A RISK ANALYSIS OF DIFFERENT SMR DESIGNS

by

Shatha Abumousa

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Abstract

This thesis investigates the risk analysis of various Small Modular Reactor (SMR) designs, focusing on the three critical aspects: safety, security, and safeguards (3S's). SMRs, with their innovative design, promise enhanced safety, modularity, and flexibility in nuclear power generation. However, their deployment introduces unique risks that require thorough evaluation.

The study involves a detailed assessment of ten diverse SMR designs, including water-cooled reactors, High-Temperature Gas-Cooled Reactors (HTGRs), fast reactors, and molten salt reactors. It explores the impact of specific threats such as Loss of Coolant Accidents (LOCA), cyber incidents, and spent nuclear fuel theft on these designs. The methodology used includes identifying potential threats, prioritizing them, assessing vulnerabilities, and calculating overall risk, emphasizing the integration of 3S principles.

The thesis examines the tolerance of each SMR design to these risks, revealing how different designs respond to various threats. This comprehensive analysis provides critical insights into the strengths and weaknesses of the proposed SMR designs, aiding stakeholders in managing risks and ensuring the safe and secure implementation of SMRs in the nuclear energy sector.

Glossary

3SBD	Safety, Security, and Safeguards by Design
3Ss	Safety, Security, and Safeguards
AI	Artificial Intelligence
ACS	Autonomous Control System
BWR	Boiling Water Reactor
CSA	Comprehensive Safeguards Agreement
DBT	Design Basis Threats
DiD	Defense-in-Depth
GHG	Greenhouse gases
GW	Gigawatts
HALEU	High-Assay Low-Enriched Uranium
HTGR	High Temperature Gas-cooled Reactor
IAEA	International Atomic Energy Agency
iPWR	Integral Pressurized Water Reactor
LFR	Lead-cooled Fast Reactor
LMFR	Liquid Metal Fast Reactor
LW	Light-Water
MOX	Mixed Oxide fuel
MMR	Micro Modular Reactor
MSR	Molten Salt Reactor
MTTR	Mean-Time To Recover
NDA	Non-destructive Assay
NMA	Nuclear Material Accountancy
NNWS	Non-Nuclear Weapons State
NPP	Nuclear Power Plants
NPT	Non-Proliferation Treaty
NWS	Nuclear Weapons State
OPG	Ontario Power Generation
PPS	Physical Protection System
PSA	Probabilistic Safety Analysis
PWR	Pressurized Water Reactor
QV	Qualitative Value
SBD	Safeguard by Design
SBO	Station black-out
SeBD	Security by Design
SFR	Sodium-cooled Fast Reactor
SFM	Spent Fuel Management
SMR	Small Modular Reactor
SQV	Semi Quantitative Value
UN	United Nations
WATSS	Waste To Stable Salt

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1 Introduction

With the surge in the world's population and metropolitan growth, the demand for energy has increased rapidly (WNA, 2022). By 2050, it is expected that two-thirds of the world's population will live in urban areas. This is a challenge facing efforts to reduce greenhouse gas (GHG) emissions (WNA, 2022). The goal of net zero emissions policies is to reduce greenhouse gas emissions as close to zero as possible while balancing any residual emissions through strategies such as reabsorption by oceans and forests (IEA, 2023) .This goal is critical in addressing climate change since limiting global temperature rises to 1.5°C over pre-industrial levels, as defined in the Paris Agreement (UN, 2023), is critical to avoiding severe climatic impacts. Achieving net-zero energy necessitates a considerable shift in energy production and consumption, with a focus on non-emitting energy sources. As well, a global effort is underway, with various governments, cities, businesses, and institutions pledging to achieve net-zero emissions, but current promises fall short of what is required. It would take stronger regulations and stronger government commitment to keep the world on track to reach net-zero emissions (UN, 2023).

Nuclear energy is gaining increasing recognition as a climate-friendly option and plays a pivotal role in the transformation of the energy sector, thanks to its unique characteristics, including low GHG emissions, 24/7 availability, operational flexibility, a small land footprint, and its capacity to decarbonize challenging industries (IAEA, 2021). Nuclear power contributed 14% of world electricity production by 2022, down from 18% in the late 1990s. It is the second-lowest carbon source of energy after hydropower and ranks highly in developed countries such as the USA, France, and Russia (BP, 2023). By 2022, there are 439 existing reactors spread across 32 countries, with a combined capacity of 413 GW. Nuclear power has had a significant impact on limiting the growth of global CO_2 emissions since the 1970s, offsetting about 66 Gt of CO_2 between 1971 and 2020 (IEA, 2022).

Renewable sources of energy, notably solar and wind, have zero fuel costs but require some form of backup because their production can vary throughout the day. Renewables are projected to take the lead in shaping our future electricity supply. Nuclear energy, a less prominent choice, can complement renewables, improving dependable energy supply and flexibility. The combination of nuclear and renewable resources can expedite the move towards a net-zero future. However, the extent of its utilization is uncertain due to limited public acceptance and policy support. Between 2011 and 2020, global nuclear energy generation capacity saw a slow growth with the addition of 59 gigawatts (GW) of capacity, although 48 GW was decommissioned due to reactor shutdowns in Germany, the USA, Japan, and the UK (IAEA, 2021).

More than 70 countries have embraced net-zero objectives, encompassing 76% of global energy-related CO2 emissions, and 60 countries have committed to achieve net-zero or carbon neutrality without a specific timeframe (IEA, 2022). While renewables are anticipated to be the primary electricity source in a net-zero future, countries are also making investments in nuclear energy. For instance, France intends to build 14 new reactors by 2028, which will be commissioned by 2035 (CNN, 2022). Additionally, South Korea is restarting construction on two new reactors after it has been halted since 2017, which will increase the country's power generation to 30% (CNN, 2022).

In the path toward achieving net-zero emissions, a set of five key elements, present in nearly all strategies aligned with ambitious climate objectives, create avenues for nuclear energy to contribute: first, the extensive electrification of various end-use applications, with electricity playing an increasingly central role in final consumption; second, the rapid expansion of low-emission electricity production; third, the imperative to reduce emissions stemming from heat production; fourth, the surging demand for low-emission hydrogen; and finally, the ongoing necessity to foster innovation, enabling the advancement of sophisticated nuclear technologies (IEA, 2022).

1.1 The role of nuclear power in achieving clean energy goals

Despite experts' agreement on the critical need to address climate change, there are opposition voices to eliminating nuclear energy. Their arguments refer to the high cost of building a nuclear power plant and the long period of operation; they also flag the risks of nuclear weapon proliferation, lung cancer in miners, and radioactive waste (Jacobson, 2023).

On the other hand, the UN has developed an agenda for the 2030 sustainable development goals. It has a significant framework to achieve net zero, consisting of seventeen interrelated worldwide objectives to achieve a more sustainable world by 2030 (UN, 2023).These goals do not favor specific technologies but rather highlight their effectiveness in attaining them. Furthermore, nuclear energy has been found to pose no greater risk to human health or the environment than other already-considered sustainable methods of producing electricity by the EU Taxonomy for Sustainable Activities, which directs financial investment in environmentally sustainable economic activities (IAEA, 2021).

The United Nations' goals aim to promote prosperity and protect the planet, focusing on ending poverty, economic growth, social needs, and climate change. However, all goals influence climate change, and progress on climate action requires accelerating the achievement of goals like Affordable and Clean Energy and Responsible Consumption and Production (UN, 2023).

Although the nuclear energy offers a plenty of clean continuous energy, but some challenges appear to limit its spread. One of the most debated topics for nuclear energy is the spent fuel and the ways to disposal, storage, and transport, which the process is expensive and need for a restrict regulations. Another challenges, the long time between the planning for a reactor till operation, which increase the capital cost of the plant (enCore energy, 2022).

To sum up, nuclear energy can contribute to the development of a resilient energy system and economy that can withstand the challenges posed by climate change. Compared with other technologies, nuclear energy has one of the lowest carbon emissions, so it would contribute to mitigating climate change (IAEA, 2021).

1.2 Nuclear Power Plants

A nuclear reactor produces energy in the form of heat by splitting the atoms of radioactive isotopes. This process is called nuclear fission and is started by firing a neutron at an atom, causing the atom to split and release a new neutron, which starts a new reaction (WNA, 2022). This is referred to as a chain reaction.

This reaction releases a huge amount of energy, usually using uranium and plutonium in nuclear reactors (DOE, 2021).The energy released by this reaction can be transported by a circulating liquid, usually water, to produce steam which powers turbines to generate electricity. The production of the electricity can be running 24 hours a day for months without any interruption. The reaction must be controllable to either slow or shut it down (WNA, 2022).

Uranium found naturally in three forms of isotopes U-234, U-235 and U-238, which it is the most available isotope. But U-235 is the only isotope capable to fission and it is rare as well, for each 100 Kg of natural uranium there is 0.7 Kg of U-235, which can concentrated by process called enrichment to be used in nuclear reactors (Orano, 2024)

Nuclear power plants (NPP) come in different shapes and sizes, but the components of all reactors have the same basic structure. For example, the reactor core, which, referred to as the hot side, as shown in Figure 1 ,contains the following (WNA, 2022):

Fuel rods: The fuel rods are usually using uranium oxide (UO_2) pellets, they are arranged in tubes, for example PWR with 1000 MW might have 51,000 fuel rods with 18 million pellets.

Moderator: Moderator is a material helping to slow down fission released neutrons and confine them inside the reactor core.

Control rods: Control rods are made of neutron absorbing material to control the rate of the chain reaction or to stop it.

Coolant: A fluid that transfers the heat out of the core.

On the other side of the reactor core (the hot side), there is a cooling system consisting of a steam generator for transferring the reactor's heat to an electric generator. All the reactor's components will be held inside a containment, which it is a structure to protect the surrounding environment from the radiation, typically it is a meter thick concrete and steel structure (WNA, 2022).

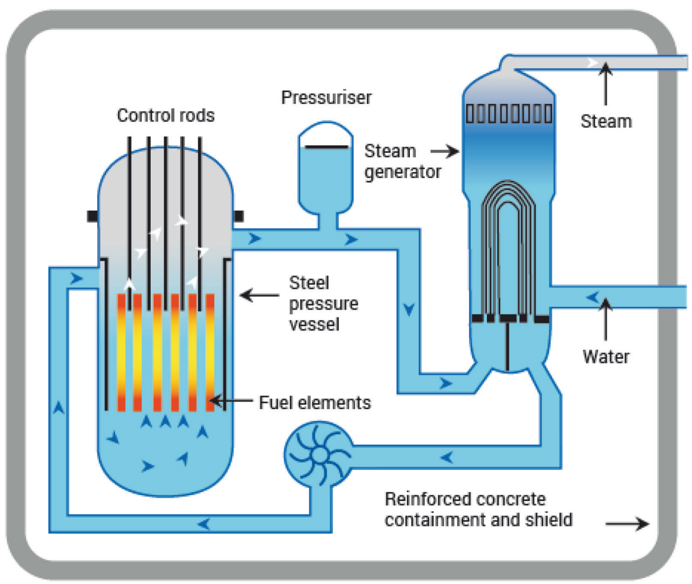

Figure 1: Nuclear Power Reactor (PWR) (WNA, 2023)

At present, there are more than 439 NPP operating around the world in 32 countries. Their energy output is transmitted through regional grids. Some countries such as Italy and Denmark have 10% of their electricity demand from the imported nuclear power (WNA, 2023). In 2020, thirteen countries produced about one-quarter of their electricity from nuclear; for example, in France, around 70% of its electricity comes from on nuclear power (WNA, 2022) . NPP can produce more 700 and up to 1600-megawatts NPP facility of one square mile, would produces 1000-megawatts (WNA, 2024).

To meet Paris Agreement objectives, nuclear energy must contribute significantly to the global energy mix, however the nuclear power is not on track to achieve the decarbonization goals, that's because of the high cost of building new nuclear plants. Moreover, the notion that new nuclear reactors involve significant project risks has discouraged investors and hindered countries' ability to get financing for upcoming projects (NEA, 2021) . In parallel, introducing innovative technology started to attract the policymakers and could overcome the existing challenges and can fulfill the target of decrease greenhouse gases. Small modular reactors (SMRs), which they are small size reactors compared with NPP, with smaller capacity up to 300 MW (DOE, 2022).

Accidents are frequent in all industries, and industry like nuclear energy will have the probability to have accidents as well, but because nuclear power have all been designed with high energy density, highlighting the possible risk. While few accidents are spectacular and noteworthy, they have a significant influence on human fatalities, making them more significant (WNA, 2022). Some risks are related to NPP are considered and affecting the public opinion and the legislation processes.

Accidents and Meltdowns: Although the industry has been successful in avoiding accidents, with only three significant accidents in the 60-year history of civil nuclear power generation: Three Mile Island (1979), Chernobyl (1986), and Fukushima Daiichi (2011). Only the Chernobyl and Fukushima accidents resulted in radiation doses greater than those from natural sources, while Fukushima only resulted in radiation exposure of workers at the plant (WNA, 2022). These accidents, if they are man-made or naturally, they resulted in the release of radioactive materials into the environment and pose significant health and environmental risks.

Radioactive Waste: is a byproduct of nuclear facilities, is classified into high-level waste, primarily spent fuel, and low-level waste, arising from reactor operations and commercial uses of radioactive materials. High-level radioactive waste is primarily uranium fuel used in NPP that is no longer efficient in producing electricity. This thermally hot and highly radioactive waste requires remote handling and shielding. Low-level wastes, including radioactive materials, are typically disposed of in near-surface facilities rather than geologic repositories. Another source of waste from the milling ores of uranium or thorium extraction (USNRC, 2019).

High Capital and Operating Costs: NPPs are some of the most complex energy systems ever designed, with failure being a significant feature of technological complexity. As nuclear power grows, the scale of problems associated with failures has grown, leading to increased construction times and escalating costs. Technical complexity and safety-enhancing strategies have also led to increased construction times and escalating costs. The site-specific nature of nuclear reactors has inhibited standardization, putting further pressure on nuclear plant costs due to the "one-of-a-kind" approach to large reactor design, construction, and operation (Kessides, 2012) .

Decommissioning: NPPs involves safely removing and storing spent fuel, decontaminating the plant, dismantling structures, transferring contaminated materials to disposal facilities, and releasing the property for other uses. The process can take decades, with lax regulations allowing it to last up to 60 years. Decommissioning costs are typically $500 million per unit but can be higher due to health and safety risks (Padmaparna Ghosh, 2022).

1.3 Small Modular Reactors

Small Modular Reactors (SMRs) are designed to produce from 5 to maximum of 300 MW. they are facilities have the same concepts of the NPP and using same technology. The size of SMR is physically smaller than NPP. The Modularity term comes from the components of the reactor will be prefabricated before being installed on-site, while the existing NPP are using factory fabricated components, but it required a considerable amount of work in field to assemble these components, but in SMRs are expected to have less work and preparation on-site. SMRs are anticipated to have less capital expenses than NPP, due reducing construction time and capital costs (IAEA, 2022).

SMRs can provide energy for rural areas, small size grids, and could be helpful in different applications not only electricity production, many non-electrical application like, seawater desalination, pulp, paper manufacture, Methanol production, Hydrogen production applications as well, these applications are depending on the reactor type and output temperatures (IAEA, 2022). The new designs of SMRs are proposing higher level of efficiency in safety, security, and safeguard, they offer increased protection for nuclear materials and facilitate tracking to prevent nuclear proliferation and sabotage (DOE, 2022).

Potential for subgrade (underground or underwater) installation of the reactor unit, increasing protection against man-made (aircraft impact) or natural (e.g., tsunami or seismic activity, depending on the location) hazards (WNA, 2022) . Some SMRs will be built to operate for lengthy periods of time without need to be refueled. These SMRs may be manufactured and fueled at a factory, sealed, and transported to power generation or process heat sites, and then returned to the factory for defueling at the end of the life cycle. This strategy may aid in reducing the transportation and handling of radioactive material (DOE, 2022).

The proposed advantages of SMRs promise to have less dependency on active safety systems such as AC power or additional pumps to mitigate accidents. Instead, the designs exploit passive safety feature, which is dependent on natural features like gravity and pressure circulation. Furthermore, as a design base component, the designs consider the entire life cycle, particularly spent fuel management (SFM) and radioactive waste management (RWM), as well as the decommissioning process. Moreover, SMR can use the generating equipment in decommissioned coal-fired plants, which are usually under 500 MW and some under 50 MW (WNA, 2022).

In addition, the proposed designs incorporate new materials, fuel, and fabrication technologies, as well as a high level of automation and new human-machine interface principles. The engineered system codes' predictions are new or developed; this prediction could be under normal/accident events. Moreover, the designers will adopt alternative ways of safety assessment and new approaches for maintenance (CNSC, 2016). Although SMRs new features like modularization might raise safety concerns for nuclear materials transport. The current framework may not be suitable due to regulatory involvement and multinational licensing of modules and components. Additionally, Multi-module SMR designs may require specific nuclear safety considerations due to shared systems and shifting manufacturing from on-site to factories. These changes may impact initial plant tests and licensing stages, challenging traditional licensing approaches (NEA, 2021).

Canada's approach to developing SMRs is guided by a strategic roadmap that emphasizes collaboration between government, industry, and indigenous communities. This roadmap outlines several key objectives, including enhancing regulatory frameworks, ensuring environmental protection, and developing a secure supply of SMR fuel. The federal government aims to support SMR projects through policy measures that reduce financial risks, such as cost-sharing and loan guarantees. There is a focus on leveraging Canada's existing nuclear expertise and infrastructure, notably at national laboratories and universities, to develop and demonstrate SMR technologies (CNA, 2018).

Ontario Power Generation (OPG) has committed to building four GE-Hitachi boiling water SMRs (BWRX-300) at the Darlington New Nuclear Project site. The construction of new nuclear facilities in Canada has been limited by licensing restrictions (OPG, 2024); the Darlington Nuclear Generating Station in Ontario is the only location in Canada where new construction is possible. Space for new construction is restricted due to the presence of an existing 3,500 MW four-unit CANDU facility on the site (GE Hitachi, n-d). The first BWRX-300 is scheduled for completion in 2028, with first power to the grid beginning in 2029. The additional SMRs could be operational between 2034 and 2036, pending regulatory approvals.

By building multiple units, OPG expects to achieve cost savings through shared infrastructure and lessons learned from the initial unit. The four reactors will collectively generate 1,200 megawatts, enough to power 1.2 million homes, aiding Ontario's electricity demands and net-zero goals (WNN, 2023).

Apart from the Russian KLT-40S floating SMR, there are no operating SMRs. Most of the risks relating to SMRs are theoretical, although some are based on existing NPP risks (IAEA, 2022). Vendors' claims notwithstanding, there are still risks associated with SMRs, including:

Proliferation: Nuclear proliferation involves nations or terrorist groups acquiring nuclear weapons. The Non-Proliferation Treaty (NPT) has been effective in discouraging this, but it requires commitment from major nuclear states, such as the United States, Russia, and China (Atomic Archive, 2023). The nuclear weapons are linked to uranium enrichment and plutonium separation from spent fuel. Advanced reactors can be fueled with plutonium or uranium at high levels, which posing greater risks of proliferation. Molten salt reactors involving thorium use uranium 233, which is fissile and easier to use in nuclear weapons. Moreover, some reactor technologies are "integral" designs, processing used fuel on-site to recover fissile material. Separation of fissile materials increases nuclear proliferation risks compared to leaving fission products mixed in spent fuel (Ramana, 2021).

Safety considerations: SMRs are highly depending on passive safety features, would minimize potential failure scenarios. Additionally, with more simplification of design and integration could rise risks could be easy mitigate in NPP, such as small reactor core, leads to have higher surface-to-volume ratio, which higher the risk of decay heat removal (NEA, 2021).

Licensing process: is different than licensing NPP, because of smaller power output, fully passive safety features, modular design, mass production, and integral units, and Licensing processes in most countries are mainly developed for large NPPs built one at a time, which may not be optimal for SMRs with multiple reactor modules in one plant. Licensing should consider the modularity of the design and be planned with mass production in consideration, additionally, prospective SMR licensees are exploring scenarios that involve the use of several identical modules (reactors) within a single unit and potentially constructing and licensing multiple units in stages at the same site. Licensing in this technique must be able to be repeated through an efficient yet strong process, especially if each module has its own license (Söderholm, 2012).

1.4 Thesis content

The next chapter will present background information on the evolution of nuclear power, along with statistics regarding its contribution to the worldwide energy portfolio. The text will transition to discussing the historical development of SMRs, then delve into the benefits they provide compared to NPPs. The chapter will also cover the essential role of '3Ss' (Safety, Security, and Safeguards) in the nuclear business.

Chapter three will elucidate the intricate relationship between the '3Ss' and SMRs, highlighting how these factors can influence the safety of SMRs. To illustrate this relationship, we will carefully select ten SMRs based on specific criteria. Through an in-depth study of these SMRs and an analysis of the probability of specific events, we aim to assess associated risks and apply a risk assessment methodology to the chosen SMRs.

In chapter four, several events will be examined using the risk assessment methodology. This investigation will highlight differences in the impacts, likelihoods, and risks of events that may influence the '3Ss' and the entities directly.

Chapters five and six will explore the differences in risk among the chosen SMR designs and visually display the analysis. A conclusion will be made about the approach and its results, while highlighting its significance in the field of nuclear energy and risk analysis.

2 Background

2.1 The historical context of nuclear power development

At present, there are more than 430 NPP operating in 32 countries. Their energy output is transmitted through regional grids. Some countries such as Italy and Denmark have 10% of their electricity demand from the imported nuclear power (WNA, 2024). In 2022, thirteen countries produced about one-quarter of their electricity from nuclear as shown in Figure 2; for example, in France, around 65% of its electricity is comes from on nuclear power, while Ukraine, Slovakia, Belgium, and Hungary receive approximately 50% of their energy from nuclear sources (WNA, 2023) .

