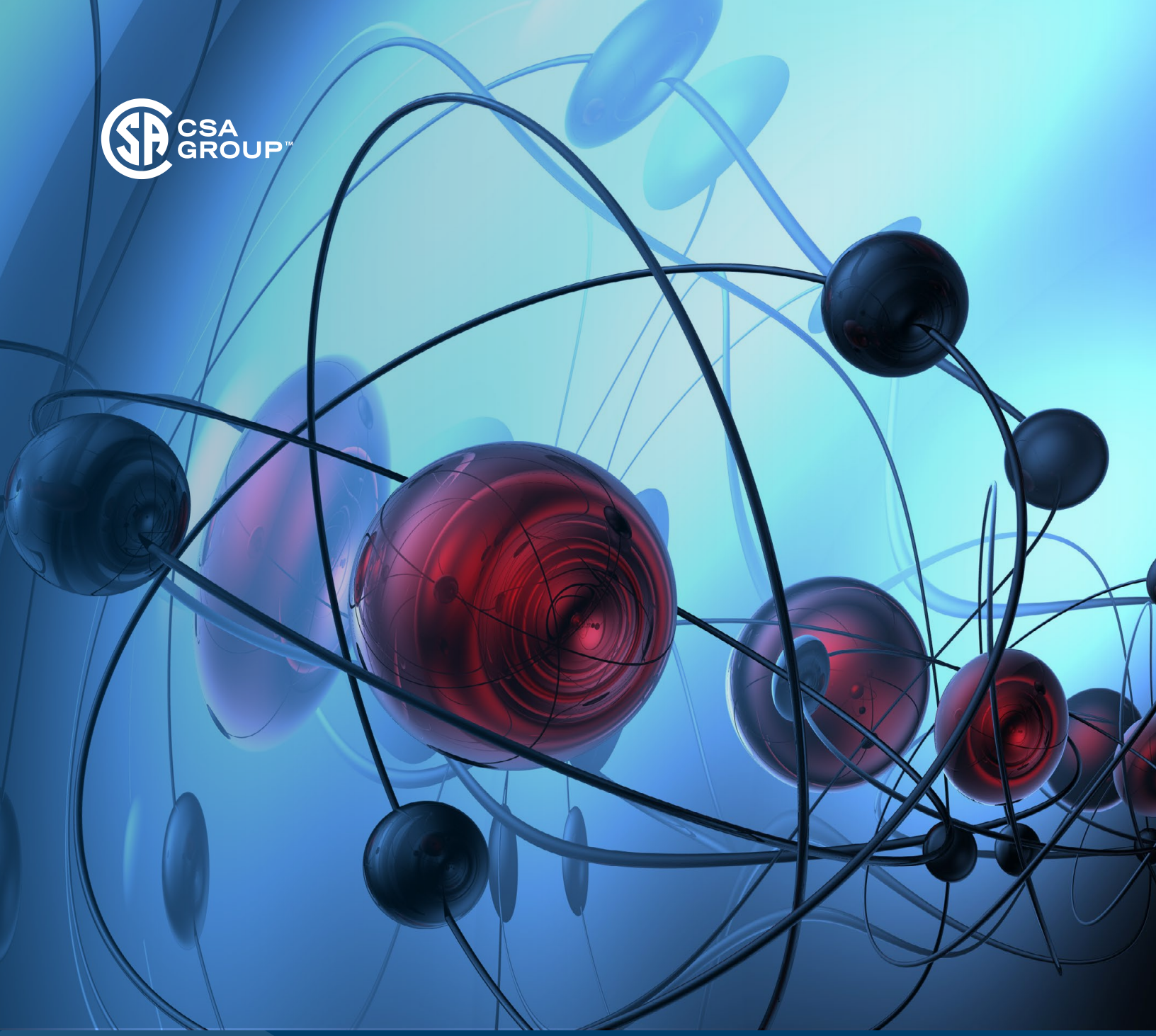


STANDARDS RESEARCH

The Role of Standards in Facilitating Deployment of SMRs in Canada

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Executive Summary

As Canada's energy demand continues to increase, experts are looking for solutions to reduce carbon emissions and provide Canadians with clean and reliable electricity. A technology that is poised to meet these needs is the development of small modular reactors (SMRs), an emerging class of nuclear reactors with a smaller capacity and more flexibility than conventional large nuclear power plants (NPPs). The SMRs' promise of economical, greenhouse-gas free power allows for their potential deployment in a wide range of industries and for a variety of process applications, beyond merely power production. Over 50 SMR vendors are currently working to commercialize their designs worldwide, with a wide range of technologies from small integral pressurized water reactors (an evolution of existing nuclear power plant technology) to novel Generation IV and advanced reactors.

The objective of this report is to provide high-level recommendations on standardization approaches that would benefit the Canadian nuclear sector in the deployment of SMRs. To accomplish this, a review was conducted on potential standardization approaches, the current SMR landscape in Canada, and the use of standardization to support the deployment of new technologies through two case studies. The results of these reviews were then assessed to provide recommendations based on the best practices and lessons learned from the case studies and analysis of standardization and harmonization activities within the nuclear sector. Where applicable, specific opportunities for collaboration on current SMR standardization and harmonization activities are noted.

SMR technologies can be divided into two groups based on their technological heritage and the availability of operating experience from other jurisdictions: light water reactors, and Generation IV and advanced reactors.

Light water reactors use light water as a coolant, and generally include pressurized water reactors (including integral pressurized water reactors) as well as boiling water reactors. The SMR designs that are classified as light water reactors are based on existing reactor technologies that are well established globally. Due to the presence of multiple existing international regulatory frameworks associated with these types of reactors, it is recommended that Canada engage with other jurisdictions to assess, update, and reference existing standards to fill identified gaps in addressing light water reactor requirements. Adopting international standards or developing new regional or international standards to address gaps would also increase harmonization of standards between jurisdictions.

Generation IV and advanced reactor designs have fewer experimental, demonstration, and commercial reactors that can be leveraged for operating experience. Consequently, existing standards are less equipped to accommodate the more novel aspects of these reactor technologies. For Generation IV and advanced reactors, it is recommended that Canada develop new national standards that reference existing standards, or collaborate with other jurisdictions to develop harmonized regional and international standards where needed, based on progress of ongoing technology demonstration and commercialization efforts.

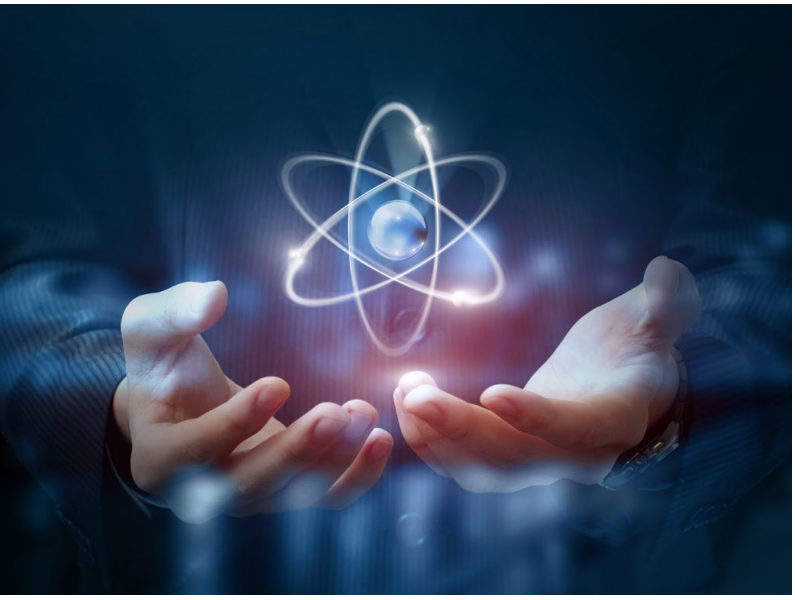
As the development and initial regulatory review of SMRs are in progress, the development of standards in parallel with these processes can be beneficial to support and facilitate SMR deployment. In cases where SMR designs are being considered in multiple markets (for example the US and Canada), standard development organizations (SDOs) should consider collaborations where regional or international standards could be developed. These standards could help to improve commonalities in the regulatory review processes based on the demonstration of common design goals, thereby enabling multiple jurisdictions to leverage best practices and lessons learned from early operations.

Acronyms

The following acronyms are used throughout this report:

ABWRWG	Advanced Boiling Water Reactor Working Group
AECL	Atomic Energy of Canada Limited
ANSI	American National Standards Institute
ARIS	Advanced Reactors Information System
ASEAN	Association of Southwest Asian Nations
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing Materials
BWR	Boiling water reactor
CANDU	CANadian Deuterium Uranium
CANENA	Council for Harmonization of Electrotechnical Standardization of the Nations in the Americas
CEN	European Committee for Electrotechnical Standardization
CENELEC	European Committee for Electrotechnical Standardization (French: Comité Européen de Normalisation Électrotechnique)
CGSB	Canadian General Standards Board
CNL	Canadian Nuclear Laboratories
CNRA	Committee on Nuclear Regulatory Activities (CNRA)
CNSC	Canadian Nuclear Safety Commission
COG	CANDU Owners Group
CORDEL	Cooperation in Reactor Design Evaluation and Licensing
CSA	Canadian Standards Association
CSWG	Codes and Standards Working Group
DICWG	Digital Instrumentation and Controls Working Group
EBR-II	Experimental Breeder Reactor II
ELSMOR	European Licensing of Small Modular Reactors
EPRI	Electric Power Research Institute
ETSI	European Telecommunications Standards Institute
EU	European Union
EV	Electric vehicle
HTGR	High- temperature gas-cooled reactor
IAEA	International Atomic Energy Agency
ICAO	International Civil Aviation Organization
ICE	Internal combustion engine
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IMSR	Integral Molten Salt Reactor
ISO	International Organization for Standardization
MDEP	Multinational Design Evaluation Programme

MoA	Memorandum of agreement
MoOC	Memorandum of Ccooperation
NEA	Nuclear Energy Agency
NEI	Nuclear Energy Institute
NERC	North American Electric Reliability Corporation
NPP	Nuclear power plant
NPM	NuScale Power Module
NRC	Nuclear Regulatory Commission (US)
NRCan	Natural Resources Canada
OECD	Organisation for Economic Co-operation and Development
ONR	Office for Nuclear Regulation (UK)
PASC	Pacific Standards Congress
PHWR	Pressurized heavy water reactors
PWR	Pressurized water reactor
RHWG	Reactor Harmonization Working Group
SAE	Society of Automotive Engineers
SARPs	Standards and recommended practices
SCC	Standards Council Canada
SDO	Standard Development Organization
SMR	Small module reactor
SSR-W	Stable Salt Reactor-Wasteburner
UAS	Unmanned aircraft system
VDR	Vendor design review
VICWG	MDEP Vendor Inspection Cooperation Working Group
WENRA	Western European Nuclear Regulators' Association
WPGBWR	Working Party on Boiling Water Reactors
WGCS	Working Group on Codes and Standards
WGRNR	Working Group on the Regulation of New Reactors
WGWD	Working Group on Waste and Decommissioning
WNA	World Nuclear Association
ZEEP	Zero Energy Experiment Pile



"While traditional nuclear power plants (NPPs) are widely used for power generation around the world, innovation within the nuclear industry has led to a new wave of reactor design known as small modular reactors (SMRs)."

1 Introduction

Nuclear power generation is a key component of Canada's electricity grid and represents up to 15% of Canada's total electricity generation, 36% of New Brunswick's generation, and 57% of Ontario's generation [1], [2]. Nuclear power is a form of power generation that uses nuclear reactions to release energy in the form of heat. This heat can be used for a variety of applications, including electricity generation, district heating, hydrogen production, and desalination. While traditional nuclear power plants (NPPs) are widely used for power generation around the world, innovation within the nuclear industry has led to a new wave of reactor design known as small modular reactors (SMRs). SMRs are smaller in size than traditional NPPs with electric outputs typically below 300 MWe[1] [3], [4]. Key benefits of SMRs include [5]:

- Modular components that allow for large portions of the reactor to be manufactured in a factory and transported to a construction site;
- Enhanced safety features making use of passive safety;
- Lower capital investment requirements due to the use of modular manufacturing and construction methods;
- Increased flexibility in addressing non-utility power markets due to their smaller electric outputs; and
- The ability to replace greenhouse gas emitting power sources such as diesel generators, in remote industrial developments and off-grid communities.

Currently all power-generating nuclear reactors in Canada are pressurized heavy water reactors of CANDU®[2] (CANada Deuterium Uranium) design. As such, the Canadian regulatory framework and standards were initially developed to support pressurized heavy water reactors. The potential deployment of SMRs in Canada brings not only new international designs, challenges, and risks but also opportunities to the Canadian nuclear sector.

The purpose of this report is to provide high-level recommendations on standardization approaches that would benefit the Canadian nuclear sector in the deployment of SMRs in Canada. The report consists of the following five sections:

1. Introduction to standards and the Canadian nuclear sector;
2. Overview of standardization approaches;
3. Analysis of the standardization approaches used in the aerospace and electric vehicle industries and a summary of best practices and lessons learned;
4. Overview of the Canadian SMR landscape, existing standardization and harmonization activities within the SMR industry, and recommendations for standardization and harmonization;
5. Summary and conclusions.

1 CNSC REGDOC-3.6 [6] defines small reactors as: "A reactor with a power level less than approximately 200 megawatts thermal."

2 CANDU® is a registered trademark of Atomic Energy of Canada Ltd. used under exclusive license by Candu Energy Inc., a member of the SNC Lavalin Group.

The SMR landscape is changing rapidly both nationally and internationally. The information provided within this report is current as of December 23, 2020.

2 Study Methodology

The insight provided within this document was developed based on literature reviews and environmental scans of available published information regarding the nuclear sector in Canada, small modular reactors (SMRs), and standardization approaches (including general approaches and those used in the aerospace and electric vehicle industries). Resources included regulatory and standards development organizations (SDOs) websites, SMR vendor websites, international nuclear organization websites, published papers, and books. Additionally, interviews were conducted with 16 stakeholders from SDOs, experts from the aerospace and electric vehicle industries, nuclear utilities, regulators, nuclear industry organizations, and SMR vendors. These interviews were used to validate the findings from the literature reviews and environmental scans.

3 Introduction to Standards & the Canadian Nuclear Sector

3.1 Standards

Standards are used throughout the world as a means of applying best practices, requirements, and recommendations [7]. The Standards Council of Canada (SCC) defines a standard as "a document that provides a set of agreed-upon rules, guidelines or characteristics for activities or their results. Standards establish accepted practices, technical requirements, and terminologies for diverse fields" [8]. Standards help ensure alignment of design, quality, safety, performance, and processes within an industry or region and can be used as a foundation for establishing public confidence. Standards can either be mandatory, when invoked by a regulator, or voluntary, when used as a best practice within industry [9]. For the purpose of this report, the definition of a standard is inclusive of codes (e.g., the Canadian Electrical Code), which are broad in scope and intended to carry the force of law when adopted [9], [10].

The development of and adherence to standards can bring many benefits for consumers, regulators, and the economy [11]. Some of these benefits include:

- The establishment of safety requirements to enhance consumer confidence that a product or service meets the required level of safety;
- Fostering innovation by providing a framework for the safe and consistent application of evolving technologies;
- Providing economic advantages by establishing minimum requirements and best practices that allow companies to optimize their products and designs in early stages;
- Allowing for the acceptance of a product within a larger market by removing trade barriers through standards harmonization (as defined in Section 4.1); and
- Supporting regulations by outlining methodologies to comply with regulations.

