SPECIAL REPORT FOR SC D1
MATERIALS AND EMERGING TEST TECHNIQUES

Special Reporters
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Chair and Secretary
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A few words about Session Papers

Session Papers are focussed on a number of Subjects, referred to as 'Preferential Subjects', selected in advance by the 16 Study Committees of CIGRE and available in the Call for Papers.

Session Papers are selected through a two-phase review process – abstracts and full Papers.

To gain an overview of subjects that will be discussed, have a look at the Technical Programme for a list of the Papers selected for the Session. It is updated as the Full Paper review proceeds.

CIGRE Sessions

At CIGRE Sessions authors are given the opportunity to present their Paper during half-day specific meetings – the Poster Sessions.

Four days are also dedicated to 'Group Discussion Meetings' organised by Study Committees. Four meetings run simultaneously each day from Tuesday to Friday, under the presidency of the Study Committee Chairs. The purpose of these meetings is the discussion of the "Special Reports" which incorporate the gist of the Session Papers and pose a number of questions for discussion: the questions and how to respond are below.

The Special Reports are available to all (from the end of May) on the Session page of the CIGRE website.

For fruitful discussions delegates are strongly encouraged to read the Papers before the Session.

The Session Papers are made available for downloading to all duly registered delegates before the Session through their private account on the registrations portal. Papers are also readable on the Session smartphone application while on site in Paris.

Follow the latest Session news and General Programme by regularly visiting our website!

PARTICIPATING IN THE 2026 PARIS SESSION

You are invited to participate in discussing this Special Report at the SC D1 session held on Wednesday 26th August starting at 08:45 in Havane Room at the Palais de Congress de Paris.

The Special Reporters have compiled 27 questions, these are not specifically aimed at the papers' authors, but are synthesised from common issues and trends identified across the papers. This provides the opportunity for a broader response and participation in the Group Discussion Meeting (GDM). Any delegate can respond to these questions and we encourage you to share your views or experiences in response to the specific questions in this report. During the GDM, each prepared contribution will be allocated a time slot of around three to four minutes for a presentation.

Procedure for contributions.

1. Contributors should upload contributions on the registrations portal in the "Contributions to Group Discussion Meetings" section; use your existing account and credentials to submit your contribution before 7th August 2026. To ensure the smooth running of the Group Discussion Meeting all submissions will be reviewed.
2. Access to upload contributions is given only to duly registered delegates.
    - As a consequence, registration to the CIGRE Session must be finalised before uploading contribution(s) online.
    - Register now for the Session registrations.
    - Contribution can be uploaded from the start of June.
3. Special Reporters will review the prepared contributions (Powerpoint presentation with max 4 slides including the title slide and a written word file with max 1000 words per contribution). A guide for contributors as well as templates and sample pages will be available on the Paris Session webpage. Important notice: no commercial names are to be included in presentation or the written summary (even TSO/DSO names).
4. Any recommendations for improvement or changes to the contributions will be provided to the contributors by the Special reporters directly on the Registration platform between 7th of August and 14th of August 2026. Contributors are encouraged to visit their account on the registrations portal to see the result of this review.
5. All contributors with accepted/finalised contributions will be contacted by the Special reporters between 7th of August and 14th of August 2026, to finalise the presentation and receive the instructions regarding the session.
6. Important note:
    - All contributions must be uploaded prior to the Conference in Paris.
    - Last minute changes to the contributions will not be granted.
7. During the GDM the Study Committee Chair may call for spontaneous contributions, which will only be verbal with no slides. All attendees are eligible to make such a contribution. Attendees who provide a spontaneous contribution are allowed to deliver a written contribution after the GDM which will be included in the Session Proceedings. This text should be sent to the SC Secretary, Gordon Wilson, (gordon.wilson@nationalgrid.com) within two weeks after the GDM (i.e. by 9th September).
8. It is expected that the questions relevant to the Preferential Subjects will attract many prepared contributions. The number of contributions for each Preferential Subject (PS1, PS2 and PS3) may need to be limited. The selection will be based on relevance, quality and time of submission of the contribution.

