Center for
Advanced Nuclear
Energy Systems

Massachusetts Institute of Technology
77 Massachusetts Avenue, 24-215
Cambridge, MA 02139-4307

(617) 452-2660
canes@mit.edu
canes.mit.edu

Advanced Nuclear Power Program

A Preliminary Study on the Feasibility of Nuclear Batteries for Offshore Power Generation

Emile G. R. Germonpre, and
Jacopo Buongiorno

Department of Nuclear Science and Engineering
Massachusetts Institute of Technology

MIT-ANP-TR-202
November 2024

Executive summary

Nuclear batteries (NBs) are a class of factory-fabricated microreactors (output on the order of a few megawatts) that are transportable and autonomously operated. They promise quick deployment with little site preparation and a small total footprint. In addition, at the end of their multiple-year fuel lifetime, the reactor is shipped to a central facility for refueling and maintenance. Due to their unique features, NBs are a versatile energy platform that can provide energy as a service to customers with a drastically lowered up-front investment compared to traditional nuclear reactors. Figure 1 shows what a NB site looks like.

An application of particular interest for the project sponsors Shell, Equinor, and ExxonMobil using NBs to generate power for Floating Production Storage and Offloading platforms (FPSOs), as the large emissions of the current gas turbine systems pose a risk to their operation. In this context, our work investigates the feasibility of using NBs to produce power for FPSOs. Although the primary focus is on FPSOs, many results can be translated for the general use of NBs for offshore power services.

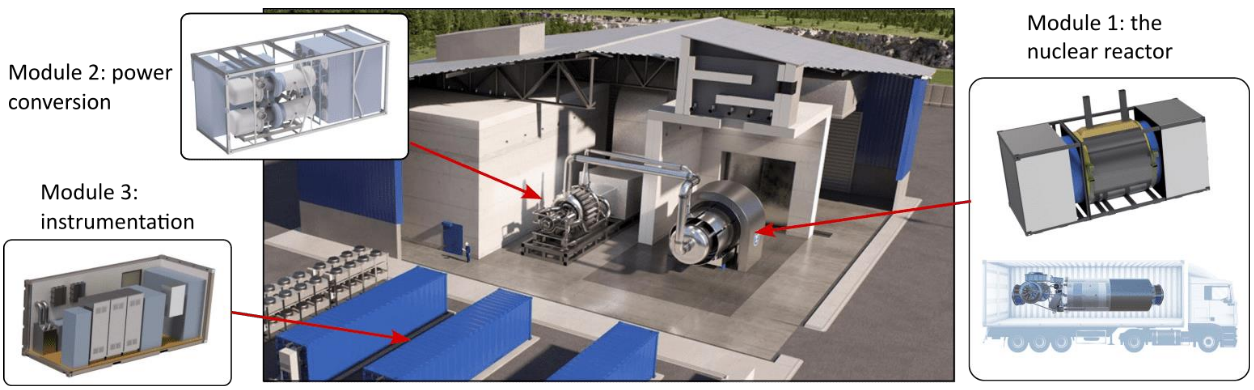


Figure 1 The eVinci site layout rendering [1] annotated to show the typical NB modules

The power system requirements and performance metrics on FPSOs differ significantly from those for onshore power generation. Particularly, there is a need to minimize system weight and footprint as deck area is scarce, and heavy systems require stronger decks and hulls, as well as heavy-duty lifting cranes. In addition, there are important cost drivers beyond the LCOE of a potential low-carbon power system, notably lost production costs, which can outweigh the cost of the alternative power system itself. Moreover, the system must show high reliability for safety reasons and to ensure continuous operation while also ensuring minimal personnel needs for maintenance and operation. Section 2.1 details the many other system requirements and targets. Not all targets of Section 2.1 are treated explicitly in the report, but they underlie the reasoning throughout the work.

Our focus is restricted to three credible commercial NB designs: Westinghouse's eVinci microreactor [2], X-energy's Next-generation Integrated Transportable High-temperature (XENITH) microreactor [3], and BWXT's Advanced Nuclear Reactor (BANR) [4]. We also include an in-house design for a sodium-cooled, graphite-moderated, UO_2-fueled microreactor (referred to in the report as the MIT NB) [5]. The features of these reactors are discussed in Section 3.2.

Additionally, Section 3.1 provides a high-level overview of the opportunities and challenges presented to the microreactor industry, from which it is clear that the NB paradigm is not possible under current regulations. The first generation of microreactors will instead be licensed like traditional reactors and be refueled on-site and maintained on-site [6]. The second-generation microreactors will feature centralized refueling and maintenance but will require significant on-site testing, hindering the "plug-and-play" nature of NBs – which are the third and final generation of microreactors [6].

There is also no regulatory framework that deals with the offshore use of non-LWR reactors for power services – see Section 4.2 for more details. Instead, the current regulations are based on the old Code of Safety for Nuclear Merchant Ships from the International Maritime Organization (IMO) [7] – further referred to as the IMO Code – which is LWR-focused and only deals with propulsion – the impact of which will be further discussed below. Fortunately, the American Bureau of Shipping (ABS) is working on a technology-inclusive classification for power services [8]. However, it will not be adapted to the context of NBs. There is, thus, no near-term regulatory framework that allows for the envisioned use of NBs to supply power to FPSOs.

The intuitive implementation of NBs on the FPSO deck is complicated by various factors – as discussed in Section 4. For starters, there is the immense weight of the NB system that results from the need for a concrete reactor bay to provide radiation shielding and protection from intrusion and aircraft impacts, resulting in weight-to-power ratios that are hundreds of times higher than those of the current gas turbines, see Table 1. Moreover, even under optimistic minimum footprint calculations, the size occupied by the deck-area-to-power ratio of NBs is about ten times that of the current gas turbine systems. Note that these size and weight issues are only further exacerbated by the need for additional onboard structures that provide collision protection mandated by the IMO Code [7]. That optimization of the reactor bay for offshore use might help, but not to the extent needed.

Further adding to the problem, the FPSO's power demands are high relative to the power output of the NBs, resulting in the need for many NBs, see Table 2. For example, a medium-demand FPSO (50 – 60 MWe and 15 – 25 MWth) requires about twelve eVinci reactors, which exceeds the total footprint and weight limits by a factor of 3 and 5.6, respectively. As a result, we judge that high-demand FPSOs cannot be powered by NBs cost-effectively compared to larger-scale technologies, such as Small Modular Reactors, regardless of the size and weight constraints.

Table 1 Total minimal footprint and weight of the current gas turbines and the four NB designs

Design	**Size [m²/unit]**	**Size [m²/MW]**	**Weight [MT/unit]**	**Weight [MT/MW]**	**Bay weight [%]**
Current turbines	100	3 – 5	150- 250	3.3	/
eVinci	150	30	3788	758	95.7
BANR	583	49	/	/	/
XENITH	198	30	4829	732	96.6

MIT NB	159	34	2785	599	94.9

Table 2 The number of NBs needed to service the entire FPSO demand, assuming the utility heat can be supplied by the waste heat of electricity generation or is provided by dedicated NBs (italics). Both cases use an N+1 redundancy sparing.

	Low	**Medium**	**High**
Electrical demand [MWe]	20 – 30	50 – 60	100 – 150
Thermal demand [MWth]	7.5 – 12.5	15 – 25	30 – 45
MIT NB	6 – 8 *6 – 9*	12 – 14 *13 – 16*	23 – 34 *25 – 37*
eVinci	5 – 7 *6 – 8*	11 – 13 *13 – 15*	21 – 31 *24 – 35*
XENITH	5 – 6 *5 – 7*	9 – 11 *10 – 12*	17 – 24 *18 – 26*
BANR	3 – 4 *3 – 4*	6 – 6 *6 – 7*	10 – 14 *10 – 15*

Moreover, the hydrocarbon environment of the FPSO makes providing adequate fire safety highly challenging and presents an important security vulnerability. It is thus challenging to develop an adequate safety and security case for this application – at least without adding many additional engineered safety layers that only increase the system's size and weight.

Another issue lies with replacing the reactors at the end of their fuel lifetime, as the reactor modules are too heavy to be lifted with offshore cranes, and the NBs must be left to cool down before transport, potentially increasing the outage schedule significantly and resulting in lost production. Note that first-generation microreactors must be refueled on deck, which is technically infeasible.

Finally, the on-deck use of the reactor also scores poorly with regard to the cost drivers. For one, there will be large lost production costs due to the installation of the systems (for brownfield) and the rigorous, lengthy testing required in periodic surveys and during commissioning. Furthermore, there could be substantial FPSO retrofit costs due to the diffusion of nuclear safety grade towards FPSO components and potential modifications needed to meet the requirements of the IMO Code [7]. Lastly, there will be an increase in personnel costs due to the additional radiation hazard training and expected increased staffing needs to cover operation, maintenance, and surveying.

Note that the consideration of the aforementioned cost drivers also leads us to recommend to wait until microreactors mature onshore before implementing them for use on FPSOs. This ensures faster installation, higher system reliability, and less on-site testing, all of which help to prevent lost production and reduce personnel burden.

To circumvent the many issues with the on-deck use of the reactors, we propose to house them on a separate power platform located near the FPSO, which is fully detached from it except for a cable to transmit the electric power. The power platform can be either floating or submerged. Detached power platforms enjoy complete design flexibility, allowing design with safety and security in mind and obviating the weight and size constraints that apply to the FPSO. The safety and security case is aided by the decoupling between events on the power platform and the FPSO – notably, fires on the FPSO would not affect the reactors. Furthermore, we expect the detached platforms to save on cost through standardization by avoiding FPSO modification and component replacement and by lowering the personnel cost and lost production. Finally, the detached platforms can easily be used in brownfield as the characteristics of the FPSO do not matter beyond its demand.

On the negative side, we expect there to be excessive motion and fatigue to allow for the use of flexible steam lines to carry heat from the power platform to the FPSO, so electrical heating will be the preferred approach, which adds to cost. Moreover, the power platforms might prove difficult to access in rough weather.

Mechanically attaching the power platform to the FPSO hull would still allow for heat delivery by the NBs through flexible steam lines. However, this approach has many of the same downsides as on-deck use regarding cost drivers and safety and security, so its performance lies between that of the detached platforms and on-deck use. Consequently, we do not recommend this option and suggest using detached platforms with an alternative heat source - or electric heating.

After discarding the attached platform option, we develop high-level designs for a floating barge (Figure 2, left) and a semi-submersible with a fully submerged barge (Figure 3), each housing six eVinci reactors. The designs are such that they maximize platform stability by virtue of a large waterplane area and ensure technical feasibility by mirroring the layout of the onshore eVinci plant. Note that the buoyant stability of each design is verified as it is a prerequisite to acceptable hydrodynamic performance, but further work is needed to ensure acceptable platform stability in rough weather. Also, note that the ballasting of the semi-submersible allows the barge to be resurfaced to replace the reactors at a yard. Moreover, the ballasting is such that the barge floats up if the semi-submersible cylinders are damaged.

However, the initial power platform designs do not satisfy the regulations of the IMO Code, notably the need for a collision-protected, leak-tight safety enclosure around the containment of the reactors. The collision protection results in the prescription of minimal standoff requirements between the safety enclosure and the outer hull, which limits the number of reactors that can fit on the platform to four instead of six, see Figure 2.

Thus, compliance with the old IMO Code increases the platform's size relative to its power output. In addition, it is difficult to justify the large investments needed to develop a custom-built power platform, given the current absence of a market for them. Converting large, existing ships to become power platforms offers a solution to both problems and is most likely the ideal near-term choice. Figure 4 shows the conversion of a small 550 TEU containership. However, if the demand for the NB power platform grows, the cost of developing standardized designs can become preferred, as it avoids individual licensing and can enjoy economies of multiples.

Note that the power platforms could become a versatile energy source used for a variety of applications beyond powering FPSOs, e.g., powering deep sea mining, providing disaster relief to communities that live near the shore, or powering industries as river-going barges.

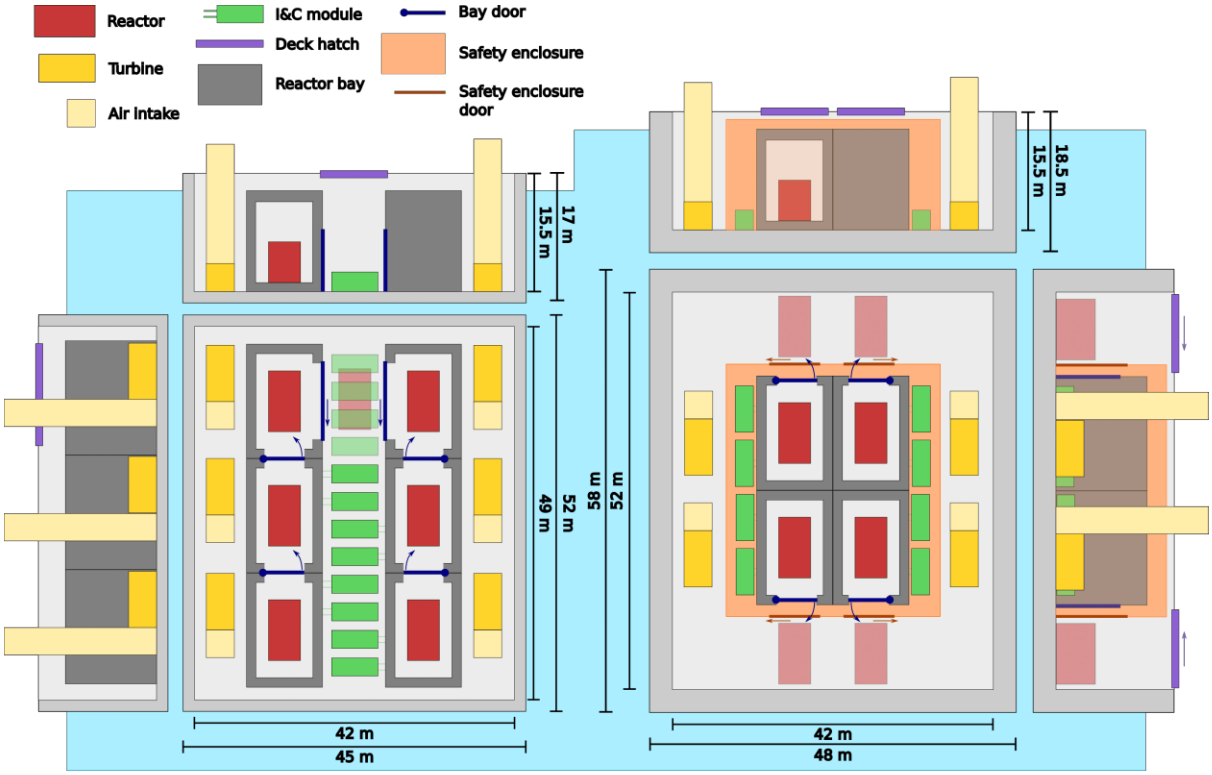


Figure 2 Top-down view (with side views) of two designs for a floating power platform that houses eVinci NBs. The left design does not comply with the IMO Code regulations for collision protection of the safety enclosure, whereas the right design does. All elements are drawn to scale

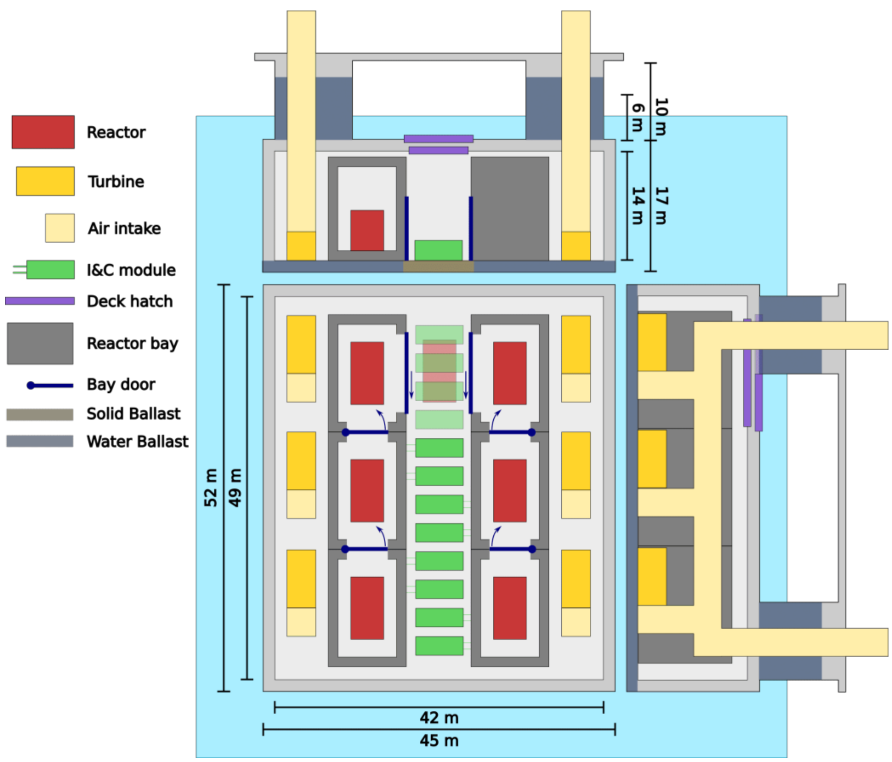


Figure 3 Top-down view (with side views) of a semi-submersible design for a power platform that houses six eVinci NBs; elements are drawn to scale

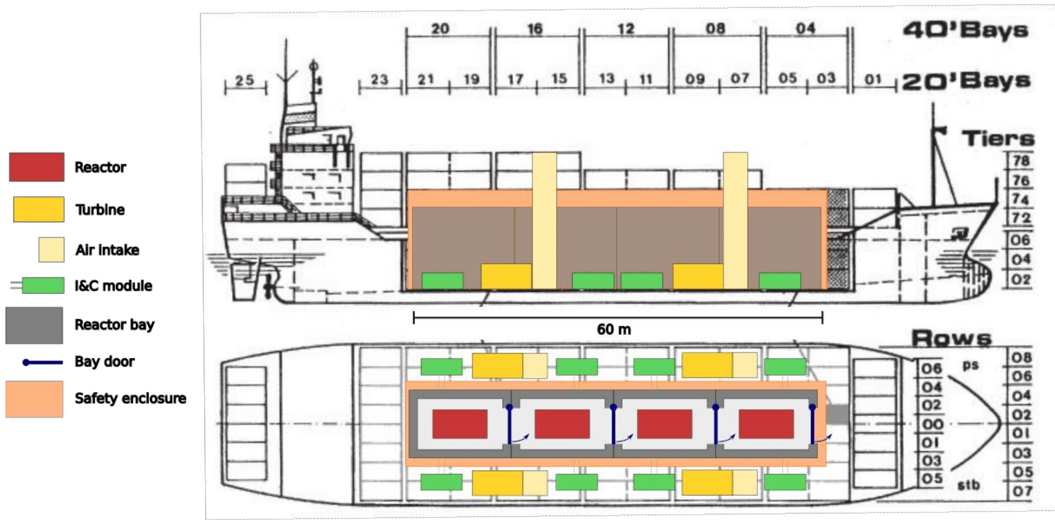


Figure 4 Top-down and side view of a small converted containership that houses four eVinci NBs and complies with the IMO Code regulations for the safety enclosure spacing; elements are drawn to scale

More broadly speaking, we argue that the regulations based on the old IMO Code cannot allow for simple, small, and cheap power platforms due to their outdated focus on the safety enclosure and application to ship propulsion. The safety enclosure is intended to protect the active safety systems of old LWR technology and is thus overconservative in the context of passively safe NBs. In fact, it is even counter-productive, as it does not allow for the passive decay heat removal using atmospheric air. Moreover, for cost-effective power services, the goal is to design a vessel that is as small as possible compared to the reactor size, whereas the goal of efficient propulsion is the opposite – i.e., to minimize the reactor compared to the ship. Regulations for offshore nuclear power services should keep this difference in design intent in mind and allow for innovative ways to ensure collision protection.

Evidently, the specific regulations will sensitively impact the design and attractiveness of the power platforms, and the lack of an elegant regulatory framework presents a large uncertainty regarding the feasibility of using NBs to provide power to FPSOs. Particularly impactful topics are the ease with which regulations allow for ship conversion, the prescription of a safety enclosure, standoff requirements for collision protection, and regulations regarding on-site operators, guards, and autonomous operation. Consequently, early and continued engagement with the regulators is needed to shape future regulations to address the context of the project adequately.

Based on a qualitative assessment of the reactor safety on the platform, it seems that there are no safety-related showstoppers to using NBs on power platforms. For starters, the accident categories directly related to the core and balance of plant are not appreciably different on the power platform compared to onshore. In addition, adequate design of the power platform combined with the passive safety features of NBs can prevent a threat to nuclear safety even under the most severe, offshore-unique ones – e.g., sinking or ship-collision. Finally, the acceleration expected due to the platform's motion in storms is lower than the tolerable acceleration during design-basis earthquakes for onshore reactors.

Although we do not foresee any major safety-related hurdles to offshore NB use, its licensing will still be a long and costly undertaking because it will require additional modeling and may require the redesign of safety systems. For example, excessive listing of the platform might prevent the development of stable and adequate airflow for passive decay heat removal, and capsizing can block the pathway to the atmosphere, cutting off airflow entirely. Given the long lead times and high cost of the design and licensing for offshore use, we recommend engaging with and incentivizing the vendors early.

As a result of using separate power platforms, the main interaction between the FPSO and NBs is through changes in demand and generation, for which the load-following capabilities of the NBs and the presence of backup diesel generators are sufficient. Other than that, the FPSO is unaffected by events on the power platform, including those with radioactivity releases. Similarly, the NBs are not affected by events on the FPSO, except that there may be a loss or distraction of the operators.

Regarding safety, the semi-submersible is preferable over the floating barge design due to its ability to better withstand sea motion, capsizing, hull failure under shallow water sinking, and collisions from both ships and aircraft. However, in case of an emergency, the semi-submersible may pose more challenges with operator intervention as the submerged structure may be more difficult to access - which can actually be an advantage from a security perspective. Moreover, the semi-submersible is expected to be more expensive than a floating barge.

Ensuring sufficient security measures may pose a significant economic challenge due to the need for on-site guards and is further complicated by the FPSO operation. Due to the extended response time of external forces and the need to minimize security personnel, it is advisable to adopt a consequence-based security approach that assumes a knowledgeable attacker has access to the power platform until external forces can intervene. Additionally, considering the limited potential harm to the public, we assert that the primary security objective is investment protection, with the FPSO itself being the primary vulnerability to address. As a result, we judge that the existing FPSO security personnel, along with a robust platform design, should provide a sufficient foundation for security purposes.

The list below summarizes the key takeaways of the study:

- NBs have the potential to fully decarbonize small to medium-demand FPSOs or partially decarbonize high-demand FPSOs.
- However, the NBs cannot be placed on the FPSO deck and instead require a separate power platform, with another means of utility heat generation on the FPSO or electrical heating. The most attractive near-term solution is likely the conversion of large, existing ships and these power platforms could see use in a variety of applications beyond FPSOs.
- There is currently no regulatory framework that elegantly addresses the use of NBs for offshore power services, which may seriously hinder their cost-effective use.
- Achieving adequate safety and security appears feasible, but it might require the redesign of certain safety systems and a shift in the security approach – and possibly in the security objective.

