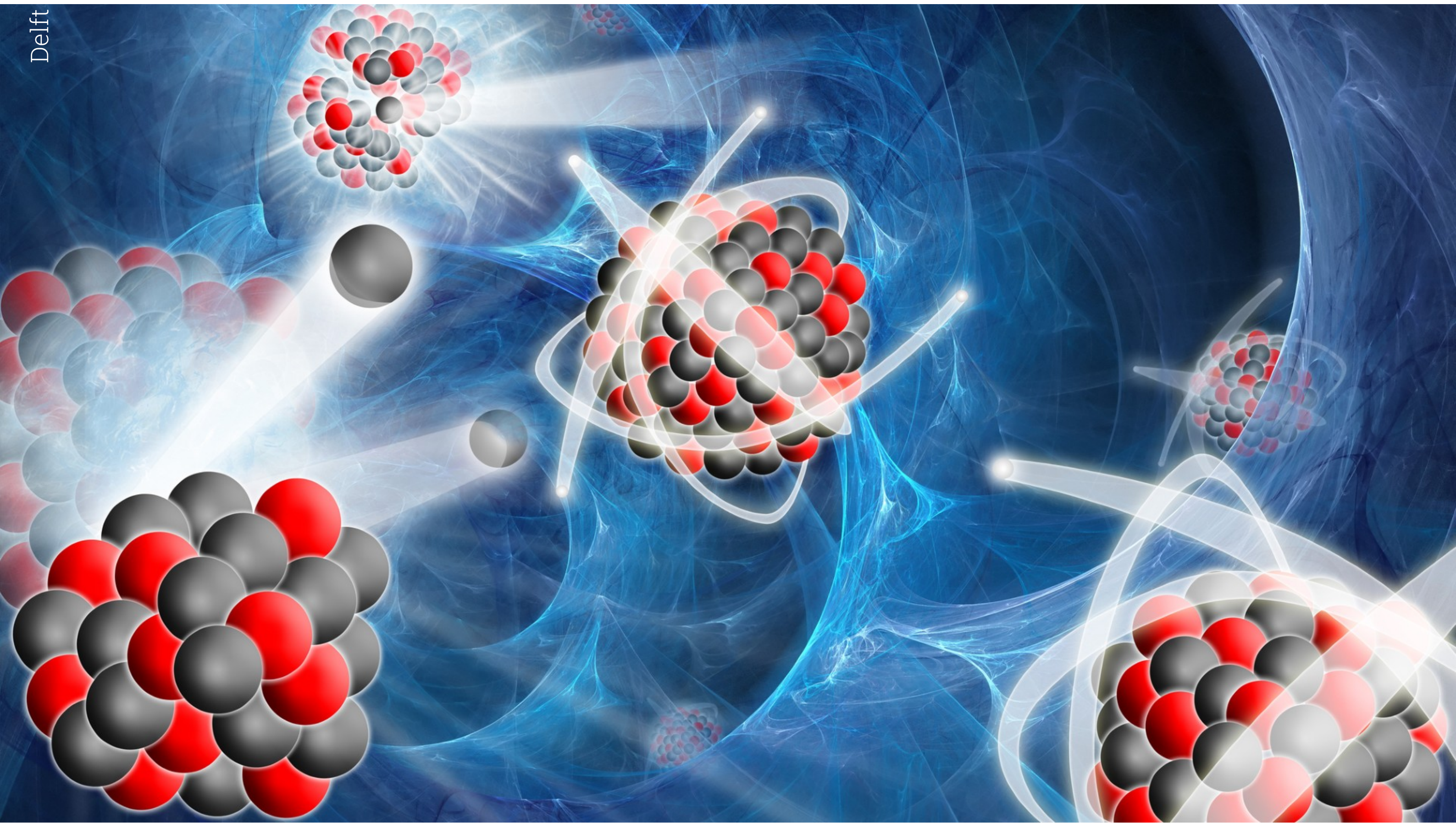
Understanding the Commercialization Timelines, Barriers and Strategies for Next Generation Nuclear Fission Technologies.

Master Thesis

Shubhanga Kulkarni



by

Shubhanga Kulkarni

Student Name	Student Number
Shubhanga Kulkarni	5711568

Supervisor:	Stefan Pfenniger
Project Duration:	Dec, 2023 - Sep, 2024
Faculty:	Faculty of EEMCS, Delft

TU Delft

Preface

This thesis represents the culmination of my Master's journey in Sustainable Energy Technology at TU Delft, integrating both the extensive coursework and the research presented here. Completing this program has been an enriching experience that has significantly broadened my understanding of the energy sector and the complex challenges associated with advancing next-generation nuclear fission technologies. Throughout this process, I have gained valuable insights and skills that have shaped my approach to addressing these challenges.

I am deeply grateful to my supervisor, Dr. Stefan Pfenninger, for his unwavering support and guidance. His expertise and constructive feedback have been instrumental in refining my research and pushing me to achieve my best. I would also like to extend my heartfelt thanks to Dr. Linda Kamp, whose valuable input and encouragement were crucial in navigating the intricacies of this research. Lastly, I am thankful to my family, friends, and peers, whose support has been a constant source of motivation throughout this journey. Their belief in my abilities has been a driving force in completing this thesis and the overall program.

Shubhanga Kulkarni
Delft, September 2024

Summary

This thesis, titled ”Understanding the Commercialization Timelines, Barriers, and Strategies for Next-Generation Nuclear Fission Technologies” focuses on the process of bringing advanced nuclear technologies to market. As the world moves towards cleaner energy, next-generation nuclear fission has the potential to replace fossil fuels, but its commercialization is a complex and slow process. This research maps the commercialization timelines of 10 companies developing these technologies, tracking their progress through stages like ideation, design, prototyping, production, and launch. By comparing these timelines, the study shows how factors like early regulatory engagement and diverse funding can help companies move forward more quickly through the commercialization process.

The research also draws on interviews with experts from leading nuclear fission companies, each with 10 to 20 years of experience in the field. From these interviews, key barriers to commercialization were identified, including high development costs, long regulatory approval processes, public concerns about safety, and the need for further technological advancements, such as long-term testing of materials. These challenges not only slow down the commercialization process but also increase the financial risks for companies, making it harder for them to secure investments.

The experts also shared strategies for overcoming these barriers. Successful companies often engage with regulators early, diversify their funding sources, and communicate openly with the public about safety and progress. The interviews highlighted the importance of early regulatory involvement, innovative financial solutions, and a strong focus on safety research to help move these technologies towards commercialization.

In conclusion, this thesis provides a comprehensive look at how next-generation nuclear fission technologies are being commercialized, examining both the challenges and the strategies being used by companies to overcome them. By mapping out the progress of 10 leading companies and drawing insights from expert interviews, the research offers practical recommendations for how the commercialization process can be improved, helping these technologies play a key role in the future of clean energy.

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Research Introduction

1.1. Introduction

Humanity faces an unavoidable truth: climate change is happening, and immediate action is required. It is crucial to tackle the issue. Human activities that release greenhouse gases are the main cause of climate change [1]. One important approach to address this issue is to decrease these discharges. Since a large portion of greenhouse gas emissions come from generating electricity. A major revamp of the electricity supply system is crucial in the energy industry [2]. Greenhouse gas emissions are inherently connected to the burning of fossil fuels in power plants. Therefore, there is an urgent requirement to substitute these power stations with alternatives that do not emit GHGs in the next few decades. Nuclear technology is an advanced energy option without greenhouse gas emissions that can replace fossil fuel sources in the necessary time frame, while ensuring that safety, economic feasibility, reliability, and sustainability are all maintained [3].

Currently, nuclear power plants generate over 2700 terawatt-hours (TW h) annually, constituting approximately 16% of global electricity production and around 6% of primary energy consumption[4]. The growth in nuclear electricity generation is modest, at a rate of 1% per year. This increase is less than half of the rise in primary energy consumption, itself less than half of the escalation in coal consumption during the initial decade of the 21st century. Presently, boasting 27 member states, the European Union (EU) hosts a population exceeding 492 million consumers and approximately 25 million companies, establishing itself as the second-largest energy market globally [5]. Despite this, the EU relies on importing 50% of its energy requirements, incurring an annual expenditure of 240 billion Euros. Furthermore, the EU observes a con- sistent 2% annual growth in primary energy consumption. Without fundamental alterations, the imported share of primary energies, primarily sourced from fossil origins, might escalate to 70% by the year 2030[6]. The primary era of substantial nuclear energy deployment occurred in the 1970s and 1980s, primarily in OECD countries, with the central focus of present nuclear energy endeavors concentrated in Asia, notably the Far East. An economically notable aspect of nuclear energy is its considerable initial investment costs. However, the levelized cost of electricity from nuclear sources is among the lowest in the energy mix of numerous countries with commercial nuclear energy. This economic aspect, coupled with the commendable performance of nuclear plants, provides a rationale for extending the operational lifespan of these plants [7].

The commercialization of nuclear fission technology encounters difficulties in the present era owing to challenges such as substantial upfront costs, public apprehensions regarding safety and nuclear waste, intricate regulatory procedures, competition from alternative energy sources, and the necessity for advancements in reactor technology [8]. These factors collectively contribute to the complexities of making nuclear fission a widely accepted and economically feasible energy solution which will be discussed in this thesis.

1.2. Background

1.2.1. Basics of Nuclear Fission

Nuclear fission is a crucial process in nuclear physics, involving the splitting of a heavy atomic nucleus into two or more lighter nuclei, accompanied by the release of a substantial amount of energy as shown in figure 1.1. This process was first discovered by Otto Hahn and Fritz Strassmann in 1938 and later explained by Lise Meitner and Otto Frisch in the same year [9]. Fission typically occurs when a heavy nucleus, such as uranium-235, absorbs a neutron, becomes unstable, and splits into two smaller nuclei, known as fission fragments, along with additional neutrons and energy [10].

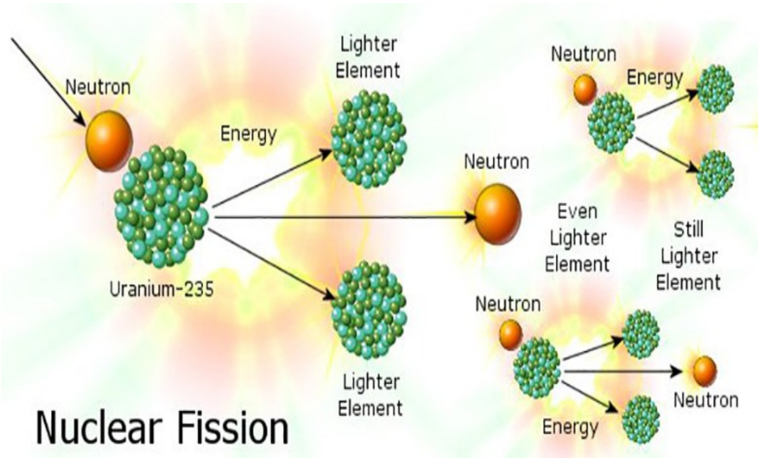


Figure 1.1: Fission process diagram [11]

The energy released during fission is primarily due to the conversion of a small amount of mass into energy, as described by Einstein's equation $E = mc^2$ [12]. This substantial energy release makes nuclear fission particularly useful in applications such as nuclear power generation, where the heat produced from fission reactions is used to generate electricity [13].

In a nuclear reactor, a controlled chain reaction is maintained, where the neutrons produced by one fission event go on to induce further fission in other nuclei, sustaining the reaction and energy output [14]. The ability to control this chain reaction is crucial for the safe operation of nuclear reactors. The figure 1.2 explains the fission process in a nuclear reactor.

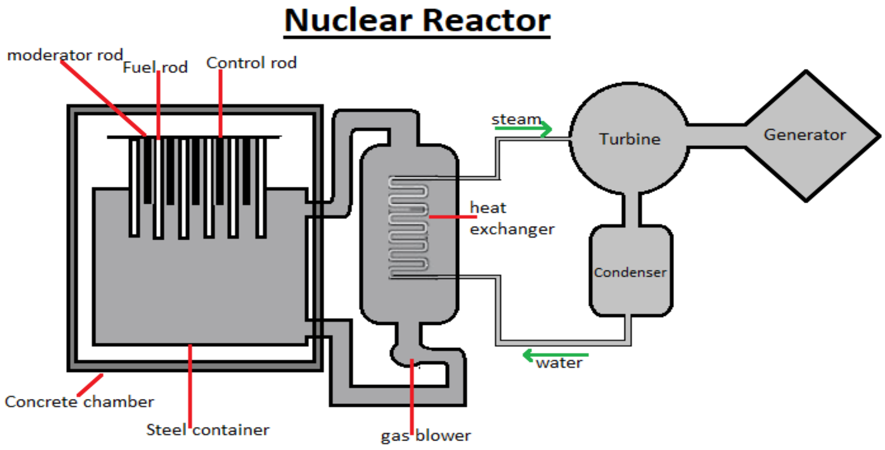


Figure 1.2: Fission process schematic diagram [15]

Modern theoretical models, such as nuclear density functional theory, play a significant role in understanding the fission process by simulating the behavior of nucleons within the nucleus as it undergoes fission . These models are supported by experimental data, which provide insights into fission fragment distributions and the energy released during the process [16].

1.2.2. Types of Conventional Nuclear Fission Technologies

Conventional nuclear fission technologies, primarily encompassing Light Water Reactors (LWRs) such as Pressurized Water Reactors (PWRs) and Boiling Water Reactors (BWRs), have been the foundation of nuclear power generation since the 1950s. These reactors are known for their reliability and efficiency, utilizing uranium fuel and water for cooling and neutron moderation. Despite their widespread use, they face challenges such as high costs, long construction times, and the need for effective nuclear waste management.

Light Water Reactors (LWRs)

Nuclear power generation is led by Light Water Reactors (LWRs), which are essential in supplying the world's expanding need for efficient and sustainable energy sources. Developed over many years, these reactors allow for controlled nuclear fission processes by using light water, or ordinary water, as both a coolant and a neutron moderator. LWRs can use either enriched uranium or natural uranium. Enriched uranium is uranium that has been artificially increased in the concentration of the fissile isotope U-235. Natural uranium contains only about 0.7% U-235, and the rest is U-238. LWRs that use natural uranium are called heavy water reactors [17].

A number of benefits that Light Water Reactors (LWRs) provide help explain their popularity in the nuclear power production industry. First off, the large-scale viability of LWRs is ensured by the economical and widely accessible resource provided by using regular water for both neutron moderating and cooling purposes. LWR designs have notable safety precautions, such as redundant safety systems and passive cooling systems, which improve the overall safety profile of the designs [18]. Moreover, the resistance to proliferation exhibited by LWRs, which is ascribed to the arduous process of extracting material of military quality from its blueprint, confers an extra degree of protection upon their deployment. An further noteworthy benefit is the well-established technology behind LWRs, which has been developed over many years of study and practical use, making them dependable and easily understood devices [19].

