MSc Program
Environmental Technology & International Affairs

A Comprehensive Assessment of Gen-IV Small Modular Reactors: Challenges and Opportunities

A Master's Thesis submitted for the degree of
“Master of Science”

supervised by
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Vienna, 11.06.2024

Affidavit

I, **HARRISON MAVRIC, BA**, hereby declare

1. that I am the sole author of the present Master's Thesis, "A COMPREHENSIVE ASSESSMENT OF GEN-IV SMALL MODULAR REACTORS: CHALLENGES AND OPPORTUNITIES", 62 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
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Abstract

Generation-IV Small Modular Reactors (GEN-IV SMRs) with power levels between 10 and 300 MW_e have the potential to transform the nuclear energy landscape by providing safer and more efficient alternatives to traditional nuclear power plants (NPPs). While there is great potential for these reactors, challenges are found in each aspect of their development. The current status of active, land-based Generation-IV Small Modular Reactor projects, falling under the categories Very-High Temperature Reactor (VHTR), Gas-cooled Fast Reactor (GFR), Sodium-cooled Fast Reactor (SFR), Lead-cooled Fast Reactor (LFR), and Molten Salt Reactor (MSR), is presented. The challenges and opportunities applying to Gen-IV SMRs in the context of national and international regulations and nuclear safety, security, and safeguards are discussed. An analysis of the complex interdependence between private finance, government support, supply chains, technological development, and international competition emphasizes the importance of government decision-making. Challenges and opportunities regarding public trust finds Gen-IV SMRs have unique opportunities. A synthesis of this research is given in the discussion, and conclusions are provided.

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List of Abbreviations

CNS	Convention on Nuclear Safety
CNSC	Canadian Nuclear Safety Commision
CSA	Comprehensive Safeguards Agreement
DHR	Decay Heat Removal
EIA	Environmental Impact Assessment
Gen-IV SMRs	Generation-IV Small Modular Reactors
GFR	Gas Fast Reactor
GIF	Generation-IV International Forum
HTGR	High-Temperature Gas Reactor
IAEA	International Atomic Energy Agency
LBE	Lead-Bismuth Eutectic
LEU	Low Enriched Uranium
LFR	Lead-cooled Fast Reactor
LoFC	Loss of Forced Cooling
LoPC	Loss of Power/Cooling
MOX	Mixed Oxide Fuel
MSR	Molten Salt Reactor
MWe	Megawatts electricity
NHSI	Nuclear Harmonization and Standardization Initiative
NPP	Nuclear Power Plant
NPT	Non-Proliferation Treaty
PPP	Public-Private Partnerships
SCWR	SuperCritical Water-cooled Reactor
SDC	Safety Design Criteria
SFR	Sodium-cooled Fast Reactor
SMR	Small Modular Reactor
TRISO	TRi-structural ISOtropic
VHTR	Very-High Temperature Reactor

1. Introduction

Averting the worst effects of the climate crisis will only be possible through a global concerted effort to develop sustainable, resilient low-carbon energy sources. The IPCC's Sixth Assessment Report (2022) underscores the critical window for limiting global warming to 1.5 degrees Celsius, which requires immediate and large-scale reductions in greenhouse gas emissions. It also stresses that achieving this goal is still possible with rapid and far-reaching transitions in energy, land, urban infrastructure, and industrial systems. Technological innovation and rapid uptake of new technologies is necessary to address growing energy demand and reduce greenhouse gas emissions. While renewable energy technologies should be invested in heavily, there is need to provide an alternative to traditional base load power sources. Within this context, fourth generation Small Modular Reactors (SMRs) have the potential to transform the nuclear energy landscape by providing safer and more efficient alternatives to traditional nuclear power plants (NPPs).

Generation IV Small Modular Reactors are the embodiment of the latest advancements of nuclear technology. For the purpose of this research, and in many cases, Generation-IV SMRs are defined as nuclear reactors with a power output between 10 and 300 Megawatts electricity (MWe) and fall under one of the following categories: Very High Temperature Reactor (VHTR), Gas-cooled Fast Reactor (GFR), Sodium-cooled Fast Reactor (SFR), Lead-cooled Fast Reactor (LFR), Molten Salt Reactor (MSR), and SuperCritical Water-cooled Reactor (SCWR) (Pioro and Rodriguez, 2023; NEA, 2024b). Reactors in these categories differ from previous generations by using novel cooling technologies and passive safety systems. Additionally, they use advanced fuel and material which are able to operate under higher temperature.

Generation IV Small Modular Reactors represent a significant milestone in the evolution of nuclear technology. They have the advantage over generation 3(+) SMRs by offering inherent safety features, higher efficiencies, and simpler designs. Their versatility in application, siting, scalability and deployment provides a nuclear option where large NPPs would be considered impractical. Gen-IV SMRs have the potential flexibility to accommodate energy systems with high intermittent energy generation (solar, PV), being used as the base load source. Other applications, such as hydrogen production, desalination, and industrial heat gases, are also potential opportunities.

Construction costs and times are significantly reduced by constructing SMRs off-site and transporting them to their final location, and their scalability allows for step-up deployment in order to meet increasing demand over time. The smaller size, reduced material cost and nuclear waste also lead to a reduced environmental impact. The reduced capital costs for developing SMR projects has allowed for private companies to invest in and develop the technology. This represents a paradigm shift in the nuclear energy regime, as traditional NPP projects have typically been developed through government projects and investment. Economies of scale through standardization could allow for lower capital costs in all phases of a reactor's lifetime. Gen-IV SMRs can be a flexible, inherently safe, environmentally friendly, and commercially viable alternative to traditional NPPs.

Commercial interest in SMR technology has the potential to accelerate innovation and propel the nuclear industry forward. However, Gen-IV SMRs face several unique challenges in reaching large-scale technological adoption including, but certainly not limited to: Engineering, design, government regulation and support, safety, supply chains, finance and competition, and public perception. All categories of Gen-IV SMRs face one or more forms of engineering and design challenges. Most Gen-IV SMRs in active development are still in the design phase. There are many concerns regarding new, untested technology. Selecting the resilient materials and components, able to withstand the high temperatures and radiation over the lifetime of the reactor, is critical to reactor design. Advanced cooling systems, such as those found in the Gas-cooled Fast Reactor (GRF), Sodium-cooled Fast Reactor (SFR), Lead-cooled Fast Reactor (LFR), and Molten Salt Reactor (MSR), each have their own set of challenges when it comes to material integrity, power supply, and safety. Designs must ensure that scaling up and adding additional reactors does not increase risk in any substantial form. As these technologies progress from the design phase to testing and eventual deployment, continuous innovation and rigorous validation will be key to overcoming these concerns.

Additional challenges come in the form of regulation on international and national levels. On an international level, there are several legal instruments concerning safety, environmental protection, and public participation which apply to SMRs. There is also the issue of a lack of harmonization between states when it comes to licensing approaches, which can lead to issues in deploying internationally. Nationally, depending on the licensing and development framework of the regulatory organization, it may be more or less difficult to receive design and deployment approval. However, on the other side of the matter, states must make a concerted effort to establish harmonized frameworks, codes, and standards to facilitate the development of Gen-IV SMR technology through international collaboration. This may involve significant revamping of numerous processes within national regulatory organizations.

There is a complex interplay between government support, economies of scale, international competition and supply chains, and technology choice when it comes to developing Gen-IV SMRs. Commercial viability for SMR reactors is only possible with a handful of international competitors due to economies of scale and high cost of development. Meanwhile there are many Gen-IV SMR designs in active development globally. States will have to decide on whether to pursue development of a wide range of Gen-IV technology, or to 'lock-in' to a particular design and facilitate its commercialization. As research continues, the superior designs should become more apparent, and decision-making will become more informed. As Gen-IV reactor technology develops and the number of competitors reduce, private companies will be able to attain greater market share, thus reducing costs and creating a more robust, secure, and standardized supply chain. Choosing the correct design to commercialize will be critical to national regulatory organizations, and it can only be done through long-term support in the development of these projects through to their deployment.

Public perception of nuclear technology has been a major challenge to the development of the industry for several decades. This has led to the reduction and stoppage of construction of new NPPs and has hindered technological innovation in the nuclear industry. While it can be said that the public is becoming more aware of the importance of nuclear technology and its need in the energy transition, public trust has remained low. Major nuclear accidents, while sporadic, have had an enormous impact on the public's perception of the nuclear industry. The only remedy for this issue is the continued enhancement of safety features, technologies, standards, and processes throughout the lifetime of all nuclear projects to reduce the risk of any accidents. Indeed, a strong safety culture is critical throughout the design, construction, and operation of any nuclear reactor. Nevertheless, the absence of nuclear accidents does not do much to improve public trust in nuclear energy. Public engagement, particularly in areas of potential siting, is vital to building trust. Public awareness and education campaigns, transparency regarding safety measures and risk assessments, and independent assessments by third parties in addition to regulatory bodies are just some actions that can be taken to improve public trust. Ultimately, building a partnership between the nuclear industry and the public based on transparency, engagement, and education will be key to overcoming skepticism and fostering a more informed and supportive attitude towards nuclear technology.

The goals of this research are to identify the current state of development for Generation IV Small Modular Reactors, to analyze the potential opportunities that may arise in their development and examine the challenges that are and will be encountered in development, deployment, and operation. The research will be presented as follows: The methodology to this research will be provided in the following chapter. After which a list of all active Gen-IV SMR projects, and the international groups working toward the development of Gen-IV SMR technology, will be presented. Also included in this chapter are the individual categories of Gen-IV SMRs and the development challenges that each category of reactor faces. International and national regulations are discussed in chapter 4. In chapter 5, the safety challenges and opportunities will be addressed. Nuclear security and safeguards will be the main topic in chapter 6. Chapter 7 will analyze the complex interdependence of private finance, government support, international competition, market concerns, supply chains, and economies of scale. Chapter 8 will consider the challenges of public perception of the nuclear industry and the potential to improve this perception. Chapter 9 will review the contents of the research to present a synthesis of the literature, as well as conclude the research by identifying the reactor category with highest deployment potential.

