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Summary Report on the Joint NEA-IAEA Technical Meeting on Management of Direct Current Power Systems and Application of New Devices in Safety Electrical Power Systems

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NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

Summary Report on the Joint NEA-IAEA Technical Meeting on Management of Direct Current Power Systems and Application of New Devices in Safety Electrical Power Systems

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NUCLEAR ENERGY AGENCY

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The mission of the NEA is:

- to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes;
- to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include the safety and regulation of nuclear activities, radioactive waste management and decommissioning, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

The Committee on the Safety of Nuclear Installations (CSNI) addresses Nuclear Energy Agency (NEA) programmes and activities that support maintaining and advancing the scientific and technical knowledge base of the safety of nuclear installations.

The Committee constitutes a forum for the exchange of technical information and for collaboration between organisations, which can contribute, from their respective backgrounds in research, development and engineering, to its activities. It has regard to the exchange of information between member countries and safety R&D programmes of various sizes in order to keep all member countries involved in and abreast of developments in technical safety matters.

The Committee reviews the state of knowledge on important topics of nuclear safety science and techniques and of safety assessments, and ensures that operating experience is appropriately accounted for in its activities. It initiates and conducts programmes identified by these reviews and assessments in order to confirm safety, overcome discrepancies, develop improvements and reach consensus on technical issues of common interest. It promotes the co-ordination of work in different member countries that serve to maintain and enhance competence in nuclear safety matters, including the establishment of joint undertakings (e.g. joint research and data projects), and assists in the feedback of the results to participating organisations. The Committee ensures that valuable end-products of the technical reviews and analyses are provided to members in a timely manner, and made publicly available when appropriate, to support broader nuclear safety.

The Committee focuses primarily on the safety aspects of existing power reactors, other nuclear installations and new power reactors; it also considers the safety implications of scientific and technical developments of future reactor technologies and designs. Further, the scope for the Committee includes human and organisational research activities and technical developments that affect nuclear safety.

Foreword

Recent operating experience at nuclear power plants has highlighted two safety issues of concern related to electrical systems. One is associated with direct current (DC) safety power systems due to the accelerated ageing of batteries, and the other with the use of new industrial devices and technology including power electronic and smart devices (e.g. digital protection relays) in electrical power equipment for replacement, modernisation, obsolescence or new build on both alternating current (AC) and DC systems.

A direct current system supplies DC loads without interruption from batteries. The DC power systems include batteries, rectifiers/chargers and inverters. An uninterruptible AC power system supplies power from inverters or motor generator sets that are in turn supplied by a DC power source, such as dedicated batteries, or from the electrical power system through rectifiers. Such a system often includes a bypass circuit to allow the feeding of safety loads directly from safety class AC power systems for maintenance and emergency cases. The expected service life of a station battery is normally based on the manufacturer's information and the anticipated operating conditions of the plant. Accelerated degradation of the batteries, if not managed properly, may lead to a scenario where the DC safety power systems are unable to perform their intended safety functions. The accelerated ageing of the battery may affect redundant trains and has the potential to lead to common cause failure.

The active components of AC/DC power systems, such as rectifiers, inverters, bypass systems, circuit breakers and electrical protective devices, often contain industrial digital devices that are not specifically designed to meet the standards of the nuclear sector. In some cases, the presence of such digital devices may remain unknown to the plant operator. This is a concern because safety-classified equipment that contains a digital device requires more rigorous qualification. There should be evidence that the principal safety functions of integrated industrial digital devices in safety applications meet the requirements for the application, and that the device is free from faults that could credibly result in common cause failures where defence in depth should be preserved. These digital devices need to be free from cyber threats that could compromise their safety functions.

In these contexts, the Working Group on Electrical Power Systems (WGELEC) under the Committee on the Safety of Nuclear Installations (CSNI) of the Nuclear Energy Agency (NEA) initiated its tasks on safety DC power systems (batteries) and new power electronic and digital devices in safety power systems. To implement those tasks, the WGELEC organised a technical meeting in collaboration with the International Atomic Energy Agency (IAEA) that aims at widening participation beyond the regular WGELEC countries, in the hope of promoting knowledge in those areas.

This report is a summary of the "Joint NEA–IAEA technical meeting on the management of direct current power systems and application of new devices in safety electrical power systems", held in Vienna, Austria on 2-5 December 2019.

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Executive summary

In 2016, the Nuclear Energy Agency (NEA) Committee on Safety of Nuclear Installations (CSNI) established a permanent Working Group on Electrical Power Systems (WGELEC) as a follow up to the activities DIDELSYS (Defence in Depth of Electrical Systems and Grid Interaction) and ROBELSYS (Robustness of Electrical Systems of Nuclear Power Plants in Light of the Fukushima Daiichi Accident). The working group's objectives are to improve international understanding on the issues that can lead to a degraded power supply challenging the functionality of equipment relying on electrical power systems, and sharing good practice techniques to prevent, detect and mitigate such events.

As part of their initial tasks, the WGELEC selected several activity items including management of direct current power systems (activity 4), and application of new power electronic and digital devices in safety electrical power systems (activity 5). Since any potential benefit may be gained by promoting knowledge in these two areas (activities 4 and 5) and thereby enhancing nuclear safety, the WGELEC decided to hold a technical meeting, which was jointly organised by the NEA and the IAEA. This technical meeting was designed to be a part of the implementation of activities 4 and 5 by widening participation beyond NEA member countries.