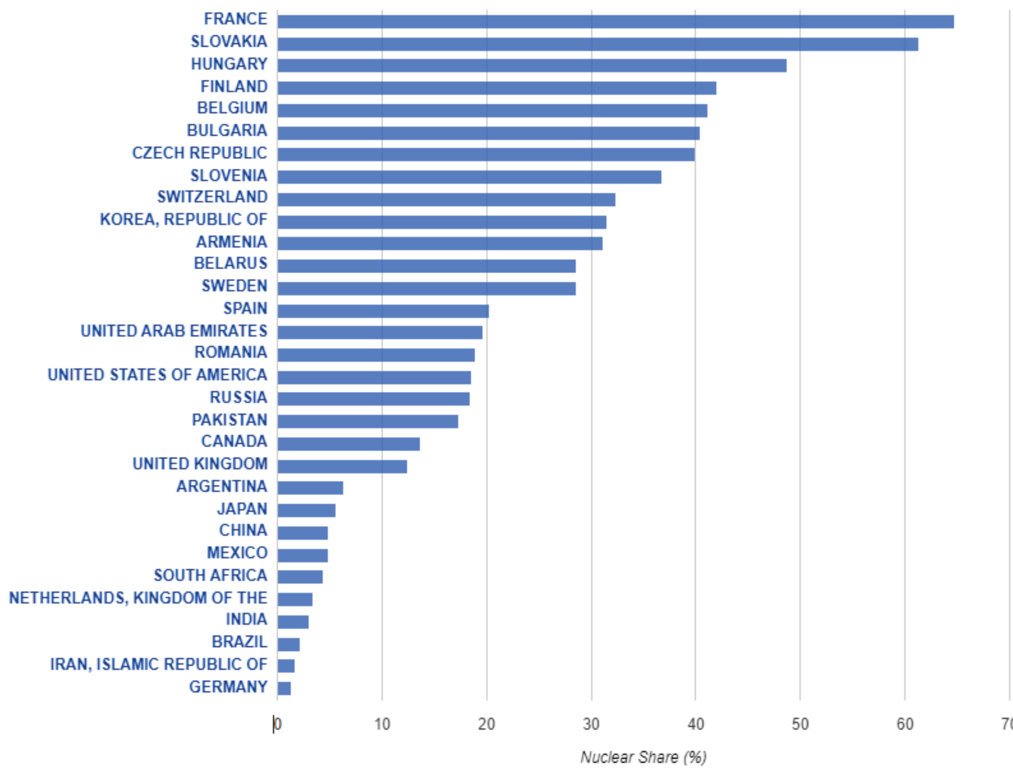

Figure 2: Nuclear power share of electricity generation in 2023 (IAEA PRIS, 2023)

The design of NPPs has been evolving ever since the first-generation of power reactors (Gen I) were developed in the late of 1940s for civilian applications. This was followed by the second-generation (GEN II), such as PWR, CANDU, and BWR, with commercial lifetimes of 40 years, most of which are still in operation. The need of increased thermal efficiency, safety, and fuel cycle technologies led to the development of third generation reactors (GEN III and GEN III+), with higher safety standards for protection and security (Goldberg & Rosner, 2011). Fourth-generation reactors (GEN IV) are now being developed with enhanced safety features, increase sustainability by applying the closed fuel cycle principle, which refers to reprocessing the spent fuel and partly reused (Nuclear-Power, 2022) , reduce nuclear waste, increase proliferation resistance, and allow for applications such as hydrogen production.. GEN IV includes six new designs, notably VHTR (Very-high-temperature reactor), SFR (Sodium-cooled fast reactor), SCWR (Supercritical-water-cooled reactor), GFR (Gas-cooled fast reactor), LFR (Lead-cooled fast reactor) and MSR (Molten salt reactor) (GENIV, 2021).

Another fundamental problem that affects the future of nuclear power is the cost uncertainties of building a new reactor. The economic viability of a reactor depends on four main factors (Kessides, 2012):

- Capital and Construction costs: these costs including all the processes, starting from the planning, design, and construction.
- Operation and maintenance: which include the management of the plant, taking in account labor, security, spares, periodic maintenance, and overhead costs.
- Fuel costs.
- Back-end costs: this reflects the decommissioning of the plant and waste management and disposal costs.

More challenges are facing NPP, such as the lack of grid coverage in rural regions and the high costs associated with connecting rural electrification to the grid create a challenge to expanding access to electricity (IAEA, 2021) . Additionally, there are many countries considered "newcomers" to nuclear technology, such as Albania, Algeria, Congo, and Uganda, which they are interested in adding nuclear energy to their national electricity supply. The expansion of NPP technology in these countries, this should be well-planned and assessed, particularly in terms of economic, social, and safety, and fulfil the treaty of non-proliferation. Although developing a strong safety culture is critical into the countries that already have nuclear power plants, achieving the required safety aspects can be difficult for newcomer countries, especially if the significance of safety is not recognized by society and the political establishment (Budnitz, Rogner, & Shihab-Eldin, 2018).

Nuclear power investment in advanced economies has halted during the last two decades due to high prices, long building durations, adverse electricity market and policy environments, and public trust challenges resulting from the Fukushima Daiichi accident. Construction of Generation III reactors has also been delayed, with cost overruns. Insufficient payment in most electricity markets further reduces the competitiveness of new nuclear power facilities. Nuclear power plant retirements are likely to accelerate in advanced countries as current facilities run out of operating licenses, close due to policy-driven phase-outs, or cease operation for economic reasons (IEA, 2022).

2.2 Enter the Small Modular Reactor

NPPs require a long time to be in service and generate electricity, to compensate for the costs of building them. While a new innovative technology scales up the global nuclear capacity and creates a new market for energy production without GHG. Small Modular Reactors (SMRs) are designed to produce a maximum of 300 MW and are prefabricated, simplifying manufacturing, shipping, and installation (WEF, 2022).

The term Modular refers to reactor components that are prefabricated before being installed on-site, while existing NPPs use factory fabricated components, but require a considerable amount of work in field to assemble them on site. SMRs are expected to require less work and on-site preparation. SMRs are anticipated to have fewer capital expenses than NPPs, due to reduced construction time and capital costs. SMRs can provide energy for rural areas, small size grids, and could be helpful in different applications not only electricity production, such as seawater desalination, pulp, and paper manufacture and so. The new designs of SMRs are offering higher level of efficiency, and obvious advantage of safeguards and security. Most SMRs are expected to be built below grade for added safety and security, addressing vulnerabilities to both sabotage and natural disaster scenarios. Some SMRs will be built to operate for lengthy periods of time without needing to be refueled (DOE, 2022).

The concept of SMR dates to the 1940s when the U.S armed forces began R&D on small reactors. The Navy developed nuclear power for aircraft carriers and submarines. The Army Nuclear Power Program in the US military led to the construction of eight small reactors, some of which were in isolated spots like Antarctica, Greenland, and remote Army bases. However, the experience at these sites was not encouraging, with leaks resulting in significant contamination. The Army canceled the program in 1976, stating that the development of complex, compact nuclear plants was expensive and time-consuming to develop and producing these types of plants (Ramana, 2015).

The dream of small nuclear reactors continued in the 1980s, as the nuclear industry faced high costs and schedule overruns. Analyst Joe Egan proposed a factory-based approach to manufacturing reactors under 400-MWe size, which could lower capitally cost and reduce regulation. However, these vision never materialized, and turnkey reactors were deemed too expensive (Ramana, 2015).

As a result of the ongoing demand for clean energy sources to aid in the fight against climate change, and the market for large capacity power plants is limited to countries with a grid capacity capable of accepting them. After 2010, countries embarking on nuclear power programs started construction projects for large nuclear power reactors with advanced technology. Limitations of grid capacity and slow growth in power demand are leading factors in exploring whether smaller, more incremental nuclear power technologies can be used instead of new large nuclear power plants or to supplement existing installed capacity (IAEA, 2021) .

SMR development in Western countries is gaining private investment, including small companies, indicating a shift from government-led nuclear R&D to private sector-led, entrepreneurial-driven projects. This shift is often linked to a social purpose, aiming to deploy affordable clean energy without GHF emissions. That's because the expectations of building SMRs exceed the simplicity in design and the economic advantages, but also because SMR designs comprise less dependency on active safety systems such as AC power or additional pumps to mitigate accidents. Instead, the designs exploit passive safety feature, which is dependent on natural features like gravity and pressure circulation. Furthermore, as a design base component, the designs consider the entire life cycle, particularly spent nuclear fuel (SNF) management and radioactive waste management, as well as the decommissioning process. Moreover, SMR can use the generating equipment in decommissioned coal-fired plants, which are usually under 500 MW and some under 50 MW (WNA, 2024).

The first SMR in operation since May 2020, the Akademik Lomonosov, is a floating power unit built by Rosatom in the Russian Federation (WNA, 2024). The reactor type is PWR (Pressurized Water Reactor) with two KLT-40S reactor systems, each reactor with a 35 MWe and 150 MW capacity. There are two more SMRs in advanced stages of construction: CAREM in Argentina, which has an integral PWR (primary circuit components are placed within the reactor pressure vessel, which decrease the pipework) and passive safety systems, while allow core heat removal by natural circulation; and HTR-PM in China, a pebble bed high temperature gas cooled two identical reactors with a 250 MW capacity capable of producing 210 MWe. The HTR-PM uses active and passive safety systems, and the distinctive characteristic is the inherent safety.

There are now more than 80 SMR designs, which are classified into one of six categories (IAEA, 2020):

- Water Cooled SMRs (terrestrial)
- Water Cooled SMRs (marine)
- High Temperature Gas Cooled SMRs (HTGR)
- Fast Neutron Spectrum SMRs
- Molten Salt SMRs (MSR)
- Micro-sized SMRs (MMR)

SMR sizes and designs are more suitable for partial or full use in non-electrical applications such as heating industrial processes, producing hydrogen, or desalinating seawater. The thermal efficiency of cogeneration or process heat is significantly increased, which increases the return on investment. Some SMR designs may also target specific niches, such as isolating small islands or remote areas and using microreactors in place of diesel engines (IAEA, 2020).

2.3 The advantages of SMRs over existing NPPs

Small modular reactors (SMRs) have been advanced as a new technical alternative to traditional large reactors, according to their potential for significantly improved safety performance, smaller unit sizes, resulting in lower up-front capital requirements and affordability, grid considerations, and better matching to demand and market uncertainty. While their initial deployment is likely to occur in countries with existing nuclear-power activities, these characteristics have made them an appealing option for many “newcomer” countries, even though the commercial availability of SMRs in the global marketplace is still a distant prospect. (Budnitz, Rogner, & Shihab-Eldin, 2018) . The advantages of SMRs can be summarized as follows:

Modularity. SMRs are designed to be modular and scalable, allowing for more flexible deployment. This modularity refers to the ability to manufacture large components of the nuclear steam supply system in an industrial environment and ship them to the place of usage. In comparison to larger units, they require less on-site preparation and have shorter building times. In comparison to larger plants, SMRs provide more design simplicity, increased safety measures, factory production costs, quality, and flexibility. As energy consumption grows, additional modules can be added incrementally (Energy.Gov, 2023).

Inherent Safety Features. The proposed designs offer improvements in passive safety systems by using natural phenomena such as gravity, also by incorporating a smaller core, providing higher surface-to-volume ratios, and lowering power output. Furthermore, a heightened reliance on passive cooling systems allows for simpler designs, thereby facilitating easier operation and maintenance (NEA, 2021).
Reduced Capital Costs. SMRs have the potential to be more cost-effective compared to traditional nuclear reactors due to their smaller size. The constructability of SMRs is also advantageous, as factory-built modules lead to shorter and more predictable construction timelines. While there might be some reduction in scale regarding operational and site costs, these drawbacks can be mitigated by safer designs and reduced maintenance expenses (Vlahoplus & Sean, 2021).
Flexibility. SMRs can supply power for situations where large plants are unnecessary or where sites lack the infrastructure to accommodate a sizable unit. This encompasses smaller electrical markets, isolated regions, smaller grids, sites with restricted water and land availability, or distinctive industrial applications. Additionally, SMRs are anticipated to be appealing choices for replacing or upgrading aging or retiring fossil plants, as well as offering an option for supplementing existing industrial processes or power plants with a greenhouse gas-free energy source (Energy.Gov, 2023).
Despite the apparent advantages of SMRs and the steps the countries have already taken, the market will see a delay in having SMRs, because they are based on the same concept as NPP technology and are complex systems, even if their designs and features are simpler. In addition, many technical issues still challenge their future deployment, such as the effectiveness and efficiency of passive safety systems, the proliferation resistance, and the licensing process, which is challenging because of the lack of experience in the case of the new designs.

2.4 The importance of nuclear power in the energy landscape

Nuclear power is responsible for 10% of global electricity production, operated through 440 reactors spanning 31 nations (WNA, 2024). Within advanced economies, it constitutes 18% of the overall electricity generation. France, the Slovak Republic, and Hungary received more than 50% of their electricity from nuclear power during that period. Notably, the European Union, Korea, and the United States heavily depended on nuclear energy. In advanced economies, nuclear power emerged as the primary low-carbon energy source, contributing 40% to the total low-carbon generation and holding the top position among low-carbon sources in 13 countries (IEA, 2019).

In general, the production of electricity overall the world in 2022 was 2610 TWh, also there is a sharp decrease in the nuclear output in 2011, that’s due to Fukushima tsunami in Japan in 2011, some countries shut down the plants due to safety reasons (Our world in data, 2023), that is clear in Figure 3 which represent the production of electricity from nuclear energy from 1970 until 2022.

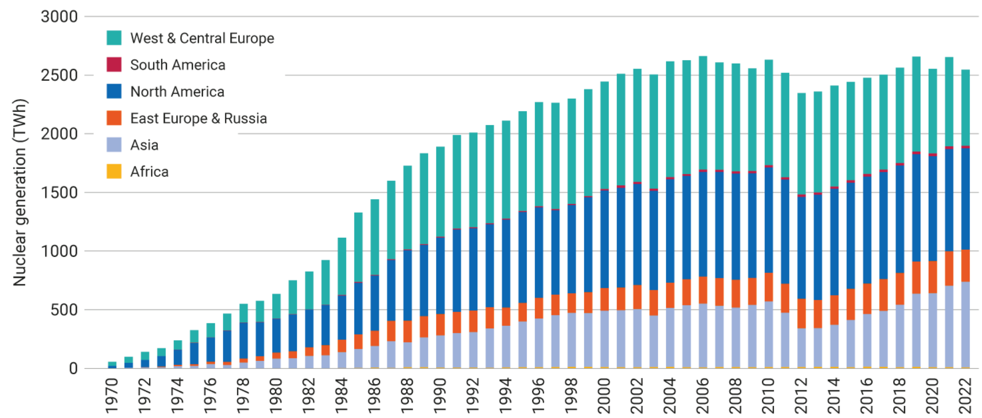

Figure 3: Nuclear Electricity Production (WNA, 2023)

SMRs, typically ranging from 150 to 300 megawatts, offer benefits such as lower costs, quicker construction, and improved safety features. However, their current levelized cost of electricity, which is the total cost to build and operate a power plant over its lifetime divided by the total electricity output dispatched from the plant over that period, is over $120 per megawatt-hour in markets like Europe, the US, and Japan (WNA, 2024). To be competitive, SMR costs need to fall by 50%, with potential reductions to under $80/MWh by the 2030s through government support and technological advancements. China's success in reducing costs for other technologies suggests it might achieve similar results with its SMRs (Mackenzie, 2021).[1]

[1] Public-private partnerships will be essential. According to the Canadian SMR road map (2018), the federal and provincial governments play a crucial role in supporting the development of SMRs in Canada by sharing risks and reducing the cost of capital. Without this support, private sector investment may fall short, missing opportunities for innovation, expertise building, and supply chain benefits. Effective policy measures include cost-sharing in the development phase to mitigate early-stage risks; loan guarantees during construction to lower financing costs for first-of-a-kind SMRs, which include the new technology SMR; and long-term agreements such as power purchase agreements or tax incentives to decrease the levelized cost of electricity by providing revenue certainty. A decline in costs is expected as SMR technology matures, which could potentially reduce the need for government risk-sharing. Also, governments could encourage the use of SMRs in off-grid markets by setting up frameworks and using risk-based criteria to make sure that smaller, simpler, and safer SMRs do not have to deal with too many rules (Canadian Small Modular Reactor (SMR) Roadmap Steering, 2018).

The net-zero scenario predicts a 2.5% annual increase in global electricity generation from 2022 to 2050, driven by electrification, economic development, and population growth. This growth will increase the share of electricity in final consumption from 20% to over 50% by 2050. To achieve this goal, apply four keys of milestones for the electricity sector: first, the tripling of fossil fuel reserves by 2030; second, the doubling of grid investments by 2030; third, by 2040, reducing 95% of fossil fuel share; and fourth, for 2050, the milestone of the electricity sector from nuclear power will be more than double from 417 GW in 2022 to 916 GW. Figure 4 shows the growth of the renewable capacity surge by three times by 2030, for nuclear energy power, which will increase by over 65% (IEA, 2023).

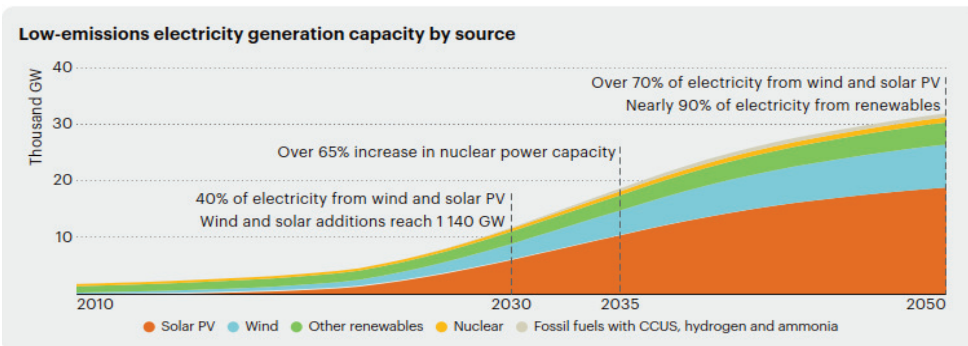

Figure 4: Low emissions electricity generation by source in 2050 (IEA, 2023)

2.5 Nuclear events, their risks, and potential outcomes

Generally, nuclear power plants are usually designed to operate safely, during normal operation and shut down, to ensure safety in the event of any malfunction or accident However, it is important to realize that they cannot consider any technical activity to be completely risk-free. Incidents and accidents can happen, as with other industries the lessons learned from such incidents contribute to the continuous improvement of safety measures This improvement can be a new system of safety features that do not work includes, and established long-term operational facilities based on the development of capital for these, further strengthening their safety systems and overall reliability (WNA, 2022).

There are risks that could occur in SMR as in NPPs, and as per the proposed designs, the designs come over these challenges, such as the decay removal heat, emergency cooling system, emergency planning zone, and station blackout. Besides these common risks, with the novelty of the SMR designs, there are new challenges appearing, such as the high dependency on the passive safety features, the remote controlling of the SMR, the new fuel concepts and their highly enrichment ratios, and the complexity of the designs, such as the multi-modularity reactors. In the fourth chapter, we will study the likelihood and impact of these risks on the SMR.

2.5.1 Decay Heat Removal

During the reactor shutdown process, the chain reaction can be rapidly stopped by inserting the control rods, but the nuclear fuel will continue to release heat, known as "decay heat." Decay heat is a small fraction of the reactor's full power—about 6-7% immediately after shutdown, dropping to 1% within a day—and can be released over weeks until the fuel fully cools. This energy must be managed to prevent the reactor from becoming extremely hot, which could compromise the containment's integrity and allow radioactive particles to escape into the environment. Effective decay heat removal is crucial for preventing many accident scenarios, making robust cooling systems essential. (Touran, 2023).

2.5.2 Loss Of Coolant Accident (LOCA)

A loss of coolant accident (LOCA) could threaten the reactor safety, especially for water cooled reactors. Due to the raising of the temperature in cladding and fuel due to decay heat generation and core energy storage. In a NPP, there is emergency core cooling system (ECCS), which is particularly designed to deal with a LOCA. The function of this system to transfer the heat emitted (Handwiki, 2022) .

2.5.3 Emergency Planning Zone (EPZ)

There are two emergency planning zones (EPZs) established around the nuclear reactors (USNRC, 2020): a 10-mile EPZ to protect communities from radiation exposure, which it offers immediate protective actions include sheltering in place or evacuation, with delayed releases providing more time for emergency response actions. There is also a 50-mile EPZ to monitor food products, livestock, and water to protect the public from radiological exposure, while federal and state governments may monitor and test food and water supplies that could become contaminated and remove any unsafe supplies from public consumption in case of severe accident (NEI, 2016).

2.5.4 Station Black-out (SBO)

Station Black-out (SBO) refers to the complete loss of AC electric power to essential and non-essential switchgear buses in reactors, as well as the loss of the offsite electric power system. For safety purposes, the reactor core will remove the decay heat by relying on AC power. SBO risk could increase the likelihood of severe core damage (Volkanovski & Veira, 2015)

2.5.5 Cyber Incidents (CI)

With increasing the dependency on cyber space which refer to the domain of self-regulating computing, digital telecommunications and digitally encrypted communications, remote operating systems, this will add risk on the reactor security (WNA, 2022). Cyber incidents (CI) include access attacks, cyber crime, or even cyber war where it is a nation act against another one. CI could be internal from the nuclear entity or external attack (Cho & Woo, 2016).

2.5.6 Spent Nuclear Fuel (SNF)

The most controversial aspect in the nuclear technology is how to deal with the spent nuclear fuel (SNF). Approximately 70% of spent fuel from NPPs globally is stored, awaiting recycling or disposal choices. In recent years, there has been a minor drop in the amount of SNF produced due to improved nuclear fuel efficiency in reactors and the closure of several NPPs. The NPP operating environment in the 2000s aimed to boost fuel cycle efficiency through higher fuel burnups and other methods, which often required fuel enrichment and decrease the SNF amount relative to the energy being produced (IAEA, 2024). In addition, there is a risk of illicit trafficking of nuclear or radioactive materials encompasses various activities, including diversion, purchase, sale, transportation, or storage of nuclear material in violation of local, national, or international law (Kershner, 2014).

2.6 Risks in nuclear industry

All industries have risks and accidents. These accidents can help improve the safety of each industry, but in case of the nuclear industry the public acceptance of these risks is different than any other industry. This is due to the high energy density, which can lead to more harmful consequences (WNA, 2022). The source of risks in nuclear industry can be summarized in four categories (IAEA, 2001):

1. Safety related risk
2. Production / operations
3. Commercial / financial
4. Strategic

Safety related risk is including nuclear, radiological, industrial, and environmental areas. IAEA has a several technical documents related to the nuclear safety and the Probabilistic Safety Analysis (PSA) (IAEA, 2001).Production or operations risk is related to the electricity sales and resources, such as marketing process, labor, inventory management. Commercial or financial risk is taking in consideration the financial variable such as prices, currency exchange rate which could pose a risk. The final risk is strategic risk, formed by the economic, commercial, and political changes, such as shifts in government types, spending trends, marketplace competition, public sentiment, ownership patterns, and regulatory changes. (IAEA, 2001).

In general, the nuclear facility as an entity has its consumption and production requirements as shown in Figure 5, if these requirements are satisfied the entity will be in normal state and the stress will be minimal, if these balancing conditions have been changed due to an event, the entity will experience tension or disruption , some entities can bear different levels of stress and continue to operate (Hughes, Jong, & Wang, 2016). The event could be a threat if it has potential consequences will impact the organizational operations, the threats could be external threat, which involve a change in the input for the entity; $\text{Energy}_{\text{IN}}$, $\text{Policy}_{\text{IN}}$, $\text{Demand}_{\text{IN}}$, or $\text{Enviroment}_{\text{IN}}$, the threat could be also internal due to accidental or structural sources (Hughes, Jong, & Wang, 2016).