The potential for Generation-IV Small Modular Reactor to play a significant role in the future energy transition is quite high due to their diverse applicability and intrinsic safety. However, significant challenges, specifically related to economics, regulation, public perception, and design, indicate that large-scale adoption and use of Gen-IV SMR technology will be incremental. The path forward will require a concerted effort by national and international institutions to develop a framework under which this technology can grow, and for private SMR companies to communicate and cooperate to standardize various aspects of Gen-IV SMRs across the industry.

2. Methodology

As the goal of this research was to understand the current state of development of Gen-IV SMRs, analyzing the potential opportunities and challenges in their development, the method of research chosen was a literature review. A list of all active Gen-IV SMR projects was produced, including the country in which the reactor was developed, the designer, and current status. Projects which showed no indication of being in development were not included. This list contributes directly to understanding the current status of Gen-IV SMRs – The number of projects, where they are located, and the company's webpage are all useful pieces of information. This list is a powerful tool in understanding and keeping track of advancements in the industry. In addition, completing the list confirmed that there are no SCWR SMRs in active development, as a result of this, SCWR reactors are not included in this research. The Gen-IV SMR categories as defined by the Generation-IV International Forum (other than SCWR) were analyzed. In this analysis, the design challenges for each category, as well as their opportunities in utilization and application, were examined. Furthermore, the safety concerns/considerations for each category of reactor were established. This directly contributes to the research questions by exploring the challenges and opportunities unique to each category of Gen-IV SMR. This is a necessary step in this research, as each category of reactor has distinct operational parameters that influence their design, potential applications, and safety concerns. In addition, a comparative assessment of the categories may allow for identification of the most promising of these reactor categories. The topics of national and international regulation, nuclear safety, nuclear security, private finance, public perception, and government support directly influence the development of Gen-IV SMRs. Each of these topics are examined from the frame of both challenges to development and opportunities created for the Gen-IV SMR industry, rather than each reactor category.

Each reactor category was assessed via the criteria below to score the reactors based on their potential for deployment relative to the other categories. The scoring was a basic +, -, or 0 for a reactor that has an advantage, disadvantage, or equal, respectively, for a given category. The reactor scores are considered and compared to the number of active projects in each category. This comparison allows conclusions to be drawn about the influence of private finance on the industry and the potential for deployment. The categories and aspects under those categories used for scoring are given in table 1 below.

Table 1: Categories for Reactor Scoring and Aspects Consider under each Category

Category	Aspects Considered
Nuclear Safety	Reactor design, engineering challenges, material and component challenges, passive features, previous safety demonstrations, cooling, fuel cycle, supply chain
Nuclear Security	Security by design, fuel cycle, supply chain, walkaway capability, monitoring
Nuclear Safeguards	Safeguards by design, fuel cycle, supply chain, monitoring, verification
Utilization	Application, scope of application, co-location, power density

Digital data collection and analysis was done using academic search engines such as Google Scholar and Science.gov. Many publications were also found via basic Bing search and Elsevier. Data was initially analyzed by surveying its applicability to the subject. Following initial survey, applicable data was saved while non-applicable data was discarded. Further analysis of the data was then organized via highlighting, comments, and organizing them into appropriate categories (safety, regulation, design, etc.) for ease of access. Mendeley was used as the citation software and annotation software.

Research bias was avoided in the following manner: A comprehensive literature search was conducted to reduce selection bias. Inclusion and exclusion criteria remained strict throughout the collection process. Only active designs were included in the list of reactors – to be considered 'active' within the context of this research, the reactor's developer must be operational and must have relevant publications on research, advancements, or project updates published from 2016 onwards. Only land-based Gen-IV SMR reactors with 10 to 300 MWe output with designs falling into the 6 categories (VHTR, SFR, LFR, MSR, GFR, and SCWR) could be considered in this research. Considering marine based challenges in addition would be too large a scope for this research. Literature addressing the non-design facets of SMRs (regulation, public perception, safety, etc.), could be considered for inclusion if the information is relevant to the specific challenges and prospects encountered by Gen-

IV SMRs. There were several times, due to the projects excluded, that revisions of the initial criteria were considered, this was, however, ultimately rejected in favor of keeping to the original methodology. The research methodology employed a critical and comprehensive approach to the selection of literature to mitigate the risk of research bias.

3. State of the Art

An understanding of the current status of Gen-IV SMR development requires an overview of the current projects in active development, as well as the international collaborations and organizations working to develop the technology.

Active Gen-IV SMR projects

Table 2 below provides a list of all active Gen-IV SMR projects. Many of these projects are in various stages of design, while a few are in the pre-licensing or licensing stages of their development.

Table 2: List of all Active Generation IV Land-Based Small Modular Reactors in Development

Design	Power Output (MWe)	Type	Designer	Country	Status
4S [1,3]	30 - 135	SFR	Toshiba Corporation	Japan	Detailed Design
ALFRED [9]	125	LFR	Ansaldo Energia	Italy	Conceptual Design
Allegro[4]	75 (Thermal)	GFR	V4G4 Centre of Excellence	Czech Republic	Conceptual Design
ARC-100 (PRISM) [1,2]	100	SFR	ARC Nuclear Canada Inc.	Canada	Pre-Licensing
BREST-OD-300 [1]	300	LFR	NIKIET	Russian Federation	Under Construction
CA Waste Burner [11]	100 (thermal)	MSR	Copenhagen Atomics	Denmark	Conceptual Design
EM^2 [1,2,3]	265	GMFR	General Atomics	United States of America	Conceptual Design
HTMR-100 [5]	35	HTGR	Stratek Global Advanced Energy Solutions	South Africa	Pre-Licensing
HTR-PM [1,2,3]	210	HTGR	INET, Tsinghua University	China	Operational
HTTR-30 [6]	30 (thermal)	HTGR	JAEA	Japan	Operational
Integral MSR [1,2]	195	MSR	Terrestrial Energy Inc.	Canada	Basic Design
KP-FHR (Hermes) [1,2]	140	MSR	KAIROS Power, LLC.	United States of America	Construction Phase
LFLEUR [12]	25 - 100	MSR	Flibe Energy, Inc.	United States of America	Conceptual Design
LFR-AS-200 [10]	200	LFR	NewCleo	United Kingdom	Conceptual Design
LFR-AS-30 [10]	30,00	LFR	NewCleo	United Kingdom	Basic Design
LFTR [13]	100 - 250	MSR	Flibe Energy, Inc.	United States of America	Conceptual Design
SC-HTGR [7]	272	HTGR	Framatome, Inc.	France	Conceptual Design
Seaborg MSTW [14]	100	MSR	Seaborg Technologies	Denmark	Conceptual Design
smTMSR-400 [1]	168	MSR	SINAP, CAS	China	Pre-Conceptual Design
Stable Salt Reactor – Wasteburner [1,2]	300	MSR	Moltex Energy	UK/Canada	Conceptual Design

Table 2: List of all Active Generation IV Land-Based Small Modular Reactors in Development

Design	Power Output (MWe)	Type	Designer	Country	Status
StarCore [8]	14/20/60	HTGR	StarCore Nuclear	Canada/US/UK	Pre-Conceptual Design
SVBR-100 [1, 3]	100	LMFR	JSC AKME Engineering	Russian Federation	Detailed Design
ThorCon [15]	250	MSR	ThorCon International	International Consortium	Basic Design
Xe-100 [1, 2, 3]	82.5	HTGR	X-Energy LLC	United States of America	Basic Design

Sources:

[1] – IAEA (2020a)
[2] – NEA (2024b)
[3] – Ingersoll (2020)
[4] – ÚJV Řež, a. s. (2024)
[5] – Stratek Global (2024)
[6] – JAEA (2021)
[7] – Framatome (2019)
[8] – Starcore Nuclear (2024)
[9] – Nuclear Engineering International (2021)
[10] – newcleo (2024)
[11] – Copenhagen Atomics (2024)
[12] Flibe Energy (2024a)
[13] Flibe Energy (2024b)
[14] Schønfeldt and Klinkby (2017)
[15] ThorCon (2024)

A total of 24 projects have been included in the list. Among these projects, 5 are being developed in the United States of America alone. Canada has 2 projects developing on their own while 2 additional projects are working together with the United Kingdom and USA. China is developing 2 projects, as well as Denmark, and Japan. France, Italy, and South Africa each have one active project in development, as well as the international consortium ThorCon. The V4G4 Centre of Excellence is a consortium with members from Hungary, Poland, the Czech Republic, Slovakia, and France. Eight reactors falling into the MSR category are in development – this is the most of any reactor category. There are 5 LFRs and 6 VHTRs in development, while GFRs, SFRs, and SCWRs number 2, 2, and 0, respectively. While this list is considered complete within the context of this research, additional Gen-IV SMRs which fall outside of the scope can be found in the sources listed below table one. These include marine-based designs, designs with electrical outputs far exceeding 300 MW or below 10 MW, and reactors where designs have stopped or were completed without moving further.

Notice a lack of standard nomenclature regarding the 'type' and 'status' columns of Table 2. Although a standard set of categories for reactor type has been prescribed by the Generation-IV International Forum (Pioro and Rodriguez, 2023; GIF, 2024), there is still significant variation in how developers describe and name their reactors, as well as their description of the reactor's status. Standardizing nomenclature is an issue for many aspects of Gen-IV SMR development – including licensing and safety criteria (Duffey and Hughes, 2023). A reason that developers are using non-standard nomenclature for their reactors could be to distinguish themselves from their competition, which is an important aspect when seeking private capital investment. Statuses of design stages also have varying nomenclature, and the terminology which is used is not often defined. Of course, private companies have an interest in keeping certain information about their reactor's status confidential, which would be a reason to remain ambiguous.