There are different types of standards, such as those developed by industry associations, government agencies, or by standards development organizations (SDOs), following an accredited process. SCC is the national standards accreditation body in Canada. In Canada, SCC-accredited SDOs develop standards using a process that involves approval by a balanced committee of experts, public notification and consultation, and periodic review and maintenance. The accredited standards development process might vary in other countries and by industry. For instance, the Canadian automotive and aerospace industries are regulated by bodies such as Transport Canada, which can develop standards for Canada following a different process than that used by the SCC. In this report, even through the examples or principles lean towards the SCC approach, they are meant to be sufficiently generic to apply to other types of standards.

3.2 Nuclear Sector in Canada

3.2.1 History of CANDU Technology

The nuclear industry in Canada was launched in 1942 when research towards the design of a heavy-water nuclear reactor was moved from Cavendish Laboratory

in England to Canada [12], [13]. As the technology developed, it was decided that Canada would benefit from gaining operating experience through a small experimental reactor [14]. In 1945, after 11 months of construction, the Zero Energy Experiment Pile (ZEEP) reactor began operation, making it the first reactor to operate outside of the United States [14]. After the success of the ZEEP experimental reactor, Canada decided it would continue to focus its research and development on heavy-water reactors due to its experience working with these types of reactors and the ability to use Canadian uranium as reactor fuel without needing to enrich it in foreign facilities [12].

In 1952, Atomic Energy of Canada Limited (AECL) was established as a federal Crown corporation, and the ownership of Chalk River Laboratories (located in Deep River, Ontario), a Canadian nuclear research facility, was transferred to AECL. The AECL board recommended General Electric be selected to design and construct a demonstration nuclear electric power plant with Ontario Hydro participation [15].

In 1955, the first prototype CANDU (CANadian Deuterium Uranium) reactor, the Nuclear Power Demonstration, was built in Rolphton, Ontario, near AECL's Chalk River Laboratories [12], [13]. This pressurized heavy water reactor (PHWR) began operation in 1962 and produced 20 MWe [12]. The success of this demonstration reactor led to larger CANDU reactors being built both nationally and internationally: nationally, reactors were built at what is now the Bruce Nuclear Power Development site, the Pickering Nuclear Generating Station, and the Darlington Nuclear Generating Station in Ontario, Canada, and internationally in India and Pakistan [12]. In the 1980s a new CANDU design, the CANDU-6, which produced 600 MWe, was proposed and reactors were built nationally in Quebec and New Brunswick, and internationally in Argentina, South Korea, Romania, and China [12].

There are currently 19 operating nuclear power reactors in Canada:

- Six CANDU reactors at Pickering Nuclear Generating Station in Ontario, Canada;
- Eight CANDU reactors at Bruce Nuclear Generating Station in Ontario, Canada;
- Four CANDU reactors at Darlington Nuclear Generating Station in Ontario, Canada; and
- One CANDU 6 at Point Lepreau Nuclear Generating Station in New Brunswick, Canada.

It is expected that nuclear power from these reactors will continue to provide Canada with a net capacity of 13.5 gigawatts until they begin decommissioning.

3.2.2 Canadian Nuclear Regulatory Framework

Canada's nuclear regulator is the Canadian Nuclear Safety Commission (CNSC). The CNSC was established in 2000 through the *Nuclear Safety and Control Act* (NSCA) to replace the previous nuclear regulator, the Atomic Energy Control Board, and to update the focus of regulation from the security of atomic secrets to the current mandate of the CNSC, which is "to protect the health and safety of Canadians, as well as our environment" [16], [17].

Canada's nuclear regulatory framework is composed of four distinct components [18]:

- Acts
- Regulations
- Licences and certificates
- Regulatory documents

Acts are laws passed by Parliament that govern the regulation of Canada's nuclear industry, such as the NSCA. Regulations support acts and commonly outline what is meant by certain terms used in an act, procedure and process, or standard that must be met [18]. Regulations are not made by Parliament but rather by an authority that has been delegated by Parliament, which in the nuclear sector is the CNSC. Licences and certificates outline mandatory requirements that a licensee must meet to use nuclear substances or operate a nuclear facility, as determined by the delegated authority. Regulatory documents support licences and certificates by explaining to licensees and applicants what they must achieve to meet the requirements for licensing or certificates under the NSCA and corresponding regulations. Regulatory documents can include requirements, which must be met to obtain a license or certificate to use nuclear

substances or operate a nuclear facility, and guidance which provides direction on how to meet regulatory requirements [18]. The CNSC uses a combination of internal and external guidance as a part of licensing [18]. Internal forms of guidance can include any other documents and applicable reports, CNSC publications, staff review procedures, and CNSC inspection procedures. External forms of guidance can include information on best practices and on domestic and international standards [18].

One of the significant differences between the CNSC and other nations' nuclear regulators is its use of licences [19]. The CNSC is one of the only nuclear regulators that uses a licence-based approach to regulate the entire life cycle of a nuclear power plant [19]. While other regulators do grant licences, they are typically more limited in scope and pertain to a limited set of activities [19]. The CNSC's approach to regulation is achieved through multiple licensing phases (site preparation, construction, operation, and decommissioning), which must all be considered prior to building the plant [19]. The CNSC nuclear regulatory framework is comprehensive and, in large part, technology neutral, using performance- and prescriptive-based regulations that encourage innovation while ensuring safety requirements are appropriately met [19], [20].

3.2.3 Nuclear Standards Development

Standards for the nuclear sector in Canada emerged in the 1970s, following the start of construction of commercial nuclear power plant reactors in the 1960s. These standards reflected topics on design, construction, and operation of structures, systems, and components to establish minimum requirements and best practices guidance. Over the next decades, the suite of nuclear standards was maintained and expanded to address topics that included fire protection, seismic design, environmental radiation protection, and radioactive waste management [21]. By 2013, the scope of facilities addressed by the standards had also expanded to include management systems, decommissioning, and fire protection requirements for various nuclear facilities, including mines and mills, research and isotope processing facilities, and radioactive waste management facilities [21].

Currently, most Canadian nuclear standards are developed by CSA Group, and cover 12 main topics [21]:

- Emergency Management for Nuclear Facilities
- CANDU Nuclear Power Plant Pressure-Retaining Systems and Components
- Periodic Inspection of Nuclear Power Plant Components
- Management Systems for Nuclear Facilities
- Concrete Containment and Safety-Related Structures for Nuclear Power Plants
- Environmental Management for Nuclear Facilities
- Seismic Design for Nuclear Power Plants
- Reactor Control Systems, Safety Systems, and Instrumentation for Nuclear Power Plants
- Reactor Safety and Risk Management
- Radioactive Waste Management
- Fire Protection
- Decommissioning of Nuclear Facilities

These standards are developed by consensus, via multi-stakeholder groups, including regulators, utilities, vendors, and academics, and are referenced in the national regulatory framework, in regulatory documents, licences, and compliance handbooks for nuclear facilities across Canada.

Around 2008, the possibility of licence applications for non-CANDU designs being submitted in Canada raised the need for standards to incorporate more technology-neutral requirements. As a result, the Canadian nuclear standards were updated using an approach, where applicable, to capture CANDU-specific requirements, benchmark other international standards, and distinguish CANDU-specific requirements in meeting overall safety goals. While many of these standards are specific to Canada, they reference and benchmark other national and international standards, including those published by the International Atomic Energy Agency (IAEA), the American Society of Mechanical Engineers (ASME), and the Institute of Electrical and Electronics Engineers (IEEE) [21].

4 Standardization Approaches

4.1 Introduction to Harmonization

Harmonization of standards is the process of minimizing conflicting and repetitive requirements between standards in multiple jurisdictions [22]. Harmonized standards are intended to capture common or fundamental requirements among national, regional, and international bodies [22]. An international standard inherently encourages harmonization by documenting a globally accepted set of requirements. Similarly, regional or national standards encourage harmonization either between the regional bodies utilizing the standard or within a nation (such as provinces and territories in Canada). National standards can also be benchmarked to existing international or regional standards to ensure that they do not act as a barrier to trade [8]. Standards may also reference other standards to incorporate existing provisions referenced either in full or in part, as mandatory requirements or informative guides. Harmonization allows lessons learned within an industry or technology to be shared through the evolution or update of a standard [11].

4.2 Review of Standardization Approaches

4.2.1 International Standards

International standards are developed through the consensus of experts from many countries and are approved and published by a globally recognized body or international standard development organization [23]. Examples of globally recognized bodies that develop standards include organizations such as the International Organization for Standardization (ISO) or the International Electrotechnical Commission (IEC).

International standards usually address either generalized high-level requirements applicable to multiple countries or topic areas that are treated in a similar manner between jurisdictions. Requirements in an international standard can include fundamental principles that leave flexibility in how the requirements are met to allow the standard to be more widely accepted. In advance of formal international standards development activities, working groups are established at the international level to investigate both the need for and the potential form of international standardization efforts. These groups can subsequently support international standard development efforts. The process for development of an international standard involves a technical committee comprised of representatives from many of the participating national bodies or jurisdictions. A country's participation in the development of an international standard ensures that unique national characteristics and specific national requirements are considered during the development of an international standard.

An example of a well-known international standard is ISO 9001, *Quality Management Systems – Requirements* [24]. This standard, which is implemented at the organizational level [33], has seen widespread international adoption and is used as the basis for quality management systems in many industries. An example of an international standard that has been jointly published by two international SDOs, as well as adopted into Canada (discussed in Section 4.2.4), is CAN/CSA-ISO/IEC 15026-2:13, *Systems and Software Engineering – Systems and Software Assurance – Part 2: Assurance Case.* The joint publication of a standard is typically reserved for topics that overlap between two or more standard development organizations as in this example, which provides minimum requirements for the structure and contents of an assurance case for systems and software engineering [25].

There are also organizations that develop standards using individual technical expert members rather than countries like the ISO and IEC. This includes the American Society for Testing Materials (ASTM), IEEE, and ASME. Standards produced by these organizations can be used as a basis when developing national standards or referenced in national standards rather than being adopted (refer to Section 2.2.4).

4.2.2 Regional Standards

Regional standards (also referred to as binational, trinational, or multinational standards) are standards developed for multiple nations. Regional standards generally provide harmonization of requirements



"Harmonized standards are intended to capture common or fundamental requirements among national, regional, and international bodies. Harmonization allows lessons learned within an industry or technology to be shared through the evolution or update of a standard."

within a regional group and for a topic area under consideration. These standards can be developed through a single SDO or can be jointly developed and published by more than one SDO. Regional standardization is well suited to nations or jurisdictions that have similar regulatory approaches, where products or services are being developed or implemented jointly, where there is alignment on a particular topic or technology, where trade agreements or other regional agreements are in place, or where geographical proximity leads to a joint need.

Regional standards tend to be established between countries with similar levels of economic, social, political, and technical development. However, they may also be established between developed and developing countries in an effort to help the latter establish or enhance their standards development and conformity assessment infrastructures [26]. Stakeholders from each of the participating national bodies or jurisdictions generally support the development of regional standards. This includes the establishment of a regional membership/grouping, which then typically leads to the development of a regional standards framework. Benchmarking to pre-existing standards within the group membership is also generally considered.

When defining the scope of regional standards, potential areas of conflict between nations or bodies due to differences in legislative or regulatory requirements should be assessed. In such cases, regional standards may be developed at a high level and may be complemented by national standards that provide specific guidance on divergent aspects. Alternatively, the regional standard development efforts may focus on those areas unaffected by differences between the nations or bodies, which may include technical topics.

The European Union (EU) has achieved strong regional standardization and harmonization through the establishment of three regional SDOs that develop standards for the member states: the European Telecommunications Standards Institute (ETSI), the European Committee for Electrotechnical Standardization (CENELEC), and the European Committee for Standardization (CEN) [27]. While ETSI and CENELEC have specific technical focus areas, CEN addresses a broad range of standardization topics. EU regional standards must be adopted as national standards and any previously existing conflicting national standards must be removed [28]. This “forced” adoption of regional standards supports the removal of barriers to trade and helps to promote consistent public safety, performance, and environmental treatment within the boundaries of the region. It is worth noting that EU regional standards are often adopted from international standards (see Sections 4.2.1 and 4.2.4).

Both CENELEC and CEN, in addition to closely working with each other, have established co-operative agreements with their respective international counterparts: the IEC and ISO [87], [88]. The

relationship between CEN and ISO is quite novel and is governed by the Vienna Agreement. This agreement is intended to ensure the communication of standardization efforts between the organizations to avoid duplicating work at the regional or international level by allowing for ISO standards to be adopted by CEN and vice versa [87], [88]. It is noted that ISO international standardization takes precedence over CEN national standards, with the intent that more national standards and technical regulations will be harmonized with international requirements [87]. However, the agreement does allow for the CEN to develop its own regional standards rather than adopt international standards when [87] no international standards exist or are recognized, and when standardization is urgently required in Europe but is not prioritized at the international level.

An example of regional standardization in North America is the North American Electric Reliability Corporation (NERC). With representation from the United States, Canada, and Mexico, the NERC establishes standards related to bulk power systems on the electricity grid using the ANSI-accredited process [29]. This supports trade among these jurisdictions through a standardized regional supply chain. In Canada the NERC is not accredited by the SCC, however, memorandums of understanding between the NERC and British Columbia, Alberta, Saskatchewan, Manitoba, Ontario, Quebec, and New Brunswick have been established that recognize the NERC as a standard-setting organization at the provincial level [80]. As a result, most Canadian provinces have adopted or modified NERC standards through the appropriate provincial organizations, such as the Ontario Energy Board and the Independent Electricity System Operator in Ontario [81].

Another example of regional standardization in the Americas is the Council for Harmonization of Electrotechnical Standards of the Nations in the Americas (CANENA). CANENA acts as a facilitator for electrotechnical harmonization across the Americas [82]. Standards are harmonized but issued by each participating nation's national SDO. To identify electrotechnical standards that require harmonization, CANENA contacts industry stakeholders from the involved countries [83]. Although international standards are generally preferred (see Section 4.2.1), many standards are not compatible with the North American distribution infrastructure and therefore require regional adjustments to be compatible [83]. It is thought that regional electrotechnical standardization within North America could influence international standards within the same scope [83]. There are also similar standardization groups that lobby for regional standards in Asia, such as the Pacific Standards Congress (PASC) and the Association of Southwest Asian Nations (ASEAN).

4.2.3 National Standards

National standards are developed for use in a specific nation. They can be developed by creating a new standard or by adopting an international standard (refer to Section 4.2.4). The preferred approach may depend on a number of factors, including the existence of relevant standards for potential adoption and the applicability of the standard(s) to the local landscape [31]. National standards may build on international practices or reference existing international requirements, but they may also provide specific requirements and guidelines in the context of a nation's needs and local requirements, including technology, regulatory requirements, and industry best practices.

The stakeholders included in the development process are selected based on the impact the standard will have on them and on their expertise. Where applicable, national standards incorporate input from impacted stakeholders across the nation to ensure that harmonization within the nation is achieved. This helps to ensure the standard is compatible with the local resources and supply chain and encourages local production and investment. Specific requirements relating to the local environment can also be integrated within the standard framework, such as the public outlook, climate, and geographical considerations.

An example of a national standard is CSA N285.0/CSA N285.6, *General Requirements for Pressure-Retaining Systems and Components in CANDU Nuclear Power Plants/Material Standards for Reactor Components for CANDU Nuclear Power Plants,* which references ASME

codes and standards [32]. The requirements in this standard consider provincial and federal regulations, practices developed in the design and construction of CANDU nuclear power plants, and the proven and widely adopted rules of the ASME *Boiler and Pressure Vessel Code, Section III, Rules for Construction of Nuclear Facility Components Set,* Division 1 (ASME BPVC, Section III, Division 1).

