be found in the use of vacuum technology. However, interruption is an area of research that is very much active and it is possible that other alternatives may be developed which have not been presented in this project.

If it were possible to replace SF_6 within existing switchgear on the network, its removal and replacement with an alternative solution would be deemed a fundamental change to the constitution of the switchgear it is stored in. Therefore, full type testing of the device would be required to regain certification for commercial use. With the introduction of new mediums comes reduced familiarity and the need for increased validation for their use, as explored in the Test Methodology document. Additional guidance is advised, on the recommendation of T&D Europe, for use, if not before, type testing is performed on the modified switchgear. The information aims to specify the additional information and testing criteria required to ensure the performance of the electrical equipment throughout its service life, while also familiarising the end user with the composition of the gas in use, from a Health, Safety and Environmental stand point.

While ability to match the capability of SF_6 as an insulator or interrupter is key to the success of developing alternatives, the compatibility of new technologies and interfaces to physical dimensions of existing infrastructure is critically important. DNOs must carefully consider their needs if any retro-fit to design is required. Current asset deployment is focused on current equipment and radical alterations to existing equipment may require extensive labour and high costs, making any derived solution uneconomical. Current solutions that utilise CO_2, N_2 and solid insulation in their design are not recommended due to the expenditure required to match the network infrastructure.

To explore this in more detail a cost analysis for full scale retro-fit of new equipment was performed, on the basis it was compatible to existing infrastructure. Using a combination of network data and strategies from our current RIIO-ED1 plan for 2015-2023, the cost to replace the entire SF_6 RMU network was determined to amount to between £422 million over 42 years or £312 million over a 20 year period, should replacement/installation rates be doubled. For context, the worst case would require the entire budget for four consecutive regulatory periods. A target that is far beyond feasible, especially given that this analysis does not consider the need for additional civil works.

Unable to propose a direct retrofit solution within current RMUs, the extent of regulation and the price of penalties are likely to determine the strategy taken by DNOs given the large-scale cost of full asset replacement outlined by the analysis of this project.

Unless driven by regulation, it is likely that DNOs implement a scheme of asset replacement in line with current processes of age and condition profiling with an increased contingency for SF_6 devices. This would spread the replacement over a greater time frame, maximising the life span of existing assets and limiting any short-term increase in expenditure. This will enable DNOs to remain flexible, enabling conformance with future regulation while monitoring the progress of SF_6 alternative technologies to determine the optimal time to adopt them.

Irrespective of any such initiatives we remain committed to the investigation of SF_6 alternatives and will monitor the market place with an aim of revisiting this in 12-18 months. During this period two solutions will be monitored for the possibility of retrofit or for replacement of existing equipment; Nuventura Synthetic Air and HFO1234zee. Both would be as insulators only, as they meet many of the criteria outlined in the Literature Review and have a similar physical footprint to SF_6. Synthetic Air is currently being pilot tested by an unnamed DNO in Germany but we remain in contact with the parent company and await results of the current pilot.

10. Data Access Details

In addition to the Closedown report, the following documents have been produced and made available during the course of the project:

- *A Literature Review on SF6 Gas Alternatives for use on the Distribution Network*
- *SF6 Alternatives- Test Methodology*

Electronic copies of the above documents can be found here:

https://www.westernpower.co.uk/innovation/projects/sf6-alternatives

11. Foreground IPR

All new learning that has been created throughout the project has been captured and made publicly available. More information can be found on the project webpage:

https://www.westernpower.co.uk/innovation/projects/sf6-alternatives

12. Planned Implementation

We remain committed to the investigation of SF_6 alternatives.

The learnings of the Literature Review and Test Methodology will be maintained. However, no further implementation is planned at this stage. Until such time that a suitable alternative to SF_6 switchgear is available, we will continue to monitor this area with a proposed timescale of 18 months before revisiting this topic.

13. Contact

Further details on replicating the project can be made available from the following points of contact:

Future Networks Team
Western Power Distribution,
Pegasus Business Park,
Herald Way,
Castle Donington,
Derbyshire
DE74 2TU
Email: wpdinnovation@westernpower.co.uk

Glossary

Abbreviation	Term
BaU	Business as Usual
CIRED	International Conference on Electricity Distribution
DNO	Distribution Network Operator
EHV	Extra High Voltage
ENA	Energy Networks Association
GIS	Gas Insulated Switchgear
GM	Ground Mounted
GWP	Global Warming Potential
HV	High Voltage
LC	Lethal Concentration
LCNI	Low Carbon Networks & Innovation
NIA	Network Innovation Allowance
PM	Pole Mounted
R&D	Research and Development
RMU	Ring Main Units
SF_6	Sulphur Hexafluoride
TRL	Technology Readiness Level
TWA	Time Weighted Average
WPD	Western Power Distribution