A brief description of the individual reactor characteristics, features, and their potential applications are given in the following section.

4S

The 4S reactor stands for Super-Safe, Small and Simple. It is a sodium-cooled pool-type reactor capable of electrical outputs of either 10 or 50 MWe. Potential applications are remote electrical generation, hydrogen production, and water desalination (for the larger configuration). The core lifetime is expected to be 30 years without refueling (for the smaller configuration), and the fuel used in the reactor is Low Enriched Uranium (LEU) – enriched to less than 20% (Toshiba Energy Systems & Solutions Corp., 2019; IAEA, 2020a).

ALFRED

ALFRED is a lead-cooled fast reactor developed by Ansaldo Energia in Italy. A demonstration unit is under construction near Pitesti (Nuclear Engineering International, 2021). ALFRED is currently designed to be a 125 MWe reactor using MOX fuel. Its application is largely intended for electrical generation.

Allegro

The gas-cooled fast reactor, Allegro, is being developed in the Czech Republic by an international consortium. It is intended to work as a demonstration for GFR technology and is not necessarily intended to be used further. The design of Allegro was chosen to use as many proven materials and technologies as possible to minimize cost, maximize reliability, and shorten development times (ALLEGRO, 2024; ÚJV Řež, 2024).

ARC-100

ARC-100 is an SFR in development by Arc Clean Technologies. It is a 100 MWe reactor with 20 year refueling cycles. It is intended to work with renewable energy sources and can also be utilized for hydrogen production and isotope generation, in addition to electrical generation. Construction is planned for the 2030s (ARC Clean Technology Canada, 2023; ARC Clean Technology, 2024).

BREST-OD-300

The BREST-OD-300 reactor employs LFR technology to produce 300 MWe using fuel enriched to no higher than 14.5%. As a result, the refueling cycle is significantly shortened to around 3-5 years. The reactor's intended purpose is as a demonstration reactor. The goal being to confirm the intrinsic safety aspects which are assumed in Gen-IV reactors and to optimize systems in processes involved in the reactor's operation (IAEA, 2020a).

CA Waste Burner

Copenhagen Atomics' Waste Burner is a molten salt breeder reactor, which uses thorium within its fuels to allow for breeding. Designed to fit in a shipping container, the reactor is foreseen to be applied in desalination and biofuel production. Coupling with existing nuclear sites allows for the possibility of converting transuranic wastes and starting a thorium-based cycle (IAEA, 2020a; Copenhagen Atomics, 2024).

EM^2

General Atomics' EM^2 is a gas-cooled fast reactor using helium. It has 265 MWe output with a core outlet temperature of 850°C. Refueling cycles are estimated to be around 10 years for the reactor, using LEU of around 14.5%. The net thermal efficiency of the reactor is 53%, as the reactor is designed for greater levels of fuel burnup. Applications for EM^2 are for electrical generation and process heat usage. (IAEA, 2020a; General Atomics, 2024)

HTMR-100

HTMR-100 is a pebble bed very high temperature reactor which uses graphite as a moderator and helium as a coolant. The reactor is able to produce 35 MWe and generate process heat for use in industry. The reactor is designed to accommodate numerous fuel types and cycles. The conceptual design of the reactor has been completed since 2022, and licensing procedures are underway (IAEA, 2020a; Stratek Global, 2024).

HTR-PM

One of the few Gen-IV SMRs currently operational (having begun commercial operation in December 2023), the High Temperature gas-cooled Reactor – Pebble-bed Module, developed by INET and Tsinghua University, consists of 2 reactor modules and a steam generator. Able to produce 210 MWe, the reactor is used to produce steam and electricity for industrial use. While larger versions of this design are foreseen, such as the HTR-PM600 (outside the scope of this research), additional modules of HTR-PM are proposed for construction at the same site (IAEA, 2020a; World Nuclear News, 2021, 2023).

HTTR-30

Another operational Gen-IV SMR is the High Temperature Engineering Test Reactor, designed by the Japanese Atomic Energy Agency (JAEA). This reactor was operational prior to 2014, but the events of Fukushima paused operation of reactor until the summer of 2021. The purpose of this reactor and the reason for its construction is the advancement of Gen-IV nuclear technology – material testing, proof of concept, and as a test bed for international cooperation and future projects (IAEA, 2020a; JAEA, 2021, 2024).

Integral MSR

The IMSR differs itself slightly from the other designs found in this research. Most importantly, the design of the core unit is done so as to allow the entire unit to be replaced at the end of the unit's lifetime (about 7 years) (IAEA, 2020a). This reduces the risk greatly as there is no requirement for maintenance or opening of the reactor. The reactor's output is 195 MWe and electrical generation is seen as its only major application (Terrestrial Energy, 2024). The IMSR is undergoing licensing and pre-licensing in Canada and the USA, respectively.

KP-FHR (Hermes)

The Kairos Power Fluoride salt-cooled High temperature Reactor is a pebble-bed molten salt reactor with 140 MWe output.(IAEA, 2020a) Its application is foreseen as purely for electrical generation (Kairos Power, 2024a). It has recently received its construction permit approvals from the United State Nuclear Regulatory Commission (USNRC) for a demonstration reactor in Oak Ridge, TN. (Kairos Power, 2023). In addition, an agreement was reached with the United States Department of Energy (USDOE) for a milestone-based approach for funding the design, construction, and commissioning of the reactor (Kairos Power, 2024b).

LFLEUR

The Lithium Fluoride Low Enriched Uranium Reactor is one of two relevant projects being developed by Flibe Energy. As this project was announced mere weeks before the publication of this research, there is significant data about this project missing (Flibe Energy, 2024a). It is a molten salt reactor using LEU fuel and will have between 25 and 100 MWe output.

According to preliminary descriptions, it seems that the reactor is intended to excel in water scarce regions (Flibe Energy, 2024b).

LFR-AS-200

This reactor's intellectual property holder was sold to Newcleo in 2021. Since then, the 200 MWe Lead-cooled Fast Reactor has been in development by the firm located in the UK. Non-electrical applications such as hydrogen production and sustainable chemicals are being explored (IAEA, 2020a; Battistin, 2022).

LFR-AS-30

Also being developed by Newcleo, the LFR-AS-30 is also a Lead-cooled Fast Reactor which is currently the focus of the developer. It produces 30 MWe power, uses Uranium/Plutonium oxide (MOX) fuel, and its application is largely for validation of new components on larger, more commercial reactors (newcleo, 2024). A demonstration plant, as well as an MOX fuel fabrication unit, are intended to be built in France by 2031 (Battistin, 2022; World Nuclear News, 2024).

LFTR

The Lithium Fluoride Thorium Reactor is the second reactor being developed by Flibe Energy. The MSR reactor is designed for 100 to 250 MWe power output, and the use of thorium is intended to reduce waste, increase reactor efficiency, and guarantee a stable supply of fuel. The reactor is intended to be coupled with a supercritical CO_2 gas turbine to generate electricity at high efficiency (IAEA, 2020a; Flibe Energy, 2024c).

SC-HTGR

The SC-HTGR is a high-temperature, helium-cooled reactor capable of producing 272 MWe and high temperature steam for industrial use. The reactor is intended to be built underground, and located near industrial facilities, where the steam, process heat, and electricity can be utilized (IAEA, 2018; Framatome, 2019).

Seaborg MSTW

The Seaborg Molten Salt Thermal Wasteburner is a MSR reactor operating on spent nuclear fuel and thorium. It is expected to produce 115 MWe output and can be utilized in district heating/cooling, as well as desalination (Schønfeldt and Klinkby, 2017).

smTMSR-400

The smTMSR-400 is a 168 MWe thorium breeding reactor. The thorium conversion is driven by LEU fuel and the power contribution from thorium is expected to be greater than 40%. Typical applications such as electricity generation and heat supply are intended, as well as possible uses for water desalination and hydrogen production (IAEA, 2020a; Guo *et al.*, 2023).

Stable Salt Reactor – Wasteburner

The Stable Salt Reactor – Wasteburner is a molten salt reactor which uses spent nuclear fuel and plutonium. In its continuous, baseload configuration, the reactor outputs 300 MWe. It is intended for use in countries with large stocks of spent nuclear fuel, where the waste can be burned to leave smaller volumes of shorter half-life waste. The reactor is currently in its second design review phase and hopes to soon be applying for licenses for construction (IAEA, 2020a; Moltex Clean Energy, 2024).

StarCore

StarCore is a VHTR built 30 meters beneath ground level, meant to withstand "the harshest environment" (IAEA, 2020a). The core lifetime is anticipated to be 5 years, after which the core will be removed and cooled before being sent to permanent storage. The fuel is expected to be TRIstructural Isotropic particles (TRISO). The reactor is expected to produce 14 – 60 MWe (Starcore Nuclear, 2024).

SVBR-100

The SVBR-100 is a Lead-bismuth cooled fast reactor being developed by JSC AKME Engineering in Russia. It produces 100 MWe power and can be utilized in electricity generation and desalination. The lead-bismuth coolant allows the reactor to operate at low pressure, and the core outlet temperature is relatively low. The project is planned for construction begin as early as 2025 (Zrodnikov *et al.*, 2011).

ThorCon

The ThorCon reactor is a 250 MWe reactor which has completed the basic designs under the development of ThorCon International (IAEA, 2020a). This is largely due to the fact that it is a scaled-up version of the Molten Salt Reactor Experiment which took place at Oak Ridge National Laboratory (Thorcon, 2024). The reactor's utilization is intended for developing states with fragile electrical grids, so the reactor is flexible in its output and can be started without external electrical supply (ThorCon, 2024).