Another example of a national standard is CSA C22.1, *Canadian Electrical Code.* This standard supports the overall regulation of installation and maintenance of electrical equipment and is developed with the participation of provinces and territories. It is nationally adopted by regulators across Canada, and therefore ensures harmonization within Canada.

Finally, CAN/CGSB-44.227-2017, *Free-Standing Office Desk/Table, Storage Products and Components* is an example of a national standard that was developed by the Canadian General Standards Board (CGSB). The standard provides requirements that are aligned with the generally accepted international ergonomics guidelines or standards. The standard references these existing national and international standards to incorporate relevant requirements and best practices.

4.2.4 Adoption of International Standards

The development of national standards can include the adoption of existing international standards, where appropriate international standards exist. The adoption process involves the establishment of a mirror committee of the international committee by a national SDO. A mirror committee is a technical committee composed of subject matter experts from that nation that facilitate the country's participation in international standardization efforts by reviewing and ensuring that the international requirements are applicable to their local country [34]. The mirror committee formally reviews the subject standard after it is published, evaluates whether it can be adopted, and drives the adoption through an accredited development process. Unique national requirements that are identified by the mirror committee can be developed and included as part of a regional annex of the international standard or be published separately by the nation as deviations or national differences.

An example of a standard that has been adopted by Canada is ISO 14001:2015, *Environmental Management System,* which helps businesses manage and minimize their environmental impact by providing practical tools to support responsible usage of resources and reduction of industrial production impacts. Canadians were among the experts who provided technical expertise during the development of this standard. This standard was adopted (without any deviation) and published by CSA Group as CAN/CSA-ISO 14001-16, *Environmental Management Systems – Requirements for Guidance for Use* [24].

4.3 Key Considerations for Selection of Standardization Approaches

Several key considerations related to the selection of a standardization approach for a particular scenario or standard need are described below.

4.3.1 International Standards

The application of international standards inherently results in harmonization among many nations. The development of international standards can also support discussions between the member countries, leading to further collaboration in the application and harmonization of standards.

If an industry is globally established, and involves global trade or potential global trade, international standards may be beneficial for some topic areas. This allows for a larger market base and reduces trade barriers within the industry on a global scale, while allowing products or services to flow internationally.

Potential drawbacks to international standards development can include limited considerations for unique national variations. It may also be more difficult to reach consensus in the international setting due to broader national perspectives and priorities [30]. This can result in international standards addressing general high-level requirements (to allow for flexibility in meeting the requirements), necessitating other standards or approaches to address unique national considerations, or provide guidance on how to meet these requirements.

4.3.2 Regional Standards

Similar to international standards, regional standards promote a harmonization of requirements between the participating national bodies or jurisdictions. This can lead to more efficient technology adoption in each of the jurisdictions and support future incorporation of lessons learned and best practices from each of the participating nations or bodies. Additionally, regional standards can leverage a broad range of experts across regions, international best practices and lessons learned, and encourage an efficient supply chain structure between the participating national bodies or jurisdictions. However, by focusing on regional needs, regional standards could be misaligned with other regional standards, or with broader, more internationally accepted standards [30], which could limit the overall degree of harmonization achieved and potentially result in barriers to trade. Additionally, depending on the size of the region or jurisdiction, and the number of participants, overall coordination and establishing consensus is likely to be more challenging than in the case of national standards.

4.3.3 National Standards

National standards allow for unique national considerations to be addressed and for requirements to be tailored to national needs. A corresponding drawback is that these requirements may not be aligned with international approaches, which could result in barriers to trade. Where possible, national standards should be benchmarked to existing standards to ensure alignment with international standards and practices, and to minimize conflict and avoid barriers to trade. The Standards Council of Canada requires that SDOs "shall ensure that standards developed do not create unnecessary obstacles to international and/or interprovincial trade" [36]. Additionally, national standards can decrease harmonization for end-products, which could result in potential increases to capital and operating costs for those using the standard.

In comparison to regional and international standards development approaches, national standards can provide benefits in terms of the greater level of control over the content of the standard. Also, the development and approvals process for these standards normally involve participants from one nation and may be faster than those involving multi-jurisdictional participants. While this may be advantageous in certain situations, it can also create barriers for future harmonization. To mitigate this risk while maintaining the benefits of a national standard development approach, new national standards can be benchmarked against existing international, regional, or other national standardization efforts.

4.3.4 Adoption of International Standards

The adoption of an existing international standards promotes the international harmonization of requirements and the removal of trade barriers. However, the development of extensive deviations to address specific national requirements may counteract international efforts to establish a single standard that encompasses a global approach.

5 Case Studies

To assess standardization approaches that could be applied to the nuclear industry, two case studies were explored involving the aerospace industry and the electric vehicle industry. These case studies were chosen due to their similarities to SMRs within the nuclear industry. For both industries, the relevant background information and an overview of standardization approaches are presented. To conclude this section, a summary of the best practices and lessons learned that may be relevant to the SMR industry are included.

5.1 Aerospace Industry

5.1.1 Background

The aerospace industry is comprised of five sectors [37]:

1. Military aircraft
2. Missiles
3. Space
4. Commercial airliners
5. General aviation

General aviation covers the operation, manufacturing, development, and design of aircraft that are used for flight activities including personal / private travel, air tourism, recreational flying, air sports, business aviation / travel, corporate aviation, and fractional ownership operations [38]. Due to the high level of risk associated with general aviation, this established sector is highly regulated with both standards and regulations. Other sectors within the aerospace industry, such as commercial airliners and military aircraft, have many common or similar standards with general aviation that allow for this sector to reasonably represent the aerospace industry. Therefore, the primary focus of this case study is on standardization approaches for general aviation.

The nuclear industry is often compared to the general aviation sector because both industries operate under highly regulated conditions and are held to a high degree of safety and reliability, which highlights the importance of standardization [39]. Additionally, aircrafts often cross international borders, while nuclear safety is paramount for countries sharing borders due to security, safeguards, and the impacts of potential radiological accidents, which creates demand for regional or even international safety standards [39].

The aerospace industry has been largely evolutionary in nature and has taken an approach of developing and updating standards to address technological advancements after they have been implemented in industry [37], [40], [41]. As a result, most general aviation standards have been developed within the last 100 years, including the events that established the foundation for the standardization approach used today.

The first international air law code meeting within the aerospace industry occurred in 1910 and is known as the International Air Navigation Conference, Paris 1910 [42], [43]. Up to this point, international flight was largely unregulated and free hot-air balloons launched from one European state would occasionally drift over another state's borders due to inconsistent wind patterns. Over a period of seven months, at least ten free hot-air balloons carrying German military officers crossed into France without permits, which alerted France to the fact that the aviation sector could directly affect national defence and international commerce and therefore should be regulated [42]. Internal discussions led to the French government organizing the conference and inviting 18 European states[3] that were geographically close enough to impact each other in terms of flight space [42], [43]. With the goal of regionally standardizing an air law code, the European states met and drafted a convention consisting of 55 articles and three annexes [44]. While being close to establishing the first regional standards for aviation, political differences between three states caused the conference to end early [42], [44]. No formal aviation regulations were produced; however, three accepted understandings were reached [42]:

- States have full sovereignty in flight-space over their national lands and waters as part of their territory;
- Any division of territorial flight-spaces into zones is impractical and unnecessary; and
- No general right of international transit or commerce exists for aircraft of other states through territorial flight-space.

Unfortunately, plans to reconvene and finalize the aviation regulations discussed at the conference were not realized due to the outbreak of the First World War.

The next major international regulation landmark in the aviation sector occurred after the First World War at the Paris Peace Conference of 1919. By this time aircraft engines had advanced to the point where aircraft from the United States could reach Europe and thus more countries were included in developing international aerial navigation regulations and the corresponding technical standards. This conference was more successful than the 1910 conference and resulted in the creation of a convention consisting of 42 articles and eight technical annexes covering all technical, operational, and organizational aspects of aviation [45]. The convention was immediately signed by 27 of 38 attending states [45]. It was also at this conference that a new aeronautical commission, the International Commission for Air Navigation (ICAN), was established, based on the First World War's Inter-Allied Aviation Committee made up of France, Great Britain, Italy, and the United States. The ICAN

3 The 18 European states at this conference were Austria-Hungary, Belgium, Bulgaria, Denmark, France, Germany, Great Britain, Italy, Luxembourg, Monaco, Netherlands, Portugal, Romania, Russia, Spain, Sweden, Switzerland, and Turkey.

was given the responsibility of coordinating aircraft fabrication and standardizing airplanes, motors, and other materials [43], [44], [45]. Much of the standardization work completed by ICAN is still in effect today, contained within the technical annexes of the Chicago Convention of 1944 [45].

The final important historical international standardization event was the Convention on International Civil Aviation, also known as the Chicago Convention of 1944. This convention looked to further establish international civil aviation regulations, codes, and standards by having more countries accept its contents and place regulations on peaceful global air navigation [46]. This convention was an even bigger success than the previous with 52 out of 54 international states signing the new convention and the formal establishment of the International Civil Aviation Organization (ICAO) [46]. The ICAO, which continues to operate today, was established to help organize and support the intensive international cooperation required to achieve the highest possible degree of homogeneity in civil aviation regulations, standards, procedures, and organizations [46].

Standards developed by the ICAO appear in the annexes of the Chicago Convention of 1944 as Standards and Recommended Practices (SARPs) [47]. These standards require two-thirds of the council's support before being categorized into one of 19 annexes such as Annex 2, Rules of the Air, or Annex 8, Airworthiness of Aircraft [47]. While it is completely voluntary to accept and follow these international standards, the Chicago Convention has continued to be adopted by countries and is considered universally accepted today [39].

5.1.2 Standardization Approaches

5.1.2.1 International

Within the aerospace industry, many standards are accepted internationally. As discussed in Section 4.1.1, a strong framework for international civil aviation standards was established in 1919 and then strengthened in 1944 through the Convention on International Civil Aviation (also known as the Chicago Convention of 1944) and the establishment of the ICAO. While no technical SARPs were developed at the convention, the ICAO has since released technical guidance materials, and updates as needed, to support the original document [48]. It is expected that signed nations will incorporate the minimum safety SARPs into their national framework through regulations; however, ICAO SARPs do not replace national regulations but rather aid in harmonization while national codes outline the details required for aircraft certification, which helps to ensure that safety requirements are met [39], [48].

In addition to the ICAO SARPs, other widely accepted standards exist within the aerospace industry. An important example of this is the 9100 series standard. This standard is an adaptation of ISO 9001: *Quality Management Systems – Requirements* that is implemented at the organization level to better meet the needs of the aerospace industry [49]. By taking an internationally accepted standard and tailoring it to better fit the aerospace industry's needs through the addition of 83 requirements, the 9100 series standard has seen rapid adoption and success around the globe [49]. Developed by the International Aerospace Quality Group (IAQG), the 9100 series standard is universally adopted and harmonized but has different naming designations on different continents [50] – [54]:

- AS9100D, *Quality Management Systems – Requirements for Aviation, Space, and Defence Organizations,* for the Americas;
- EN 9100:2018, *Quality Management Systems – Requirements for Aviation, Space, and Defence Organizations,* for Europe, the Middle East, Russia, and Africa; and
- JIS Q 9100:2016, *Quality Management Systems – Requirements for Aviation, Space, and Defence Organizations,* for Asia and Oceania.

This standard series is designed to standardize and improve aerospace quality expectations on a global level while also reducing costs [50]. AS/EN/JIS Q 9100 is an internationally developed standard that is implemented at the organization level and organizations that use the standard are subject to annual audits by IAQG to ensure compliance. This standard applies to all organizations that design, develop, or provide products within the aerospace industry including parts, materials, and assemblies [55].



"By taking an internationally accepted standard and tailoring it to better fit the aerospace industry's needs through the addition of 83 requirements, the 9100 series standard has seen rapid adoption and success around the globe."

In addition to international quality standards, international technical standards exist that were developed outside of the ICAO. An example of this is DO-178: *Software Considerations in Airborne Systems and Equipment Certification* [56]. Unlike AS/EN/ JIS Q 9100, which is implemented at the organization level, this standard is applied at the national level. Initially developed in the United States, this standard has been accepted by the Federal Aviation Administration (FAA), Transport Canada, and the European Union Aviation Safety Agency (EASA) [56].

5.1.2.2 Regional

Within Europe, a third standardization level exists between the national and international level. Regional standardization first arose through the European Civil Aviation Conference (ECAC), an intergovernmental organization established by the ICAO and the Council of Europe to promote harmonized aviation policies and the continued development of a safe, efficient, and sustainable European air transport system. In 1990 the national regulatory members of ECAC signed the Cyprus Arrangement, which advocates for the following [39], [57]:

- Common national rules and certification procedures;
- The joint certification of products across their countries; and
- The requirement of regular inspections to ensure the appropriate rules and procedures are properly implemented and followed.

To aid in the establishment of common national rules and certification procedures, the Joint Aviation Authorities (JAA) worked towards the goal of certifying aircrafts across Europe and creating more aligned national standards between Europe and the United States by having Joint Aviation Requirements (JARs) be incorporated into the national regulations of JAA countries [39].

A level of regional collaboration within a heavily regulated industry like aerospace is rare but has benefits, including requiring fewer equivalent certification processes, sharing best practices and lessons learned, and increasing equivalent safety in countries with less developed aerospace sectors.

5.1.2.3 National

In addition to widely accepted international standards and regional standards, the general aviation sector contains national regulations that take effect within a nation's borders. Nations have full sovereignty in flight-space over their national lands and waters as part of their territory, so these regulations apply to both domestic and international aircraft [42], [58]. National regulation of international air transport is often composed of two components [58]:

1. An organizational body tied to the government that operates as the state's air transport authorities; and
2. Legal components in the form of national laws, rules and regulations, judicial and administrative decisions, licenses or permits, declared policies, and relevant international agreements.

As defined by the ICAO, airworthiness is the measure of an aircraft's suitability for safe flight. The corresponding airworthiness standards are the minimum detailed design and safety measures that must be met for the aircraft to be considered safe [59]. As with other SARPs within the general aviation sector, the ICAO has developed Doc 9760, A*irworthiness Manual,* which outlines basic national airworthiness requirements and rules [59]. Using this document, each nation has the responsibility to develop its own comprehensive airworthiness regulations and rules that adhere to Doc 9760 with room for small deviations where specified [59]. Each national airworthiness document must be approved by the ICAO before it can be enforced at the national level [48]. Even though airworthiness is determined on a national basis, the differences between national requirements is typically small due to the ICAO governing airworthiness and member countries having voting power over airworthiness decisions [39]. This standardizes the design requirements for aircraft across many different nations [39].

A unique component within the ICAO national airworthiness requirements and rules is the requirement of the state in which an aircraft is registered to ensure the aircraft complies with the airworthiness standards over the entire life cycle of the aircraft [59]. Before an aircraft can fly, either nationally or internationally, it must complete a detailed certification process. This certification occurs at the national level and once completed allows for that aircraft to operate in all ICAO member countries without needing certification in each country.

Occasionally, adjustments have been made to national airworthiness standards, although these often impact other countries and are therefore implemented at the international level. An example of this is Swissair 111, in which a plane travelling through Canadian airspace caught fire and was destroyed [60]. Canadian investigations into this tragedy found that the existing national aircraft certification standards for material flammability were inadequate and needed to be revised [60]. As a result, the Transportation Safety Board of Canada assembled 14 safety recommendations during investigation and nine recommendations through analysis that included revisions to existing airworthiness standards and regulations [60]. To help ensure that a similar event would not occur in the future, these recommendations were shared with the ICAO and, where applicable, were incorporated into existing national standards and regulations around the world [60].