In addition, our main recommendations are:

- To wait for the maturity of microreactors onshore to ensure reliable operation and minimize lost production and personnel costs due to testing on-site
- To engage with the regulator to ensure that regulations are developed that allow for efficient power service solutions based on NBs
- To engage with the vendors and to incentivize them early to begin the long and costly offshore licensing process

CANES PUBLICATIONS

Topical and progress reports are published under seven series:

Advances in Nuclear Energy Disciplines (ANED) Series
Advanced Nuclear Power Technology (ANP) Series
Nuclear Fuel Cycle Technology and Policy (NFC) Series
Nuclear Systems Enhanced Performance (NSP) Series
MIT Reactor Redesign (MITRR) Series
Nuclear Energy and Sustainability (NES) Series
Nuclear Space Applications (NSA) Series

Please visit our website (mit.edu/canes/) to view more publication lists.

MIT-ANP-TR-201	Koroush Shirvan, **2024 Total Cost Projection of Next AP1000** (July 2024).
MIT-ANP-TR-200	Jérémy Mangin, Amaury Le Person, Koroush Shirvan, Jeong Ik Lee, Andrew Whittaker, and Neil Todreas, **Consequence-based security of a sodium-cooled graphite-moderated thermal microreactor (SGTR)** (April 2024).
MIT-ANP-TR-199	Emile Germonpre and Jacopo Buongiorno, **Feasibility study of decentralized hydrogen production using nuclear batteries** (January 2024).
MIT-ANP-TR-198	Lucas Lallemant, Jacopo Buongiorno, Shafiqul Islam and Laurent Vernon, **Design of Fission Batteries Process (FIBAPRO) Facility** (October 2023).
MIT-ANP-TR-197	Matthew Chew and Jacopo Buongiorno, **A Cybersecurity Framework for Nuclear Microreactors** (June 2023).
MIT-ANP-TR-196	Paul E. Roege(MIT ANPEG), Alexander L. Schoonen(INL), James R. Case (INL), Corey L. Beebe(INL), Ryan Cumings (MIT LL), Zachary A. Collier (Collier Research Systems), **Assessment of Potential Ground Force Capability Enhancement Using Nuclear Microreactors** (August 2022).
MIT-ANP-TR-194	W. Robb Stewart and K. Shirvan (MIT), **Capital Cost Evaluation of Advanced Water-Cooled Reactor Designs With Consideration of Uncertainty and Risk** (June 2022).
MIT-ANP-TR-193	K. Shirvan (MIT), **Overnight Capital Cost of the Next AP1000** (March 2022).
MIT-ANP-TR-192	R. MacDonald and J. Parsons (MIT), **The Value of Nuclear Microreactors in Providing Heat and Electricity to Alaskan Communities** (October 2021).
MIT-ANP-TR-191	C. W. Forsberg (MIT) and A. W. Foss (INL), **Markets and Economic Requirements for Fission Batteries and Other Nuclear Systems** (March 2021).

MIT-ANP-TR-190 J. Buongiorno (MIT), **An Economic Evaluation of Micro-Reactors for the State of Washington** (January 2021).

MIT-ANP-TR-189 C. W. Forsberg (MIT), P. Sabharwall (INL)and A. Sowder (EPRI), **Separating Nuclear Reactors from the Power Block with Heat Storage:** A New Power Plant Design Paradigm (November 2020).

MIT-ANP-TR-188 X. Zhao and M. Golay, **Symptom-Based Conditional Failure Probability Estimation for Selected Structures, Systems, and Components:** Minor Milestone Report: Project on Design of Risk-Informed Autonomous Operation for Advanced Reactors DOE/EXT- DE-NE0008873 Project number: 19-17435 (July 2020).

MIT-ANP-TR-187 J. Buongiorno, K. Shirvan, E. Baglietto, C. Forsberg, M. Driscoll, W. Robb Stewart, Enrique Velez-Lopez (MIT), H. Einstein (Civil & Environmental Engineering), Iain Macdonald (ArtEZ), Kennard Johnston (Morgan State Univ.) and Go Hashimoto (Univ. of Tokyo), **Japan's Next Nuclear Energy System (JNext)** (March 2020).

MIT-ANP-TR-186 Y. Cai and M. W. Golay, **A Framework for Analyzing Nuclear Power Multiunit Accident Scenarios and Providing Accident Mitigation and Site Improvement Suggestions** (September 2019).

MIT-ANP-TR-185 C. W. Forsberg (MIT), P. Sabharwall and H. D. Gougar (INL), **Heat Storage Coupled to Generation IV Reactors for Variable Electricity from Base-load Reactors: Changing Markets, Technology, Nuclear-Renewables Integration and Synergisms with Solar Thermal Power Systems** INL/EXT-19-54909 (September 2019).

MIT-ANP-TR-184 C. W. Forsberg, **Implications of Carbon Constraints on (1) the Electricity Generation Mix For the United States, China, France and United Kingdom and (2) Future Nuclear System Requirements (**March 2019).

MIT-ANP-TR-183 C. W. Forsberg, **Fluoride-Salt-Cooled High-temperature Reactor (FHR) Temperature Control Options: Removing Decay Heat and Avoiding Salt Freezing** (January 2019).

MIT-ANP-TR-182 J. Buongiorno, N. Sepulveda and L. Rush, **White Paper: Potential Applications of the Modern Nuclear Fuel Cycle to (South) Australia** (November 2018).

MIT-ANP-TR-181 C. Forsberg and P. Sabharwall, **Heat Storage Options for Sodium, Salt and Helium Cooled Reactors to Enable Variable Electricity to the Grid and Heat to Industry with Base-Load Reactor Operations** (September 2018).

MIT-ANP-TR-180 C. W. Forsberg, et al. **Integrated FHR Technology Development Final Report: Tritium Management, Materials Testing, Salt Chemistry Control, Thermal Hydraulics and Neutronics with Associated Benchmarking** (September 2018).

MIT-ANP-TR-179 C. W. Forsberg, N. Sepulveda and K. Dawson **Implications of Carbon Constraints on Electricity Generation Mix For the United States, China, France and United Kingdom** (August 2018).

Table of contents

List of Abbreviations

ABS	American Bureau of Shipping
ALARA	As Low As Reasonably Achievable
AP	Advanced Passive
ATH	Acceleration Time History
BANR	BWXT's Advanced Nuclear Reactor
BIL	Bipartisan Infrastructure Law
CFR	Code of Federal Regulations
CHIPS	Creating Helpful Incentives to Produce Semiconductors
DNSR	(UK) Defence Nuclear Safety Regulation
ESBWR	Economic Simplified Boiling Water Reactor
FOAK	First-of-a-kind
GAIN	Gateway for Accelerated Innovation in Nuclear
HALEU	High-Assay Low-Enriched Uranium
IMO	International Maritime Organization
INL	Idaho National Laboratory
IRA	Inflation Reduction Act
LWR	Light Water Reactor
MIT	Massachusetts Institute of Technology
NB	Nuclear battery
NEA	Nuclear Energy Agency
NOAK	Nth-of-a-kind
NRC	Nuclear Regulatory Commission
NQAP	Nuclear Quality Assurance Program
OBE	Operating Basis Earthquake
PPC	Plant Process Conditions
PSD	Power Spectral Density
SOLAS	International Convention for the Safety of Life at Sea
SSE	Safe Shutdown Earthquake
XENITH	X-energy's Next-generation Integrated Transportable High-temperature

List of Tables

List of Figures

1. Introduction

1.1. Nuclear batteries: a new paradigm for nuclear power generation

The business case for GW-scale nuclear reactors has come under pressure due to the frequent cost overruns and project delays in recent history, e.g., Vogtle units 3 and 4 [9]. As a result, the trend of producing bigger reactors to chase economies of scale may now be reversed, with an increasing focus on Small Modular Reactors (SMRs) and standardization in an effort to keep the budget and schedule of new nuclear projects under control. At the extreme end of such downscaling and standardization, we find “nuclear batteries” (NBs), a special class of microreactors.

The definition of microreactors varies, but it typically refers to reactors with a thermal output of up to a few tens of megawatts [10], [11], [12], which is thus the power range for NBs. What sets NBs – as defined here – apart from other microreactors is that they are transportable, can be installed rapidly with minimal site preparation (“plug-and-play”), and operate semi-autonomously with remote monitoring for many years without the need for refueling. In addition, the NBs do not need on-site refueling or maintenance, as this is done at a centralized facility [13]. Figure 5 shows a rendering of a NB site. When a NB has fully utilized its fuel, it is replaced by a fresh NB, quite like traditional batteries, hence the name. As highlighted by Abou-Jaoude et al. [6], the NB concept, as described here, is the epitome of microreactor technology, and many regulatory challenges remain in achieving this paradigm.

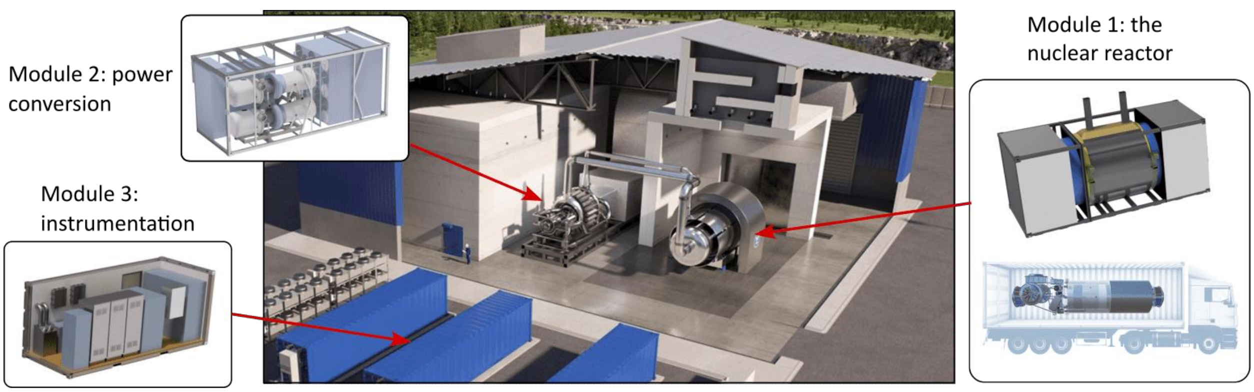


Figure 5 The eVinci site layout rendering [1] annotated to show the typical NB modules

NBs do not enjoy the same economies of scale as traditional plants, resulting in a high expected Levelized Cost of Electricity (LCOE) of hundreds of $/MWh for a single first-of-a-kind (FOAK) unit [14], which is where the extreme standardization of NBs may make a difference. The business model of NBs is built on the assumption that these systems will be mass-produced in a factory setting, driving the cost down through economies of multiples, as shown in Figure 6. A recent study by Abou-Jaoude et al. [6] indeed confirms that radical cost reductions – up to 70% – are possible under factory fabrications.

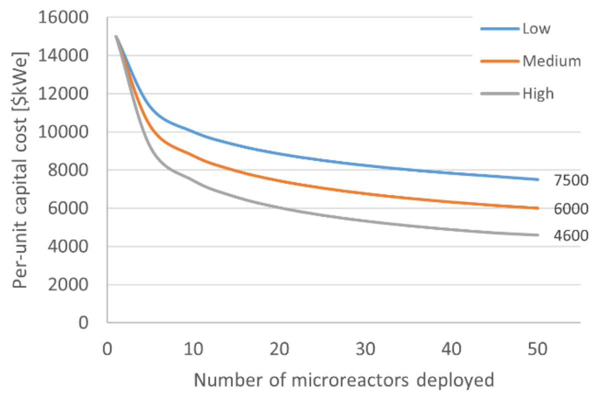


Figure 6 NB capital cost as a function of the number of units deployed under different learning rates:11.5 % (low), 15 % (medium), and 19 % (high). The FOAK cost is 15 000 $/kWe [15]

Still, the Nth-of-a-kind (NOAK) costs of these systems remain high, which is why they are often only considered for niche applications such as powering remote Arctic communities [14]. However, the authors second the sentiment of Buongiorno et al. [12] that the potential of NBs to penetrate larger markets is underestimated. And so, in this work, the focus is on a more mainstream and larger market, namely offshore power generation. This application has been identified as attractive by the project sponsors Shell, Equinor, and ExxonMobil, as the unique features of NBs might be able to meet the specific, stringent demands of the offshore environment elegantly. Note that this work is part of a larger project in which decentralized hydrogen production using NBs is also evaluated.

1.2. The difficulty and relevance of decarbonizing offshore oil and gas operations

Oil and gas extraction result in large direct emissions, e.g., 27 % of Norway's emissions in 2020 [16]. Back-of-the-envelope calculations based on input given by the project sponsors show that the emissions of a medium-sized Floating Production Storage and Offloading (FPSO) platform are on the order of 850 ton_{CO2} /day, with a high-demand FPSO emitting on the order of 1850 ton_{CO2}/day. Under a carbon tax, these high emissions present a large loss to operations, see Figure 7. As a result, oil and gas companies are looking to decarbonize these operations in an effort to hedge against the large economic risk posed by a carbon tax and to meet their climate goals.

However, offshore oil and gas production is exceptionally difficult to decarbonize due to the isolated nature of the platforms, space and weight constraints, and stringent reliability requirements. In countries where frequent natural gas flaring is no longer allowed, on-site power production is now the main source of emissions on offshore platforms (see Figure 8). Thus, decarbonizing power production is the main goal.

Currently, power is produced using aeroderivative gas turbines, where the gas is produced from the well [16]. Installing traditional Carbon Capture and Sequestration (CCS) equipment is not possible because of the platforms' stringent size and weight constraints. Thus, other low-carbon power production methods must be considered.

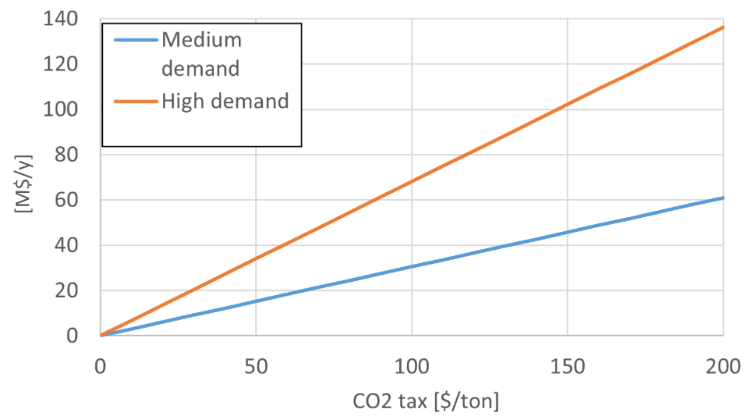


Figure 7 The annual cost of FPSO emissions as a function of the carbon tax for medium-demand FPSOs (taken as 55 MWe and 19 MWth) and high-demand FPSOs (taken as 125 MWe and 37 MWth)

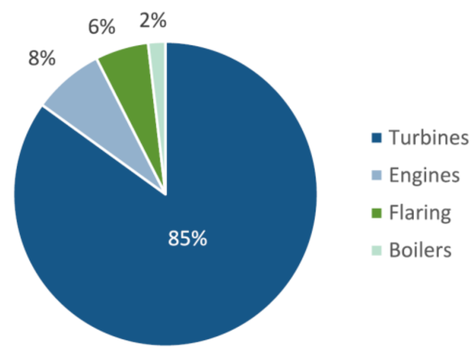


Figure 8 A high-level breakdown of the carbon emission sources on offshore platforms in Norway [16]

In their recent study, Voldsund et al. [16] performed a review of thirty mature and novel technologies to evaluate their decarbonization potential for offshore applications. The reviewed technologies included, amongst others, compact CCS, renewables, switching to hydrogen or ammonia fuels, and power from shore. Their main conclusion is that there are already technologies available that are mature and that can achieve partial decarbonization of offshore operations.

However, only one of the thirty options is mature and has the potential to deliver full decarbonization: connecting the platform to the onshore grid. This, of course, requires that the grid itself is fully decarbonized, and it is not feasible for the furthest platforms from shore. Thus, they recommend focusing more research efforts on solutions that allow for deep decarbonization. NBs might be one such solution, as they provide carbon-free energy locally and have many appealing features for offshore use, e.g., long uninterrupted operation and their small size.

1.3. Overview of the report

Section 1 introduces NBs and gives a short motivation for the interest in using NBs on FPSOs. Some general background on FPSOs is given at the start of Section 2, after which we detail the major performance targets for an alternative power system on FPSOs. Afterward, Section 3.1 provides an overview of the microreactor industry, how it is expected to evolve, what challenges it faces, and what enables further microreactor development. In addition, Section 3.2 discusses the features of the NBs considered in this study.

The issues with using the NBs on-deck are explained in detail in Section 4, resulting in the conclusion that on-deck use is not feasible and leading to the consideration of alternative reactor placements in Section 5. Section 5.1 begins by motivating the focus to separate floating or submerged power platforms, after which a high-level design is given for each in Sections 5.2. However, the Section 0 finishes by pointing out the near-term benefits of converting large vessels to power platforms rather than using custom-built platforms.

Futhermore, Section 6 highlight safety and security implications of the offshore use of NBs for power generation for FPSOs. And finally, the conclusions and future work are given in Section 7.

2. Background on Floating Production Storage and Offloading platforms

The oil and gas industry employs various offshore structures to best suit the needs of each oil field – Figure 9 gives a schematic overview of the main types. However, one type of structure is of particular interest to this study, the Floating Production Storage and Offloading (FPSO) platforms. This section will briefly highlight some characteristics of FPSOs – and their power generation systems – that are of interest to the study.

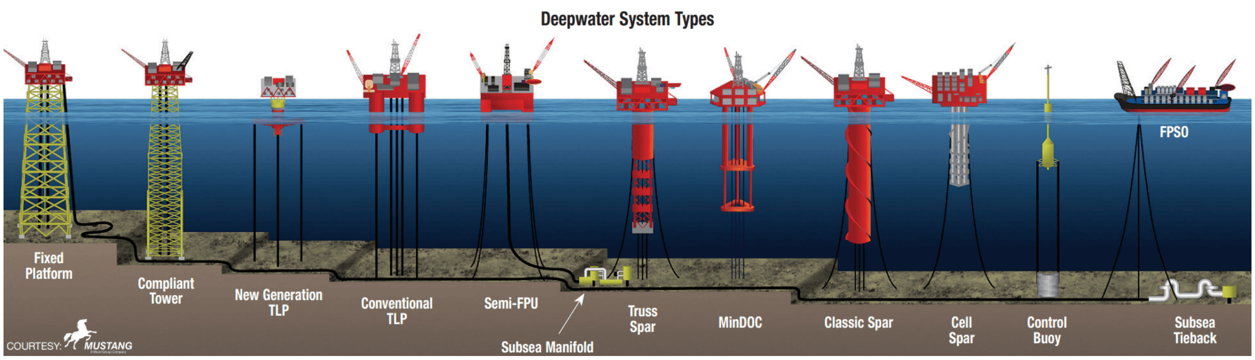


Figure 9 An overview of different types of platforms used for offshore oil and gas production [17]

As the name suggests, an FPSO is a floating vessel that is used to produce and process oil and gas from a field, which is then stored on board and later offloaded into separate tanker vessels. Note that nearby platforms or subsea elements can also produce the oil. FPSOs do not require pipelines to shore and are easy to install, so they can effectively exploit new or far away fields and deep waters [18]. In our study, a distance to shore of 200 – 300 km (130 – 200 mi) is assumed. In addition, we will focus existing platforms, called “brownfield” platforms, and new-built platforms, called “greenfield” platforms.

FPSOs can be classified as ship-type, cylindrical, or multi-body based on the shape of their hull – shown in Figure 10. The ship-type FPSOs are the most common, and they can be a converted tanker or newly built [18]. Besides the hull, the major components of an FPSO are the topside module, the mooring system, and the turret. The mooring system limits the motion of the FPSO at sea to avoid drift and aid stability, and the turret connects the mooring system and any subsea oil lines to the FPSO hull [18]. It is the topside module that carries out the main function of the FPSO; it produces, processes, and stores the oil. Figure 11 gives an overview of the different topside modules on the Ichthys FPSO.

There are two main trains in the processing system: the oil train and the gas train. The oil train consists of separation vessels, heat exchangers, and booster pumps, and it is a significant heat consumer and a secondary electrical consumer. The gas train, on the other hand, is a significant electrical consumer and a secondary heat consumer with its multiple stages of compression, dehydration units, and heat exchangers. Besides the two trains, there is a mixed thermal and electrical demand coming from miscellaneous sources such as HVAC, subsea pumping, drilling, water injection, etc. Overall, the demand remains relatively stable, with the 24-hour peak being approximately the same as the average power. Yet, there are slow changes in demand over the lifetime of the FPSO [19]. So, for the purpose of this study, the demand is treated as constant.

Figure 10 FPSOs with a different type of hull: ship-type (top left) [20], cylinder-type (top right) [21], and multi-body type (bottom) [22]

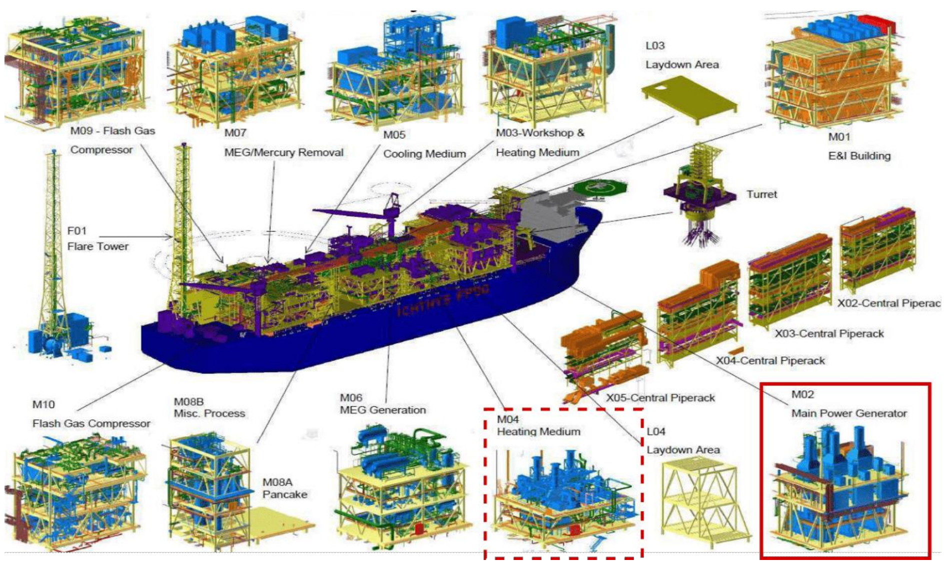


Figure 11 An overview of the different modules on the Ichthys FPSO, taken from Ref. [23]. Note the power generation module at the bottom-right corner

As mentioned before, power generation is the main source of emissions (60-80 %) in countries where routine flaring is prohibited [16]. Power is generated by simple aero-derivative gas turbines – e.g., a Siemens SGT-A35 or GE LM2500+G4 – that use the well gas directly at an efficiency of 35-40% [16], [24]. Typically, there are some 3 to 6 units with individual capacities of about 5-25 MWe [19]. On old platforms, turbines were frequently used to drive rotating equipment directly, whereas they are used almost exclusively for electricity generation on new platforms, with motors driving the equipment [25].

Energy supply reliability is crucial for FPSOs, so the main generator equipment has an N+1 redundancy [11]. In addition, there are two layers of backup diesel generators: essential generators providing a few megawatts of power to run essential processes and a smaller emergency generator to ensure the operation of critical safety functions to ensure life at sea [25].

Low maintenance needs are another main requirement for the power system besides reliability because lost production costs on FPSOs are enormous. The gas turbines score well in both regards, as they need little on-site maintenance and have high reliability and availability. Other advantages are their small footprint and light weight [19]. Unmistakable advantages on an offshore platform where weight and size are significant cost drivers [16], [26]. Drawbacks of using gas turbines include their emissions, high unit cost, and noise levels [19].