Xe-100

The Xe-100 is a high-temperature, helium gas-cooled reactor with 80 MWe output (IAEA, 2020a). The reactor uses TRISO particles in a pebble bed as fuel and is capable of online refueling. Its application are largely electricity and process heat generation. The reactor is currently undergoing pre-licensing review by the USNRC and the Canadian Nuclear Safety Commission (CNSC) (NEA, 2024b; X-energy, 2024).

Relevant International Organizations and Collaborations

In addition to the individual reactor projects being developed, much work is being done by various international groups to help further Gen-IV SMR technology.

The Gen-IV International Forum (GIF) has been one of the leading efforts to develop Gen-IV technology for the last 2 decades (GIF, 2024). The forum is responsible for establishing working groups which have worked to create coherent and acceptable objectives for the furthering of GEN-IV technology. The forum's goals have emphasized safety, economics, reliability, and sustainability, while acknowledging the urgency to develop this technology for large-scale deployment in the coming decades (Pioro and Rodriguez, 2023). The six categories of Generation-IV SMRs used in this research are the categories established by GIF.

The International Atomic Energy Agency has played a major role in the development of Gen-IV SMRs. Numerous initiatives, Coordinated Research Projects, working groups, and international workshops were created and are being worked on in support of GEN-IV SMRs. Extensive safety design criteria have been established through international workshops led by the IAEA (Pioro and Rodriguez, 2023). Between 2014 and 2022, before joining the Nuclear Harmonization and Standardization Initiative (NHSI), the SMR Regulators Forum produced several reports through different working groups intended to further develop technical knowledge and address challenges to the industry's development (IAEA, 2024c). The NHSI was established in 2022 (Donovan and Calle Vives, 2023) with the ultimate goal of "effective global deployment of safe and secure advanced nuclear reactors" (IAEA, 2023d) through the standardization of SMR design, regulation, and construction practices. The NHSI was split into 2 major working groups, labelled "tracks". The NHSI Regulatory Track has worked to establish an international framework for cooperation between regulatory authorities on licensing and design reviews (IAEA, 2023f). It hopes to open the possibility of multinational design reviews in the future. The NHSI Industry track focuses on the developer side of the standardization and harmonization process – this focuses on the manufacturing, design, and operation of SMRs (IAEA, 2023f). This work is essential to the development of Gen-IV SMRs and has accelerated technological advancement.

The Nuclear Energy Agency's Small Modular Reactor Dashboard "provides a comprehensive assessment of the progress made by SMR designers…worldwide" (NEA, 2024a). The agency's annual publication on the subject assesses the progress of SMR projects in development based on 6 criteria: Licensing, Siting, Financing, Supply Chains, Engagement, and Fuel (NEA, 2024b). Within this assessment, the weaknesses and strengths of individual projects are highlighted. By identifying project weaknesses, developers have a better understanding of how they can bring their projects to deployment. The latest NEA SMR Dashboard publication lists 56 SMRs, including previous generation SMRs. The NEA also acts as the technical secretariat to GIF (Pioro and Rodriguez, 2023).

The European Industrial Alliance on small modular reactors is a European Union initiative intended to facilitate SMR deployment by the next decade. This is a novel initiative, having begun in 2024. Given the set of objectives set by the initiative, major topics of consideration seem to be supply chains, investment barriers, engagement and communication, and developing technology. However, it does not seem that work harmonizing regulatory considerations will take place in this initiative (European Commission, 2024).

Categories of Gen-IV SMR Design

Of the 6 categories of most-promising Gen-IV SMR technology, as adopted by GIF, 5 are currently under active development. Each of these categories face their own unique sets of challenges when it comes to reactor design and safety. In the section below, the general concepts and characteristics of the individual categories of reactor are provided and the technical challenges to developing the technology are given.

Very High Temperature Reactor (VHTR)

VHTRs, also known as High-Temperature Gas-cooled Reactors (HTGR) operate, as the name suggests, at temperatures typically higher than what would be seen in most reactors (usually around 750 – 950 °C). They are helium-cooled, graphite moderated and typically employ prismatic or pebble bed core designs with TRISO-coated fuel (OECD/NEA, 2022). Their high temperature makes them well suited for supplying process heat for a wide application of industrial purposes (Yan, 2023). In addition, the temperature increases the efficiency of thermal conversion for power generation (Duffey and Hughes, 2023).

There are a number of reactor and fuel characteristics that enhance the reactor's overall safety and make it such an attractive technology: The TRISO-coated fuel, helium coolant, and graphite moderator enable the removal of heat from the core without active (powered) cooling systems. HTTR in Japan has recently demonstrated that in the event of a Loss of Forced Cooling (LoFC), there are no accidents or release of radioactive material (JAEA, 2024; NEA, 2024b). TRISO-coated fuel has a very high thermal resistance, capable of reaching 1600 °C without issue. Reactors can be designed to never reach these temperatures even in the case of an accident, as a result the fuel will never be in danger of melting (Yan, 2023). If, despite these features, a reactor accident was to occur, the low core power density and high volume of graphite moderator should limit the rate at which the temperature rises, allowing significant time for response (NEA, 2024b). In addition, the negative temperature coefficient of reactivity would lead to a core shutdown in the case of rising temperatures (Nuclear Power, 2024).

There are nevertheless challenges to the VHTR. Advanced materials capable of resisting the high temperature and radiation for the duration of the reactor's lifetime is critical to the technology. At such high temperatures, interaction with water or other moderator with result in explosion (Duffey and Hughes, 2023). Designs need to take into account the potential ingress and assure that this is avoided. TRISO-coated fuel, while providing a stable barrier to the fission material within, is also not without its issues. Spent TRISO fuel has the disadvantage of taking up a large volume, with a relatively small amount of the fuel (10% volume) containing fission products. While technology for separating the uranium oxide from the TRISO-coating exist, significant work and time is required for the technology to reach practical utilization (OECD/NEA, 2022).

Gas-cooled Fast Reactor (GFR)

Of all categories of reactors, GFR are the most promising when it comes to the broad range of applications in which the reactor can be utilized coupled with the high-power density available in the core. These applications include electricity and heat generation, desalination, waste reduction, and breeding through the use of the fast spectrum (Waltar, Todd and Tsvetkov, 2012). They employ inert gases with high thermal conductivity such as helium or carbon dioxide as coolant. The use of air poses challenges to corrosion. The fast spectrum of the GFR allows for more efficient fuel cycles and reduced waste(Tsvetkov, 2023a).

Although GFR technology is extremely enticing due to the possible utilization, immense engineering challenges face this reactor, slowing progress to a near halt. A major obstacle to GFR development is the lack of advanced materials required for the reactor vessel and primary system components (Tsvetkov, 2023a). Thermal barriers protecting the metallic structure are exposed to temperatures of "up to 1 250°C for 1 hour; withstand helium velocities of about 60 m.s1 and depressurisation rates in the range of 2 MPa.s-1" (IAEA, 2021, pg. 21). In addition, temperature measurement at the core outlet needs to be improved – whether through improvement in measurement certainty or novel measurement methods (IAEA, 2021c). Extensive testing of novel materials in conditions mimicking that of a GFR core requires international cooperation to test and validate the results. Developing a Decay Heat Removal (DHR) system that does not require an external power input is also a significant challenge to developing a safe GFR (Tsvetkov, 2023b). Upon loss of cooling, gas fast reactors experience rapid temperature increases – this has created the need to develop high-temperature resistant, high-density fuel (Tsvetkov, 2023a). Major safety concerns and engineering challenges face the development of GFR technology.

Sodium-cooled Fast Reactor (SFR)

The most mature Gen-IV SMR design is the sodium-cooled fast reactor. Liquid sodium has excellent properties for use as a coolant, such as high boiling point, density, and thermal conductivity (IAEA, 2021c; Ohshima and Kubo, 2023). Its small neutron cross-section allows for a fast neutron system which generates greater fuel burnup and less waste (Joyce, 2018). The ability for SFRs to operate with a closed fuel cycle also reduces waste. The reactor can operate at low pressure with a high-power density (IAEA, 2021c). The low-pressure design of the core also eliminates the risk of coolant leakage due to flashing, reducing safety risks (Ohshima and Kubo, 2023). Further safety features come in the form of inherent negative reactive feedback in the reactor core, which has been proven for SFRs during demonstrations at EBR-II (Mochizuki *et al.*, 2014; Mochizuki and Muranaka, 2018; Kamide *et al.*, 2023).

Although the reactor design is close to deployment, there are still some challenges left in reducing safety risk. Foremost among these challenges is avoiding interactions between the liquid sodium and air/water. A reliable heat exchange system between the liquid sodium and cooling water is essential for the reactor's safety (IAEA, 2021c). Robust containment structures, with advanced material capable of withstanding the temperatures, corrosion, and radiation while ensuring that no leaks occur, are also needed. Regarding fuel, developing minor actinide bearing fuels with high temperature resistance will be a necessary step to utilizing the sustainability and waste reduction aspects of the reactor (Ohshima and Kubo, 2023). Finally, DHR in the event of Loss of Forced Cooling (LoFC) requires that the reactor be designed for natural convection (Vaidyanathan, 2024). These design concerns must be addressed in order to maximize the safety of the reactor.

Lead-cooled Fast Reactor (LFR)

LFRs are fast spectrum, high-temperature, low pressure reactors using lead or lead bismuth eutectic (LBE) as a coolant. Lead and LBE possess several advantages as a coolant: The reactor is able to run at atmospheric pressure and high-temperature due to the high boiling point and low vapor pressure of the coolant (Smith and Cinotti, 2023). The coolant does not react with air or water, which eliminate concerns which the SFR had. Lead acts as a reflector, ricocheting neutrons back at the core, improving the neutron economy. LBE has both its advantages and disadvantages when compared to lead as a coolant. LBE has a lower melting point than pure lead (125 °C v 327 °C), which reduces the risk of damage to the reactor and freezing of the coolant in the event of a reactor shutdown(Locatelli, Mancini and Todeschini, 2013). However, LBE is more expensive, and leads to higher maintenance and facility costs as it produces Polonium-210, a radioactive isotope which require removal from the coolant and primary circuit (Obara *et al.*, 2008).