5.1.2.4 New Technologies

An example of new technology in the aerospace industry is the development of unmanned aircraft systems (UAS), also known as drones. Proposed applications for this technology are extensive, ranging from recreational drone flying to passenger-carrying "flying taxis" [61]. As a result, standardization of UAS is paramount in ensuring the safety of persons, aircrafts, property on the ground, and national security [61].

The ICAO has noted that UAS will be regulated using the proven regulatory framework used for the general aviation sector with the addition of special standards to account for their unmanned nature [62]. Therefore, Canada's national regulator for UAS is Transport Canada, which will incorporate ICAO's UAS SARPs into the national framework.

Over the last ten years, both Canada and the rest of the world have seen rapid development within the UAS industry [63]. This has led to new UAS products being released on a regular basis with unique commercial applications in mining, forestry, scientific research, law enforcement, and beyond [63]. Industry experts have noted that, although it is difficult to predict the future of UAS technology, the sector would benefit from standard and regulation development [63]. The Canadian House of Commons Standing Committee on Transport, Infrastructure, and Communities (TRAN), which has investigated existing Canadian UAS regulations, believes that rules should be flexible to encourage technological innovation and industry growth in Canada [63]. To achieve this objective, 24 high-level UAS recommendations were developed by the TRAN Committee to adapt existing standards and regulations, and to influence future standards and regulations for UAS [63].

Similar to Transport Canada's regulation of UAS in Canada, the Federal Aviation Administration (FAA) has taken the lead on regulating UAS development in the

United States. Through ANSI, the Unmanned Aircraft Systems Standardization Collaborative (UASSC) was established with the goal of accelerating the development of standards and conformity assessment programs for UAS in the United States [61]. The UASSC has published two versions of a standardization roadmap that includes an extensive summary table of gaps and recommendations. Some, but not all, of the identified gaps have been closed through the release of new standards. For example, existing avionics and subsystem standards for UAS were found to be unacceptable due to issues related to the weight of airborne equipment and traffic congestion; this gap led to the development of more appropriate standards by the Society of Automotive Engineers (SAE) and ASTM[4].

At the international level, SDOs have begun forming committees to develop standards for UAS. One of these is ISO/TC 20/SC 16, which deals with general standardization of UAS design, manufacturing, operation, maintenance, and safety management [64]. At the time of writing this report, the committee is composed of 21 participating members, including Canada (SCC), the United States (ANSI), and the United Kingdom (BSI), along with eight observing members [64]. So far, the committee has developed four ISO standards, several of which have been identified to address gaps present in the United States standards, and another 20 standards are currently under development [61], [64].

5.2 Electric Vehicle Industry

5.2.1 Background

Initially developed in the 1890s, electric vehicles (EVs) have regained popularity in the 21st century due to their ability to reduce greenhouse gas emissions and fossil fuel dependence [65] – [69]. By replacing a conventional internal combustion engine (ICE) with an electric motor, electric vehicles receive power from electricity stored in batteries. Within the electric vehicle industry, three primary domains that require design, safety, manufacturing, and installation regulation have been identified [66], [70]:

1. Electric vehicles;
2. Electric vehicle infrastructure; and
3. Support services like education and training.

The electric vehicles themselves can be further broken down into four classifications [71]: battery electric vehicle (BEV), plug-in hybrid electric vehicle (PHEV), hybrid electric vehicle (HEV), and fuel-cell electric vehicles (FCEV). BEVs operate using a battery and electric drive train without an IICE; PHEVs and HEVs operate using batteries and gasoline; and FCEVs use a hydrogen fuel cell to convert hydrogen and oxygen into electricity [74]. As most EVs are equipped with batteries rather than gasoline tanks, charging infrastructure is required to "fuel" the vehicle. In addition to standards for EV design and safety, an array of standards for charging infrastructure are needed. Standardized electric charging stations are required to increase EV uptake through harmonized communication protocols, system protection, physical requirements, and more [68]. BEVs and their corresponding charging infrastructure are the focus of this case study due to their ability to disrupt the ICE industry.

The regulatory framework for the EV industry varies from country to country. Overall, there are two main models for regulating EV technologies:

1. Self-declaration against regulations; and
2. Detailed technology review and certification against regulations.

Self-declaration against regulations, the approach used by Canada and the United States for onboard vehicle components, involves technology developers self-assessing against the required regulations [72]. Minimal regulatory steps initially exist through this method. Although manufacturers and suppliers perform required testing, if an issue occurs then the technology developer is held liable and can face strict consequences [72]. Detailed technology review and certification against regulations, used by Canada and

4 These standards include: SAE AS8024-19, *JAUS Autonomous Capabilities Service Set;* SAE AS6983, *Process Standard for Qualification of Aeronautical Systems Implementing AI: Development Standard;* and ASTM F3298-19, *Standard Specification for Design, Construction, and Verification of Lightweight Unmanned Aircraft Systems (UAS).* SAE AS6983 has not been published and is still a work-in-progress.

the United States for offboard EV charging stations and components, applies to new technologies, which need to be approved and licensed before entering the market to help ensure compliance with regulatory requirements.

In Canada, there are several regulators involved with electric vehicles, including:

- Transport Canada, which is responsible for the regulation of manufacturing and importing of motor vehicles and motor vehicle equipment;
- Environment Canada, which is responsible for emissions regulations through the Canadian Environmental Protection Act (EPA);
- United Nations Economic Commission for Europe (UNECE), in which Canada participates, is a world forum for the creation of global technical regulations and develops harmonized requirements for electric vehicles.

More information on the standardization approaches these regulators use can be found in Section 5.2.2.3.

5.2.2 Standardization Approaches

5.2.2.1 International

The EV sector recognizes the need for more international regulatory collaboration and alignment on standards [70]. From a standardization perspective, electric vehicles are unique as they are a mixed technology composed of components from road vehicles and electric devices [73].

At the international level, three SDOs develop the main standards within the electric vehicle industry: IEC, ISO, and SAE International [74]. IEC and ISO have entered a Memorandum of Understanding (MoU) to establish jurisdiction over the electric vehicle industry [73], [74]. ISO focuses on standards development related to the electric vehicle as a whole and IEC focuses on electrical components and electric supply infrastructure [74]. Some topics remain within both organizations' jurisdictions and are addressed by an IEC/ISO Steering Group [28]. SAE International is a global association that has been a major contributor towards standard development for EVs with a focus on standards for the vehicle themselves. SAE International has also led a number of initiatives for EV charging infrastructure and has published standards across a range of topics, including charging communications, conductive and inductive charging, and charging safety guidelines.

ISO and IEC take a similar approach in developing international standards. In this process the ISO and IEC standards are often, but not always, developed through technical committees and are not based off other standards. In 1992 several national committees felt that requirements for EV charging infrastructure were not appropriately addressed by existing IEC standards [28]. To address this gap, the European Committee for Electrical Standardization (CENELEC) created a task force that developed a new regional standard to update the standard [28]. As a result of the development of this improved standard, IEC incorporated the CENELEC task force into IEC TC69 *Electrical Power/ Energy Transfer Systems for Electrically Propelled Road Vehicles and Industrial Trucks* [28]. Through this IEC task force, this new standard, IEC 61851, *Electric Vehicle Conductive Charging System,* was published to address the identified gap and improve upon an existing IEC standard [28]. This process of standards being passed between the international and regional SDOs has occurred several times in the EV field and is discussed more within Section 5.2.2.2.

SAE International's approach to developing international standards also involves identifying a need for a new technical standard and assembling a technical committee [75]. SAE International has three different types of standards, referred to as technical reports, relevant to the electric vehicle industry [75]:

- SAE Standards, which document broadly accepted engineering practices or specifications;
- SAE Recommended Practices, which document practices, procedures and technology for guides to standard engineering practice; and
- SAE Information Reports, which compile engineering reference data or educational material.

Table 1: Equivalent harmonized electric vehicle charging infrastructure standards across Canada, the U.S., and Mexico [68] [76]–[79], [209].

Standard Name	Canadian Standard	U.S. Standard	Mexican Standard
Flexible Cords and Cables	CSA C22.2 No. 49	ANSI/UL 62	NMX-J-436-ANCE
Electric Vehicle Supply Equipment	CAN/CSA C22.2 No. 280	ANSI/UL 2594	NMX-J-677-ANCE
Standard for Safety for Personnel Protection Systems for Electric Vehicle (EV) Supply Circuits: General Requirements	CAN/CSA C22.2 No. 281.1	ANSI/UL 2231-1	NMX-J-668/1-ANCE
Standard for Safety for Personnel Protection Systems for Electric Vehicle (EV) Supply Circuits: Particular Requirements for Protection Devices for use in Charging Systems	CAN/CSA C22.2 No. 281.2	ANSI/UL 2231-2	NMX-J-668/2-ANCE
Plugs, Receptacles, and Couplers for Electric Vehicles	CAN/CSA C22.2 No. 282	ANSI/UL 2251	NMX-J-678-ANCE

5.2.2.2 Regional

Within the electric vehicle industry, regional standards have been developed for the charging infrastructure. The EV charging infrastructure must comply with regional grid requirements, which can be a barrier to entry into the market. For example, across the globe, at least five different standards exist for charging connectors, which makes it difficult for EV and EV infrastructure manufacturers to serve multiple markets.

Currently, charging infrastructure standards are typically harmonized on a regional scale. In North America, five different infrastructure standards have been harmonized at the trinational level through CANENA in Canada, the United States, and Mexico [68]. Table 1 outlines the equivalent standards by each country [50].

Another example of regional standardization within the EV industry can be seen in Europe through CENELEC and CEN. As discussed in Section 4.2.2, these regional SDOs publish standards that must be adopted as national standards across Europe. Since 2010, both CENELEC and CEN have been developing standards related to EV charging under a standardization mandate from the European Commission [84] such as EN 50620:2017, *Electric Cables – Charging Cables for Electric Vehicles,* from CENELEC and EN 17186:2019, *Identification of Vehicles and Infrastructures Compatibility – Graphical Expression for Consumer Information on EV Power Supply,* from CEN [85], [86].

Europe has also established co-operative agreements between regional and international SDOs through the Vienna Agreement, as mentioned in Section 4.2.2, and within the electric vehicle field there are many joint standards between CEN and ISO, including EN ISO 15118-1:2019, *Road Vehicles – Vehicle to Grid Communication Interface – Part 1: General Information and Use-Case Definition* [89].

The EU has also tackled the regional harmonization of electric vehicle regulations, although these efforts have affected countries outside of the EU [90]. Through the United Nations (UN) World Forum for Harmonization of Vehicle Regulations (WP.29), harmonized requirements and test procedures for vehicle approval and components are outlined and adopted by participating countries [91]. Canada and the United States do not adopt UN regulations and therefore do not use harmonized codes or import UN vehicles. To accommodate countries that do not use UN regulations and in an attempt to increase regulatory harmonization, WP.29 developed a set of UN Global Technical Regulations that implement a performance-based approach to regulations [91]. These technical regulations have been accepted within Canada and the United States, although due to their legal stature are able to be adapted or modified for regional variations [91], [92].

5.2.2.3 National

The Canadian regulatory framework for electric vehicles is composed of three levels:

1. Acts, such as the *Motor Vehicle Safety Act (1993, c. 16);*
2. Regulations, such as the *Motor Vehicle Safety Regulations (C.R.C., c. 1038);* and
3. Standards, such as the *Canadian Motor Vehicle Safety Standards* (CMVSS).
4. As discussed in Section 5.2.1, Transport Canada is Canada's regulator for the manufacturing and importing of motor vehicles and motor vehicle equipment. Regulations written by Transport Canada must be pursuant to the corresponding acts contained within Canadian legislation. The regulations reference standards, known as the Canadian Motor Vehicle Safety Standards (CMVSS), which prescribe minimum performance levels for vehicles and equipment [93]. The CMVSS are published by Transport Canada and include standards developed by SDOs, including CSA Group, ANSI, and SAE International.

In 2018, the United States Department of Transportation investigated the current state of harmonization between the CMVSS and the American equivalent: Federal Motor Vehicle Safety Standards (FMVSS). It was found that many of these standards are harmonized [94].

Outside of the CMVSS, the Canadian Electrical Code has been expanded to address the unique requirements for electric vehicles and two IEC EV battery standards have been adopted in Canada [95], [96]. Some lessons learned from developing electrical safety standards to help introduce electric vehicles into Canada have been identified as follows [96]:

- The scope of responsibility for relevant parties should be clearly defined. For example, original equipment manufacturers are responsible for everything on or in the vehicle, while charging infrastructure and other off-board equipment is regulated and managed by national safety standards and codes;
- North America has unique regional requirements and can benefit from the development of harmonized standards; and
- Canadian experts should participate in both national and international standard development committees.

5.2.2.4 New Technologies

When developing standards for a new technology, existing standards from similar technologies should be assessed to determine whether they can be directly applied or adopted. In the case of electric vehicles, existing standards from ICE vehicles and general electric standards provide the basis from which tailored EV standards can be developed. Through the completion of an analysis on the applicability of existing Canadian standards in the EV sector, CSA Group has determined that three different approaches have been used to develop standards to address this new technology, public safety, and environmental protection [97]:

1. Referencing existing standards that are already in place and found to be adequate;
2. Adapting existing standards to account for either the unique aspects of EVs or regional requirements; and
3. Developing new standards for areas where technological change or systems impacts need to be standardized.

To successfully develop electric vehicle standards that promote harmonization, sector stakeholders will need to determine where international standards can be used, or where regional standards are needed to account for infrastructure differences [97]. As an example, there are currently many national standards for batteries, but it has been noted that the development of advanced battery technologies would be aided by developing consistent standards at the international level to lower production costs and make electric vehicles more affordable [97].

In addition to developing standards to meet the current needs, sector stakeholders must consider the future evolutions of new industries. For example, CSA C22.2 No 348, *Vehicle to Grid Charging Equipment,* is being developed, and will address bidirectional power transfer from vehicles to the grid, which will allow parked electric vehicles to act as a form of energy storage [98].

5.3 Best Practices and Lessons Learned from Case Studies

The standardization approaches discussed within the aerospace and electric vehicle industries provide a valuable opportunity to highlight best practices and lessons learned that can be considered when evaluating standardization approaches for the nuclear industry.

5.3.1 International

A key strength from the aerospace regulatory system is the strong international safety framework that operates in conjunction with national standards, such that they do not interfere or undermine one another. This helps to promote harmonization while still allowing for nations to be accountable for regional requirements. As discussed in Section 5.1.2.1, ICAO regulations and SARPs create the foundation from which each country's national framework is established but do not replace national regulations or the need for a national regulator [48]. The lesson learned is that other industries could increase harmonization by adopting a similar approach to develop baseline international regulations and SARPs that shape each country's national framework while still allowing for a specific regional requirement. However, it should be noted that establishing a framework such as this can take a very long time and could encounter barriers due to the international agreements that might be needed.

One other area of strength from the aerospace regulatory system is the international certification of quality systems, which allows for parts to be sourced from participating jurisdictions without requiring organizations to audit suppliers to national standards. This leads to a more highly integrated and harmonized supply chain and the removal of trade barriers and inefficiencies.

5.3.2 Regional

Within the aerospace industry, the Cyprus Arrangement highlights the benefits of establishing regional harmonization. The establishment of common national rules and certification procedures, joint certification of products across countries, and regular inspections is difficult to achieve within a highly regulated industry such as the aerospace industry, but several key benefits have been made for the general population and for manufacturers, including:

- Fewer equivalent certification processes between countries;
- The sharing of best practices and lessons learned; and
- Increased equivalent safety in less developed country's aerospace programs.