These reactors can be essential to supply the world's energy needs, maintaining grid stability, and laying the groundwork for nuclear power's further assimilation.

Pressurized Water Reactors (PWRs)

Pressurized Water Reactors (PWRs) stand as a pivotal development in nuclear power, showcasing technological progress that enhances the safety, efficiency, and dependability of nuclear energy. PWRs, which rely on ordinary water as both coolant and neutron moderator, are a widely adopted and proven reactor design [18].

PWRs operate by maintaining water at elevated pressure to prevent boiling, utilizing a closed-loop system with separate primary and secondary coolant circuits. In the primary loop, water absorbs heat from the reactor core where nuclear fission reactions occur. The heated, pressurized water is then transferred to a heat exchanger in the secondary loop, generating steam to drive a turbine connected to a generator for electricity production [20].

An inherent strength of PWRs lies in their robust safety features. The pressurized coolant minimizes the risk of boiling, ensuring stable reactor operation [21]. Additionally, PWRs incorporate multiple safety systems, such as emergency core cooling and passive safety measures, to prevent overheating and maintain core integrity during potential emergencies. This design reliability underscores the confidence in deploying PWRs for large-scale power generation.

PWRs offer operational flexibility, capable of adjusting output to match fluctuations in electricity demand, contributing to grid stability [22]. The reactors have a rich operational history, providing a foundation for continuous improvements, refinements, and safety enhancements. This extensive experience underscores the maturity and reliability of nuclear technology.Despite these merits, challenges, including nuclear waste management and economic competitiveness, persist.

Boiling Water Reactors (BWRs)

Boiling Water Reactors (BWRs) play a pivotal role in the field of nuclear power, addressing global energy demands through their distinctive and efficient design. As a subtype of light water reactors, BWRs employ ordinary water for both cooling and neutron moderation, distinguishing them in the landscape of nuclear energy production [18].

In BWRs, the reactor core elevates the water temperature until it reaches the boiling point, generating steam directly within the reactor vessel. This steam is then utilized to drive a turbine connected to a generator, ultimately generating electricity. Unlike Pressurized Water Reactors (PWRs), which maintain water under high pressure to prevent boiling, BWRs embrace the boiling process as an integral part of their energy conversion mechanism [23].

A noteworthy characteristic of BWRs is their simplified design relative to PWRs. The absence of a separate steam generator streamlines the overall system architecture, potentially reducing both construction and maintenance costs [24]. This design also facilitates a more direct and streamlined process in converting heat to electricity, enhancing the overall efficiency of BWRs.

Operational flexibility is another distinctive advantage of BWRs. The inherent boiling process allows for a more responsive control of power output, making BWRs well-suited for applications that require adjusting power levels. This flexibility enhances the integration of BWRs into power grids, assisting in dynamically balancing electricity supply and demand.

However, like any nuclear technology, BWRs face challenges. Nuclear waste management remains a critical concern, demanding continual research and development efforts to address issues related to long-term disposal and environmental impact. Additionally, ensuring the economic competitiveness of BWRs in the rapidly evolving energy landscape requires ongoing innovation and adaptability.

Pressurized Heavy Water Reactors (PHWRs)

Pressurized Heavy Water Reactors (PHWRs) hold a pivotal position in the nuclear energy domain, presenting a unique method for tapping into the potential of nuclear fission. Unlike their light water counterparts, PHWRs employ heavy water, containing deuterium, as both a moderator and a coolant. This distinctive design comes with various benefits, rendering PHWRs a dependable and efficient contributor to sustainable energy production [18].

In PHWRs, heavy water moderates neutrons, facilitating continuous nuclear fission reactions. The pressurized heavy water also acts as a coolant, absorbing the heat produced in the reactor core. This heated heavy water is then employed to generate steam, propelling turbines connected to generators for electricity generation [25]. The use of heavy water enables PHWRs to operate with lower uranium fuel enrichment levels, heightening their resistance to proliferation.

A notable strength of PHWRs is their capacity to utilize natural uranium as fuel, reducing dependence on expensive enrichment processes [26]. This characteristic enhances the economic viability of PHWRs, making them an appealing choice for nations with abundant uranium resources. Additionally, employing heavy water for both moderation and cooling results in a more forgiving neutron economy, allowing for flexibility in fueling and operation [27].

PHWRs are recognized for their intrinsic safety features. The combination of pressurized heavy water coolant and passive safety systems ensures steady reactor operation and mitigates the risk of accidents. Moreover, PHWRs excel in dual-purpose applications, producing both electricity and valuable isotopes for medical and industrial uses [28].

Despite these advantages, challenges persist, including concerns about the cost of heavy water production and the management of radioactive waste. Advances in technology and ongoing research endeavors aim to tackle these challenges, ensuring the continual advancement and deployment of PHWRs in the ever-changing energy landscape [29].

1.2.3. Types of Next Generation Nuclear Fission Technologies

Next-generation nuclear fission technologies, particularly those classified as Generation IV reactors, represent a transformative step forward in the field of nuclear energy [30]. These technologies aim to address the limitations of current nuclear systems by enhancing safety, sustainability, and economic viability while minimizing environmental impact. The Gen IV reactors are designed to meet four main goals: sustainability, economic competitiveness, safety, and proliferation resistance [31].

Gen IV reactors are expected to utilize fuel more efficiently, produce less nuclear waste, and offer the potential for recycling spent fuel, thus significantly reducing the environmental footprint of nuclear energy [32]. The safety enhancements in Gen IV reactors are another critical advancement. These reactors are designed to have inherent safety features, such as passive safety systems that do not require human intervention or external power to operate. This greatly reduces the risk of accidents and ensures a very low likelihood of core damage. Additionally, Gen IV reactors aim to eliminate the need for offsite emergency response, further increasing public confidence in nuclear energy.

Small Modular Reactors (SMRs)

Small Modular Reactors (SMRs) are emerging as a transformative solution in nuclear energy, providing an alternative to conventional large-scale reactors. These compact and versatile nuclear reactors offer various advantages, from improved safety features to increased flexibility in deployment and operation [18].

SMRs, characterized by their smaller size and electricity production typically ranging from 1 to 300 megawatts, introduce scalability that allows for modular construction, streamlining manufacturing and reducing initial costs. This modular design also facilitates easier transportation and installation, making SMRs suitable for diverse locations, including remote or off-grid areas.

One of the main benefits of SMRs is their enhanced safety profile. The reduced size inherently mitigates the potential consequences of accidents, and many SMR designs incorporate passive safety features requiring minimal human intervention. Additionally, the option to deploy SMRs underground or underwater further enhances safety and security [33].

SMRs contribute to grid resilience by offering a more flexible and scalable solution to electricity generation. Their modular nature enables incremental capacity additions, allowing for a customized approach to meeting specific energy demands. This flexibility also supports load-following capabilities, effectively responding to fluctuations in electricity demand and complementing intermittent renewable energy sources [34].

The deployment of SMRs holds promise for addressing energy needs in remote or isolated areas, fostering economic development opportunities, and providing a reliable source of clean energy. Furthermore, SMRs can play a crucial role in industrial applications, such as supplying heat for various processes, contributing to a more sustainable and diversified energy landscape [35].

While SMRs offer numerous advantages, challenges persist, including regulatory frameworks, public perception, and standardization. Overcoming these challenges requires collaborative efforts among industry stakeholders, policymakers, and the public to ensure the successful integration of SMRs into the global energy mix [36].

Fast Neutron Reactors (FNRs)

Fast Neutron Reactors (FNRs) exemplify a pioneering stride in nuclear energy innovation, presenting an advanced method for tapping into the potent energy of fast neutrons to generate electricity. In contrast to traditional thermal neutron reactors, FNRs operate with high-speed neutrons, yielding distinct advantages in efficiency, fuel utilization, and nuclear waste management [37].

A defining characteristic of FNRs lies in their utilization of fast neutrons with energies exceeding 1 MeV to sustain nuclear fission reactions. This attribute allows for a more effective deployment of nuclear fuel, as fast neutrons possess the capacity to transmute fertile materials into fissile isotopes, broadening the spectrum of fuel options beyond conventional uranium isotopes. Consequently, FNRs hold the promise of significantly reducing nuclear waste and contributing to a more sustainable nuclear fuel cycle [38].

Among the noteworthy designs in the FNR domain is the Sodium-cooled Fast Reactor (SFR). SFRs leverage liquid sodium as a coolant, optimizing heat transfer efficiency and enabling the utilization of fast neutrons. The inherent features of SFRs enhance their ability to operate at elevated temperatures, thereby increasing thermal efficiency and providing versatility in power generation [39].

FNRs also present advantages in their breeding capability. By producing more fissile material than they consume, FNRs have the potential to function as self-sustaining fuel factories, extending the lifespan of nuclear fuel resources. This capability addresses concerns related to resource availability and augments the overall sustainability of nuclear power [40].

Furthermore, FNRs contribute to nuclear non-proliferation initiatives. The fast neutron spectrum inherently minimizes the risk of generating weapons-grade material, rendering FNRs an appealing option for countries seeking a secure and proliferation-resistant nuclear energy solution. While promising, challenges persist in the development and deployment of FNRs, including technological intricacies, safety considerations, and economic viability [41].

Liquid Fluoride Thorium Reactors (LFTRs)

Liquid Fluoride Thorium Reactors (LFTRs) mark a groundbreaking advancement in the pursuit of advanced and sustainable nuclear energy[37]. By leveraging thorium and a liquid fluoride salt as both fuel and coolant, these reactors promise a safer, more efficient, and proliferation-resistant alternative to conventional uranium-based nuclear reactors.

In contrast to traditional counterparts, LFTRs utilize thorium as the primary fuel, a naturally abundant material. Through a breeding process, thorium transforms into fissile uranium-233, sustaining the nuclear fission chain reaction. This feature allows LFTRs to maximize fuel resources and significantly diminish long-lived radioactive waste [42].

The liquid fluoride salt coolant in LFTRs serves dual roles, efficiently transferring heat generated by fission reactions and facilitating fuel circulation. The liquid nature enhances heat transfer and temperature control, minimizing accident risks and bolstering overall safety [43].

A prominent safety feature of LFTRs lies in their inherent negative temperature coefficient of reactivity. As temperatures rise, the reactor's reactivity decreases, creating an automatic feedback mechanism that prevents overheating and ensures self-regulation. This passive safety feature enhances LFTR resilience to potential accidents, marking a significant improvement in nuclear reactor safety [44].

Molten Salt Reactors (MSRs)

Molten Salt Reactors (MSRs) emerge as a pioneering frontier in nuclear energy, introducing a paradigm shift in power generation. These reactors utilize a liquid blend of salts as both the fuel and coolant, bringing forth a multitude of advantages in terms of safety, efficiency, and sustainability [18].

Diverging from traditional nuclear reactors, MSRs employ a liquid fuel composed of fluoride or chloride salts containing fissile material like uranium or thorium. The fluid nature of the fuel allows for superior temperature control and inherent safety features, as the fuel expands with heating, curtailing the risk of overheating and facilitating passive cooling mechanisms. This characteristic significantly bolsters the overall safety of MSRs, mitigating potential severe accidents [45].

MSRs demonstrate exceptional fuel utilization capabilities. The liquid fuel permits online reprocessing, enabling the continual extraction of fission products and the addition of new fuel components. This not only enhances fuel efficiency but also minimizes nuclear waste, addressing concerns tied to the enduring radioisotopes produced by conventional reactors [46].

A noteworthy MSR variant is the Thorium Molten Salt Reactor (TMSR), which employs thorium as the primary fuel. Thorium, a fertile material, undergoes a breeding process, transforming into fissile uranium-233. This characteristic not only prolongs the availability of nuclear fuel resources but also reduces the risk of nuclear proliferation, as the fissile material produced is less conducive to weapons production [47].

The high operating temperatures achievable in MSRs offer additional advantages, including the potential for high-efficiency power generation and integration with various industrial processes such as hydrogen production and desalination [48].

Accelerator-driven Systems (ADSs)

Accelerator-Driven Systems (ADS) mark a significant leap forward in nuclear fission technology, presenting an innovative approach to bolster safety, diminish nuclear waste, and potentially revolutionize energy production. These systems utilize particle accelerators to propel sub-critical nuclear reactions, offering a promising avenue to address challenges inherent in conventional nuclear reactors [37].

The fundamental concept of ADS involves deploying a high-energy particle accelerator, typically a proton accelerator, to generate a beam of particles that interacts with a sub-critical nuclear target. This interaction initiates controlled fission reactions, sustaining a controlled release of energy. The sub-critical design prevents a self-sustained chain reaction, adding an extra layer of safety compared to traditional reactors [49] [50].

A significant advantage of ADS lies in its potential to transform long-lived radioactive waste into less hazardous isotopes with shorter half-lives. By subjecting nuclear waste to the high-energy particle beam, ADS can facilitate the conversion of specific isotopes, significantly reducing the environmental impact and the duration of nuclear waste storage [51].

Moreover, ADS technology boasts inherent safety features. The sub-critical configuration allows for the swift shutdown of the system by turning off the accelerator, minimizing the risk of uncontrolled reactions or meltdowns. This passive safety characteristic enhances the resilience of ADS to potential accidents, elevating its safety profile [52].

ADS also introduces new prospects for nuclear fuel cycles. Utilizing thorium or other advanced fuel alternatives, ADS has the potential to contribute to a more sustainable and proliferation-resistant nuclear energy landscape. The flexibility in fuel choices and the reduction of long-lived nuclear waste align with the global pursuit of cleaner and safer energy sources [53].

Lead-cooled Fast Reactors

Lead-cooled Fast Reactors (LFRs) are characterized by their use of a fast neutron spectrum, high operating temperatures, and cooling through either molten lead or lead-bismuth eutectic (LBE). These coolants allow for low-pressure operation, possess excellent thermodynamic properties, and are relatively inert when exposed to air or water. The versatility of LFRs includes applications in electricity generation, hydrogen production, and providing process heat. The Generation IV International Forum (GIF) System Research Plan (SRP) outlines concepts such as Europe's ELFR lead-cooled system, Russia's BREST-OD-300, and the US-designed SSTAR system. Additionally, numerous LFR concepts are under development in countries including China, Russia, the USA, Sweden, Korea, and Japan [54].

LFRs excel in materials management due to their operation within the fast-neutron spectrum and use of a closed fuel cycle, which efficiently converts fertile uranium. They can also serve as burners to consume actinides from spent Light Water Reactor (LWR) fuel and as burner/breeder reactors with thorium matrices. The safety of LFRs is enhanced by the use of molten lead as a relatively inert and low-pressure coolant. Lead's abundance ensures its availability even with extensive reactor deployment. Fuel sustainability is further improved by the LFR fuel cycle's conversion capabilities. The use of a liquid coolant with a high boiling point and minimal interaction with air or water provides significant advantages in safety, design simplification, proliferation resistance, and economic performance [55].