Utility heat is provided by the gas turbines through Waste Heat Recovery Units (WHRU) that extract heat from the turbine exhaust – all heat is supplied this way, no dedicated heating system is used [16]. Overall, the heat requirements are at low temperatures, with the heating medium entering the WHRU at 90-140 °C and exiting it at 140-170 °C [19].

2.1. Performance targets and requirements for alternative power generation

This section presents the performance targets and requirements for the NB power system that serve as the foundation of this study. The list provided is not comprehensive due to the high-level nature of a feasibility study, and it is important to note that safety and security requirements are not covered in this section, as they will be discussed in Section 6.1.

2.1.1. Size and weight

Table 3 Size and weight targets for a replacement power system

Parameter		**Target**	**Source**
Footprint	Specific area	≈ 100 m^2 per 20-30 MWe	[19]
	Total area	186 - 558 m^2	[19]
Height	Upper deck	Flexible	[19]
	Lower deck	3 m	[19]
Volume	Specific volume	≈ 600 m^3 per 20-30 MWe	[19]
	Total volume	None	[19]
Weight	Specific weight	150 - 250 MT per 20-30 MWe	[19]
	Total weight	500 - 8000 MT	[19]
	Lifting limitations	50 MT	[19]

Weight and size are significant cost drivers on offshore platforms and are thus subject to stringent targets [16], [26]. Table 3 shows the performance of the current gas turbine system including auxiliary equipment in these metrics, which serve as targets for the NB system. For existing (i.e., "brownfield") platforms, the targets can be seen as effective requirements, as significantly increasing the available area or allowable weight during retrofitting will incur large costs. For new (i.e., "greenfield") platforms, there is more flexibility in the weight and size of the power system. Note that the footprint of the generation system is more important than the volume because there is no height limit on the upper deck – within reason, of course.

As mentioned before, the current gas turbine systems perform exceptionally well in terms of compactness and weight-to-power ratio, with a specific area of 3-5 m^2/MW and a specific weight of 3.3 MT/MW. It is unlikely that the NB system will reach the same performance, so in addition to the data of current ystems given in Table 3, we will use the following categorization of the weight-to-power ratio used in the study of Voldsund et al. [16]:

- Low: < 10 MT/MW
- Medium: > 10 MT/MW and < 30 MT/MW
- High: > 30 MT/MW

Note that there are also lifting constraints that are more stringent than for onshore cranes. These affect the refueling of the NBs, as the spent reactor must be transported to a central facility for refueling – more information in Section 3.1.1.

2.1.2. Maintenance, reliability, and availability

Table 4 Maintenance, reliability, and availability targets for a replacement power system

Parameter		Target	Source
Availability	Single train	> 97.5%	[19]
	Combined	> 99 %	[19]
Reliability	Single train	> 99.5%	[19]
Outage length and frequency	Interval	≈ 4 years *≈ 6 months*	[19]
	Duration	≈ 3 weeks *< 24 h*	[19]
Demand during outage		≈ 10 % of full power	[19]

Constant power provision to the platform is crucial to ensure the safety of life at sea and its continued operation, which is critical for economic performance. As a result, high availability and reliability are expected for the power generation system. At the same time, however, maintenance work should be kept to a minimum to minimize platform downtime and operator burden. The FPSO has an extensive maintenance outage every four years, with smaller maintenance windows every six months (Table 4). This combination of both high-performance expectations and low maintenance effort presents a significant challenge.

The current gas turbine systems perform well on both fronts. They have no dedicated maintenance staff on site and are instead serviced onshore. The downtime for a turbine replacement is small, at only three to five days. Yet, despite the limited maintenance, the gas turbines meet the demanding reliability targets.

2.1.3. Electrical and thermal demand

Table 5 Output requirements for a replacement power system

Parameter		**Requirement**	**Source**
Electrical demand	Low	20 – 30 MWe	
	Medium	50 – 60 MWe	[19]
	High	100 – 150 MWe	[19]
Thermal demand	Low	7.5 – 12.5 MWth	
	Medium	15 – 25 MWth	[19]
	High	30 – 45 MWth	[19]
	Temperature	140 – 170 ° C	[19]
Redundancy		N + 1	[19]

There are differing levels of demand across assets due to differences in size, infrastructure, and changes in demand over the field lifetime. So, representative demand ranges are used for low, medium, and high demand cases – shown in Table 5. The medium and high-demand ranges are direct input from the project sponsors, whereas a lower demand case is created to better match the power output of NBs – more information in Section 4.1. This case could also be seen as a partial decarbonization of a larger platform.

The demand is relatively stable on a 24-hour cycle [19], so no separate treatment of power peaking is done. In addition, changes in demand over the lifetime of an FPSO are not accounted for explicitly. However, NBs offer scalability of power in the number of units used. So, it is expected that accommodating slow changes in demand over the asset's lifetime will not be a challenge.

Overall, the FPSOs are primarily electrical consumers, with the low-temperature thermal demand traditionally being served through waste heat recovery. If the NB system cannot supply the thermal demand directly, a separate heating system must be installed, or heating must be provided electrically. Both options are clearly suboptimal but potentially acceptable.

All NB designs considered in this study can deliver heat at far higher temperatures than what is required for process purposes – see Section 3.2. On greenfield platforms, this high-temperature heat could potentially be used to further refine the oil, adding value in the process. However, the high-temperature heat delivery will not be valorized on brownfield platforms due to the need to redesign the topside module.

Ensuring the reliability of the power supply is one of the main design criteria, so redundancy is used in both the main and backup power generation systems [25]. Several sparing options are available for the backup systems (2 x 100 %, 3 x 50 %, etc.), but for the main generators, N + 1 sparing is typically used.

2.1.4. Power quality

Table 6 Electrical quality targets and requirements for a replacement power system

Parameter		Target or requirement	Source
General	Voltage	11 or 13.8 kV	[19]
	Frequency	50 or 60 Hz	[19]
Capabilities	Load following	Preferred	[19]
	Black start	Preferred	[19]
Tolerance	Voltage	< 2.5 %	[27]
	Frequency	5 % (steady state) 10 % (transients)	[27]
Recovery times	Power	< 3 s	[28]
	Voltage	< 1.5 s	[27]
	Frequency	< 5 s	[27]

Power quality is important for FPSOs, as they are microgrids with a large demand coming from (rotating) equipment. Power, frequency, and voltage must thus be maintained precisely and restored quickly to protect the equipment. Recovery times and deviations outside the targets given in Table 6 can be acceptable depending on the transient (e.g., a load change) and the distribution system – more information is given in the comprehensive standards on power quality given by the International Electrotechnical Commission [27], [28]. Note that new platforms typically run on 50 Hz.

2.1.5. Cost and timeline

The project sponsors did not provide a specific cost target, but ranked cost considerations high, as expected. Similarly, no timeline targets were given, but the window of opportunity for NBs to play a role in decarbonizing FPSOs may shrink as alternative solutions mature.

Importantly, the full cost of implementation must be considered beyond purely the levelized cost of electricity (LCOE) of the NBs – which is often the main means of comparing different power systems. For example, the lost production cost of implementing a low-carbon power solution on a platform can outweigh the cost of the system itself [24]. Note that the high cost of lost production again underscores the importance of the reliability of the power supply. Besides lost production, other cost drivers could be platform modification, increased personnel requirements (if applicable), and the cost of onshore facilities. Although there is no dedicated analysis regarding the cost of implementing NBs on FPSOs, we provide some insights into the cost drivers throughout Sections 4 and 5.

3. **Background on nuclear batteries**

3.1. Industry overview

3.1.1. The industry structure and microreactor lifecycles

The licensing of reactors has been a major hurdle in reactor commercialization for the modern nuclear industry [13], and as things stand, it will also be for the NB development. Traditionally, reactors could be licensed through Title 10, "Energy", Part 50, "Domestic Licensing of Production and Utilization Facilities" of the Code of Federal Regulation (CFR) – further denoted as 10 CFR Part 50. Under this two-step licensing approach, a construction permit is first issued for the site to allow for construction to begin, and later, an operating license is issued to allow for the reactor's operation [29]. Clearly, this process is not well-suited for the licensing of NBs that can be sent to different sites over their lifetime. Another option is to obtain a combined construction and operation license (COL) under 10 CFR Part 52 "Licenses, Certifications, and Approvals for Nuclear Power Plants" [30]. However, this approach is similarly "project" rather than "product" oriented.

Despite the recent efforts of the Nuclear Regulatory Commission (NRC) to streamline the licensing process for microreactors, no current or near-term regulatory framework allows for the envisioned rapid, site-flexible deployment of microreactors [6]. As a result, the first microreactors will thus likely be licensed under the traditional frameworks, with the industry evolving over time. Furthermore, the lack of a clear regulatory framework also hampers the development of the microreactor fuel cycle and maintenance strategies [13]. Abou-Jaoude et al. [6] outline three "production lifecycle scenarios" in which the industry might evolve toward the full nuclear battery paradigm. In the following paragraphs, these three lifecycle scenarios will be discussed.

In the first scenario, the reactor module is fabricated at a dedicated factory with separate fuel fabrication in a different facility – which might be collocated with the reactor factory. Both the fuel and reactor are transported to the site, where the reactor is to remain throughout its lifetime. All initial testing and further inspection, maintenance, and refueling are done at the site. Thus, this paradigm does not differ substantially from the proposed Small Modular Reactor paradigm – except that more of the initial construction is done in the factory – and it carries little regulatory risk. Because the reactor factory does not handle any nuclear material, it is only subjected to the Nuclear Quality Assurance (NQA-1) certification. Figure 12 gives a schematic overview of the reactor lifecycle. Note that only aspects related to the reactor are included; there will still be some on-site construction of the structures housing the reactor.

Figure 13 shows the second-generation paradigm. The major difference with the first-generation microreactors is that they are now fueled, inspected, maintained, and refueled off-site at a dedicated facility, which allows for substantial efficiency gains. This facility performs fuel loading and will thus require an adequate license – most likely a manufacturing license under 10 CFR 53 [6]. In addition, this paradigm requires the transport of fueled reactors, for which there is no precedent at this time. Both of these aspects increase the regulatory risk significantly compared to the first generation.

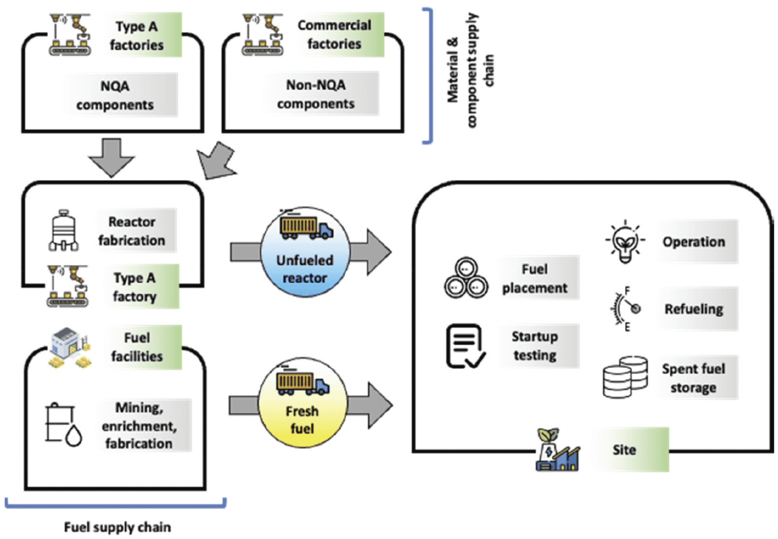


Figure 12 A schematic overview of the first-generation microreactor lifecycle taken from Ref. [6]

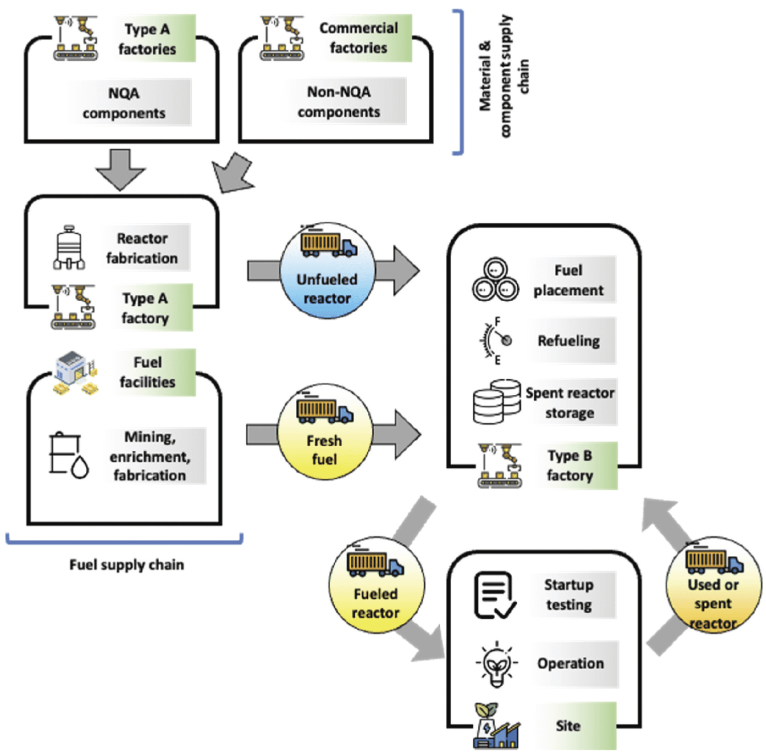


Figure 13 A schematic overview of the second-generation microreactor lifecycle taken from Ref. [6]

The third-generation microreactor lifecycle closely resembles the second-generation, with the key difference that all initial criticality testing can be done at the servicing facility, see Figure 14. The reactors are now truly "plug-and-play" with minimal on-site preparation needed before operation, and this paradigm represents the "nuclear battery" concept. Although including startup criticality testing in the central facility might seem minor, it has important regulatory consequences, requiring the facility to have a COL license. As a result, this paradigm has the highest regulatory risk.

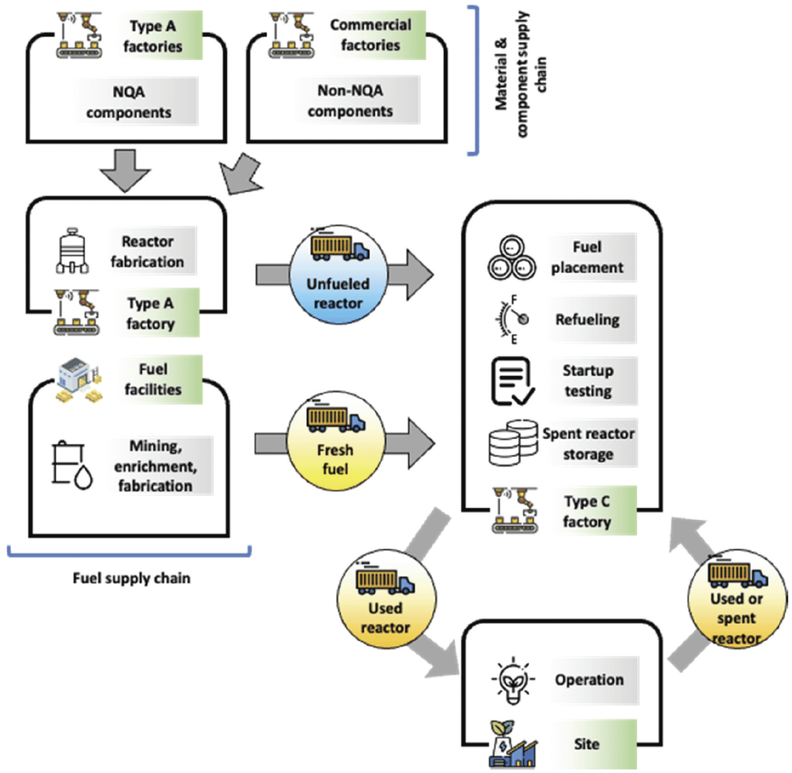


Figure 14 A schematic overview of the third-generation microreactor lifecycle taken from Ref. [6]

The type B and type C facilities of the second and third generations could be built separately for each microreactor design, resulting in many semi-identical facilities that perform similar tasks. Fakhry et al. [13] propose consolidating all those facilities into one Central Facility that maintains and refuels the fleet of different microreactor designs, thereby concentrating regulatory, operational, commercial, and safety expertise. The discussion below summarizes some of the key points of their study on the effect of a Central Facility on the microreactor industry.

One of the major benefits of the Central Facility is its ability to significantly reduce the regulatory burden and cost for the microreactor industry by removing the inefficiencies that stem from having multiple facilities that perform the same functions. Not only does this benefit the industry, but it also takes a significant burden from regulators who would otherwise have to license and oversee multiple similar facilities. Additionally, concentrating refueling operations and spent fuel storage in one Central Facility reduces proliferation and security risks because authorities can focus their attention on a single site rather than many scattered sites, making it easier to maintain a secure and safe environment. Finally, the Central Facility can serve as a centralized point of interaction between the many regulators involved – the Nuclear Regulatory Commission (NRC), the Department of Transportation, and potentially the National Nuclear Security Administration and the International Atomic Energy Agency.

Second, a Central Facility provides significant de-risking for all stakeholders. Two examples: (i) reactor customers can point to the well-respected Central Facility, facilitating public acceptance, and (ii) vendors can free up capital away from developing their refueling and maintenance facility – which is not part of their core business – towards further developing the technology.

However, there remain many challenges to the development of a Central Facility. The main ones, in order of importance, are garnering the support and participation of the vendors, developing a new regulatory approach that involves more cooperation and transparency, gaining political support for the Central Facility, and overcoming technological barriers. A few aspects that make getting vendor participation difficult are the intellectual property protection risks, the technical difficulty of servicing different reactors in a single facility, and the different commercialization timelines. Fakhry et al. [13] thus conclude that it is crucial to find a catalyst to facilitate vendor engagement.

A Central Site approach might alleviate some of the challenges faced by the Central Facility approach. In the Central Site paradigm, each vendor would have their own refueling and servicing facility but collocated on the same site, which avoids intellectual property risks and the difficulty of servicing multiple technologies at the same facility, and it allows for different commercialization timelines. However, it still provides efficiency gains – some examples are that spent fuel storage can be consolidated, security can be provided for the site as a whole, and the many regulators are still collocated at the same site.

3.1.2. Enablers, challenges, and game-changers for microreactor development

We give a brief overview below of what enablers drive the development of microreactors, what challenges the industry faces, and what to look out for as potential game-changers. Note that the discussion is intended to give a feel for important developments but is not a comprehensive review.

Enablers for microreactor development

There is an undeniable market potential for microreactors driven by the need for deep decarbonization of the economy. Remote communities are typically seen as the first customers, where microreactors compete with expensive diesel generation [14], [31], [32]. This interest is backed by the public sector, as the State of Alaska recently adopted regulations to streamline the deployment of microreactors [33]. Besides these rather niche applications, Buongiorno et al. [12] also identified more mainstream applications for the use of microreactors, e.g., shipping and water desalination. A study by the INL assessing the market in Wyoming found applications in mining, data centers, cryptocurrency mining, and more [34]. The market potential is only further increased by the clean energy requirements that are put in place on a state and federal level [34].

Furthermore, there is policy support for both the development and deployment of microreactors. An example of the former is the GAIN Microreactor Program at INL, which lowers the development risk for microreactors through fundamental and applied research into technologies that are critical to their operation [35]. Another example is the Advanced Reactor Demonstration Program of the Department of Energy, which includes Westinghouse's eVinci microreactor (Section 3.2.2) and the BWXT Advanced Nuclear Reactor (BANR, Section 3.2.4) [36].

The Inflation Reduction Act (IRA), on the other hand, aids the deployment of microreactors – and other low-carbon technologies – through tax credits [37], [38]. In addition, the IRA includes funding for the development of a domestic High-Assay Low-Enriched Uranium (HALEU) fuel supply chain [37], [38]. HALEU has a higher enrichment than traditional commercial reactor fuel and is needed to provide sufficient reactivity and core lifetime for TRISO-fueled microreactors. The development of this supply chain is a prerequisite for microreactor deployment at scale since all commercially developed microreactors (discussed in this study) use TRISO fuel – see Section 3.2.

Other programs that aid the development of microreactors indirectly are (1) the Creating Helpful Incentives to Produce Semiconductors (CHIPS) and the Science Act, which include funding for advanced nuclear research, (2) the Defense Production Act, which allocates funding towards the provision of critical materials that advanced nuclear technologies use, and (3) the Bipartisan Infrastructure Law's (BIL) Nuclear Credit Program that provides investment for the existing nuclear fleet [31].

Finally, there is interest from the Department of Defense in microreactors for strategic purposes [39]. Project Pele helps fund the development of two microreactors from BWXT and X-energy. Additionally, there is a pilot project at Eielson Air Force Base, which is expected to resume after a delay due to a bidder dispute [40].

Challenges for microreactor development

The first set of challenges is related to microreactor commercialization. As noted by Shirvan et al. [5], there is a lot of movement in the microreactor space, but it is not coordinated, and it remains to be seen if the uncoordinated momentum will lead to a commercially viable product.

Obviously, microreactors suffer from significant diseconomies of scale, with personnel and other fixed costs - such as licensing - increasing the LCOE significantly [15]. The business case of microreactors instead relies on economies of multiples and cost reductions through mass production [12], [14]. However, it remains to be seen whether the needed market volume and learning rates can be achieved for the economies of multiples to substantially lower costs – the recent study by Abou-Jaoude et al. [6] seems to confirm that aggressive cost-cutting is possible.

In addition, new business models and risk-sharing structures are needed to allow for the development of a Central Facility or Site in which multiple vendors can converge to realize the many regulatory, operational, and commercial benefits that it provides – see Section 3.1.1 for more details. Moreover, new business models and risk-sharing might be needed to provide energy as a service to customers who have no experience with nuclear technology.

The second set of challenges are technical in nature. Due to the need to limit on-site staff as much as possible, microreactors intend to be operated autonomously, which is an approach yet to be demonstrated for commercial nuclear systems. Furthermore, a novel security approach must be developed to drastically reduce the need for on-site guards compared to traditional plants while also ensuring security during operation in remote areas. Similarly, the remote operation and the increased number of reactors necessitate the development of new safeguards to prevent illicit access to nuclear material [41]. Finally, there is also a concern for the HALEU fuel availability that might limit the growth of advanced reactor deployment in general [42].

Finally, deploying microreactors also faces numerous regulatory challenges - particularly in the "nuclear battery" paradigm. For starters, the current regulatory framework is LWR-oriented, which hampers the implementation of all advanced reactor concepts, including microreactors. In addition, a flexible site licensing system is necessary for the efficient deployment of microreactors at scale – i.e., a “product” rather than a “project” approach. Moreover, significant regulatory changes are required to accommodate the autonomous operation and security systems to permit the necessary down-staffing of operators and on-site guards. Finally, the transport of fueled reactors is unprecedented in the civil sector, and a new set of transport regulations is necessary.

3. Background on nuclear batteries

Potential game-changers

Extensive regulatory reform as is needed to facilitate microreactor deployment at scale is difficult, but it has happened in the past. For example, the creation of NUREG-1537 in 1996 allowed for easier licensing of non-power and test reactors, which up until then had to follow the same licensing process as commercial power reactors [43]. The change was motivated by the orders of magnitude difference in the power level of commercial and research reactors [43]; an argument that also holds true for microreactors. In fact, microreactors with a thermal output under 20 MWth are classified as Hazard Class 2 under 10 CFR 830 rather than Hazard Class 1 [10]. So, there already is recognition of the different risk profiles at lower power ratings. It is thus not unreasonable to assume that a new regulatory framework can be implemented to address the licensing of microreactors better so that the industry can grow to its full potential.