Amongst the greatest challenges in the development of LFRs is the corrosive nature of the coolant on structural materials inside the core and the fuel cladding (Mikityuk, 2010). Developing materials capable of withstanding the corrosion and erosion caused by the coolant is critical to LFR viability. A solution is proposed an oxide coating is applied to the exposed steel by introducing oxygen to the reactor coolant. However, this process risks precipitating PbO in the reactor coolant, possibly leading to blockages and damage within the reactor, also, too low levels of oxygen reduce the oxide coating (Mikityuk, 2010; Locatelli, Mancini and Todeschini, 2013). The coolant is also relatively heavy, which will need to be considered in the structural design. The opacity of lead presents challenges to the monitoring of in-core components (IAEA, 2021c; Smith and Cinotti, 2023). Ultimately, ensuring development of this technology will require significant innovation and development of advanced materials.

Molten Salt Reactor (MSR)

Unlike the reactors listed above, MSRs employ a mixture of molten salts as both fuel and coolant. This is a closed cycle that allows for greater fuel burn up and greater thermal efficiency as the heat is being produced directly in the molten salt(World Nuclear Association, 2021). There is no need for fuel fabrication due to the nature of the fuel (Locatelli, Mancini and Todeschini, 2013). The molten salt is stable at high temperature and ambient pressure and does not react with air and water, reducing design complexity and costs (IAEA, 2021b). MSR SMRs can operate in the thermal or fast neutron spectrum. Negative coefficients of voiding and temperature reactivity feedback indicate that there is significant potential for safety benefits in the development of the reactor (Joyce, 2018).

Challenges to MSR technology development mostly stem from engineering, salt chemistry, and material issues. The molten salt is corrosive to metallic surfaces and removes the oxide coatings from vessels. Internal components such as valves and heat exchangers are also a major issue (IAEA, 2021b). Advanced nickel coatings are considered possible solution but require further development (Locatelli, Mancini and Todeschini, 2013). The fission reaction produces gaseous fission products, lanthanides, and actinides, as well as noble metals and gases. These products need to be removed using various processes occurring both online and offline (Locatelli, Mancini and Todeschini, 2013). The graphite moderator also requires periodic replacement to avoid a positive reactivity coefficient (IAEA, 2021b). Novel material structures are critical to MSR development as current materials are largely insufficient for the duration of the expected lifetime of these MSRs. In addition to the engineering and material challenges, further research on the potential salt and material combinations is critical for development of SMR technology (Aguiar *et al.*, 2020; IAEA, 2021b). However, experimentation of new salts and validation of the data is a significant task, and reducing this burden by developing a salt properties database would be a significant step in the right direction (IAEA, 2021b). Overcoming these challenges depends upon both innovative engineering solutions and international scientific research to ensure the viability and safety of this reactor.

4. National and International Regulation

All nuclear facilities are governed by comprehensive national and international regulations ensuring safety, security, and non-proliferation of nuclear material (ENS, 2024). The applicability of many of these regulations to Gen-IV SMRs however, has been questioned (IAEA, 2020b, 2023a; OECD, 2021). In addition to nuclear-related regulation, topics of environmental protection and public involvement are also aspects of international law affecting Gen-IV SMR development, particularly in the siting and deployment stage. Within this chapter, the licensing regime of states is also examined. The national legal and regulatory frameworks vary across states. This can be due to the varying goals, expectations and requirements, or foundational aspects of the framework (IAEA, 2022). It is not only the developers which must adapt to the regulations, but regulators may need to adapt their legal frameworks, regulations, or guidelines to allow for effective technological development and eventual deployment (IAEA, 2022).

International Regulation

International legal instruments and treaties governing nuclear facilities fall under the topics of safety, security, safeguards, liability and compensation. While these are not specific to Gen-IV SMRs, these regulations remain influential to their development. Developers of Gen-IV SMRs must adhere to existing regulations by demonstrating their reactor designs meet safety, security, and safeguards requirements. Early engagement with international organizations and regulatory bodies is essential to the successful design and development of Gen-IV SMR projects (IAEA, 2022). On the other hand, international regulation, particularly those related to safety, needs to effectively apply to Gen-IV SMRs without hindering their development (IAEA, 2023a).

The IAEA, according to its statutes, is to establish "standards of safety for protection of health and minimization of danger to life and property, and to provide for their application" (IAEA, 2016, pg. XI). This has led to the establishment of the IAEA safety standards, a set of documents reflecting an international consensus which establishes "fundamental safety principles, requirements and measures" to assure proper protection from the effect of ionizing radiation (IAEA, 2016, XII). These documents are not legally binding; however, they should be, and are, used as reference points for national regulatory bodies. The work done to produce updated versions of these documents is an immense task which requires significant international collaboration, input, and review. The Convention on Nuclear Safety (CNS) is the treaty established under the auspices of the IAEA which commits member states to high levels of safety for all nuclear installations (IAEA, 2023c). The treaty mandates that member states maintain a legislative and regulatory framework, maintain a regulatory body, and prioritize safety, among numerous other activities (Convention on Nuclear Safety, 1994). The Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management is an international treaty on the safety of spent fuel management and radioactive waste management. Similar to the CNS, the convention mandates a number of activities required to be undertaken by the member states in order to minimize ionizing radiation effects, prevent accidents, and maintain a high level of safety in spent fuel and waste management (Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, 1997).

There are not many applicable legally binding international instruments regarding nuclear security which are also relevant to Gen-IV SMRs. The relevant conventions are: The Convention on the Physical Protection of Nuclear Materials, the Convention on Early Notification of a Nuclear Accident, and the Convention on Assistance in case of a Nuclear Accident or Radiological Emergency. The conventions collectively aim to enhance nuclear security by requiring member states to safeguard nuclear material during use, storage and transport, provide notification in case of an emergency, and provide assistance in case of a nuclear accident or radiological emergency, respectively (IAEA, 2011). In the case of non-binding instruments, the IAEA's nuclear security series provides guidance on all nuclear security aspects (IAEA, 2024a). These international instruments form the basis of international nuclear security.

Nuclear safeguards are based on the Treaty on the Non-Proliferation of Nuclear Weapons (NPT). The passages of Art. 3 of the treaty are those relevant for Gen-IV developers (Treaty on the Non-Proliferation of Nuclear Weapons, 1968). Art. 3 requires that a Comprehensive Safeguards Agreement (CSA) is concluded between non-nuclear weapon member states and the IAEA in order to enter into the NPT. Under a CSA, "the IAEA has the right and obligation to ensure that safeguards are applied on all nuclear material in the territory, jurisdiction or control of the State for the exclusive purpose of verifying that such material is not diverted to nuclear weapons or other nuclear explosive devices" (IAEA, 2024b). While the obligations of these treaties are imposed on the IAEA and member states, Gen-IV SMR developers still must account for safeguards in their development. Safeguards-by-design is a concept that would facilitate reactor development (IAEA, 2022). More information on safeguards-by design will be given in chapter 6. However, it prescribes early engagement with both national regulatory bodies and the IAEA in order to promote efficient implementation.

The Vienna Convention on Civil Liability for Nuclear Damage is an additional treaty which "establish[es] some minimum standards to provide financial protection against damage resulting from certain peaceful uses of nuclear energy" (IAEA, 2024d). It makes the operator of nuclear installations liable for any nuclear damage and requires that operators be insured. The Protocol to amend the Vienna Convention expanded the scope and liability of the operator (Protocol to Amend the Vienna Convention on Civil Liability for Nuclear Damage, 1997). In this regard, developers need to account for the additional insurance costs when it comes to financial planning for SMR deployment.

Gen-IV SMRs fall under Appendix I of the Convention on Access to Information, Public Participation in Decision-Making and Access to Justice in Environmental Matters, otherwise known as the Aarhus convention. As a result, Gen-IV SMR project developers will need to proactively provide access to information to the public about their proposed activities. Furthermore, developers with need to allow for public-participation in decision-making – allowing for comments on the project (Convention on Access to Information, Public Participation in Decision-making and Access to Justice in Environmental Matters, 1998). This input needs to be considered in final decision-making for a project. Developers will need to plan for the obligations entailed within the Aarhus convention and proactively work to engage with the public, ensuring that concerns are addressed. Although a legal requirement, engaging with the public offers opportunities for learning and trust-building (Duvic-Paoli and Lueger, 2022). Finally, the Convention on Environmental Impact Assessment in a Transboundary Context, or the Espoo Convention, may be argued to apply to Gen-IV SMRs (OECD, 2021). This once again entails early engagement with national regulatory bodies.

National Regulation and Licensing

There is significant variation across different national nuclear regulatory bodies regarding overall framework, reactor design and licensing, operational standards and procedures, and more (Sharma, 2024). All of these factors will influence the development of Gen-IV SMRs; however, reactor design and licensing approaches are by far the most important consideration. As a result, this will be the focus of this section.