Development of LFRs necessitates advancements in fuels, materials performance, and corrosion control [56]. Over the next five years, significant progress is anticipated in materials, system design, and operating parameters. Extensive testing and demonstration activities are ongoing and planned within this timeframe.

Sodium-cooled Fast Reactors (SFR)

The Sodium-cooled Fast Reactor (SFR) utilizes liquid sodium as its coolant, enabling it to achieve high power density with a low volume of coolant and operate at low pressure. The oxygen-free environment within the reactor prevents corrosion, but the sodium must be contained in a sealed system because it reacts chemically with air and water [57].

The closed fuel cycle of the SFR allows for the regeneration of fissile fuel and aids in managing minor actinides [58]. However, this necessitates the development and qualification of recycle fuels for use. Key safety features of the Generation IV SFR include a long thermal response time, a considerable margin to coolant boiling, a primary system that operates near atmospheric pressure, and an intermediate sodium system that separates the radioactive sodium in the primary system from the power conversion system.

Much of the fundamental technology for the SFR has been validated through previous fast reactor programs and is currently being confirmed by the Phenix end-of-life tests in France, the restart of the Monju reactor in Japan, and the lifetime extension of the BN-600 reactor in Russia. New initiatives involving SFR technology include the Chinese Experimental Fast Reactor (CEFR), which was connected to the grid in July 2011, and India's Prototype Fast Breeder Reactor (PFBR), which is planned to achieve criticality in 2013 [58].

The SFR presents an appealing energy solution for countries seeking to optimize limited nuclear fuel resources and manage nuclear waste by closing the fuel cycle [59].

1.3. Barriers for the Commercialization of New Products

The commercialization of new products, particularly those involving sustainable technologies and energy transitions, faces a variety of barriers that can significantly hinder market entry and growth. These challenges are multifaceted, encompassing financial, technological, regulatory, social, and infrastructural aspects. Understanding these obstacles is crucial for developing strategies to successfully bring innovative and sustainable solutions to market.

Financial and Economic Barriers

Financial constraints are among the most significant barriers to the commercialization of new products. Khomenko et al. (2023) emphasize that insufficient funding for research and development (R&D) is a critical issue, particularly in regions where access to capital is limited [60]. This lack of financial resources can delay or even prevent the commercialization of products, as companies struggle to bring their developments to market without adequate investment.

John et al. (2023) further highlight that the high initial costs associated with sustainable technologies, such as renewable energy systems, can be a major deterrent to commercialization [61]. These costs are not limited to the technologies themselves but also include the necessary infrastructure, which can be prohibitively expensive. The financial risks associated with these high upfront costs can make it difficult for companies to secure the necessary funding, especially when the return on investment is long-term and uncertain.

Market dynamics also present significant economic challenges. Brown et al. (2023) note that established market structures, particularly those that favor traditional technologies, create a competitive disadvantage for new products[62]. These market conditions are often reinforced by subsidies and financial incentives that support incumbent technologies, making it difficult for new entrants to compete on equal footing.

Technological and Infrastructural Challenges

The technological readiness of new products is a crucial factor in their successful commercialization. Huang (2021) argues that many emerging technologies are not yet mature enough for broad commercial application [63]. For instance, renewable energy technologies like solar and wind power face challenges related to their intermittent nature and the current limitations in energy storage systems. These technological hurdles can prevent these innovations from being viable in the marketplace, as reliability and consistency are key concerns for potential adopters.

Infrastructural challenges further aggravate these technological issues. Molloy et al. (2020) discuss how the lack of necessary infrastructure, such as charging stations for electric vehicles or sufficient grid capacity for renewable energy, can significantly hinder the commercialization of these technologies [64]. Without the appropriate infrastructure, even the most advanced products may struggle to gain market traction, as they cannot be effectively utilized or integrated into existing systems.

Regulatory and Policy Barriers

Regulatory frameworks play a pivotal role in either facilitating or obstructing the commercialization of new products. Vasylieva et al. (2023) highlight that outdated and inconsistent regulations can create significant hurdles for companies attempting to bring new technologies to market [65]. Regulatory uncertainty increases the risks associated with commercialization, as companies may face unanticipated compliance costs or delays due to shifting regulatory requirements.

Moreover, the lack of supportive government policies presents a significant barrier to commercialization. Rontanini et al. (2020) emphasize that without financial incentives, such as subsidies or tax breaks for sustainable technologies, it is challenging for new products to compete with established alternatives [66]. Government support is often crucial for reducing the financial risks associated with bringing new technologies to market, and its absence can delay or even prevent commercialization efforts.

Social and Cultural Barriers

Social acceptance and cultural attitudes are critical factors influencing the commercialization of new products. Al-Emran and Griffy-Brown (2023) observe that cultural resistance to new technologies can significantly impede their market adoption [67]. In many cases, communities and consumers may prefer traditional products and practices, which creates a substantial barrier to the commercialization of more sustainable alternatives.

Molloy et al. (2020) also discuss how social norms and a lack of awareness about the benefits of new and sustainable technologies can hinder their commercialization [64]. In regions where traditional energy sources are deeply embedded in the local economy and culture, there may be significant resistance to adopting renewable energy technologies, even if they offer long-term benefits. This resistance can be compounded by misinformation or a lack of understanding of the potential advantages of these new products, making it difficult for companies to successfully commercialize their innovations.

The commercialization of new products, particularly those involving sustainable technologies and energy transitions, faces complex and interrelated barriers. Financial constraints, technological challenges, regulatory obstacles, and social resistance all play significant roles in limiting the market success of these innovations. Overcoming these challenges requires coordinated efforts, including supportive policies, technological advancements, and strategies to increase public awareness and acceptance. Addressing these barriers is essential for successfully bringing innovative and sustainable products to market, where they can contribute to broader economic and environmental goals.

1.4. Knowledge Gap

1.4.1. Nuclear Fission

The advancement of next-generation fission technologies holds significant promise for addressing global energy demands in a sustainable and efficient manner. Given the urgent need to transition to clean energy sources, understanding the commercialization processes of these advanced technologies is crucial.

Extensive research has been conducted on various aspects of next-generation fission technologies, including technological innovations, safety improvements, and environmental impacts. For instance, the ”Advanced Nuclear Reactors: Technology Overview and Current Issues” (2019) report provides a comprehensive overview of technological advancements, highlighting significant improvements in safety and efficiency[68]. Additionally, studies such as ”Sustainable and Safe Nuclear Fission Energy” (2012) explore the environmental benefits and potential risks associated with these technologies[69].

Despite the wealth of research on technical and environmental aspects, a significant gap remains concerning the commercialization timelines of these next-generation technologies. Reviewed studies fail to provide a comprehensive analysis of the stages involved in bringing advanced nuclear technologies from ideation to market readiness. While Marques (2010) [70] and Till (1999) [71]discuss reactor designs and safety features extensively, they do not address the practical timelines for commercialization. Similarly, reports by the International Atomic Energy Agency emphasize safety and sustainability but omit detailed commercialization processes[72].

1.4.2. Barriers for the Commercialization of Next Generation Fission Technologies

Although there is extensive literature on the barriers to commercialization for new products as discussed in section 1.3, there is little to no research focused on the specific challenges of next-generation nuclear fission technologies. The literature covers common issues such as financial constraints, regulatory hurdles, and technological readiness, but these studies do not fully address the unique complexities of nuclear fission, such as stringent safety regulations, public opposition, and long-term environmental concerns.

While the barriers for new products are well-documented across various sectors, the commercialization of nuclear fission technologies involves additional layers of complexity. These technologies face specific regulatory and societal challenges that are not sufficiently explored in the current literature.

While next-generation nuclear fission technologies show great potential, there is a clear gap in research on their commercialization timelines and specific barriers and strategies employed to overcome them. This paper focuses on addressing these gaps.

1.5. Research Question

This thesis focuses on the commercialization of next-generation nuclear fission technologies. In light of the rising demand for energy throughout the world, it is imperative that we comprehend and advance these technologies in order to secure a stable and sustainable energy future. With this thesis, the aim is to answer the following research question:

What are the commercialization timelines of next-generation nuclear fission technologies, and how have different companies navigated the barriers and opportunities in this process?

- What are the commercialization stages and timelines for next-generation nuclear fission technology companies, and how do these timelines compare across the industry?
- What barriers have next-generation nuclear fission technology companies encountered during their commercialization journey, and how have these barriers impacted their timelines?
- What successful strategies have companies used to overcome barriers and achieve commercialization, and how have these strategies evolved over time?

2

Research Methodology

In this research methodology section, two complementary approaches are described to gather and analyze data: primary research and secondary (desk) research. Primary research involved direct data collection through interviews with industry experts and stakeholders to gain firsthand insights. Secondary research, or desk research, involved the systematic review of existing literature, reports, and other relevant documents to contextualize findings and build on existing knowledge in the field.

2.1. Desk Research

2.1.1. Commercialization Stages

The methodology for this research was structured to provide a comprehensive analysis of the stages of commercialization. The approach involved systematically identifying and evaluating relevant literature to establish a well-rounded understanding of the commercialization process.

Data collection

1 - Sources

- Google Scholar
- ScienceDirect
- IEEE Xplore

These databases were selected for their extensive coverage of topics related to product development, innovation management, and commercialization processes.

2 - Keyword Search

- Stages of commercialization
- Commercialization process
- Technology commercialization
- Product development life-cycle
- New product development process
- Phases of commercialization

Data Analysis

The selected literature was carefully examined to identify the key stages of the commercialization process. This approach provided a theoretical foundation for understanding how commercialization stages are articulated across different sources. However, to ensure that the identified stages are also valid for the commercialization of nuclear fission technologies, these stages were subsequently validated through expert interviews with industry professionals from leading nuclear fission companies. The experts confirmed that the stages identified in the literature align well with the commercialization paths observed in nuclear fission projects.

This dual approach—combining desk research with validation from industry experts—ensures that the commercialization stages identified are robust and applicable to the context of next-generation nuclear fission technologies.

2.1.2. Commercialisation Timeline Analysis for Nuclear Fission

Search Strategy

The search strategy employed for this desk research involved the identification of next generation nuclear fission companies through systematic online research. The following steps were taken to gather a comprehensive list of companies:

1 - Search Engines: The primary search engine used was Google, chosen for its extensive database and ability to return relevant results from a wide range of sources[73].

2 - Keywords and Phrases: Specific keywords and phrases were employed to capture a broad spectrum of companies involved in next generation nuclear fission technologies. The search terms included:

- ”Companies using next generation nuclear fission technologies”
- ”Nuclear fission startups”
- ”Startups”
- ”Energy”
- ”Nuclear fission”
- ”Innovative nuclear energy startups”
- ”Advanced reactor technologies companies”
- ”Emerging nuclear fission companies”

3 - Search Process: Multiple searches were conducted using the above keywords and phrases. The results were meticulously reviewed, and relevant companies were noted.

This approach allowed for the identification of a broad and varied list of companies involved in next generation nuclear fission technologies, providing a comprehensive starting point for further analysis.

Selection Criteria

Following the identification of 38 companies through the search strategy, a filter was applied to narrow down the list to a smaller number of companies for detailed analysis. The selection criteria were as follows:

1 - Activity Level: To ensure the relevance and currency of the companies, the activity level of each company was assessed. This was determined by evaluating:

- **Website Updates:** The company’s official website was checked for recent updates. Key indicators of activity included recent news articles, press releases, blog posts, and any updates on ongoing projects or technological advancements[74].
- **LinkedIn Presence:** The company’s LinkedIn profile was examined to assess recent activity. Factors considered included recent posts, updates, job advertisements, and the activity of the company’s employees.

2 - Field of Operation: To focus the scope of the review, companies were filtered based on their field of operation. Those companies engaged in design and manufacturing or research and development of next generation nuclear fission technologies were considered. Companies operating solely in other fields (e.g., consultancy, policy advocacy, etc.) were excluded from the subset.

The final list was narrowed down to 10 companies that met the criteria of being a research and development or manufacturing company along with them being active and current in their operations and public communications. By applying these selection criteria, the review focused on companies that are currently engaged in significant activities within the next generation nuclear fission sector.

Data Extraction and Analysis

Once the final list of 10 companies was established, the next steps involved detailed data extraction and analysis:

1 - Company Profiles

- **Basic Information:** For each of the 10 selected companies, basic details such as company name, location and founding year were documented.
- **Technology and Products:** Descriptions of the nuclear fission technologies and products developed by each company were compiled. This included types of reactors, unique technological innovations, and any proprietary processes or materials.
- **Funding and Investment:** Information on funding rounds, amounts raised, key investors, and strategic partnerships was collected. This provided insight into the financial health and backing of each company.
- **Projects and Milestones:** Major projects, milestones, and achievements were recorded.

2 - Timeline Mapping

- **Founding to Present:** A chronological timeline from the founding date of each company to the present was created, highlighting significant events and milestones[75].
- **Technological Milestones:** Key technological milestones were mapped, including prototype developments, technological validations, and advancements in reactor designs.
- **Announced Collaborations and Market Entry**: Information on market entry, including commercial deployments and partnerships with energy providers was recorded which was found from company press releases.

3 - Comparative Analysis

- **Comparative Timelines:** Timelines of all 10 companies were compared to identify common patterns, trends, and outliers. This included analyzing the average time taken from founding to key milestones such as prototype development, regulatory approval, and market entry[76].
- **Milestone Correlations:** Correlations between technological milestones, regulatory approvals, and funding rounds were examined to understand how these factors interact and influence each other.

This methodology ensures a comprehensive and systematic approach to reviewing the commercialization timelines of next generation nuclear fission companies, providing valuable insights into the current state and future prospects of the industry.

2.2. Industry Expert Interviews

2.2.1. Barriers faced and Strategies used for Nuclear Fission

The interview process involves the following steps:

- **Identification of Experts:** The expert interviews involved approaching professionals with extensive experience in next-generation nuclear fission technologies. Participants included senior engineers, project managers, R&D directors, and top executives (such as CEOs and CTOs) from relevant companies, as well as specialists from organizations like the International Atomic Energy Agency (IAEA) and the Nuclear Energy Agency (NEA). These experts, as highlighted in the table 2.1, each with around 10-20 years of experience in the field, were chosen for their deep expertise and valuable insights, which were crucial to gaining a comprehensive understanding of the challenges and strategies involved in commercializing these technologies.
- **Interview Structure:** A semi-structured method was used to guide the interviews. The structure included open-ended questions designed to elicit detailed responses about the barriers these companies face and the strategies they employ to overcome these challenges. Topics covered included technological hurdles, regulatory issues, market acceptance, and operational challenges.

- **Interview Process:** Interviews were conducted via video conferencing tools to ensure convenience and accessibility for all participants. This method allowed flexible scheduling, effectively addressing the logistical challenges of coordinating in-person meetings across various locations. Each interview lasted approximately 60 minutes and was recorded with the consent of the participants for accuracy in data transcription and analysis.
- **Data Analysis:** The interview transcripts were analyzed by thoroughly reading each transcript, identifying key points and recurring themes, and extracting relevant information about barriers and strategies. This information was then categorized and synthesized to provide concise summaries, ensuring accurate representation of the insights from each interview.