An obvious path forward would be to license microreactors similarly to research reactors, which are licensed based on a limiting accident: the maximum hypothetical accident (MHA) or the maximum credible accident (MCA) [43]. By contrast, commercial reactors must assess the performance under a wide range of postulated accidents and show that the expected dose satisfies the regulatory limits. The benefit of the research reactor approach over traditional licensing is that it does not require a probabilistic risk assessment – which is costly and time-consuming – and it does not change over the lifetime of the facility [43].

A potential downside, however, is that the MHA and MCA approach are both highly conservative – especially the MHA, as it does not have to be a realistic accident – and might be too constraining for using microreactors in populated areas [43]. On the other hand, gathering the data needed for best estimate licensing will be disproportionally expensive for microreactors compared to traditional reactors. Microreactors might thus prefer conservative regulations – at least in the near term [43].

A licensing pathway that would definitely benefit microreactors is joint DOE-NRC licensing. This would allow the microreactors to have a demonstration at a DOE national lab site – under somewhat less stringent regulation because of the remote location – before going through the NRC licensing process [10]. A secondary benefit is that this approach would partly alleviate the burden on the NRC staff [10]. Other regulatory innovations that would benefit microreactors are allowing for off-site criticality testing – the relevance of which is discussed in Section 4.2.2 – and the finalization of technology-agnostic regulations such as 10 CFR 53.

Finally, the construction of a refueling facility would signal a clear turning point from the first to the second generation of microreactors and would allow the microreactor fleet to grow substantially – even if the facility is not a Central Facility or Site as discussed in Section 3.1.1 but privately owned by a single vendor.

3. Background on nuclear batteries

Summary

- Enablers for microreactor development
    - Private and public interest
    - Policy support for R&D
        - Gateway for Accelerated Innovation in Nuclear (GAIN) Microreactor Program at INL
        - Advanced Reactor Demonstration Program
    - Clean energy subsidies and requirements
        - Inflation Reduction Act (IRA)
        - Bipartisan Infrastructure Law (BIL)
        - Creating Helpful Incentives to Produce Semiconductors (CHIPS)
        - Defense Production Act
    - Department of Defense interest
        - Eielson Air Force Base microreactor pilot project
        - Project Pele
- Challenges for microreactor development
    - Technological:
        - Autonomous operation
        - Safeguards and security
        - Fuel availability
    - Regulatory:
        - Transportation of fueled reactors
        - Flexible siting
        - Security requirements
        - LWR-oriented offshore regulation
    - Economics:
        - Diseconomies of scale
        - Realizing cost reductions through factory fabrication
        - Business models and risk sharing for a Central Facility and providing energy as a service
- Potential game-changers
    - Microreactor-oriented licensing
        - Joint DOE-NRC licensing
        - Licensing approach similar to the NUREG 1537 for non-power reactors
        - Technology agnostic licensing
        - Allow for criticality testing off-site
    - The construction and operation of a servicing facility

3.2. Nuclear battery designs considered in this study

There are many microreactor designs being pursued commercially, but for the purpose of this study, the focus is on three credible designs with promising development activity, namely Westinghouse's eVinci, X-energy's Next-generation Integrated Transportable High-temperature (XENITH), and BWXT's Advanced Nuclear Reactor (BANR). Additionally, an in-house MIT design is considered to highlight the potential benefits of a UO_2-fueled design and because all design information is available to us.

The upcoming sections provide a brief overview of each design and discuss their key features. Section 3.2.5 then compares the designs in Table 7. It is important to note that the information presented is accurate to the best of the author's knowledge, but as the microreactor industry is new and constantly evolving, some details may be subject to change.

3.2.1. The sodium-cooled MIT design (MIT NB)

In a recent study by Shrivan et al. [5], a series of UO_2-fueled reactors were developed to evaluate their economic performance and feasibility. The motivation is that UO_2-fueled systems have lower fuel-related costs and a higher fuel readiness than the TRISO designs that are predominantly pursued in the microreactor industry. In this study, only the sodium-cooled design is considered. It is a 15 MWth – 4.65 MWe – graphite-moderated reactor that uses conventional 4.8 wt% enriched UO_2 pellets and operates using a supercritical CO_2 Brayton cycle [5]. The core layout is given in Figure 15. At the time of writing, the design is not commercially pursued.

The discharge burnup of the fuel is significantly lower than for traditional reactors at 9.5 MWd/kg HM, which is a result of the single-core refueling and the higher leakage and parasitic absorption for microreactors [5]. As a result, a relatively large fuel loading of 1770 kg U is needed for the core to reach the design fuel lifetime of 3 Effective Full Power Years (EFPY).

Furthermore, the design is based on traditional materials in the nuclear industry, i.e., SS316 stainless steel cladding, graphite for the moderator and reflector, and liquid sodium as the coolant. The sodium enters the core at 358 °C and exits at 510 °C [5].

Control drums are used as a primary means of control, with a central control rod being used as a secondary shutdown mechanism. In addition, a passive, air-cooled Reactor Vessel Auxiliary Cooling System (RVACS) removes decay heat – as shown in Figure 16.

The reactor is designed to be road transportable and is placed above ground alongside a power conversion module and an instrumentation and controls module. Overall, the site has a small footprint, Figure 17. However, it must be noted that the design is at an early stage and that many factors affecting the site layout and size are still to be addressed – e.g., a full security plan [44]. Finally, there is expected to be minimal on-site staff due to the autonomous control of the reactor with remote monitoring.

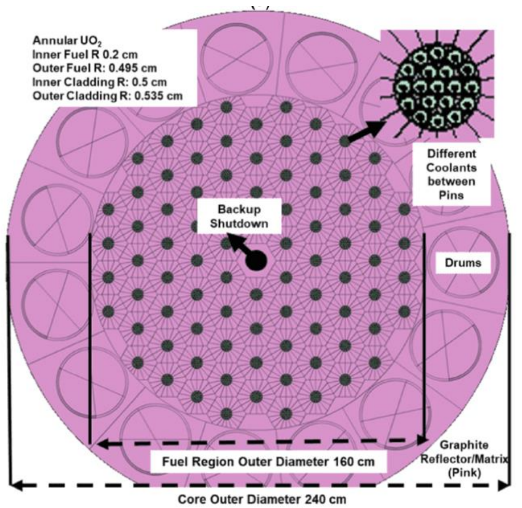


Figure 15 Sodium-cooled NB core design of Shrivan et al. [5]

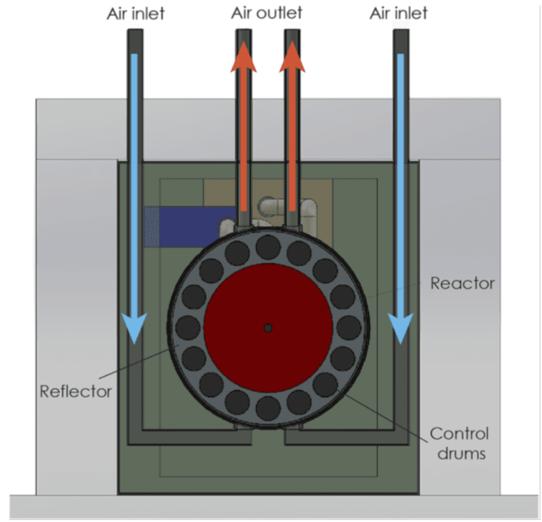


Figure 16 A schematic representation of the passive, air-cooled RVACS [5]

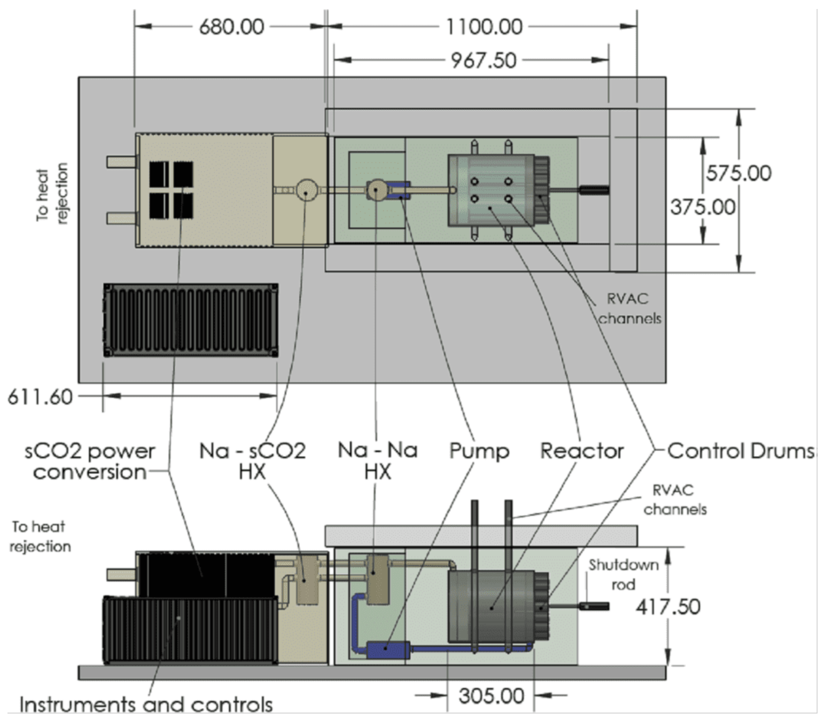


Figure 17 The site layout of the sodium-cooled NB [5]

3.2.2. The eVinci microreactor by Westinghouse

Westinghouse is developing a 13 MWth – 5 MWe – microreactor called the eVinci to be a flexible and reliable power platform that can serve a wide variety of customers such as remote communities and mining operations [2]. Note that some of the power output goes to powering the facility itself – on the order of 100 to 150 kW – so that the actual net power output is somewhat lower [45]. However, in the remainder of the study, this effect in neglected. The design runs on an open-air Brayton cycle, is graphite-moderated, and uses heat pipes to cool the core. Figure 18 shows the reactor module.

Figure 18 eVinci reactor core cutout showing the main components [2]

Like most commercially pursued designs, the eVinci plans to use 19.75 wt% enriched High Assay Low Enriched Uranium (HALEU) TRISO fuel. The HALEU TRISO fuel allows it to reach higher burnups than traditional UO_2 fuel due to its higher enrichment and improved stability over traditional claddings. As a result, the 8 EFPY fuel lifetime can be achieved with a relatively low fuel loading of 880 kg U. Additionally, the TRISO fuel eliminates the need for cladding.

Much like the MIT reactor, the reflector and moderator are made from graphite. However, the core is cooled by heat pipes containing sodium at sub-atmospheric pressures, which significantly simplifies the reactor design. Furthermore, the heat pipes allow for high-temperature operation of the reactor above 800 °C [5].

Primary control is achieved by control drums and burnable absorbers, with shutdown rods as a secondary shutdown mechanism [1]. Decay heat removal is done passively using a heat-pipe-based cooling of the reactor vessel [45].

Figure 19 shows a rendering of the site layout. The canister of the reactor module forms the functional containment and the module is placed in a concrete reactor bay, which provides radiation shielding and protection against airplane impact and unwanted intrusion. There are two bays per site to allow a spent core to cool down in one bay while a new reactor is installed in the second bay [46].

Figure 19 A rendering of the eVinci site highlighting the reactor building and auxiliary systems [1], [46]

The three blue modules seen outside the reactor building are two I&C modules – presumably one per reactor bay – and a load-following battery [46]. While not stated explicitly, we suspect these electrochemical (lithium ion) batteries to be necessary to attain the advertised <1 s load-following capabilities [46], as power changes of nuclear reactors typically occur over longer timescales – on the order of a few percent per minute [47].

To allow for easy operation in remote areas, the reactor is designed to be road, sea, and rail transportable – with the power conversion and instrumentation modules shipped separately – and refueling, inspection, maintenance, and decommissioning are all done off-site [1]. Installing a new reactor is expected to take less than 30 days – assuming some prior on-site construction of the bays – and replacing a reactor that has spent its fuel can be done in 24 hours [46]. For the moment, any criticality testing is expected to be done at the site after the construction of the bays and installation of the reactor [1]. So, at most, a second-generation paradigm is envisioned for now. Furthermore, limited on-site staff will be needed since the design uses autonomous control and remote monitoring.

Westinghouse plans to license the eVinci reactor through a standard design certification under 10 CFR 52 Subpart B [48], i.e., through a traditional regulatory framework. However, they plan to use modern guidance from the NEI 18-04 "Risk-Informed Performance-Based Technology-Inclusive Guidance for Non-Light Water Reactor Licensing Basis Development" [1]. At the time of writing, Westinghouse has already had extensive pre-application engagement with the NRC and is expected to submit their design certification application in the near future.

In addition, their goal is to license the eVinci both in the US and Canada with a single design that meets the requirements of both regulators [1]. This effort is supported by the recent joint US NRC and Canadian Nuclear Safety Commission (CSNC) Licensing Modernization Project report [49], which compares the non-LWR regulatory frameworks of both regulators. At the time of writing, Westinghouse is waiting for the approval of their Phase 2 Vendor Design Review with the CSNC [50].

The eVinci reactor's initial deployment is planned for Saskatchewan and is expected to be completed by 2029. The Saskatchewan Research Council has pledged $80 million (CAD) to assist with the project's development, following an earlier announcement by the Canadian government that it will provide $27.2 million (CAD) for the eVinci technology's development [51], [52]. The eVinci deployment timeline is illustrated in Figure 20.

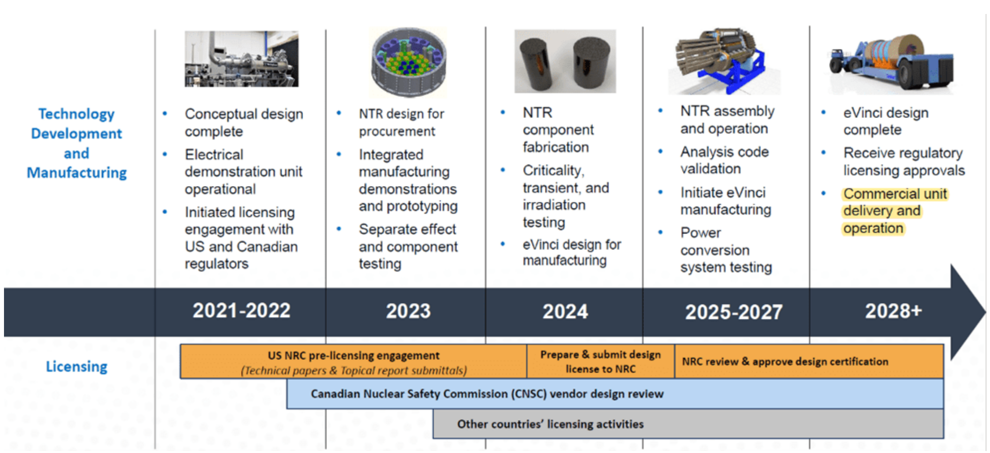


Figure 20 The eVinci development and licensing timeline [53]

3.2.3. X-energy’s Next-generation Integrated Transportable High-temperature (XENITH) microreactor

X-energy is developing a 20 MWth – 6.6 MWe – high-temperature gas-cooled microreactor for civilian use [54], [55] alongside their microreactor design work in light of the Department of Defense’s Project Pele [56]. Much like the eVinci reactor, XENITH uses an open-air Brayton cycle for power conversion and is graphite-moderated. However, cooling is achieved by helium gas circulating through the core, rather than sodium-filled heat pipes.

The core runs on X-energy’s proprietary TRISO-X fuel, which contains 19.75 wt% enriched HALEU fuel and is designed to have a fuel lifetime of 3 EFPY [3]. Moreover, the core is designed for high-temperature operation, with a core outlet temperature of > 750 °C and the ability to deliver > 700 °C process heat [54]. Primary control is provided by control drums [54].

Overall, the XENITH reactor site is similar to the eVinci site in that there is a concrete reactor bay housing only the reactor, with separate power conversion and instrumentation modules. A rendering of the site layout is given in Figure 21. Unlike the eVinci reactor, the XENITH reactor module consists of two parts: the reactor core and an intermediary heat exchanger, Figure 22.

The XENITH design fits the NB paradigm, as it is designed to be transportable (road, sea, and rail), installed in a short period (under 3 weeks), refueled and maintained off-site, and to have remote monitoring [54].

X-energy is currently in pre-application discussions with the US NRC and is preparing a Phase 1 Vendor Design Review with the CNSC. There are no publicly announced commercial projects for the XENITH reactor, but it is important to note that XENITH is the commercial version of the Project Pele X-energy reactor design. This means that once the Project Pele reactor is fully designed, XENITH could potentially have a shorter licensing and deployment timeline despite the relatively minor level of regulatory and private engagement at the moment.

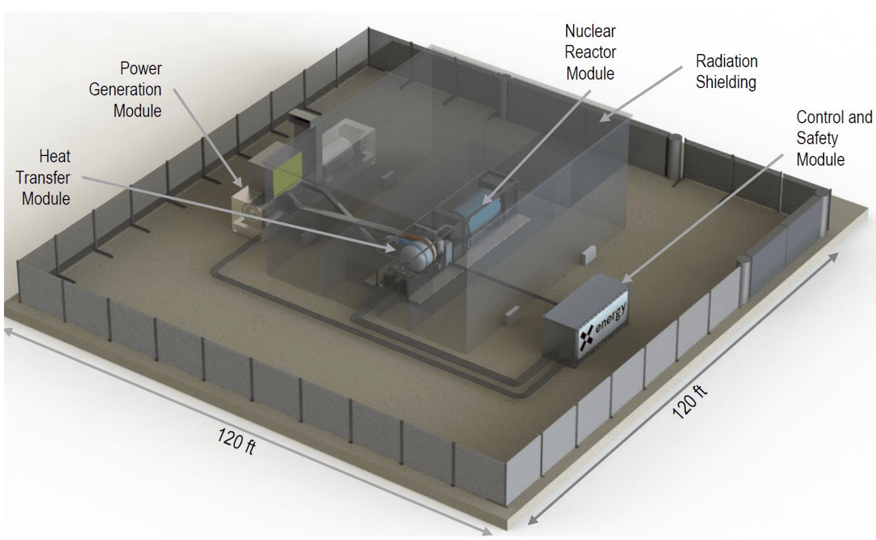


Figure 21 Rendering of the XENITH reactor site [54]

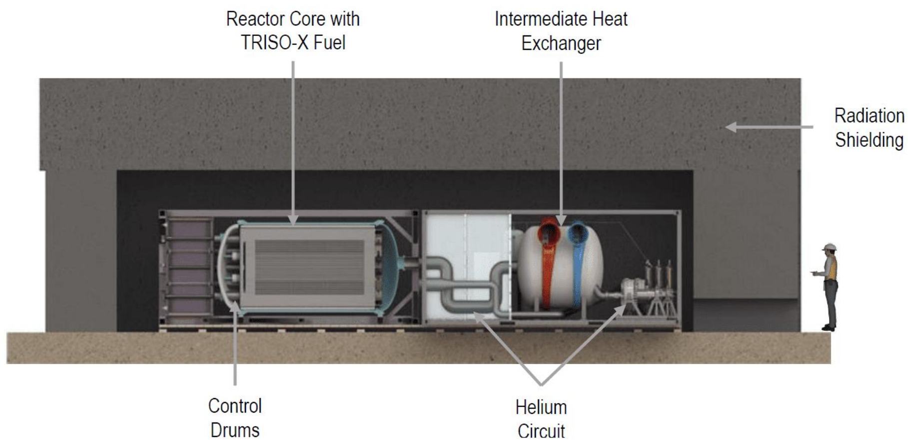


Figure 22 Cross-sectional view of the XENITH reactor bay [54]

3.2.4. BWXT's Advanced Nuclear Reactor (BANR)

BWXT's Advanced Nuclear Reactor (BANR) is the commercial spin-off of the microreactor that BWXT is developing for the Department of Defense under Project Pele [56]. It has a significantly larger output than the other microreactor designs considered in this study, namely 50 MWth and 12 MWe, and it uses a Rankine cycle instead of a Brayton cycle [57].

As a result of its thermal output being greater than 20 MWth, BANR is classified as a Hazard Category 1 under 10 CFR 830 – rather than Hazard Class 2 like the other designs – which could potentially have far-reaching regulatory consequences if future microreactor-oriented streamlining of regulations is based on the classification as a Hazard Category 2.

Thanks to the use of 19.75 wt% enriched HALEU TRISO fuel, the core can have a large power output and a long fuel lifetime of 10 EFPY with a fuel loading of 2900 kg U [57]. As always, the TRISO fuel also eliminates the need for cladding.

High-pressure helium is used to cool the core and allows for operation at high temperatures – the core outlet temperature is 650 °C [57]. In addition, moderation and reflection are provided by graphite, as is typical for high-temperature gas reactors. Primary control and shutdown are achieved using control rods, and decay heat removal is provided by the Reactor Vessel Passive Cooling System (RVPCS).

The BANR reactor is placed inside a reactor bay, with the power conversion system outside the bay and a separate control building (Figure 23). Like the other reactors, it is designed to be transportable. However, the larger size of the BANR system makes the transport of a single reactor module impossible, and instead, some on-site installation is required.

BWXT seems to show little action on the regulatory front, as there is little engagement with the NRC – besides the submission of a topical report – and there is no engagement with the CNSC [58]. However, it is worth noting that BANR, which is a spinoff of BWXT's Project Pele reactor, has the potential for accelerated commercial development similar to that of the XENITH reactor.

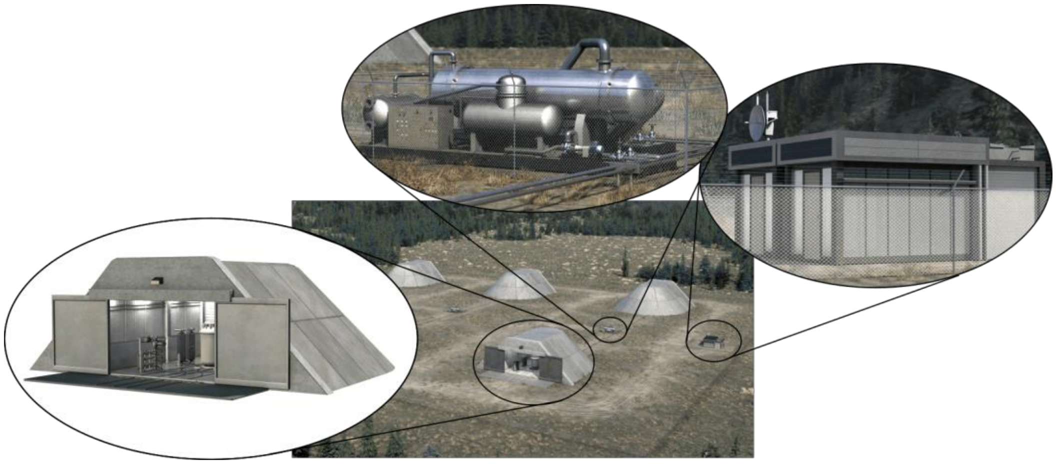


Figure 23 A rendering of the BANR site layout where the reactor bay, power conversion system, and control building are highlighted [57]

Figure 24 A rendering of the power service vessel concept envisioned by the Crowley-BWXT partnership [59]

In September of 2023, BWXT announced its memorandum of understanding with Crowley to develop a ship with an onboard microreactor that can bring power to shore via floating power cables to “strategically deliver power for military applications” or provide disaster relief [59]. Figure 24 shows a rendering of the concept.