The IAEA distinguishes between two major types of licensing approach: Prescriptive-based and performance-based (goal setting) approaches (IAEA, 2010). Prescriptive-based approaches are usually based on a deterministic safety assessment where the projects are assessed in their ability to meet pre-defined principles and standards (Sainati, Locatelli and Brookes, 2015). The IAEA found that regulatory bodies with performance-based approaches are prepared for Gen-IV SMRs with only some regulatory changes needed (IAEA, 2022). However, additional standards need to be developed to be adopted by these prescriptive-based regulatory bodies (IAEA, 2010). Performance-based licensing approaches works on the basis of risk-informed regulation. Compared to prescriptive approaches, performance-based approaches allow better consideration for new designs and technologies. Regulatory bodies using such approaches have greater agency in the approval or rejection of reactor designs (Sainati, Locatelli and Brookes, 2015). Gen-IV SMR developers will likely find it less challenging to receive approval for reactor designs in states with performance-based approaches.

A challenge facing regulators is the lack of experience for Gen-IV SMRs. They are unable to provide guidance on how developers can demonstrate their compliance with regulations (IAEA, 2022). This was due to the fact that operating experience is almost nonexistent and international safety standards for Gen-IV SMRs have not yet been finalized. There is need for demonstration of Gen-IV designs in order to approve the designs, but there is need for approval in order for a demonstration to be possible.

There is significant opportunity for the harmonization of regulations across different national nuclear regulatory bodies. Harmonization would lead to standardization of globally approved designs which facilitates Gen-IV SMR deployment through advantages of economies of scale (Tronea, 2010). However, such harmonization is quite difficult, given that this harmonization would need to come from the national regulators cooperating, collaborating, and compromising on their own domestic regulation in favor of a globally accepted standard. While regulatory bodies may be keen on collaborating, compromising on their own regulatory standards and codes seems to be an unlikely prospect (Eom *et al.*, 2023). Ultimately, the issue lies in the sovereignty of states and their right to decide their nuclear regulations (OECD, 2021).

5. Safety

Safety is and must remain the absolute focus in the development of all nuclear technology. "The fundamental safety objective is to protect people and the environment from harmful effects of ionizing radiation" (IAEA, 2006, pg. 4). Safety standards, according to the IAEA, apply to the nuclear installation, radiation, radioactive waste management, and transport of radioactive material (IAEA, 2006). Safety considers risk under both normal and incidental circumstances, including Loss of Power and/or Cooling (LoPC) and LoFC (Duffey and Hughes, 2023). Gen-IV SMRs tout several safety features inherent to the characteristics of the reactor, reducing risk. These features are what make the next generation of reactors so enticing.

Safety-by-design is a major concept in the development of Gen-IV SMRs (SMR Regulators' Forum, 2023b). Safety by design incorporates safety considerations at the design stage of the reactor, ensuring that it is a foundational concept. The IAEA defines the goals of the safety in design concept (IAEA, 2016b):

a. To prevent accidents with harmful consequences resulting from a loss of control over the reactor core or over other sources of radiation, and to mitigate the consequences of any accidents that do occur;
b. To ensure that for all accidents taken into account in the design of the installation, any radiological consequences would be below the relevant limits and would be kept as low as reasonably achievable;
c. To ensure that the likelihood of occurrence of an accident with serious radiological consequences is extremely low and that the radiological consequences of such an accident would be mitigated to the fullest extent practicable.

Gen-IV technologies are at the forefront of this concept, as their characteristics are salient to reducing risk. Gen-IV SMRs are smaller, with smaller nuclear inventories and lower power. Natural, passive circulation of coolant, gravity-driven safety mechanisms, and reduced system complexity are major reactor features. High thermal conductivity of Gen-IV coolant facilitates DHR and reduces the risk of core damage (SMR Regulators' Forum, 2023a). The modular nature of the reactors is likely to improve quality control of material and components, as the reactor is fabricated in-factory. Refueling considerations have led to reactor designs with longer fuel cycles and refueling periods, which substantially reduces risk due to spent fuel storage reduction and reduced fuel transport/refueling requirements. (SMR Regulators' Forum, 2023b). In essence, Gen-IV SMRs are the pinnacle of the evolution of nuclear safety, with their designs implemented with safety as a foundational characteristic of the reactor.

The defense-in-depth approach is also considered in the Gen-IV designs. Defense-in-depth is a "fundamental approach to hazard control for nuclear facilities that is based on several layers of protection to prevent the release of radioactive material (O'Brien, no date, pg. 4). These layers of protection, or barriers, can be physical, procedural, and managerial, and can be classified as proactive, reactive, and interactive (Duffey and Hughes, 2023). Defense-in-depth ensures that singular failures would not result in an incident due to separate and independent systems and processes working to provide protection (IAEA, 2016b). According to the IAEA, there are 5 levels to defense-in-depth. Briefly, they are as follows (IAEA, 2016b):

I. Prevention of deviation from normal operation and the failure of items important to safety;
II. Detection and control of deviations from normal operation;
III. Inherent/Engineered safety features, systems, and procedures prevent damage to the reactor core;
IV. Mitigation of accident consequences and prevention of progression in order to minimize off-site contamination;
V. Mitigate radiological consequences of radioactive release.

Defense in depth also considers aspects such as site selection, management system, and comprehensive operating and accident managing procedures (IAEA, 2006).

Safety Design Criteria (SDC) for Gen-IV SMRs have been established by GIF and the IAEA (Duffey and Hughes, 2023). This is an extensive list of 83 criteria intended to reduce the safety risks associated with nuclear technology. The list is not yet fully public; however, many points can be found at Duffey and Hughes (2023) pgs. 526-528. In addition, the 10 safety principles established by the IAEA remain applicable to Gen-IV SMRs (IAEA, 2006).

The principle as given by the IAEA are below; a more detailed establishment of these principles can be found on pages 6 – 15 of IAEA (2006).

1. Responsibility for Safety: The prime responsibility for safety must rest with the person or organization responsible for facilities and activities that give rise to radiation risks;
2. Role of Government: An effective legal and governmental framework for safety, including an independent regulatory body, must be established and sustained;
3. Leadership and Management for Safety: Effective leadership and management for safety must be established and sustained in organizations concerned with, and facilities and activities that give rise to, radiation risks;
4. Justification of Facilities and Activities: Facilities and activities that give rise to radiation risks must yield an overall benefit.
5. Optimization of Protection: Protection must be optimized to provide the highest level of safety that can reasonably be achieved.
6. Limitation of Risks to Individuals: Measures for controlling radiation risks must ensure that no individual bears an unacceptable risk of harm
7. Protection of Present and Future Generations: People and the environment, present and future, must be protected against radiation risks.
8. Prevention of Accidents: All practical efforts must be made to prevent and mitigate nuclear or radiation accidents.
9. Emergency Preparedness and Response: Arrangements must be made for emergency preparedness and response for nuclear or radiation incidents.
10. Protective Actions to Reduce Existing or Unregulated Radiation Risks: Protective actions to reduce existing or unregulated radiation risks must be justified and optimized.

These 10 safety principles provide the foundation for the development of any nuclear installation.

Gen-IV SMR technology presents both significant opportunities and challenges to nuclear safety. The integration of passive safety mechanisms and inherent characteristics of the reactors have the potential to significantly reduce safety risks. The safety-in-design and defense-in-depth approaches that are taken in the development of these technologies provides for comprehensive and redundant processes and mechanisms which reduce safety risk. Furthermore, mechanisms, processes, and technology developed for Gen-IV SMRs may later be applied to larger Gen-IV installations, thereby reducing future safety risks.

The challenges, however, are also substantial. The new technologies created in the pursuit of Gen-IV SMRs require testing and validation (Aguiar *et al.*, 2020). Novel and varied designs will pressure nuclear regulatory authorities due to the lack of experience and validation for these designs (OECD, 2021). The previous chapter has shown that engineering challenges are abundant for each reactor category. Material advances must be made in order to reduce the risk of incidents due to degradation, radiation and corrosion. This is the case for both the structural materials of the reactor as well as its internal components. The components' measurement accuracies and precision will also need to be verified via high-temperature and radiation testing (Locatelli, Mancini and Todeschini, 2013). Experimentation and validation of advanced fuel is necessary to improve Gen-IV SMR technology. Moreover, the standardization of safety protocol is a major challenge due to the wide variety of designs present within the Gen-IV SMR industry (Duffey and Hughes, 2023). Another issue is the consideration of increased plant risk due to multiple modules. Touted as a major advantage of SMRs, adding numerous modules to the same site poses safety concerns (IAEA, 2023e). The Fukushima accident has demonstrated the possibility of unexpected interactions between co-located nuclear facilities (Modarres, 2015). This issue will need to be tackled within regulatory safety assessments of designs, including cases where a scale-up of modules occurs over time (Duffey and Hughes, 2023). The challenges to safety of Gen-IV SMRs underscore the need for rapid innovation in several fields, balanced with significant experimentation and validation.

6. Nuclear Security and Safeguards

Nuclear security is defined by the IAEA (2022, pg. 140) as “The prevention and detection of, and response to, criminal or intentional unauthorized acts involving or directed at nuclear material, other radioactive material, associated facilities or associated activities.” Nuclear safeguards are defined by the IAEA (2023, pg. 18) as “The technical means by which the IAEA verifies States’ undertakings under their safeguards agreements and protocols thereto”. Chapter four indicates that most of the international obligations relating to security and safeguards ultimately rests on the states. This does not mean, however, that Gen-IV SMR developers can afford to be inactive when it comes to the topics of security and safeguards. Security by design and safeguards by design are early-stage activities which Gen-IV SMR developers should implement to better facilitate reactor development. Security by design incorporates nuclear security in all phases of a facility, from design to decommissioning (SMR Regulators’ Forum, 2023a). The Bureau of International Security and Non-proliferation states that successful security by design results in (O’Brien, no date):

- “Minimizes insider access to nuclear material and the opportunities for and risk associated with malicious acts (theft/diversion/sabotage),
- Provides flexibility to respond to a changing threat environment,
- Decreases operational security costs by reducing the reliance on the Protective Force,
- Increases efficacy of Protective Force in the event of an attack.”