	Company Name	Designation	Experience
Expert 1	Seaborg Technologies	Nuclear Licensing Engineer	10 years
Expert 2	Boston Atomics	Chief Executive Officer	9 years
Expert 3	Thorizon	Chief Business Development Officer	16 years

Table 2.1: Expert Details

3

Results

3.1. Results of Desk Research

3.1.1. Commercialization Stages

Commercializing a new product involves navigating a series of crucial steps that transform an initial idea into a fully marketable product. Each step plays an essential role in ensuring that the product is both technically sound and commercially viable. Various experts have identified these stages, providing a clear pathway for successfully bringing innovative products to the marketplace.

Stage 1 - Ideation and Concept Development: The commercialization journey begins with ideation and concept development, where the foundation of the product is laid [77]. This phase focuses on generating and refining ideas that could potentially be developed into successful products. According to Ulrich and Eppinger (2015), this stage is vital for identifying promising opportunities that align with market demands. Activities in this phase typically include brainstorming, conducting market research, and performing feasibility studies to ensure the concept addresses a genuine market need [78].

Stage 2 - Design: Once a solid concept is in place, the next step is to move into the design phase [79]. This stage is where the idea takes a more concrete form, as the product's features, functionality, and overall design are carefully crafted. Cooper (1990) underscores the importance of this phase, which sets the technical specifications and lays the groundwork for subsequent stages of development and production. A well-executed design process is essential to ensure the product can be efficiently manufactured and meets the necessary quality standards [77].

Stage 3 - Prototyping: The transition from design to production involves the creation of a prototype [80]. In the prototyping stage, a working model of the product is developed, allowing for testing and refinement. Jolly (1997) emphasizes that prototyping serves as a critical bridge between the design phase and full-scale production. This stage is characterized by iterative testing, where the prototype is evaluated and modified based on user feedback and technical performance.

Stage 4 - Production and Launch Preparation: Once the prototype has been perfected, the process advances to production and launch preparation [81]. This stage involves setting up the necessary manufacturing systems and preparing the product for its market debut. Smith and Reinertsen (1991) highlight the need for careful planning during this phase to ensure that production can scale up efficiently while maintaining high quality. Additionally, this stage includes finalizing the supply chain, developing marketing strategies, and establishing distribution channels to support a successful product launch [82].

Stage 5 - Market Entry and Commercialization: The commercialization phase is where the product is officially introduced to the market [80]. During this stage, the product's launch strategy is executed, sales efforts are initiated, and production is scaled to meet consumer demand. Jolly (1997) notes that this stage is crucial for testing the product's viability in the marketplace. Effective marketing, competitive pricing, and the ability to quickly respond to market feedback are key factors in ensuring successful commercialization [82].

Stage 6 - Post-Launch Evaluation and Improvement: The final step in the commercialization process is the post-launch evaluation and improvement phase [78]. After the product has been launched, it is essential to monitor its market performance and make necessary adjustments. Crawford and Di Benedetto (2011) describe this stage as crucial for gathering customer feedback, analyzing sales data, and optimizing the product or marketing strategies. Continuous improvement during this phase is vital for sustaining the product's success in the market and ensuring long-term growth [77].

The commercialization process involves a series of critical steps, each designed to ensure that a product is both market-ready and capable of achieving commercial success. From the initial ideation and design to market entry and post-launch optimization, these stages help manage the risks associated with bringing new products to market. By following this structured approach, businesses can enhance their chances of successfully commercializing their products and achieving sustained market success.

3.2. Results of Commercialization Timeline Analysis for Nuclear Fission

3.2.1. Selected Companies and their Timelines

Table 3.1: Next Generation Nuclear Fission Companies

Company Name	Technology Used	Country
Newcleo	Lead-cooled and SMR	UK
Kairos Power	Fluoride salt-cooled high temperature reactor	USA
Seaborg Technologies	Molten salt reactor	Denmark
Thorizon	Molten salt reactor	Netherlands
Oklo	Liquid-metal-cooled, metal-fueled fast reactor	USA
Stellaria	Molten salt reactor	France
X-energy	Gas Cooled Reactors	USA
TerraPower	Nuclear Fast Reactors	USA
NAAREA	Molten salt reactor	France
Boston Atomics	Modular, Integrated, Gas-cooled, High Temperature Reactor	USA

Newcleo

Country of Origin : United Kingdom
Field of Operation : Research and Development
Type of Technology : Lead-cooled and SMR
Current stage of Commercialization : Design

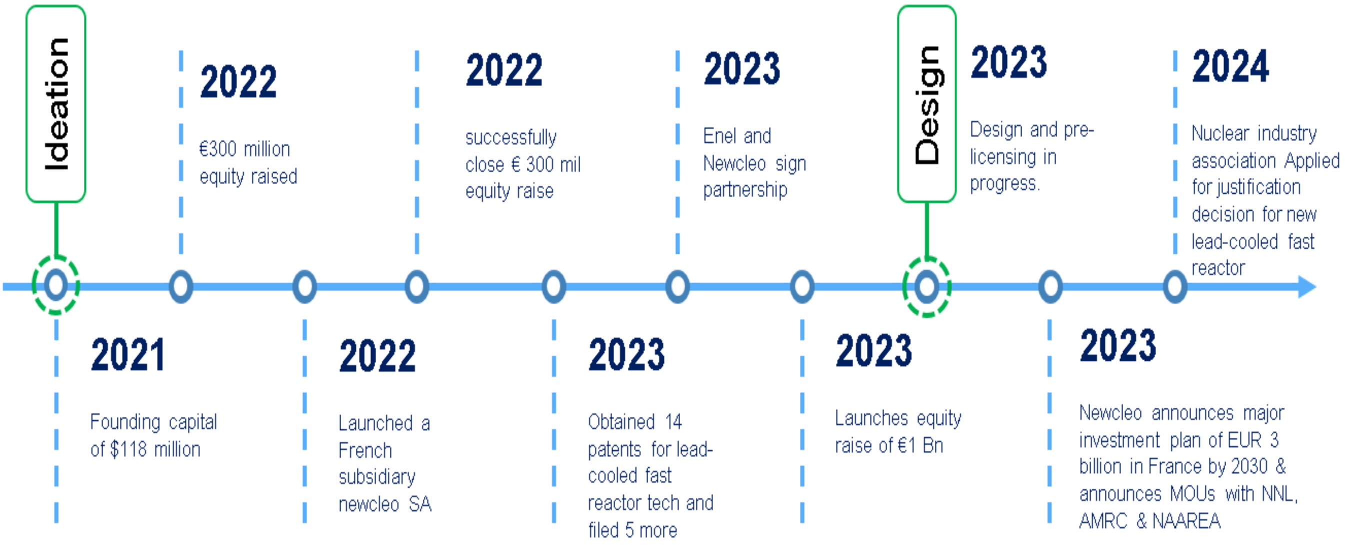


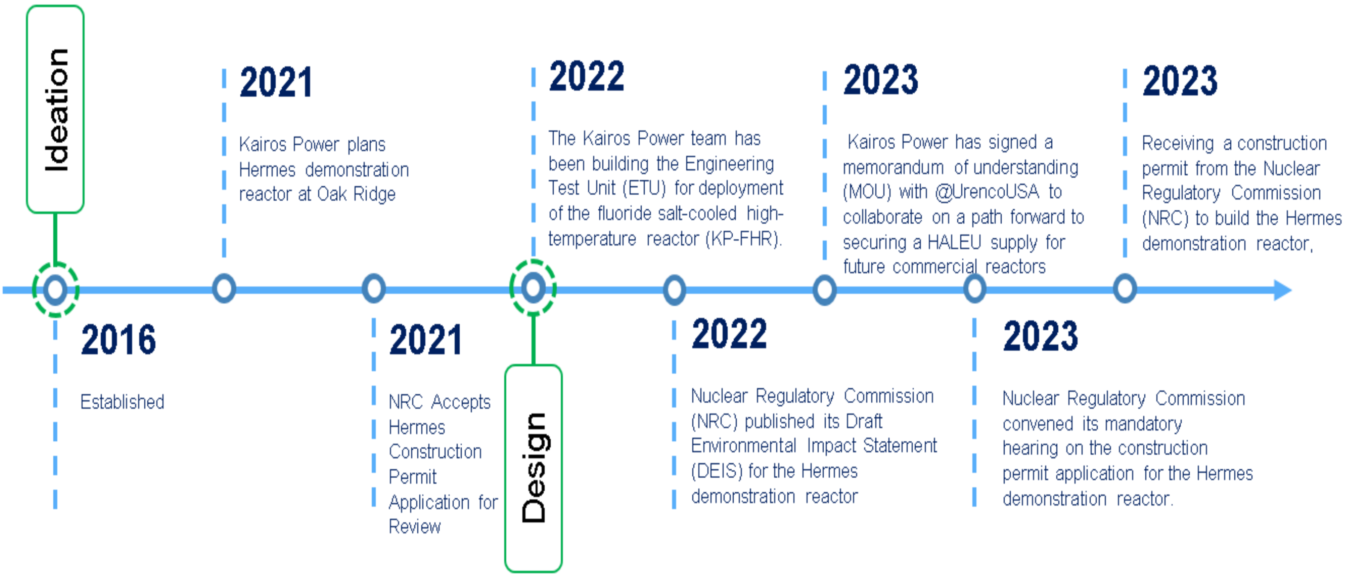
Figure 3.1: Newcleo's Timeline [83] [84] [85]

Newcleo began its journey in the Ideation and Research phase with a solid foundation, securing $118 million in initial capital. The company quickly moved forward, successfully raising an additional €300 million in equity and launching a French subsidiary, Newcleo SA. These early financial successes laid the groundwork for their ambitious plans in developing Lead-cooled Fast Reactors (LFRs), a technology they have protected with a robust portfolio of international patents [86].

Currently, Newcleo is in the Design and Development stage, where they are making significant progress. They have launched an equity raise of €1 billion and have signed strategic partnerships, including one with Enel and another with the UK's National Nuclear Laboratory (NNL). Additionally, they have announced a major investment plan of €3 billion in France by 2030, aiming to commission a 30 MWe reactor. The company has also formed a strategic partnership with NAAREA and has submitted a justification decision application for their LFR-AS-200 reactor to the UK Nuclear Industry Association, marking a critical step towards regulatory approval.

Kairos Power

Country of Origin : USA
Field of Operation : Research and Development
Type of Technology : Fluoride salt-cooled High Temperature Reactor
Current stage of Commercialization : Design



2016 Established

2021 Kairos Power plans Hermes demonstration reactor at Oak Ridge

2021 NRC Accepts Hermes Construction Permit Application for Review

2022 The Kairos Power team has been building the Engineering Test Unit (ETU) for deployment of the fluoride salt-cooled high-temperature reactor (KP-FHR).

2022 Nuclear Regulatory Commission (NRC) published its Draft Environmental Impact Statement (DEIS) for the Hermes demonstration reactor

2023 Kairos Power has signed a memorandum of understanding (MOU) with @UrencoUSA to collaborate on a path forward to securing a HALEU supply for future commercial reactors

2023 Nuclear Regulatory Commission convened its mandatory hearing on the construction permit application for the Hermes demonstration reactor.

2023 Receiving a construction permit from the Nuclear Regulatory Commission (NRC) to build the Hermes demonstration reactor,

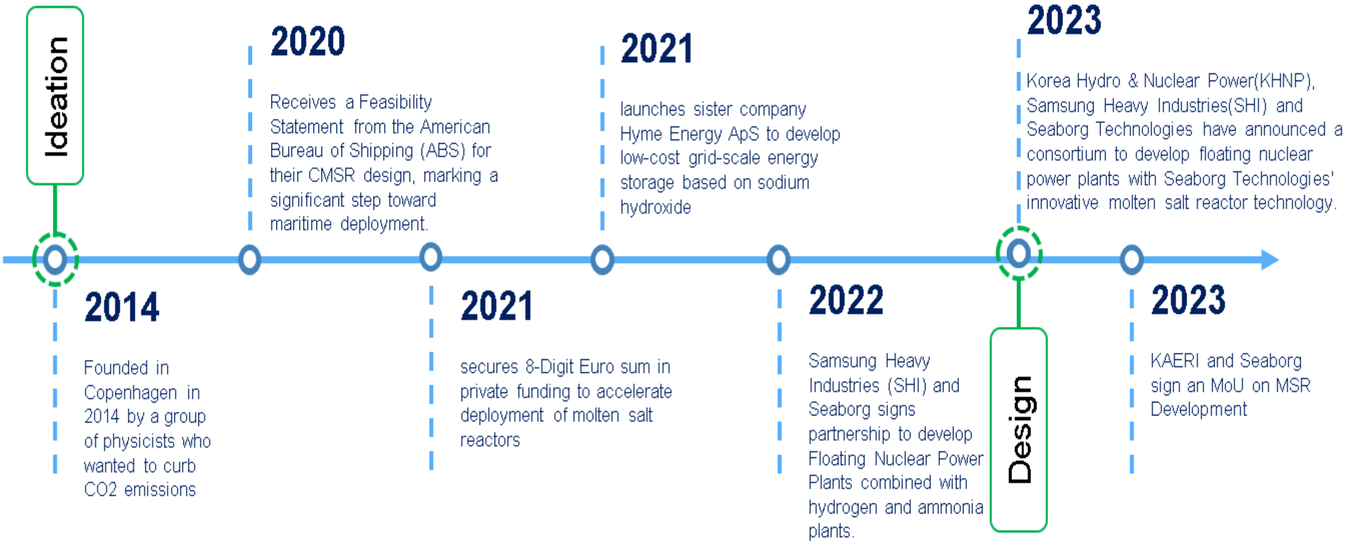
Figure 3.2: Kairos' Timeline [87] [88] [89] [90] [91]

Kairos Power started in the Ideation phase in 2016, focusing on developing Fluoride Salt-Cooled High-Temperature Reactors (FHRs). A significant milestone was the establishment of the Hermes demonstration reactor, which is crucial for proving their technology's viability. Their strategic approach to progressing from research and design to practical applications has been supported by forming key partnerships and advancing technical projects [92].

Now in the Design stage, Kairos Power is actively working on bringing their reactor technology closer to market readiness. They have secured a federal grant and established partnerships that are vital for the development and testing of their reactors. Their journey reflects a careful balance between innovative technology development and strategic collaboration, setting the stage for future commercialization.

Seaborg Technologies

Country of Origin : Denmark
Field of Operation : Research and Development
Type of Technology : Molten Salt Reactor
Current stage of Commercialization : Design



2014

Founded in Copenhagen in 2014 by a group of physicists who wanted to curb CO2 emissions

2020

Receives a Feasibility Statement from the American Bureau of Shipping (ABS) for their CMSR design, marking a significant step toward maritime deployment.