Important information about file naming

Guidance on file naming is given on the registrations portal in the "Contributions to Group Discussion Meetings" section. In summary, question responses must follow this format, to be considered on the contributions platform:

D1_PSx_Qx_Author Name_Version_x e.g. D1_PS2_Q2.3_SUTTON_Version_1

Poster session

Authors of Session papers are required to present their papers during the **SC D1 Poster Session scheduled on 24th August 08:30 to 12:30** in Halle Ternes on level 1. Note:

- Posters for PS1 will be displayed 08:30-10:30
- Posters for PS2 and PS3 will be displayed 10:30-12:30

Template and instructions on poster preparation are available on the CIGRE 2026 Session website. Posters will be displayed on digital screens. **Poster presentations must be uploaded on the ConfTool platform from 18th May by 29th June at the latest** for review by the poster session convener. Poster conveners may ask for a final version, incorporating any requested changes, must be uploaded by August 14th. It should be noted that authors will **not** have the possibility to upload their own file on the day of the Poster Session. If the author(s) cannot attend the Poster Session he/she or the relevant National Committee is requested to send a substitute.

Thank you very much!

THE PARIS WEEK FOR SC D1

Introduction

Study Committee D1 aims to facilitate progress in engineering, and international exchange of information and knowledge in the field of materials and emerging test techniques. In this role SC D1 provides specialist knowledge and support to many of the other Study Committees, as well as responding to requests from standards bodies, such as IEC, for recommendations for new and revised tests.

The activities of SC D1 include evaluation of new developments and assessing performance within:

- New and existing materials for electrotechnology
- Diagnostic techniques and related knowledge rules
- Emerging test techniques which may be expected to have a significant impact on power systems in the medium to long-term

In 2024 CIGRE published its latest Strategic Plan covering the period to 2030. This plan expands CIGRE's scope to consider the End-to End generation to consumption of electricity: this reflects CIGRE's desire to support the energy transition. SC D1's scope will correspondingly broaden to incorporate these new topics.

SC D1 Agenda

During the CIGRE week there are many opportunities to participate in the activities of SC D1, including one tutorial, two workshops, the poster session and Group Discussion Meeting (GDM). The poster session is your opportunity to meet the authors of the Session papers and discuss their work. The GDM is where the questions posed in this Special Report are discussed; anyone is free to contribute, and you are encouraged to do so.

Here is a brief summary of the SC D1 activities to help you plan your week:

Date	Time	Room	Description
24/08/26	08:30 – 12:30	Halle Ternes	**Poster Session**
25/08/26	08:30 – 10:30	Room 342AB	**Joint Workshop** A3/B3/D1 SF6 replacement and alternatives
25/08/26	10:40 – 12:30	Bordeaux	**Tutorial** Latest developments of test methods for polymeric insulating materials under high-voltage outdoor conditions
25/08/26	14:00 – 17:00	Regency 15	**Workshop** Frontiers in PD diagnostics
26/08/26	08:45 – 18:00	Havane	**General Discussion Meeting**

For the 2026 Session, papers were invited on the following three Preferential Subjects (PS) which are aligned to SC D1's activities:

PS1: Testing, monitoring and diagnostics

- Testing and condition monitoring for reliability in conventional high voltage systems and power electronics applications.
- Assessment of diagnostics for equipment in remote or inaccessible locations.
- PD measurement under DC, rectifier, and impulse stress.

PS2: Materials for electrotechnical purposes and modelling

- Ageing of materials under electrical, mechanical or thermal stresses and ageing markers.
- Modelling materials and field simulations for AC and DC applications.
- Assessment of compatibility of aged and new materials resulting from refurbishment or life extending activities.

PS3: Materials to enable the energy transition

- Alternative electrotechnical materials or manufacturing processes which reduce environmental footprint.
- Materials and systems for energy storage; batteries, charging devices, capacitors etc.
- Materials to enable a hydrogen economy.

The removal of National Quotas in 2024 has led to an increase in papers for all Study Committees. Following a rigorous review process supported by 50 peer reviewers from around the globe, 74 papers have been accepted this year. These papers come from 25 countries; a good reflection on the international nature of CIGRE. The breakdown of submissions is as follows: 34 for Preferential Subject 1, 34 papers cover Preferential Subject 2, and 6 papers are aligned with Preferential Subject 3.

This year we had two proposed papers from the Next Generation Network (NGN); these are papers 12620 (PS2) and 12621 (PS3). Both are excellent papers and will be presented during the Group Discussion Meeting (GDM).

Information about participating at the SC D1 Activities at the Paris Session

Guidelines for the GDM Contributions and Poster Sessions, as well as templates must be strictly observed and are posted on the CIGRE website Session page. A summary is given at the start of this document.