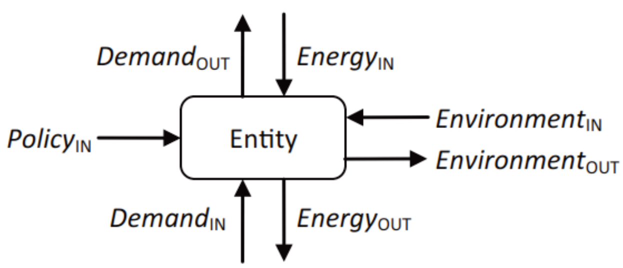

Figure 5: Generic entity (Hughes, Jong, & Wang, 2016)

The resistance of the entity to high stress levels, is described as the vulnerability of the entity and it measure how resilient the entity and how the countermeasures can reduce the stress to back to the normal state of the entity. To measure the risk of the threat , we need to know the likelihood of the threat and its frequency , and determine the impact of the threat, the impact of a threat occurs when the threat materializes, and the vulnerability either restores the entity to its normal state or leads it to a new state of tension or destruction (Hughes, Jong, & Wang, 2016).

2.7 The 3Ss (Safety, Security, & and Safeguards)

The expansion of nuclear materials, new technologies, and nuclear activities poses a challenge to maintaining a balance between the safe, peaceful use of nuclear energy and nuclear non-proliferation. To achieve this balance, the concept of enhancing the relationship between safety, security, and non-proliferation safeguards is critical for any nation pursuing or currently running nuclear plants. However, none of these factors should jeopardize the primary design objectives of the others.

Regardless, in nuclear operations three major elements are required: safety, security, and safeguards or 3Ss. If the capability of one element is reduced, it may be compensated by another that can carry out the functions of the damaged element. This is known as the synergetic effect. The goal of 3S synergy is to increase the efficiency of these elements (Kroening, Sednev, & Chumak, 2012)
First, it is important to understand the differences between these three components and how they interact together in any nuclear facility.

2.7.1 The 3Ss interrelationship

Safety, security, and safeguards are of paramount importance in an existing or proposed nuclear facilities. All have a number of equally significant components, such as confinement, containment, and protection of radioactive materials. Sharing nuclear facility process data systems could increase the effectiveness of safeguards and safety, while passive and inherent devices like double-entry doors could satisfy both security and safety requirements. However, emergency response requirements in facilities, including numerous access and exit points, could result in inconsistencies between security and safety (Suzuki, Burr, & Howell, 2021).

Figure 6 illustrates the relationship between and interrelationship of the 3S's. Safety in general is concering of protection of the public and the enviroment from the radiation, while the security is to prevent, detect and repsonse for any sobatage for the faciltiy , and safegurads concern about non-proliferation of nuclear weapons (Muti, n.d). Later in the following sections will discuss each S indiviually.

Figure 6: 3S's interrelationship (Muti, n.d)

The three disciplines of 3S have evolved independently, and it's crucial to understand their interrelationships and interactions in a trilateral manner. When one discipline is a concern, the other two disciplines become interconnected concerns. For instance, the radiation safety issues during the

Fukushima Daiichi accident raised concerns about security and safeguards as well. Identifying conflicts and synergies among the 3S disciplines is challenging due to a lack of combined technical skills in all three areas. A better understanding of 3S, considering the objectives of each field, could lead to more effective management and execution. An analytical technique, framework, or methodology is necessary to comprehensively examine 3S and identify potential conflicts (K.E. Sanders, 2015).

2.8 How the 3S's relate to SMRs

Maintaining the safety, security, and safeguards of nuclear facilities are crucial. SMRs offer an opportunity to integrate these requirements into reactor design, eliminating the need for costly retrofitting. SMRs can enhance plant safety beyond larger facilities due to integral designs, reduced core inventories, potential to eliminate accident vulnerabilities, and passive response to transients (NEA, 2021). Moreover, SMRs also facilitate the development of innovative safeguards and verification methods, such as long refueling intervals and reduced waste generation. Additionally, their small size allows for site placement below ground level, improving resistance to external sabotage events and making safety systems and reactor containment easier to protect (Middleton & Mendez, 2013).

Proposed SMR designs feature smaller core sizes with integrated coolant configurations, especially in light water (LW) SMRs, and include inherent safety measures to prevent system malfunctions and accidents. These designs emphasize passive safety systems, which enhance reliability and reduce the need for auxiliary systems, resulting in lower core damage frequency estimates compared to earlier reactors. Security considerations for SMRs are like those for traditional nuclear power plants (NPPs), with proposed below-grade siting and longer refueling intervals potentially lowering security costs and risks. However, essential above-ground operations still require adequate protection. Safeguards for SMRs follow the IAEA's Comprehensive Safeguards Agreements (CSA), but unique features of SMRs may affect their implementation. Enhancing safeguard capabilities involves improving the "proliferation resistance" of SMRs, but there is currently no solid international framework for incorporating "safeguards-by-design." Thus, practical knowledge of implementing safeguards at SMR facilities is still lacking (Williams, et al., 2018).

With respect to SMRs, there are very few the papers discussing SMRs and the 3Ss and identified many challenges and gaps. The first important debate is related to SMR safety, security, and safeguards will be less expensive. The challenge is maintaining the same levels of risk reduction when there are fewer resources available for security, safety, and protection. Second, the implementation of current safety, protections, and security methods to SMRs, including technical analysis and practice guidelines, such as applying NPP probabilistic risk assessment (PRA) based methodology in SMR passive safety. Third challenge is the absence of the harmonized, strong regulatory framework to limit the acceptable risk for the new technology.

2.8.1 How the 3Ss can affect the safety of SMRs

SMRs designs offer distinct advantages to enhance safety, security, and safeguards. For example, some SMRs will be built below grade to improve the safety and security of the reactor. Another advantage of some designs that will be fabricated and fueled in factory. sealed and transported for the site which reduce the need for transportation and nuclear material. Some light water SMRs will be fueled by low enrichment uranium or mixed oxide (MOX) fuel. (NE, 2023). Theoretically, SMR designs are providing complete scenarios about the implementation of the 3Ss. This is a challenge where all these scenarios are not based on previous solid experiences or practical proof.

In an NPP, analysis of safety, security, and safeguard is done individually because of the large size of these reactors and the spread of buildings and functions. This results in the separation of each of these requirements. Furthermore, each domain receives separate attention in the sponsored research. For example, an international safeguard sponsored research wouldn't fund research on nuclear safety, which create a challenge to find a sponsor funding a research group study the 3Ss for the advanced reactors and SMR (Williams, Cipiti, & Evans, 2021).

In case of SMR, the size is smaller and for the microreactors as well, and the modularity feature will increase the challenge to examine the 3Ss. Figure *7* shows the overlaps between safety, security, and safeguard. This might be a tectonic shift in nuclear power operations because small sites would not have the luxury of distinct safety, security, and (international) safeguards staff roles with only tens of individuals on site. The trend towards "inherently safe" designs may also result in new regulatory choices that benefit from more integrated thinking about the 3S's. Taken together, a 3S approach appears well positioned to solve the problems of SMR while also enhancing its potential benefits (Williams, Cipiti, & Evans, 2021).

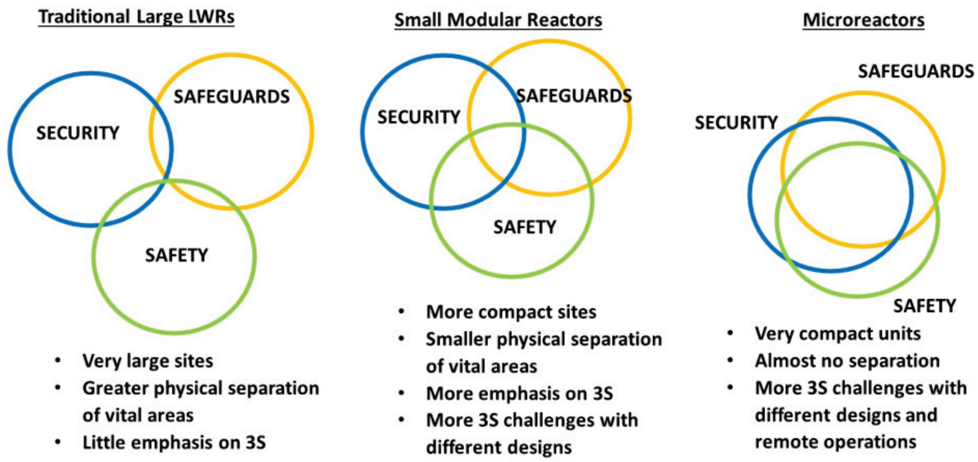

Figure 7: Changes in SMR 's 3Ss (Williams, Cipiti, & Evans, 2021)

The main aim of studying the interaction between the 3S's is to identify gaps, interdependencies, conflicts, and leverage points through the application of safety, security, and safeguards techniques (William, Cohn, & Osborn, 2019) . In the following chapters, we will apply risk method assessment and will examine the relationship between them.

Safety, security, and safeguard by design (3SBD) is an approach that taking in the consideration each of these variables early in the design phase to create safe, secure, and economically competitive reactors. Consideration of the 3S (and related regulatory requirements) early in the design phase aids in design optimisation and avoids costly retrofits in the future (Sandia National Laboratories, 2008).

The approach of studying 3SBD is useful for exploring connections and engage safety, security, and safeguards experts in a comprehensive analysis. This strategy might yield financial benefits for invested parties and offer a competitive edge. Nuclear security, along with physical protection, shields nuclear facilities against potential dangers, while international safeguards guarantee adherence to non-proliferation agreements. For example, use of various instrumentation like video surveillance, and non-structural assay instrumentation, which are often used twice for different records, such as safeguard verification or operator quality control (Morichi, 2012).

2.8.1.1 Safety

Nuclear safety focuses on protecting the public and the environment from radiation and hazards associated with nuclear plants throughout their lifecycle, including fuel transportation, storage, and radioactive material usage. Safety measures aim to limit radiation exposure to workers, the public, and the environment. Mitigating accident consequences is crucial, achieved through proper safety measures and regulations such as the Defense-in-Depth (DiD) concept, which provides multiple layers of protection and barriers to prevent radioactive material release (Kroening, Sednev, & Chumak, 2012) .

To meet the highest safety standards, it is essential to control radiation exposure, reduce the likelihood of events that could threaten reactor and environmental safety, and mitigate the impact of any potential incidents. These measures ensure that both safety and environmental protection are effectively maintained (IAEA, 2016).

To meet safety principles, nuclear power plants must ensure that radiation exposure to workers and the public, as well as any planned radioactive releases, remain below regulatory limits and as low as reasonably achievable. This involves designing and operating plants with strict technical and administrative controls to manage all radiation sources. Although some controlled radiation exposure and releases are permitted, they must be minimized and regulated. Additionally, the plant's design should ensure that radiation doses are maintained within acceptable limits throughout the plant's life and during any accidents, with ongoing measures to keep doses as low as reasonably achievable for operational personnel (IAEA, 2016; WNA, 2022).

Safety in design concept is to ensure that the fundamental safety objective is achieved in nuclear power plant design, a comprehensive safety assessment is essential. This assessment identifies all potential radiation sources, evaluates possible doses to workers and the public, and considers environmental effects. It examines normal operation, anticipated operational occurrences, and accident conditions. Based on this analysis, the design's ability to withstand initiating events and accidents can be confirmed, demonstrating the effectiveness of safety-critical items and establishing prerequisites for emergency planning (IAEA, 2009; IAEA, 2016).

One of the most important measures for the safety of the nuclear facility is the DiD approach, this is an approach to optimize the safety of reactor design. It is based on addition layers or barriers of defence in the design of nuclear facilities, using levels of equipment and procedures to keep the workers protected from the radioactive materials effects. Moreover, it is intended to protect the public and environment from any risk of accident or abnormal event. (NEA, 2016)

These levels are independent, which means the failure of one level won't affect the others. It can be summarized in five levels (nuclear-power, 2021):

1. Prevent the abnormal operations and failures, this step could be achieved by the design of the nuclear facility, with applying high quality of quality assurance, and inspection.

2. Control, limit and detect the failure if it happened, which include the simultaneous functions and control system will be active in case of the failure.
3. Control of the accidents by engineered safety features and protection procedures.
4. Control of severe conditions which applying the accident management to protect the damage of the core and mitigate the consequence of the accident.
5. Mitigation of radioactive releases consequences, using the of-site emergency response would help to protect the workers.

Dealing with radioactive waste is a critical challenge for safety measures. It is crucial to isolate or dilute it so that any radionuclides returned to the biosphere remain harmless. Most radioactive waste is contained and managed, with some requiring deep and permanent burial. Nuclear power generates a large amount of energy from a small amount of fuel, producing relatively small but hazardous waste. All parts of the nuclear fuel cycle produce radioactive waste, and the cost of managing and disposing of this waste is included in the electricity cost, ensuring it is internalized and regulated (Goverment of Canada, 2023).

Radioactive waste from nuclear power constitutes a small proportion of total industrial hazardous waste. It includes low-level waste (LLW), intermediate-level waste (ILW), and high-level waste (HLW). LLW, such as paper and clothing, requires no shielding and is often compacted or incinerated. ILW, including resins and metal fuel cladding, requires shielding and is often solidified for disposal. HLW, arising from uranium fuel 'burning' in reactors, generates significant heat and requires cooling and shielding, making up 95% of the total radioactivity of all produced waste. Additionally, very low-level waste (VLLW) includes materials from demolition and certain industries, disposed of with domestic refuse or in specifically designed facilities (WNA, 2022).

Decommissioning is critical for the safety principles, as many nuclear facilities are approaching the end of their operational lives. This process involves removing or dispose radioactive materials, which may be treated as waste or recycled. Effective decommissioning strategies are essential to manage and minimize the impact of these materials on health and the environment. Nuclear decommissioning marks the end of a facility's lifecycle and includes steps such as decontamination, dismantling, or cleanup. The process involves several phases: planning, preparation, execution, and completion. Each phase ensures that the facility is safely retired and that all regulatory and safety standards are met. Decommissioning strategies may vary, including immediate, deferred, or in-situ approaches, each tailored to the specific needs of the facility (Natural Resources Canada, 2020).

Safety in SMRs is designed to ensure the preservation of safety risk events despite potential material failures or human errors. The inherent safety of SMRs can be significantly enhanced by their design features. For example, SMRs often utilize a low inventory of fissile material, which reduces residual heat and the potential for large releases in the event of an accident. Their compact size also allows for reduced cooling requirements and better integration of components. Additionally, SMRs can incorporate passive safety systems, such as natural convection cooling, which does not rely on external power sources and provides an extended grace period during emergencies (IAEA, 2022). However, challenges remain in demonstrating the safety of SMRs, particularly those relying on passive safety systems and modular configurations. Ensuring reliable activation and performance of these systems, addressing multi-unit risks, and harmonizing safety requirements across jurisdictions are critical for effective SMR licensing and operation. Continuous development and testing are essential to refine safety protocols and meet evolving standards (Cognet, Bartak, & Bruna, 2021).

2.8.1.2 Security

Security-by-design (SeBD) is a method that integrates Physical Protection System (PPS,) safety, and operations into nuclear facilities design, requiring careful consideration from regulators, designers, and operators. Successful SeBD leads to an enhanced physical security infrastructure, which reduces the possibility of insiders gaining access to nuclear material, as well as the risk and opportunity for malicious activities. It also offers flexibility in responding to a dynamic threat environment, boosts the effectiveness of protective force in the case of an attack, such as on-site security guards (Duguay, 2020).

While the primary functions of a PPS are detection, delay, and response by security personnel. An effective PPS must achieve these objectives by either deterrence or a combination of these functions. Detection involves the discovery of an adversary action, while delay slows down adversary progress through personnel, barriers, locks, and activated delays. Response personnel can be considered elements of delay if they are in fixed and well-protected positions. The primary functions of a PPS are detection, delay, and response by security personnel. An effective PPS must achieve these objectives by either deterrence, or a combination of these functions as shown in Figure 8 (Zakariya & Kahn, 2015).

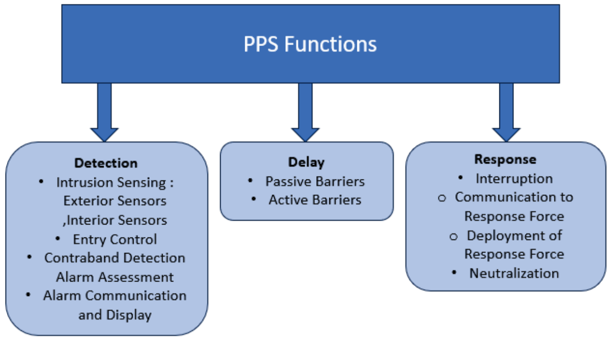

Figure 8: PPS Functions (IAEA, 2021)

Detection involves the discovery of an adversarial action, while delay slows down adversary progress through personnel, barriers, locks, and activated delays. If response personnel can be considered elements of delay if they are in fixed and well-protected positions. A central alarm station operator assesses alarms generated by an intrusion detection system to determine if they stem from intrusions of concern for nuclear security. It typically includes sensors, CCTV, access control measures, alarm communication systems, and personnel working together (IAEA, 2021). Exterior sensors require an unobstructed area for functionality and visual evidence. Designers aim for uniform detection conditions along the perimeter, maintaining a clear zone parallel to fences. This zone excludes people, animals, and vehicles. If primary sensors are not deployed, alternative sensors like active infrared can be used (IAEA, 2021).

Barriers play a crucial role in providing a delay function, increasing the time an adversary needs to complete a malicious act. They complement access control measures, support detection at the perimeter, and can mitigate stand-off attacks. While natural elements may provide delay, engineered barriers are typically used. The delay provided depends on the nature of physical obstacles and the adversary's capabilities. The distance between the barrier and the protected target may also contribute.

Response consists of actions taken by the response team to prevent adversary success, which may include interruption and neutralization. Interruption refers to enough response personnel arriving at the appropriate location to stop the adversary's progress, while neutralization describes the actions and effectiveness of responders after interruption (IAEA, 2021) (Evans, Byrum, Stanford, Sandt, & Goolsby, 2021). Based on that, to achieve an effective PPS system design requires a response that interrupts and neutralizes the threat, arrives timely, and has proper protocols. It should be adequate, documented, and validated. The placement of response forces is crucial for sabotage events. The decision to use offsite or onsite response forces should be based on thorough analysis. An effective response strategy with appropriate detection and delay elements is vital for avoiding costly upgrades (IAEA, 2019; Evans, Byrum, Stanford, Sandt, & Goolsby, 2021; Zakariya & Kahn, 2015) .

Moreover, SeBD is crucial for cost-effective deployment of SMR technologies, ensuring facility design aids the security system's effectiveness. By considering security in SMR design, construction materials can be chosen to increase adversary task time, targets can be placed below-grade, and site locations provide inherent advantages. SeBD also allows for security features to defend against beyond-design basis threats, enhancing facility flexibility (Evans, Byrum, Stanford, Sandt, & Goolsby, 2021).

The security risk assessment is necessary to understand threats, national threats, and Design Basis Threats (DBT), DBT assesses the operator's PPS to identify potential insider and external adversaries who might remove nuclear or radioactive materials without authorization. Terrorists and insiders with permission to access locations, events, or private data are examples of external adversaries (IAEA, n.d).

Nuclear security requires considering DBT in the design of nuclear security measures. Operators should consider both external and internal threats, such as blended attacks and cyber-attacks on security surveillance systems. For SMRs must consider DBT when possible, and it is crucial to ensure both national and foreign vendors and designers are security-vetted for access to classified information. The DBT evolves over time, and the design concept is usually fixed once the facility is built. To minimize the effects of certain ballistic threats, an SMR should be built out of range of the applicable DBT. Alternatively, additional land can be acquired to increase the buffer zone and stand-off distance for credible DBT type threats. A well-engineered solution to one hazard may also provide good resistance to others (Duguay, 2020).

Another concept is considered in SeBD, the DiD of security zones. Normally NPP have three security zones: controlled, protected, and vital. Controlled area limits to the site, while the protected area is closer to the reactor and equipped with physical barriers and intrusion detection systems. Vital areas contain equipment that could lead to high radiological consequences if sabotaged. High-risk sites have an inner area with additional protection and staff security screening (Duguay, 2020). SeBD must ensure equipment reliability and redundancy for continuous operations, including multiple detection sensors, backup power supplies, Central Alarm Stations and Secondary Alarm Stations, and strategic response forces. Cyber security design protection measures are crucial for protecting these functions and critical digital assets (Duguay, 2020) .

Cyber terrorism in NPPs poses significant psychological and economic risks by combining computer-based and nuclear terrorism threats (Cho & Woo, 2016). Cyber risks encompass safety, security, and protection, highlighting the need to integrate cyber safety and security to avoid overlooking crucial safety concerns (Robert Forrest, 2017). Types of cyber attacks include access attacks, where viruses compromise systems; passive attacks, involving eavesdropping without direct interference; and cyber terrorism, which seeks widespread disruption and destruction. Effective defenses are crucial to mitigate these risks and address the psychological impact of potential attacks (Cho & Woo, 2016).

Because SMR are proposing flexible nuclear technologies that can scale up or down to meet energy demands and power areas, they might be rely on artificial intelligence, wireless and automated technologies, miniaturization of components, and digitally controlled operations. All SMR designs are promising to deliver innovative solutions for nuclear security standards, which it could be a challenge at same time. For example, for remote supervisory control and autonomous operations, AI, and machine learning all pose risks to SMRs (Siserman-Gray & Landine, 2023).

2.8.1.3 Safeguards

Nuclear safeguards refer to the application of international commitments to present nuclear material from being diverted from peaceful nuclear activities to the production of nuclear weapons (Hanks, 2013). Safeguards are focused on material accountability and the surveillance of nuclear activities. These activities involve tracking nuclear material from the point of shipping and receiving until the removal of spent fuel from the reactor. This process enables the tracing and prevention of any illicit transfer of nuclear material (NNSA, n-d).

Safeguards by Design (SBD) involves defining the functional requirements of a facility's safeguards system alongside its detailed design, starting from the Pre-Conceptual Design stage. This ensures the system meets safeguards goals and evaluates its performance as the facility design progresses. The system is completed in coordination with the facility design, and concurrent development occurs throughout the construction and operation stages to prevent design or operational changes that undermine the system's effectiveness (Durst, et al., 2010). Moreover, SBD has another objective, which is avoiding cost and time consumption during design processes to accommodate safeguards rules (IAEA, 2014).

IAEA forms agreements with states and regional safeguards authorities to implement safeguards. There are three main types of agreements and two protocols (IAEA, 2014; Whitlock, 2021; IAEA, 2015):

- Comprehensive safeguards agreements (CSAs): This agreement includes non-nuclear weapons states (NNWS) under Non-Proliferation Treaty (NPT) and States party to nuclear weapons free zone treaties.
- Voluntary Offer Agreement: This agreement includes nuclear weapon states (NWS) under NPT.

The main measure of the safeguard is inspection, regular inspections are conducted at several hundred sites in 57 NNWS as well as nearly 400 nuclear plants. Both their documentation and the nuclear material itself are audited. Additional precautions like instrumentation and surveillance cameras are used in addition to IAEA inspections (WNA, 2021). In addition, it serves as an alert system to prevent nuclear material diversion from peaceful activities. They involve material accountability, physical security, and containment and surveillance. Material accountability involves tracking transfers and flow of materials in nuclear facilities, while physical security restricts access to materials. Containment and surveillance use seals, cameras, and spot checks to detect unauthorized movement or tampering (WNA, 2021; CNSC, 2018).