2021

secures 8-Digit Euro sum in private funding to accelerate deployment of molten salt reactors

2021

launches sister company Hyme Energy ApS to develop low-cost grid-scale energy storage based on sodium hydroxide

2022

Samsung Heavy Industries (SHI) and Seaborg signs partnership to develop Floating Nuclear Power Plants combined with hydrogen and ammonia plants.

2023

Korea Hydro & Nuclear Power(KHNP), Samsung Heavy Industries(SHI) and Seaborg Technologies have announced a consortium to develop floating nuclear power plants with Seaborg Technologies' innovative molten salt reactor technology.

2023

KAERI and Seaborg sign an MoU on MSR Development

Figure 3.3: Seaborg Technologies' Timeline [93] [94]

Seaborg Technologies, founded and Ideated in 2014 in Copenhagen, with focus on exploring compact molten salt reactors. In 2020, they achieved a major milestone by obtaining a Feasibility Statement, validating the practicality of their reactor technology. This achievement allowed Seaborg to transition to more advanced stages of development [95].

Currently, Seaborg is in the Design and Development stage, where they are actively working on transforming their conceptual designs into deployable technologies. The company's journey has been marked by strategic partnerships and a steady progression from research to development. They are well-positioned to bring their innovative reactors to market, with continued focus on meeting both technological and regulatory standards[96].

NAAREA

Country of Origin : France
Field of Operation : Research and Development
Type of Technology : Molten Salt Reactor
Current stage of Commercialization : Design

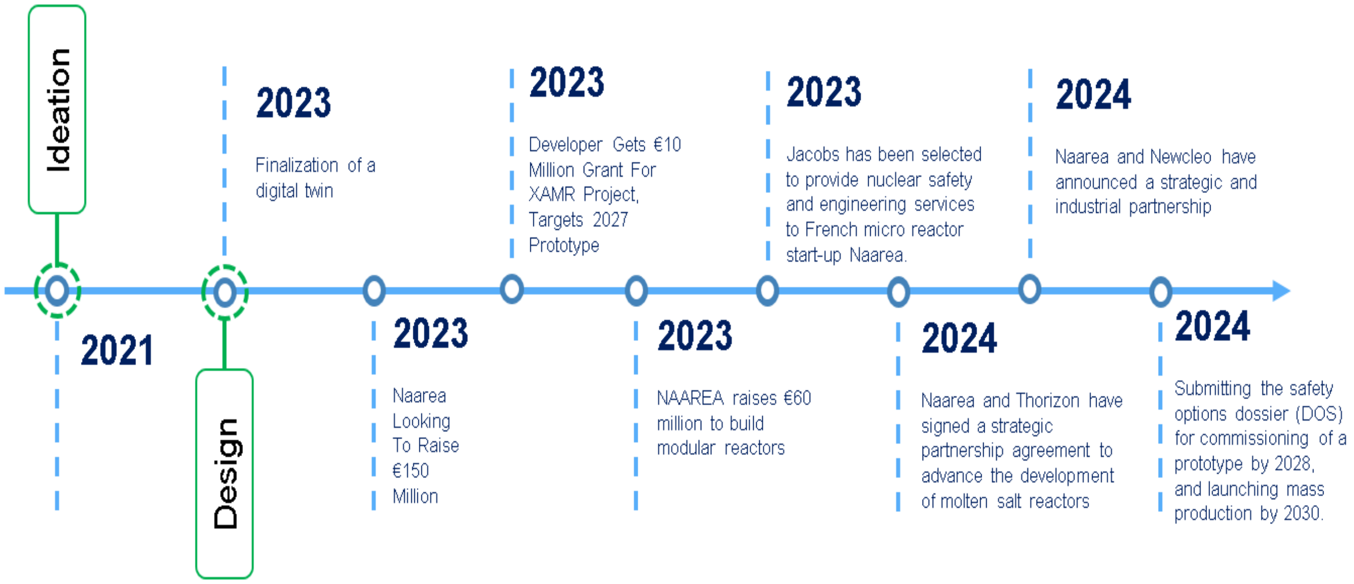


Figure 3.4: NAAREA's Timeline [97] [98] [99] [100] [101] [102] [103]

NAAREA started its journey in the Ideation & Research phase in 2021, focusing on innovative nuclear technologies. By 2023, they had progressed to the Design & Development stage, moving from research to more tangible developments. NAAREA's journey has been marked by steady progress, with a focus on ensuring their technology is both innovative and practical [104].

Currently, NAAREA is refining its designs and preparing for the next stages of commercialization. Their strategic approach to development reflects a commitment to thorough research and careful planning, ensuring that their technologies are ready for the market. As they continue to develop, NAAREA is likely to engage in partnerships to support their growth and expansion in the nuclear sector.

Thorizon

Country of Origin : Netherlands
Field of Operation : Design and Manufacture
Type of Technology : Molten Salt Reactor
Current stage of Commercialization : Ideation

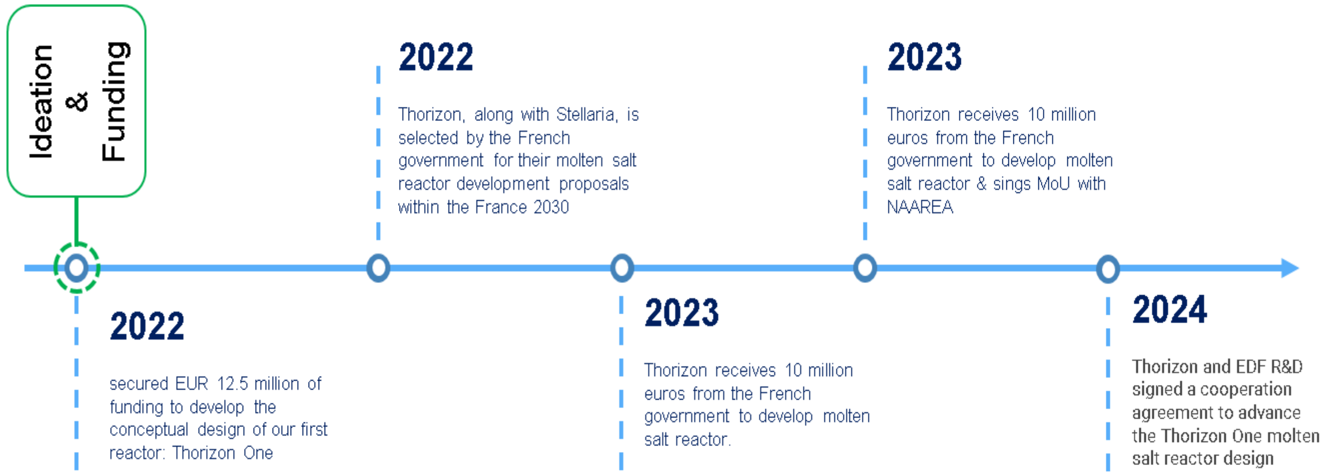


Figure 3.5: Thorizon's Timeline [105] [106] [107] [97] [108]

Thorizon's journey began in the ideation and funding phase, where they secured EUR 12.5 million in funding, enabling significant advancements in their work on molten salt reactors. The company has formed strategic partnerships, notably with Stellaria, to leverage mutual strengths in reactor development. These collaborations have been crucial in overcoming technical challenges and pushing forward their reactor designs.

Currently, Thorizon is moving towards Design & Development stage, refining their molten salt reactor technology and preparing for commercialization. Their journey highlights the importance of strategic funding and collaboration, which have been key to their progress. Thorizon is focused on ensuring their reactors are both technologically advanced and market-ready, positioning themselves for future success.

Oklo

Country of Origin : USA
Field of Operation : Research and Development
Type of Technology : Liquid-metal-cooled, Metal-fueled Fast Reactor
Current stage of Commercialization : Design

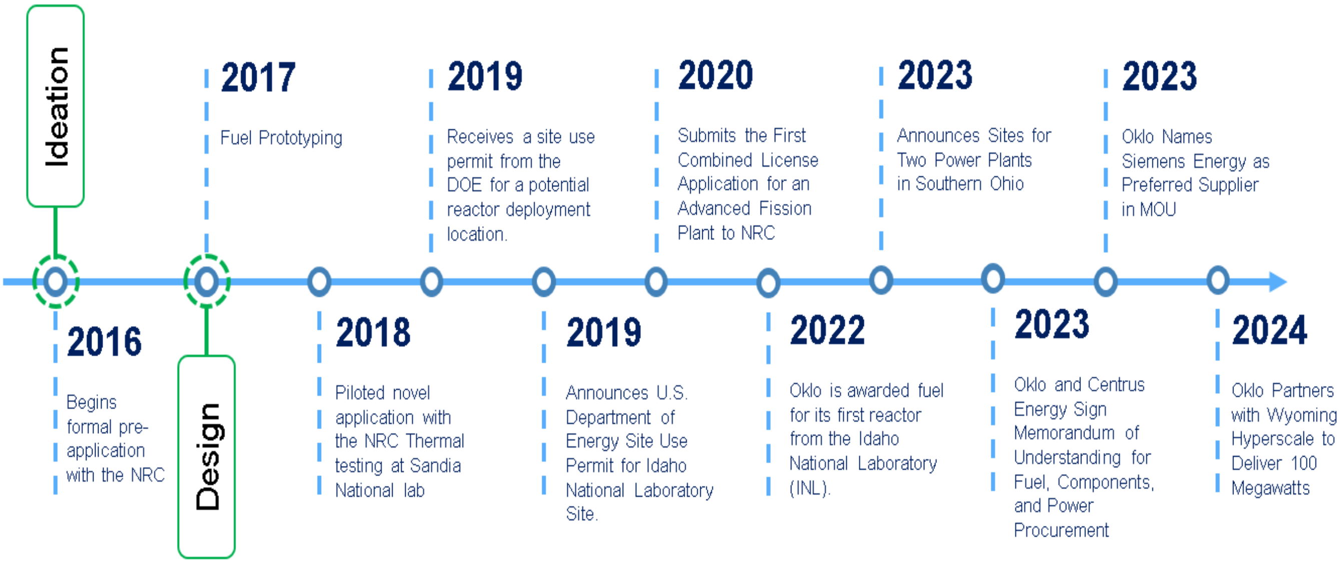


Figure 3.6: Oklo's Timeline [109] [110] [111]

Oklo entered the nuclear sector in the Ideation phase in 2016, with a strong focus on regulatory engagement from the outset. They began the pre-application process with the NRC early in their journey, laying the groundwork for future regulatory compliance. This proactive approach allowed Oklo to address regulatory challenges while still in the ideation stage, setting them up for smoother development [112].

Now in the design stage and moving towards prototyping, Oklo is focused on developing fuel prototypes, a critical step in advancing their fission reactors. Their journey has been characterized by a meticulous approach to both technology and regulatory requirements, ensuring that they are well-prepared for commercialization. Oklo's strategy of early regulatory engagement combined with technical development has positioned them as a forward-thinking player in the nuclear industry.

Stellaria

Country of Origin : France
Field of Operation : Research and Development
Type of Technology : Molten Salt Reactor
Current stage of Commercialization : Ideation

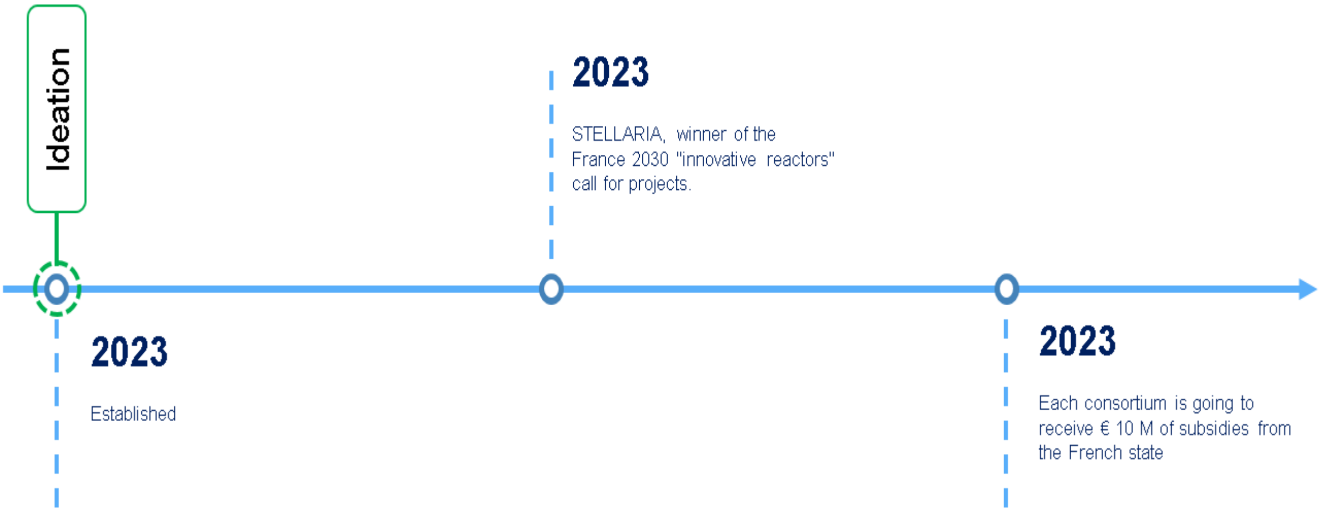


Figure 3.7: Stellaria's Timeline

Stellaria, established in 2023, began in the Ideation phase and quickly gained recognition by winning the France 2030 innovation competition. This early success provided both validation and resources, enabling Stellaria to accelerate its development efforts. The company's journey has been marked by significant milestones, including securing €10 million in subsidies from the French government [113].

Stellaria remains in the Ideation phase but is making rapid progress towards more advanced stages of commercialization. Their strategic focus on innovation and early recognition suggests that they are well-prepared for future growth and development in the nuclear sector. Stellaria's early achievements position them as a promising player in the industry.