Finally, the technical meeting entitled "Joint NEA–IAEA technical meeting on the management of direct current power systems and application of new devices in safety electrical power systems" was held at the IAEA headquarters in Vienna, Austria on 2-5 December 2019. Fifty participants attended the meeting representing regulatory bodies, nuclear power plant operators, utility organisations, design and engineering consultant organisations, as well as of international organisations engaged in activities related to nuclear power plant safety and regulation from 24 countries. Half of them belong to NEA member countries and the rest of them belong to IAEA member countries. Apart from the opening session, the technical sessions included 22 topical presentations organised in the three thematic areas according to WGELEC activities 4 and 5 and complemented by cross-cutting topics related to both thematic areas.

In the opening session, welcome addresses by representatives of the NEA and IAEA were delivered first. The session was complemented by keynote presentations on the importance of the technical meetings' overall theme and a general introduction regarding the WGELEC. The chairpersons responsible for each session introduced the topic of the technical sessions.

There were two technical sessions for WGELEC activity 4 on 2 and 3 December 2019 and another two technical sessions for WGELEC activity 5 on 4 December 2019. After each thematic topic regarding activities 4 and 5, a panel discussion was organised to identify key deliverables from each thematic topic discussion. A technical session was also held on 4 December 2019 to discuss several common topics to both WGELEC activities 4 and 5.

Finally, through two separate discussions, conclusions of the technical meeting were summarised. The key takeaways identified for activities 4 and 5 are outlined below.

WGELEC activity 4 (management of direct current power systems):

- In general, current practices related to the design, qualification, installation, testing, inspection and replacement of station batteries are very similar and follow guidance established either in national or international standards.
- Most of the member countries prefer using vented lead-acid battery types.
- Corrosion is a phenomenon that cannot be avoided. New designs try to avoid or delay this phenomenon.
- Most of the battery-related events involve cracks due to different degradation mechanisms; e.g. corrosion, manufacturing defects and incorrect ambient conditions.
- Nuclear power plants adopt a conservative criterion to replace the batteries before the degradation symptoms or problems appear.
- It should be taken into account, as an important fact, that the heat generated during fast charging cycles can dramatically reduce the duration of lead-acid batteries. The same happens in lithium and nickel batteries, but to a lesser extent.
- The experience accumulated in vented lead-acid batteries shows that most of the detected problems are known. Continuous monitoring and visual inspection are the best ways to detect any early degradation earlier than the capacity test that is performed over longer time intervals (2-5 years).

WGELEC activity 5 (application of new power electronic and digital devices in safety electrical power systems):

- It is necessary to have a reasonable process to use pre-developed components/commercial off the shelf components;
- Qualification of digital equipment is difficult, therefore a qualification method, especially for software qualification, should be developed;
- However, rather than sharing qualification of devices, licensees could share results of techniques and measures assessments, which may be common across both approaches;
- In addition, international collaboration to work on an approach for software qualification would be helpful.

List of abbreviations and acronyms

AC	Alternating current
BWR	Boiling water reactor
CCF	Common cause failure
COTS	Commercial off the shelf products
CPLD	Complex progammable logic device
CSN	Nuclear Safety Council (Consejo de Seguridad Nuclear, Spain)
CSNI	Committee on the Safety of Nuclear Installations (NEA)
DC	Direct current
DIDELSYS	Defence in Depth of Electrical Systems and Grid Interaction
EDG	Emergency diesel generators
FMEA	Failure mode and effects analysis
HVAC	Heating, ventilation and air-conditioning
I&C	Information and communication
IAEA	International Atomic Energy Agency
IEC	International Electrotechnical Commission
IEEE	Institute of Electronic and Electrical Engineers
IRSN	Institut de Radioprotection et de Sûreté Nucléaire (French Institute for Radiological Protection and Nuclear Safety [ASNR since January 2025])
NEA	Nuclear Energy Agency
NRA	Nuclear Regulation Authority (Japan)
NRC	Nuclear Regulatory Commission (United States)
OECD	Organisation for Economic Co-operation and Development
ONR	Office for Nuclear Regulation (United Kingdom)
OPC	Open phase condition

PWR	Pressurised water reactor
ROBELSYS	Robustness of Electrical Systems of Nuclear Power Plants in Light of the Fukushima Daiichi Accident
SBO	Station blackout
SIL 4	Software integrity level 4
UDG	Ultimate diesel generators
UPS	Uninterruptible power supply
V&V	Verification and validation
VRLA	Valve-regulated lead-acid battery
WGELEC	Working Group on Electrical Power Systems (NEA)

1. Introduction

1.1. Background

Recent operating experience at nuclear power plants has identified two significant safety concerns related to electrical systems. One is associated with direct current (DC) safety power systems due to the accelerated ageing of batteries and the other with the use of new industrial devices and technology, including power electronic and smart devices (e.g. digital protection relays) in electrical power equipment for replacement, modernisation, obsolescence or new build on both AC and DC systems.

1.1.1. Direct current power systems

A DC system supplies DC loads without interruption through the use of batteries. DC power systems include batteries, rectifiers/chargers and inverters. Separate DC power systems are sometimes provided to support loads of different safety classes. An uninterruptible AC power system supplies power from inverters or motor generator sets that are in turn supplied from a DC power source, such as the DC power system or dedicated batteries with rectifiers. Such systems often include a bypass circuit to allow feeding safety loads directly from safety class AC power systems in maintenance and emergency situations.

The expected service life of a station battery is normally based on the manufacturer's information and the anticipated operating conditions of the plant. The frequency of battery tests is usually derived from the expected battery service life and an understanding of the anticipated degradation rate. An accelerated degradation could render the periodic testing ineffective to detect early degradation of a battery. Accelerated degradation of the batteries, if not managed properly, may lead to a scenario in which the DC safety power systems are unable to perform their intended safety functions. The accelerated ageing of the battery may affect redundant trains and has the potential to result in a common cause failure.