An arrangement such as this works best in conjunction with a strong international safety framework similar to that established by the ICAO, which requires that a certain level of harmonization already exists amongst the participating countries [99].

When developing standards, SDO collaboration is important for avoiding overlap and promoting harmonization. The EV industry has shown that SDOs can collaborate, as demonstrated in North America through CANENA and the development of regionally harmonized standards issued through each country's respective national SDOs.

Through the work of CENELEC, CEN, IEC, and ISO, the EV industry has highlighted that communication between regional and international SDOs can facilitate the sharing and adoption of standards among these organizations. Where there are commonalities that make the development of regionally harmonized nuclear standards the most feasible initial approach, these standards could become universally accepted or eventually published as international standards.

5.3.3 National

A unique approach to harmonization within the aviation industry can be observed through the airworthiness standards that outline details for certification. Within the aviation industry, harmonized SARPs are mandated at the international level but allow for national SDOs to implement small changes to tailor the requirements to their specific needs.

The national standardization approach used by the Canadian EV industry identifies two key benefits. First, it is beneficial that Canadian experts actively



"Within the EV industry, studies have shown that the rate at which EVs are adopted is directly connected to standards, public health and safety, and environmental sustainability."

participate in both national and international standards development opportunities. Their participation in international standards will help ensure that Canada's requirements are considered in standards and will help support harmonization. Second, the approach of developing standards that are applicable to new technologies, which is further summarized in the next section, allows for and encourages innovation while still promoting safety.

5.3.4 New Technologies

When developing standards for a new technology, a combination of standardization approaches is typically required to develop standards and promote harmonization. For example, with EVs, international harmonization was appropriate for batteries and battery components, but not for the charging infrastructure because of different regional requirements between Europe and North America. Additionally, new technologies benefit from the use of performance-based standards, which allow for the technology developer to meet the standard using various methods, instead of design-based standards, which specify how the technology developer must meet the standard [35]. This allows for developed standards to be applicable to variations in technology and can allow for regional differences.

As noted in the UAS case study (Section 5.1.2.4), new technologies can be disruptive to their industry. Most new technologies require that new standards be developed to address gaps in existing frameworks. It can be efficient to address these gaps through international SDOs in order to reduce duplication in standards development resources and to increase harmonization between countries. In situations where this cannot be achieved, or there are urgent gaps to be filled, regional or national standards can be developed that may subsequently be used as the basis for new international standards. While developing standards for UAS, Transport Canada outlined high-level recommendations that can be applied to standard development, which include [63]:

- The establishment of a flexible regulatory framework and accompanying standards that can effectively adapt to meet the needs of a rapidly evolving industry while ensuring safety and security;
- Benchmarking and harmonizing standards and regulatory structures with other regulators; and
- Ensuring regulations and standards exist to account for autonomy and remote operations.

Within the EV industry, studies have shown that the rate at which EVs are adopted is directly connected to standards, public health and safety, and environmental sustainability [97]. The development of early electric vehicle infrastructure standards in the 1990s helped the electric vehicle industry rapidly grow to the point where the standards have had to be updated to meet the current needs of the industry [68].

6 Small Modular Reactors

6.1 Background Information

The small modular reactor (SMR) landscape within Canada has experienced a significant increase in interest and development in recent years. SMRs have been recognized as an important component of Canada's future energy composition by federal and provincial governments, the federal regulator, power utilities, and national laboratories. A brief summary of three important milestones related to the deployment opportunities for SMRs in Canada is presented below to provide some context to the market and their current status.

In 2017, Canadian Nuclear Laboratories (CNL) initiated a process that offered SMR vendors a potential demonstration site. Four SMR vendors have publicly announced their participation in this multi-stage application and approvals process: U-Battery Canada Ltd., StarCore Nuclear, Terrestrial Energy, and Global First Power [100].

In 2018, Natural Resources Canada (NRCan) collaborated with provinces, territories, power utilities, and other stakeholders to develop and publish *A Call to Action: A Canadian Roadmap for Small Modular Reactors* [101]. This roadmap outlines a vision to support SMR development and deployment within Canada. In December 2020, NRCan launched a follow-up document, *Canada's SMR Action Plan,* to outline the progress of ongoing SMR efforts across Canada, including updates on commitments made by stakeholder groups within the SMR roadmap [102], [105].

At the provincial level, Saskatchewan, Ontario, and New Brunswick signed a memorandum of understanding (MoU) in 2019 to work cooperatively and advance the development and deployment of SMRs [103]. In 2020, Alberta noted its intent to join as the fourth signatory to the MoU. The MoU calls on the provinces to work cooperatively to achieve the following [103], [104]:

- Support the development and deployment of SMRs to address the needs of the provinces with respect to climate change, energy demand, economic development, and R&D;
- Address key issues for SMR deployment including technological readiness, regulatory frameworks, economics and financing, nuclear waste management, and Indigenous engagement; and
- Maintain a dialogue with the federal government with respect to the support of SMRs.

Supporting the activities under this MOU, provincial utilities – including SaskPower, Ontario Power Generation, Bruce Power, and NB Power – have been progressing SMR deployment activities under a three-stream approach outlined as follows [105]:

- **Stream 1:** Development of grid-scale SMRs around 300 MWe (first-of-a-kind [FOAK] in Ontario at the Darlington nuclear site by 2028);
- **Stream 2:** Deployment of an advanced reactor SMR design that can utilize existing nuclear power plant fuel (FOAK demonstration unit in New Brunswick by 2035); and
- **Stream 3:** Deployment of micro SMRs for remote power, or industrial applications to replace the use of diesel in remote communities and mines (FOAK 5 MWe demonstration unit at Chalk River by 2026).

In support of Stream 1, Ontario Power Generation announced in October 2020 that it would be working with three utility-scale SMR developers (GE Hitachi, Terrestrial Energy, and X-Energy) in the development of their nuclear technology with the goal to deploy a new nuclear reactor at Darlington's new nuclear project site [106].

In support of Stream 2, NB Power announced partnerships with ARC Clean Energy and Moltex Energy in 2018, and committed to the establishment of an advanced small modular reactor research cluster in New Brunswick [107].

Stream 3 activities to date have been focused on the Global First Power project which involves Ontario Power Generation and Ultra-Safe Nuclear Corporation partnering to build a FOAK reactor at Chalk River following CNL's site application process [108].

Additionally, in late 2020, Bruce Power announced an MOU under which it would be supporting the Westinghouse Electric Company through the CNSC VDR process for the eVinci micro SMR design [109].

Within this landscape, Section 6.1.1 of this report highlights existing international regulatory and industry harmonization activities and collaborations while Section 6.1.2 provides a high-level overview of SMR designs currently undergoing the CNSC VDR process.

6.1.1 Harmonization Activities

6.1.1.1 Regulatory

Before a country can develop a domestic nuclear program, it must accept several international treaties. An example of this is the Treaty on the Non-Proliferation of Nuclear Weapons, which promotes the peaceful use of nuclear energy and prevents the spread of nuclear weapons and weapon technologies [110]. While aligned through international agreements, most countries establish and enforce their nuclear regulatory framework at the national level through national regulatory authorities [111], [112]. These regulatory frameworks generally rely on a combination of IAEA safety standards and framework documents, national governance, and stakeholder inputs. Variance in the local national regulatory framework and stakeholder inputs can result in different regulatory requirements between countries [111].

Though national regulators may act independently, some national nuclear regulators have started to collaborate on the development of regulatory, license, and guidance documents, which has led to similar requirements between participating jurisdictions [111]. Some of the organizations and initiatives involved in collaboration initiatives include the International Atomic Energy Agency (IAEA); the Multinational Design Evaluation Programme (MDEP); the Western European Nuclear Regulators' Association (WENRA); several national regulators, including the CNSC in Canada, the US Nuclear Regulatory Commission (NRC), and the UK Office for Nuclear Regulation (ONR); and two technical consortiums, including the European Licensing of Small Modular Reactors (ELSMOR) and GEMINI+ among others [113].

International Atomic Energy Agency (IAEA)

The IAEA is an intergovernmental forum composed of member states that lobby for nuclear scientific and technical cooperation while also providing a forum for coordination of harmonization activities. The IAEA also plays a key role in the development and publication of international safety standards that often serve as a baseline and are integral for member states when developing national regulations and standards as they outline fundamental principles, requirements, and recommendations to advocate for public safety [114], [115].

In addition to developing international safety standards, the IAEA has expressed interest in harmonizing the licensing process for nuclear power plants [116]. An example of this is the harmonization of digital instrumentation and controls (I&C) licensing requirements [116]. To date, the IAEA has published a report on this topic that outlines the first steps required to harmonize licensing requirements and outlines high-level requirements for SDOs, regulators, utilities, and vendors to aid in achieving this goal [116]. Additionally, the IAEA Integrated Regulatory Review Service (IRRS) exists to conduct national regulatory system reviews and identify best practices in licensing that can be shared with other regulators [117].

Many of the IAEA safety standards have been developed to be technology neutral and can be applied towards SMRs. The SMR Regulators' Forum, an IAEA group established in 2015 with the goal of enabling discussions around SMR regulatory knowledge and experience, has produced several reports, and established working groups for SMRs to support national regulators, like the CNSC, by providing guidance to resolve common safety issues and regulatory barriers associated with SMR technologies [118]. This working group focuses on licensing issues, design and safety analysis, and manufacturing, commissioning, and operations for SMRs [118]. In addition to these efforts, the IAEA also maintains the Advanced Reactor Information System (ARIS) which is a comprehensive database with up-to-date information about SMR designs and concepts [119]. A supplemental booklet to the ARIS, which contains concise information about all major SMR technologies lines, is also maintained by the IAEA with the latest version being published in September 2020 [120].

Nuclear Energy Agency (NEA) & Multinational Design Evaluation Programme (MDEP)

Established in 1958, the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA) is an intergovernmental agency that facilitates co-operation among countries with advanced nuclear technology [121]. Composed of members from the Americas, Europe, and the Asia-Pacific region, the objectives from the NEA include the following [122], [123]:

- Assisting member countries in maintaining and further developing the scientific, technological, and legal bases to safety operate nuclear power plants;
- Providing authoritative assessments for nuclear power plants; and
- Establishing common understandings on key issues, such as nuclear energy policy decisions from governments.

As the NEA operates as a forum, it uses a series of working groups across a range of topics. One of the more notable working groups is the Working Group on the Regulation of New Reactors (WGRNR). This group examines the regulatory issues of the siting, licensing, and regulatory oversight for all new commercial nuclear power reactors [124]. In addition to publishing 13 reports, the WGRNR is responsible for the co-ordination of the Committee on Nuclear Regulatory Activities (CNRA) and the Multinational Design Evaluation Programme (MDEP), an important nuclear harmonization program.

The MDEP is a temporary multinational regulatory initiative established in 2006 whose main objectives include the following [125], [126]:

- Enhancing multilateral cooperation within existing regulatory frameworks; and
- Increasing multinational convergence of standards, codes, guides, and safety goals.

MDEP is currently composed of 16 national regulatory authorities, including the CNSC, the US NRC, the UK ONR, and respective regulators from other large nuclear power countries such as India, Korea, the Russian Federation, and the People's Republic of China [125]. Additionally, the IAEA participates in MDEP activities, while the NEA of OECD acts as the MDEP Technical Secretariat [125]. To achieve harmonization, MDEP recognizes the need for technical support from SDOs as well as owners' groups [127].

Significant progress has been made towards the MDEP goals of increased cooperation, and convergence of requirements and practices [126]. A key example of this is the MDEP Vendor Inspection Cooperation Working Group (VICWG), which has the goal of facilitating the cooperation of safety design reviews of new reactors through joint inspections, harmonization, and the exchange of information [128], [129]. Between 2017 and 2018, 15 opportunities for cooperation were identified and five witness inspections involving multiple regulators occurred [126]. In addition to vendor inspection programs, MDEP has reviewed codes and standards harmonization through working groups such as the Codes and Standards Working Group (CSWG) [126]. The CSWG completed a code comparison to understand the extent of similarities and differences among pressure boundary codes, established a global framework to achieve code harmonization, and collaborated with SDOs to limit code divergence where realistic and practical [126]. In 2018 this working group was placed under the jurisdiction of the Nuclear Energy Agency (NEA) as the Working Group on Codes and Standards (WGCS) after the goals of the working group left the purview of MDEP [130]. Here, the WGCS plans to continue working with CORDEL and national SDOs to facilitate pressure boundary code convergence through the following [126]:

- Modifying existing national code requirements; or
- Jointly developing new code requirements with international interest.

Currently, MDEP operates a combination of design-specific and issue-specific working groups. While the design-specific working groups revolve around a specific reactor design, like the AP1000 design by Westinghouse, MDEP has not yet established such a group for an SMR design [125], [131]. MDEP's issue-specific working groups are more applicable to SMR technologies, although three quarters of these working groups have achieved their initial goals within MDEPs temporary scope and have transitioned to other organizations with larger scopes. At the time of

writing this report, the only operational issue-specific working group within MDEP is the VICWG [125]. Both the Digital Instrumentations and Controls Working Group (DICWG), and the CSWG have transferred under NEA, while the Advanced Boiling Water Reactor Working Group (ABWRWG) merged with the CNRA BWR Regulator's Forum [125], [126]. Of all the working groups within MDEP, the current and past contributions from the VICWG, DICWG, CSWG, and their counterparts under the NEA are most applicable to SMRs due to their focus on harmonization and collaboration of regulatory, I&C, and pressure boundary related requirements in the nuclear industry.

Western European Nuclear Regulators' Association (WENRA)

At the regional level, the Western European Nuclear Regulators' Association (WENRA) has been established with the goal of developing and regulating a common approach to nuclear safety to protect people and the environment [132]. Composed of the leadership of nuclear regulatory bodies from 18 countries, WENRA has contributed to national nuclear safety requirements, improved IAEA safety standards, created a platform for open information exchange between regulators, and published several reports on the harmonization of reactor safety in WENRA countries [132], [133]. In 2016, the CNSC gained observer status in WENRA with the goal of exchanging experiences with regulators, learning from international best practices, and developing Canadian regulations [134].

In 2019, WENRA released a strategy plan for 2019 to 2023 that outlines objectives for the association. These objectives show that WENRA plans to promote the harmonization of regulatory practices within Western Europe, promote collaboration between national regulators, increase WENRA's involvement outside of Europe, and tackle several key topics that include SMRs, cyber security, and the nuclear supply chain [135]. These efforts are being supported by two WENRA working groups: the Reactor Harmonization Working Group (RHWG) and the Working Group on Waste and Decommissioning (WGWD), although additional working groups may need to be established to tackle WENRA's new objectives [136].

Canadian Regulatory Collaboration

In 2019, a binational agreement was reached between the CNSC and the US NRC in the form of a memorandum of cooperation (MoC) [137]. This MoC calls for expanded cooperation on activities with advanced reactors and SMR technologies through the following [137], [138]:

- Continuing and establishing new cooperation on advanced reactor and SMR technologies through the US NRC-CNSC Steering Committee;
- Strengthening the CNSC and NRC commitment to share best practices and experiences reviewing advanced reactor and SMR technology designs; and
- Establishing the Advanced Reactor Technology (ART) SMR Committee (ART-SMR) to assess the progress of activities, deliverables, and establish new work plans.