Nuclear material accountancy involves licensee activities to determine the quantity of nuclear material in defined areas and changes over time. This includes measurement, record keeping, preparation of accounting reports, and verification of information. it includes establishing material balance areas and key measurement points. For licensees with Group 1A material, which it is group of materials subject to full-scope safeguard and open t routine verification by IAEA and detailed material accountancy. That's include pure Uranium, Plutoinium-239 and thorium, which are pure enough for fuel fabrication or isotopic enrichment, including materials in the nuclear fuel cycle and depleted uranium, and uranium ore concentrate. The measurement of nuclear material will include inventory racking, physical inventory taking, and calculate the inventory difference (CNSC, 2018) .

Commercial reactors fresh fuel is not attractive material for nuclear weapons as the used fuel, including BWR and PWR, can gain attractiveness in the years following discharge, depending on factors like burn-up, composition, and reactor type. The emergence of SMR designs presents advantages such as portability, lower initial investment, scalability, and enhanced security. Variances in the appeal of fuel assemblies between conventional LWRs and assessed SMRs mainly stem from differences in size and facility characteristics (Robel, et al., 2013).

Nuclear materials are found in five areas, each area has its own consideration of safeguard (IAEA, 2014):

- Shipping/Receiving area: Nuclear power reactors receive fresh fuel and ship spent fuel, with nuclear material entering fresh fuel transport containers with an IAEA seal.
- Fresh fuel storage: Fresh fuel storage can be dry or wet.
- Spent fuel storage: LWR spent fuel is stored in spent fuel pools for cooling.
- Core: Off-load refuelled reactors.
- Fuel transfer chambers: The fuel loading and unloading areas.

Finally, in the decommissioning process, after shutdown the reactor there are another path for safeguard to track the materials, ensuring that nuclear material is removed, waste containing nuclear material is measured and removed, and essential equipment is removed or rendered inoperable The IAEA uses an essential equipment list to determine decommissioned facilities. Designers assist in creating this list, which can be part of early design verification activities. The facility is considered available for use when essential equipment arrives and is verified to be removed or non-functioning. (IAEA, 2014). This is a critical point for designer to take in consideration the decommissioning process steps to avoid any contamination or extend the process of decommissioning.

To sum up all methods and tools are applied to ensure the safeguard standards (NNSA, n-d):

- Nuclear material accountancy (NMA): Detecting the current and previous nuclear materials in specific areas and in specific periods using surveillance measures.
- Containment and surveillance: The detection of undeclared activities such as altering nuclear material composition.
- Environmental sampling: Involves collecting and analyzing samples from facilities or local environments to detect traces of materials revealing information about nearby nuclear processes.
- Non-destructive Assay (NDA): it is a method used to measure nuclear material content or elemental/isotopic concentration without causing significant physical or chemical changes in the item.

SMRs designers must develop and implement SBD concepts in their designs and aspects to be considered to apply safeguard ability in all SMR stages starting from building till decommissioning. For instance, new fuels and fuel cycles, such as Th/U-233, MOX, and TRU fuels, are being developed, reactor designs are changing, with longer operation cycles and higher excess reactivity. Supply arrangements are changing, with new spent fuel management and diverse operational roles. However, remote locations pose access and cost-benefit issues (Whitlock, 2021) .

SMRs are designed with extended core lifetimes, exceeding those of current nuclear reactors, which reduces the need for frequent core access and enhances safeguards. While many SMRs claim over four years of core lifetime, twice as long as the current fleet, challenges arise if a state control refueling equipment, potentially compromising the design plan. To address this, SMR designers must find solutions for maintenance and materials inspection to prevent unauthorized access during tests. The longer core lifetime may not effectively reduce access frequency without addressing regular maintenance and inspection challenges. Although SMRs' longer core lifetimes and higher burnups can impact their reliability for weapons purposes, the technical difficulty of creating a nuclear weapon remains unchanged (Prasad, Abdulla, Morgan, & Azevedo, 2014).

2.9 Summary

This chapter discussed the historical development of nuclear power and its evolution, focusing on the status of nuclear power worldwide and the countries heavily dependent on nuclear energy for electricity generation. It highlighted the challenges of high costs, safety concerns, and limited grid coverage, particularly in newcomer countries. The chapter also introduced the concept of SMRs, which offer a promising alternative to traditional NPPs due to their modular design, reduced capital costs, and potential applications beyond electricity production. Despite their advantages, the deployment of SMRs faces challenges due to technical complexities and regulatory processes.

The chapter emphasizes the importance of nuclear power in the global energy landscape, its contribution to low-carbon energy generation, and its potential to meet rising electricity demand sustainably. It also discusses the risks associated with nuclear power, including decay heat removal, emergency core cooling, emergency planning zones, and station blackouts. It emphasizes the need for continuous safety improvements and the implementation of the DiD approach to mitigate these risks effectively.

The chapter also explored the concepts of nuclear safety, security, and safeguards, emphasizing their interrelationships and the importance of their synergy. It highlights the role of each component in ensuring the safe, secure, and peaceful use of nuclear energy and the challenges and opportunities associated with their implementation in nuclear facilities.

In the next chapter, we will discuss in more details the relationship between the three components of nuclear 3Ss and SMRs, exploring how they can be influenced by the size of the reactor. We will address each component of the 3Ss individually and analyze how it impacts nuclear facilities. To study the effects of the 3Ss on SMRs and the potential risks associated with them, we will select SMRs with different designs at various maturity levels. Additionally, we will discuss the methods of risk assessment that will be employed in our analysis.

3 Method

This chapter presents the risk assessment methodology used in this study. The six-step process includes identifying threats, ranking threat events, assessing vulnerability, evaluating impacts, determining likelihood, and calculating overall risk. By applying this methodology to SMRs, we aim to assess and mitigate potential threats, ensuring the safety, security, and safeguards of these systems

3.1 Risk Assessment Methodology

There is no single framework or assessment capable of comprehensively measuring all the risks to an entity. However, employing various risk assessment measures can significantly improve the entity's overall quality and resilience against potential threats. These assessments play a crucial role in informing decision-making processes and regulatory frameworks, especially in high-risk sectors such as nuclear facilities, they are typically designed with these risks in basis, adhering to acceptable limits based on the potential impact and likelihood of various scenarios. By minimizing the likelihood of threats and their potential impacts, nuclear facilities aim to ensure the safety of the public and the environment (Vitázková & Cazzoli, 2013). In this thesis we are using the generic framework of energy security analysis in energy system, described in (Hughes L. , A generic framework for the description and analysis of energy security in an energy system, 2011) ,and originally developed from the Guide for Conducting Risk Assessments (NIST, 2012) .The method involves six steps, as described below.

3.1.1 Threats

A threat is an event that could occur within or outside the entity, leading to adverse effects on organizational operations (Hughes, Jong, & Wang, 2016). This threat may originate from one or multiple sources, including internal factors (such as accidents or structural issues), such as LOCA or the failure of active safety systems (such as recirculation pump failures) in SMRs. Alternatively, it could stem from external sources (as referenced in Figure 5 in chapter 2), impacting $\text{Energy}_{\text{IN}}$, $\text{Demand}_{\text{IN}}$, $\text{Enviroment}_{\text{IN}}$, or $\text{Policy}_{\text{IN}}$. Examples include sabotage or theft of nuclear material, increased SMR distributions, tsunamis, or tightening of SMR regulations and licenses respectively.

3.1.2 Threat event ranking

The threat event could have the potential to increase the stress on the entity, there are different levels of stress, if the stress determined, the effect of the threat could be described in qualitative value (QV) and semi-quantitative value (SQV) as listed in Table 1, with possible effects on the operations of the entity.

Table 1: Threat event scale (Hughes, de Jong, & Wang, 2016)

QV	SQV	Description
Very-low stress	0 to <0.05	Minor effect, the entity could operate normally
Low stress	0.05 to <0.2	Limited effect, could affect some operations
Moderate stress	0.2 to <0.8	More wide range effects, affect a significant number of operations
High stress	0.8 to <0.95	Serious effects, affecting most of the entity operations
Very High stress	0.95 to 1.0	Massive effects, suspend all the operations

3.1.3 Vulnerability

Once the level of stress caused by the threat on the entity is determined, it is crucial to assess the entity's vulnerability to the event. This assessment indicates the entity's resilience and the effectiveness of its countermeasures in mitigating the stress. Additionally, it outlines the entity's ability to revert to pre-event stress levels, as indicated by the Mean-Time To Recover (MTTR) factor. As vulnerability decreases, the entity's tolerance increases accordingly. Table 2 outlines the scale of vulnerability, aiding in this assessment process.

Table 2: Vulnerability scale (Hughes, de Jong, & Wang, 2016)

QV	SQV	Description
Very-low stress	0 to <0.05	MTTR → 0, the entity is resilient, no concern of vulnerability
Low stress	0.05 to <0.2	Recovery of the entity is tolerable with minor concern of vulnerability
Moderate stress	0.2 to <0.8	Recovery of the entity is possible tolerable with moderate concern of vulnerability
High stress	0.8 to <0.95	Longer time to recover, it is almost intolerable, with higher concern of vulnerability
Very High stress	0.95 to <1.0	MTTR →∞, the entity is intolerable, high concern of vulnerability

3.1.4 Impact

The consequence of the threat event on the entity and its response (vulnerability) determines whether the entity transitions to a new state—either tension or disruption—or returns to its normal state. Table 3 delineates the impact of different vulnerability levels at various threat event ranks in SQV and QV. A SQV or QV of 0 to <0.05 indicates a normal impact, 0.05 to <0.2 refers to low tension, 0.2 to <0.8 is moderate tension, 0.8 to <0.95 is high tension, and 0.95 to <1.0 indicates disruption.

Table 3: **Impact ranking (Hughes, de Jong, & Wang, 2016)**

Threat - Event Ranking						
		Very Low Stress	**Low Stress**	**Moderate Stress**	**High Stress**	**Very High Stress**
Vulnerability	**Very Low (< 0.05)**	Normal	Normal	Normal	Low tension	Moderate tension
	Low (< 0.2)	Normal	Normal	Low tension	Moderate tension	High tension
	Moderate (< 0.5)	Low tension	Low tension	Moderate tension	High tension	Disruption
	High (< 0.8)	Low tension	Moderate tension	High tension	High tension	Disruption
	Very High (≤ 1.0)	High tension	High tension	Disruption	Disruption	Disruption

3.1.5 Likelihood

The probability of the occurrence of a threat event can vary and may depend on historical data for similar events within the same entity or similar entities. In our case, some data may be referenced from NPP data, also it could be described by using QV and SQV, as shown in Table 4.

Table 4: **Likelihood ranking (Hughes, de Jong, & Wang, 2016)**

QV	SQV
Very unlikely	0 to <0.25
Unlikely	0.25 to <0.5
Moderately likely	0.5 to <0.75
Likely	0.75 to <1.0
Very likely	1.0

3.1.6 Risk

The risk encompasses more than just the impact of the threat; it also measures the vulnerability of the entity and the likelihood of the threat occurring. By multiplying the likelihood by the impact, we can obtain the resulting risk, which can guide the entity's actions and responsibilities. Additionally, it provides insights to enhance the entity's tolerance to potential threats. Table 5 lists the QV and SQV of the risk we will be using to determine the risk.

Table 5: **Risk ranking (Hughes, de Jong, & Wang, 2016)**

	Impact					
	QV (SQV)	**Normal**	**Low tension**	**Moderate tension**	**High tension**	**Disruption**
Likelihood	**Very unlikely (<0.05)**	Very low	Very low	Very low	Very low	Very low
	Unlikely (<0.25)	Very low	Very low	Low	Low	Low
	Moderately likely (<0.5)	Very low	Low	Low	Moderate	Moderate
	Likely -0.75	Very low	Low	Moderate	Moderate	High
	Very likely-1.0	Very low	Low	Moderate	High	Very high

3.2 Applying the methodology to the 3S's

The methodology explained above can be used for any entity to assess its potential risks. Although SMRs are still in the development phase, this method can be used to identify threats that may stress the reactor and lead to failure.

In the previous chapter, we highlighted the 3S concepts (Safety, Security, and Safeguards) and their influence on SMRs. We will apply this method to evaluate a threat that could affect one of the 3S aspects. For example, we will use the method to assess the safety of an SMR under a LOCA threat. Additionally, we will evaluate how each selected SMR's security is resilient to a Cyber Incident (CI) and assess the safeguard concept concerning the theft of spent fuel.

To apply the method on the proposed SMRs, we will need to select a group of SMRs so can be studied and comparing the results based on the method and the available information, either provided by IAEA or the vendor of the SMR. The criteria used to select the SMRs will be discussed later in this chapter, however selection aims to cover a wide range of upcoming SMRs and highlight the differences between the various designs and their risks.

3.3 Summary

This chapter introduced the methodology for assessing risks in entities, focusing on energy systems, with particular emphasis on SMRs. It explains that no single framework can cover all risks, but using various assessment methods can significantly enhance resilience and decision-making processes. This is especially critical in high-risk sectors like nuclear facilities, where assessments help maintain public and environmental safety. The chapter outlines a six-step methodology: identifying threats, ranking threat events, assessing vulnerability, evaluating impacts, determining likelihood, and calculating overall risk.

Applying this methodology to SMRs involves identifying potential threats such as LOCA or CI or spent fuel theft. The chapter also discussed applying this risk assessment framework to SMRs' safety, security, and safeguards, emphasizing the need to study different SMR designs. It also explores various SMR reactor types, coolant types, fuel types, and their respective safety features, highlighting the diversity and potential of SMR technology in advancing nuclear energy.

In the upcoming chapter, the focus will be on utilizing selected SMRs as the entities of study. Threat events will also be introduced, with each threat corresponding to one of the 3Ss (Safety, Security, and Safeguards). The chapter will examine of the effects of each threat event on each 'S' individually, as well as assessing whether the impact on one 'S' will have consequences on the others.

4 SMR selection, Risk analysis, and Results

This chapter will briefly outline various types of SMRs and select ten specific designs for a detailed application of the risk assessment methodology from the previous chapter. The selection process will ensure a diverse representation of SMR technologies, including water-cooled reactors, HTGRs, fast reactors, and molten salt reactors. Following section, the chapter will apply the risk analysis framework to evaluate the potential impacts of three critical threat events—Loss of Coolant Accident (LOCA), Cyber Incidents (CI), and Spent Nuclear Fuel (SNF) theft—based on the 3S's (Safety, Security, and Safeguards) concepts. This approach aims to identify vulnerabilities and strengths within each SMR design, providing insights into their risk management capabilities and guiding future developments in nuclear energy technology.

4.1 Types of proposed SMRs

There are over 80 different SMR design proposals, different on the type of the reactor, fuel types, and coolant types (IAEA, 2022). In this section, we explore the types of the reactors, fuel types and the maturity levels of the SMRs according to the IAEA (2022). We will then select ten SMRs to apply the risk assessment method explained in the previous section.

4.1.1 Reactor types

4.1.1.1 Water-cooled SMRs

Water-cooled reactors dominate the nuclear industry, representing 96% of the current operational fleet. These reactors employ either normal/light water (LW) or heavy water (HW, deuterium oxide, D2O) as coolants (IAEA, 2016).. The principal types include Pressurized Water Reactors (PWRs), Boiling Water Reactors (BWRs), and Pressurized Heavy Water Reactors (PHWRs). PWRs are the most prevalent, utilizing a primary circuit where water is pressurized to prevent boiling, while a secondary circuit generates steam to drive turbines (WNA, n.d). BWRs, the second most common type, operate with a single circuit where water is maintained at a pressure that allows it to boil, with the generated steam driving the turbine directly (U.S.NRC, 2023).. PHWRs use unenriched natural uranium and heavy water as both coolant and moderator. Heavy water improves neutron economy, enabling the reactor to function without fuel enrichment facilities and enhancing efficiency in various fuel cycles (Nuclear Street, n-d).

Recent innovations in SMR technology include integral PWRs (iPWRs), which integrate primary circuit components within the reactor pressure vessel, thereby eliminating the need for large-diameter piping. This design significantly reduces the potential for Loss of Coolant LOCAs (Zeliang, Mi, Tokuhiro, Lu, & Rezvoi, 2020). iPWRs also utilize natural circulation for heat removal, which simplifies the system and decreases mechanical complexity. By 2022, fourteen iPWR-type SMRs were in development, reflecting progress in making water-cooled reactors safer and more efficient. These advancements aim to enhance safety and operational reliability by incorporating modern features that address previous limitations, such as reducing the risk of accidents and improving overall reactor performance (IAEA, 2020).

In general, water-cooled SMRs have characteristics that enhance the safety and operating conditions, for instance, reducing the amount of piping which reduces the likelihood of LOCA. The reduction of overall power would lower the fuel inventory in the core, in addition, using inherent and passive safety features will reduce the dependence on active safety and human actions and reducing the requirement of supporting power supply (IAEA, 2020).

4.1.1.2 High Temperature Gas-cooled SMRs

HTGRs provide high-temperature heat (≥750°C) for efficient electricity generation and industrial processes like coal gasification and hydrogen production (IAEA, 2022).. Unlike water-cooled SMRs, HTGRs use helium as a coolant and graphite as a moderator. Their safety relies on TRISO-coated particle fuel and a full ceramic core, which prevent radioactive material releases and allow passive decay heat removal through radiation, conduction, and natural convection, eliminating the need for active cooling or off-site power (IAEA, 2020; Fang, Morris, & Li, 2017). This design supports spent fuel storage in casks or tanks without water cooling (IAEA, 2020). HTGRs also feature two independent shutdown mechanisms, including a negative temperature coefficient of reactivity, where an increase in moderator temperature leads to a negative decrease in reactivity due to reduced neutron slowing, that stabilizes operations by decreasing reactivity with increased moderator temperature. This ensures automatic reactor shutdown even if other mechanisms fail. In cases of LOCA, where helium release from the core is considered a safety action rather than a severe accident, HTGRs maintain a robust safety profile (IAEA, 2009; Cognet, Bartak, & Bruna, 2021)

4.1.1.3 Liquid Metal Fast Reactors

LMFRs are advanced Gen IV reactors designed to use Pu-239 as the primary fuel due to its suitability for sustaining fast neutron chain reactions. Unlike thermal reactors, which rely on U-235 or Th-232 (to produce U-233), fast reactors necessitate higher U-235 enrichment to offset the lower fission probability and the increased neutron capture by U-238. These reactors operate as burners (CR <1), converters (CR ≈1), or breeders (CR >1), based on their conversion ratio, which measures the amount of fissile material generated versus consumed (NASM, 2023).

The rising interest in fast reactors stems from their efficiency and waste reduction potential. Key types include Sodium Fast Reactors (SFR), Lead Fast Reactors (LFR), and Gas Fast Reactors (GFR) (IAEA, 2022). SFRs, the most mature type, use liquid sodium coolant, enabling operation at high temperatures and reduced pressures, enhancing system efficiency and safety. They utilize a fast neutron spectrum that allows them to use both fissile material and spent fuel from other reactors (Energy.gov, 2021).. Additionally, SFRs often employ a small fissile inventory, which minimizes waste production and increases safety by reducing the risk associated with reactivity-initiated accidents such as LOCA. Countries like France, Russia, China, and India are actively developing and operating these reactors, demonstrating their operational maturity and potential for future nuclear energy advancements (WNA, Generation IV Nuclear Reactors, 2020).

4.1.1.4 Molten Salt Reactors

MSRs use fluoride-based fluids, such as UF_4 (Uranium tetrafluoride), PuF_3 (Plutonium trifluoride), and ThF_4 (Thorium tetrafluoride), combined with carrier salts like lithium-beryllium fluoride and lithium fluoride, to create a molten coolant that operates at temperatures ranging from 500°C to 1400°C without pressurization. This approach departs from traditional reactors by employing molten fluoride salts as the primary coolant, which flows between a critical core and an external heat exchanger, with a secondary coolant transferring heat to steam or a gas cycle (WNA, 2021; LeBlanc, 2009). The fuel is dissolved in the coolant, facilitating online reprocessing, while graphite is used as a moderator due to its chemical stability with fluoride salts. MSRs feature high inherent safety through a pipe-less, fail-safe design that minimizes reactivity swings and operates at low pressure, reducing risks associated with traditional reactors. The absence of fuel cladding and the use of a molten core prevent fuel failures and mitigate the release of fission products, ensuring that control, cooling, and containment functions are maintained without operator intervention or external power (Cognet, Bartak, & Bruna, 2021).

4.1.1.5 Micro Modular Reactors

MMRs are compact systems designed to produce up to 10 MWe, targeting niche markets like micro-grids, disaster recovery, and seawater desalination. They use various coolants, including light water, helium, molten salt, and liquid metal, with several designs under licensing in Canada and the USA for near-term deployment (IAEA, 2022). Notably, heat-pipe MMRs stand out due to their use of sealed horizontal steel heat pipes that passively transfer heat from the core to an external condenser, eliminating the need for pumps. These reactors use liquid metal as the heat transfer fluid and feature a notable negative temperature reactivity coefficient. Heat-pipe MMRs come in gravitational and capillary types, which differ in how they utilize gravity or vapor pressure differences for heat transfer. Although promising, MMRs face challenges related to licensing and limited operational experience (Grabaskas, 2019; WNA, 2024).

4.1.2 Fuel Types

SMRs are being designed to be compatible with a nuclear fuel cycle, requiring the use of current infrastructure or the development of new industrial capabilities through dedicated investments (NEA, 2021). Currently, each fuel type is in various stages of development, ranging from proof of performance, proof of principle, to proof of concept. For SMRs to be effectively deployed, they necessitate established fuel designs that have undergone testing, received licensing approval, and a dependable supply chain to support these fuels consistently. the SMR use front-end nuclear fuel (IAEA, 2022). Figure 9 illustrates the different nuclear fuel cycles.

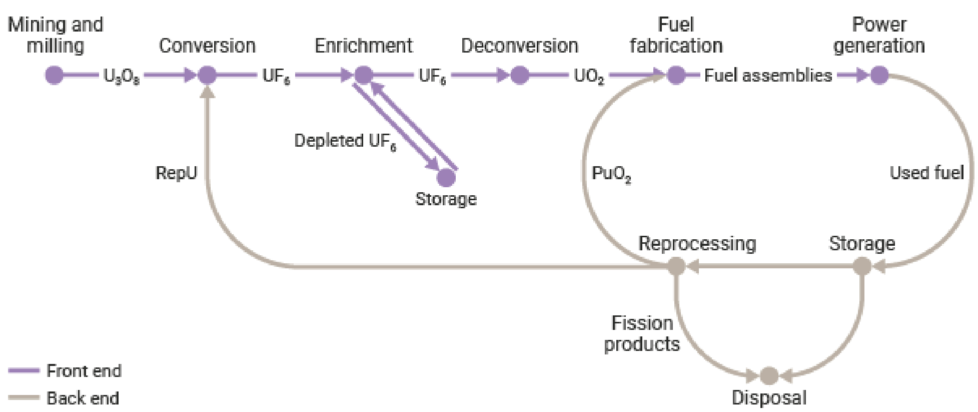

Figure 9: Nuclear fuel cycle (WNA, 2021)

The nuclear fuel cycle begins with uranium mining and ends with delivering enriched uranium to reactors, involving stages such as mining, milling, conversion, enrichment, and fuel assembly. Post-irradiation, spent fuel management includes interim storage, reprocessing, and disposal (WNA, 2021). . The fuel cycle types are once-through (fuel is used once and stored), twice-through (fuel is reprocessed to recycle uranium and plutonium) and closed (aiming for sustainability by reducing waste and improving resource use) (Nuclear Fuel Cycle, 2022). Natural uranium requires enrichment to increase U-235 concentration for use in reactors. Enrichment methods include gaseous diffusion and gas centrifugation. High-Enriched Uranium (HEU) has over 20% U-235, while Low-Enriched Uranium (LEU) has up to 5% (CNA, 2020; Nuclear 101, 2023).