1.1.2. Application of new devices in electrical power systems

The active components of AC/DC power systems, such as rectifiers, inverters, bypass circuits, circuit breakers and electrical protective devices, often now contain industrial digital devices designed according to non-nuclear standards. In some cases, the presence of such digital devices may remain unknown to the plant operator. This is a concern because safety-classified equipment that contains a digital device requires more rigorous qualification. There should be evidence that the principal safety functions of the integrated industrial digital devices meet the requirements for the application, and that the device is free from faults that could credibly result in common cause failures where defence in depth should be preserved. These digital devices need to be free from online threats that could compromise their safety functions.

Therefore, the design of the complete safety power system needs to be evaluated, tested and inspected systematically and periodically to advance the system durability in the context of such safety concerns.

1.1.3. International co-operation

The IAEA and NEA have implemented a number of activities that have involved consideration of specific electricity-related issues at nuclear power plants across the world.

The IAEA revised a number of safety standards, including: IAEA Safety Standards Series No. SSR-2/1 Rev. 1, *Safety of Nuclear Power Plants: Design* (IAEA, 2016a); IAEA Safety Standards Series No.SSG-34, *Design of Electrical Power Systems for Nuclear Power Plants* (IAEA, 2016b), and developed several technical reports, including IAEA TECDOC-1770, *Design Provisions for Withstanding Station Blackout at Nuclear Power Plants* (IAEA, 2015), and Safety Reports Series No. 91, *Impact of Open Phase Conditions on Electrical Power Systems of Nuclear Power Plants* (IAEA, 2016c).

The NEA published several reports to resolve issues identified after the Forsmark 1 event and the Fukushima Daiichi accident such as "Defence in Depth of Electrical Systems and Grid Interaction" (NEA, 2009); "Status of OECD/NEA Country Regulatory Responses to the Forsmark-1 Event of 25 July 2006 and NEA/CSNI DiDELSYS Task Group Report Recommendations " (NEA, 2011); and "Robustness of Electrical Systems of Nuclear Power Plants in Light of the Fukushima Daiichi Accident (ROBELSYS)" (NEA, 2015). In 2016, the NEA Committee on Safety of Nuclear Installations (CSNI) established a permanent Working Group on Electrical Power Systems (WGELEC) as a follow up to the DIDELSYS[1] and ROBELSYS[2] activities. The WGELEC objectives are to improve international understanding of issues that can lead to a degraded power supply challenging the functionality of equipment that relies on electrical power systems, and sharing best practices and techniques to prevent, detect and mitigate such events. The IAEA participates in the WGELEC activities.

Since the WGELEC and the IAEA recognised that there could be benefits from promoting knowledge and nuclear safety in the areas of direct current power systems and the application of new devices in electrical power systems by widening the scope of participation, the joint NEA–IAEA technical meeting (hereinafter referred to as "the technical meeting") was organised on 2-5 December 2019 at the IAEA, in Vienna.

1.2. Objective

The purpose of this report is to summarise the discussions of current challenges related to the operation, maintenance and plant modifications of battery systems and the implementation of power electronics and smart (digital) devices in the electrical power systems of nuclear power plants, as covered during the technical meeting, and to identify the lessons learnt.

1. The Defence in Depth of Electrical Systems and Grid Interaction (DIDELSYS) Task Group was established in January 2008 based on the findings of an NEA-sponsored workshop on lessons learnt from the July 2006 Forsmark-1 event held in Stockholm, Sweden on 5-7 September 2007.

2. Robustness of Electrical Systems of Nuclear Power Plants in Light of the Fukushima Daiichi Accident (ROBELSYS) was a continuation of the DIDELSYS Task Group.

1.3. Scope

The main theme of the technical meeting was the safety demonstration of nuclear power plants addressing the following topical issues:

Safety of DC power systems

- identifying experience of significant events related to batteries and associated equipment such as chargers, inverters and diagnostic tools;
- gathering major current provisions for capacity and in-service testing in plant technical specifications, and other maintenance activities;
- identifying possible new approaches to establishing improved programmes for maintenance and monitoring of safety batteries and associated equipment;
- establishing common themes, lessons learnt, if any, and measures against early detection of degradation or failure of batteries.

New power electronic and digital devices in safety power systems

- identifying common safety issues and lessons that have been learnt from the plant electrical events and replacement programmes;
- measuring the impact of new equipment on existing system design;
- assessing regulatory expectations of the use of modern equipment;
- identifying safety benefits and plant efficiencies realised from the use of modern equipment;
- describing approaches taken to qualify and utilise such systems and new equipment;
- identifying whether additional guidance for each type of event would be beneficial to the international community.

These two topics appear linked since battery chargers and uninterruptible power supply systems are the types of equipment that have often been cited as causing difficulties for replacement. It is therefore anticipated that the same technical experts would be involved in both discussions.

1.4. Structure

This publication is comprised of three main sections and two appendices.

Chapter 1 lays out the background, objective, scope and structure of the document. Chapter 2 summarises the technical meeting on the main topics such as the management of direct current power systems and the application of new devices in safety electrical power systems. Chapter 3 provides conclusions and recommendations based on participating countries’ presentations.

The appendices to this publication include the technical meeting agenda. The PowerPoint presentations shown at the meeting can be made available by the NEA Secretariat upon on request.

2. Summary of the technical meeting

A total of 50 participants from 24 countries attended the technical meeting. The participants comprised professionals from regulatory bodies, nuclear power plant operators, utility organisations, design and engineering consultant organisations, as well as international organisations engaged in activities related to nuclear power plant safety and regulation.