3.2.5. Comparison of the different designs

Table 7 A comparison of the characteristics of the MIT NB, eVinci, XENITH, and BANR reactors

	MIT NB	**eVinci**	**XENITH**	**BANR**
Developer (country)	MIT (US)	Westinghouse (US)	X-energy (US)	BWXT (US)
Electrical power [MWe]	4.65	5	6.6	12
Thermal power [MWth]	15	13	20	50
Thermal efficiency [%]	31	38.5	33	24
Power conversion cycle	Supercritical CO_2 Brayton	Open-air Brayton Cycle	Open-air Brayton Cycle	Rankine
Fuel type	UO_2 Pellets	HALEU TRISO	HALEU TRISO	HALEU TRISO
Fuel enrichment [wt%]	4.8	19.75	19.75	19.75
Fuel loading [kg U]	1770	880	n/a	2900
Discharge burnup [MWd/kg HM]	9.5	43	n/a	63
Energy content [MWyr]	46	104	60	500
Refueling period [EFPY]	3	8	3	10
Cladding material	SS316	None	None	None
Moderator	Graphite	Graphite	Graphite	Graphite
Reflector	Graphite	Graphite	Graphite	Graphite
Coolant	Liquid sodium	Sodium heat pipes	Helium gas	Helium gas

	MIT NB	eVinci	XENITH	BANR
Core outlet temperatures [°C]	510	> 800	> 750	650
Coolant pressure [MPa]	Atmospheric	Sub-atmospheric	n/a	2.8
Coolant core volume [m^3]	0.09	n/a	n/a	2.3
Primary control mechanism	Control drums	Control drums	Control drums	Control rods
Secondary shutdown mechanism	Central control rod	Shut down rods	n/a	Control rods
Decay heat removal	RVACS	Passive removal with heat pipes	n/a	RVPCS
Containment	Concrete containment	The reactor canister	n/a	n/a
Siting	Fixed and above ground	Fixed and above ground	Fixed and above ground	Fixed and above ground
Installation time	n/a	< 30 days	< 3 weeks	n/a
Replacement time	n/a	< 24h	n/a	n/a
Transportable	Road	Road, rail, sea	Road, rail, sea	Road, rail, sea
On-site staff	Minimal	Minimal	n/a	n/a
Autonomous operation	Yes	Yes	Yes	Yes
Remote monitoring	Yes	Yes	Yes	Yes

4. **The difficulty of deploying NBs on-deck**

This section shows why on-deck use of NBs is infeasible by highlighting the many challenges related to it. Section 5 will then discuss how separate power platforms can be used instead.

4.1. Footprint and weight constraints

Table 8 shows the number of NBs needed to cover the thermal and electrical demand of an FPSO entirely. For the eVinci, waste heat at up to 150 °C is available [2], whereas utility heat is needed at temperatures between 140 °C and 170 °C. Consequently, not all utility heat can be supplied with waste heat alone.

On the other hand, it reasonable to assume that the high-temperature heat from one reactor – greater than 500 °C for all designs – would be used directly to supply the low-temperature heat needed for oil and gas treatment. Thus, the number of reactors required falls between the two extremes listed in Table 8, where either all or no waste heat is utilized.

Regardless, a large number of reactors is required, especially for high-demand platforms, which need almost two dozen NBs. In our judgment, it is unlikely that such a large number of NBs would be economically competitive with alternatives such as small modular reactors which typically have electric power outputs of 100s of MW. However, the numbers in Table 8 assume that NBs meet the entire demand, whereas an important benefit of using NBs is that they allow for modular power scaling. Partial decarbonization of a high-demand FPSO might thus still be attractive, e.g., to ensure firm capacity when using renewables.

Table 8 The number of NBs needed to service the entire FPSO demand, assuming the utility heat can be supplied by the waste heat of electricity generation or is provided by dedicated NBs (italics). Both cases use an N+1 redundancy sparing.

	Low	**Medium**	**High**
Electrical demand [MWe]	20 – 30	50 – 60	100 – 150
Thermal demand [MWth]	7.5 – 12.5	15 – 25	30 – 45
MIT NB	6 – 8 *6 – 9*	12 – 14 *13 – 16*	23 – 34 *25 – 37*
eVinci	5 – 7 *6 – 8*	11 – 13 *13 – 15*	21 – 31 *24 – 35*
XENITH	5 – 6 *5 – 7*	9 – 11 *10 – 12*	17 – 24 *18 – 26*
BANR	3 – 4 *3 – 4*	6 – 6 *6 – 7*	10 – 14 *10 – 15*

The BANR reactor is an exception due to its significantly higher power output, requiring roughly half the number of units. As a result, N+1 sparing is particularly costly for the BANR. For other designs, medium-demand platforms need nearly one dozen reactors, and low-power FPSOs need approximately six.

As discussed in Section 2.1.1, the deck area is scarce on FPSOs, and hence, the footprint per unit power is an important performance indicator for any alternative power system. Similarly, the weight per unit power is an important indicator, as large weights require upgrades to the FPSO structure. It is, therefore, crucial to estimate the footprint and weight of the NB systems

In Appendix A, the "total minimal" footprint and weight of the reactors are estimated, and Table 9 shows the results compared to the current gas turbines. "Total" refers to the fact that not only the reactor module is accounted for, but so are the turbine, I&C modules, and the reactor bay – i.e., all systems without which operation is impossible. However, many other structures are neglected, e.g., the security perimeter and working space for operators. In that sense, the estimate is "minimal".

Unfortunately, the NBs perform exceptionally poorly in both regards due to the need for a concrete reactor bay to provide radiation shielding and protection from intrusion and aircraft impacts. For reference, Voldsund et al. [16] categorize a low-carbon offshore power solution as "high" weight if its power-to-weight ratio is higher than 30 MT/MW.

In all cases, the reactor bay accounts for about 95 % of the total system weight, and it is a significant driver of the footprint. It might be possible to downsize the bay for offshore use, as collison-protection can be provided by external structures – namely the safety enclosure and reactor compartment, refer to the discussion in Section 5.2.3 for more information – and shielding can be provided by other means, e.g., double-walls filled with water.

On a medium-demand platform, the twelve eVinci modules would exceed the 600 m^2 area target by a factor of 3 and the 8000 MT weight target by a factor of 5.6. Greenfield installations can accommodate large footprints and weights but at a high cost. Consequently, the use of NBs on-deck is impossible on brownfield installations and prohibitively costly for greenfield platforms.

Table 9 Total minimal footprint and weight of the current gas turbines and the four NB designs

Design	**Size [m2/unit]**	**Size [m2/MW]**	**Weight [MT/unit]**	**Weight [MT/MW]**	**Bay weight [%]**
Current turbines	100	3 – 5	150- 250	3.3	/
eVinci	150	30	3788	758	95.7
BANR	583	49	/	/	/
XENITH	198	30	4829	732	96.6
MIT NB	159	34	2785	599	94.9

4. The difficulty of deploying NBs on-deck

4. The difficulty of deploying NBs on-deck

The estimates are based on renderings for onshore use of the NBs without any optimization for weight or footprint. As mentioned before, the bay can likely be made lighter, e.g., by downsizing or using other means of shielding and collision protection. In that way, the weight estimates are somewhat conservative. On the other hand, we assumed that all structures and systems without which operation is still technically possible can simply be omitted on the FPSO, e.g., security-related fencing. In addition, the calculations assume that stacking of the turbine and I&C modules on the reactor bay is possible for the eVinci and XENITH. Thus, in terms of footprint, the estimates are optimistic.

Finally, note that the superior weight-to-power ratio of the MIT NB is likely an artifact of its design stage, with many functions of the bay still undefined. This can be seen in the vastly different bay layout between the work of Shirvan et al. [5] and the work of Jérémy Mangin and Amaury Le Person [44] not much later. In addition, insufficient information was available at the time of writing to estimate the total weight of the BANR reactor and auxiliary systems.

4.2. Regulation of offshore nuclear

4.2.1. A brief overview of the incomplete regulatory landscape

International Convention for the Safety of Life at Sea, Chapter VIII

Chapter VIII of the International Convention for the Safety of Life at Sea (SOLAS) [60] sets out the basic requirements for commercial nuclear-powered shipping, with a particular focus on the radiation hazards [7], [61]. It forms a basis for further regulations by outlining the high-level safety objectives. For instance, regulation 6 regarding radiation safety states, “The Administration shall take measures to ensure that there are no unreasonable radiation or other nuclear hazards, at sea or in port, to the crew, passengers or public, or to the waterways or food or water resources.” Thus, not much is learned concerning the feasibility of the project from the SOLAS Chapter VIII regulations due to their high-level nature.

The Code of Safety for Nuclear Merchant Ships

In 1981, the International Maritime Organization (IMO) adopted Resolution A.491, “Code of Safety for Nuclear Merchant Ships” [7] – further referred to as the IMO Code. It is a complete regulatory framework for the licensing of commercial shipping using pressurized light water reactors (LWRs) for propulsion, but it is, of course, not as extensive as the body of regulation and guidance provided by the NRC for onshore reactors. In fact, the IMO Code does not intend to replace the guidance of the nuclear regulator but to add to it.

The IMO code classified Plant Process Conditions (PPCs) according to their estimated frequency: PPC 1 is normal operation, PPC 2 is infrequent minor occurrences, PPC 3 is major occurrences with a remote probability, and PPC4 is severe accidents with an extremely remote probability. Note that this classification roughly corresponds to the NRC Conditions I (PPC 1), II (PPC 2), III (PPC3), and IV (PPC 4). However, unlike the NRC regulations, the IMO Code does not address beyond design basis accidents. That said, the design basis of the IMO Code already includes several accidents that are very severe. For example, collision with a ship resulting in a fire/explosion, and the sinking or capsizing of the ship are all PPC 4 conditions.

In contrast to the onshore regulation, nuclear safety is not the primary objective of the IMO Code; the overall safety of the ship is. It could thus be that the reactor is kept operational to ensure the safety of the ship in cases where you would shut the reactors down at a land-based site. If, however, the overall safety of the ship can no longer be guaranteed, the safety of the NPP becomes the primary objective.

Regardless, the three main design criteria are similar to those onshore, i.e., (1) the exposure to the workers, public, and the environment should be kept *as low as reasonably achievable* (ALARA) through shielding and sequential barriers, (2) decay heat removal must be provided, and (3) control systems must be able to keep the reactor in a safe shutdown state for as long as necessary. In addition, the same safety philosophy regarding the single failure criterion, so that the safety systems must be redundant, independent, diverse and segregated.

The defense-in-depth prescriptions of the IMO Code go beyond those of onshore reactors, requiring a safety enclosure in addition to the familiar containment structure, pressure boundary, and fuel cladding. The safety enclosure is intended to "prevent the unintentional release of and limit the leakage of radioactive material". It thus appears to be a secondary containment in its primary safety function and in the further description of the requirements it must satisfy. However, a key difference between the containment and the safety enclosure is that the former must prevent the escape of radioactive material under all PPCs.

Additionally, a reactor compartment is required to surround the safety enclosure, which serves several safety functions, such as (partial) fire and collision protection, but it is not prescribed to be leak-tight. Due to its role in providing collision protection, there are also prescriptions on the location and performance of the reactor compartment. As a final safety barrier, there is the double hull, which is meant to provide protection against grounding and low-energy collisions.

Although there are several guidelines on collision protection, the function is not uniquely assigned to the reactor compartment, the hull, or any other structure. However, it is explicitly mentioned that all safety critical systems must be placed in collision-protected areas and that the safety enclosure may not be penetrated during a design basis collision. Finally, within the many layers of defense, all areas must be categorized according to the radiological risk at that location.

Due to the role that the ship's structure plays in ensuring nuclear safety under, e.g., grounding or collisions, the ship must be designed, constructed, tested, and inspected under the Quality Assurance Program (QAP). Unfortunately, the Code does not refer to specific standards for quality assurance of the vessel. However, it does specify that the nuclear steam supply system needs to follow the IAEA Safety Series No. 50-C-GA – a then-current nuclear quality assurance standard, which has now been replaced by the IAEA *Quality Assurance for Safety in Nuclear Power Plants and other Nuclear Installations: Code and Safety Guides Q1-Q14* [62]. The present industry standard for nuclear quality assurance is the American Society of Mechanical Engineers (ASME) Nuclear Quality Assurance (NQA-1) [63].

Some ship components can become nuclear safety grade if their failure could result in a scenario that affects nuclear safety. For example, all ship components whose failure could cause a PPC 3 belong to the second highest safety class, which includes items such as the containment structure and its safety systems. In addition, the safety enclosure and collision-protection structures also get a nuclear safety classification. However, it is unclear how the IMO Code's safety classes compare to any current industry standards.

Furthermore, the IMO code prescribes meticulous testing – both initial and periodic – of the safety systems and their components, as well as the inspections of the ship's hull to ensure structural integrity. For example, the gastightness of the containment and safety enclosure should be verified periodically using pressure testing. The personnel is similarly expected to undergo rigorous training before certification and many drills during the reactor operation.

To summarize, the IMO Code provides a full regulatory framework for the licensing of nuclear ships that use LWR technology. It provides requirements and guidance for the safety case of these ships, which is similar to the NRC approach for onshore nuclear power plants – with the key differences highlighted above. Although safety is treated extensively, little is said about security other than that it should be sufficient.

American Bureau of Shipping Classification for Nuclear Power Service Vessels

At the time of writing, the American Bureau of Shipping (ABS) is developing a set of requirements needed for the classification of "Power Service (Nuclear)" – further referred to as the ABS Code, which would be mandatory for any vessel on which nuclear power is generated and transferred externally [8]. The authors were able to preview a draft version of the regulation, on which the following discussion is based. Only generalities are highlighted, as the details may be subject to change.

The classification builds on the IMO Code and SOLAS Chapter VIII, so most of the discussion above still applies to the ABS Code. However, recognizing the developing advanced reactor landscape, the ABS Code moves beyond the LWR focus and is risk-informed and technology-inclusive. Although this is already an important step in the right direction, it is still not well adapted to the context of NBs – as are all current and near-term regulations – in that it does not allow for unmanned vessels with autonomously operated reactors, requires on-site testing, etc. Finally, note that the requirements of the ABS Code are in addition to those of the nuclear regulator.

Merchant Shipping (Nuclear Ships) Regulations 2022

Recently, the UK government passed the Merchant Shipping (Nuclear Ships) Regulations 2022 to implement the SOLAS Chapter VIII and the IMO Code [64], [65], [66] – the discussion given regarding the IMO Code thus applies here. They are implementing the regulation to comply with the SOLAS and to prepare for the possibility of nuclear merchant ships in light of the decarbonization efforts of the maritime industry.

Although it is a full regulatory framework [65], there is no extensive guidance, with clarification being given on a case-by-case basis [66]. And like the IMO Code, the regulation points toward the UK nuclear regulator for some aspects of the nuclear lifecycle [65].

Defence Nuclear Safety Regulation (DNSR) of the Defence Nuclear Enterprise

The Defence Nuclear Safety Regulations (DNSR) of the Defence Nuclear Enterprise (DNE) form a complete regulatory framework for the nuclear-related activities of the UK military, which includes their nuclear submarines [67]. The licensing process is based on 36 general Authorization Conditions that outline the high-level safety and security objectives, with 6 Further Authorization Conditions that address the issues specifically related to the strategic nature of the activities. In addition, there is one more Transport Condition for the transportation of nuclear material [67].

Unlike the IMO Code, the DNSR is not prescriptive. It instead ties together regulations from other regulatory bodies, including International Atomic Energy Agency and the Office of Nuclear Regulation – the UK nuclear regulator. Again in contrast to the IMO Code, there is extensive guidance on the DNSR [68], making it potentially well-suited to be adapted for civilian use – if the 6 Further Authorization Conditions are dropped.

4.2.2. The impact of the offshore regulations on the project

In this section, we will highlight the implications of the IMO Code regulations for using NBs on the FPSO deck. We focus primarily on the IMO Code as it currently forms the only full civilian regulatory framework for offshore nuclear – the Merchant Shipping (Nuclear Ships) Regulations are equivalent to the IMO Code, and the ABS Code is largely based on the IMO Code.

Developing the safety case for the use of NBs on FPSOs will not be an easy task. For one, the IMO Code design basis includes severe accidents such as sinking, deflagration of the onboard cargo, and ship collisions. Second, the Code requires that the reactor and its safety systems remain operational under various static and dynamic tilt angles, potentially requiring new modeling and experiments in addition to the work done in light of the onshore licensing. Third, the local meteorological conditions, as well as the FPSO hydrodynamic performance, must be accounted for in the safety analysis. And finally, fire safety will need to be demonstrated – which will not be an easy task on a vessel full of hydrocarbons. Consequently, we expect long lead times for the first deployment of NBs on an FPSO and recommend to engage in conversation with both the vendors and regulators as soon as possible.

The difficulty in the licensing of NBs for offshore applications is only further exacerbated by the lack of a regulatory framework that addresses the application elegantly. The IMO code is LWR-oriented, meaning that it does not consider the new reactor technologies that the NBs employ. The upcoming ABS Code, however, will be technology-inclusive. Furthermore, the regulation has mainly dealt with nuclear power for propulsion, which creates a different safety philosophy to prevent the loss of life at sea compared to using nuclear as a power service. For example, the Code explicitly mentions that nuclear safety is not the primary objective, but the safety of the ship – and its crew – is. On an FPSO, the essential and emergency diesel generators can ensure the safety of the crew and vessel, easing the performance requirements for the NBs, e.g., by not demanding operation under large tilt angles. This lack of regulatory readiness pushes back the deployment timeline for the NBs and it adds uncertainty to the conclusions presented in this work.

Moreover, the prescribed, rigorous surveying, testing, and training will likely increase the operational cost of the FPSO significantly. For one, the personnel will need to undergo additional training to be qualified to operate the reactors and to deal with radiological hazards. Furthermore, more personnel might be needed to operate the reactor as the staffing must be "to the satisfaction of the Administration" – paragraph 7.1.1.7 of the IMO Code [7], which is counter to the objectives of the sponsors who expressed their ongoing efforts to reduce staffing as much as possible.

On top of increasing personnel costs, the testing and surveying are expected to incur lost production costs. For example, there are dedicated surveys annually, during refueling, and on a four-year basis. These surveys can be matched quite well to the existing downtime schedule of the FPSO: the annual survey can be done during a short (< 24h) outage that happens every six months, and the four-year survey matches the longer (3 weeks) outage window. However, it will be extremely challenging to fit the diligent surveying and testing into the already short and busy downtime windows – which does not include the operator drills yet. As a result, there will be lost production.

NBs might offer significant advantages regarding both the increase in personnel (cost) and the lost production costs through surveying and testing because they are operated (semi-) autonomously, and much of the testing can be done at the Central Facility during refueling. However, these benefits do not apply to the first-generation microreactors, and they only apply to a lesser extent to the second-generation. Consequently, it seems advisable to wait until the microreactor industry matures before considering them for application on FPSOs.

Finally, there are a host of difficulties with integrating the NBs in brownfield platforms. First, the IMO Code requires additional structures beyond the containment, namely the safety enclosure and the reactor compartment – and a double hull but FPSOs will already have one. Together, they must form a collision-protected area for the safety systems, which means they will add a considerable amount of weight and deck area to the power system– both of which are already unacceptably high, see Section 4.1. Further exacerbating the problem are the guidelines on the positioning of the reactor compartment and safety enclosure, which do not allow the reactors to be located near the side of the vessel, where the existing gas turbines might be. For example, the safety enclosure must be at least B/5 m or 11.5m inboard from the side of the ship in the IMO Code – whichever is less, and where B is the beam width.

Second, a redesign and upgrade of the FPSO might be needed. For starters, certain requirements, such as minimizing asymmetrical flooding, might not be met by the FPSO. As another example, the ABS Code draft included stricter guidelines for the double hull separation than the OPA 90 regulations – at the time of writing. Moreover, the vessel is subject to the highly demanding QAP over its entire lifetime, for which the FPSO owner might not have the required records up to the standards and format of the QAP. This might lead to a costly process of testing or replacing parts of the FPSO to show compliance.

Third, in addition to the vessel being subjected to the QAP, there will be a diffusion of nuclear safety grade to various components on the FPSO whose failure could affect reactor safety. This list will likely include many components, given that FPSOs are a high-energy environment. Unfortunately, the nuclear safety grade (NQA-1) does not follow traditional quality assurance standards such as ISO 9001. In case the nuclear safety grades of the offshore regulator are similar to those of the NRC, the nuclear safety classification will necessitate a component replacement at a significant cost premium.

Fourth, the IMO Code demands a lengthy commissioning phase (called the "trials phase"), which will incur substantial lost production costs. The phase includes verifying the compliance of each component with its safety class, performing onshore (pre-) criticality tests, performing various tests at sea, and more. This process might seem like no more than a headache, but it is expected to be an economic deal-breaker, given that the lost production cost of implementation can outweigh the cost of the low-carbon system itself [24].

Consequently, using NBs on brownfield platforms is impossible for technical and economic reasons – e.g., the required safety structures take even more space on deck, and there will be considerable lost production costs.

The discussion above highlights many ways in which the regulations for offshore nuclear can complicate the project, but there is one piece of (potentially) good news: the ABS Code accounts for proximity to population and land usage in the required risk assessments, as they recognize the difference in risk profiles of accidents at differing locations. This could potentially allow for relaxed safety requirements for the NB power systems on FPSOs, as they only operate far away from shore.

4.3. Replacement of the reactors

At the end of the fuel lifetime, the reactors are transported to a Central Facility onshore, where they are refueled, inspected and maintenance repairs are made. This transport runs into two difficulties. First, the reactor modules have to be moved onto another vessel using cranes. Yet, for the eVinci and the MIT NB, the reactor module weight exceeds the 50 MT offshore lifting constraints – a similar conclusion is expected for the BANR reactor, although its weight is unknown. At first glance, the 50 MT XENITH reactor module appears to satisfy the limit. However, this does not include the weight of the transportation cask, which is substantial [69].

Second, the reactor cannot be moved immediately after shutdown, as the decay heat and radiation levels need to decrease to facilitate transport. In her work on microreactor transportation, Carmen Crawford finds that one month is a sufficient cooldown period but does not specify a minimum necessary cooldown time, as it is a tradeoff between transportation costs and the reduction in capacity factor [69]. Furthermore, the eVinci site layout shows an empty “replacement reactor bay”, where a freshly fueled reactor can begin operation while the old reactor cools down. Thus, we expect the cooldown time to be sufficiently long not to be able to fit the NB replacement easily in the short and busy maintenance outage, therefore resulting in lost production.

Note that first-generation microreactors need to be refueled on-site, which avoids the issues with lifting constraints. However, on-site refueling will be technically infeasible due to the shielding needs during spent fuel handling and the need to perform high-precision operations on a moving platform. And even if it were feasible, it is unadvisable to use first-generation reactors due to large expected lost production and personnel costs – as mentioned in Section 4.2.2.

5. **Alternative reactor placement**

5.1. Downselection of the placement options

Section 4 highlighted the difficulties with using the NBs on deck, forcing us to consider other options for the reactor placement. As an alternative, we propose a separate, smaller, unmanned structure that houses the reactors, which will be referred to as the "power platform". The power platform is designed to be as simple as possible, so the reactor control room will be onshore or on the FPSO, with only emergency control positions on the power platforms. In addition, the power platforms will be towed to the site using standard industry practice.

In the following, we will consider three broad placement categories for the power platform. In the first, the small platform is attached to the FPSO hull. Alternatively, it could be fully separated from the FPSO with no attachment other than a power cable. In that case, we consider both a floating and submerged platform. Figure 25 gives a schematic representation of each option and Table 10 summarizes the discussion on the attractiveness of each option given in the text. The on-deck use of NBs is given as a reference for the performance but will not be discussed – as this was done in Section 4.