The cooperation outlined in this MoC has the potential to expand and facilitate a joint technical review of an advanced reactor or SMR design [137]. Subsequent to this, it was announced that the CNSC and US NRC would be conducting a joint technical review on the Terrestrial Energy Integral Molten Salt Reactor (IMSR) design [139].

Canada has also entered an MoC with the UK ONR regarding advanced reactor and small modular reactor technologies [140]. Agreed to in October 2020, this collaboration is expected to help both regulators streamline regulatory assessments for common technologies in both jurisdictions by providing a framework for enhanced collaboration.

Currently, Canada uses a performance-based approach where the regulator sets general acceptance criteria and requires the licensee to meet the acceptance criteria as they see fit, the United States uses a prescriptive-based approach where the regulator prescribes or approves acceptance criteria which the licensee must meet and follow, while the United Kingdom uses a goal-setting-based approach where the regulator sets safety goals and licensees must justify any design code or specific acceptance criteria used to meet the safety goal [141]. This has resulted in regulatory divergence as observed through previous

CNSC VDRs due to regulators operating independently and relying on different regulation approaches [142]. While the CNSC, NRC, and ONR remain independent regulators, increased collaboration between regulators may help to support the harmonization of standards or regulatory approaches.

6.1.1.2 Industry

In addition to regulatory harmonization, industrial groups – reactor developers, nuclear operators, and other stakeholders, for example – have been working to foster increased harmonization in different areas. This includes developing common standards and completing code comparisons between jurisdictions such that common industry standards can be developed [117]. Initiatives are calling for increased long-term design knowledge management that will contribute towards information exchange and design improvement across international nuclear power plant fleets [117].

Cooperation in Reactor Design Evaluation and Licensing (CORDEL)

The Cooperation in Reactor Design Evaluation and Licensing (CORDEL) group was established in 2007 by the World Nuclear Association (WNA) with the goal of promoting and facilitating international standardization of nuclear reactor designs and the harmonization of regulatory requirements [113], [143]. This group represents the views of participating nuclear vendors and utilities across the globe [117]. CORDEL was established to be the industry counterpart to MDEP, and these organizations often communicate and share information amongst one another [144].

Through the publication of a roadmap entitled *International Standardization of Nuclear Reactor Designs* in 2010, a detailed pathway to standardization and harmonization within the nuclear industry was presented in 2019 [143]. CORDEL has been acting on this roadmap to achieve harmonization through the following:

- Shared design assessment for licensing;
- Common design approval processes between competent authorities; and
- Internationally issued design certifications.

CORDEL recognizes that achieving international regulatory harmonization is difficult and, in 2019, it stated that, while progress is being made, it has yet to achieve its original goals [143]. To highlight this, CORDEL adjusted its process to reflect its experience based on what it has found nuclear regulators are willing to accept by updating Step 2 of its roadmap from recognizing reactor certification across all jurisdictions to developing a common regulatory design approval process [143].

Currently CORDEL has six task forces within its organization. These task forces include the Design Change Management Task Force (DCMTF), the Licensing and Permitting Task Force (LPTF), the IAEA Nuclear Safety Standards Task Force, the Digital Instrumentation and Control Task Force, the Small Modular Reactors Task Force, and the Mechanical Code and Standards Task Force, in which Canada actively participates [143]. While only one of these task forces is dedicated to SMRs, they all have activities that can support the deployment of SMRs as a new nuclear technology. In 2020 CORDEL released a paper in collaboration with the CANDU Owners Group (COG) outlining the lessons learned and best practices on the harmonized international transportation regulations for radioactive material [145]. The international transportation regulations were first established by the IAEA and recommended to member states and international organizations as a basis for their own regulations [145]. Lessons learned include the following [145]:

- The importance of setting aside national differences and establishing common quantitative performance and testing criteria and terminology;
- Successful harmonization requires strong engagement and commitment from governments and the nuclear industry; and
- Multinational regulatory advisory panels are important in helping to facilitate international standardization and harmonization.

Electric Power Research Institute (EPRI)

The Electric Power Research Institute (EPRI) conducts research, development, and demonstration projects related to electricity generation, delivery, and use [146]. EPRI's research covers a wide range

of industries, including the nuclear industry where they look to develop safe, reliable, cost-effective, and environmentally responsible technologies for existing NPPs, aid in the deployment of advanced nuclear plants, and support the long-term success of the nuclear industry [147].

Within the nuclear industry, EPRI has developed technical tools to minimize deployment and operational risks and has developed harmonized utility requirements for new reactor designs in both the United States and Europe [117]. In 2014, due to growing interest in SMRs, EPRI updated the utility requirement documents to address some of the unique attributes of SMRs, including reactor coolant systems [148].

International Organization for Standardization (ISO)

ISO is an independent, non-governmental organization made up of members from the national standards bodies of 165 countries. ISO's membership structure allows for input from multiple nations which inherently results in internationally harmonized standards. The nominated representatives from impacted member countries provide their input and agreement using the consensus process to develop voluntary international standards covering various topics, including nuclear energy [149].

The ISO technical committee (TC) 85 on nuclear energy and technologies and radiological protection develops over 200 standards either directly through the TC or with the aid of subcommittees. The TC has published many standards applicable to water cooled reactors and has begun to address some topics related to SMRs such as the ISO 18229:2018, *Essential Technical Requirements for Mechanical Components and Metallic Structures Foreseen for Generation IV Nuclear Reactors* [150].

CANDU Owners Group (COG)

The CANDU Owners Group (COG) is a private, not-for-profit Canadian corporation composed of members across seven countries that project and facilitate research, information exchange, and alignment of standards and regulations within the nuclear industry [151]. COG focuses on collaboration for both CANDU and advanced nuclear technologies [151].

An important harmonization program that COG operates is the Small and Medium-Sized Reactor Technology Forum, which has the goal of identifying key issues and promoting policy harmonization [152]. Another is the COG SMR Vendor Participant Program (VPP) that brings together SMR vendors involved in design reviews [153]. Currently, ten vendors participate in this program, all of which are involved in the CNSC VDR process [153].

Additionally, COG has collaborated with EPRI on the topic of harmonization. COG and EPRI have jointly identified that regulators will play a large role in harmonization and should exchange lessons learned, compare regulatory practices, and develop cooperative relationships with national laboratories and academia [154]. National nuclear regulators, such as the CNSC in Canada, take part in numerous international standards settings, which can further international harmonization efforts for the application of safety standards to SMRs [154].

Technical Consortiums

There are several technical consortiums with interests in SMRs, including, ELSMOR and GEMINI+, which are outlined below.

ELSMOR is a collaboration of experienced nuclear safety researchers with interests in advancing technological solutions for light water SMRs, such as PWRs and BWRs, through the following [155]:

- Collecting, analyzing, and sharing information about the challenges of SMRs to stakeholders;
- Developing high-level safety analysis methods for light water SMRs;
- Improving experimental research infrastructures to aid in evaluating novel safety features in light water SMRs; and
- Improving nuclear safety analysis codes to help ensure compatibility against safety requirements.

In addition to ELSMOR, which is focused on light water reactors, the GEMINI+ international agreement fosters collaboration between nuclear vendors, research centers, investors, and governments in the United

States and European Union. This initiative looks to build upon knowledge, experimental data, and modelling tools to develop a collaborative high-temperature gas-cooled reactor (HTGR) that can be licensed in both the United States and Europe [156].

6.1.2 Overview of Small Modular Reactor Technologies

As of the end of 2020, 12 SMR vendors have engaged with the Canadian Nuclear Safety Commission (CNSC) by entering into their Pre-Licensing Vendor Design Review (VDR) process [157]. The CNSC VDR is an optional feedback mechanism that is meant to provide a vendor with early feedback on its reactor technology [160]. Initiated by the vendor prior to submitting a license application, the VDR process aims to help ensure compliance with Canadian regulatory requirements, expectations, and standards while also alerting the CNSC to fundamental barriers to licensing for new reactor technology that are required to be addressed [158]. There are three phases within a VDR [158]:

- **Phase 1:** Pre-Licensing Assessment of Compliance with Regulatory Requirements, which involves a high-level assessment of the NPP design against the current CNSC design requirements;
- **Phase 2:** Pre-Licensing Assessment for Any Potential Fundamental Barriers to Licensing, which identifies any fundamental barriers to licensing within Canada; and
- **Phase 3**: Follow-up, which looks to provide vendors with more information regarding results from Phase 2.

Regulatory decisions and licensing are not based off pre-licensing VDRs and are independent from one another. During the licensing process, a more detailed assessment of the entire reactor design is conducted through the site preparation, construction, operation, and decommissioning licensing process, which is led by the proponent, typically an operating utility [159].

Many of the SMR designs have significant differences from the pressurized heavy water reactor (PHWR) designs in Canada, known as CANDUs. The current status of these 12 reactors within the VDR service are summarized in Table 2 and more details are provided in the following sections.

6.1.2.1 Light Water Reactors

6.1.2.1.1 Pressurized Water Reactors

Two vendors with SMR designs based on pressurized water reactor (PWR) technology have engaged in the CNSC VDR process: the NuScale Power Module (NPM) and the SMR-160 reactor design [158], [160].

PWRs work by using a pressurized (light) water primary coolant loop to carry heat away from the reactor core. This hot water is transported to a steam generator and used to turn water from a secondary loop into steam before being transported back to the reactor core [161]. The steam produced in the secondary loop drives a steam turbine to create electricity before being condensed and cycled through the process again [161].

Of the designs currently under review in the VDR process, PWRs are the most analogous to the existing PHWR design used in CANDU reactors. However, there are also several key differences between the technologies. As an example, CANDU reactors use fuel manufactured from natural uranium while PWRs use fuel manufactured from enriched uranium.

PWRs are the most common type of nuclear reactor with large operating fleets in the United States, France, and other countries [162]. As such, many PWR SMR vendors are engaged in several jurisdictions. For example, NuScale has completed its design certification with the US NRC [163].

6.1.2.1.2 Boiling Water Reactors

Currently, there is a single vendor with a boiling water reactor engaged in the CNSC VDR process: the BWRX-300 reactor.

Similar to PWRs, boiling water reactors (BWRs) also use light water. However, they only have a single coolant loop. BWRs pump water through the reactor core to directly produce steam [164]. This steam is then transported to a turbine generator to produce electricity before being condensed back into water and sent back to the reactor core.

BWRs have operating experience around the world. The BWR designed by GE Hitachi Nuclear Energy will be similar to existing BWR nuclear power plants operating in other jurisdictions such as the United States, Japan, and Germany [160], [165].

Table 2: Summary of vendor reactor technologies and their status through the CNSC VDR pre-licensing process as indicated on the CNSC website as of the end of 2020 [158].

Reactor Type	Vendor	Name of Design	Approximate Electrical Capacity [MWe]
Light Water Reactors			
Pressurized Water Reactor	NuScale Power, LLC	NuScale Power Module (NPM)	60
Pressurized Water Reactor	SMR, LLC (A Holtec International Company)	SMR-160	160
Boiling Water Reactor	GE-Hitachi Nuclear Energy	BWRX-300	300
Generation IV and Advanced Reactors			
High-Temperature Gas-Cooled Reactor	X Energy, LLC	Xe-100	80
High-Temperature Gas-Cooled Reactor	Ultra Safe Nuclear Corporation	MMR-5 and MMR-10	5 / 10
High-Temperature Gas-Cooled Reactor	U-Battery Canada Ltd.	U-Battery	4
High-Temperature Gas-Cooled Reactor	StarCore Nuclear	StarCore Module	10
Molten Salt Reactor	Terrestrial Energy Inc.	IMSR	200
Molten Salt Reactor	Moltex Energy	Moltex Energy Stable Salt Reactor	300
Molten Lead Reactor	LeadCold Nuclear Inc.	SEALER	3
Sodium-Cooled Reactor	ARC Clean Energy	ARC-100	100
Solid Core Reactor	Westinghouse Electric Company, LLC	eVinci Micro Reactor	Adjustable < 25

6.1.2.2 Generation IV & Advanced Reactors

6.1.2.2.1 High-Temperature Gas-Cooled Reactors

Four vendors with high-temperature gas-cooled reactor (HTGR) designs are engaged with the pre-licensing VDR process in Canada: the Xe-100, the MMR, the U-Battery, and the STARCORE.

HTGRs are a type of Generation IV reactor that use gas (typically helium) at high temperatures as a coolant. This reactor type circulates high pressure helium through the reactor core before passing it to a heat exchanger where it is used to heat up a secondary fluid for the production of electricity or to process heat [166]. The helium is then repressurized and pumped back through the core to continue to cycle [166]. All of the HTGR designs under review in the CNSC VDR process use TRISO (tri-structural isotropic) fuel, though in varying configurations [160], [167]. TRISO fuel is manufactured by surrounding a small quantity of uranium fuel with layers of carbon and ceramic to provide a robust, high-temperature barrier to the release of fission products [167].

High-temperature gas reactors exhibit some key differences from PHWRs that will impact technical requirements, such as the higher operating temperature range and the use of a gaseous coolant.

6.1.2.2.2 Molten Salt Reactors

Two vendors with molten salt SMR designs are engaged with the CNSC VDR process: the Integral Molten Salt Reactor (IMSR) and the Stable Salt Reactor-Wasteburner (SSR-W) reactor.

Molten salt reactors are pool-type reactors in which the primary coolant is a fluoride or chloride salt. Many different MSR designs exist, but all share the use of a low pressure and high temperature primary coolant salt, with additional salt loops used to generate steam or process heat [168].

While there are significant differences between the SSR-W and the IMSR, there are also some broad similarities based on their joint heritage. Historical operating experience for common design challenges may be gained from the Aircraft Reactor Experiment (ARE) and the Molten Salt Reactor Experiment (MSRE), which both operated at the Oak Ridge National Laboratory in the United States [160], [169], [170].

As with HTGRs, molten salt reactors have some key differences from PHWRs that will impact technical requirements, including the higher operating temperature range, and the use of a different coolant – notably fluoride or chloride salts.

6.1.2.2.3 Sodium-Cooled Reactors

Currently, there is a single vendor with a sodium-cooled reactor engaged in the CNSC VDR process: the ARC-100 reactor.

Sodium-cooled reactors use molten sodium metal as the reactor coolant to remove heat from the reactor core through a sodium-sodium heat exchanger [171]. The sodium within this secondary sodium coolant loop is transported to a second heat exchanger where it us used to generate steam from water and then generate electricity [172].

As with molten salt reactors, sodium-cooled reactors operate under different conditions from PHWRs, which will impact technical requirements. Examples include a higher operating temperature range and the use of a different coolant that inherently comes with new safety requirements.

6.1.2.2.4 Solid Core Reactors

There is only one vendor with a solid core reactor design engaged in the CNSC VDR process: the eVinci Micro Reactor.

Solid core reactors make use of heat pipes to remove heat and eliminate the need for high-pressure pipes and coolant [160]. The use of heat pipes can avoid many of the complexities associated with traditional reactor designs as they require no moving mechanical components, such as pumps, to operate.

As with other advanced reactors, solid core reactors operate under different conditions than PHWRs that will need to be addressed such as the use of advanced heat pipes, coolant fluid requirements, and high operating temperatures.

6.2 Standardization & Harmonization Activities

The following subsections present an analysis of relevant national and international standardization and harmonization activities relevant to the SMR technologies engaged in the CNSC VDR process.