Each of these points are objective benefits to reactor projects, and ultimately costs will be reduced as security measures are introduced early in design, rather than retrofitted after design finalization (SMR Regulators’ Forum, 2023a).

Safeguards by design is also an early engagement concept, where developers, at the early stages of design, work with the IAEA to implement safeguard design measures and procedures. This reduces the need for IAEA inspections, facilitates IAEA equipment installation, and reduces the risk for proliferation (SMR Regulators’ Forum, 2023a).

Gen-IV SMRs have characteristics that favor both nuclear security and safeguards. Regarding security, several Gen-IV SMRs are designed to be constructed underground, providing improved physical protection than above-ground sites (Hussein, 2020). Multimodule reactor sites reduce risks in transportation and storage of nuclear material due to the centralization of storage and reprocessing facilities. As Gen-IV SMRs have a reduced need for the number of on-site personnel, the risk of sabotage is also greatly reduced (IAEA, 2021c). Indirectly, the smaller size and power of SMRs in general makes them a lower priority target when considering critical energy targets in the case of a war or terrorist attack.

Regarding safeguards, Gen-IV SMR characteristics have significant resistance to proliferation (IAEA, 2021c). All Gen-IV SMRs are designed using LEU fuel, and typically have higher fuel burnup. This reduces proliferation risk by reducing plutonium in spent fuel. In addition, off-site refueling and closed fuel cycles reduce the risk of fuel tampering (Hussein, 2020). Smaller volumes of nuclear material and longer fuel cycles also reduce the risk of proliferation (IAEA, 2023b). Gen-IV SMRs fuel waste can be made unattractive for proliferation use due to high actinide burnup (Hussein, 2020).

There are still challenges, particularly regarding safeguards, which face Gen-IV SMRs. Novel fuels will require new fabrication and reprocessing facilities, adding complexity to safeguards regarding logistics. New approaches to safeguards will also be required to monitor new designs (SMR Regulators' Forum, 2023b). The opacity of coolants such as lead and sodium lead to issues in verification (Smith and Cinotti, 2023). In case of future high-quantity deployment of SMRs, the monitoring of sites on such a scale will require either series expansion of IAEA safeguards personnel or rework of current processes. From a legal perspective, the manufacturing and fuel of a reactor in one state and subsequent transport to a facility in another poses issues due to differing safeguards agreements each state has with the IAEA (Hussein, 2020). The small size of SMRs makes it nearly impossible to withstand catastrophic events such as missile attacks. This issue cannot truly be solved through design and engineering. Security risk needs to be considered in this regard.

7. Complex Interdependence

The coming decade will be critical for Generation-IV SMRs. In all likelihood, there will be major advancements in technological capabilities and updates to regulatory processes and standards, allowing for Gen-IV technology to reach deployment (NEA, 2024a). However, the nature of the industry and the nuclear energy market has a great influence on the progression and commercial viability of Gen-IV SMRs (Boarin *et al.*, 2020). The interest of private finance in nuclear energy has been a paradigm shift for the industry, as historically, building nuclear energy infrastructure was solely the activity of governments (World Nuclear News, 2022). This new dimension has the potential to spur innovation and push the technology forward. Yet, the addition of market competition poses new complexities on the industry. Government support of projects through Private-Public Partnerships (PPP) until deployment is critical, as demonstrator reactors play a major role in technological development (Ingersoll, 2020). However, there is a balance that must be considered here. Even in the most optimistic deployment scenarios for Gen-IV SMRs, there will not be more than a handful of major players (developers) globally holding significant market share. In this regard, the SMR industry is analogous to the aircraft industry; A critical, high-tech industry, which requires enormous initial investment, as well as focus on safety. As deployment occurs, supply chains mature and the economies of scale begin to come into effect, costs should continue to reduce for developers (Mignacca and Locatelli, 2020). The scale of operations regarding regulatory and safeguards inspections, security and safeguards in transport, processing, and storage, and the demand for experienced personnel will substantially increase, adding enormous complexity to an already complex industry (SMR Regulators' Forum, 2019). It is not the tasks of states in the coming decades to just support development of Gen-IV technology according to industrial standards. States need to apply the correct strategy to ensure that the industry remains efficient and commercially viable without the need for subsidies.

The typical cost of developing a new SMR design and bringing it to deploy is in the ballpark of $1 billion and the time to develop such projects can last for more than 10 years (Ingersoll, 2020). Government support in the form of grants can help to alleviate some of the financial burdens, but the reality is that many of the projects currently in development and yet to be developed will never be brought to market (Ingersoll, 2020). The investment cost and span of time is simply too large. As a result, governmental support for can have an enormous influence on which technologies and reactor designs reach deployment. This can be seen as a positive for states, as they have greater influence over the direction of their nuclear industry (Sharma, 2024). However, there is then the issue of technology choice and lock-in. Certain reactor categories or designs may turn out to be superior as Gen-IV SMRs develop. The resulting argument is that a wide variety of projects should be supported and brought to initial deployment (IAEA, 2021a). This would allow for proper development of all categories of Gen-IV SMR to at least the demonstrator phase. However, this strategy is also not without issue. Too much support to too many projects will induce competition within the industry at still a fledgling phase. Constructing production installations for Gen-IV SMR reactors, as well as the fuel processing and storage installations will require enormous investment, and their operation will have high running costs (Mignacca and Locatelli, 2020). In order for such investments to be made, the investment risk must be low due to low competition or governments must subsidize the projects to ensure construction and expansion of infrastructure. Once the infrastructure is in place, if market share is not consolidated, and factory production does not lead to economies of scale, then commercial viability may not be reached and developers risk bankruptcy.

In the case of international competition, each state has a strategic interest in developing their own domestic Gen-IV SMR infrastructure and industry. It is reasonable to assume that states will try to promote their own industry through subsidies. While this will assure that technological advancement in Gen-IV technology does occur, it leads to inefficiencies and would ultimately be more damaging to the industry than beneficial. The simple argument is once again that too many competitors would make commercial success unviable. A better approach would be for states to collaborate on developing a global Gen-IV infrastructure, including production facilities, fuel fabrication and reprocessing plants, and storage facilities, based on logistical efficiency, commercial viability, safety, security, and safeguards. A global focus on establishing such infrastructure would optimize resource allocation and maximize the economies of scale necessary for economic viability (OECD, 2021). Notice, this is not a prescription for harmonization and standardization found in many texts, rather this calls for states to collaborate on a global industrial strategy for the industry's development. This would not only benefit the development of the technology, but nuclear safety, security, and safeguards would benefit from a comprehensive, global strategy.

In the case that Gen-IV SMRs reach large-scale deployment, the operations related to regulatory oversight, security, and safeguards would expand dramatically. The number of nuclear installations foreseen in a large-scale deployment would make such operations very difficult without significant expansion to the number of personnel (Ingersoll, 2020). Complexity in supply chains would increase and would inevitably become more opaque, which increases security and safeguard concerns. States must either work to expand personnel supply chains or new, innovative methods and processes for oversight must be developed. Ultimately, increased nuclear activities on a global level increases the security and safeguards risks, regardless of level of oversight. Governments need to be proactive in collaborating on an international strategy to overcome the challenges that will be faced in the next decade.

8. Public Perception and Trust

A major challenge to the development of Gen-IV SMRs is public perception of nuclear technology and the fear of nuclear accidents. There are three major factors that contribute to this issue: The tendency for the public to emphasize the consequences of nuclear accidents over their probability (OECD, 2021); The tendency for the public to overestimate the risk of nuclear accidents compared to other disasters (Hacquin *et al.*, 2022); and the tendency for the public to minimize the benefits of nuclear energy. These factors must be faced by Gen-IV SMR developers as they plan for deployment of their reactors.

The Aarhus convention has given the public the right to participation in decision-making when it comes to SMR projects. Typically, such participation is illustrated as public protests and demonstrations against the construction of installations. However, this is far from the reality. Public engagement with nuclear authorities has shown to increase trust, knowledge, and facilitate citing and construction (Kelleher, 2017; Iqbal, Moss and Van Woerden, 2022; Wang *et al.*, 2024). Public acceptance towards nuclear technology also improves when trust in nuclear authorities is high (Wang and Kim, 2018). In order to improve public perception, developers can engage by educating the public about the benefits of nuclear energy, acknowledge the concerns of the public, and educate and reiterate the low probability of nuclear accidents (Duvic-Paoli and Lueger, 2022; Iqbal, Moss and Van Woerden, 2022).

The advantages of Gen-IV SMRs present significant opportunity to improve public perceptions and trust in nuclear energy. The inherent characteristics of these reactors, and their extremely low likelihood of disaster may make them more attractive to the public. Their small size in comparison to traditional reactors may also reduce opposition (OECD, 2021). The long construction times of traditional nuclear installations may have contributed to governments responding to public protests and terminating projects. This sort of capitulation further reduces public perception of nuclear energy (Bull, 2023). Shorter construction times and off-site fabrication of reactors should reduce this concern. As low-carbon energy sources become ever more critical, Gen-IV SMR developers can emphasize the compatibility of their reactors with renewable energy. Furthermore, as Gen-IV SMRs begin their deployment in increased quantities, repeated, successful demonstration of the technology is likely to improve public trust (Duffey and Hughes, 2023). As SMR deployment is envisioned to occur at a scale much larger (numerically) than previous generations, and it has been shown that proximity to nuclear installations tends to *improve* public perceptions, it is logical to expect that public perception and trust in nuclear energy will improve (Iqbal, Moss and Van Woerden, 2022).

As the transition to low-carbon energy sources continues and the demand for base-load energy alternatives rises, Gen-IV SMRs are given a unique opportunity to deploy on a large-scale. Developers will need to seize this opportunity with early engagement of the local public near potential sites - Emphasizing the benefits of nuclear energy and the low inherent risk of Gen-IV technology.