X-Energy

Country of Origin : USA
Field of Operation : Research and Development
Type of Technology : Gas Cooled Reactors and SMR
Current stage of Commercialization : Prototyping

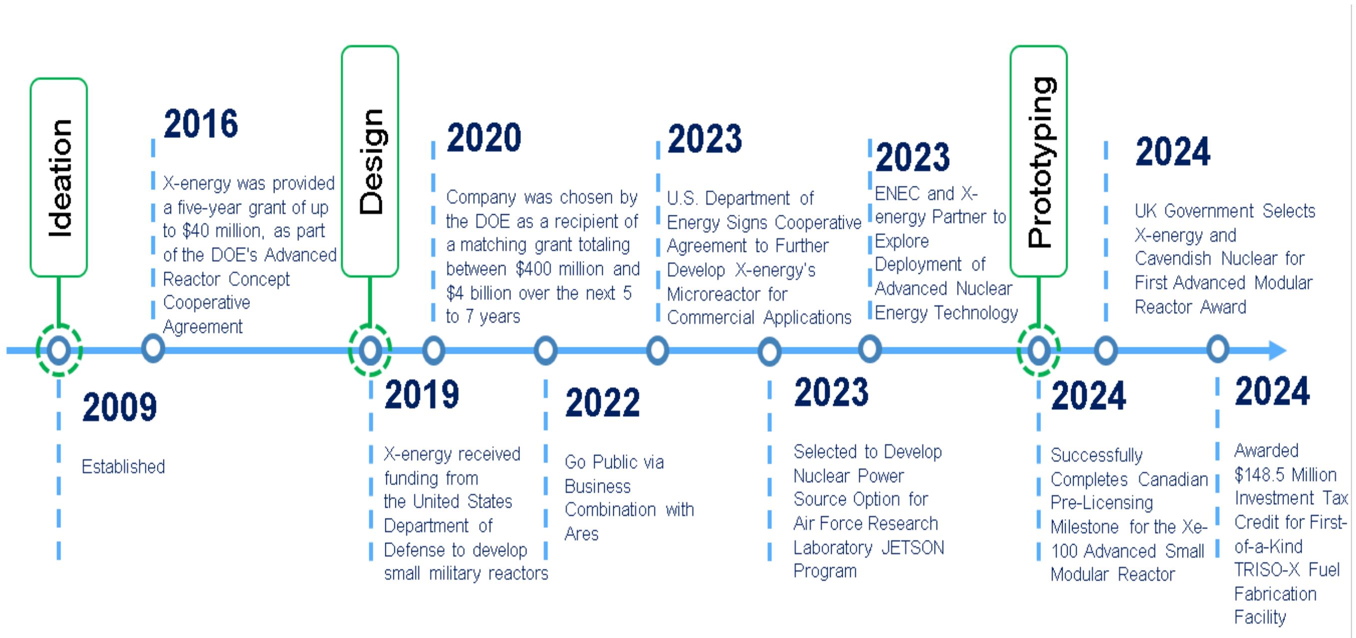


Figure 3.8: X-Energy's Timeline [114] [115]

X-Energy, founded in 2009, started in the Ideation phase with a focus on developing innovative nuclear reactor designs. A significant milestone was securing a five-year funding initiative in 2016, which provided crucial support for advancing their reactor technology. Over the years, X-Energy has formed partnerships and achieved several milestones, including signing agreements with the U.S. Department of Energy and completing pre-licensing milestones in Canada [116].

Currently in the Development Prototyping stage, X-Energy is focused on bringing their reactor designs closer to practical application. Their journey has been characterized by strategic investments in both research and development, ensuring that their technologies are commercially viable. X-Energy continues to advance its reactors with the support of key partnerships and federal funding, positioning themselves for future success.

TerraPower

Country of Origin : USA
Field of Operation : Research and Development
Type of Technology : Nuclear Fast Reactors
Current stage of Commercialization : Design

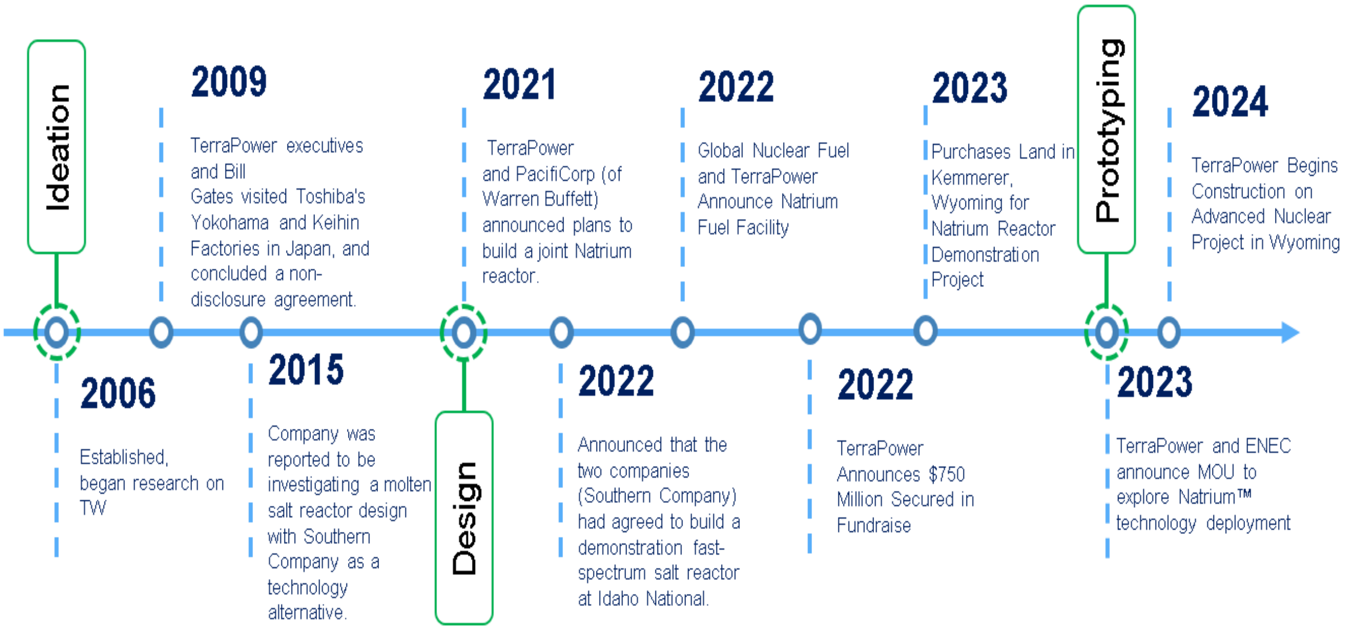


Figure 3.9: TerraPower's Timeline [117]

TerraPower's journey began in 2006 in the Ideation phase, focusing on the Traveling Wave Reactor (TWR), a revolutionary nuclear reactor design. Over the years, TerraPower has made significant progress in research and development, and have been focused on developing Nuclear Fast Reactors in the 2010s [118].

Today, TerraPower is in the Development & Design stage, and moving strongly towards Prototyping stage, working on bringing their next generation reactor technology closer to market readiness. In September 2015, TerraPower entered into an agreement with the China National Nuclear Corporation to construct a prototype 600 MWe reactor unit in Xiapu, Fujian province, China, slated for development between 2018 and 2025. Initial plans included the construction of commercial power plants generating approximately 1150 MWe by the late 2020s. Their journey has been marked by a long-term commitment to innovation and strategic partnerships. TerraPower's focus on advanced reactor designs and sustained research efforts has positioned them as a leader in the nuclear technology sector.

Boston Atomics

Country of Origin : USA
Field of Operation : Research and Development
Type of Technology : Modular, Integrated, Gas-cooled, High Temperature Reactor
Current stage of Commercialization : Design

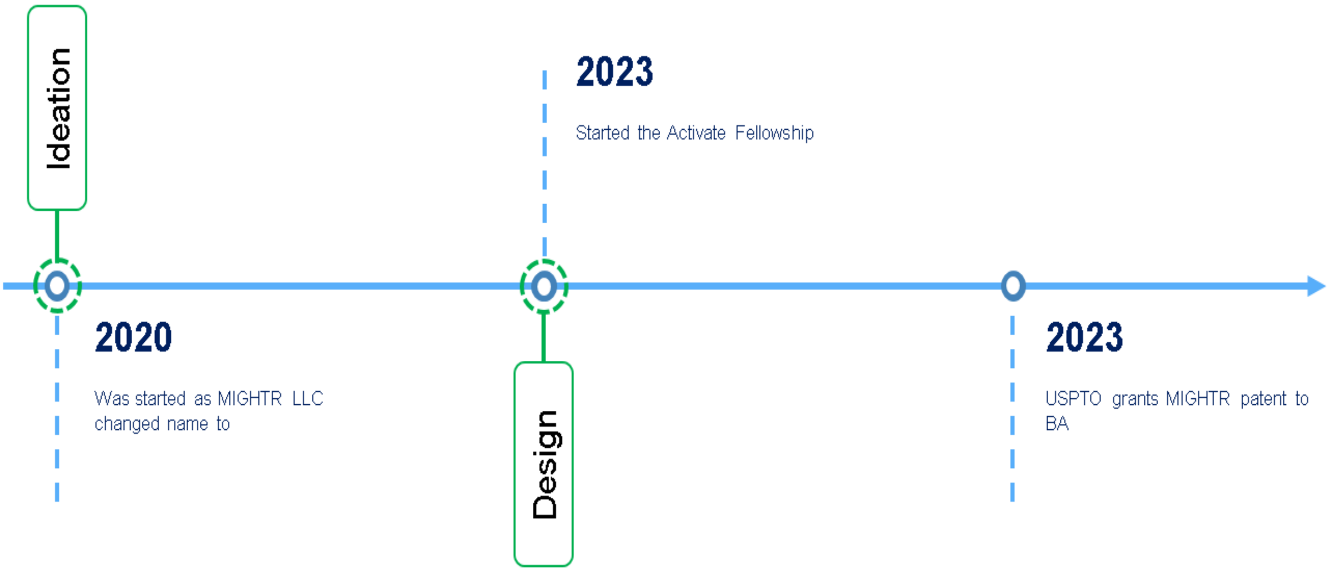


Figure 3.10: Boston Atomics' Timeline [119] [120]

Boston Atomics, initially started as MIGHTR LLC in 2020, began in the Ideation & Research phase. The company's journey included a strategic rebranding and participation in the Activate Fellowship in 2023, which provided resources and visibility needed to advance their work. A key milestone was the granting of a patent by the U.S. Patent and Trademark Office (USPTO), which has been pivotal in shaping Boston Atomics' path towards commercialization [121].

Currently in the Design & Development stage, Boston Atomics is focused on refining their reactor designs and preparing for prototyping. Their journey reflects a commitment to innovation, supported by strategic partnerships and intellectual property protection. Boston Atomics is positioning itself as a forward-thinking company in the nuclear sector, with a clear path towards bringing their technology to market.

3.2.2. Comparative Analysis

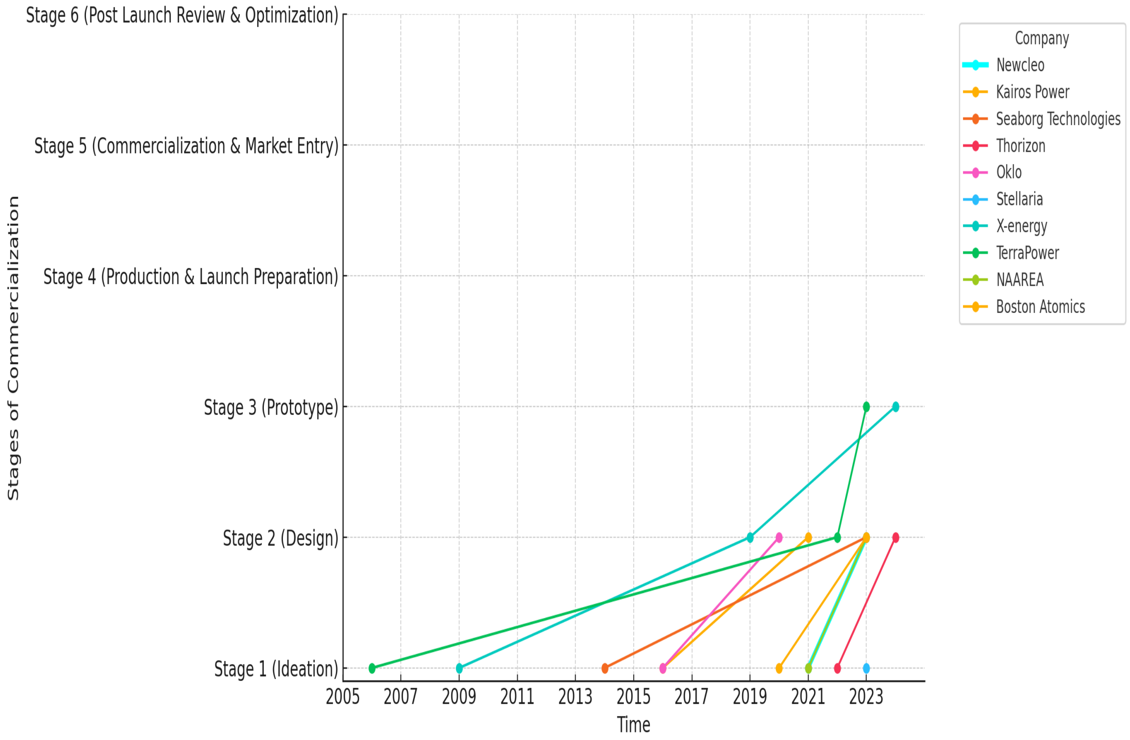


Figure 3.11: Timeline Comparison

The line chart in the figure 3.11 provides a comparative analysis of the commercialization timelines for selected nuclear fission companies. The y-axis represents the stages of commercialization—Ideation, Design, Prototype, Production & Launch Preparation, Commercialization & Market Entry and Post launch Review & Optimization —while the x-axis shows time. Each company's progression through these stages is illustrated with distinct lines. Several companies, such as TerraPower, NAAREA, and Stellaria, initiated their ideation phases much earlier than others, around the early 2000s. In contrast, companies like Newcleo and X-energy began their ideation phases closer to 2010 and 2015, respectively. This indicates a wide range in the starting points for commercialization efforts within the nuclear fission sector.

1 - Early Stages of Development:

- Many companies began their ideation phases at different times, reflecting a broad range of starting points. Early starters like TerraPower and X-energy began in the early 2000s, while newer entrants like Newcleo and Stellaria started closer to 2010 and 2015.
- Companies such as Oklo and Kairos Power initiated their commercialization processes around 2016, and Boston Atomics in 2020, demonstrating a mid-range starting point compared to the earliest and latest entrants.

2 - Transition to Design & Development:

- The transition from ideation to design often occurred within a few years, with many companies clustering around the mid-2010s. This stage includes securing funding, forming strategic partnerships, and obtaining regulatory approvals. For instance, Thorizon and NAAREA leveraged government programs and partnerships to advance their projects.
- Significant milestones like securing construction permits, as seen with Kairos Power, and extensive design work, such as Seaborg Technologies' collaboration with Samsung Heavy Industries, mark this critical phase.

3 - Prototype Development:

- Fewer companies have reached the prototype stage. Notable examples include X-energy and

TerraPower, which are progressing into the 2020s. This stage requires significant investment and collaboration with regulatory bodies and industry partners.

- TerraPower's purchase of land in Wyoming and commencement of advanced nuclear projects demonstrate concrete steps towards building prototype reactors.