D1 Group Discussion Meeting and Preview Meeting

You are invited to participate in discussing this Special Report at the SC D1 session held Wednesday 26th August, in the Havane Hall from 08:45 to 18:00.

The reporters have compiled 27 questions, these are not specifically aimed at the papers' authors, but are synthesised from common issues and trends identified in across the papers. This provides the opportunity for a broader response and participation in the discussion session. We encourage you to share your views or experiences in response to the specific questions in this report.

Information on the Poster Session

The poster session will be held on Monday 24th August between 08:30 and 12:30. Due to the number of papers the session will be split as follows:

- 08:30 to 10:30 posters relating to PS1 will be displayed
- 10:30 to 12:30 posters relating to PS2 and PS3 will be displayed

Additionally, for the first time this year, every active D1 Working Group will display a poster relating to their work. This is a great opportunity to discover the breadth of the work happening within SC D1.

PREFERENTIAL SUBJECT 1 – Testing, Monitoring and Diagnostics

Here papers were sorted on topics related to the measurement and understanding of material ageing under real world conditions. This includes diagnostic testing methods and continuous monitoring, and the interpretation of data by both subject matter experts and automated systems. The published topics were:

- Testing and condition monitoring for reliability in conventional high voltage systems and power electronics applications.
- Understanding of space charge and PD behaviour under AC, DC, rectifier, and impulse stress.
- Advances in knowledge rules and tools for improved diagnostics including ML, AI, explainable AI (XAI) etc. considering multiple data sources or contextual information.

The following lists all the accepted papers for PS1.

PAPER ID	TITLE
10308	Partial discharge monitoring and localization in HV bushings using fiber optic-based acoustic emission sensing technology
10516	Transmission line insulator defect detection and diagnostics using machine learning models
10517	Advanced monitoring technique for leakage current and partial discharge in inverter-fed motor insulation
10994	Advanced PD sensor technology for dry air-insulated switchgear
10995	Discussion on tolerance of relative overshoot magnitude of lightning impulse voltage waveforms in impulse test of power transformers
11159	On-site dielectric tests for synchronise condensers
11223	Integrated approach to high-voltage equipment x-ray inspection at the electric power facilities
11225	Condition diagnosis of oil-filled transformers based on online DGA data using machine learning
11250	An integrated diagnostic framework of electrochemical analysis for assessing silicone oil health in HV cable outdoor terminations
11306	UHF-based partial discharge diagnostics in SF6-alternative gases
11377	Continuous monitoring and interpretation of total gas pressure of dissolved gases in power transformers
11395	An alternative non-destructive method for evaluating the remaining service life of thermal and nuclear power plants: miniaturized-specimen creep testing

11396	Remaining useful life prediction methodology for ferritic steel aged in components of thermal and nuclear power plant
11401	Online monitoring strategy of high voltage assets in AIS based on partial discharge detection by radiometric method
11537	Real-time visualisation of capacitive and depolarisation discharge after DC insulation testing for improved safety, accuracy, and productivity
11559	Multifactorial accelerated ageing tests of overhead line insulators including a sandblasting stage
11562	Local defect location method for long cables based on improved MUSIC-pseudospectrum
11565	Electrostatic ionization VOC sensor driven by triboelectric nanogenerator for power equipment surrounding monitoring
11680	Separation of partial discharge sources by application of feature extraction and clustering methods
11707	A UHF PDM system for arc detection and signal location in GIS
11733	Overcoming challenges in visual technologies for continuous monitoring of high voltage stations
11763	Comparative analysis of lightning properties of different types ester fluids
11782	Test current effect on reliability of dynamic contact resistance measurements for circuit breakers
11861	End-to-end design automation for reliable power system components
11884	Impact of switched voltages from electronic power converters on high voltage insulation systems and components
11949	A case study on the signal delay effect of cable terminations on time-of-flight measurements in GIS
12022	Resistance threshold method for accurate and reliable both-sides grounded timing measurements for high-voltage circuit breakers
12023	Minimizing shock risk during high-voltage measurements with fast fault detection
12251	Bio-based epoxy resin for high-voltage bushings: insight into more sustainable materials with improved insulation performance
12332	Evolution of gas composition under switching of fault currents in a 420 kV SF6-free circuit breaker
12396	AI based compression and analysis of partial discharge current pulse waveform in HVAC and HVDC systems
12415	Advanced optical PD diagnostics of GIS at onsite testing and service including transient overvoltages
12420	Investigation on aging of paper and liquid insulation during overload test of natural ester immersed transformer
12523	Degradation characteristics of insulation discharge at the interface of moisture-affected cable accessories
12524	Contact electro-erosion assessment of generator circuit breaker based on vibration-fingerprint-RQA