Light water-cooled SMRs adapt various fuel cycles depending on design. PWR-type SMRs typically use LEU with less than 5% U-235 for land applications and up to 20% for marine use to extend refueling intervals (IAEA, 2022). TRISO (TRI-structural Isotropic) fuel particles are robust and resistant to high temperatures, making them suitable for various reactor types including MMR, HTGR, and MSR, and for extreme applications like nuclear thermal propulsion (Ultra, 2023).. MOX (Mixed Oxide) fuel, which includes uranium and plutonium, is used primarily in light water reactors, and constitutes about 5% of new nuclear fuel globally (Foro Nuclear, 2022). High-Assay Low-Enriched Uranium (HALEU), with U-235 levels between 5% and 20%, is crucial for advanced reactor fuels and is predominantly produced by Russia and China, posing challenges for increasing its availability and infrastructure (WNA, 2023).

4.1.3 Maturity

SMR vendors are proposing over 80 designs, some introducing new physical phenomena requiring careful regulatory consideration. Collaboration among vendors, license applicants, national regulators, and governments is crucial for successful SMR deployment and acceptance globally (IAEA, 2022). Vendors must complete significant R&D, demonstrate a clear future technical development program, and conduct gap analyses before pre-licensing in new countries. A systematic approach to documenting design modifications and safety decisions is essential for regulatory confidence. Early engagement with national regulators and safety case elements can minimize delays. International engagement and timely licensing framework changes are also crucial. Governments should assess technology readiness before the licensing process (WNA, 2021).

The nuclear reactor design process involves several stages: determining requirements (operating capacity, regulatory needs, life-cycle factors, and delivery schedule), pre-conceptual design (analyzing new technologies for the design), conceptual design (developing and optimizing the nuclear process based on specified requirements), and detailed design (producing documentation that meets operational standards and business needs). This structured approach ensures a comprehensive and effective design that meets facility and user requirements, as illustrated in Figure 10 (Middleton & Mendez, 2013).

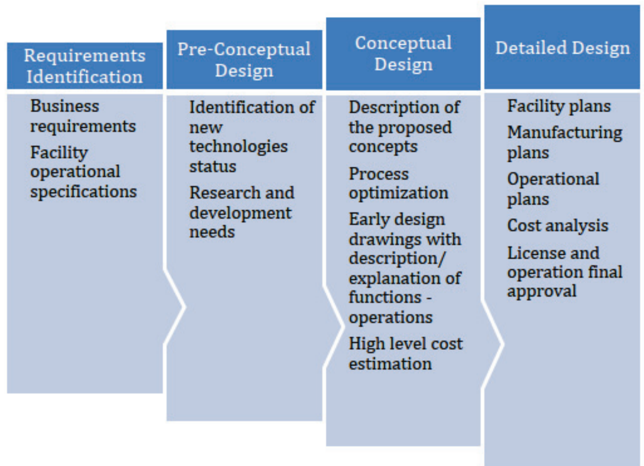

Figure 10: Traditional Design Process (Middleton & Mendez, 2013)

4.2 Criteria for Selecting SMRs for Study

Among the various proposed designs of SMRs, we selected ten with distinct features. By applying the risk method discussed above and based on the brief description of the types of proposed SMRs in the previous section, fuel types, and maturity, we identified three main selection criteria. The first criterion involves selecting various reactor types, such as water-cooled reactors (light and heavy water coolants), HTGR, two distinct types of LMFR, MSR, and MMR heat pipes. The second criterion involves selecting SMRs based on fuel type, including well-known fuel types like UO_2 and natural uranium, as well as new fuel types like TRISO, MOX, and recycled spent fuel. The third criterion pertains to each SMR's maturity and the extent of its design approval. By these selections, we cover most reactor types, fuel types, and maturity levels, making our results applicable to similar cases and providing a valuable reference for future work. Table 6 summarizes the selected SMRs.

Table 6: Selected SMRs (IAEA, 2022)

SMR/Country	Reactor Type	Coolant Type	Fuel Type	Level of Maturity
CAREM/ Argentina	IPWR	Light Water	UO_2	Prototype under construction
CANDU/Canada	PHWR	Heavy water (D_2O)	Natural Uranium	Conceptual design
Rolls-Royce/UK	PWR	Light Water	UO_2	Detailed design
BWRX/USA-Japan	BWR	Light Water	UO_2	Detailed design
RITM-200M/Russia	IPWR (Floating)	Light Water	UO_2	Basic design completed
HTR-PM/China	HTGR	Helium	TRISO-Pebble-Bed	In operation
LFR-AS-200/Italy	LMFR	Lead	MOX	Conceptual design
ARC-100/Canada	LMFR	Sodium	HALEU	Preliminary design
Moltex SSR-W/Canada	MSR	Molten Salt (MgCl/NaCl)	Recycled Spent Fuel	Conceptual design
Westinghouse eVinci /USA	Heat Pipe	Metal hydride moderator	TRISO	Conceptual Design Completed

Each of the selected reactors is now briefly described.

CAREM

CAREM is an iPWR SMR with 30 MW capacity, using UO_2 as a fuel and light water as coolant and moderator, it designed to supply electricity for regains with small demands, with additional feature of seawater desalination processes. (IAEA, 2022). CAREM25 (27 MW capacity) is a prototype for the CAREM SMR, to validate the design concept and then developed to commercial version (Magan, et al., n-d). CAREM has high levels of safety including integrated in the reactor vessel, primary cooling system which depends on passive safety feature, natural circulation, with no need for recirculation pumps, and it will have self-pressurized vessel, CAREM will adopt open fuel cycle concept (IAEA, 2022). In 2017 CAREM 25 was banned to startup, timeline was pushed to 2020 but due to some delays and design changes the new launch date is by the end of 2027 (neimagazine, 2023).

CANDU

The CANDU SMR has the same concept of the CANDU traditional NPP which ease the regulation processes (Alberta Politics, 2023), it is PHWR type, with heavy water coolant and moderator and output of 300 MW, as all CANDU reactors using natural uranium (no enrichment) as fuel, open cycle fuel, also available in Canada (Alberta Politics, 2023). The design focusing on DiD concepts, integrating inherent safety features and reliable engineered systems, balancing active and passive elements. The design aims to minimize overall energy costs by reducing capital expenses, construction time, and operational and maintenance costs while facilitating plant life extension. Additionally, enhances traditional CANDU advantages like safety, low exposure to radiation, high-capacity factor, and ease of maintenance. It incorporates proven technologies and concepts from various industries to ensure reliability and efficiency. The design concept ready for contracting since 2020 (IAEA, 2022).

Rolls-Royce

The Rolls-Royce SMR is three-loop PWR design with light water coolant and moderator, 470 MW capacity and UO_2 fuel, open cycle. SMR intended to supply electricity for coastal and inland siting with promising to deliver electricity with capital cost (IAEA, 2022). Additionally, SMR safety is ensured through multiple layers of fault prevention and protection through diverse active and passive systems. These systems provide heat removal through the closed loop vertical steam generators and feed cycle, the Passive decay heat removal system, and the ECCS, providing multiple means of decay heat removal in response to faults. The construction planned to start on 2025 and operation on 2030 (IAEA, 2019).

BWRX

BWRX is a boiling water SMR, with light water as coolant and moderator, capacity of 270-290 MW, and UO_2 fuel open cycle, design depending on natural phenomena driven safety systems. The basic application of SMR is electricity generation, besides district heating, synthetic fuel production, hydrogen production and other process heat applications, the primary containment vessel is below grade, with two passive cooling systems to remove decay heat (IAEA, 2022). Additionally, the SMR is same as traditional BWR design, integrates various features aimed at simplifying its design and reducing costs. These include integral reactor pressure vessel isolation valves to swiftly mitigate the effects of an LOCA, the elimination of safety relief valves to lessen the risk of LOCA occurrence, a design-to-cost approach ensuring optimization for constructability and reduced system complexity, and the use of commercial off-the-shelf equipment, minimizing expenses by employing commonly available components (GE Hitachi, 2023).Planned to commercial operation in 2028.

RITM-200M

RITM-200M is a floating iPWR SMR, with capacity 50 MW, light water for coolant and moderator, UO_2 fuel, there are six prototypes manufactured and installed on icebreakers, two of them are in process of testing. SMR can provide electricity for domestic and industrial consumers addition to use it for heat supply and seawater desalination. It contains passive and active safety systems to mitigate any threat event. The construction country load first core then it could transport in territorial water, it could provide heat and power till ten years without refueling, for maintenance, refueling and radwaste, the SMR should back to the construction country (IAEA, 2022).

HTR-PM

HTR-PM is a HTGR SMR with TRSIO pebble bed fuel, helium coolant and graphite moderator, open cycle (IAEA, 2022). SMR has two small reactors (each of 250 MW thermal) that drive a single 210 MWe steam turbine. It contains over 245,000 spherical fuel elements (pebbles) with a 60 mm diameter and 7 g of fuel enriched to 8.5%, the fuel has high safety characteristics and can remain intact and contain radioactivity at temperatures up to 1620°C (WNN, 2022). The HTR-PM's inherent safety features ensure that in all possible accident scenarios, the maximum fuel element temperature will never exceed the design limit temperature, even in the absence of dedicated emergency systems. Because of its low power density and geometry, the HTR-PM's core would not melt in the event of a total coolant loss and active cooling. Due to the high temperature of the fuel, this ensures that accidents, such as core melting, or the release of radioactive fission products into the environment, cannot happen (WNA, Constructing a high-temperature gas-cooled reactor, n-d). SMR is on operation full power since 2022 (IAEA, 2022).

LFR-AS-200

LFR-AS-200 is a LMFR SMR with 200 MW capacity, lead coolant, MOX fuel, AS in the SMR name refers to Amphora-Shape for the inner vessel of the reactor, SMR is a pool-type fast reactor featuring innovative spiral-tube steam generators, mechanical pumps, flag-type control rods, and redundant decay heat removal systems. It operates without in-vessel refueling machines or intermediate loops, with provisions to eliminate pressurization risks during accidents. Safety relies on lead's chemical inertness as a coolant, preventing violent reactions. The reactor primarily operates at constant power but can undergo load following within a range of -10% to +10% of nominal power by adjusting steam spillage and using stored hot water. Control mechanisms maintain core and steam temperatures constant, with mechanical pumps operating at variable speeds to ensure stable core inlet temperature. The conceptual design completed in 2019 (IAEA, 2022).

ARC-100

ARC-100 is a LMFR SMR pool type as well but with sodium coolant, 100 MW capacity, HALEU fuel open cycle with 13% enrichment, with ability to recycle its used fuel, with 20 years fueling cycle and passive and redundant decay heat removal. SMR emphasizes inherent safety, fuel recycling to manage nuclear waste, and applicability to grid-scale electricity generation in developed regions, as well as remote locations and smaller grids in the developing world. Additionally, it targets industrial heat, hydrogen production, and water desalination. The reactor's safety philosophy relies on simple, passive features ensuring safety under normal and accident conditions, with a DiD approach encompassing prevention, thermal inertia, diverse systems, passive safety features, and minimal operator intervention, aiming to confine potential accidents within the site boundary. Planning to ger licence to operate first unit by 2029 (IAEA, 2022).

Moltex SSR-W

Moltex SSR-W is a molten salt SMR with 300 MW capacity, coolant is molten salt MgCl/NaCl and no moderator, molten salt fuel within vented fuel tubes, the fuel is recycled CANDU spent fuel, SMR is powered by low-purity reactor-grade plutonium derived from recycled used uranium oxide fuel and manufactured by an inexpensive technique known as Waste To Stable Salt (WATSS). The reactor releases its heat in the form of molten chloride salts, which can be stored in large amounts at a cheap cost. This allows the reactor to function as a low-cost peaking power plant, rather than being limited to baseload operation. This method allows the steam cycle to be the same as coal-fired power stations and to operate separately from the nuclear plant. The steam cycle is exempt from nuclear rules, also, a capital cost of $1000/kW when used as a peaking plant, which is more affordable than using fossil fuels. First vendor design review licence in Canada was completed in 2021 (Thompson, 2022; IAEA, 2022).

eVinci

eVinci is a heat pipe cooled MMR, with capacity of 5 MW and 13 MW thermal, fuel is TRISO with enrichment 19.75%, inherent and passive safety for shutdown and heat removal, with 12 foot of nuclear grade heat pipe which eliminate the risks of LOCA and completely pre-assembled at the manufacturer and may be transported in shipping containers by rail, barge, and truck. Decay heat is removed through natural convection and radiation heat transfer. The core transmits heat to the canister, ensuring safe and dependable heat convection removal into the atmosphere without the need for operator intervention. In 2024 will have first nuclear demonstration (IAEA, 2022; eVinci™ Microreactor, n-d).

In the next section, we will explain the method of risk assessment that will be applied to the selected SMRs mentioned earlier. This method will identify potential threats to the new SMRs and assess their potential impact on safety, security, and safeguards.

4.3 Risk analysis assessment

In Chapter 2, we briefly explained some of the threat events that could pose risks to NPPs, and consequently, to SMRs, which would face similar threats due to the basic conceptual similarities between NPPs and SMRs. Chapter 3 detailed the risk assessment methodology to be applied in our study. In this chapter, we selected ten SMRs to apply this methodology, analyzing their behavior under various threat events based on available information.

The events selected for the case study are based on the 3Ss: safety, security, and safeguards. First, a loss of coolant accident (LOCA) is examined to assess the safety resilience of an SMR against one of the most common NPP events. Second, cyber incidents (CI) are considered, emphasizing the importance of securing SMRs against increasing cyber complexities due to their reliance on information systems. Finally, spent nuclear fuel (SNF) is evaluated for its impact on the safeguard of an SMR, particularly focusing on the theft of SNF and its potential for illicit trafficking. The next chapter will delve into the interrelationship between our findings and the 3Ss and their overall impact.

4.3.1 Safety: LOCA

As discussed previously , a LOCA or Loss of Cooling Accident, is an accident in which the coolant water leaks from the reactor due to a breach in the pressure boundary causing the core of the reactor to overheat and resulting in the melting of the fuel cladding (NRC, 2023).

The increasing interest in SMRs and the new proposed designs means there are many different designs for the ECCS (Emergency Core Cooling System), required to provide cooling in case of LOCA to reduce the damage of the fuel cladding (Nuclear Power, n-d).

Due to their design, water-cooled and LMFR SMRs are prone to LOCA, while HTGR and MMR are unlikely to have a LOCA (IAEA, 2009).

4.3.1.1 Threats and threat-events

In PWR and BWR reactors, a LOCA occurs when a primary pipe breaks in the recirculation loop, causing an increase in the fuel temperature and a potential core melt. This can lead to fuel damage and core melt if not adequately cooled. LOCA phases include blowdown, refill, and reflood. During blowdown, high pressure core injection removes heat but in small flow rate due to the high core pressure, after the core reaches lower pressure level, refill begins with low pressure core injection, with spraying a massive amount of coolant to remove the heat from the core. After filling the lower plenum with emergency coolant, the fuel bundles cool from bottom to top, starting the replenishment process. Additionally, this phase maintains the saturation temperature of the cladding during quenching. After removing surplus decay heat from the core and cooling the fuel to its saturation temperature, the LOCA scenario finishes (Radaideh, Kozlowski, & Farawila, 2019).

The size of the break determines the threat posed by the LOCA. Break sizes are defined as small (from 0.5 to 2.0 inches), medium (2 to 6 inches), and larges (any break greater than 6.0 inches) (Eide, Rasmouson, & Atwood, 2008).

We classify the threat ranking for a small LOCA to be a normal stress event for all types of SMRs and that all SMRs would be safe if the design took LOCA into consideration. If a medium or large LOCA occurred, the stress would begin to rise for water-cooled SMRs, and would rise even more for LMFR and PWR SMRs. The presence of a large amount of coolant surrounding the core in a water-cooled SMR heightens the risk of LOCA, whereas in the LMFR, the coolant's reaction with air or water makes the LOCA hazardous. This will be discussed further when examining LOCA vulnerabilities. Table 7 summarises the threat ranking for each SMR and the three LOCAs.

Table 7: Threat event ranking

Threat Event	HTR-PM	Moltex SSR-W	eVinci	CAREM	RITM-200M	CANDU	BWRX	Rolls-Royce	LFR-AS-200	ARC-100
Small LOCA	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal
Medium LOCA	Normal	Normal	Normal	Low stress	Low stress	Low stress	Low stress	Moderate stress	Moderate stress	Moderate stress
Large LOCA	Normal	Normal	Normal	Low stress	Low stress	Low stress	Low stress	Moderate stress	Moderate stress	Moderate stress

4.3.1.2 Vulnerabilities

We now consider the LOCA vulnerabilities for the 10 SMRs under consideration.

HTR-PMs use helium as coolant, which does not react with the fuel or the reactor components (Cognet, Bartak, & Bruna, 2021) Moreover, the absence of large diameter piping in the primary circuit reduces the possibility of LOCA (IAEA, 2009). The quantity of radioactive inventory in the primary helium coolant is negligible under normal operating conditions, and even if released, there is no requirement for immediate emergency actions. In the event of a reactivity accident or LOCA, the increase in temperature of the fuel elements will not result in a substantial additional release of radioactive materials. However, the consequences of accidents involving water or air ingress are dependent on the size of the ingress. If the ingress processes and the accompanying chemical reactions exhibit a slow pace and can be promptly stopped during an interval of many hours (or even a few days) by implementing straightforward measures (IAEA, 2022). The HTR-PM design includes a feature where accidents progress over a long time due to the high heat capacity of the fuel elements and the internal structures of the graphite. The fuel elements need several days to reach their maximum temperature in the absence of cooling (IAEA, 2022). We consider the vulnerability for this SMR to be very low because its tolerance for LOCA is very high making the vulnerability very low (Hughes L. , A generic framework for the description and analysis of energy security in an energy system, 2011).

Moltex SSR-W is intended to use molten eutectic fluoride salt, which has a 25% higher volumetric heat capacity than pressurized water or liquid sodium (LeBlanc, 2009). Six salt pumps, primary heat exchangers, downcomers (six coolant loops), jet nozzles, and downcomers within the reactor coolant channels transfer heat from fuel assemblies to the thermal storage system. To obstruct the shine pathways (i.e., the neutron or gamma radiation escaping from the shielding), the tubes traverse a biological shield made of concrete. Under normal circumstances, coolant is directed towards the lower plenum and withdrawn from the upper plenum. Since there is no logical leakage path that may allow the core to become exposed and the coolant has a very high boiling point, there is no ECCS (IAEA, 2022), which makes the vulnerability of a LOCA very low.

Heat pipe SMRs are constant temperature devices that reduce differential expansion stresses in fuel pins and support structures. They transfer thermal energy through evaporation and condensation of a working fluid, returning condensed fluid to the evaporator region via capillary action. Heat pipes address safety issues and reliability concerns in commercial nuclear reactors, including LOCA (Yan, Wang, & Li, 2019). We consider the vulnerability for eVinci to be very low because the SMR does not use primary coolant, the decay heat is removed by using passive heat pipes and associated systems and cooling water, which simplifies the reactor design and decreases the threat of a LOCA (IAEA, 2022).

For water-cooled reactors, the vulnerability is low except for the Rolls-Royce SMR, which has moderate vulnerability, because the likelihood of a LOCA is higher then than in other types of SMR due to the large quantity of coolant in the pressure vessel. SMR designs with integral features are expected to reduce the vulnerability to a large LOCA by eliminating the external coolant loop piping. In the case of small LOCAs, it is not a vulnerability because of the passive safety features used in these SMRs (IAEA, 2020).

The CAREM SMR's reliance on natural circulation within the reactor pressure vessel for coolant flow makes it vulnerable to LOCA risks. While the reactor is equipped with active systems, including water tank accumulators designed to provide coolant for up to 36 hours, any failure in these systems could compromise cooling effectiveness during a LOCA (IAEA, 2022; Buchholz, et al., 2020).Similarly, the RITM-200M's Emergency Core Cooling System (ECCS) combines passive hydraulic accumulators with active water tanks and make-up pumps to address small LOCAs. However, its dependence on multiple components introduces potential points of failure that could impact its performance during a significant LOCA (IAEA, 2022).

The CANDU SMR uses heavy water coolant with an ECCS that operates in two phases: short-term injection and long-term recirculation. Although the system can quickly inject coolant from accumulator tanks and later switch to long-term recirculation, the complexity of managing these phases and potential delays in restoring normal cooling could heighten the risk during a LOCA. Additionally, smaller LOCAs may employ steam generator crash cooldown methods, which could be less effective if systems experience LOCA (IAEA, 2022).

The BWRX SMR features an isolation condenser system that relies on gravity as a passive safety mechanism, designed to cool the reactor autonomously for up to seven days without power or operator intervention. Despite this, any malfunction or insufficient gravity-driven cooling could present vulnerabilities in effectively managing LOCA scenarios (IAEA, 2022).

The Rolls-Royce SMR is not integral, using ECCS as its primary defense. Smaller leaks are handled by the small leak injection system. Reactor shutdown is ensured by control rods (scram) and emergency Boron injection, offering diverse and highly reliable means of halting the nuclear chain reaction. Furthermore, three safety relief valves are installed to mitigate overpressure hazards, each capable of independently relieving excess pressure from the reactor vessel. These combined measures ensure the reactor's continued safe operation under various emergency scenarios (IAEA, 2022; IAEA, 2019) . The vulnerability of LOCA is considered moderate due to the increase of piping networks.

While the vulnerability for LMFRs is defined as moderate, where the coolant options include lead, such as LFR-AS-200, or sodium, as in ARC-100. Both designs incorporate passive safety features to mitigate LOCAs and remove decay heat. However, there are specific challenges associated with each coolant. In the case of lead coolant, there is a likelihood of corrosion and abrasion of components due to the high operating temperature caused by the melting point of the coolant metal (IAEA, 2022). On the other hand, with sodium coolant, there is a potential for a violent exothermic reaction between sodium, water, and air. Additionally, there is a risk of core melt due to blockage in the subassembly flow and the possibility of sudden reactivity rise or stagnation in the event of a LOCA (Cognet, Bartak, & Bruna, 2021; IAEA, 2022).

The vulnerabilities of the different SMRs are listed in Table 8.