6.2.1 Light Water Reactors

6.2.1.1 Pressurized Water Reactors

Pressurized water reactors are the most common type of nuclear power reactors in the world [173]. Due to their widespread use, there are many jurisdictions that have applicable regulations and standards addressing this reactor technology. Canada's current CANDU nuclear power plants are PHWRs, which are supported by standards and regulations that have been specifically developed to address PHWR designs. PWRs and PHWRs are broadly similar in implementation and, as such, many existing Canadian nuclear standards are also applicable to PWRs [172]. Comprehensive regional and international standards also exist to address light water reactor designs (both PWR and BWR) from key SDOs such as the IAEA, IEC, and IEEE. International SDOs are continuing to develop harmonized standards to address light water reactor designs, including IEC SC 45A, which is focused on the development of standards in the area of Instrumentation, control, and electrical power systems for nuclear facilities.

As discussed in Section 6.1.1.1, MDEP has an interest in harmonizing national PWR standards through its work with the Digital Instrumentation and Controls Working Group (DICWG) and Codes and Standards Working Group (CSWG), which both now operate under the NEA. By comparing national pressure-



"...international harmonization can be increased by developing joint standards that engage national SDOs, SMR vendors, and other stakeholders..."

boundary standards, the MDEP CSWG concluded that current national standards varied in their levels of harmonization, but all resulted in acceptable levels of quality and safety when used within the originating country [174]. It is believed that existing pressure-boundary standards were developed using similar underlying intents but using different industry practices, industry and regulatory guidance, and philosophical and cultural factors that could result in divergence if used in another country [174]. Moving forwards, the MDEP CSWG believes that international harmonization can be increased by developing joint standards that engage national SDOs, SMR vendors, and other stakeholders while leveraging the completed work from MDEP and CORDEL [174]. The MDEP DICWG took its work a step further and looked to harmonize national digital instrumentation and control standards and regulatory requirements. This working group established a set of common positions generally agreed upon at the international level through the consensus of national regulators, including the CNSC, US NRC, and UK ONR [175]. The harmonized instrumentation and controls (I&C) standards outlined by this group are comprised of IEEE, IEC, and IAEA standards, many of which are already recognized or used as best practices in Canada [175]. The effort completed by the MDEP DICWG shows that standard harmonization activities are aided by support from national regulators.

The AP1000 Working Group has also been working to achieve standard and regulatory harmonization for PWRs. In this working group, Canada, China, India, the United Kingdom, and the United States have collaborated and cooperated on specific design evaluations and construction oversight associated with the Westinghouse AP1000 PWR design [131], [176]. This cooperation between regulators established commonality between jurisdictions and was found to benefit participants by sharing evaluation efforts and lessons learned [177]. While both Canada and the United Kingdom have withdrawn from this program as active members, this working group was successful in aiding the participating regulators in evaluating the reactor design [178]. In this collaboration, all regulators were still ultimately responsible for their own licensing decisions but benefited in making this decision by having access to other regulators' conclusions [179]. Regulatory collaboration, such as through a design-specific working group, is important in fostering harmonized standards. As the CNSC references standards in licensing requirements and regulatory documents, harmonized standards will need support from regulatory bodies.

Finally, ELSMOR is also conducting research around assessing and verifying the safety of light water reactors. It has published a paper on improved safety features of light water SMRs in which it compiles current nuclear safety directives and practices through IAEA, WENRA, ENSREG, and specific national requirements, including Canada [180]. The results outlined in this report, along with an overview of safety systems and features, contain a valuable collection of thoughts regarding PWR safety that may influence regulatory reviews for light water reactors in Europe

and beyond. Similarly, the overview of safety systems could be used by other regulators to highlight key differences between countries and increase the desire for harmonized safety standards among regulators.

6.2.1.2 Boiling Water Reactors

Boiling water reactors (BWRs) are a commercialized reactor technology that is successfully operating within several countries, including the United States and Japan. Like with PWRs, BWRs will give Canada the option to leverage existing standards, best practices, and lessons learned from other jurisdictions with established fleets of BWRs.

Internationally, BWR harmonization activities have been conducted through the MDEP Advanced Boiling Water Reactor Design Specific Working Group (ABWRWG). This group was similar in intent to the AP1000WG in the PWR space, but only included regulators from Japan, Sweden, the United Kingdom, and the United States [126]. The ABWRWG achieved two major milestones through its work: a report outlining the differences identified through a comparison of international ABWR designs, and the sharing of files between the United Kingdom and Japan supported the licensing process of the ABWR in Japan [126]. This working group highlights that regulators are willing to collaborate and share files related to licensing applications.

In 2017 the members of the ABWRWG determined that this working group was no longer needed within the scope that MDEP had identified and it disbanded [126]. Common areas of interest outside of the MDEP working group scope were identified by the involved regulatory organizations and a new collaboration, the CNRA Working Party on Boiling Water Reactors (WPBWR) , was established [126]. A scope for this working group has not yet been identified, but it is expected to be a regulatory forum for BWRs that exchanges information and experience, identifies international safety challenges, and allows for international collaboration on regulatory activities related to BWRs [181]. The establishment of working groups designed to foster collaboration for a specific reactor type as seen for both PWRs and BWRs seems to have been historically successful. This allows for regulators with specific interests to focus on that specific reactor type and developed harmonized standards and regulatory practices while also benefit from opportunities to share lessons learned, best practices, and potentially conduct joint technical reviews.

Work from ELSMOR is also applicable to BWRs due to their use of light water as a coolant. Because of this, the ELSMOR paper on improved safety features light water SMRs and future publications should be considered as resources [179].

After the Fukushima Daiichi Nuclear Power Plant accident in 2011, a series of groups investigated the accident to determine what went wrong and to recommend how similar accidents could be avoided in the future. While the Fukushima Daiichi NPP was a BWR, investigations into this accident provided lessons learned that are applicable to all reactor types. Two prominent groups that provided lessons learned were the IAEA and the MDEP EPR Working Group (EPRWG) [182], [183]. The resulting documents from these groups include an array of lessons learned and recommendations for standards such as improved defence in depth for reactor cooling and the protection of containment integrity, and methodologies to handle long-term loss of electrical power. Additionally, this accident sparked discussion around passive safety systems for NPPs that are capable of cooling the reactor core without needing electrical power to function [182]. It is expected that new standards will need to be developed to aid in the design and assessment of these passive safety systems to ensure they are effectively implemented and operate as expected.

6.2.2 Generation IV & Advanced Reactors

6.2.2.1 High-Temperature Gas-Cooled Reactors

HTGRs, while considered Generation IV technology, have found success through demonstration reactors across five countries[5], including Germany and the

5 HTGRs include the Dragon Reactor in the United Kingdom, the AVR and THTR-300 in Germany, the Peach Bottom 1 and Fort St. Vrain reactors in the United States, the HTTR in Japan, and the HTR-10 in China [174].

United States [184]. As these reactors use gas coolants rather than water, some existing Canadian standards and regulations that were developed to be applicable to water-cooled reactors may not be applicable and will need to be reviewed [185].

In 2003, the US NRC conducted a study that reviewed its existing standards against those needed for HTGRs. Some of the major gaps identified within this study include the ASME pressure boundary codes not addressing high temperature pressure boundary conditions, new high temperature materials being required, and new environmental requirements for impure helium and the high temperature behaviour of material [186]. It is assumed that Canada will likely have gaps similar to the ones noted by the US NRC that will need to be addressed.

A consistent concern among regulators and SDOs with HTGRs is their unique operating conditions that fall outside of current pressure boundary codes requirements, including operating at high temperatures. The most common and internationally referenced pressure boundary standards are those developed by ASME. In response to a gap identified by ASME for reactors whose temperatures exceed 425 °C, Division 5, "High Temperature Reactors," was added to the *ASME Boiler and Pressure Vessel Code,* Section III, "Rules for Construction of Nuclear Facility Components," in order to address the high-temperature conditions and material requirements [6] under which these reactors operate. However, this code has not yet been used as the basis for an operational reactor [187]. Additionally, in 2020 a collaboration between the US NRC and the American Nuclear Society (ANS) discovered several gaps for HTGR temperature and monitoring requirements and I&C standards [188]. Due to the high temperatures that HTGRs reach, adjustments to sensors may be needed to ensure that variables are accurately monitored within the reactor under extreme conditions [188]. It is likely that Canada will have similar gaps to those identified within the I&C field that will need to be investigated to determine applicability.

GEMENI+ is an international collaboration of partners looking to develop a HTGR for licensing in the United States and Europe. As this initiative calls for regulators to work with industry to develop a commercial reactor, regulators and SDOs have the opportunity to identify additional gaps or areas that require more guidance to aid in the development of future reactors through the development of harmonized standards or joint certification between the United States and Europe.

6.2.2.2 Molten Salt Reactors

There are two types of molten salt reactors: chloride salt and fluoride salt. Historically, most MSR designs have been fluoride based, however, there is a chloride-based MSR that is undergoing the CNSC VDR process.

The need for new standards to address fluoride MSRs was highlighted in the 1960s through the Molten Salt Reactor Experiment at Oak Ridge National Laboratory (ORNL). This experiment confirmed that tritium is produced within the heat exchanger tubes, which impacts corrosion, and that this could be addressed through material standards [189]. Additionally, methods to decommission and fully deconstruct MSRs are still being developed. These lessons can be applied to the molten salt reactor technology and the development of standards in future.

Some MSR designs use dissolved fuel rather than the dispersed fuel approach used in existing PHWRs [190]. This represents a novel approach to reactor fuelling that is not directly addressed by existing experience and could lead to new standard opportunities [191]. However, the same concepts used to prove the safety case of existing reactors are assumed to hold and can be used by vendors to address this new technology application.

The Nuclear Energy Institute (NEI) conducted a study in March 2020 that reviewed various standards to identify gaps relating to the SMR industry. There were several standards identified that were recommended for development or have already been initiated relating to the molten salt reactor designs [188]. There have

6 Note that ASME Section III Division 5 does not account for material deterioration that may occur in service due to radiation, corrosion, erosion, thermal embrittlement, or instability of material which may need to be addressed if adopting into Canada for all reactor types.

been efforts to develop a new code by ANS, ANS-20.2, *Nuclear Safety Design Criteria and Functional Performance Requirements for Liquid-Fuel Molten-Salt Reactor Nuclear Power Plants.* This standard establishes the nuclear safety design criteria and functional performance requirements for liquid-fuel molten-salt reactor nuclear power plants. The document uses risk-informed performance-based (RIPB) criteria wherever possible. It also describes the design process to be followed to establish those criteria and perform SSC classifications. This standard is under development [188]. There have also been efforts to develop a new code by ANS, ANS-20.1, *Nuclear Safety Criteria and Design Criteria for Fluoride Salt-cooled High-temperature Reactors.*

As fluoride molten salt reactors form a sodium short-lived beta/gamma emitter in their core, they require adequate leak protection as this presents a safety hazard [192]. Oak Ridge Laboratory proposed that a new standard be developed to capture this safety risk equivalent to SFR-DC 73 (RG 1.232), *Guidance for Developing Principal Design Criteria (PDC) for Non-Light-Water Reactors.* This standard is proposed to address the method of detecting sodium leakage, the extent to which the design enables sodium-air and sodium-concrete reactions, the mitigation approach of fires, and the evaluation of design aspects involving sodium to help ensure safety functions are upheld.

Additionally, standards, best practices, and lessons learned from other industries can be drawn on when setting standards for MSRs. For example, the concentrated solar industry has standards to address high temperature, corrosive nitride molten salts. While these standards may not necessarily be directly applied within the nuclear industry, they could serve as a basis from which new standards are adapted.

6.2.2.3 Sodium-Cooled Reactors

Sodium-cooled reactors, like with other types of Generation IV and advanced reactor designs, are far less common than light water reactors with most acting as experimental plants. For example, the Experimental Breeder Reactor-II (EBR-II) operated from 1963 to 1994 in the United States and was designed to produce 62.5 MWt [193]. This demonstration reactor allowed reactor concepts to be demonstrated while confirming that the reactor could be safely and efficiently operated and maintained. It also enabled testing of reactor fuels, structural materials, and components throughout its operation [194]. Current sodium-cooled reactor designs may rely on the technology used in the EBR-II demonstration [195]. Having an operating plant as a reference may allow comparisons to be drawn and references to be made from current designs to the EBR-II during the VDR process depending on the degree of variation between current designs and the reference plant design [196].

One of the significant safety hazards associated with sodium-cooled reactors is metallic sodium leaks, which are potentially corrosive and reactive with incompatible materials (i.e., air, water), resulting in heat and harmful byproducts [190]. Furthermore, these leaks can result in the production of toxic aerosol substances as well as hydrogen, thus presenting a risk of hydrogen explosions [197]. Due to the high risk and high consequence of these scenarios, fire protection provisions specific to this hazard will be required.

Due to the unique operating conditions of sodium-cooled reactors, there have been limited standardization and harmonization activities surrounding them. All things considered, existing standards, lessons learned, and best practices from other industries, like the concentrated solar industry with MSRs, may be able to act as basis documents to develop standards for sodium-cooled reactors.

6.2.2.4 Solid Core Reactors

Heat pipe cooled reactors are, like other Generation IV and advanced reactor designs, based on a technology that has found itself in experimental and demonstration reactor designs in the past, such as the AECL Nuclear Battery and NASA DUFF test reactor.

Due to the limited commercial presence of this reactor technology, there has been limited to no standardization and harmonization activities for solid core heat pipe cooled reactors. However, parallel standards have been developed for other industries, such as the computer and space industries, which may be able to act as basis documents to develop standards for solid core reactors.

6.3 Recommendations for Standardization & Harmonization

Based on the summary of best practices and lessons learned from the case studies, overview of the current SMR landscape in Canada, and the analysis of standardization and harmonization activities within the nuclear sector, recommendations for standardization and harmonization approaches to support the deployment of SMRs in Canada are presented in this section.

6.3.1 Light Water Reactors

6.3.1.1 Pressurized Water Reactors

As discussed in Section 6.2.1, due to the large number of PWRs operating around the globe, there are many opportunities for collaboration. One such example exists with the NuScale Power Module SMR. As of the date of this report, the NuScale Power Module is engaged in Phase 2 of the CNSC VDR process and has received US NRC design certification [158], [163]. Canadian standards could be evaluated against this design and the technical basis for its US NRC design certification to identify gaps and relevant technical expertise that could be leveraged to update existing standards and/or reference standards from the United States. In addition, Canada could reference existing standards from Europe, which has established PWR fleets in many countries such as the United Kingdom, France, and Germany, or international standards such as IEC TR 63335:2021, *Nuclear Power Plants – Instrumentation and Control Systems, Control Rooms and Electrical Power Systems – Specific Features of Small Modular Reactors and Needs Regarding Standards,* which addressed gaps with light water reactors that could not be addressed through updating existing IEC standards [198].

For PWR SMR designs that are being evaluated for licensing / design certification in multiple jurisdictions, design-specific working groups could be established (similar to the AP1000 Working Group established by MDEP) to help foster cooperation and share evaluation efforts and lessons learned among regulators. Such groups could facilitate Canada's efforts to benchmark and reference relevant standards or adopt existing international standards. In the executive summary for the AP1000 Phase 2 VDR, the CNSC noted that participation in the MDEP AP1000 Working Group led to the identification of regulatory divergence between the US NRC and CNSC frameworks due to their different regulatory approaches [142]. However, with the recent MoC between CNSC and the US NRC, further opportunities to develop harmonized regional standards for Canada and the United States may be identified.

6.3.1.2 Boiling Water Reactors

As with PWRs, BWRs are currently being operated in many countries around the world, including but not limited to the United States and Japan [173]. At the time of writing this report, the only BWR SMR design engaged in the CNSC VDR process is the BWRX-300 by GE-Hitachi Nuclear Energy. This SMR design is known to have been heavily influenced by the ESBWR reactor, another GE-Hitachi design that has been certified in the United States [160]. As such, Canada could leverage the CNSC MoC with the US NRC to engage in a joint technical review of the BWRX-300 as this SMR design is currently being reviewed by both regulators [199]. Using this approach, any identified gaps in Canadian standards could be addressed through updating existing standards and/or referencing standards from the United States, which could lead to the harmonization of standards between both countries. Alternatively, or in addition to referencing US standards, Canada could update existing standards and/or reference BWR standards from other jurisdictions with established BWR fleets or adopt existing international standard where available.