The measurement of partial discharge (PD) and the associated diagnostics or continuous monitoring is one of the most important methods for assessing the condition of high-voltage systems. It is often the case that PD measurement is the only effective means of determining the health of the insulation system while energised. The detection and analysis of PD signals are among the fundamental measurements performed on HV components and have a long history. Due to the continuous advancement of PD applications under both laboratory and field

conditions, there is an ongoing need to support this technology with guidelines for PD detection and testing which describe both proven and new methodologies. As a result, PD measurement has become a globally recognised method for insulation diagnosis and a mandatory part of acceptance testing for most AC high-voltage installations.

This is reflected not only in the large number of papers on this topic, but also in the working groups that have been working on this topic within D1 over the past few years and continue to do so. The following working groups focus on PD-related topics:

- WG D1.63 Partial discharge detection under DC voltage stress
- WG D1.74 PD measurement on insulation systems stressed from HV power electronics
- WG D1.61 Optical corona detection and measurement
- WG D1.83 Optical spectral sensing technologies for partial discharge (PD) and arc detection in gas insulated equipment
- WG D1.78 Partial discharge properties of non-SF6 insulating gases and gas mixtures.

In addition, SC D1 is organising a workshop during the 2026 Paris session; Frontiers in Partial Discharge (PD) Diagnostics. In this workshop, SC D1 aims to present the current state of knowledge from a CIGRE perspective, with a focus on current trends, new applications, and new technical approaches, all combined with insights from the field of standardisation.

In general, diagnostic and monitoring functions are becoming increasingly important. This is due in part to the growing number of ageing assets, but also to the optimisation of maintenance tasks. For example, Dissolved Gas Analysis (DGA) remains one of the most effective techniques to diagnose transformer incipient faults. Various interpretation methods including key gas method, ratio-based method, Duval's triangle and pentagon have been established mainly based on mineral oils but progressively adapted for other alternative liquids. JWG D1/A2.77 is going to produce a technical brochure which will include state-of-the-art knowledge on DGA measurement and interpretation.

The diagnosis and assessment of liquid dielectric systems is increasingly constrained by the complex, non-uniform and dynamic nature of the liquids themselves. Diagnostics for complex system require frameworks that integrate multiple condition indicators. For example, field studies on silicone oil filled terminations demonstrate that water content and breakdown voltage are only weakly correlated under operational conditions, largely due to spatial heterogeneity and sampling limitations. Similarly, classical DGA interpretation methods struggle to interpret high-resolution online data, with machine learning approaches offering improved performance but introducing new challenges around implementation and interpretability.

Papers in this section indicate that there is a growing reliance on integrated and continuous monitoring approaches, which have been enabled by digitalisation. Multi-parameter diagnostics combining chemical, electrical, and thermal indicators are shown to be useful. Examples include combined moisture, breakdown voltage and DGA approaches for cable terminations, coupled thermal-chemical models for estimating transformer insulation life, and hybrid forecasting-classification frameworks using machine learning for DGA data.

Looking to the future, automated, AI-supported assessment of diagnostic and monitoring data has the potential to play a key role in supporting asset owners undergoing the loss of experienced engineers and the drive to reduce costs in a world where technologies and materials are changing. However, there seems to be a lack of papers, or WGs, in D1 that would account for this frontier. Less surprising, PD analysis is one of the areas where AI tools have found

some use. Some of this has to do with the need for lower bandwidth, considering the increasing need for online monitoring. Elsewhere, some novel use of machine learning has been suggested for optimising the inspection workflow of UAV for transmission line inspection, or automated design of power system components; although again, this is not represented in the accepted papers.

In the field of insulating gases and GIS, once again a trend in this year's papers is a focus on condition monitoring and PD measurement. Although the application of alternative insulating gases to replace SF6 has reached a more mature stage, their influence on PD behaviour and defect detectability is still under investigation within the technical community, while practical experience grows. Cross-comparison of new gases to SF6 is essential to build on the foundational experience with SF6. Adaptation of sensors and PD measurement techniques are being discussed. Conventional and ultra-high-frequency (UHF) PD measurement methods for SF6 gas-insulated systems have been state of the art for decades, but alternative techniques offer advantages in specific situations. Optical PD measurement may improve the detection of certain defect types in environments with high electrical interference, but up to now the experience is limited. CIGRE is supporting in both topics, in particular:

- WG D1.78 Partial discharge properties of non-SF6 insulating gases and gas mixtures
- WG D1.83 Optical spectral sensing technologies for partial discharge (PD) and arc detection in gas-insulated equipment

Decomposition of the new insulating gases is a further topic of relevance, and here the experience is growing.