Table 8: Vulnerability assessment

Threat Event	CAREM	CANDU	Rolls-Royce	BWRX	RITM-200M	HTR-PM	LFR-AS-200	ARC-100	Moltex SSR-W	eVinci
LOCA	Low	Low	Moderate	Low	Low	Very low	Moderate	Moderate	Very low	Very low

4.3.1.3 Impacts

The impact of the LOCA is the result of the ranking of the threat event listed in Table 7 and the vulnerability in Table 8. Now Table 9 lists the impact, described in terms of both qualitative and semi-quantitative values for each type of LOCA.

Table 9: Impacts ranking

		Threat - Event Ranking				
		Very Low Stress (small LOCA)	**Low Stress (small LOCA)**	**Moderate Stress (Medium LOCA)**	**High Stress (Medium LOCA)**	**Very High Stress (Large LOCA)**
Vulnerability	**Very Low (0.05)**	Normal (0)	Normal (0)	Normal (0)	Low tension (0.05)	Moderate tension (0.25)
	Low (0.2)	Normal (0)	Normal (0)	Low tension (0.05)	Moderate tension (0.25)	High tension (0.75)
	Moderate (0.5)	Low tension (0.05)	Low tension (0.05)	Moderate tension (0.25)	High tension (0.75)	Disruption (0.95)
	High (0.8)	Low tension (0.05)	Moderate tension (0.25)	High tension (0.75)	High tension (0.75)	Disruption (0.95)
	Very High (1.0)	High tension (0.75)	High tension (0.75)	Disruption (0.95)	Disruption (0.95)	Disruption (0.95)

4.3.1.4 Likelihood

The prediction of the likelihood or frequency should be calculated based on a probability assessment. Since no data exists for SMR LOCA events, we can refer to data from exiting NPPs to estimate the likelihood. According to (Eide, Rasmouson, & Atwood, 2008), results for BWRs, mean frequency for small, medium, and large LOCAs are 5.41 x 10^{-4} per reactor-calendar year, 9.9 x 10^{-5} per reactor-calendar year and 9.62 x 10^{-6} per reactor-calendar year respectively. With respect to PWRs, mean frequency for small, medium, and large LOCAs are 1.96×10^{-3} per reactor-calendar year, 1.52×10^{-4} per reactor-calendar year and 1.07×10^{-5} per reactor-calendar year respectively. Table 10 lists the estimated likelihood for each type of LOCA.

Table 10: Likelihood of threat events

Threat Event	HTR-PM	Moltex SSR-W	eVinci	CAREM	RITM-200M	CANDU	BWRX	Rolls-Royce	LFR-AS-200	ARC-100
Small LOCA	1×10^{-5}	1×10^{-5}	1×10^{-5}	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}
Medium LOCA	1×10^{-6}	1×10^{-6}	1×10^{-6}	1×10^{-4}	1×10^{-4}	1×10^{-4}	1×10^{-4}	1×10^{-4}	1×10^{-4}	1×10^{-4}
Large LOCA	1×10^{-7}	1×10^{-7}	1×10^{-7}	1×10^{-5}	1×10^{-5}	1×10^{-5}	1×10^{-5}	1×10^{-5}	1×10^{-5}	1×10^{-5}

4.3.1.5 Risks

The risk is the result of impact and the likelihood of the LOCAs, Figure 11 shows the impact of the different LOCAs on different types of reactors.

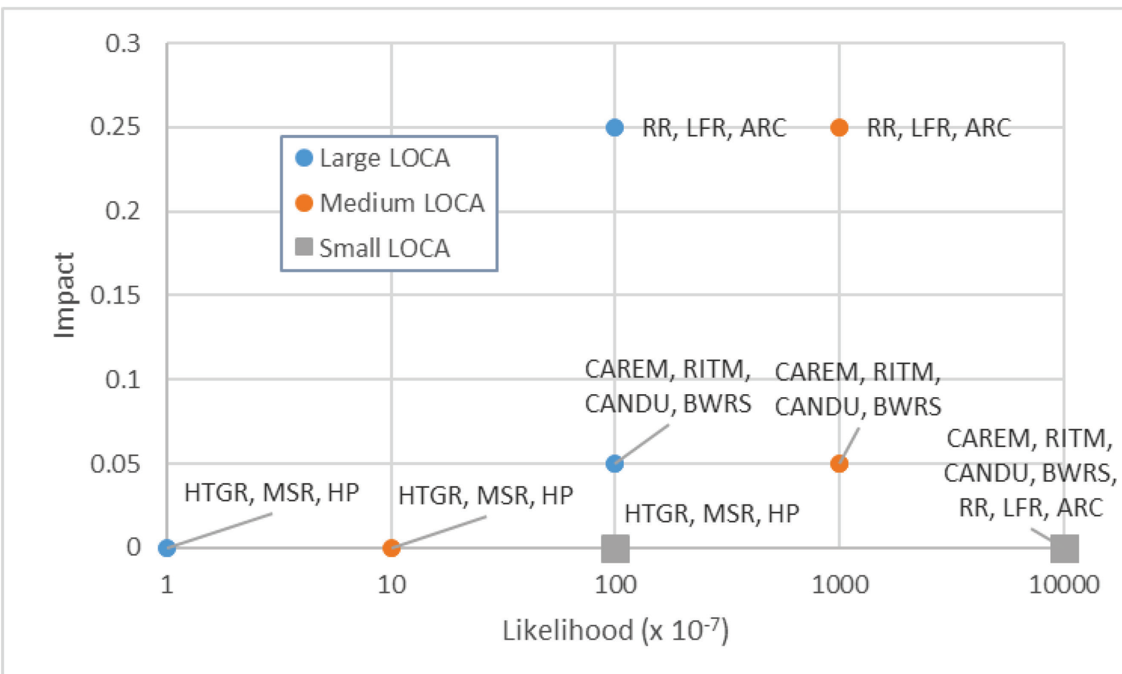

Figure 11: LOCA risks

The likelihood of a LOCA in HTR-PM is very low, as is the impact of any type of LOCA. The use of helium as a coolant, its leakage won't require any emergency measures, and the high temperature of fuel elements will not release radioactive substances. Moltex SSR-W does not expect to have a LOCA accident since the coolant is salt, and even in the event of an accident, the SMR design prevents the fuel from encountering the coolant. Additionally, eVinci does not use a primary coolant.

For LMFR SMRs such as LFR-AS-200 and ARC-100, the likelihood and impact are identical for all three types of LOCAs due to the possibility of explosion caused by the reaction of the coolant. In the case of sodium, it is the reaction with water or air, and for lead, because of the lead's corrosion and abrasion of components.

Water-cooled SMRs have the highest likelihood and impact due to the increasing pipe size and massive quantity of coolant surrounding the fuels. Integral SMRs, such as CAREM and RITM-200, have less impact because of their design, as do CANDU, which has two systems to mitigate LOCA, and BWRX, which has a passive safety feature and seven days as a grace period. Rolls-Royce SMRs, on the other hand, have a greater impact on large and medium LOCAs because the piping works are larger than other types of water-cooled SMRs.

4.3.2 Security: Cyber incidents

In the previous chapter, we discussed cyber incidents (CIs), which can come from internal or external sources and cause different levels of impact, from reconnaissance attacks, which affect the computer network, to the most serious event, cyber war, which causes a disruption impact and could be associated with physical war (Cho & Woo, 2016) . cyber security is getting harder because new SMR technologies depend less on human operators and more on AI. For example, some designs use online refuelling processes and MMRs that are in remote areas.

We have based our analysis on the concepts of PPS, as discussed in chapter 2 (Detect, Delay, Response). Implementing PPS promptly after an incident occurs can reduce the impact of the threat. For instance, the remote operation of SMRs establishes an adversarial pathway, which onsite control rooms cannot counter. The control over the physical communications medium extends beyond the site's boundaries, removing the benefits of the plant's PPS. This implies that we cannot effectively prevent or promptly respond to certain disruptive attacks. The severity of such events depends on the systems involved, their functions, and the consequences of loss or impairment (Siserman-Gray & Landine, 2023).

4.3.2.1 Threats and threat-events

In an SMR, the cyber-attack surface is significantly expanded due factors including a reduction in operations and maintenance personnel, higher levels of automation, the complicated nature of digital instrumentation and control (I&C) components, the operation of multiple units, the presence of diverse energy outlets, and the potential for remote operation (Fasano, Lamb, & Rowland, 2021). Additionally, in the case of SMRs producing multiple end-products such as district heat or desalination of seawater, there is a need for further automation to facilitate smooth transitions between output products, thereby avoiding operational disruptions. However, this automation increases the complexity of I&C systems (IAEA, 2017).

The security of SMRs can be compromised by this complexity. With SMRs comprising numerous digital systems, understanding their functionalities, interactions, and security implications becomes challenging. Despite the possibility of initially characterizing the network, the relevant data is usually not consistently updated (Dine, Assante, & Stoutland, 2016). Moreover, implementing PPS concepts could pose significant challenges due to the complexity of I&C structures and the insufficient staffing levels. For certain SMR designs, extended operation cycles can increase capacity factors and provide flexibility in scheduling maintenance outages. However, this poses challenges for I&C systems, as it extends the time between inspections and maintenance outages. This is particularly critical for sensing devices and actuators in harsh environments, where degradation can lead to unsafe control system behavior. Reliability models for I&C systems must demonstrate well-understood degradation mechanisms and ensure high-confidence materials performance between maintenance intervals (IAEA, 2017).

Table 11 displays the CI ranking for the chosen SMRs. The construction of SMRs in rural areas for district heat, like the eVinci, and the use of floating SMRs like the RITM-200M, may pose a significant threat. The intricacy of the I&C, which we will delve into further in the upcoming section, may cause a delay in responding to any threat. SMRs with new technology face moderate stress because of their lack of experience handling this threat.

Table 11: Threat event ranking

Threat Event	CAREM	CANDU	Rolls-Royce	BWRX	RITM-200M	HTR-PM	LFR-AS-200	ARC-100	Moltex SSR-W	eVinci
Cyber Incident	Moderate stress	Low stress	Low stress	Low stress	High stress	Moderate stress	Moderate stress	Moderate stress	Moderate stress	High stress

4.3.2.2 Vulnerabilities

Our assessments of the vulnerability of an SMR to a cyber event are based on the complexity of I&C systems for each SMR. While the more complied I&C system will be more vulnerable to CI.

Water-cooled SMRs depend on sensors to monitor and control critical operational parameters, such as rod positioning, internal pressure, temperature, and flow rates. This reliance is due to limited operator access and the need for precise measurements, especially in systems using natural circulation. Although iPWRs aim to simplify designs and incorporate passive safety features to reduce costs and expedite deployment, these simplifications pose significant challenges from an I&C perspective. Each control system or component in these reactors often performs multiple functions, making them crucial for overall performance (Fasano, Lamb, & Rowland, 2021). This complexity can result in longer mean time to repair (MTTR) during a cyber attack, potentially extending downtime compared to other reactor types like BWRs, PWRs, and PHWRs, which have less complex I&C systems.

HTGR SMRs are designed to operate with lower power densities, leading to slower reactor power and temperature responses, which are generally beneficial for control and safety. However, this design results in significant temperature differences and high coolant velocities, which can impact the calibration of nuclear instrumentation and reactivity controls (IAEA, 2017). For HTGRs, especially the HTR-PM models, the complexity of the I&C systems is heightened due to the interaction of two reactor units with a single steam and power turbine. These systems need to monitor a wide range of parameters, including temperature, flow rates, neutron flux, helium leaks, and fuel pebble burnup. This high level of dependency on sensors and extensive data collection increases the vulnerability of HTR-PM SMRs to cyber attacks, as the complexity and volume of information managed by the I&C systems make them more susceptible to security breaches compared to simpler, water-cooled SMRs (Fasano, Lamb, & Rowland, 2021; IAEA, 2017).

LMFR SMRs, such as the ARC-100, face heightened vulnerability to cyber incidents due to their complex I&C systems. These reactors use advanced in-core instruments for monitoring and control, which, while enhancing operational efficiency with fewer on-site operators, also increase the potential for cyberattacks. The opacity of sodium coolants complicates visual inspections and necessitates remote monitoring and maintenance, further intensifying I&C system complexity and security risks (Fasano, Lamb, & Rowland, 2021).

Similarly, MSR SMRs encounter challenges with their I&C systems due to the need for diverse data types for fuel salt reprocessing, corrosion monitoring, and passive residual heat removal. The integration of on-load refueling and the WATSS process adds to the system's complexity, making it more susceptible to cyber vulnerabilities. The reliance on remote operation and status monitoring of electrical outputs further complicates onsite operations and heightens security risks (IAEA, 2022; Fasano, Lamb, & Rowland, 2021).

MMR (eVinci) is using an autonomous control system (ACS) in the primary I&C system, utilizing fiber optic sensors for temperature measurement, neutron flux sensors for core operation, and load following logic. It ensures the reactor doesn't exceed predefined limits and adjusts the control drum position based on load variances. The ACS collects environmental and operating data and can relinquish control to an operator if needed (IAEA, 2022). However, recent developments in autonomous control systems and digital twin technologies rely on off-the-shelf algorithms for non-nuclear applications, making them more vulnerable to infiltrations. However, these solutions can be adapted or modified for each SMR design, ensuring greater security. The vulnerability of a SMR to cyberattack depends on the specific reactor design (Siserman-Gray & Landine, 2023). Table 12 summarizes the vulnerability of CI.

Table 12: SMR cyber incident vulnerability

Threat Event	CAREM	CANDU	Rolls-Royce	BWRX	RITM-200M	HTR-PM	LFR-AS-200	ARC-100	Moltex SSR-W	eVinci
Cyber Incident	Low	Very low	Very low	Very low	Low	Moderate	Low	Low	Low	Moderate

4.3.2.3 Impacts

Table 13 shows the impact of a cyber event on SMRs, based on the threat event and vulnerability estimates for each SMR. eVinci and HTR-PM have the highest tension among the other SMRs, because of novelty of the design and remotely operations. New designs of SMRs have higher tension due to the complexity of I&C systems and the lack of experience of the CI impact. While the water-cooled SMRs based on existing design of NPPs, would have normal tension.

Table 13: Impacts ranking

Threat Event	CAREM	CANDU	Rolls-Royce	BWRX	RITM-200M	HTR-PM	LFR-AS-200	ARC-100	Moltex SSR-W	eVinci
Cyber Incident	Low tension	Normal	Normal	Normal	Low tension	Moderate tension	Low tension	Low tension	Low tension	Moderate tension

4.3.2.4 Likelihood

Between 1990 and 2016, the frequency of cyber incidents reported for different nuclear facilities ranged from no incidents per year to three incidents per year (Dine, Assante, & Stoutland, 2016). However, considering the complexity of I&C systems as previously explained, the following table will incorporate assumptions based on the SQV of likelihood.

The following assumptions will consider the complexity of I&C systems: the more complex systems have a higher likelihood of a cyber incident. Water-cooled SMRs have the lowest likelihood of an incident because these reactors are already existing NPP technology. For integral SMRs, the likelihood increases due to the complexity of the I&C system. LMFR and MSR SMRs have complicated I&C systems, and some of them are expected to operate in remote regions, so the dependency on digital systems increases with fewer maintenance and inspection personnel. Both eVinci and HTR-PM have the most complicated systems, increasing the likelihood of a cyber incident, as shown in Table 14.

Table 14: Likelihood of threat events

Threat Event	CAREM	CANDU	Rolls-Royce	BWRX	RITM-200M	HTR-PM	LFR-AS-200	ARC-100	Moltex SSR-W	eVinci
Cyber incident	Moderately likely	Unlikely	Unlikely	Unlikely	Moderately likely	Likely	Moderately likely	Moderately likely	Moderately likely	Likely

4.3.2.5 Risks

As Figure 12 shows, water-cooled SMRs (include Rolls-Royce, BWRX and CANDU) have a lower likelihood and impact, whereas floating SMRs have a higher impact due to their travel, and the Physical Protection System (PPS) to any CI may be slower than that of a land-based SMR. The impact of LMFR, MSR, and iPWR is also greater due to potential delays that may occur when applying PPS concepts to more complex systems. New SMR technologies, such as heat pipes and HTGR, could also have a greater impact on PPS.

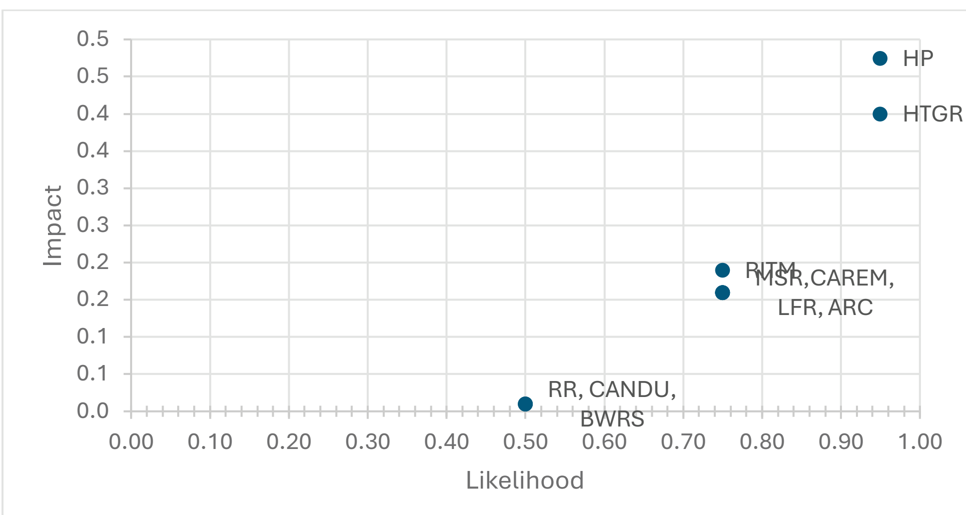

Figure 12: Risks from Cyber Incidents (CI's)

4.3.3 Safeguard: Spent Nuclear Fuel (SNF)

While many proposed SMR designs incorporate safeguard measures by design, such as fuel element size, core lifetime, and burnup rate to ensure non-proliferation, some advanced reactor designs feature extended refueling periods, potentially up to 20 years, or adopt online refueling approaches. Water-cooled SMRs rely heavily on existing technologies, making safeguard implementation relatively straightforward if parameters such as fuel types and enrichment levels remain within current standards. However, future SMR designs may utilize higher enrichment levels, such as MOX fuel (with a 3% to 10% plutonium proportion) or HALEU (with enrichment between 5% and 20%), which have a higher enrichment percentage, both could be more attractive to theft (Bentoumi, Chaudhri, Ennde, Sur, & Trask, nd; IAEA, 2023).

4.3.3.1 Threats and threat-events

As mentioned in the previous chapter, the illicit trafficking of the SNF, this trafficking involves both nuclear materials, such as fissile materials like plutonium (Pu) and high-enrichment uranium, which emit strong gamma-rays, and can be sourced from NPPs or SMRs, and radioactive materials (such as cobalt-60 and cesium-137, commonly used in medical or industrial fields). This illicit trafficking poses a significant threat, as malicious organizations may seek to acquire nuclear material to develop nuclear devices or use them to harm civilian populations by spreading radioactive contamination or exposing them to harmful radiation doses (Vertic, 2012).

To develop or build a nuclear explosive device, it requires acquiring enough nuclear materials, processing them, and utilizing them in a device. The selection of these materials is based on factors such as radiation dose rate and overall weight (lighter, easily portable materials are more attractive than, for example, heavier, vehicle-sized), as well as the compositions of the acquired material, which include the time and complexity required to convert the material into a metal or alloy. Additionally, factors such as the mass of the nuclear material and heat production rate contribute to the attractiveness of the material for illicit trafficking purposes (Ebbinghaus, Bathke, Dalton, & Murphy, 2013).

To understand the attractiveness of nuclear materials, particularly spent fuel, a study categorized materials into four levels of attractiveness for weapons based on their potential value (Bathke, et al., 2012): high (preferred materials), medium (potentially usable materials), low (impractical materials), and very low (impossible materials). These classifications depend on factors such as burnup rate (the amount of energy obtained from one ton of enriched fuel, measured in gigawatt-days (thermal) per tonne-

(GWd/t)) and proportional to the level of enrichment (WNA, 2021), fuel composition, reactor type, and cooling time (age) (Robel, et al., 2013). Table 15 summarizes the threat ranking based on the burnup and enrichment of fuel of each SMR, where the less burnup rate and higher enrichment level will increase the stress on SMR (IAEA, 2022).

Table 15: Threat event ranking

SMR	**Fuel Data**		**Threat event ranking-Qualitative values (QV)**
	Fuel type /Enrichment %	**Burn up GWd/ton**	
CAREM25-iPWR	UO_2/3.1	24	Low stress
CANDU-PHWR	Natural Uranium/ not enriched	5.8	Low stress
Rolls-Royce-PWR	UO_2 /<4.95	50-60	Very low stress
BWRX-BWR	UO_2 /3.81-4.95	49.6	Very low stress
RITM-200M-iPWR	UO_2 /<20	-	Low stress
HTR-PM-HTGR	TRISO /8.5	90	Moderate stress
LFR-AS-200-LMFR	MOX /19-23.2	100	Moderate stress
ARC-100-LMFR	HALEU /13.1	77	Very low stress
Moltex SSR-W-MSR	Recycled fuel	100	Moderate stress
Westinghouse eVinci -Heat Pipe	TRISO /5-19.75	45	Moderate stress

4.3.3.2 Vulnerabilities

The vulnerabilities of theft of SNFs from various reactors is determined from the enrichment and burnup rates shown in Table 15, and the threat rankings described in (Robel, et al., 2013).

The Rolls-Royce SMR waste treatment systems utilize proven technologies and best available techniques, incorporating industry lessons and good practices to minimize both active and non-active wastes and discharges. Standardized waste treatment components and modules provide flexibility in design, and the operation without soluble boron in the primary coolant significantly reduces environmental discharges and simplifies the waste treatment systems. This comprehensive approach to waste management helps mitigate the threat of spent fuel theft (IAEA, 2022). The BWRX-300 applies lessons learned and best practices from decades of BWR fleet operations in waste management and disposal. Waste will be optimally segregated for treatment, storage, and final disposal. Gaseous wastes will be removed from the steam system by steam jet air ejectors and passed through charcoal beds for absorption. This approach helps to effectively manage waste and reduce the potential threat of spent fuel theft (IAEA, 2022).

iPWRs use standard fuel elements with reduced lengths to achieve typical diameter-to-length ratios for their core size and longer refueling frequencies. These reactors have relatively low burnup levels, increasing the amount of uranium, enrichment level, and fuel demand compared to standard PWRs, leading to 67% more waste. Consequently, the cumulative plutonium in the spent fuel is 40% higher than in a standard PWR (Glaser, Hopkins, & Ramana, 2013). This makes the spent fuel from iPWRs highly attractive to theft than the PWR and BWR, increasing the vulnerability to such threats.