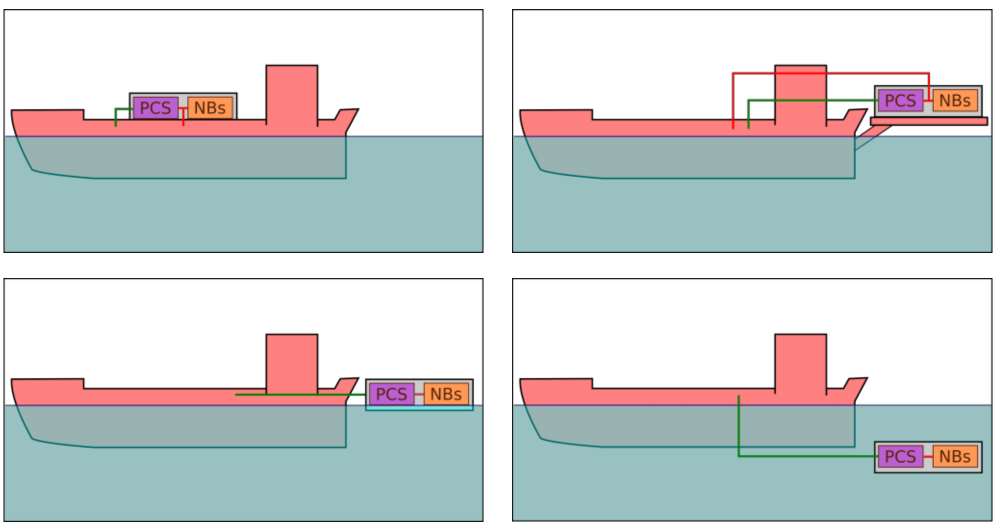


Figure 25 Schematic representation of the reactor placement options: on-deck use (top left), attached power platform (top right), floating power platform (bottom left), and submerged power platform (bottom right)

There is full design flexibility for the floating and submerged power platforms, as they are not subject to the stringent size and weight constraints that apply to the FPSO – but obviously, the size of these platforms and the weight they must carry should still be minimized to minimize their cost and complexity. This design freedom allows the development of safety and security systems more easily – e.g., designing with collision protection in mind – thereby helping to simplify the safety and security case of these platforms.

The attached platform, on the other hand, will enjoy less freedom in terms of size and weight to minimize its impact on the FPSO's stability and hull. For the on-deck use and attached platform, there is significantly more freedom in terms of size and weight in greenfield than in brownfield, whereas the distinction between brownfield and greenfield does not matter for the floating and submerged platforms.

Table 10 A qualitative comparison of the different reactor placement options; green indicates good relative performance in that category, yellow indicates medium relative performance, and orange indicates poor relative performance

	On-deck	Attached	Floating	Submerged
Technical challenges				
Footprint	orange	yellow	green	green
Weight	orange	yellow	green	green
Heat delivery	green	green	orange	orange
Emergency access	green	yellow	yellow	orange
Motion and acceleration	green	yellow	orange	yellow
Safety and security				
Tailored design	orange	yellow	green	green
Disconnected events	orange	yellow	green	green
Cost drivers				
Component replacement	orange	yellow	green	green
Personnel	orange	yellow	green	green
FPSO redesign	orange	orange	green	green
Lost production: installation	orange	orange	green	green
Lost production: maintenance	orange	yellow	green	green
Standardization	orange	yellow	green	green
Platform cost	green	yellow	yellow	orange

Power cable fatigue is an important and non-trivial issue when using a floating or submerged platform and will necessitate tightly controlled station keeping. In our judgement, these fatigue issues will also prevent the use of flexible steam lines to supply heat to the FPSO [70]. Therefore, the utility heat must be provided by electric heating or another energy source on the FPSO. Providing heating with another energy source should not be difficult, though, since there will be ample area available where the gas turbines were initially located. Note that for the attached platforms, these fatigue issues can be limited by linking the power cable and steam lines to the connection between the FPSO and platform.

The power platforms are accessible during operation by helicopter or boat. However, there are limits to the weather conditions in which this is possible. Thus, ensuring access to the emergency control positions is challenging when using power platforms – more so for the submerged design, as it will likely have fewer access points. Finally, the smaller power platforms will likely experience higher wave and wind-induced motion and acceleration than the large FPSO.

A major benefit of the detached platforms is their simplified safety and security, as they disconnect the initiating events on the FPSO and the power platform. For example, the fire and explosion hazard on the FPSO would no longer threaten reactor safety when using floating or submerged platforms. Since accidents on the FPSO no longer affect nuclear safety, there is no need for the FPSO or its components to fall under the QAP.

Vice versa, an accident on the reactor platform with a potential release of radioactivity no longer poses a direct radiation hazard to the FPSO, given enough separation between both. This will drastically reduce or even negate the additional training of the personnel to deal with radiological hazards. If the control room is on the FPSO, the associated operators will still need nuclear training, of course.

Similar arguments regarding the disconnect of accident scenarios also hold for the attached platform but to a lesser extent. Major occurrences and severe accidents on the FPSO will affect the power platform and, hence, the nuclear safety. Thus, there will still be components that fall under the QAP, but less than in the on-deck case. Furthermore, events like sinking or extreme listing of the FPSO also influence the attached platform, meaning that the vessel itself needs to comply with the stringent IMO Code requirements.

The attached platform will require significant modifications to be made to the hull, whereas no FPSO redesign is needed for the floating and submerged platforms, given that they are fully detached from the FPSO. Thus, the detached platforms can be built and commissioned while the FPSO is in operation, only providing disruption when installing and connecting the cable between both. Therefore, FPSO will be out of service for considerably longer when using an attached platform, thereby incurring substantial lost production costs.

Another way lost production can arise is through extended maintenance outages. All power platforms provide a significant benefit over on-deck reactors through their ability to be towed to and from the site as a whole. By doing so, one avoids the issue of needing the reactors to cool down before transportation, as the platform is moved in its entirety – with the reactors remaining in their shielded area. This allows for a shorter reactor replacement time. In addition, the ability to tow the power platform as a whole circumvents the issues regarding offshore crane lifting constraints when replacing the on-deck reactors.

Furthermore, the lengthy commissioning process of a platform with new reactors can begin while the old platform and the FPSO are still in operation. Replacing the power system would then only incur the downtime needed to detach the old platform and hook up the new one – plus some testing afterward. In addition, for the floating and submerged platforms, the hull inspection requirements only apply to the power platform itself, meaning that it can be done onshore without disrupting the FPSO operation. For the attached platform, however, there FPSO hull will also need to be inspected under the IMO Code, adding maintenance work during the outage.

Extensive standardization of the power platform is possible when using a floating or submerged one, as the specifics of the FPSO itself do not matter beyond the total demand – e.g., brownfield or greenfield are the same. This enables the development of a set of platforms that house differing numbers of reactors depending on power demands. Any combination of these standard designs can then be used to fill the needs of the FPSO in question. Such an approach allows for modularity, which can accommodate changes in demand over the field lifetime and allows for a gradual switch towards nuclear power. Furthermore, standardization allows for cost reduction through learning by doing, and it allows the company to build up experience with the standardized system, resulting in efficiency gains across the fleet. Finally, the standard platform designs would only need to go through the licensing process once, drastically reducing lead times. Standardization of the attached platform is also possible, but to a lesser extent, as the connection to the FPSO will be unique in each project.

Finally, due to its added complexity, the submerged platform is expected to be the most expensive power platform.

All things considered, we expect the floating and submerged platforms to be preferable to attaching the power platform to the FPSO – all of which are preferable to using the reactors on deck. The main benefit of attaching the platform to the FPSO is the ability to have the utility heat provided by the NBs. However, this benefit is overshadowed by the many downsides such as an FPSO redesign, QAP requirements for the vessel and nuclear safety grade for some components, and the lack of standardization in design and licensing. Consequently, only designs for a floating and submerged barge are given in Sections 5.2.1 and 5.2.2.

5.2. Power platform design

5.2.1. Floating barge design

Here we adopt Westinghouse's eVinci to be our our reference reactor technology. The design of the floating barge is such that: (1) the layout of equipment matches the onshore eVinci plant layout as closely as possible, thereby maximizing technical feasibility, (2) the barge has a large waterplane area to ensure stability and prevent capsizing, (3) the reactors can be replaced with minimal disruption to other parts of the platform. All elements and their spacing are thus sized according to our best estimates resulting from Refs. [1], [46] – refer to Appendix A for more information. Figure 26 shows the resulting layout with all elements in the schematic drawn to scale.

A deviation from the onshore eVinci plant layout, as seen in Refs. [1], [46], is that there are only two I&C modules instead of two I&C modules and a load-following battery. The assumption is that the redundancy in the I&C modules in Refs. [1], [46] comes from the redundancy in the reactor bays, which is not present in our barge. Half of the modules labeled as I&C modules in our design drawing can thus be load-following batteries. Another deviation is the air ducts, whose (roughly) 2 m by 2 m cross-section is based on the air intake of the gas turbines on an LNG-producing unit [71]. They must extend above the upper deck significantly to avoid water intake during rough weather. However, this is not sized in the design.

For safety and security reasons, a double hull configuration is used, e.g., to limit the impact of low-energy collisions. To estimate the distance between both hulls, inspiration is drawn from tanker ships. The Oil Pollution Act of 1990 mandates that all tankers have a double hull to minimize oil leakage in low energy collisions and during grounding, and it specifies a minimum separation distance of 1 meter between the inner and outer hull [72]. However, typically, the actual separation between the tanks and outer hull is the lesser of B/15 and 2 meters where B is the beam width of the tanker, and it is thus often 2 meters [73]. For our design, an intermediate hull separation of 1.5 meters was chosen. A clear shortcoming of this equivalence is that the tanker hulls are designed for low-energy collisions, whereas security considerations of the platform will likely necessitate design for medium to high-energy collisions, too.

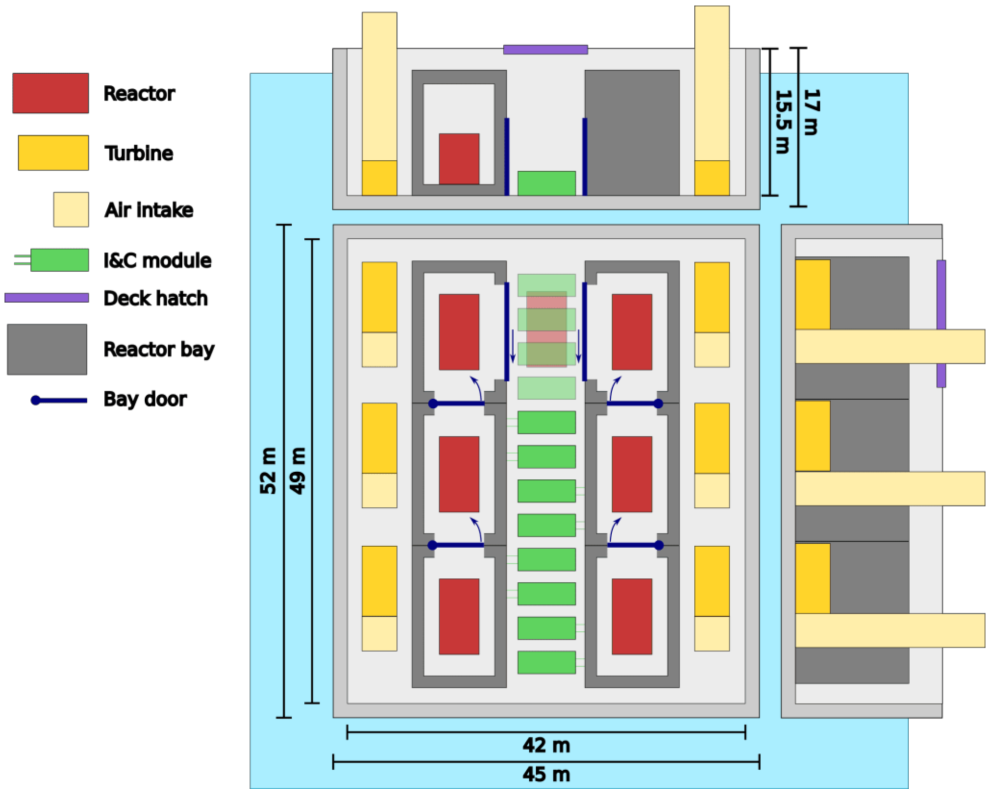


Figure 26 Top-down view (with side views) of a floating barge design for a power platform that houses six eVinci NBs; elements are drawn to scale

No optimization was performed on the presented design, and many questions remain open or poorly addressed – e.g., the hull separation or hull thickness, emergency power supply, mooring equipment, etc. In addition, it is assumed that no optimization is done on the reactor system side to make it more suitable for offshore use. The goal of this section is thus to present a high-level design to give a sense of the scale of the power platform; an optimized and completed design will likely look different. In the following paragraphs, we present a rudimentary assessment of the platform draft and assess its buoyant stability.

The total weight of the platform – referred to as its displacement, denoted Δ – must be known to find its displaced volume and, hence, its draft. The displacement is often divided into the weight of the platform itself – i.e., the structural steel, any mooring equipment, etc. - called the “lightweight” (L), and the weight of the cargo, called the “deadweight” (DWT) [74]. Since all components and weights of the eVinci module are known, the deadweight of six modules is easy to estimate as 22 731 MT. Given some margin, that puts the deadweight estimate at 24 000 MT.

The lightweight is harder to pin down, however. In ship design, it is often the deadweight capacity that is a design specification, after which initial estimates of the displacement are made using known ratios between the displacement and deadweight for given ship types. This method works well for deadweight carriers but is inaccurate for volume carrier [74]. Deadweight carriers are primarily characterized and limited by the amount of weight they can carry – e.g., tanker ships or bulk carriers for ore – whereas volume carriers are primarily characterized and limited by their cargo volume and transport lighter cargo such as cars, containers, tobacco, etc. [74]. The capacity factor of deadweight carriers is typically below 1.5 m^3/ton [74]. Based on the inner dimensions of 49 m x 42 m x 15.5m and the deadweight of 24 000 MT, our capacity factor is 1.33 m^3/ton, putting our platform in the range of deadweight carriers.

Yet, the method remains flawed in our case, as there is no direct equivalence between our platform and any of the traditional ship types. The question is, then, which ship type best represents our case? Essentially, our platform represents only a hull around a cargo bay, so bulk carriers or tanker ships are a better comparison than, for example, containerships, which also have many structures to keep the containers in place. As a result, the DWT/Δ ratio for a bulk carrier of 20 000 MT DWT is used, i.e., 74 % [74]. Using this ratio gives a displacement of 32 400 MT and a lightweight of 8 400 MT.

The estimate can be refined further by neglecting the propulsion component of the lightweight, as the platform would be towed to the site. So, the average machinery weight fraction of 14 % is subtracted, resulting in a final lightweight estimate of 7 300 MT. It is unclear whether this lightweight estimate is an over- or an underestimation of our platform weight. On the one hand, bulk carriers contain many structures irrelevant to our platform, notably living quarters. On the other hand, our platform hull will be subject to stringent safety and security requirements, likely resulting in a greater hull thickness. As a result of the ambiguity, no further refinement to the estimate is made.

To make sense of the top-down estimate using bulk carrier weight ratios, a bottom-up estimate is also provided in which an outer hull thickness of 2”, an inner hull thickness of 1.5”, and a steel density of 8 tons/m^3 are assumed. The resulting hull weight is 4 700 MT, which is on the same order of magnitude as the bulk-carrier-inspired estimate above. Unsurprisingly, the bottom-up estimate is far lower since it does not account for any support or auxiliary structures. So, the top-down estimate of 7 300 MT is used in further analysis, which puts the displacement at 31 300 MT.

The displaced seawater volume is found to be 30 500 m^3, assuming a seawater density of 1.025 tons/m3. From it, the draft is calculated to be 13 m, which is sufficiently low to allow general access to ports and shipyards, which typically allow for a draft of 15 m [70]. In addition, the 4 m freeboard also seems reasonable.

To assess the buoyant stability, the location of the center of gravity of the ship, the center of buoyancy, and the metacenter must be known. The center of buoyancy is simply the center of mass of the displaced water volume, and the metacenter is the point where the line of action of the center of buoyancy intersects the line of action of the center of gravity in the neutral position (i.e., the symmetry axis of the ship). If the metacenter is above the center of gravity, the structure is buoyantly stable, see Figure 27.

The following equation can be used to find the distance between the metacenter and the center of gravity:

$$MG = \frac{I}{\Delta} + KB - KG \tag{1}$$

where KG and KB are the distances of the center of gravity and buoyancy to the keel, I is the moment of inertia of the water plane area, and Δ is the displaced volume. The stability criterion is satisfied if $MG > 0$. Intuitively, the criterion can be understood as I/Δ representing a resistance to tipping, whereas $KB -$

KG represents the inherent (in)stability of the weight distribution – if the center of buoyancy lies above the center of mass, the structure will always be stable.

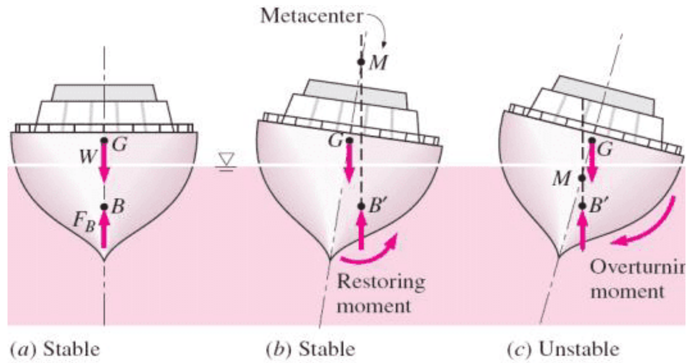


Figure 27 Schematic showing how the relative position of the metacenter and center of gravity affect the ship's stability [75]

The center of buoyancy is easy to find as 6.5m above the keel, given the constant transversal area. Locating the center of gravity, however, is not as straightforward and is done by first finding the center of gravity of the lightweight and deadweight separately. For the lightweight, the center of gravity is approximated by assuming the weight of the double hulls is exactly twice that of the deck and that the weights are concentrated on the outer plane. This results in a center of gravity that lies at 41 % of the side depth, i.e., about 7 m from the keel. The center of gravity of the deadweight, on the other hand, is calculated from the known distribution of weights in the platform shown in Figure 28, and is located about 8 m above the keel, putting the total center of gravity at around 7.8 m. Note the two peaks in transversal density that result from the bay floors and roofs.

Although the center of gravity lies above the center of buoyancy, the structure is stable due to the immense resistance to tipping provided by the large waterplane area. Further improvements to stability can be made by lowering the bay roofs to lower the center of gravity – although there might be technical reasons that make this infeasible. Another option is to add ballast to the lower hull, but this might make the freeboard unacceptably small.

However, buoyant stability is only the prerequisite for acceptable hydrodynamic behavior, which remains an open question and is a high-priority piece of future work for the continued design of the power platforms. The platform's motion should be minimized to ensure safe reactor operation, potentially requiring specialized mooring and stabilization equipment. For example, the use of synthetic mooring lines improves stability and limits the acceleration experienced by the platform [70]. In addition, station keeping should be given particular attention to limit the power cable fatigue mentioned in Section 5.1.

5.2.2. Semi-submersible design

The semi-submersible design has a fully submerged barge, which strongly resembles the floating barge discussed in the previous section and follows the same design philosophy. The main layout differences are the lower internal height of 14 m and a different air intake system that runs through the pillars of the semi-submersible. Additionally, there are structural differences in that the semi-submersible has a top deck that can be used as a landing area for helicopters and that accommodates the air intakes. Furthermore, it has ballasted cylinders, which are 10 m in diameter and height, and that can be used to change the draft of the system. Finally, the submersed barge has both water and solid ballast in the double bottom, and it has a double hull roof in contrast to the single hull deck of the floating barge. Figure 29 shows the resulting layout, with all elements drawn to scale. Once more, no optimization was done to improve the design.

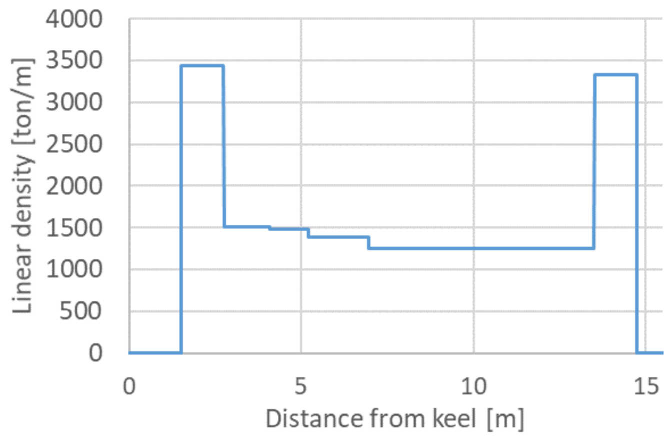


Figure 28 The transversal density of the deadweight of the floating barge design

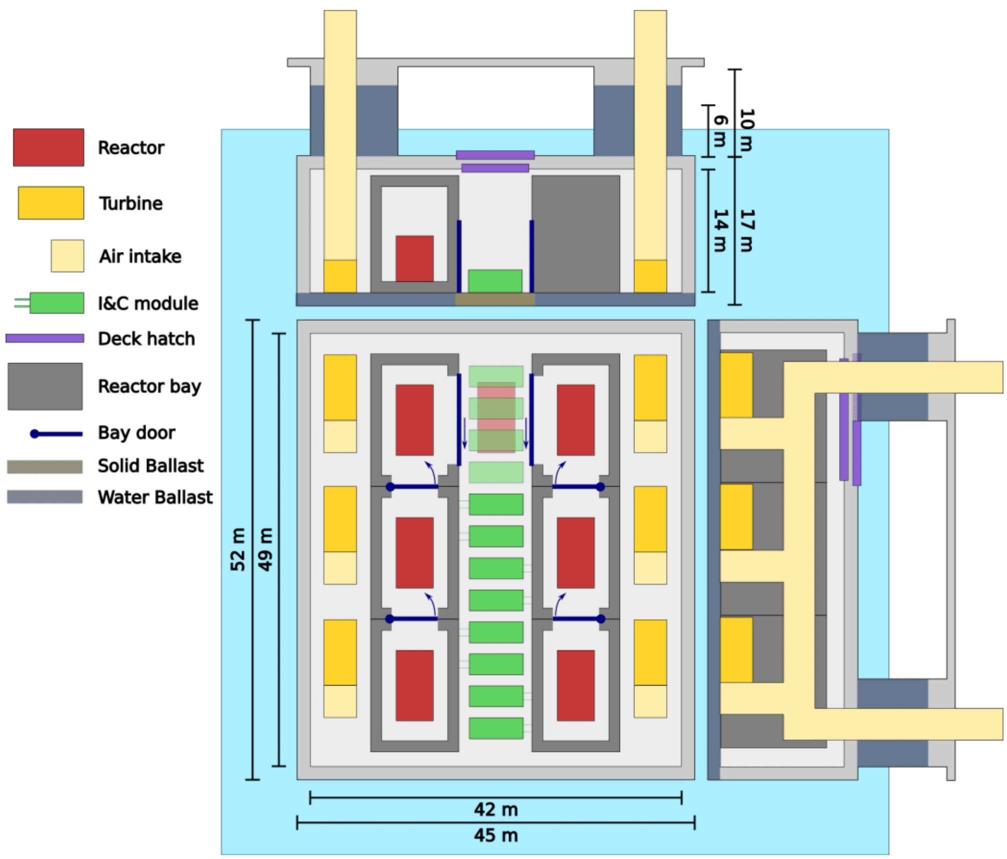


Figure 29 Top-down view (with side views) of a semi-submersible design for a power platform that houses six eVinci NBs; elements are drawn to scale

Given the similarity in the layout of the submerged and floating barge, the same deadweight of 24 000 MT is used. However, the lightweight has to be increased to account for the larger amount of structural steel. The weight of the cylinders is estimated by assuming a hull thickness of 2”, resulting in an added weight of 700 MT. For the additional weight of the top deck and the double-hull roof of the barge, we again use the approximation that the double-hull walls weigh exactly twice as much as a single-hull deck. Combined with the relevant areas, this approximation allows determining the weight of a single-hull deck of the floating barge to be 17 % of its lightweight, i.e., 1 250 MT. Thus, the added lightweight of the top deck and double-hull barge roof is estimated to be 2 500 MT, which puts the total lightweight at 10 500 MT – compared to 7 300 MT for the floating barge. Note that this 34 500 MT minimum displacement leaves the barge floating with a freeboard of 2.6 m.