PS1 Questions

Q1.01. Despite the long history of PD diagnosis, there is still a significant need to optimise existing methods, develop new and unconventional approaches, or combine them. Can real-world examples be used to highlight the shortcomings of established diagnostic procedures? Are traditional methods not sensitive enough, or do overly sensitive measurements make interpretation even more difficult? And how can the accuracy of the diagnosis be improved by using new measurement methods or combinations of existing ones?

Q1.02. PD diagnostic methods are gaining importance in the MV sector, HVDC installations, and power electronics/drives. These are often new areas of application for traditional methods. What specific requirements need to be taken into account here?

Q1.03. Reports indicate that there are minor, but no major, differences in the PD behaviour of new insulating gases, compared with SF6. PD measurement is an essential tool to estimate the criticality of defects. Can you give specific examples of critical defects in new insulating gases, compared with the experience of SF6?

Q1.04. The interpretation of PD measurements remains a topic of much debate. It is often believed that only experts can assess the risk associated with the causes of PD. Numerous new features, increasingly based on AI, are designed for, or are already capable of, classifying phase-resolved partial-discharge (PRPD) patterns and assessing risks. Are there any examples where these methods or expert systems are already being used in decision-making?

Q1.05. There are very few contributions this year specifically mentioning Machine Learning or AI, which seems in contrast to much of the focus in public perception where technology is moving. Excluding PD, what are the experiences with Machine Learning in testing, monitoring and diagnostics of power systems? Are real-world decisions being taken based on these approaches?

Q1.06. There is a recurring disconnect between results obtained in laboratory studies and field studies. Diagnostics based on laboratory studies do not always result in diagnostic reliability when put to the test for in-service equipment. To what extent are diagnostic limits for tests based on selective data and calibrated by laboratory studies? How can a utility determine appropriate limits for its own assets based on its own experience?

Q1.07. Are there compelling case studies for online condition monitoring systems detecting and tracking incipient faults, leading to the removal of the asset which have subsequently been verified by a detailed examination?

Q1.08. Data-driven (AI) approaches to diagnostics for complex insulation systems are being explored more widely and they may increase our understanding significantly when combined with digital twins and enhanced sensing capabilities. But whether the investment in the technology will improve our capability sufficiently to justify its cost is a question an asset owner needs to answer. How do asset managers approach the problem of cost benefit of implementing novel diagnostic approaches?

Q1.09. Several papers highlight that liquids are not uniform diagnostic media (as often assumed) and that their behaviour is strongly influenced by time, location, interactions in their system and transportation dynamics. Diagnostics therefore need to account for time, spatial gradients and transient phenomena. Are current sampling practices fit for purpose in supporting condition assessment of liquid-filled systems? With this in mind, is there still a place for manual sampling or should all testing be continuous and online?

Q1.10. HVDC systems continue to become more prevalent. What advances are there in diagnostics and monitoring, such as PD, to detect, monitor and diagnose developing faults? What metrics can be used to track the severity of an emerging fault?

Q1.11. Inverter-based voltage sources distort the sinusoidal waveforms to which dielectrics are subjected during operation. Working group D1-74, is considering PD measurement on insulation systems stressed from HV power electronics, but what challenges to online monitoring and sensitive testing methods do these distorted waveforms pose? What approaches can be taken to minimise the impact of high frequency switched voltages?

Q1.12. An increased number of contributions relate to improved safety of HV testing, especially in the field – does the rapid expansion of renewable energy and BESS require updated safety standards?

PREFERENTIAL SUBJECT 2 – Materials for Electrotechnical Purposes and Modelling

This Preferential Subject sorts papers on understanding the ageing and modelling of materials conventionally used in the power industry, often based on laboratory testing. Papers were also invited on materials aligned to the energy transition, new manufacturing approaches and developments in superconducting systems. The published topics were:

- Ageing of materials under electrical, mechanical or thermal stresses and associated ageing markers.
- Modelling materials and field simulations under AC, DC and composite voltages.
- Application of novel materials and processes; eco-friendly and recycled materials, materials to enable energy storage or cryogenic systems, additive manufacturing etc.