Apart from the opening session, the technical meeting included 22 topical presentations organised in the three thematic areas according to WGELEC activity 4 on the management of direct current power systems, activity 5 on the application of new devices in safety electrical power systems and complemented by cross cutting topics related to both thematic areas. The discussions at this meeting focused on addressing comments submitted by subject matter experts. An important aim of the meeting was to ensure that the practices of the participating countries or standards developed by other international organisations are identified and assessed for appropriate application.

2.1. Opening session

The opening session started with welcome addresses by representatives of the NEA and the IAEA, followed by keynote presentations on the meeting's overall theme.

The topics of the technical sessions were introduced by each session chairperson.

Mr Pepper, the Chairman of WGELEC, introduced the WGELEC objectives and activities, as well as the WGELEC inputs to other international activities through members of the group. That includes the application of IAEA safety standards and development of related technical reports, as well as the development of IEC[3] standards on electrical power systems.

He noted that the WGELEC mission is to advance current understanding and to address safety issues related to electrical systems of nuclear installations, with the aim of making significant contributions towards three goals:

- enhancing the robustness of electrical systems;
- enhancing the analysis and simulation of electrical systems;
- addressing safety challenges from the use of power and software-based electronics in electrical systems.

He concluded his presentation by informing the participants of six activities launched by the WGELEC:

- early identification of electrical failure mechanisms that affect safety at nuclear facilities;
- identification of good practices for advancing electrical power system robustness in case of deviation from their normal operating conditions;
- comparison of methodologies for simulation of electrical systems;
- establishment of measures against accelerated degradation of batteries and failure of batteries that affect safety at nuclear facilities;
- new devices for electrical equipment replacement/retrofit and new build;

3. International Electrotechnical Commission, a standard development organisation.

- experiences with the solutions implemented to identify and manage open phase conditions (OPC).

Afterwards, Mr Martinez Sánchez, Mr Takita and Mr Kawanago, the technical session chairs of the technical meeting, introduced the WGELEC activities 4 and 5 to the participants in detail. They informed the participants of each activity's milestone, the questionnaires and pre-analysis results.

2.2. Management of direct current power systems (WGELEC activity 4)

An introductory session and overview presentation on WGELEC activity 4 was given by Mr Martinez Sánchez (Spain), followed by two sessions on the "management of direct current power systems (WGELEC activity 4)" on 2 and 3 December 2019.

2.2.1. WGELEC (activity 4)

Batteries are normally on stand-by in nuclear power plant electrical systems. In normal operations, the battery charger maintains the battery in a state of readiness. When an abnormal condition results in a failure of delivery of electrical power to all AC and DC loads, the associated battery is called upon to provide the necessary power, thereby ensuring continuity of operation. Batteries may only be needed during a short period of time to start the emergency diesel generators, or they may be called upon to supply power for an extended period of time in the event of a loss of all AC power sources, known as station blackout (SBO). For these reasons, batteries provide a significant defence in depth contribution to the electrical systems.

The events at the Fukushima Daiichi Nuclear Power Plant highlighted how batteries have a prominent role and, since then, several measures have been taken to enhance their capacity and capability to provide power.

At various meetings and activities of the WGELEC, batteries have been identified as a further discussion area because accelerated ageing occurs, multiple failure modes exist and there are different approaches to assess battery condition. It was decided to establish a special activity to improve the robustness of DC electrical systems by:

- identifying experience from significant events related to batteries and associated equipment, such as chargers;
- gathering major current provisions for capacity and in-service testing in plant technical specifications, and other maintenance activities;
- identifying possible new approaches to establishing improved programmes for the maintenance and monitoring of safety batteries and associated equipment;
- establishing common themes, lessons learnt, if any, and measures against early or accelerated degradation or failure of batteries;
- identifying whether additional guidance for each type of event would be beneficial to the international community.

Since battery life is determined by many factors such as temperature, operating charge status, duty cycle, etc. it is impossible to differentiate the minimum/maximum life expectancy in this regard. Periodic maintenance is therefore important.

Presentations of each session were as follows:

- (a) Session: Day 1: Session Chair: Mr D. Ndomba (Canada)

- Battery systems – An independent view of maintenance and monitoring requirements for the modern nuclear power plant (Mr C. Gilliard, United Kingdom).
- Increasing of power supply reliability of the first category DC/AC consumers at Kozloduy Nuclear Power Plant (Mr E. B. Krastev, Bulgaria).
- Accelerated degradation of batteries (Mr M. van Berlo, the Netherlands).
- Battery discharge testing under simulated SBO conditions (Mr J. Frelich, Czechia)

- (b) Session: Day 2 (Tuesday, 3 December 2019)
  - (b1) In the morning; Session Chair: Mr C. Martinez Sánchez (Spain)
    - Nuclear battery tests on extended operation and float current indication for state of charge (Mr T. Koshy, United States).
    - Battery back-up time extension in Korea and possible new approach: Li-ion battery (Mr S. Park, Korea).
    - Isolation of long direct current circuits for better performance of earth fault detector (Mr A. Kandelwal, India).
    - New design of DC power systems for VVER-1200 (Mr E. Akbulut, Türkiye).
    - Battery degradations in safety electrical power systems for nuclear power plants (Mr D. Ndomba, Canada).

  - (b2) In the afternoon; Session Chair: Mr K. S. Pepper (United Kingdom)
    - Experiences from Finnish nuclear power plants and the perspective of authorities (Mr S. Hankivuo, Finland).
    - Management of batteries in French nuclear power plants (Mr A. Dubois, France).
    - Current practice and events regarding batteries in German nuclear power plants (Mr R. Arians, Germany).