Additionally, as discussed in Section 6.2.1.2, the scope for the CNRA WPBWR working group is in the process of being established [181]. As Canada has limited operating experience with BWRs, it would be beneficial to actively participate in this working group and, if the opportunity arises, develop harmonized regional standards while exchanging information and experience, identifying international safety challenges, and allowing for international collaboration on regulatory activities related to BWRs [181]. Similar groups could be established for other reactor types to help promote collaboration between regulators and, potentially, harmonize standards between national SDOs.



"Design-specific working groups could facilitate Canada's efforts to benchmark and reference relevant standards or adopt existing international standards."

6.3.2 Generation IV & Advanced Reactors

6.3.2.1 High-Temperature Gas-Cooled Reactors

High-temperature gas-cooled (HTGR) reactors have been identified as a promising Generation IV nuclear technology, in many countries including the United States, United Kingdom, Germany, Japan, and China.

One potential collaboration that Canada could foster for HTGR is with the United States through the Xe-100 SMR. This reactor vendor is engaged in the CSNC VDR process and is seeking certification by the US NRC. As the United States has operating experience with two HTGRs and has developed regulatory documents based on operating experience (i.e., NUREG/CR-6824, *Materials Behavior in HTGR Environments*), it may be beneficial for Canada to leverage the MoC between the CNSC and US NRC to collaborate [173], [200], [201] and develop harmonized regional standards or develop new national standards that reference existing standards to address gaps as discussed in Section 6.2.2.1 [187]. Canada could also look to engage the United Kingdom and its HTGR experience through U-Battery, since this reactor vendor is based out of the United Kingdom and is pursuing deployment in both jurisdictions [202].

Germany also has operating experience with HTGRs and can be considered when looking for collaboration opportunities to develop harmonized standards or new national standards that reference existing standards for HTGRs. Both Japan and China are actively pushing for the development of HTGR technologies as well and can be pursued for potential collaboration.

6.3.2.2 Molten Salt Reactors

A binational collaboration between the United States and Canada on molten salt reactors exists through the joint technical review by the CNSC and US NRC of Terrestrial Energy's IMSR. As both these regulators conduct reviews of this technology, gaps in standards could be addressed through the development of regional (binational) standards that would support this parallel regulatory process. The NEI completed a study in March 2020 that identified gaps related to the SMR industry and noted several opportunities related to molten salt reactors, such as the development of new standards, including ANS-20.2, *Nuclear Safety Design Criteria and Functional Performance Requirements for Liquid Fuel Molten Salt Reactor Nuclear Power Plants,* which is a standard that is currently under development and which Canada could look to collaborate on [188], [203]. Additionally, lessons learned from the operation of the Molten Salt Reactor Experiment discussed in Section 6.2.2.2 could be shared [189]. Opportunities for binational molten salt reactor collaboration with the United Kingdom also exist. The Stable Salt Reactor by Moltex is a design based out of the United Kingdom and supported by the UK government's Advanced Modular Reactor initiative [204]. A joint review between the UK and Canada could support standards collaboration with the United Kingdom to address any gaps noted in the existing standard framework. Additionally, Canada may be able to collaborate on the development of chloride MSR standards, which will differ from fluoride

MSR standards. Moltex, from Canada and the United Kingdom, and TerraPower, from the United States, are vendors that use chloride salt in their designs, and future collaboration and lessons learned may allow for opportunities for binational or trinational standards to be developed.

When searching for collaboration opportunities for MSRs, Canada should consider developing international standards with the United States, China, Japan, Russia, China, and France, all of which have past experience with MSRs. Historically, the United States has been more engaged with MSRs; however, other countries now have increased interest in this reactor type. While China is considered the global leader for research, Japan, Russia, France, and the United States have increased their interest in MSRs due to the advancement of Generation IV technology [205].

6.3.2.3 Sodium-Cooled Reactors

To help address identified gaps in Canadian standards associated with sodium-cooled reactors, Canada could take advantage of the ARC-100 design being based off the EBR-II reactor that operated at Oak Ridge National Laboratory. By collaborating with stakeholders with ARC-100 expertise and reviewing publications regarding the EBR-II demonstration reactor, existing standard gaps within Canada may be closed. There is significant industrial experience on the proper handling of caustic and reactive molten materials as well as direct experience from reactors such as the EBR-II to inform the development of an appropriate standard for Canada.

Like other technologies, there may be situations where it would be beneficial for Canada to participate in or reference existing standards rather than developing new national or international standards. For example, Canada could reference ANS-54.1 [R], *Nuclear Safety Criteria and Design Process for Liquid-Sodium-Cooled Nuclear Power Plants,* published in 2020, and participate in the development of ANS 30.1, *Integrating Risk and Performance Objectives into New Reactor Nuclear Safety Designs,* which is in the process of being drafted [206]. Particular attention should be given to standards that are being developed with support from national regulators, such as ANS-30.1, referenced above [206].

Metallic sodium is being developed in concentrated solar power applications as a heat transfer fluid. The nuclear industry could draw from lessons learned and best practices as concentrated solar draws from over 30 years of experience handling liquid metals [207]. An example of where this could be useful is isolation between high-temperature liquid sodium and steam, which react and can cause fire [208]. Lessons learned and best practices from the concentrated solar industry may be adapted to address needs within the nuclear industry.

Other jurisdictions such as the United States, China, India, the United Kingdom, Russia, Japan, Germany, and France have experience operating sodium-cooled reactors [173], and this experience could be leveraged to develop international standards. New build reactors are also planned or in progress in the United States, India, and China which may present additional collaboration opportunities for new standards development [173].

6.3.2.4 Solid Core Reactors

Westinghouse is actively engaged with both the CNSC and US NRC with respect to its eVinci micro reactor. The US Department of Energy (DOE) experience with heat pipe cooled reactors comes from its research at Los Alamos National Laboratory on scalable megawatt power heat pipe cooled reactors. This could be valuable for Canada if it were to leverage the existing research efforts for heat pipe cooled reactors to develop standards.

Additionally, heat pipes are commonly used in many other industries, including spacecraft and computer systems; as such, there may be opportunities to identify best practices and lessons learned. For example, the aerospace industry case study in Section 5.1 highlighted that the establishment of regional harmonization can lead to national agreements for common national rules, certification procedures, and joint certification of products across countries provided regular inspections occur to ensure compliance.

When looking for collaboration opportunities, Canada should consider the work completed by Atomic Energy of Canada Ltd. in the mid-1980s in collaboration with

Los Alamos National Laboratory, and the work of NASA on sodium heat pipe cooled reactors. Canada could collaborate with other jurisdictions like the United States to develop harmonized regional standards and, depending on the progress of the technology and the status of demonstration efforts, international standards could be developed as well.

7 Summary & Conclusions

The availability of appropriate standards will help support the successful deployment of SMRs. In developing standards to support these new technologies, nuclear sector stakeholders should consider the available standardization approaches and harmonization opportunities and should benchmark approaches to other sectors that have developed standards for new technologies.

Four high-level standardization approaches have been discussed in this report: national standards, regional standards, international standards, and the adoption of international standards. Generally, international standards are used to document best practices or requirements that are used around the globe, regional standards can be used to address specific regional requirements, and national standards can be developed to close gaps in more broadly harmonized standards and provide country-specific best practices or requirements.

Two case studies were completed examining standardization approaches of the aerospace and electric vehicle industries, due to their similarities to the nuclear industry. By evaluating these industries, best practices and lessons learned were identified with respect to development of international standards, regional standards, national standards, and standards for new technologies. It was shown that:

- At the international level, highly regulated industries can benefit from the development of mandatory international safety standards that must be incorporated into the national framework while allowing for small national variations.
- At the regional level, regionally similar countries can establish harmonized national rules and licencing procedures and develop harmonized standards through national SDOs that have different designations.
- At the national level, countries can adopt international standards and incorporate specific national requirements to better fit their needs, SDOs should actively participate in international standards development opportunities, and SDOs should consider the future evolution of industries and maintain standards to allow for innovation while still promoting safety.
- A combination of national, regional, and international standardization approaches should be used for new technologies; performance-based standards should be implemented to allow for variations in technology; and harmonized standards should be developed where possible.

To support the evaluation of appropriate standardization approaches for SMRs in Canada, the SMR landscape in Canada was investigated. This investigation included the development of an overview of each of the SMR technologies progressing through licensing evaluations within Canada. Existing standards or gaps associated with each of the technologies were also discussed at both the national and international levels. Due to the close relationship between standards and regulations, SMR harmonization activities at both the regulatory and industry levels (such as MDEP and CORDEL) were evaluated.

For light water reactors, due to their widespread deployment, there are a significant number of national standards and working groups around the world addressing both pressurized water reactors and boiling water reactor designs. As such, and based on similarities with existing CANDU PHWRs, any gaps within the Canadian nuclear standards for these reactor designs could be addressed by referencing existing standards from similar jurisdictions. International collaboration could also be leveraged to support harmonization between jurisdictions, by adopting existing international standards or developing new regional or international standards.

Generation IV and advanced reactor designs have fewer experimental, demonstration, and commercial reactors that can be leveraged for operating experience. Consequently, existing standards are less equipped to accommodate the more novel aspects of these reactor technologies. For jurisdictions

considering the deployment of the same reactor technologies, collaboration between both SDOs and regulators could support increased regulatory and standards-based approvals. Canada could also collaborate with these jurisdictions to develop new national standards that reference existing standards or develop harmonized regional and international standards where needed, based on progress of ongoing technology demonstration and commercialization efforts.

Based on the best practices and lessons learned from the case studies, the current SMR landscape in Canada, and analysis of standardization and harmonization activities within the nuclear sector, recommendations on potential SMR standardization approaches for Canada have been developed. The selected standardization approach will depend on the reactor technology, assessment of gaps against existing national standards, urgency to address gaps, possibility of collaborating with other jurisdictions with relevant operating experience or those considering the technology for deployment, and availability of existing standards.

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Appendix

List of Referenced Standards and Regulations

The following standards and regulations are referenced throughout the report. This list contains standards and regulations from several industries, including but not limited to the nuclear industry, electric vehicle industry, and aerospace industry. The standards and regulations found here serve as examples within the report and are not meant to serve as a comprehensive list for any industry, including the nuclear sector.

- Nuclear Safety and Control Act (NSCA)
- ISO 9001, Quality Management Systems – Requirements
- CAN/CSA-ISO/IEC 15026-2:13, Systems and Software Engineering – Systems and Software Assurance – Part 2: Assurance Case
- CSA N285.0/CSA N285.6, General Requirements for Pressure-Retaining Systems and Components in CANDU Nuclear Power Plants/Material Standards for Reactor Components for CANDU Nuclear Power Plants
- ASME Boiler and Pressure Vessel Code Section III, Rules for Construction of Nuclear Facility Components Set, Division 1 (ASME BPVC, Section III, Division 1)
- CSA C22.1, Canadian Electrical Code
- CAN/CGSB-44.227-2017, Free-Standing Office Desk/Table, Storage Products and Components
- ISO 14001:2015, Environmental Management System
- CAN/CSA-ISO 14001-16, Environmental Management Systems – Requirements for Guidance for Use
- AS9100D, Quality Management Systems – Requirements for Aviation, Space, and Defence Organizations
- EN 9100:2018, Quality Management Systems – Requirements for Aviation, Space, and Defence Organizations
- JIS Q 9100:2016, Quality Management Systems – Requirements for Aviation, Space, and Defence Organizations
- DO-178: Software Considerations in Airborne Systems and Equipment Certification
- Doc 9760, Airworthiness Manual
- SAE AS8024-19, JAUS Autonomous Capabilities Service Set
- SAE AS6983, Process Standard for Qualification of Aeronautical Systems Implementing AI: Development Standard
- ASTM F3298-19, Standard Specification for Design, Construction, and Verification of Lightweight Unmanned Aircraft Systems (UAS), SAE AS6983
- IEC 61851, Electric Vehicle Conductive Charging System
- CSA C22.2 No. 49 / ANSI/UL 62 / NMX-J-436-ANCE, Flexible Cords and Cables
- CAN/CSA C22.2 No. 280 / ANSI/UL 2594 / NMX-J-677-ANCE, Electric Vehicle Supply Equipment

- CAN/CSA C22.2 No. 281.1 / ANSI/UL 2231-1 / NMX-J-668/1-ANCE, Standard for Safety for Personnel Protection Systems for Electric Vehicle (EV) Supply Circuits: General Requirements
- CAN/CSA C22.2 No. 281.2 / ANSI/UL 2231-2 / NMX-J-668/2-ANCE, Standard for Safety for Personnel Protection Systems for Electric Vehicle (EV) Supply Circuits: Particular Requirements for Protection Devices for use in Charging Systems
- CAN/CSA C22.2 No. 282 / ANSI/UL 2251 / NMX-J-678-ANCE, Plugs, Receptacles, and Couplers for Electric Vehicles
- EN 50620:2017, Electric Cables – Charging Cables for Electric Vehicles
- EN 17186:2019, Identification of Vehicles and Infrastructures Compatibility – Graphical Expression for Consumer Information on EV Power Supply
- EN ISO 15118-1:2019, Road Vehicles – Vehicle to Grid Communication Interface – Part 1: General Information and Use-Case Definition
- Motor Vehicle Safety Act (1993, c. 16)
- Motor Vehicle Safety Regulations (C.R.C., c. 1038)
- Canadian Motor Vehicle Safety Standards (CMVSS)
- Federal Motor Vehicle Safety Standards (FMVSS)
- CSA C22.2 No 348, Vehicle to Grid Charging Equipment
- ISO 18229:2018, Essential Technical Requirements for Mechanical Components and Metallic Structures Foreseen for Generation IV Nuclear Reactors
- ASME Boiler and Pressure Vessel Code Section III, Rules for Construction of Nuclear Facility Components Set, Division 5, High Temperature Reactors (ASME BPVC, Section III, Division 5)
- ANS-20.2, Nuclear Safety Design Criteria and Functional Performance Requirements for Liquid-Fuel Molten-Salt Reactor Nuclear Power Plants
- ANS-20.1, Nuclear Safety Criteria and Design Criteria for Fluoride Salt-cooled High-temperature Reactors
- SFR-DC 73 (RG 1.232), Guidance for Developing Principal Design Criteria (PDC) for Non-Light-Water Reactors
- IEC TR 63335:2021, Nuclear Power Plants – Instrumentation and Control Systems, Control Rooms and Electrical Power Systems – Specific Features of Small Modular Reactors and Needs Regarding Standards
- NUREG/CR-6824, Materials Behavior in HTGR Environments
- ANS-54.1 [R], Nuclear Safety Criteria and Design Process for Liquid-Sodium-Cooled Nuclear Power Plants
- ANS 30.1, Integrating Risk and Performance Objectives into New Reactor Nuclear Safety Designs

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In order to encourage the use of consensus-based standards solutions to promote safety and encourage innovation, CSA Group supports and conducts research in areas that address new or emerging industries, as well as topics and issues that impact a broad base of current and potential stakeholders. The output of our research programs will support the development of future standards solutions, provide interim guidance to industries on the development and adoption of new technologies, and help to demonstrate our on-going commitment to building a better, safer, more sustainable world.

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