The following lists all the accepted papers for PS2.

PAPER ID	TITLE
10916	Flow electrification risk assessment of conventional and new alternative insulating liquids for power transformers
10996	Suppression of gas pressure and tank diameter of dry air GIS by combination of FGM spacer and insulating coating conductor
10997	Water tree degradation impacting on the insulation performance of highly-aged MV/HV-class XLPE cable
10998	High-throughput synthesis of size-controlled nanoparticles for lithium ion battery using tandem-coil modulated induction thermal plasmas
10999	Anomalous electric conduction in polymeric insulating materials: analysis by integrated current
11000	Investigation of ageing factors and long-term reliability in synthetic air-insulated switchgear
11120	Ageing kinetics of insulating paper immersed in a near carbon neutral re-refined oil
11142	Quantum chemistry simulations for multi-scale modelling of polymer ageing
11202	Additive manufacturing of reusable moulds for rapid prototyping of electrification devices
11387	Biodegradability testing of transformer insulating liquids: decoding the OECD 301 for the electrical industry
11399	Isotopic monitoring: a novel diagnostic and life-prediction tool for paper–oil insulation in transformers
11400	Accelerated aging experiments of silicon rubber insulation for the first 500 kV dry-type air-core shunt reactor in Brazil
11424	The effect of hotspot conditions on DGA key gas generation on novel insulating liquids
11549	Overview of long-term compatibility and ageing tests for materials used in high-voltage gas insulated switchgear
11568	Artificial intelligence assisted development of dielectric materials
11569	Research on the performance improvement of bio-based magnolol epoxy resin
11570	Study on the arc erosion resistance characteristics of silicone rubber under DC voltage
11571	Colorimetric and self-sealing photonic crystal film for early detection of SF_6 leakage in gas-insulated equipment

11572	Analysis of the impact of mechanical shearing on the properties of grain-oriented silicon steel
11624	Extrusion additive manufacturing of polydimethylsiloxane materials and their performance for potential insulation applications
11785	Enhancing HVDC insulation performance of XLPE via tailored vinyl silane additives: correlating microstructure, DC breakdown, and space charge behavior
11800	Assessment of material compatibility with insulating liquids through spectroscopic analysis
11887	Quality and performance of reclaimed mineral oils
11995	Advanced dielectric diagnostics for aging analysis of silicone elastomers
12334	Experience on the application of IEC corrosion tests on sealing systems of enclosures and auxiliary equipment to gas-insulated metal-enclosed switchgear
12336	Improved sealing technology for switchgear with alternative gases
12347	A novel method for the monitoring of degradation of inhibitors by means of dissolved gas analysis
12358	Aging of two natural esters in the presence of transformer construction materials
12373	Material analysis of composite hollow core insulator housings after long-term ageing test
12484	Long-term Stability of synthetic air in gas-insulated systems and the impact of gas quality on the electric and ageing performance
12526	Research on the water absorption and insulation deterioration of insulating oil for high-voltage cable terminations
12527	Design and thermal conductivity enhancement strategies of MWCNTs-PDA@BCN coaxial nanotube structures and their epoxy composites
12620	Greener grids: bio-derived epoxies for next-generation HV insulation

While ageing assessment of liquid impregnated insulation systems has attracted continuous interest in the past decades, compatibility issues have emerged as a hot topic more recently. This is mainly driven by the fast adoption of various insulating liquids, e.g. ester liquids and new generations of hydrocarbon liquids. Compatibility tests could easily become an enormous effort for end users and suppliers due to the large number of different insulation and construction materials used in transformers. IEC63177, published in 2024, provides a guidance on testing compatibility of construction materials with insulating liquids. Multiple working groups will tackle compatibility issues from different perspectives including:

- JWG D1/A2.80 Functional properties of non-metallic solid materials for liquid filled transformers and reactors and their compatibility with insulating liquids
- JWG D1/A2.84 Silver corrosion in power transformers
- JWG A2/D1.71 Modern insulating liquids qualification for OLTC, bushings and other accessories
- JWG A2/D1.72 Retrofill of mineral oil in transformers – motivations, considerations and guidance

The papers submitted to this PS2 related to liquids and liquid systems touch on a theme that came across in PS1, that complex insulating systems require more complex diagnostic frameworks for those looking to manage them. DGA and FFA are no longer sufficient in isolation since measurement artefacts and the behaviour of new materials introduce ambiguity or, at least, behave differently than traditional materials. A recurring point is that measurements are not purely from degradation mechanisms but shaped by the whole environment of the system. For example, a headspace study shows that gas ratios depend on gas-liquid partitioning

not just on the chemistry of faults. A study of inhibitors considers the production of iso-butene, not a primary gas studied but used by some, as a non-fault gas arising from antioxidants. This is not the first time gases have been linked to additives and challenges the usual assumption that all gases in DGA arise from faults.