9. Conclusion

The purpose of this research was to develop a comprehensive assessment of the current status of Generation-IV Small Modular Reactors, the challenges that they face in their development, and the potential opportunities related to their development.

- *Conclusion 1*: There are still several design and engineering challenges facing Gen-IV SMRs which will require significant innovation and development.
- *Conclusion 2*: National and international regulations require some adjustments to deal with new designs, standards, and processes of Gen-IV SMR, which would optimally be done via international cooperation to establish harmonized regulations and standards.
- *Conclusion 3*: Gen-IV SMR developers can overcome challenges set by international and national regulation by early engagement with all stakeholders, particularly the IAEA and national regulatory body.
- *Conclusion 4*: The Aarhus Convention obligates Gen-IV SMR developers to give the public access to information regarding the project and the right to participation in decision-making. Rather than seeing this as an obstacle to development, developers should view this as an opportunity. Developers should use these engagements as opportunities to share knowledge with the public about their reactor and nuclear technology in general, as well as to reiterate the benefits and low risk of nuclear energy.
- *Conclusion 5*: Gen-IV SMRs have characteristics that make them attractive from the standpoint of nuclear safety, security, and safeguards. It is the responsibility of both the designers and the regulatory bodies to develop effective and efficient standards, codes, and procedures necessary to properly regulate Gen-IV SMRs.
- *Conclusion 6*: The introduction of private finance signals a paradigm shift in nuclear energy from traditional, public-funded nuclear power plants to private investment in SMRs. States must work to envision and apply the correct strategies to ensure Gen-IV SMR industry viability.

- *Conclusion 7*: Characteristics of the nuclear industry and economies of scale indicate that there are likely to be only a handful of major developers holding large market share.
- *Conclusion 8*: There are currently 25 active, land-based Gen-IV SMR projects. The United States of America hosts the largest number of active projects with 5. Among the Gen-IV SMR categories, Molten Salt Reactors have the most active projects with 9. 0 SuperCritical Water Reactors are being actively developed.
- *Conclusion 9*: Generation-IV SMRs are on the verge of deployment, with fewer and fewer engineering and design challenges left to tackle. The IAEA and national nuclear regulatory bodies are working to accommodate Gen-IV SMRs regarding their compatibility with regulatory standards, and work to bring this technology to large scale deployment is occurring at all levels.
- *Conclusion 10*: Certain categories of Gen-IV SMR are likelier to reach large-scale deployment than others. The research above has shown that international competition between private companies and between states to develop a domestic Gen-IV industry will heavily influence the development path for these reactors.
- *Conclusion 11*: While the research has shown that there are numerous challenges, regarding design, engineering, regulations, standards, and procedures to the development of Gen-IV SMRs, there are also many opportunities which developers are in the unique position to take advantage of.
- *Conclusion 12*: International cooperation on challenges regarding design, engineering, regulations, standards, and procedures is key to a successful global deployment of Gen-IV SMRs. This cooperation comes in the form of regulatory standardization, coordinated research projects, and collaboration on nuclear infrastructure for Gen-IV SMRs.
- *Conclusion 13*: Developers benefit enormously from early engagement with stakeholders. Regarding safety, developers should engage their national regulatory bodies – doing so will ensure that safety goals, objectives, procedures, and standards are met at an early stage of the reactor's development. Early engagement regarding nuclear security and safeguards leads to reduced costs as security by design and safeguards by design concepts are introduced early in the design process, reducing

the need for retrofitting post-construction. Early engagement with the public improves public perception and trust in nuclear energy.

- *Conclusion 14*: Early and active engagement between Gen-IV SMR developers and all stakeholders at various levels is critical to a successful project. This will ultimately lead to reduced costs as developers are able to acknowledge and act upon concerns from regulators and the public early in the design process. No negative effects were seen due to early engagement with any stakeholder.
- *Conclusion 15*: The unique opportunities for Gen-IV SMR come from their potential attractiveness to all stakeholders, due to the inherent safety, size, versatility, and compatibility with renewable energy sources.
- *Conclusion 16*: Gen-IV SMR developers should be sure to take into account all aspects of project management when it comes to their reactor. Meaning that, while the design of the reactor is important, there are several activities that are almost as important to the success of the reactor when it comes to project viability.

When distinguishing the likelihoods of deployment of these reactors, there are only a few deciding characteristics. The characteristics of the reactors when it comes to nuclear safety and the implementation of security and safeguards are important to distinguishing the most promising category. Licensing depends on demonstration of nuclear safety, and deployment on a large scale can only occur in the absence of security and safeguards risks. Utilization can be considered a factor. The number of projects in active development for each category is perhaps the most important consideration for potential deployment – this is explained below. Table 3 shows a scoring for each category based on the research. The higher the relative scoring, the greater the relative advantage.

Table 3: Relative Scoring for Gen-IV SMR Categories

	VHTR	GFR	SFR	LFR	MSR
Safety	+	-	+	0	0
Security	0	0	0	-	0
Safeguards	-	0	0	-	+
Utilization	0	+	0	0	0
Score	**0**	**0**	**+1**	**-2**	**+1**
Number of Active Projects	6	2	2	5	8

- *Conclusion 17*: When it comes to the challenges of technical development needed to ensure safety for these reactors, a significant part of the advancements made will be applicable to all reactor types. Meaning that advances if materials for SFRs are likely be applicable to LFRs and vice-versa. The technical challenges for these reactors when it comes to safety can be considered largely equal. VHTR reactors have their advantage as having demonstrated safe LoFC in Japan. GFRs have been shown to have challenges unique to their development and significant barriers to deployment, as a result it is seen as the weakest among all categories in regards to safety.
- *Conclusion 18*: When it comes to nuclear security, the challenges for all reactors are similar across the board. LFRs are at a disadvantage compared to all others due to issues with verifying proper use of nuclear fuel. This is due to the opacity of the lead coolant. Otherwise, all categories must face the same issues of security. Reactors with walkaway capability will have greater security capabilities, but this is considered a case-by-case basis, rather than the advantages of categories. Considering safeguards, VHTR and LFR are at a disadvantage. The high volume of TRISO fuel (VHTR) and the opacity of the lead coolant (LFR) both contribute to safeguard verification challenges. MSR technology is at a unique advantage in this case. The absence of need for fuel fabrication and the high burnup of the fuel within the salt greatly reduces the security risk.

- *Conclusion 19*: Ultimately, SMRs must begin to consider innovative methods for security and safeguards in the event of large-scale deployment. These activities in case of large-scale deployment require immense time and manpower which is currently available to neither national regulatory bodies nor the IAEA. As a result, new methods must be developed or the safety and security risk for these reactors will be considered too high, and states will not deploy them.
- *Conclusion 20*: GFRs are considered the reactor with the widest potential for application due to its high-power density. Most cases of reactors were intended for electrical and process heat generation – category was mostly irrelevant.
- *Conclusion 21*: The number of projects in active development is perhaps the most significant indicator for the deployment of Gen-IV SMRs. This is not simply a consideration of research time and innovation. Investment in a certain category of reactor means that developers believe that reactor to be most commercially viable.
- *Conclusion 22*: GFRs are unlikely to find any deployment, given the lack of interest from developers.
- *Conclusion 23*: Lead-cooled Fast Reactors, despite scoring most negatively, are tied for second most in active projects. Although this reactor category can be viewed as having the greatest challenges when it comes to Gen-IV (scoring -2, the lowest by a large margin), private finance believes that there is serious opportunity.
- *Conclusion 24*: There is equal interest in LFRs and VHTRs from an active project standpoint, although VHTRs possess fewer challenges to their deployment.
- *Conclusion 25*: MSRs have 50% more active projects than any other category. At 36% of the total active projects, private finance has a clear preference for MSR reactors. Meanwhile, SFRs have not been considered attractive to private developers with 1 in active development.
- *Conclusion 26*: MSRs and SFRs tie for the highest score among all reactor categories. LFRs score the worst.
- *Conclusion 27*: Given the equal scoring of MSRs vs SFRs, the difference in active projects indicates the significant influence of private finance on the development of Gen-IV SMRs.

- *Conclusion 28*: Given the above considerations, the reactor category most likely to see large-scale deployment is the *Molten Salt Reactor*. The reactor is more capable of dealing with safeguards concerns and did not have any disadvantages, unlike all other reactors. Most significantly, the number of active projects shows that, internationally, private companies and developers view this technology as the one with the greatest potential for commercial viability and success.

This study has considered many aspects of Generation-IV Small Modular Reactors: their design, law and regulation, safety, security, safeguards, and public perception and trust. The challenges to their development and their opportunities were explored. There were a number of limitations to this research. Foremost among them being the strict definition under which Gen-IV SMRs were defined – Too many important Gen-IV SMR projects were excluded from the provided list due to not fitting the criteria such as too high-power level or marine operation. Furthermore, marine-based projects have their own implications regarding international law, security and safeguards which were not discussed in this research. This research chose not to look at specific cost projections for Gen-IV SMR projects, as relevant, specific data was not available for Gen-IV SMRs. A more advanced scoring system may have provided better insight but would have introduced greater subjectivity in ranking. This research would have benefitted from contacting and interviewing Gen-IV SMR developers to see their viewpoints; however, a lack of time and resources did not allow for this.

Further research on this topic should consider the international and national regulatory implications for mobile, marine-based Gen-IV SMRs and their impact on security and safeguards processes. Looking ahead at long-term large-scale deployment, studies should be done on projections of nuclear energy markets and their sizes in the coming decades. This will give developers and regulators a better understanding of future market, allowing for better planning and decision-making. Finally, there is a lot of data on the activities surrounding regulations for Gen-IV SMRs, in the future, a sort of meta-analysis of these activities may present useful research on how collaboration on complex topics on multiple levels can be implemented successfully.

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