CANDU uses unenriched natural uranium with a low burnup rate, but the online fuelling process may require more safeguard resources than batch-refueled reactors like LWRs due to fuel loading and unloading during operation, rather than only during shutdown periods for inspections (National Academies, 2023). A CANDU SMR could use the thorium (Th-232) cycle, a more attractive option because thorium is more abundant in nature than uranium. It is also more fertile once it absorbs a neutron, causing it to transmute to uranium-233 (U-233), making it an excellent fuel. However, while thorium is promoted as having excellent non-proliferation credentials, its production of U-233 makes it highly attractive to theft. IAEA classified U-233 in same category as highly enriched uranium; eight kilograms of plutonium is equivalent to approximately 32 kilograms of highly enriched uranium (Bathke C. , et al., 2010). In fact, Bathke and the WNA consider U-233 to be the most attractive material to theft of all nuclear materials (2010; 2020), increasing the vulnerability to SNF theft in CANDU SMRs.

The floating RITM-200M SMR uses a high percentage of enriched uranium, although the burnup rate is not publicly available (IAEA, 2022). The spent fuel will contain different radionuclides and higher thermal outputs (Espartero & Hill, 2022), which increase the vulnerability as well.

TRISO-based SMRs such as HTR-PM and eVinci, require complex and time-consuming chemical processes to extract fissile material from the fuel (IAEA, 2023). The small size of the pebbles makes theft more difficult, as each pebble contains only a tiny amount of uranium (National Academies, 2023) . HTR-PM SMR refuel by the online refueling process, may necessitate greater safeguard resources compared to water-cooled reactors. This is because the loading and unloading processes occur during operation, preventing inspectors from conducting physical inventory checks (National Academies, 2023). As shown in table 9, the enrichment of HTR-PM SMR is 8.5% which consider relatively high, increasing its vulnerability to theft.

However, eVinci's high level of enrichment and low burnup could also be attractive. After three years of continuous power operation without refueling, eVinci is to be disconnected and returned to the factory in its original canister. This will allow for either long-term storage or refueling and redeployment, which can be done inside the eVinci Micro Reactor canister itself (IAEA, 2022). But using the highly enrichment TRISO fuel still consider increasing the vulnerability of theft of spent fuel during the refuelling and shipping to the factory.

LFR-200 will employ highly enriched mixed oxide fuels such as UO_2, MOX, UF_4, and uranium oxycarbide (UCO). However, it also possesses the capability to utilize thorium, producing Pu-239 and U-233, which are classified as highly attractive materials to theft (Bathke C. , et al., 2010), While the Pu-239 produced by MOX recycling is relatively less attractive than that of discharged UOX fuel, it is still considered to have a “high” level of attractiveness. Another approach involves implementing a closed fuel cycle, where used fuels are recycled, and residual fuel waste is transported to geological repositories. Moreover, spent fuel will be transferred to a spent fuel water pool, and the incorporation of dilution with inert materials and materials with high heat content can enhance safeguards, because it reduces the attractiveness of the materials, making it less vulnerable to theft. Nevertheless, despite these measures, recycling and reprocessing technologies still require stringent safeguards and higher levels of physical (Bathke, et al., 2012; IAEA, 2022).

The ARC-100 reactor operates with HALEU fuel, consisting of uranium zirconium metallic fuel with an average enrichment of 13%. Initially designed for an open fuel cycle, there is a potential for it to transition to a closed cycle if granted a reprocessing license. Spent fuel is intended for disposal in deep geological repositories, with refueling intervals occurring every 20 years (IAEA, 2022). This approach presents both benefits and drawbacks for safeguards. The IAEA has noted that reduced core access and less frequent refueling make it more challenging to misuse and divert spent fuel. This advantage stems from the reactor vessels remaining sealed throughout their lifetime, eliminating the need for inspector visits during refueling. However, since the reactor vessel will not intend to be opened over its lifetime with traditional IAEA annual physical inventory requirements poses vulnerability of SNF or fresh fuel illicit trafficking (National Academies, 2023). Vulnerability for theft could be less than water-cooled SMRs but it still exists.

Fuel cycles involving the reprocessing and separation of fissile material are more vulnerable to theft that the once-through uranium fuel cycle, where spent fuel is directly disposed of. The separated fissile material in these closed fuel cycles may not be uniformly mixed with highly radioactive fission products, potentially including various fissionable materials beyond traditional special nuclear materials like highly enriched uranium, plutonium, and uranium-233. Despite these risks, some reactor developers, such as Moltex, continue to explore reprocessing options. Moltex aims to pyro-process spent oxide fuel to extract plutonium and other actinides for use as fresh fuel in its Stable Salt Reactor, a fast molten salt reactor (National Academies, 2023). It also argues that the pyro-processing method produces an impure extraction of minor actinides, including plutonium, which would be useless for weapons. However, material accountancy in electrochemical fuel reprocessing poses challenges due to complex material flows, including continuous phase change processes, batch transfers of material with unknown composition, and multiple salt recycle streams. Moreover, elevated temperatures and corrosive fluids make standard process monitoring technology impractical (National Academies, 2023). The vulnerabilities of the different SMRs are summarized in Table 16.

Table 16: Vulnerability assessment

Threat Event	CAREM	CANDU	Rolls-Royce	BWRX	RITM-200M	HTR-PM	LFR-AS-200	ARC-100	Moltex SSR-W	eVinci
SNF theft	Low	Low	Very low	Very low	Low	Moderate	Moderate	Very low	Moderate	Moderate

4.3.3.3 Impacts

Table 17 shows the impact of SNF theft on selected SMRs, based on the attractiveness to SNF theft, which it increases with the higher enrichment level (above 5%) and low burnup rates. Light water SMRs have the lowest impact because of the low enrichment of the fuel, as well as ARC-100, because it based on using recycled fuel. The impact increases for the iPWR, CANDU, and the new generation of SMRs which they use high enrichment level of fuels.

Table 17: Impacts ranking

Threat Event	CAREM	CANDU	Rolls-Royce	BWRX	RITM-200M	HTR-PM	LFR-AS-200	ARC-100	Moltex SSR-W	eVinci
SNF theft	Low tension	Low tension	Normal	Normal	Low tension	Moderate tension	Moderate tension	Normal	Moderate tension	Moderate tension

4.3.3.4 Likelihood

Between 1993 and 2022 there were 4,075 cases recorded of the trafficking of nuclear and radioactive materials, with 146 incidents reported in 2022 (IAEA, 2023). The likelihood of theft for each type of SMR is difficult to reach, so Table 18 is based on the attractiveness of the SNF to theft described in pervious sections.

Table 18: Likelihood of threat events

Threat Event	CAREM	CANDU	Rolls-Royce	BWRX	RITM-200M	HTR-PM	LFR-AS-200	ARC-100	Moltex SSR-W	eVinci
SNF theft	Moderately likely	Moderately likely	Unlikely	Unlikely	Moderately likely	Likely	Likely	Unlikely	Likely	Likely

4.3.3.5 Risks

The risks to spent nuclear fuel theft are summarized in Figure 13.

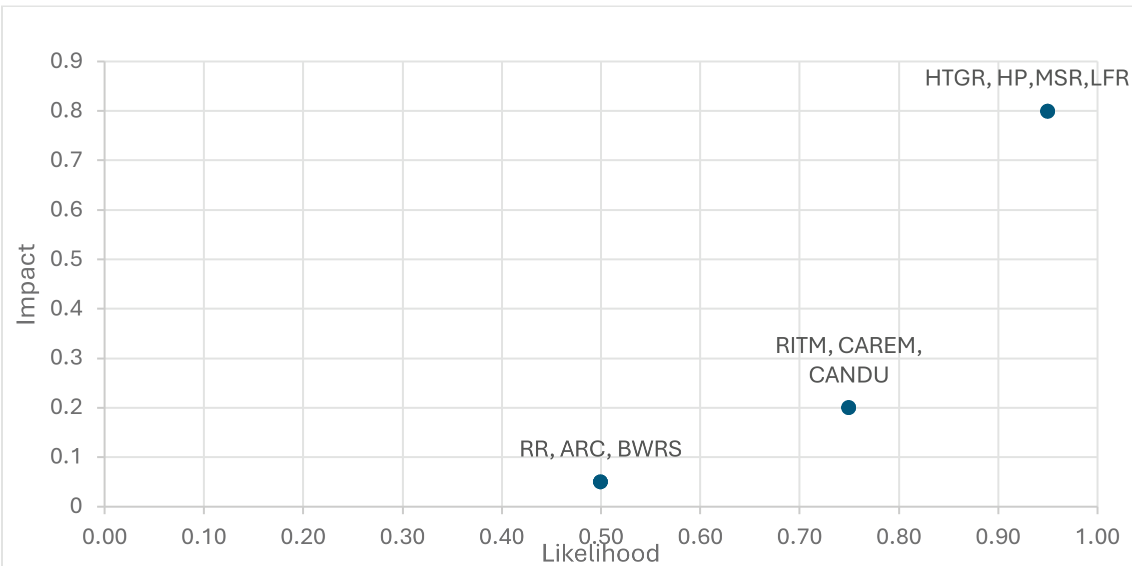

Figure 13: Spent fuel theft risks

The low fuel enrichment and high burn-up rate of Rolls-Royce and BWRX SMRs makes their spent fuel less attractive to theft. For the ARC-100, the long refueling period would reduce the likelihood and impact of any spent fuel theft. CAREM has a higher likelihood because of the lower fuel burn rates, so the attractiveness of theft of the spent fuel could increase; the same is true for RITM-200M. For CANDU, using the thorium cycle, will attract theft of the spent fuel. Higher likelihood and impact scenarios, such as HTR-PM and eVinci using TRISO fuel with a high enrichment rate, may make it challenging to apply safeguard concepts to pebble fuel. Additionally, the use of highly enrichment fuel in LFR-200, along with the potential recycling of spent fuel, may increase the likelihood of theft. Moltex SSR-W SMR uses recycled fuel, but the spent fuel would include highly desirable plutonium.

4.4 Summary

With a specific focus on ten SMRs and their vulnerability to three different threat events, the chapter explored the complex range of threats that SMRs could face. The chapter presented three main threat events: LOCA, cyber incident (CI), and spent nuclear fuel (SNF) theft.

The rupture of the primary pipe, causing a LOCA, poses a significant threat to SMRs. The different SMRs have different methods to mitigate the risks associated with LOCA, giving them a range of vulnerabilities. SMRs that use heat pipes rely on passive heat transfer mechanisms to maintain stable temperatures. In contrast has the least risk of LOCA. In contrast, water-cooled reactors, which have a higher potential for LOCA, employ natural circulation and active systems to mitigate risks.

Complicated digital architectures and I&C systems of SMRs make them vulnerable to cyber threat events. Vulnerabilities emerge due to the dependence on sensors, streamlined designs. Certain factors unique to SMRs, such as reactor power density and coolant types, influence the sensitivity to cyber threats. while heat pipe SMR has the highest risk because of depending on remotely control, and the SMRs types similar to NPPs such as PWR, BWR and CANDU have the lowest risk, because they are based on well known systems.

Finally, the chapter examines the security consequences of spent fuel theft, emphasizing variations in attractivity among SMR designs based on characteristics such as fuel type and enrichment level. Strategies such as closed fuel cycles and reprocessing possibilities aim to improve safeguards, reducing vulnerabilities, but they also pose difficulties in material accounting and proliferation threats. The SMRs with new fuel concepts are riskier for theft because the dependency on high enrichment fuel than the other SMRs with fuel have lower enrichment.

5 Discussion

In the previous chapter, we examined three possible SMR events related to one of the 3Ss: safety (loss of coolant accident); security (cyber incidents); and safeguards (spent fuel theft). In this chapter, we will discuss the relationships between these events and how they could influence each other.

This chapter discusses the results of our methodology applied to the ten selected SMRs. It examines how each threat event, correlated to one of the 3S's, can affect the other two S's. These results might impact the 3S's interrelationship either negatively or positively. This approach helps identify the interactions among the 3S's and align them with real-world operational uncertainties.

5.1 Case study results

5.1.1 Loss of coolant Accident (LOCA)

In the LOCA case study for the selected SMRs, the results showed that water cooled SMRs (CANDU, CAREM, Rolls-Royce, RITM-200M & BWRX) and LMFR (ARC-100 & LFR-AS-200) have a very high likelihood of a small LOCA making the risk almost zero. The reason of this that the small LOCA is DBA and can be mitigated by using ECCS for water cooled SMRs or using safety/guard vessel in LMFR SMRs and passive safety feature (IAEA, 2022). But in case of larger LOCAs, the risk will increase due to the impact of the LOCA and how it can increase the coolant around the core, which could be contaminated of radioactive substances, it has higher impact on Rolls-Royce SMR, it is not integral PWR as the rest of the selected PWR SMRs, so its impact could be higher because of the number of pipes. For LMFR the coolant reaction with the air or water is dangerous and core melting (Cognet, Bartak, & Bruna, 2021) .

On the other hand, HTGR (HTR-PM), MMR (eVinci), and MSR (Moltex SS-W) have almost zero risk on all types of LOCA. Even because they do not have any coolant like eVinci, or the coolant is salt so it will not react or cause any damage for the core such as Moltex SS-W, and for HTR-PM the coolant is helium so the reaction between it and the very high temperature fuel will not need any emergency measures (IAEA, 2022).

5.1.2 Cyber Incidents (CI)

Since all SMRs rely on computer networking, they are susceptible to cyber attacks at various levels, as discussed in Chapter Two. These range from internal or external access attacks to incidents of cyber terrorism. (Cho & Woo, 2016). The complexity of the instrumentation and control (I&C) architecture of the network determines the level of risk, with more complicated I&C systems being highly risky (Dine, Assante, & Stoutland, 2016). Multi-unit SMRs, different energy outlets, and remote operations increase the complexity of the I&C (Fasano, Lamb, & Rowland, 2021).

The results of our method show that even though water-cooled SMRs depend on sensors, new-generation types like iPWR (RITM-200M & CAREM) have a higher risk of CI issues compared to BWRX, CANDU, and Rolls-Royce. This is due to the reduction in components, which complicates maintenance and increases dependency on sensors (Fasano, Lamb, & Rowland, 2021). LMFR SMRs have in-core sensors and instruments to control (IAEA, 2022) , which complicates the I&C system and increases the risk of CI. For MSRs, additional data collection is needed through the WATSS process and while receiving the electrical output from the SMR .All these factors contribute to a more complex I&C system, which increases the risk of CI (Fasano, Lamb, & Rowland, 2021; IAEA, 2022).

The HTR-PM requires extensive sensor data, including temperatures, flow, neutron flux, helium leaks, and the quantity and burnup levels of used fuel pebbles (IAEA, 2017), This necessitates a specially tailored I&C system to maintain SMR stability, which increases the risk around the I&C system. Additionally, the eVinci SMR, which operates autonomously, requires its I&C system to provide more information to the operator and relies heavily on the autonomous control system (ACS). This results in a unique I&C system with complex inputs and outputs (IAEA, 2022). According to our method, this type of SMR has the highest risk among all the selected SMRs.

5.1.3 Spent Nuclear Fuel (SNF)

One of the most critical issues related to the nuclear energy industry is spent nuclear fuel (SNF), which continues to decay and release radioactive rays and neutrons. Transporting SNF to final disposal sites or for recycling is expensive and requires strategic national-level decisions that consider the 3S's (WNA, 2019). The theft of SNF is a significant concern, as it can occur during transportation or even while the fuel is still in the reactor. Stolen SNF can be used to develop nuclear weapons or by malicious organizations (Vertic, 2012). Such activities compromise reactor safeguards and non-proliferation efforts. In Chapter Four, we analyzed this threat and its risk to the selected SMRs using our method. The method considers the classification of spent fuel based on its attractiveness to theft, which depends on the fuel's enrichment level and burnup level.

Rolls-Royce and BWRX SMRs, which use UO2 fuel with an enrichment of less than 5% and a burnup level of up to 50 GWd/ton, have the lowest risk of theft. In contrast, the ARC-100, with an enrichment of around 13% and a burnup level of 77 GWd/ton, also has a very low risk of theft due to the disposal of SNF in deep geological repositories and a lengthy internal refueling period of up to 20 years. However, additional layers of security and safeguards will be necessary to ensure that transportation does not pose a threat (National Academies, 2023).

Three more SMRs have a higher risk of SNF theft, CANDU SMR will use natural uranium with low burnup, the higher risk for it due to the Thorium cycle, which produce U-233 which is more attractive for theft. SMRs RITM-200M and CAREM are iPWR, which using UO_2 as light water reactors, but due to low burnup feature, it leads to a 67% increase in uranium, enrichment, and fuel demands, which could affect uranium supply and enrichment capacities and support arguments for reprocessing. iPWRs produce about 40% more plutonium than standard reactors. This higher fuel throughput and increased plutonium production make iPWR spent fuel similarly attractive for reprocessing, raising the risk of theft (Glaser, Hopkins, & Ramana, 2013).

The higher-risk SMRs are non-water-cooled reactors because they depend on higher enrichment fuels and new fuel concepts. The HTR-PM, using TRISO fuel with 8.5% enrichment, complicates safeguard measures due to the complex online loading and unloading process (National Academies, 2023). The eVinci MMR will also use TRISO fuel, with enrichment levels up to 19.5% and a low burnup rate of 45 GWd/ton. Every three years, the reactor must be disconnected and returned to the factory for refueling, increasing the risk of theft (IAEA, 2022).

The LFR-200, using mixed fuel compounds MOX with enrichment levels up to 23.2% and incorporating the thorium cycle, produces highly attractive elements such as U-233 and plutonium-239, which are considered highly attractive and increase the risk of SNF theft (Bathke, et al., 2012; IAEA, 2022). Similarly, the Moltex-SSR-W will use recycled fuel from CANDU reactors, and plutonium will be one of the outputs of the recycling process, further increasing the attractiveness of the material and the risk of theft (National Academies, 2023).

5.2 Relationship between method results and 3S's

In chapter two, the 3S's were discussed briefly how they interact and depend on each other for SMR, with their dependency increasing for MMR as shown in Figure 7. According to Sandia National Laboratories, the interaction between the 3S's is crucial for identifying interdependencies, gaps, conflicts, and leverage points. This approach more accurately reflects real-world uncertainties, providing a clearer picture of the complex risks in multi-modal, multi-jurisdictional systems. Using integrated 3S risk assessments enables the development of more effective risk mitigation strategies by considering often-overlooked interdependencies. (William, Cohn, & Osborn, 2019). Sandia's theoretical approach defines each intersection between the 3S's, showing their positive or negative impacts on each other, as illustrated in Figure 14 (Williams A. D., 2020).

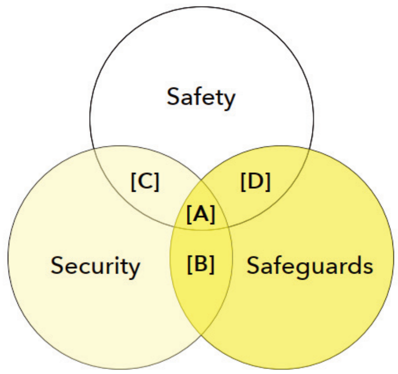

Figure 14: **Types of interactions between safety, security, and safeguards (Williams A. D., 2020)**

- Area A represents “Interdependency Area.”
- Area B represents “Conflict Area.”
- Area C represents “Gap Area.”
- Area D represents “Leverage Point.”

Sandia has identified four types of 3S’s interactions and their corresponding systems engineering design goals. Interdependencies refer to features of individual operations directly influenced by another's behavior. Conflicts are aspects or objectives that negatively overlap with expected behaviors from a separate ‘S.’ Gaps represent troublesome operations or behaviors that have yet to be detected. Leverage points are elements or aims that positively overlap with predicted behaviors from a different ‘S’. These interactions can act as "force multipliers" between safety, safeguards, and security, where advances in one ‘S’ led to simultaneous improvements in others (Williams, Cipiti, & Evans, 2021).
In the following section, we will apply Sandia's approach using our methodology and results explained in the previous chapters.

5.3 Implications on 3S’s relation

In this section, we will analyze ten selected SMRs and their associated risks using the Sandia method. The main aim is to study the causes of risks associated with one concept of the 3S's and analyze its interrelation to the other two S's. This will help us identify interdependencies between the 3S's and conduct a more accurate system analysis.

5.3.1 LOCA

In this section, we will consider the results of the large LOCA only, because it has the higher risk and impact on the selected SMRs.

Based on the assessment of large LOCA risk for the selected SMRs, three non-water coolant SMRs (HTGR, MSR, and MMR) exhibit a very low risk of LOCA. The primary reason for this low risk is the use of coolants other than water. HTR-PM uses helium as a coolant, which significantly benefits safety. While it doesn't directly impact security and safeguards, it minimizes many accident scenarios. Additionally, using graphite as a moderator results in low radiological activity, simplifying reactor decommissioning. This demonstrates a beneficial interdependency (IAEA, 2022; National Academies, 2023).

Moltex SSR-W uses molten salt as a coolant, enhancing safety. However, the low capacity for inspection, repair, and component replacement, along with the complexity of operation and continuous online salt cleaning, may pose conflict points to security and safeguards (Cognet, Bartak, & Bruna, 2021; Fasano, Lamb, & Rowland, 2021). eVinci relies on heat pipe technology. While the complex I&C systems required for control and operation pose potential conflict and security risks as discussed before. In addition, the reactor's design—fueled and sealed in the factory and transported to the customer—helps prevent radioactive material theft. However, the inspection process is only feasible at the end of the core's life, representing a potential gap in the safeguard process (Prasad, Abdulla, Morgan, & Azevedo, 2014; IAEA, 2022).

The risk of LOCA is higher for water-cooled SMRs (CAREM, RITM-200M, BWRX, Rolls-Royce and CANDU) due to the large inventory of water coolant. However, water-cooled SMRs have better security and safeguards compared to others. This advantage stems from the well-established systems, extensive experience, and existing regulations that effectively manage these reactors. This creates a notable conflict between increased LOCA risk and enhanced security and safeguards (IAEA, 2009).

LMFRs exhibit the highest risks among all selected SMRs due to the metal coolant's reactions in the event of LOCA and potential corrosion issues. Although they feature low-pressure primary coolant systems and advanced high thermal conductivity fuel designs that enhance safety and reduce fuel failure risk, traditional visual camera inspections are unfeasible. New inspection techniques are needed, and the opacity of the coolant complicates I&C systems, increasing the risk of cyber incidents, as discussed in the previous chapter, this is can be considered as conflicts between the 3S's (Cognet, Bartak, & Bruna, 2021; Fasano, Lamb, & Rowland, 2021).

Table 19: **LOCA and 3S's interaction**

SMR	Safety	Security	Safeguards	3S's Interaction
HTR-PM	Helium as coolant	Less accidents scenarios	More safe decommissioning	**Interdependency** between security, safeguards, and safety
Moltex SSR-W	Salt as coolant	Complex operations	Low capacity for inspection	**Conflict** safety, security and safeguards
eVinci	Heat pipes	Complex I&C systems	Sealed fuel till the end life of the core	**Conflict** between security and safety **Gap** between safeguards and safety
CAREM, RITM-200M, CANDU, BWRX, Rolls-Royce	Water coolant	Well-known security concepts	Existing regulations	**Conflict** between safety, security and safeguards
LFR-AS-200, ARC-100	Metal coolant	Complex I&C systems	Difficulty in inspection	**Conflict** between safety, security and safeguards

5.3.2 Cyber Incidents (CI)

Based on the results of the assessment of the risk to CI for the selected SMRs, non-integral water-cooled reactors such as Rolls-Royce, CANDU, and BWRX have the lowest risk among the selected SMRs. This can be attributed to several factors: the use of available industry-standard programmable logic controllers or distributed control systems, reduced dependency on wireless technology, and the incorporation of both active and passive safety features. Consequently, the reliance on sensing and transferring information is less critical compared to the other SMRs (IAEA, 2022).