4 - Funding and Strategic Partnerships:

- Funding is crucial for progress. Companies like Seaborg Technologies and Newcleo have raised substantial capital. Strategic partnerships with industry leaders and government bodies play a pivotal role, as seen with TerraPower's collaboration with PacifiCorp and X-energy's engagement with the U.S. Department of Defense.
- Newcleo's strategic alliances with Enel and the National Nuclear Laboratory, along with their substantial equity raises, underscore the importance of financial and collaborative support.

5 - Market Positioning and Future Plans:

- Companies are positioning themselves to address specific market needs, such as clean energy solutions and advanced reactor designs. This strategic positioning helps in attracting investment and forming valuable partnerships.
- Future plans include ambitious projects like Newcleo's investment plan in France to develop Small Modular Reactors (SMRs) and TerraPower's ongoing construction of the Natrium Reactor Demonstration Project, indicating strong forward momentum.

The commercialization timelines of nuclear fission companies show varied progress across ideation, design & development, and prototype stages. Early starters like TerraPower and X-energy have made significant strides, reaching advanced stages of prototype development, while newer entrants like Newcleo and Stellaria are rapidly advancing through initial stages with robust funding and strategic partnerships. Common strategies such as securing patents, government support, and forming industry alliances are pivotal in overcoming challenges and accelerating the commercialization process. This consolidated analysis underscores the dynamic and evolving landscape of nuclear fission technology development, driven by innovation, collaboration, and strategic investment.

3.3. Results of Barriers and Strategies

The following section synthesizes insights from interviews conducted with experts from Seaborg Technologies, Boston Atomics, and Thorizon. The interviews aimed to identify the barriers faced during the commercialization of next-generation nuclear fission technologies, the strategies employed to overcome these barriers, and the anticipated future challenges.

3.3.1. Barriers Faced During Commercialization

1. Regulatory Challenges:

- All three experts pointed to the complex and variable regulatory landscape as a major barrier. Expert 1 noted that the licensing process for innovative nuclear technologies is particularly difficult due to regulators' familiarity with traditional reactor designs, which leads to delays.
- Expert 2 emphasized the differences in regulatory requirements across regions, complicating the global deployment of these technologies. Expert 3 added that each market imposes its own stringent rules, further complicating the commercialization process.

2. Financial Constraints:

- The high capital costs associated with developing and deploying advanced nuclear reactors were another major challenge identified by the experts. Expert 1 discussed the difficulty in securing continuous funding due to the long-term nature of nuclear projects.
- Expert 2 emphasized the substantial initial investment required, which is a deterrent for many potential investors. Expert 3 also mentioned the challenge of attracting investments given the long timelines for returns, making nuclear projects less appealing compared to other energy technologies with quicker payback periods.

3. Public Perception and Political Support:

  - Public skepticism and opposition to nuclear energy were significant hurdles identified by all three experts. Expert 1 explained that public perception heavily influences national policies and the success of nuclear projects.
  - Expert 2 discussed how negative public opinion, shaped by past nuclear incidents, creates challenges in gaining support for new nuclear technologies. Expert 3 emphasized that despite advancements in safety and efficiency, public skepticism remains a barrier that affects both policy decisions and investment opportunities.
  - Changes in political leadership and policies can create additional barriers, affecting regulatory and financial support for nuclear projects.

4. **Technological Challenges:**
   - The readiness of materials and the need for long-term data to validate the safety and effectiveness of new reactor designs were discussed by Expert 1.
   - Expert 2 noted that a general barrier in the design stage for fission technologies is the lack of sufficient data on the long-term durability of materials, particularly alloys used in reactors. This impacts the ability to secure long operational licenses. Additionally, there are challenges with the development of welding technologies necessary for high-temperature applications, which are critical for the next generation of reactors.
   - Expert 2 also pointed out gaps in manufacturing capabilities, particularly for complex components like helical coil steam generators, and the challenge of developing sufficient enrichment capacity for advanced fuels. Expert 3 highlighted the need for thorough system integration and testing before full-scale deployment, presenting a significant technical challenge.
5. **Market Trends:**
   - There is a growing interest in zero-carbon power from major companies, which boosts market demand for nuclear energy mentioned by expert 1. However, local acceptance can be a hurdle when it comes to specific sites.

3.3.2. Strategies Used to Overcome Barriers

1. **Proactive Regulatory Engagement:**
   - Early Proactive engagement with regulators is a common strategy across all three interviews. Expert 1 emphasized the importance of working closely with regulators early in the development process to align new technologies with regulatory expectations.
   - Expert 2 discussed collaborating with local and international regulators to ensure compliance and avoid delays. Expert 3 mentioned the need for ongoing dialogue with regulators to navigate the varying requirements across different markets.
2. **Diversifying Funding:**
   - Diversifying funding sources was identified as a key strategy by the experts. Expert 1 discussed generating revenue through consulting, R&D projects, and government grants to sustain operations.
   - Expert 2 highlighted the importance of securing private investments from long-term-oriented investors, including venture capitalists and philanthropists. Expert 3 emphasized the strategy of modular reactor designs, which require lower initial investment and can be deployed more quickly, thus reducing financial risk.
3. **Public and Market Engagement:**
   - Improving public perception through education and transparency is another strategy employed by the companies. Expert 1 mentioned investments in public education efforts to build trust and acceptance of nuclear technology.
   - Expert 2 discussed the importance of transparent communication with both the public and policymakers to mitigate skepticism. Expert 3 highlighted the need to focus on markets with more favorable public opinion towards nuclear energy, which can facilitate smoother deployment.

4. Technological Innovation:

- Continuous innovation and validation of technology are crucial strategies. Expert 1 discussed focusing on safety advancements, such as passive safety systems, to reduce risks and improve public and regulatory acceptance.
- Expert 2 highlighted the development of modular reactor designs that are not only cost-effective but also quicker to deploy.
- Efficient Waste Management: Implementing advanced fuel cycles and waste treatment technologies to reduce the volume and toxicity of nuclear waste addresses one of the major public concerns, as mentioned by expert 2.

5. Strong Management and Organizational Structure:

- Building a Competent Team: Expert 3 mentioned that assembling a management team with diverse expertise to manage different aspects of the company effectively.
- Strategic Partnerships: All experts also believe that engaging with political stakeholders and forming strategic partnerships to gain visibility and support.

3.3.3. Anticipated Future Barriers

The anticipated future barriers in the development and commercialization of next-generation nuclear fission technologies, as discussed by the experts, cover a wide range of technical, regulatory, financial, and societal challenges.

Expert 1 from Seaborg Technologies pointed out that a significant future challenge lies in the regulatory landscape. As nuclear technologies evolve, the regulatory frameworks must adapt to accommodate new designs and safety features. However, the pace of regulatory adaptation is slow, and this could delay the approval and deployment of advanced reactors. The expert emphasized that the motivation and capability of regulators to support these new technologies might not keep pace with technological advancements, creating a potential bottleneck in commercialization efforts.

Expert 2 from Boston Atomics highlighted several technical barriers that are anticipated to emerge in the future. One of the major concerns is the readiness of materials for long-term reactor operation. While current materials and welding techniques might be sufficient for initial phases, they are not fully qualified for the extended lifetimes required for advanced reactors. The lack of long-term data on these materials could hinder the ability to obtain licenses for reactor operation. Additionally, the expert noted that manufacturing capabilities, especially for components like high-temperature gas reactor heat exchangers, have not been maintained or advanced in recent decades. This gap in manufacturing expertise is expected to be a significant challenge as the industry attempts to scale up production of these advanced systems. The development of specialized fuels, such as high-assay low-enriched uranium (HALEU) and TRISO fuel, also presents future barriers, as the current supply chains for these materials are not yet fully established.

Expert 3 from Thorizon discussed the financial and organizational barriers that are likely to arise as next-generation nuclear technologies move towards commercialization. One of the key challenges is securing the substantial investment required for full-scale deployment. While early-stage funding may be available, the larger capital needed for commercial projects will be harder to obtain, particularly given the uncertainty in return on investment due to long development cycles. The expert also mentioned the difficulty in making strategic technological choices under conditions of uncertainty, such as selecting the right materials for reactor components, which could have long-term implications for reactor performance and safety. Additionally, the expert highlighted the potential for political and social challenges, as public and governmental support for nuclear energy can be volatile. Changes in political leadership or public opinion could introduce new barriers, such as opposition to reactor siting or changes in funding priorities.

By understanding these barriers and employing strategic approaches, companies in the next-generation nuclear fission sector can navigate the complex landscape of commercialization, contributing significantly to sustainable energy solutions.

Tables 3.1 and 3.2 summarize key insights from expert interviews regarding the commercialization of next-generation nuclear fission technologies. Table 3.1 highlights the barriers, distinguishing between those commonly agreed upon by all experts and unique points raised by individual experts. Similarly,

Table 3.2 presents the strategies discussed, showcasing both widely recommended approaches and those suggested by only one expert. These tables provide a clear overview of both shared and distinct challenges and strategies in the field.

Table 3.2: Table 1: Common and Unique Barriers in the Commercialization of Nuclear Fission Technologies

Common Barriers	Unique Barriers
Regulatory Challenges: All experts mentioned difficulties with navigating the complex regulatory environment, which includes obtaining approvals and meeting safety standards.	Expert 1: Discussed the challenges with the public perception of nuclear energy, which impacts funding and support.
Funding and Capital Investment: All experts agreed that securing sufficient and sustained funding is a significant barrier due to the high costs and long timelines.	Expert 2: Highlighted the lack of qualified materials and manufacturing capabilities for advanced reactors, particularly for specialized components like heat exchangers.
Technological Maturity: All experts pointed out that the technology for next-generation reactors is not fully matured, which leads to delays and increased costs.	Expert 3: Mentioned the difficulty in finding suitable locations for reactors, which impacts site selection and development timelines.

Table 3.3: Table 2: Common and Unique Strategies for Overcoming Barriers in Nuclear Fission Technologies

Common Strategies	Unique Strategies
Collaboration with Government and Industry: All experts stressed the importance of partnerships with government bodies and other industry players to share knowledge, pool resources, and gain regulatory support.	Expert 1: Focused on improving public engagement and education to shift public perception positively.
Diversified Revenue Streams: All experts mentioned the strategy of generating revenue through consulting, R&D services, or government grants while developing the core technology.	Expert 2: Emphasized the need to invest in materials research and manufacturing capabilities to ensure that the supply chain can meet the demands of advanced reactors.
Phased Development Approach: All experts recommended a phased approach to technology development, starting with smaller, less complex systems before scaling up to full commercial reactors.	Expert 3: Prioritized securing early-stage financing and scaling up the workforce to accelerate development and commercialization efforts.

4

Discussion and Conclusion

4.1. Discussion of Results

The commercialization of next-generation nuclear fission technologies is a complex and multifaceted process. This discussion integrates insights from the commercialization timelines, stages, barriers, and strategies detailed in the literature review and expert interviews to provide a comprehensive understanding of the challenges and approaches in this sector.

4.1.1. Commercialization Timelines and Stages

The commercialization process for nuclear fission technologies, as outlined in the results, follows several key stages: ideation, design, prototyping, production and launch preparation, market entry and commercialization, and post-launch evaluation. These stages align with the general commercialization framework described by Ulrich and Eppinger (2015) and Cooper (1990), who emphasize the importance of structured progression from concept development to market deployment.

The timelines for these stages, however, vary significantly across companies. Early movers like TerraPower and X-energy began their commercialization journey in the early 2000s, reaching advanced stages such as prototyping and even market entry. In contrast, newer entrants like Stellaria and Newcleo, which initiated their projects closer to 2010-2015, are still progressing through the design and early development phases. This disparity in timelines highlights the diverse starting points and strategic approaches adopted by different companies within the nuclear fission sector.

4.1.2. Barriers Faced During Commercialization

The commercialization of nuclear fission technologies is accompanied by several barriers that differ in scale and complexity from those encountered in other sectors, such as sustainable technologies. As discussed by Khomenko et al. (2023), financial constraints are a significant barrier in the commercialization of new products, particularly in sustainable technologies. However, in nuclear fission, these financial challenges are magnified. The high capital costs and long development timelines make securing consistent and substantial funding a daunting task. Expert 2, from Boston Atomics, emphasized the difficulty in attracting long-term investors due to the extended duration before returns can be realized, a challenge less prevalent in quicker-to-market sustainable technologies.

Technological barriers also play a critical role. Brown et al. (2023) note that the technological readiness of new products is crucial for successful commercialization. This is particularly relevant in the nuclear fission sector, where the availability and readiness of specialized materials and manufacturing capabilities are essential yet often lacking. Expert 1, from Seaborg Technologies, highlighted the challenge of developing and validating new reactor designs that not only meet technical specifications but also adhere to strict safety standards. The need for continuous innovation and technological validation, as underscored by the experts, is a significant hurdle that extends commercialization timelines and complicates the path to market readiness.

Regulatory challenges are another significant barrier. Vasylieva et al. (2023) point out that outdated and inconsistent regulations can obstruct the commercialization of new technologies. This is particularly acute in the nuclear sector, where regulatory frameworks are often designed with conventional reactors in mind, making it difficult for innovative technologies to gain approval. Expert 3, from Thorizon, emphasized the complexity of navigating international regulatory environments, where requirements can vary significantly, adding layers of difficulty to the commercialization process.

Social and cultural barriers further complicate commercialization efforts. Molloy et al. (2020) discuss how social acceptance and cultural attitudes can impede the adoption of new technologies, particularly in regions with deep-rooted preferences for traditional energy sources. This is especially relevant in nuclear fission, where public skepticism and political opposition are common due to concerns about safety, waste management, and potential accidents. Expert 2 noted that gaining public trust is a critical challenge, one that requires transparent communication and sustained educational efforts to overcome.

4.1.3. Strategies to Overcome Barriers

The strategies employed to overcome challenges in the commercialization of nuclear fission technologies reflect both expert perspectives and findings from academic literature. Expert 1 highlighted the critical role of early collaboration with regulatory authorities, which ensures that emerging technologies align with existing regulations, helping to avoid delays. This approach is consistent with the literature, as Vasylieva et al. (2023) discuss how outdated regulatory frameworks often pose barriers to nuclear fission projects. Maintaining a continuous dialogue with regulatory bodies is seen as a crucial step toward smoother approval processes.

In terms of financial strategies, Expert 2 emphasized the importance of securing a mix of funding sources, such as government grants and private investments. Boston Atomics, for instance, has utilized this diversified funding model to manage the long lead times associated with nuclear projects. This approach is supported by Khomenko et al. (2023), who stress the necessity of diversified funding in capital-intensive sectors. John et al. (2023) further highlight how modular reactor designs, with their lower initial costs, can distribute financial risks, a strategy that aligns with Expert 2's experience in securing investments.

When it comes to gaining public support, Expert 3 underscored the importance of targeting regions where nuclear energy is already viewed positively and actively promoting the safety and environmental benefits of new technologies. This aligns with the literature, where Molloy et al. (2020) emphasize the need for transparent communication to build public trust in nuclear energy. Similarly, Brown et al. (2023) argue for clear messaging to address common public concerns regarding nuclear safety and waste management.