After each session a panel discussion was held with all the presenters of the day. Three basic questions of concern for the battery users were identified:

- What is the capacity and condition of the battery now?
- When should it be replaced?
- What can be done to improve/not reduce its useful life?

The following key aspects were noted from these two sessions:

- (a) In general, current practices related to design, qualification, installation, testing, inspections and replacement of station batteries are very similar and follow guidance established either in national or international standards. The common standards and practices for the maintenance of the batteries were identified to be IEEE 450, IEEE 1188, IEEE 1106.

- (b) Most of the countries prefer using vented lead-acid battery types.
- (c) The corrosion is a phenomenon that cannot be avoided. New designs try to avoid or delay this phenomenon.
- (d) Most of the battery-related events involve cracks due to different degradation mechanisms:
  - corrosion (a common failure mechanism of flooded lead-acid batteries is the corrosion of positive grids);
  - terminal leaks;
  - manufacturing defects;
  - incorrect ambient conditions.
- (e) The plants adopt conservative criteria to replace the batteries before the degradation symptoms or problems appear. As a rule, a voltage check must be carried out to know which batteries should be recharged. Furthermore, constant monitoring of the main parameters of the batteries should be undertaken to anticipate their degradation.
- (f) It should be taken into account, as an important fact, that the heat generated during fast-charging cycles can dramatically reduce the duration of lead-acid batteries. The same happens in lithium and nickel batteries, but to a lesser extent.
- (g) The experience accumulated in vented lead-acid batteries shows that most of the detected problems are known. Nickel cadmium (NiCd) batteries seem to be more robust than those of lead-acid. They are more expensive to buy, but their cost ownership is similar to that of lead-acid batteries, especially if the cost of maintenance is considered in the equation. In addition, the risks of catastrophic failures are considerably less than for valve-regulated lead-acid battery (VRLA).

- (h) The continuous monitoring and visual inspection are the best tools to detect any early degradation.
  - The service test is performed at every operating cycle;
  - The capacity test is performed in longer time intervals (2-5 years);
  - Capacity test (download test):
    - Upon installation (acceptance test).
    - In the first two years of service.
    - Periodically; test intervals should not be more than 25% of the expected useful life.
    - Annually when the batteries show signs of degradation or have reached 85% of the expected life.

  Degradation is indicated when the battery capacity drops more than 10% of its capacity in previous tests or is below 90% of what is established by the manufacturer. If the battery has reached 85% of its design life but presents the 100% of what is established by the manufacturer and has no signs of degradation, it can be tested at intervals of two years until it shows signs of degradation.

- (i) The inclusion of digital components in new battery chargers can cause problems. These include problems with failures in the programmable circuits that are included in the electronic cards complex programmable logic device (CPLD) of the new battery chargers.
  - The applications of digital equipment are necessary because of obsolescence of analogue equipment, but several elements such as schedule, cost, reliability and maintenance should be evaluated.
  - Considering digital instrument and control in accordance with the code of federal regulation (CFR) 50.59.
- (j) By using different types of batteries for different electrical divisions, too much complexity is introduced for the little safety benefit made.

2.3. Application of new devices in safety electrical power systems (WGELEC activity 5)

Following an overview presentation on 2 December, there were two sessions for "Application of new devices in safety electrical power systems" on 4 December 2019.

Presentations of each session were as follows:

- (a) Session Chair: Mr R. Arians (Germany)

  i. Regulatory expectations on the use of modern equipment in electrical power systems (Mr A. Kumar, India);

  ii. Experience with commercial off the shelf products (COTS) (Mr M. van Berlo, the Netherlands);

  iii. Application of digital protection relay in Belgian nuclear power plants (Mr R. Zeghers, Belgium);

  iv. The regulatory experience for software-based digital electrical devices (Mr K.-H. Lee, Korea);

  v. UK regulatory expectations for digital devices (Mr D. Smeatham, United Kingdom).

- (b) Session Chair: Mr S. Kawanago (Japan)

  vi. Countermeasure to extended battery discharge duration for severe accident without battery reinforcement (Mr H. Tanaka, Japan);

  vii. A "SMART" opportunity or not? (Mr K. Priddle, United Kingdom);

  viii. Precautions for the renewal of protection relays (Mr H. Jimbo, Japan).

The following key aspects were noted from the presentations in these two sessions:

- (i) Regulatory expectations on the use of modern equipment in electrical power systems:
  - Use of modern equipment with digital components is increasing, but there are some challenges, e.g. compatibility with older systems, qualification of equipment, new types of failure modes, susceptibility to common cause failures (because of software design errors), and cybersecurity issues.
  - Use of pre-developed hardware and/or software may not have been certified and therefore assessment procedures are needed.

  - In case of pre-developed devices used for safety critical applications, they shall contain only programme code that is necessary to implement the intended function and additional verification and validation should be carried out by a third party.
  - Verification and validation of pre-developed devices is challenging because source code and design documents are generally not available.
  - For preoperational tests, all possible transients and the worst combinations of input parameters should be considered.
  - A test methodology that can test and qualify a “black box” with acceptable reliability should be developed.

- (ii) Experience with commercial off the shelf products (COTS):
  - One-to-one replacement of components is difficult, and therefore, a qualification method for commercial off the shelf components shall be developed.
  - COTS with SIL-4 can be used, but additional nuclear qualification processes are still necessary.
  - Procurement of nuclear qualified equipment is difficult because the nuclear sector is small.
  - There are three experiences of using digital electrical equipment to replace old analogue equipment, including digital rectifiers.