The barge must be submerged in operation and float during servicing of the platform and reactors. Thus, variable ballast is needed. A straightforward solution is to add ballast to the barge to make it negatively buoyant and use the positive buoyancy of the empty cylinders to keep the semi-submersible afloat. A benefit of this approach is a low center of gravity, which aids stability. However, a downside is that the structure can be easily sunk by rupturing the cylinder walls, which could happen by accident, e.g., by collision, or on purpose by attackers.

A different ballasting approach is used such that the barge floats up when the cylinders are damaged. To achieve this, the barge is kept slightly positively buoyant such that the displaced volume of the cylinders is always less than the ballast volume in the cylinders – as part of this ballast needs to counteract the positive buoyancy of the barge.

Concretely, 20 % of the bottom inter-hull volume of the barge is ballasted with solid ballast – with an assumed density of 4 ton/m^3 – which lowers the freeboard of the barge from 2.6 m to 1.4 m. The remaining volume is filled with water to lower the freeboard further to 0.3 m. Then, the cylinders are filled with 8 m of water, which submerges the barge and gives a 6 m draft of the cylinders, with a remaining 4 m freeboard of the top deck. The water level inside the cylinders is thus higher than the free surface, so any rupture of the cylinder wall would make ballast water leak out of the cylinders, increasing the system's buoyancy and raising – rather than sinking – the barge. Note that little solid ballast is used to ballast the barge itself such that there is greater flexibility in the barge's draft for refueling.

The 6 m of water above the barge should already minimize the impact of airplane impacts [70] and avoid a direct collision of the barge with smaller vessels. But, if wanted, the cylinder height can be increased to lower the barge even further – one trade-off here being increased hydrostatic loads on the barge's hull.

In operation, the draft of the semi-submersible is thus 23 m – shown in Figure 29 – which can be lowered to 15.6 m by removing all liquid ballast. This is lower than the general access limit of the 15 m draft mentioned before. If needed, the minimal draft can be lowered by making the cylinders bigger or by filling them fully during operation, both of which would allow the removal of some solid ballast, thereby making the structure float higher in the water.

Once more, we estimate the buoyant stability of the system using Equation (1). The center of buoyancy is easily found by taking a weighted average of the center of the submerged cylinders and the submerged barge using their corresponding volumes. Similarly, the center of mass of the lightweight is found by taking a weighted average of the centers of the barge, cylinders, and top deck using their corresponding weights. Finally, the deadweight center of mass is calculated from the known internal weight distribution, Figure 30. Note the presence of the bottom hull and cylinder ballast in the transversal density.

For the semi-submersible, the center of gravity lies below the center of buoyancy, meaning that the system is buoyantly stable. In addition, there is also a significant resistance to typing, as evidenced by the 10 m and 13 m I/Δ terms. However, as was the case for the floating barge, the hydrodynamic performance should be further analyzed to assess its acceptability for reactor operation.

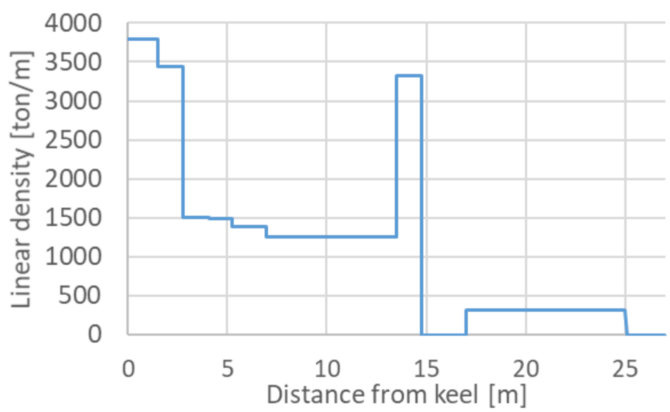


Figure 30 The transversal density of the deadweight of the submerged barge

5.2.3. The impact of maritime nuclear regulations

Sections 5.2.1 and 5.2.2 present designs for the floating barge and semi-submersible that are intended to give a sense for the scale of the system. The design philosophy was such to maximize the technical feasibility from the reactor side, i.e., to deviate from the onshore plant layout as little as possible. However, these do not account for the many additional requirements posed by the offshore nuclear regulations discussed in Section 4.2. So, in the following, we will revise the design of the floating barge to account for some of the regulations given in the IMO and ABS Codes [7], [8]. The design is shown in Figure 31. Again, there is no optimization of the designs, nor does even comply with the IMO Code fully. The goal is to give a feel for the impact regulations and some of the current regulatory uncertainty.

A particularly influential requirement is the need for the reactors and all safety systems to be placed inside a leak-tight safety enclosure, which essentially forms a second containment and encapsulates the well-known, traditional containment – more information on the safety enclosure and its function is given in Section 4.2.1. The safety enclosure must be protected from collisions – in part by the reactor compartment – resulting in the requirement that it be located no closer than B/5 m or 11.5 m inboard from the ship's side, whichever is lesser, along the longitudinal direction – where B is the beam width in meters [7].

The inboard separation requirement is written with conventional ship shapes in mind and thus leaves some ambiguity to the spacing of the safety enclosure for our barge. We thus conservatively assume the criterion applies in both directions of the barge where the beam width is 55 m, resulting in a standoff of 11 m from the outer hull in all directions. Evidently, this leaves far less space available for the reactors, and as a result, only four reactors can be placed on the barge instead of six.

Moreover, according to the IMO Code, the safety enclosure may not be closer to the bottom of the ship than B/15 m or 2 m, whichever is greater, to protect from grounding [7]. Again, this requirement does not translate well to our context of a platform without propulsion, but it is integrated regardless. Depending on which dimensions are taken to represent the beam, the safety enclosure must be about 3 m to 4 m above the bottom of the ship. We accordingly chose a 3 m double hull spacing in our design. Note that part of the required spacing could be provided by the reactor compartment so that it does not directly affect the double hull spacing. However, the reactor compartment is not specified in our design.

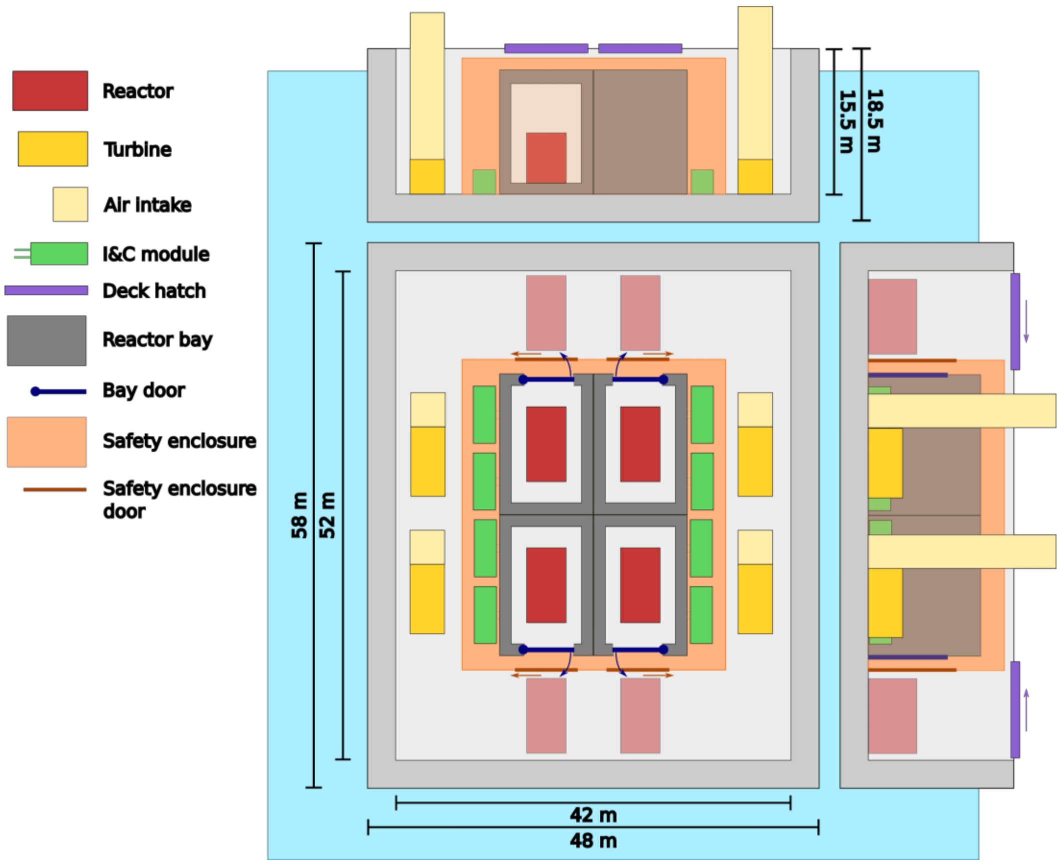


Figure 31 Top-down view (with side views) of a revised floating barge design for a power platform that houses four eVinci NBs and complies with the IMO Code regulations for the safety enclosure spacing; elements are drawn to scale

Given that the safety enclosure must already be a collision-protected area, one can wonder whether the reactor bays can be downsized to allow for more compact reactor configurations. After all, collision-protection is one of the main functions driving the design of the bay, the others being radiation shielding and protection from intruders. Here, we assume that radiation shielding does not allow changes to the bay. Note that this function could conceivably be achieved by water-filled volumes in between the reactors. In addition, protection from intruders can be achieved by the many layers surrounding the reactors – i.e., the double hull, reactor compartment, and safety enclosure.

An open question is whether the I&C modules are safety critical and must be located within the safety enclosure, as is conservatively assumed in the presented design. In the eVinci site renderings, the I&C modules are outside of the reactor building, which suggests they are not safety-critical. Having the I&C modules outside of the safety enclosure and redesigning the reactor bay will allow more reactors to fit in the safety enclosure, which will substantially reduce the cost of the barge relative to its power output.

As mentioned before, the reactor compartment is not defined in our design, as only its function is specified, not its location. The IMO Code states that a “reasonable area” must be included forward and aft of the reactor compartment to provide collision protection when striking an object and that the protective structure will be evaluated on an individual ship basis – paragraph 3.5.2 [7]. It is thus not certain that the provided standoff in our design is sufficient to comply with the regulations. In fact, it seems more likely than not that the design will need substantially more collision protection, given that a collision with a very large crude carrier with bulbous bow is part of the design basis and that the safety enclosure may not be punctured by such collisions. Note that this likely also means that the turbines cannot be within the reactor compartment.

It should be noted that it is the need for collision protection of the safety enclosure that drives up the size of the barge, which is likely an artifact of the IMO Code’s age. At the time of its writing, there were no passive safety systems. So, demanding collision protection of the safety enclosure was sensible given that it houses all safety systems needed for maintaining the reactor in a safe state after collision. However, in the context of NBs, this focus on the safety enclosure is over-conservative since reactor safety is passively provided – no external safety systems need to be protected – and the reactor module itself forms the containment – so the leak tightness of the safety enclosure is not needed. In fact, the safety enclosure is detrimental to achieving the passive decay heat removal of the eVinci and MIT NB, as it relies on the natural circulation of atmospheric air, and this pathway violates the leak tightness of the safety enclosure. Thus, we argue that the prescription of a safety enclosure should be removed and that there is no need to extend the collision-protected area beyond the reactor module[1].

The main conclusion from the above redesign is that compliance with the IMO Code – even superficially – does not allow for the simple, compact, and (relatively) cheap power platforms that we envisioned in Sections 5.2.1 and 5.2.2. The need for collision protection favors large designs that house many NBs or a single higher-power reactor.

More broadly speaking, an efficient, cost-effective design of the NB power platform is not possible under the current regulations, as they focus on using nuclear power for propulsion. This inherently assumes that the reactor and all its auxiliary systems are as small as possible compared to the size of the vessel itself. Our intent is the opposite, as we aim to design a platform for power services that is as minimal as possible compared to the reactors, resulting in tighter space constraints and the need for collision protection to be provided in innovative ways rather than a minimum standoff, e.g., by using a submerged barge with a such a deep draft that a collision with anything but a submarine is excluded. However, the current regulations do not allow to take credit for such solutions as they are focused on ships. Consequently, we again recommend early engagement with the appropriate regulatory bodies to ensure the timely development of regulations that elegantly address nuclear power platforms.

5.2.4. The conversion of existing vessels

Custom-built power platforms like those discussed in Sections 5.2.1 to 5.2.3 will be expensive to develop as they are not typical offshore structures – they are expected to cost between tens to hundreds of millions of dollars [70]. Given the nascence of the application, it is difficult to justify the large investments

[1] And its shielding, as it would be unacceptable to have an unshielded reactor after collision, even if the reactor itself is unharmed.

into their development. In addition, as shown in Section 5.2.3, the collision protection requirements of the IMO Code do not allow for a compact design, which will drive the cost up even more relative to the power output.

A potential way around both issues is to cheaply acquire large ships near the end of their life and convert them into NB power service ships. Evidently, these ships do not live up to the standards of the IMO or ABS Codes as they are, but there should be ample space in their cargo volumes to make modifications that provide, e.g., adequate collision protection. It should thus be relatively straightforward to meet all technical requirements of the IMO and ABS Codes.

However, complications might arise from the quality assurance standards. The IMO Code allows the responsible authority to develop its own QAP, given that it is consistent with its proposed QAP, and the ABS Code refers to common ABS standards for the vessel's construction. Assuming that the vessel is built according to a well-known and accepted standard, it should thus be possible to prove the compliance of the purchased vessel. In addition, all components and structures that get a safety class in the IMO Code will be added during the conversion process, again allowing to show compliance. Thus, providing quality assurance during the licensing process will get more complicated, but appears feasible under both Codes.

Figure 32 shows a rough sketch of what a converted containership might look like. With its capacity of only 554 TEU, the original containership belongs to the smallest category of containerships, the small feeders [76]. Yet, after conversion, it can house four NBs while respecting the collision-protection standoff rules and can thus provide the same power as the design presented in Figure 31. We expect the purchase and conversion of the small containership to be far cheaper than building the platform of Figure 31 from scratch. On the other hand, the engineering and licensing costs associated with each unique conversion process might justify the costly development of standardized power platforms if the demand for offshore nuclear power grows.

Another benefit of the conversion process is that the converted ship has living quarters, which can house on-site operators and guards if they are required by the regulator – which is likely the case in the early phases of microreactor development. Furthermore, note that tanker ships provide a better starting point for conversion since they already have a double hull. However, in its draft form, the ABS Code has more demanding hull spacing requirements for the double hull separation than the OPA 90, necessitating a modification of the double hull anyway [8], [72].

Maintaining sufficient inboard separation between the safety enclosure and the outer hull limits the number of NBs that fit onto a converted vessel. In the case of the small containership of Figure 32, the 23 m beam requires about 5 m inboard distance on either side, resulting in a maximum safety enclosure width of 13 m. This forces the 15 m-long reactor bays to be aligned single-file with the ship length. Increasing the ship's beam to 28 m or above allows the rotation of the reactor bays to fit more NBs on the ship per unit length, Figure 33.

From Figure 33, it is clear that ships with a larger beam can fit more NBs per unit length of the ship, allowing high-power operations to be serviced by a single large ship. For example, the moderately-sized Panamax containerships have a beam of 32 m [77] and can fit 15 eVinci reactors in the ship, resulting in a 75 MWe output – assuming half of the 294 m length is available for the reactors. If a higher output is needed, a Post Panamax ship (49 m beam [77]) can fit 24 eVinci reactors, good for 120 MWe – assuming 180 m out of the and 366 m length is available.

5. Alternative reactor placement

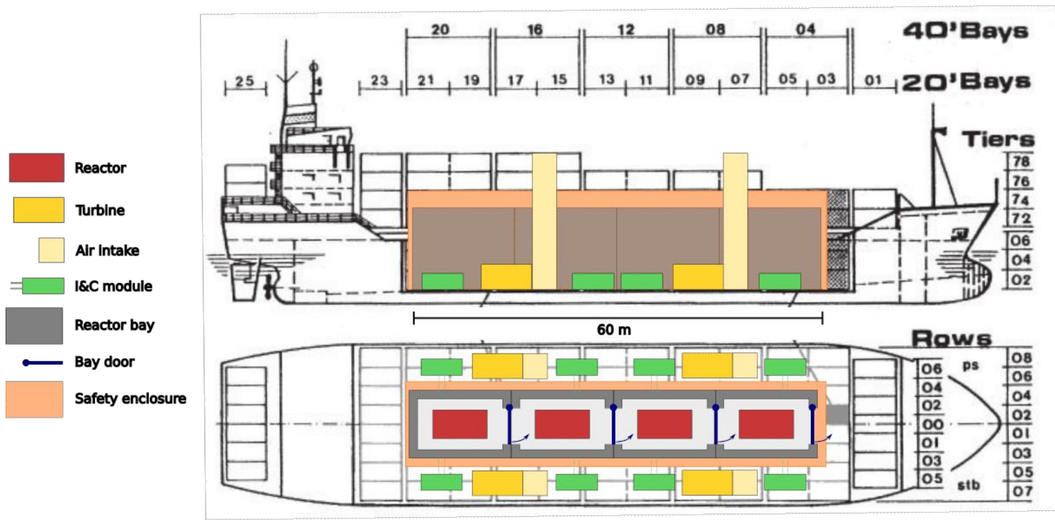


Figure 32 Top-down and side view of a small converted containership that houses four eVinci NBs and complies with the IMO Code regulations for the safety enclosure spacing; elements are drawn to scale

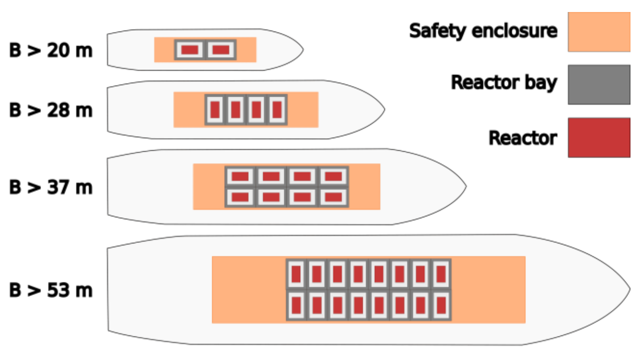


Figure 33 Schematic showing the impact of a ship's beam width on the stacking of the eVinci reactor bays

In 2021, Wan Hai Lines ordered the construction of 12 new Panamax containerships at 49 million USD each, and the Seaspan Corporation ordered ten Post Panamax ships at 86 million USD each [78]. The cost of these newly constructed vessels is in the same range as the expected cost of a custom-built platform [70]. Yet, they house four to six times more reactors, which increases confidence in ship conversion being the more attractive option over platform construction. Moreover, developing a novel power platform carries additional risk, which is avoided with ship conversion.

Larger ships can fit even more NBs. However, it does not make sense to go for the largest categories of ships, as the number of NBs involved becomes unreasonably large. For example, Ultra Large Crude Carriers with a beam width of 63 m allow for a quadruple-row configuration, which can then fit many dozens of NBs. In addition, it is advantageous to build up a fleet of vessels of a similar size and with a standardized power output, so that they can be used interchangeably and be serviced at the same yards.

Note that Figure 33 assumes that the IMO Code applies, whereas novel regulations might be more flexible in their collision-protection requirements by eliminating the outdated safety enclosure. In addition, the figure assumes that the concrete bay is not optimized for offshore use. An optimized layout might be able to fit many more NBs onto smaller ships, which will drastically improve economics.

6. **Other analyses**

6.1. Qualitative safety analysis

Table 11 categorizes different design-basis accidents according to whether they are similar to the onshore accidents, are unique to or especially relevant to our application, or do not apply to our context. In addition, it gives a highly-summarized indication of how the safety systems react to each accident. The discussion is largely focused on the eVinci design, and the presented list is not exhaustive, nor does it aim to be. The main intent is to give a flavor of how the safety analysis for the offshore use of NBs might differ from that of a typical reactor.

The accidents that directly affect the core or balance of plant are not appreciably different in the offshore environment. Table 12 and Table 13 list the main design-basis threats in each accident category and the main safety features for the different designs, respectively. Note that safety-related instrumentation malfunction is not expected to be more frequent in the offshore environment, as the instruments are within strictly controlled environments – particularly those within the functional containment.

Two notable exceptions are the isolation valve closure and overfilling events since they do not apply to our NBs; there is no containment isolation, nor can overfilling occur – so better yet, they are similar to onshore but eliminated by design. Similarly, spent fuel accidents and station blackouts are eliminated by design, as the spent fuel is stored at the Central Facility, and the NBs do not rely on external power to begin with. On the other hand, the response to fires is similar to the onshore context, but should be given additional consideration, as fires are particularly hazardous on offshore structures.

Note that although the design-basis accident scenarios related to the core are unaffected by the offshore context, there are new beyond-design-basis accidents. For example, flooding of the reactor compartment combined with a rupture in the eVinci canister might lead to water ingress into the core, which causes a reactivity increase and potentially chemical reactions with the core graphite and sodium in the heat pipes.

Back-up diesel generators on the power platform and the FPSO will start whenever the reactor has an emergency shutdown – called a SCRAM or reactor trip in the industry. However, before that, the load-following batteries of the eVinci design can be drained to smoothen the loss of power on top of the traditional inertia in the spin-down of the turbines. After all, we expect their design intent is to allow for a quicker system response – see Section 3.2.2. If wanted, additional battery capacity can be installed to further soften the discontinuity in supply after a SCRAM to protect the rotating equipment on the FPSO. Note that the batteries can also be charged to prevent excessive turbine spin-up during a loss of load event, such as the loss of the power cable.

Additionally, after a SCRAM, continuous cooling of the core is provided by the decay heat removal systems. Whenever possible, this cooling will be provided through the normal core cooling means, i.e., by circulating the reactor coolant and passing on heat to the secondary side, where it is finally rejected to the ultimate heat sink (the atmosphere in our case). However, decay heat can also be rejected passively if the active systems are unavailable, e.g., during a loss of ultimate heat sink. Note that when Table 11 does not specify the means of decay heat removal, we mean the above, i.e., active decay heat removal if available, passive otherwise.

For the eVinci and MIT NB, the passive decay heat removal relies on the natural circulation of atmospheric air through the reactor bay. However, the pathway to the atmosphere might be blocked in a capsizing event, will flood during sinking, and might not be as effective under large tilting angles. Flooding of the bay after sinking increases the heat transfer rate, so this scenario will likely not require a redesign, but it will require additional modeling to satisfy the regulator. On the other hand, a revised means of passive decay heat removal in case of capsizing and extreme tilting could be needed. Two cases that we expect to be especially challenging are the blocking of the atmospheric pathway during capsizing without flooding of the reactor bay and the dynamic rolling of the platform, which might hinder the development of stable air flow. Note that the BANR reactor also has passive decay heat removal, but its design is unknown, and the XENITH reactor likely also has passive decay heat removal. We expect similar remarks to hold for those designs.