Studies of different fluids show that classical assumptions built up over many years based on the use of mineral oils do not necessarily transfer to other fluids. Natural esters are seen to behave differently due to the presence of additives and their molecular structure, leading to gas generation and paper ageing differences. Even with mineral oils differences are observed when comparing reclaimed and re-refined oils. While they exhibit similar behaviour in most tests, accelerated ageing tests can show divergence in performance.

Although diagnostics may be more challenging, and these are likely to be improved with time and more experience, the move towards more environmentally sound solutions is apparent and will be important for those focussed on sustainability.

Papers related to insulating gas alternatives to SF6 are reporting on optimisation measures to reduce equipment size, on the long-term performance of the gases and respective test methods. While the optimisation of GIS designs with insulating gas alternatives to SF6 is still ongoing and further progress might be expected in the future, there is particular interest in the long-term performance of these new gases: experience in the field is growing but still limited.

The new insulating gases are increasingly replacing SF6 in new GIS designs, but the high-GWP gas, SF6, will still be in service for decades. Consequently, measures to limit leakage and its impact on the environment will be of high importance in the future. Two papers report on measures to improve gas tightness, but industrial application is not visible up to now.

Another trend in papers submitted to PS2 relates to bio-based materials in search of replacement for petroleum-derived polymers. In particular, bio-based epoxy resins, derived from e.g. soybean oil or glycerol diglycidyl ether, have been investigated in terms of their dielectric performance. Currently, many such alternatives still suffer from significant trade-offs, typically related to their long-term ageing performance. However, there are indications that some bio-based alternatives can conserve or even upgrade thermal, mechanical or dielectric properties. Nano-dielectrics and nanomaterials on the other hand seem to be stuck in research and development, with no clear paths towards practical use.

With the new WG D1.82 and papers related to additive manufacturing (AM), this new manufacturing technique is getting a foothold in the electrical power industry. A number of OEMs as well as users have started to look at potential AM can bring. In particular, cost savings of up to 30 times, alongside with a significant reduction in lead times, were reported when AM was used for rapid prototyping.

A number of papers report on ongoing work to better understand ageing and treeing processes, from atomistic simulation to outdoor testing of HV components over a number of years. Of particular interest seem to be polyethylene- and silicone rubber-based insulation systems, and their degradation when subjected to harsh environmental conditions, as well as high electrical stresses.

PS2 Questions

Q2.01. Although battery energy storage (BESS) is becoming ever more common in power grid systems, no papers were received on research to improve energy density, longevity or diagnostics. What is the outlook for improving these factors and helping to aid the energy transition?

Q2.02. From the end user perspective, what are the major challenges related to the long-term performance of assets using alternative gases to SF6?

Q2.03. Is there any experience with measures to reduce gas leakage from SF6-filled assets already installed in the field? How can such approaches be validated in the field?

Q2.04. At the last two Paris Sessions there have been examples of Additive Manufacturing (AM) moving out of the laboratory and being used to support the maintenance or repair of old assets. Besides maintenance of legacy equipment, AM can deliver time and development cost savings. What examples and use cases for AM are there in the power industry?

Q2.05. There is an increased interest in bio-based resins for replacing petroleum-based resins for HV applications. While there is a reduction of the carbon footprint, long-term stability of bio-based resins is unproven – are there concerns other than 'not being business as usual', which prevent adoption of bio-based resins?

Q2.06. Some papers address the substitution of fossil fuel-based materials with bio-based alternatives to produce solid dielectric materials. What advances are being made on the recycling of either traditional solid dielectrics or these "green" alternatives?

Q2.07. Electrical treeing still seems to be the main concern among ageing processes in solid dielectrics, but nano-materials which promised increased treeing resistance have found limited adoption. Why have nano-composites not been implemented as a method to increase treeing resistance?