- (iii) The application of a digital protection relay in Belgian nuclear power plants:
  - Due to obsolescence, a replacement of protection relays to digital ones was necessary.
  - IEC based programmes for software qualifications of these relays were developed.
  - Only required protection functions have been qualified (demonstration that not selected functions do not affect safety functions).
  - Cybersecurity was addressed by disabling communication protocols.
  - Software versions should be managed to avoid uncontrolled revising or updating.
  - It is essential to have full co-operation with manufacturers in order to succeed with the qualification.

- (iv) The regulatory experience for software-based digital electrical devices:
  - Use of digital electrical devices has increased.
  - Qualification for digital electrical devices is necessary, including software verification and validation for Class 1E equipment.
  - For systems performing safety functions or affecting safety functions, software integrity level 4 (SIL 4) should be applied.

  - Software verification and validation should be performed by an independent organisation.
  - Common cause failure (CCF) should be evaluated by failure mode and effects analysis (FMEA) and diverse means including manual actuations are required.

- (v) Regarding the United Kingdom's regulatory expectations for digital devices:
  - The potential of introducing systematic faults into software is high and these faults are hard to identify.
  - It must be proven that a component is able to perform its function according to its importance to nuclear safety.
  - There are two ways to ensure that a software code is qualified for its application: Ensure that no errors have been introduced and ensure that the code performs as expected through test and analysis.
  - There is increasing awareness that the security of computer-based systems is a significant issue.
  - International collaboration to work on an approach for software qualification together with licensees, requesting parties, regulators and manufacturers would be helpful.

- (vi) Countermeasure to extended battery discharge duration for severe accident without battery reinforcement:
  - A digital control panel is used in order to shed DC loads in case of an extended SBO.
  - Since the battery system is required by regulations to supply DC power for 24 hours during an extended SBO, this digital control panel is applied in order to avoid significant impact on plant designs and operations.
  - A verification and validation (V&V) process is not required because it is a non-safety system.

- (vii) A "SMART" opportunity or not?
  - As a result of the design of the Hinkley Point C Nuclear Power Plant safety system and application of digital information and communication systems (I&C), system designs become more complex.
  - The design of the Hinkley Point C Nuclear Power Plant includes additional safety features such as the addition of non-computerised safety system (I&C)., more diversity with two types of batteries, more redundancy (i.e. dual power supplies) , a dedicated and redundant heating, ventilation and air-conditioning (HVAC), bigger emergency diesel generators (EDG) and ultimate diesel generators (UDG) and increased battery capacity.
  - The applications of digital equipment are necessary because of obsolescence of analogue equipment, but several elements, such as schedule, cost, reliability or maintenance, should be evaluated.

- (viii) Precautions for the renewal of protection relays

- Electrical and instrumentation equipment are being replaced in Japanese pressurised water reactor (PWR) nuclear power plants.
- Two experiences with digital protection relay applications were introduced as lessons learnt and highlighted three aspects:
  - The importance of confirming the integrity of not only the individual equipment but the entire system.
  - The importance of re-evaluating all electrical transients.
  - The need to select the most appropriate protection method.

2.4. Cross cutting topics (WGELEC activities 4 and 5)

This session included five presentations that identified several common topics to WGELEC activities 4 and 5.

The session was chaired by Mr M. Persson (Sweden) and included the following presentations:

(a) Upgrading of the Armenian Nuclear Power Plant uninterruptible power supply system.

This presentation described modifications made and planned to improve the design, capacity and reliability of the AC and DC emergency power supply system that is implemented in the framework of the lifetime extension of the Armenian Nuclear Power Plant. This includes replacement of batteries, motor generator sets with new static rectifiers and inverters in two safety divisions of DC safety power systems, new cables and new connections to enable the use of non-permanent sources. The modernisation of the AC part includes procurement of the new mobile emergency diesel generators (EDG); 2 MW, 6 kV, 800 kW and 400 kW at 0.4 kV to enhance the plant design for coping with SBO.

(b) The incident in the DC power systems and inverter power supplies in Japanese boiling water reactors (BWR) and the solution for IN2017-06.

This presentation described the incidents in the DC power systems and inverter power supplies in Japanese BWRs. In addition, this presentation introduced a technical solution for limiting short-circuit current contributions to a fault on the direct current distribution system IN 2017-06 of Battery and Charger.

(c) The experience of modernisation emergency power supply system's first reliability group - direct current panels at nuclear power plants of Ukraine

This presentation described the modernisation phases of the DC emergency power supply system at Ukrainian nuclear power plants. Technical aspects and licensing-related issues associated with different modification phases were presented. This presentation also provided an overview of planned modifications of uninterruptible power supply systems (i.e. rectifiers and inverters, batteries) at Ukrainian nuclear power plants.

(d) Management of no-break electrical systems in nuclear power plants

This presentation discussed the management of "no-break" systems in the UK nuclear power plants. It focused on two main areas: i) the qualification and testing of VRLA and Plante (flooded cell) batteries, highlighting where applicable operational experience and degradation mechanisms; and ii) the replacement of conventional motor-alternator sets and analogue controlled uninterruptible power supply (UPS) units with modern digitally controlled rectifiers and inverters. The presentation highlighted operational experience and the technical challenges in the qualification process.

(e) Evolution of design requirements for electrical power systems

This presentation described how design requirements applicable to electrical power systems were enhanced in the IAEA safety standards to address design vulnerabilities identified through operating experience and lessons learnt from significant electrical events that occurred at nuclear power plants in the past 15 years. This presentation also provided an overview of the specific design requirements applied to electrical power systems for different plant states (i.e. operating states and accident conditions). The IAEA safety standards and related technical reports on the design of electrical power systems for nuclear power plants were introduced.