Technological innovation is another key strategy for overcoming commercialization barriers. Both Expert 1 and Expert 3 noted that advancements in reactor designs, particularly those incorporating modularity and enhanced safety features, facilitate regulatory approval and improve public confidence. Literature also points to the importance of these innovations, with Huang (2021) stating that advancements in reactor technology are essential for reducing both operational and financial risks, making next-generation reactors more commercially viable.

4.1.4. Linkages Between Timelines, Barriers, and Strategies

In analyzing the commercialization timelines of nuclear fission companies, it becomes evident that the various stages of the process—ideation, design, prototyping, production and launch preparation, market entry, and post-launch evaluation—are intricately linked to the barriers faced and the strategies deployed to overcome them. These stages, as outlined in Section 3.1.1, reveal how different companies manage their timelines based on the specific challenges they encounter, such as financial constraints, regulatory delays, technological uncertainties, and public perception issues.

At the earliest ideation stage, companies like Newcleo and Stellaria grapple with securing the necessary funding and refining their reactor concepts, often contending with financial constraints and technological uncertainty. These barriers can delay progress, but companies that employ strategies such as diversified funding sources—drawing on government grants, private investments, and public-private partnerships—are able to advance more swiftly into the next stages. Seaborg Technologies and X-energy, for instance, have successfully employed this approach, allowing them to shorten their R&D timelines and move quickly to the design phase.

During the design stage, regulatory challenges become prominent. The regulatory landscape for nuclear fission is highly complex, and outdated frameworks often struggle to accommodate innovative reactor designs. Companies like TerraPower and Oklo, which faced extended timelines due to these issues, successfully mitigated delays by employing a strategy of early regulatory engagement. By working closely with regulatory bodies from the outset, they ensured that their technologies aligned with existing requirements, smoothing the transition to the prototyping and production phases. This proactive approach significantly reduced the time spent navigating the regulatory approval process, particularly for newer technologies that pose unique challenges to regulators.

Once companies enter the prototyping stage, the focus shifts to overcoming technological barriers. Developing and testing advanced materials and reactor designs that meet safety and performance standards is a major hurdle at this stage. Companies like Boston Atomics and Kairos Power have encountered delays here due to the complexities involved in reactor development. To address this, many companies have adopted modular reactor designs, which allow them to scale their prototypes incrementally. This approach not only reduces financial risks but also accelerates the prototyping process by focusing on smaller, more manageable designs that can be deployed and tested more quickly. By integrating modularity into their development plans, these companies can navigate both technological and financial constraints more effectively.

As companies prepare for production and market entry, they must contend with public perception issues and market acceptance. The general skepticism surrounding nuclear energy has slowed down political and financial support for companies like Thorizon and Oklo, particularly during their attempts to scale production and enter the market. To counteract this, public education campaigns have been an essential strategy, helping these companies reshape public opinion by highlighting the safety and environmental benefits of their technologies. By improving public perception, these companies have been able to secure broader political backing and financial investment, ensuring a smoother transition to the market. Table 4.1 summarizes the linkage between commercialization stages, barriers and strategies used to overcome them

Ultimately, the commercialization of nuclear fission technologies requires a careful balancing of timelines, barriers, and strategies. The stages of commercialization are not isolated; delays in one stage, such as the design phase due to regulatory challenges, can have a cascading effect on subsequent stages like prototyping and production. However, strategies such as early regulatory engagement, diversified funding, modular reactor designs, and public education campaigns have proven effective in mitigating these delays and helping companies progress more efficiently through the commercialization process. The following table summarizes these interconnections between stages, barriers, and strategies:

Commercialization Stages	**Primary Barriers**	**Key Strategies**	**Example Companies**
Ideation	Financial constraints, Technological uncertainty	Diversified funding sources, Early-stage partnerships	Newcleo, Stellaria
Design	Regulatory delays, Lack of experience with new reactor designs	Early regulatory engagement, Modular reactor designs	TerraPower, X-energy
Prototyping	High testing costs, Technological validation, Regulatory complexity	Modular reactor designs, Public-private partnerships, Strategic technological collaborations	TerraPower, Kairos Power, Oklo
Production & Launch Preparation	Public skepticism, Market acceptance issues	Public education campaigns, Strategic partnerships	
Market Entry	Financial constraints, Regulatory approval hurdles	Public-private partnerships, Diversified revenue streams	
Post-Launch Evaluation	Scaling operational capacity, Market feedback	Continuous product improvement, Public engagement efforts	

Table 4.1: Linkages Between Commercialization Stages, Barriers, and Strategies

4.2. Limitations

While this study provides valuable insights into the strategies for overcoming barriers in the commercialization of nuclear fission technologies, several limitations should be acknowledged. First, the reliance on expert interviews as a primary data source, while beneficial for capturing industry-specific knowledge, introduces a degree of subjectivity. The perspectives of the experts from Seaborg Technologies, Boston Atomics, and Thorizon reflect their individual experiences, which may not fully represent the diversity of views across the broader nuclear industry.

Another limitation is the focus on advanced nuclear fission technologies, which are still in developmental stages. As a result, many of the strategies discussed by the experts, such as technological innovation and regulatory engagement, are speculative and have not yet been widely implemented or tested. This introduces an element of uncertainty regarding the long-term effectiveness of these strategies. Furthermore, the study does not extensively address the role of external factors, such as shifts in government policy or public opinion, which could significantly influence the success or failure of nuclear fission commercialization efforts.

Lastly, the literature review, while comprehensive, is limited by the availability of current research on next-generation nuclear technologies. Given the rapid advancements in this field, the literature may not fully capture the latest technological or regulatory developments, which could impact the applicability of the findings over time. Future research should aim to address these limitations by including a broader range of expert opinions, examining a wider set of nuclear technologies, and considering the evolving landscape of public and governmental attitudes toward nuclear energy.

4.3. Recommendations for Future Research

Future research should focus on developing strategies to align new nuclear technologies with existing regulatory frameworks to expedite approval processes. Comparative studies on regulatory practices across different countries can identify best practices and inform policy recommendations, potentially leading to more harmonized international standards.

Exploring diverse funding sources and innovative financial models is crucial for sustaining the long development timelines of next-generation nuclear technologies. Research should investigate the potential of modular reactor designs and incremental investments to reduce capital costs and attract venture capital. Additionally, examining successful case studies of government and private sector partnerships can provide insights into effective financial strategies. Developing financial instruments that ensure steady cash flow and financial stability throughout the lengthy development process is essential.

Ongoing research and development are vital to address the technical challenges associated with new materials, manufacturing processes, and fuel types. Future studies should prioritize the development of inherent safety features and passive safety systems to minimize risks and reassure regulators and the public. Collaborative research initiatives can accelerate technological advancements and facilitate knowledge sharing across the industry.

Following this research on the commercialization of nuclear fission technologies, future studies should focus on addressing the dynamic nature of regulatory, financial, and social barriers as they evolve over time. A critical next step would be the investigation of how regulatory frameworks can be adapted or reformed to keep pace with the rapid advancements in nuclear technology, particularly for modular reactors and other next-generation designs. Research should also examine how financial models can be optimized to sustain long-term investments, given the lengthy timelines involved in nuclear development. Additionally, understanding how public opinion on nuclear energy shifts in response to broader societal changes and environmental pressures is vital. This would involve more granular, cross-regional studies to assess the varying levels of public acceptance and its impact on policy-making.

To overcome the limitations of this research, further studies should expand the scope of expert interviews to include a wider array of stakeholders, such as policymakers, financial investors, and representatives from the public sector. This would provide a more holistic view of the commercialization challenges. Additionally, future research should focus on empirical case studies of current or near-commercial nuclear fission projects, providing real-world data on the efficacy of the strategies proposed by experts. By grounding theoretical insights in practical experiences, future research can offer more actionable recommendations to accelerate the commercialization of nuclear fission technologies.

4.4. Conclusion

This study has investigated the commercialization of next-generation nuclear fission technologies, focusing on the barriers, strategies, and timelines necessary for their deployment. Through expert interviews and an extensive literature review, key challenges have been identified, including regulatory hurdles, financial constraints, technological uncertainties, and material limitations. These obstacles highlight the complexity of advancing nuclear fission technologies from the conceptual stage to commercial readiness.

Regulatory frameworks were found to be a significant barrier, with experts emphasizing the need for early and continuous engagement with regulatory bodies. The research supports the notion that outdated regulations are slowing down commercialization efforts, and adapting these frameworks to accommodate advanced reactor designs is crucial. Moreover, the financial model for nuclear fission remains a substantial challenge due to the high upfront capital requirements and long payback periods. Modular reactor designs, which promise lower costs and scalability, emerge as a critical focus area for reducing financial risks and attracting investment.

Technological innovation is equally vital, particularly in the development of new materials, advanced safety systems, and manufacturing techniques that can support long reactor lifetimes and meet stringent safety standards. While companies have made progress, with some advancing toward prototype development, the need for further research and empirical data on the performance of these technologies is clear. Real-world case studies of ongoing projects will be essential in validating the proposed strategies.

In conclusion, the successful commercialization of next-generation nuclear fission technologies hinges on overcoming these multifaceted barriers through strategic regulatory alignment, diversified financial models, and continued technological innovation. As global energy needs grow and the demand for low-carbon solutions intensifies, the role of nuclear fission as a sustainable energy source becomes increasingly important. However, the path to widespread adoption remains long, requiring coordinated efforts from industry, policymakers, and the scientific community to realize the potential of these advanced nuclear technologies.

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A

Appendix 1

A.1. List of all the companies selected

A.2. Questionnaire for the industry experts

- What market trends and conditions currently impact the commercialization of nuclear fission technologies?
- What are the most significant barriers your company has faced in developing and deploying next-generation nuclear fission technologies?
- What strategies have you found most effective in overcoming the barriers your company has faced? Can you share specific examples?
- Are there any strategies your company tried that did not yield the desired results? What were the key reasons for their failure?
- What new barriers do you anticipate for next-generation nuclear fission technologies in the coming years?
- How do you perceive the current market acceptance of next-generation nuclear fission technologies? What strategies is your company using to enhance market adoption and public acceptance?
- How are companies addressing challenges related to nuclear waste management, and what innovations are being explored in this area?
- How do advancements in safety features and risk mitigation technologies contribute to the commercial success of nuclear fission?
- How is nuclear technology development and commercialisation different from technology development and commercialisation in general? (i.e. what are the unique challenges)

A.3. Interview Summaries

A.3.1. Interview 1

The interview highlighted several critical barriers faced by next-generation nuclear fission technologies. One of the primary challenges is the complex and often outdated licensing processes, which are heavily rooted in traditional reactor designs. Convincing regulators to adapt to newer technologies requires a significant paradigm shift, which can be slow and resistant to change. This regulatory inertia is compounded by varying levels of government support across different countries, making it difficult to standardize and streamline the licensing process globally. Public perception also poses a substantial barrier; negative attitudes towards nuclear energy in certain regions can influence national policies, limiting market entry and deployment opportunities. Moreover, the high capital costs and long lead times associated with nuclear projects further complicate commercialization efforts, as investors often perceive these projects as high-risk compared to other energy technologies.

In response to these barriers, several strategies have been employed and are being planned for the

Company name	Country
Orano	France
Newcleo	UK
Kairos Power	USA
Seaborg Technologies	Denmark
Phoenix	USA
Transmutex	Switzerland
Thorizon	Netherlands
Blue Wave AI labs	USA
Transatomic Power	USA
Madison metals	Canada
Last Energy	USA
Oklo	USA
Hexana	France
Stellaria	France
Elysium Industries	USA
X-energy	UK
TerraPower	USA
NuScale	USA
Xcel	USA
Holtecinternational	USA
Rolls Royce SMR	UK
Westinghouse Electric Company	USA
Radiant Nuclear	USA
NAAREA	France
Blossom Energy	Japan
Curio LV	USA
Deutelio	Italy
Boston Atomics	USA
Electric fusion systems	USA
Type one energy	USA
Ex-Fusion	Japan
Aalo Atomics	Canada

future. One effective approach is the focus on Small Modular Reactors (SMRs), which aim to reduce capital expenditure and shorten project timelines through modular design and manufacturing. Strategic partnerships with established industrial players are also crucial, as they provide the necessary expertise and credibility to navigate complex regulatory landscapes and gain investor confidence. Companies are increasingly selecting markets with favorable public and governmental attitudes towards nuclear energy to ensure smoother entry and operation. Additionally, innovations in safety features, such as low-pressure systems and advanced fuels, are being prioritized to reduce costs and improve public acceptance. Looking ahead, the continued emphasis on modularization, strategic partnerships, and proactive engagement with regulators and policymakers are seen as key strategies to overcome the existing and anticipated challenges in the commercialization of next-generation nuclear fission technologies.

A.3.2. Interview 2

The interview highlighted several key barriers and strategies relevant to the commercialization of next-generation nuclear fission technologies. The primary challenges identified include regulatory frameworks that are not yet fully adapted to accommodate new reactor designs, leading to a lengthy and complex licensing process. Additionally, public perception remains a significant hurdle, as skepticism towards nuclear energy persists due to historical incidents.

In response to these challenges, the company is actively engaging with regulators to help shape policies that better support the deployment of next-generation reactors. They are also investing in public outreach to educate the public on the safety and benefits of modern nuclear technologies. Technologically, the focus is on modular reactor designs and advanced safety systems, which are intended to reduce risks and make the reactors more economically viable.

Financial barriers are being addressed through partnerships with government entities and private investors who are interested in sustainable energy solutions. The company is also leveraging the modular nature of their reactors to lower initial capital expenditure and scale production more effectively. Looking forward, while regulatory adaptation and public acceptance will remain key challenges, the opportunities for nuclear energy to play a critical role in the global shift towards decarbonization are vast. Advances in reactor technology, particularly in the integration of AI and machine learning, are expected to further enhance the safety and efficiency of these systems.

A.3.3. Interview 3

In this interview, the business development officer outlined several key barriers and strategies related to the commercialization of next-generation nuclear fission technologies. The primary barriers identified include regulatory challenges, financial constraints, and public skepticism. The regulatory environment is complex and varies significantly across regions, which can slow down the approval process. Financially, the high initial investment required for nuclear technology presents a significant challenge, particularly given the long timelines for return on investment. Additionally, public skepticism towards nuclear energy, driven by historical incidents and concerns over safety, remains a significant hurdle.

To address these barriers, the company is engaging proactively with regulators to ensure compliance and smooth the approval process. They are also investing in public education efforts to improve understanding and acceptance of nuclear technology. Financial strategies include diversifying funding sources through private investment, government grants, and strategic partnerships. The company is also exploring modular reactor designs, which can be deployed more quickly and at lower costs, making them more attractive to investors and reducing financial risks. These strategies are aimed at positioning the company as a leader in the evolving market for low-carbon energy solutions, where nuclear fission technology has the potential to play a significant role.