Q2.08. Several papers in this section consider the use of additives in dielectric liquids, they are essential to ensure longevity in their applications. But there is some evidence that they are complicating the way oil test results are interpreted. How do additives alter the ageing pathways and diagnostic signatures from DGA and other tests over time and how do we account for them in standards?

Q2.09. Moisture consistently emerges as a key factor in the ageing of dielectric systems but may not be treated as such by asset managers. Is enough attention given to prevention of moisture ingress and moisture removal from oil-filled systems? How do asset managers judge when and how to intervene when moisture levels rise?

PREFERENTIAL SUBJECT 3 – Measurements and Modelling of Interfaces

This Preferential Subject was focused on the understanding of interfaces in electrical systems overall length scales, through both experiments and modelling. For example, this could include nano-composites, conventional composites, field graded materials, and interactions and compatibility between dissimilar materials. The published topics were:

- Understanding interfacial behaviour through experiments at any scale between the nano- and macro-scale.
- Modelling electric field, magnetic field, or charge dynamics at interfaces.
- Assessing material compatibility of used and unaged materials.

The following lists all the accepted papers for PS3.

PAPER ID	TITLE
10921	Surface charge measurements in non-uniform air pressurized gaps with a dielectric barrier
11001	Electrical and thermal phenomena in anisotropic CFRP composite panels
11141	Modelling of respect width for magnetic field for electrical substations of Terna
11760	Comprehensive analysis of lightning performance of the oil-wedge type electrode model immersed in selected dielectric liquids
12333	The importance of material compatibility for transformers
12621	Charge transport multiscale modelling for bridging material properties to insulation performance: case study of moisture deterioration at cellulose–oil interface

There have been a number of papers submitted to PS1 and PS2 that overlapped with this PS. Some of the submissions for PS3 focus on computational modelling for the oil-paper interface as well as carbon fibre reinforced polymers. Some work discussed the challenges on verifying compatibility between materials, but these remain vague with implementation in practice remaining a challenge.

Composite insulation systems are most widely used in high voltage power equipment. Interfaces are inevitable in composite insulation systems, which are often considered as the weakness of an insulation system. For liquid-impregnated insulation systems, creepage discharge and breakdown along the liquid/solid interface have been identified as one of the electrical failure mechanisms. Empirical rules for calculating creeping strength have been used in insulation design. There is however a lack of standardised test methods to characterise the dielectric strength of liquid/solid interface. JWG D1/A2.80, “Functional properties of non-metallic solid materials for liquid filled transformers and reactors and their compatibility with insulating liquids”, aims to review the functional properties of solid materials used in liquid immersed transformers and to identify gaps in existing test methods/standards for liquid impregnated solid materials including the liquid/solid interface.

It is generally agreed that understanding interfaces are therefore important and test methods would be a valuable contribution, but the challenges come from the difficulty in observing the performance of these systems. There is a gap between the measurable properties of a system and the behaviour at the interfaces. The paper on multiscale modelling identifies that bulk measurements such as conductivity and dielectric losses obscure the underlying charge transport processes that actually govern insulation performance; charge trapping and moisture-

induced barrier reduction occur at the nanoscale and are not captured by conventional measurements.

Greater understanding is required of insulation systems taking into account the physics and chemistry of the materials involved, realistic testing of the systems and engineering judgement of the applications and how they work as a whole.

PS3 Questions

Q3.01. There is a general agreement that compatibility between materials is important (recent examples TB 968 and ongoing work in WGs D1/B1.75, D1/A2.84), why are there few agreed upon standards on how to verify or test compatibility?

Q3.02. What are the challenges to successfully modelling and predicting the behaviour of interfaces? What have we learnt and how can we avoid the pitfalls to improve the accuracy of models?

Q3.03. Are there advances in modelling of nano-composite materials which predict macroscopic physical properties?

Q3.04. The oil-wedge study shows that traditional electrode models (e.g. needle-plane geometry) , can misrepresent interface-driven behaviour, creating inconsistency between laboratory data and real performance. How can experimental test configurations be standardised to better represent real interfacial geometries in actual insulating systems?

Q3.05. Real systems include many interacting materials, and minor components can dominate behaviour, which is not captured by current simplified testing approaches. How should compatibility testing evolve to meet these challenges rather than simple tests of pairs of materials?

Q3.06. Can measurements and experience from surface charge dynamics on GIS spacers in SF6 be used to predict the performance in non-SF6 alternative gases?