3. Conclusions and recommendations

3.1. Management of direct current power systems (WGELEC activity 4)

The group of international specialists produced the following recommendations:

- In general, current practices related to the design, qualification, installation, testing, inspection and replacement of station batteries are very similar and follow guidance established either in national or international standards.
- Most of the countries prefer using vented lead-acid battery types.
- Corrosion is a phenomenon that cannot be avoided. New designs try to avoid or delay this phenomenon.
- Most of the battery-related events involve cracks due to degradation mechanisms such as corrosion, manufacturing defects, and incorrect ambient conditions.
- The plants adopt a conservative criterion to replace the batteries before degradation symptoms or problems appear.
- It should be taken into account that the heat generated during fast charging cycles can dramatically reduce the duration of lead-acid batteries. The same happens in lithium and nickel batteries, but to a lesser extent.
- The experience accumulated in vented lead-acid batteries shows that most of the detected problems are known. Continuous monitoring with visual inspection is the best way to detect any degradation that may occur before capacity tests, which are performed in longer time intervals (2-5 years).

3.2. Application of new devices in electrical power systems (WGELEC activity 5)

Based on three sessions that included 13 presentations and 2 panel discussions with all participants, the following important aspects were identified:

Situation:

- It is necessary to recognise that the use of modern, digital equipment for electrical systems is increasing.
- Nuclear qualified equipment is often not available, which necessitates the use of pre-developed components/commercial off-the-shelf components.
- Obtaining the necessary information from suppliers to qualify smart devices is difficult.
- The nuclear sector is a relatively small purchaser in the marketplace, reducing leverage.
- Additional diversity of the systems can leads to over-complexity, which increases potential for operator error.

Recommendations:

- It is necessary to have a reasonable process to use pre-developed components/commercial off-the-shelf components.

- Qualification of digital equipment is difficult; therefore, a qualification method, especially for software qualification, should be developed.
- However, rather than sharing the qualification of devices, licensees could share the results of techniques and measurement assessments, which may be common across both approaches.
- International collaboration to work on an approach for software qualification would be helpful.

  For example:

  - Collaboration with IEC and IEEE.
  - Standardising safety categories.
  - Harmonising regulatory process by international regulations.
  - Having a database that shows several experiences or data of qualification results on digital application to reduce burdens of qualification efforts in the nuclear sector.
  - Having reasonable countermeasures against CCF based on risk assessment, or FMEA to avoid more complex designs, as electrical functions and safety functions of electrical equipment are relatively limited and simple.

References

IAEA (2016a), *Safety of Nuclear Power Plants: Design*, IAEA Safety Standards Series No. SSR-2/1 (Rev. 1), International Atomic Energy Agency, Vienna, www.iaea.org/publications/10885/safety-of-nuclear-power-plants-design.

IAEA (2016b), *Design of Electrical Power Systems for Nuclear Power Plants*, IAEA Safety Standards Series No. SSG-34, International Atomic Energy Agency, Vienna, www.iaea.org/publications/10688/design-of-electrical-power-systems-for-nuclear-power-plants.

IAEA (2016c), *Impact of Open Phase Conditions on Electrical Power Systems of Nuclear Power Plants,* Safety Report Series, No.91, International Atomic Energy Agency, Vienna, www.iaea.org/publications/11026/impact-of-open-phase-conditions-on-electrical-power-systems-of-nuclear-power-plants.

IAEA (2015), Design Provisions for Withstanding Station Blackout at Nuclear Power Plants, IAEA TECDOC Series No. 1770, International Atomic Energy Agency , Vienna, www.iaea.org/publications/10908/design-provisions-for-withstanding-station-blackout-at-nuclear-power-plants.

NEA (2009), "Defence in Depth of Electrical Systems and Grid Interaction", NEA/CSNI/R(2009)10, OECD Publishing, Paris, www.oecd-nea.org/NEA-CSNI-R-2009-10/.

NEA (2011), "Status of OECD/NEA Country Regulatory Responses to the Forsmark-1 Event of 25 July 2006 and NEA/CSNI DiDELSYS Task Group Report Recommendations", NEA/CNRA/R(2011)8, OECD Publishing, Paris, www.oecd-nea.org/NEA-CNRA-R-2011-8.

NEA (2015), "Robustness of Electrical Systems of Nuclear Power Plants in Light of the Fukushima Daiichi Accident (ROBELSYS)", NEA/CSNI/R(2015)4, OECD Publishing, Paris, www.oecd-nea.org/NEA-CSNI-R-2015-4.

Appendix I – Technical meeting agenda

Day 1 – Monday, 2 December 2019		
Time	**Item**	**Speaker**
08:00 – 09:30	Registration, badging. (IAEA visitor's entrance)	
	Opening, introductions of TM Participants	
Session Chair: Mr A. Duchac (IAEA)		
09:30 – 09:40	(1) NEA welcoming address	Mr N. Muroya, Deputy Director-General for Management and Planning (NEA)
09:40 – 09:50	IAEA welcoming address	Mr G.L. Rzentkowski, Director, NSNI (IAEA)
09:50 – 10:30	(2) Objectives and scope of the meeting, introduction of participants	Mr A. Duchac (IAEA)
10:30 – 11:00	(3) WGELEC overview	Mr K.S. Pepper, WGELEC Chairman (United Kingdom)
11:00 – 11:30	Break	
11:30 – 12:00	(4) WGELEC activity 4 overview (Management of direct current power systems)	Mr C. Martinez Sánchez (Spain)
12:00 – 12:30	(5) WGELEC activity 5 overview (Application of new devices in safety electrical power systems)	Mr M. Takita, Mr Kawanago (Japan)
12:30 – 14:00	Lunch break	
	Management of direct current power systems (WGELEC activity 4)	
	Session Chair: Mr D. Ndomba (Canada)	
14:00 – 15:00	(6) Battery systems – an independent view of maintenance and monitoring requirements for the modern nuclear power plant	Mr C. Gilliard (United Kingdom)
15:00 – 15:30	(7) Increasing of power supply reliability of the first category DC/AC consumers at Kozloduy nuclear power plant	Mr E.B. Krastev (Bulgaria)
15:30 – 16:00	Break	
16:00 – 16:30	(8) Accelerated degradation of batteries	Mr M. van Berlo (the Netherlands)
16:30 – 17:00	(9) Battery discharge testing under simulated SBO conditions	Mr J. Frelich (Czechia)
17:30	Hospitality event in the M building area	