From a safety perspective, the integration of active and passive safety features significantly enhances the overall safety of the reactor. While active safety features are crucial for accident mitigation over extended periods, they can increase the vulnerability to accidents if relied upon exclusively. However, combining active safety with passive safety features simplifies the design and improves reliability (IAEA, 2020). From safeguards perspective, there are potential gaps. The small size and compact architecture of SMRs can complicate inspection and maintenance processes. Additionally, developing radiation detectors suitable for passively safe designs with large water inventories may be necessary. However, applying the same safeguards concepts used for traditional nuclear power plants to SMRs can help mitigate these challenges (Prasad, Abdulla, Morgan, & Azevedo, 2014; Cognet, Bartak, & Bruna, 2021).

For iPWR SMRs, such as CAREM and RITM-200M, the security risk is higher due to the integrated design of the reactor, which requires more complex I&C systems (Fasano, Lamb, & Rowland, 2021). From a safety perspective, this presents a conflict. While the iPWR design offers enhanced safety features due to its quick response in the event of an accident, relying on natural phenomena, such as natural circulation for cooling (Zeliang, Mi, Tokuhiro, Lu, & Rezvoi, 2020). From a safeguard's perspective, there are conflicts arise, including the need for radiation detectors suitable for passively safe designs with large water inventories, as well as in-vessel sensors for iPWRs (Prasad, Abdulla, Morgan, & Azevedo, 2014).

LMFR SMRs (such as LFR-AS-200 and ARC-100) experience a higher risk for CI due to the type of reactor and the use of metal coolants. These factors increase the invisibility of the coolant and the dependency on sensing and complex I&C systems (IAEA, 2022). From a safety perspective, there are challenges associated with LMFR SMRs. While these reactors offer enhanced safety features through passive safety mechanisms, such as a small fissile inventory that reduces waste and decreases the risk of core melt in the event of a severe accident, there are notable risks as well. For example, sodium coolant is highly reactive and can have a violent exothermic reaction if exposed to water or air. Additionally, lead coolant presents a risk of fuel corrosion due to high operating temperatures (Cognet, Bartak, & Bruna, 2021). Similar conflicts arise in terms of safeguards. The opaque nature of the coolants makes inspections difficult. Traditional cameras are insufficient for these coolant types, necessitating the development of new detection methods. Ultrasonic visual inspection techniques may offer a viable solution (Prasad, Abdulla, Morgan, & Azevedo, 2014).

MSR SMR, specifically the Moltex SSR-W, presents certain risks for CI events due to concerns with sensors and the complexity of its protection and monitoring systems (IAEA, 2022). However, the Waste-To-Stable-Salt (WATSS) process offers significant safety and safeguard advantages. From a safety perspective, the MSR's design allows the entire steam cycle to mirror that of coal-fired power stations and operate independently of the nuclear plant, thus avoiding nuclear regulatory constraints. This not only simplifies the regulatory framework but also enhances operational efficiency. The WATSS process, which includes on-loading refueling and waste reduction, further contributes to safety by managing waste effectively and minimizing the risk of core melt in severe accidents (Cognet, Bartak, & Bruna, 2021; IAEA, 2022).

MMR with heat pipe technology (eVinci) presents one of the highest risks for CI events in our study due to its reliance on autonomously controlled systems (ACS) (Fasano, Lamb, & Rowland, 2021). This increases dependency on intricate I&C systems and necessitates a tailored system design. While the complete reactor and power conversion rely on ACS, which reduces the need for personnel and eliminates refueling requirements, which it is a conflict point for safety prospective (IAEA, 2022). This also introduces gaps in safeguards. Remote monitoring capability is essential for deploying SMRs in remote regions, highlighting the need for non-intrusive measurement techniques to ensure continuous oversight and address potential vulnerabilities (Bentoumi, Chaudhri, Ennde, Sur, & Trask, nd).

HTGR (HTR-PM) also presents a high risk of CI event due to its very high core temperatures, high coolant velocity, and the use of TRISO fuel, which necessitates specialized I&C systems. These features enhance the safety concept of the SMR, as TRISO fuel is highly resistant to neutron irradiation, corrosion, and high temperatures, and it remains intact even during severe fractures (Energy.gov, 2019). However, the accuracy of material accountancy during loading and unloading processes is challenging to achieve, posing a significant conflict in the safeguards concept for TRISO fuel (National Academies, 2023).

The interactions of the 3S's for each type of reactor are summarized in Table 20

Table 20: CIs and 3S's interaction

SMR	Safety	Security	Safeguards	3S's Interaction
CANDU, BWRX, Rolls-Royce	Passive/active safety feature	Using available industry standards	Complicate inspections	**Leverage point** between safety and security **Gap** between safeguards and safety
CAREM, RITM-200M	Enhance safety features	Integral design increases I&C complexity	Require special measurements	**Conflict** between safety and security**,** and safeguards
LFR-AS-200, ARC-100	Dangerous reaction of the coolant	Metal coolant	Opaque coolant needs special equipment	**Conflict** between safety and security**,** and safeguards
Moltex SSR-W	Less severe accidents	WATSS	Less waste	**Leverage point** between safety and security, and safeguards
HTR-PM	Highly efficient fuel	TRISO	Material accountancy difficulties	**Leverage point** between safety and security **Conflict** between safeguards and security
eVinci	No refuelling	ACS	Non-intrusive instrument	**Conflict** between safety and security **Gap** between safeguards and security

5.3.3 Spent Nuclear Fuel (SNF)

The primary cause of this threat is the type of fuel used. Water-cooled SMRs, such as Rolls-Royce and BWRX, which utilize UO_2 fuel with enrichment less than 5% and relatively moderate burnup levels, are at the lowest risk for spent nuclear fuel theft. This is due to well-established procedures for safeguards, inspection, and decommissioning. Additionally, the safety concepts applied to UO_2 are proven and well-documented. This creates a leverage point for the interdependency between the 3S's (IAEA, 2022).

The ARC-100 shows very low risk due to its 20-year refueling period, making access to radioactive materials difficult. This long refueling period is a leverage point for safety, as the core is often sealed, resulting in minimal active operator involvement (IAEA, 2022). However, there is a gap in security measures; while it is challenging to apply security measures to a long-life core, the reduced need for transportation and handling enhances security (Bentoumi, Chaudhri, Ennde, Sur, & Trask, nd).

The risk increases with iPWR SMRs (RITM-200M and CAREM), with the cumulative plutonium content being 40% higher than that of standard PWRs (Glaser, Hopkins, & Ramana, 2013). However, the safety features are enhanced in this type of SMR, which decreases the accident frequency and improves the impact by reducing the amount of piping. Additionally, inherent safety features further enhance safety (Zeliang, Mi, Tokuhiro, Lu, & Rezvoi, 2020).Although vendors and designers claim that Security By Design (SBD) is a key concept in the design process, there are still significant gaps due to the novelty of the design. These gaps are reflected in the I&C systems and the applicability of PPS measures in smaller-sized structures (Poghosyan, 2022).

CANDU reactors have a low risk of theft due to their use of the thorium cycle. This cycle offers several benefits, including lower waste production and enhanced fuel performance from a safety perspective. Additionally, from a security standpoint, the thorium cycle improves transportation and handling security benefits in the long term, as it has the potential to be a self-sustaining fuel without the need for fast neutron reactors (WNA, 2020). This could create a conflict between safeguards and safety security.

The risk associated SNF increases with the use of MOX fuel in the LFR-AS-200 reactor. While the vendor proposes MOX fuel as a solution to reduce radioactive waste, particularly plutonium **(Orano, 2024)**, it offers significant leverage from a safety perspective by decreasing high-level radioactive waste and long-lived isotopes. However, this approach creates a conflict with security considerations. Handling MOX fuel requires a high level of security due to the presence of plutonium, which poses conflicts for material control and safeguards **(WNA, 2017)**.

Moltex's SSR-W high-risk source is the WATSS process, which offers several advantages, such as recycling used CANDU fuel and reducing waste. However, there are gaps in the 3S's (Safety, Security, and Safeguards) interrelationship due to the process's current stage of development and associated risks. The WATSS process involves complex chemical and electrochemical techniques, and adherence to safety regulations and standards is crucial for its acceptance and development, additionally the high security requirement for storage and transport the recycle fuel (National Academies, 2023).

The high risk associated with eVinci and HTR-PR reactors stems from the use of TRISO fuel, which presents challenges for material accountability. TRISO fuel is proposed as a robust option due to its high thermal conductivity, which improves heat management and corrosion resistance, and its ability to withstand higher pressures, leading to more efficient fuel usage (Ultra, 2023). Consequently, the spent pebbles from this fuel would likely be classified as a highly diluted waste form, requiring less stringent security measures compared to more concentrated materials (National Academies, 2023).

Table 21: **SNF theft and 3S's interdependency**

SMR	Safety	Security	Safeguards	3S's Interaction
BWRX, Rolls-Royce	Proven concepts	Less security threats	UO_2 fuel	**Leverage point** between 3S's
ARC-100	Less operators	Security measures hard to apply	Long refuel period	**Leverage point** between safeguards and safety **Gap** between safeguards and security
CAREM, RITM-200M	Inherent safety	Applicable of PPS	Integrity	**Leverage point** between safeguards and safety **Gap** between safeguards and security
CANDU	Enhance fuel performance	Less transportation	Thorium cycle	**Conflict** between safety, and safeguards **Conflict** between security, and safeguards
LFR-AS-200	Less high-level waste	Special security measures	MOX fuel	**Leverage point** between safeguards and safety **Conflict** between safeguards and security
Moltex SSR-W	Complex technique	Transportation and storage challenges	WATSS	**Gap** between 3S's
eVinci, HTR-PM	More efficient fuel	Diluted waste	TRISO	**Conflict** between safeguards and security **Conflict** between safeguards and safety

5.4 Limitations of the results

The existing information about SMRs is mostly theoretical and doesn't rely on real experience. Even for SMR types like existing NPPs, such as PWR, BWR, HTGR, and CANDU, while we can refer to risk data, it will not scale accurately. The reduction in reactor size affects safety, as mentioned before, and could also impact security and safeguard measures. Additionally, the new generation of reactors will face the novelty of many concepts such as multi-modularity, factory-sealed cores, higher enrichment, online refueling periods, new fuel concepts, and new hazards arising from the dependence on the transportability of reactor modules and fuel, as well as remote locations (Poghosyan, 2022).

5.5 Summary

Chapter 5 of our study delves into the interactions of three critical events in the operation of SMR , such as LOCA , cyber incidents (CI), and spent nuclear fuel (SNF) theft - each impacting one of the 3S's: safety, security, and safeguards. By examining case studies, we found that while large LOCAs in water-cooled and LMFRs SMRs are manageable with established safety features, and it pose significant risks, particularly for reactors like the Rolls-Royce SMR, which has a higher vulnerability due to its extensive piping. Newer reactor designs, such as HTGR and MSR, exhibit almost zero risk for LOCAs due to their innovative coolant systems.

Cyber incidents present a considerable threat to the security of SMRs, especially those with complex instrumentation and control (I&C) systems like multi-unit SMRs and remotely operated reactors such as the eVinci MMR. These reactors face heightened risks due to their sophisticated I&C architectures, which could be exploited during cyber attacks, compromising safety and safeguards. Additionally, the risk of SNF theft is notably high for reactors using higher enrichment fuels and novel fuel concepts. Reactors such as HTGRs, MSRs, and certain iPWRs, due to their unique fuel cycles and transportation requirements, are more susceptible to malicious activities.

SNF theft is a critical threat as well, particularly for SMRs using higher enrichment fuels and innovative fuel concepts. Non-water-cooled reactors such as HTGRs, which use TRISO fuel, and Moltex SSR-W, which employs recycled fuel, are especially susceptible. The transportation and remote locations of these reactors further exacerbate the risks.

The analysis of SMRs highlights the complex interplay between 3S’s. While some SMRs enhance safety, they may introduce challenges to security and safeguards. Conversely, other SMRs with established security and safeguards might face higher safety risks. Advanced SMR designs often present increased risks across all 3S aspects, illustrating the intricate relationships and trade-offs between these factors.

6 Conclusions

This thesis has examined the risk analysis of several SMR designs, focusing on their safety, security, and safeguards (the 3S's). SMRs represent a promising avenue for the future of nuclear energy, characterized by diverse technological innovations that address the growing global demand for clean, reliable electricity. However, as with any complex technology, the successful deployment of SMRs hinges on a meticulous approach to managing the associated risks, encompassing technological, regulatory, and societal dimensions. The comprehensive analysis presented in this study illuminates the multifaceted challenges and opportunities inherent in advancing nuclear energy technology. This conclusion synthesizes the key findings of the study, elaborates on the implications for stakeholders, and outlines a roadmap for the future trajectory of SMR development and deployment.

The risk assessment technique employed for these SMR designs was rigorous and systematic, providing an in-depth review of possible risks. The study utilized a comprehensive methodology to analyze the risks associated with SMRs, involving the identification of potential threats, prioritization of threat events, evaluation of vulnerabilities, analysis of impacts, establishment of likelihoods, and calculation of total risks. This framework offered a robust basis for understanding the hazards connected with SMRs. The primary risk events examined, including LOCA, CI, and SNF theft, were chosen based on their significance and expected implications for the 3S's. This structured approach revealed significant insights into the specific vulnerabilities and strengths of different SMR designs, influenced by factors such as reactor type, fuel enrichment, digital architecture, and the presence of passive or active safety features.

The thesis highlighted the urgent need for sustainable energy solutions due to rising global energy demand from population growth and urbanization. Achieving net-zero emissions, crucial for mitigating climate change as per the Paris Agreement, requires a shift towards low-emission energy sources. Nuclear energy, with its low greenhouse gas emissions and continuous availability, is essential in this transformation despite challenges like high costs, safety concerns, and public acceptance.

SMRs offer several advantages, including modularity, reduced construction time, and the ability to serve diverse energy needs, including remote and industrial applications. However, the implementation of these reactors must address inherent challenges such as high costs, technical issues, and complex licensing processes. These new features must align with 3S's concepts to demonstrate the value of the new technology.

The integration of 3S's into SMR design represents a significant advancement in nuclear technology. SMRs incorporate innovative safety features like passive safety systems and reduced radioactive inventory, which collectively enhance their overall safety profile. Security-by-Design (SeBD) principles ensure protection against physical and cyber threats, incorporating robust detection, delay, and response mechanisms. Safeguards-by-Design (SBD) further uphold international commitments by preventing the diversion of nuclear materials for non-peaceful purposes. While SMRs offer substantial improvements, they also introduce new challenges that must be meticulously addressed. Continuous efforts to refine safety standards, harmonize international regulations, and integrate comprehensive safety, security, and safeguards measures are essential for maintaining the reliability and acceptance of nuclear power as a clean energy source.

The thesis explored the diversity of SMR designs, highlighting the innovative possibilities in the nuclear energy industry. The inclusion of ten different SMR designs, each distinguished by different reactor types, fuel compositions, and design maturities, offered a comprehensive outlook on the diverse methods employed to achieve safe, secure, and efficient nuclear power generation. The presence of diverse characteristics is crucial in comprehending the capacity of SMRs to fulfill various energy requirements and tackle distinct obstacles. By including several reactor designs, such as water cooled SMRs, HTGRs, fast reactors, and GEN IV reactors, a thorough analysis was conducted to identify the inherent advantages and disadvantages of each design. Similarly, the presence of several fuel types, ranging from conventional uranium oxide to more sophisticated fuels like thorium, emphasized the diverse approaches to achieving fuel efficiency and managing waste.

The risk assessment methodology detailed in this thesis offers a comprehensive framework for evaluating potential threats to entities, particularly in high-risk sectors like nuclear facilities. By leveraging a structured approach that includes identifying threats, ranking their impact, assessing vulnerabilities, and calculating overall risk, this methodology significantly enhances decision-making and resilience. Applying this framework to SMRs underscores the importance of integrating the 3S's principles into risk assessments.

The methodology's emphasis on assessing the impact of threats such as LOCA, CI, and theft of SNF highlighted the need for robust safety, security, and safeguards measures. This approach not only ensures the protection of public and environmental health but also supports the development and operational reliability of advanced nuclear technologies. Next, the focus will shift to examining how these assessments apply to specific SMR designs and threat scenarios, further advancing the understanding and management of risks in nuclear energy systems.

Of the more than 80 designs of SMRs, we selected ten to apply the method, each addressing specific needs and safety challenges. From the prototype CAREM and traditional CANDU to the advanced Rolls-Royce, BWRX, and RITM-200M, and the innovative HTR-PM, LFR-AS-200, ARC-100, Moltex SSR-W, and eVinci, each reactor showcases distinct technological advancements and operational strategies. As these SMRs evolve, they promise enhanced safety, cost-efficiency, and adaptability to various energy requirements. with applying a risk assessment methodology to evaluate these SMRs' potential threats and impacts on safety, security, and operational effectiveness, ensuring their readiness for future deployment.

SMRs exhibit varying levels of risk in the event of a LOCA. Water-cooled and liquid metal cooled SMRs face higher risks due to their complex piping and coolant reactions, with Rolls-Royce SMRs showing moderate vulnerability. In contrast, HTGRs and molten salt reactors have much lower risks due to their design and coolant properties. Effective Emergency Core Cooling Systems (ECCS) and reactor design play crucial roles in mitigating these risks. Overall, HTGRs and molten salt reactors are better equipped to handle LOCAs with minimal impact compared to their water-cooled and liquid metal counterparts.

The security of SMRs against cyber incidents is highly dependent on their technological complexity and operational characteristics. Newer and more sophisticated SMR designs, such as the eVinci and HTGR-PM, face increased risks and potential impacts due to their advanced control systems and reliance on remote operations. In contrast, established water-cooled SMRs like CAREM and CANDU generally experience lower risks due to their simpler instrumentation and control systems. The likelihood of cyber incidents also rises with system complexity, highlighting the need for robust security measures tailored to the unique challenges posed by each SMR design.

The safeguards for SNF in SMRs vary significantly based on reactor design and fuel type. While water-cooled SMRs benefit from established technologies and straightforward safeguard measures, advanced reactors with longer refueling intervals or higher enrichment fuels pose increased risks. Specifically, SMRs utilizing high-enrichment fuels like HALEU or MOX, or those with extended refueling periods, may face heightened vulnerability to theft. The potential attractiveness of such fuels for illicit trafficking, coupled with complex reprocessing and storage challenges, underscores the need for enhanced security measures. As SMRs continue to evolve, balancing operational efficiency with robust safeguards will be crucial in mitigating the risks associated with SNF theft.

In this research, we explored the intricate interactions between the 3S's within selected SMRs through the cases studied by the risk assessment methodology. The analysis reveals that safety risks, such as those from large LOCA, can influence security measures by complicating protective responses and impacting safeguards due to increased radioactivity. CIs present a significant threat to complex Instrumentation and Control (I&C) systems, potentially compromising both safety and security. The risk SNF theft varies with the enrichment and burnup levels of the fuel, affecting safeguards and security measures. The integration of these factors highlights that improvements or failures in one area can create leverage points or conflicts across the other 3S domains. Overall, understanding these interactions emphasizes the need for a holistic approach to risk management, addressing the interdependencies of safety, security, and safeguards to enhance the robustness of SMR designs.

6.1 Limitations and Future Work

The limitations of this study primarily stem from the reliance on theoretical data rather than empirical evidence. Many of the SMR models analyzed are still in developmental or early operational stages, and their performance under real-world conditions remains largely untested. As a result, the risk assessments and interactions between safety, security, and safeguards are based on projections rather than actual operational data. Additionally, the novel features of SMRs, such as modular designs, high enrichment fuels, and online refueling processes, introduce uncertainties that are not fully addressed by existing data. The study also faces challenges in assessing the impact of new technologies and regulatory frameworks, as these aspects are still evolving and lack comprehensive field validation. These factors limit the ability to accurately predict the practical effectiveness of safety, security, and safeguard measures in SMRs.

Future research should focus on developing more realistic risk assessment models that evaluate the interdependencies among 3S's in more SMRs. These models could be based on data from experiences to enhance our ability to predict and manage cumulative risks across these domains. Additionally, empirical data collection from operational SMRs is essential to validate and refine these models, moving beyond theoretical data. This real-world data will be crucial for improving safety protocols and security measures, ensuring they effectively address the unique challenges of SMR technologies.

Moreover, future work should address advanced cybersecurity measures tailored for the complexities of SMR instrumentation and control systems. Research into innovative fuel cycle technologies that reduce theft risk while maintaining safety is also needed. Investigating the impact of modular designs on the 3S's, conducting scenario-based testing, and examining the implications for regulatory frameworks will contribute to the development of more resilient SMR systems. By focusing on these areas, we can address the complexities and interdependencies highlighted in the current analysis and improve the overall safety and security of SMR technologies.

6.2 Summary

This thesis provides an in-depth risk analysis of various SMR designs, focusing on their safety, security, and safeguards. SMRs, with their potential to address global energy needs through clean and reliable electricity, present both opportunities and challenges. The study employed a systematic risk assessment methodology to evaluate vulnerabilities related to loss of coolant accidents (LOCA), cyber incidents (CI), and spent nuclear fuel (SNF) theft. It revealed that while advanced SMRs like HTGRs and molten salt reactors exhibit lower risks for LOCA, newer designs with complex control systems face higher cybersecurity threats. Additionally, reactors with high-enrichment fuels or extended refueling intervals are more susceptible to SNF theft, necessitating robust safeguards.

The analysis underscores the importance of incorporating safety, security, and safeguards principles into SMR design. Despite the promise of SMRs for modularity and adaptability, they must address inherent challenges related to cost, technology, and regulatory processes. The study concludes with recommendations for future research, emphasizing the need for empirical data to validate theoretical models and the development of advanced cybersecurity and safeguard measures. This holistic approach is crucial for enhancing the reliability and acceptance of SMRs in the evolving nuclear energy landscape.

Incorporating risk probabilities and likelihoods data is essential for predicting risks in SMRs, as it provides insights into failure rates and event frequencies, allowing for a robust risk assessment of potential scenarios. Understanding the consequences of past incidents through impact assessments and safety impact data is important for evaluating the severity of potential risks and informing mitigation strategies. Operational data, such as performance metrics and maintenance records, is vital for identifying patterns that could indicate emerging risks or inefficiencies. Environmental data, including monitoring results and studies on local ecosystems, helps assess the environmental impact of SMRs, ensuring compliance with regulatory standards and addressing public concerns. Additionally, technological data, such as advancements and component reliability, aids in understanding the risks associated with new technologies and informs decisions on design and deployment. These data types collectively enhance the accuracy and depth of risk assessments, supporting the safe and efficient development of SMRs in future research.

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