Day 2 – Tuesday, 3 December 2019		
Time	**Item**	**Speaker**
	Management of direct current power systems (WGELEC activity 4)	
	Session Chair: Mr C. Martinez Sánchez (Spain)	
09:00 – 10:00	(10) Nuclear battery tests on extended operation and float current indication for state of charge	Mr T. Koshy (United States)
10:00 – 10:30	(11) Battery back-up time extension in Korea and possible new approach: Li-ion battery	Mr S. Park (Korea)
10:30 – 11:00	*Break*	
11:00 – 11:30	(12) Isolation of long direct current circuits for better performance of earth fault detector	Mr A. Kandelwal (India) (not attended)
11:30 – 12:00	(13) New design of DC power systems for VVER-1200	Mr E. Akbulut (Türkiye)
12:00 – 12:30	(14) Battery degradations in safety electrical power systems for nuclear power plants	Mr D. Ndomba (Canada)
12:30 – 14:00	Lunch break	
	Management of direct current power systems (WGELEC activity 4)	
	Session Chair: Mr K.S. Pepper (United Kingdom)	
14:00 – 14:30	(15) Experiences from Finnish nuclear power plant and the perspective of authorities	Mr S. Hankivuo (Finland)
14:30 – 15:00	(16) Management of batteries in French nuclear power plants	Mr A. Dubois (France)
15:00 – 15:30	(17) Current practice and events regarding batteries in German nuclear power plants	Mr R. Arians (Germany)
15:30 – 16:00	Break	
16:00 – 17:00	Panel Session – open discussion with all the presenters of the day	All
17:00	End of the second day	

Day3 – Wednesday, 4 December 2019		
Time	**Item**	**Speaker**
Application of new devices in safety electrical power systems (WGELEC activity 5)		
Session Chair: Mr R. Arians (Germany)		
09:00 – 09:30	(18) Regulatory expectations on the use of modern equipment in electrical power system	Mr A. Kumar (India)
09:30 – 10:00	(19) Experience with commercial off the shelf products (COTS)	Mr M. van Berlo (the Netherlands)
10:00 – 10:30	(20) Application of digital protection relay in Belgian nuclear power plants	Mr R. Zeghers (Belgium)
10:30 – 11:00	*Break*	
11:00 – 11:30	(21) The regulatory experience for software-based digital electrical devices	Mr K.-H. Lee (Korea)
11:00 – 12:00	(22) UK regulatory expectations for digital devices	Mr D. Smeatham (United Kingdom)
12:00 – 12:30	Spare	
12:30 – 14:00	Lunch break	
Application of new devices in safety electrical power systems (WGELEC activity 5)		
Session Chair: Mr S. Kawanago		
14:00 – 14:30	(23) Countermeasure to extended battery discharge duration for severe accident without batter reinforcement	Mr H. Tanaka (Japan)
14:30 – 15:00	(24) A "SMART" opportunity or not?	Mr K. Priddle (United Kingdom)
15:00 – 15:30	(25) Precautions for the renewal of protection relays	Mr H. Jimbo (Japan)
15:30 – 16:00	Break	
16:00 – 17:00	Panel Session – open discussion with all the presenters of the day	All
17:00	End of the third day	

Day 4 – Thursday, 5 December 2019		
Time	**Item**	**Speaker**
	Cross cutting topics (WGELEC activities 4 and 5)	
	Session Chair: Mr M. Persson (Sweden)	
09:00 – 09:30	(26) Upgrading of the Armenian nuclear power plant uninterruptible power supply system	Mr A. Ordubekyan (Armenia)
09:30 – 10:00	(27) The incident in the DC power systems and inverter power supplies in Japanese BWRs and the solution for IN2017-06	Mr M. Sugiyama (Japan)
10:00 – 10:30	(28) The experience of modernisation emergence power supply system first reliability group - Direct Current Panels at nuclear power plants of Ukraine	Mr S. Talko (Ukraine)
10:30 – 11:00	*Break*	
11:00 – 11:30	(29) Management of no-break electrical systems in nuclear power plants	Mr M. Kearns (United Kingdom)
11:30 – 12:00	(30) Evolution of design requirements for electrical power systems	Mr A. Duchac (IAEA)
12:00 – 14:00	Lunch break	
	Technical discussion on activity 4	
	Session Chair: Mr C. Martinez Sánchez (activity 4 chair, Spain)	
14:00 – 15:00	Focused discussion to identify key areas of concerns or lessons to be learnt and recommendation for the future activities	
15:00 – 15:30	Break	
	Technical discussion on activity 5	
	Session Chair: Mr M. Takita and Mr S. Kawanago (activity 5 chairs, Japan)	
15:30 – 16:30	Focused discussion to identify key areas of concerns or lessons to be learnt and recommendation for the future activities	
16:30 – 17:00	Closing remarks	

Appendix II – Technical meeting presentations

Technical meeting presentations are provided upon request. Please contact the NEA Secretariat by emailing the contact person indicated on the website of WGELEC: www.oecd-nea.org/jcms/pl_25383.