Housing the reactors on a separate power platform rather than the FPSO largely decouples events on both. Because the power cable is the only link between them, the primary interactions between the FPSO and reactors will be related to mismatches in generation and demand. Through a sudden increase or decrease in the load, the FPSO will indirectly affect the reactors - with the worst-case scenario being a loss of the power cable and, thus, an immediate loss of the full load. Conversely, a loss of power from the reactors - through whatever accident that can cause a SCRAM - will impact the FPSO's operation and safety.

Another link between the FPSO and reactors is formed by the control room, in case it is on the FPSO rather than onshore to allow operators to remain close to the NBs and better assess the local conditions. Accidents on the FPSO can then lead to the distraction or loss of operators and the uninhabitability of the control room. Thus, the loss of operator action must be considered in the safety case of the power platform, and a redundant onshore remote SCRAM pathway might be needed.

Even though there could be a radioactivity release under the most severe accidents, they will not affect the FPSO due to the small Emergency Planning Zone for NBs. Jérémy Mangin and Amaury Le Person calculated the Emergency Planning Zone for the MIT NB to be only 400 m under the worst conceivable acts of sabotage – e.g., a deliberate and targeted plane crash [44]. The use of UO_2 fuel and sodium makes the potential radioactivity release of the MIT NB far greater than those of the other designs developed by industry. Thus, there will be no evacuation of the FPSO due to accidents on the power platform, given a separation between both on the order of a hundred meters.

Finally, as shown in Table 14, the semi-submersible design has an improved safety case over the barge due to its improved resilience against sea motion, capsizing, hull failure under shallow water sinking, and collisions - both ship and aircraft. On the flip side, the semi-submersible might have more issues with operator intervention in case of an emergency, as the submerged barge might be harder to access – which is an advantage from a security standpoint.

Table 11 The categorization of accident scenarios according to their relevance to our application alongside the response to each event type. Motivation is given for those events that do not apply to our context

Similar to onshore		**Unique to marine application**		**Not applicable**	
Accident category	**Response**	**Accident category**	**Response**	**Accident category**	**Motivation**
Undercooling	Core temperature increase + inherent power decrease	Ship collision	SCRAM + decay heat removal	Spent fuel accidents	No spent fuel handling or storage onsite
Overcooling	Core temperature decrease + reactivity insertion + automatic SCRAM	Capsizing	SCRAM + revised passive decay heat removal	Station blackout	No reliance on offsite power
Loss of flow	SCRAM + decay heat removal	Sinking	SCRAM + (potentially revised) passive decay heat removal	Isolation valve closure	There is no isolation of the (functional) containment
Loss of coolant	SCRAM + decay heat removal	Excessive motion	SCRAM + revised passive decay heat removal	Overfilling	N/A, see Table 12
Reactivity insertion	Inherent negative power feedback + potential control adjustment or SCRAM	Control room uninhabitability/ loss of operator action	Mayday + remote SCRAM + decay heat removal	Earthquakes	Ocean environment
Unintentional remote SCRAM	Start back-up diesel generators + decay heat removal	Loss of power cable	Turbine spin-up + trip + SCRAM + decay heat removal	Tsunamis	Deep waters + long wave period
Turbine trip	SCRAM + decay heat removal	Fire	Fire protection system activation + SCRAM	Loss of maneuvrability	Not self-propelled
Loss of working fluid	Turbine trip + SCRAM + decay heat removal	Green water event	Airflow filters + potential turbine trip	Grounding	NBs shutdown during towing
Loss of ultimate heat sink	SCRAM+ passive decay heat removal to atmosphere				
Instrumentation malfunction	SCRAM + decay heat removal				

Table 12 Exampels of design-basis occurrences in each accident category for the NBs

Accident category	**MIT NB**	**eVinci**	**BANR**	**XENITH**
Undercooling	• Loss of CO2 flow in power cycle • Heat rejection intake clogging	• Compressor stall • Air intake clogging	• Loss of feedwater	• Compressor stall • Air intake clogging
Overcooling	• Rupture of intermediary HX	• Turbine spin-up due to loss of load	• Loss of feedwater heater	• Turbine spin-up due to loss of load
Overfilling	• N/A (coolant is fixed mass and volume)	• N/A (coolant is fixed mass and volume)	• N/A (coolant is gas)	• N/A (coolant is gas)
Over pressurization	• Cover gas temperature increase	• Fill gas temperature increase	• Any undercooling event	• Any undercooling event
Loss of flow	• Sodium pump trip • Blockage of sodium flow	• N/A	• Helium circulator trip	• Helium circulator trip
Loss of coolant	• Coolant pipe break	• Heat pipe failure	• Coolant pipe break • Seal failure	• Coolant pipe break • Seal failure
Reactivity insertion	• Any overcooling event • Control drum rotation with positive reactivity insertion	• Any overcooling event • Control drum rotation with positive reactivity insertion	• Any overcooling event • Control rod withdrawal • Water ingress from steam generator leak	• Any overcooling event • Control drum rotation with positive reactivity insertion
Chemical reactions	• Sodium-CO_2 reaction • The containment is inertized	• N/A canister is inertized	• LOCA + air or water ingress	• LOCA + air ingress

6. Other analyses

Table 13 The safety features of each NB design

Safety features	MIT NB	eVinci	BANR	XENITH
Criticality control	• Control drums • Central control rod • Burnable absorbers	• Control drums • Shut-down rods • Burnable absorbers	• Control rods • Burnable absorbers (?)	• Control drums • Burnable absorbers (?)
Residual heat removal	• RVACS system	• Passive heat removal system using heat pipes	• RVPCS	• ?
Radionuclide retention	• UO2 pellet • SS cladding • Graphite • Primary coolant • Reactor coolant system • Containment bay	• Fuel kernel • TRISO ceramic coating • Fuel compacts • Core graphite • Reactor canister	• Fuel kernel • TRISO ceramic coating • Fuel compacts • Core graphite • Reactor coolant system	• Fuel kernel • TRISO ceramic coating • Fuel compacts • Core graphite • Reactor coolant system
Pressure control	• Cover gas pressure control	• Fill gas pressure control	• Safety relief valves	• Safety relief valves
Safety injection	• Not needed because decay heat removal is achieved even with complete loss of coolant	• Not needed (no coolant to make up)	• Not needed because decay heat removal is achieved even with complete loss of coolant	• Not needed because decay heat removal is achieved even with complete loss of coolant
Containment isolation	• Not applicable	• Not applicable	• Not applicable	• Not applicable

Table 14 A high-level comparison of the performance of the floating platform (or converted vessel) to the semi-submersible

Accident category	Best	Motivation
Ship collision or aircraft impact	Semi	The barge of the semi-submersible is far below the waterline.
Capsizing	Semi	For the semi-submersible, the center of gravity is below the center of buoyancy, which strengthens stability.
Shallow water sinking	Semi	The deeper draft of the semi necessitates a larger hull strength compared to the floating barge. As a result, hull failure under shallow water sinking will be less likely.
Deep water sinking	Equal	
Excessive motion	Semi	The semi-submersible will be significantly more stable due to its low center of gravity and the barge being far below the waterline where external forces are smaller.
Fire	Equal	
Instrumentation malfunction	Equal	
Control room uninhabitability	Barge	Operator intervention in case of an emergency might be harder on the submerged barge due to a lower number of access points that can be compromised more easily.
Green water event	Equal	
Loss of load	Equal	

6.1.1. Platform motion

To evaluate the acceptability of the platform's motion, we compare the expected acceleration on platforms to the earthquake resiliency of onshore nuclear power plants in Table 15. Appendix S to 10 CFR Part 50 *Earthquake Engineering Criteria for Nuclear Power Plants* [79] details the seismic performance requirements for onshore nuclear power plants, and it differentiates between the Safe Shutdown Earthquake (SSE) and the Operating Basis Earthquake (OBE) [79]. In short, the power plant should be able to shut down safely and maintain the reactor in a safe state if an earthquake of the magnitude of the SSE occurs. The SSE for which the reactor is licensed must then meet or exceed the maximum vibratory acceleration expected for that reactor site as necessitated by 10 CRF Part 100 *Reactor Site Criteria* [80]. On the other hand, the OBE is the most intense earthquake during which the plant can remain operational without undue risk to the public [79].

However, the NRC does not explicitly specify the ground acceleration that must be withstood by the reactor under the SSE. Instead, an Acceleration Time History (ATH) must be used to evaluate the nuclear power plant's response. Yet, the ATH is not specified by the regulator, either; it must be created based on a minimum Power Spectral Density, which is given in the Standard Review Plan section 3.7.1 [81]. The PSD measures the earthquake strength in the frequency domain, i.e., the energy content of the ground motion as a function of the motion frequency. Specifying the PSD ensures that no frequency components are underrepresented in the ATH used in the analysis [81]. Although no acceleration requirements are given as a sufficient condition, the horizontal ground acceleration should be at least 0.1 g [79].

Table 15 A comparison of the acceleration limits for onshore reactors to the expected acceleration for an FPSO and the OFNP

Onshore		**SSE**	**OBE**	**Source**
NRC limit	Vertical	/ (PSD)	/ (33% of SSE)	[79], [81]
	Horizontal	> 0.1 g	/ (33% of SSE)	[79]
AP 1000	Vertical	0.3 g	33% of SSE	[82], [83]
	Horizontal	> 0.1 g	33% of SSE	[82], [83]
ESBWR	Vertical	0.492 g	33% of SSE	[84]
	Horizontal	0.492 g	33% of SSE	[84]
Offshore		**Storm**	**Normal**	**Source**
FPSO	Vertical	0.2 g	0.03 g	[19]
	Horizontal	0.15 g	0.06 g	[19]
OFNP	Vertical	0.04 g	Negligible	[85]
(100 y)	Horizontal	0.07 g	Negligible	[85]

Since the NRC does not specify tolerable ground motion and acceleration directly, we instead look at the seismic performance of two modern onshore reactors: Westinghouse's Advanced Passive (AP) 1000 and General Electric-Hitachi's Economic Simplified Boiling Water Reactor (ESBWR). The AP 1000 reactors at the Vogtle site are licensed to withstand a vertical ground acceleration of 0.3 g [82]. The horizontal acceleration is not specified, other than that it is at least 0.1 g, satisfying the requirements of Appendix S [83]. Furthermore, the ESBWR can tolerate 0.49 g both vertically and horizontally in its SSE [84].

The maximum tolerable ground acceleration for the AP 1000 and ESBWR is large compared to the acceleration experienced by a typical FPSO and OFNP (see Table 15). Thus, we expect the platform's motion to be acceptable from a safety standpoint. The caveat is that the acceleration spectrum due to storms is different from that induced by earthquakes, even for the same peak acceleration. So different modes of vibration are excited in the structure.

Note that the OFNP experiences far lower accelerations during storms than the FPSO. Its excellent stability results from its deep draft and cylindrical hull [85], whereas FPSOs are known for their poor hydrodynamic performance [18]. We consider the FPSO to be a good proxy for the floating platform or converted vessel and the OFNP to be closer to the semi-submersible. Thus, we expect that the motion of the semi-submersible will have negligible consequences.

Although it is not expected to cause issues in terms of safety, the platform's motion could still complicate operations, necessitating frequent shutdowns if the OBE limits are exceeded. Much like the SSE, however, no requirements are given for tolerable ground acceleration during the OBE. Rather, the OBE can be specified as either one-third or less of the ground motion of the SSE, in which case no further analysis is required by the regulator, or as more than one-third, in which case the applicant should prove to the NRC that the reactor can remain operational without undue risk to the public [79].

Choosing the OBE ground motion as less than one-third that of the SSE has the clear benefit of not requiring additional, costly modeling during licensing at the risk of having a low limit to acceptable ground motion for operation. Given the infrequency of earthquakes, this is an acceptable limitation, which is why both the AP 1000 and ESBWR are licensed this way [83], [84]. However, if the NBs are licensed similarly, they risk having overly conservative limits on the acceptable platform motion.

Additionally, the platform's motion also affects fluid flows in the primary and secondary systems, particularly liquids. So, the BANR design, which uses water as the working fluid, and the MIT NB, which uses liquid sodium as a coolant, will be affected more than the eVinci and XENITH, which use either gases or heat pipes. Note that the heat pipes of the eVinci should not experience much flow redistribution as their liquid flow is driven by capillary forces.

Finally, the increased fatigue of structures and components should be accounted for in the design – the IMO Code draws explicit design attention to the cyclic loading [7]. Increased component malfunction – including instrumentation – is expected, requiring more intensive maintenance and inspection.

To conclude, we do not expect the platform's motion to be unacceptable for safety based on a rough comparison of the seismic performance of the AP 1000 and ESBWR to the acceleration experienced by the FPSO and OFNP in storms. Similarly, it should not pose a barrier to operations, although care must be taken not to have overly conservative OBE limits in favor of taking regulatory shortcuts. The MIT NB and BANR designs will be most affected due to the liquid coolant or working fluid. Finally, specific care must be given to fatigue-induced failures due to the constant cyclic loading.

6.2. Security

The cost of on-site personnel such as operators and armed guards has a tremendous impact on the LCOE of NBs [15], resulting in the need to minimize the number of armed guards as part of the security plan of the power platforms. Even if autonomous weaponry were to be used, this will be no easy task, as several features related to the application for FPSOs complicate providing adequate security. In this section, we will go over some of the difficulties that the security plan faces with the intent of highlighting the importance of this unresolved aspect of offshore NB use.

Perhaps the biggest complication is simply the large distance of a typical FPSO to shore and the correspondingly large response time of any external force that would aid in repelling the attackers. Furthermore, the operation of the FPSO itself complicates the security plan. For starters, FPSOs frequently need to offload the produced oil onto tankers, which prevents a Large Ship Exclusion Zone from being installed around the FPSO. In the security plan for MIT's design for an Offshore Floating Nuclear Plant (OFNP) [86], [87], the Large Ship Exclusion Zone extends for 6 nautical miles around the plant. If such a zone is needed around the power platform, it cannot be close to the FPSO.

Furthermore, the OFNP's security plant relies on an onshore facility where the personnel and material going to the plant are screened thoroughly on top of the regular background checks. Open questions are then whether such screening is also needed for the personnel related to the FPSO operation – e.g., the crew of the tanker ships – and who would be responsible for the onshore facility and screening in case the power platform provides energy as a service and is not owned by the FPSO owner. In any case, we expect that such screening requirements would add cost to the existing screening practices.

Security considerations only further add to the long list of challenges related to using the NBs on the deck of an FPSO – see Section 4. Most importantly, the flammability of the FPSO environment can easily be exploited to threaten nuclear safety. And second, the reactors and their surrounding safety structures are in plain sight, making them easy targets. Adding multiple layers of defense – as is done for the OFNP – would help, but this runs into issues regarding the total size and weight of the system.

With the external response being very far away, and the per-kWh cost of security being much higher for these small systems, it is not reasonable to assume that the initial security force can avert the attackers – if there even is a security force to begin with. The security plan of the NB power platform will thus need to assume that the attackers take control of the platform before any external force arrives and work from there. This is similar to the consequence-based analysis of Jérémy Mangin and Amaury Le Person for the MIT NB [44], in which they evaluate the potential consequence of an attacking force with system knowledge taking control of the plant without the intervention of a security force. Even with full control over the plant, the allowable intervention time before significant radioactivity release is large, i.e., about two weeks, largely thanks to the excellent retention properties of TRISO fuel [44]. The approach is in stark contrast with the security approach of the OFNP focused heavily on delaying attackers from gaining control over the plant until external forces arrive.

Besides rethinking the security approach, it might also be needed – and justified – to rethink the security objectives, as our application has a vastly different risk profile from that of a typical onshore nuclear power plant. For starters, the consequences that a potential attack has for the general public are far lower in our FPSO-supporting context than they are for a land-based power plant supplying the grid. Looking at the effect of each of the "attack goals" outlined in [86]:

- Disrupt: the disruption of the power platform does not impact the public (only the platform and FPSO owners); this is in contrast to the disruption of an on-grid power plant, which can hurt the public significantly
- Capture: none, only the platform and FPSO owners are affected by the disruption
- Nuclear incident: the radiological risk posed to the public resulting from radiation release this far offshore is negligible; however, there is still a risk to the environment
- Destroy: again, it is principally the owner and environment that are affected, given the small radiological risk posed to the public

Clearly, it is mainly the owner that is affected by attacks, not the public. This much reduced direct harm to the public might lead regulators to accept a change in security objectives.

Moreover, the power platform is not the ideal target for many of the motives of an attack, but it remains the FPSO. For example, disrupting the operations of the FPSO is easier to achieve by either targeting the poorly protected tanker ships rather than the FPSO or power platform. As another example, destroying the FPSO itself is both easier – by weaponizing the hydrocarbon environment – and more impactful to the owner than destroying the power platform. One cannot reason purely based on the motives of an attack. After all, the attackers could always act irrationally. However, given the limited impact on the public, it seems reasonable to view the security plan through the lens of investment protection rather than ensuring public safety. In this case, the existing security of the FPSO, alongside the clever design of the power platform, should be sufficient.

An important potential motivation not addressed above is the theft of radioactive material, against which our project is expected to be very resilient. To begin, there is no storage of spent fuel on-site, resulting in significantly less material at risk. Thus, only the fuel in the core can be stolen. However, this is not an easy task since it involves either (1) moving the platform as a whole, which is slow and easy to track for intervention, (2) moving the NBs onto another vessel, which is already deemed infeasible even if it is not done in a hurry, see Section 4.3, or (3) opening the core, which requires specialized equipment and shielding to avoid lethal radiation doses to the thieves. If thieves were to succeed in stealing the fuel, they would still have to extract the fissile material from the exceptionally robust TRISO fuel kernels, which is a highly challenging process in itself.

Note that not much regulatory guidance is given on the topic of security – e.g., the IMO Code briefly mentions that security provisions should be adequate [7], and the ABS Code intends to leave security primarily to the nuclear regulator [8]. So, we recommend early engagement with the relevant authorities.

To conclude, providing adequate security could potentially be an economic dealbreaker by requiring on-site guards and is complicated by the context of FPSO operation. The long response time of external forces and the need to minimize security forces point towards a consequence-based security approach, in which the security plan assumes that a knowledgeable attacker has access to the plant for a while before external forces can intervene. Moreover, given the limited potential harm to the public, we argue that the security objective is primarily investment protection and that the FPSO itself remains the key vulnerability in that regard. As such, the existing FPSO security force combined with a resilient platform design should form an adequate basis for security.

7. Conclusion and future work

This work investigates using NBs to replace the gas turbines that provide power for FPSOs in the context of reducing the carbon emissions of such assets. We conclude that a direct replacement of the turbines on the FPSO deck is not feasible for a host of reasons, including the enormous weight of the reactor bay. In addition, the demand of the largest FPSOs is too large to be supplied effectively using NBs, so higher-power alternatives should be considered – e.g., Small Modular Reactors.

However, NBs can still provide electrical power to the FPSO if placed on a separate power platform located near the FPSO. The utility heat must then be delivered through electrical heating or other means. The platforms should be either floating or submerged, with the submerged platform enjoying many technical and safety benefits over a floating barge at the expense of a higher expected platform (and development) cost. In the near term, the most cost-effective solution is likely the conversion of large existing ships, with standardized, custom-built designs potentially becoming more attractive as the market for offshore NB power services grows.

At present, the regulatory landscape is not ready to elegantly accommodate the project. NRC regulations do not yet allow for the NB paradigm. Moreover, regulations for offshore nuclear do not capture the safety profile of modern reactor technology, resulting in overly strict prescriptions (e.g., the safety enclosure), and they do not capture the intent of minimal design for power services. The lack of well-adapted regulations prevents cost-effective project execution and is a significant source of uncertainty for the overall feasibility.

Furthermore, we expect developing an adequate safety plan in the offshore environment to be feasible despite the potential need to redesign certain safety systems. Similarly, providing satisfactory security provisions should be possible in our context, but it will require a revision of the security approach and potentially a revision of the security objectives. However, developing and licensing both will be a costly and lengthy undertaking.

We recommend to engage with the regulators as soon as possible to guide the development of a regulatory framework that properly addresses the context of using NBs for power services. Moreover, it is advisable to show interest to vendors early to incentivize them to design (and later on license) their technology for offshore use. Lastly, we advise waiting for a minimum level of onshore microreactor maturity to avoid reliability issues and minimize lost production costs due to on-site testing.

Finally, particular areas of future work are to:

- Provide cost modeling to assess the economic viability of using NBs for FPSO decarbonization
- Further develop the design of a converted vessel
- Resolve the acceptable motion limits for continued operation (OBE) of the reactors further and compare those to the stability of the power platforms
- Resolve the security plan for NBs as it can sensitively impact the economics and is largely uncertain at the moment

8. References

[1] "Use of LMP Methodology for the eVinci Microreactor Design," Westinghouse, ML23333A835, Dec. 2023. Accessed: Apr. 21, 2024. [Online]. Available: https://www.nrc.gov/docs/ML2333/ML23333A835.html

[2] "Westinghouse Nuclear > Energy Systems > eVinci™ Microreactor." Accessed: Jan. 03, 2024. [Online]. Available: https://www.westinghousenuclear.com/energy-systems/evinci-microreactor

[3] "Xe-Mobile — Advanced Micro-Mobile Nuclear Reactor Solutions," X-energy. Accessed: Feb. 09, 2024. [Online]. Available: https://x-energy.com/reactors/xe-mobile

[4] "BWX Technologies, Inc. | BWXT Advanced Nuclear Reactor (BANR)." Accessed: Feb. 09, 2024. [Online]. Available: http://www.bwxt.com/what-we-do/advanced-technologies/terrestrial-micro-rx

[5] K. Shirvan *et al.*, "UO2-fueled microreactors: Near-term solutions to emerging markets," *Nuclear Engineering and Design*, vol. 412, p. 112470, Oct. 2023, doi: 10.1016/j.nucengdes.2023.112470.

[6] A. Abou-Jaoude *et al.*, "Assessment of Factory Fabrication Considerations for Nuclear Microreactors," *Nuclear Technology*, vol. 209, no. 11, pp. 1697–1732, Nov. 2023, doi: 10.1080/00295450.2023.2206779.

[7] "Resolution A.491 (XII) - 'Code of Safety for Nuclear Merchant Ships,'" International Maritime Organization, Nov. 1981.

[8] "Private Communication with Meg Dowling of the American Bureau of Shipping," Apr. 2024.

[9] "Georgia nuclear rebirth arrives 7 years late, $17B over cost | AP News." Accessed: Feb. 09, 2024. [Online]. Available: https://apnews.com/article/georgia-nuclear-power-plant-vogtle-rates-costs-75c7a413cda3935dd551be9115e88a64

[10] D. Owusu, M. R. Holbrook, and P. Sabharwall, "Regulatory and Licensing Strategy for Microreactor Technology," Idaho National Lab. (INL), Idaho Falls, ID (United States), INL/EXT-18-51111-Rev000, Aug. 2018. doi: 10.2172/1565916.

[11] P. Samanta, D. Diamond, and J. O'Hara, "Regulatory Review of Micro-Reactors: Initial Considerations," Brookhaven National Lab. (BNL), Upton, NY (United States), BNL-212380-2019-INRE, Dec. 2019. doi: 10.2172/1581244.

[12] J. Buongiorno, B. Carmichael, B. Dunkin, J. Parsons, D. Smit, and S. E. Aumeier, "Can Nuclear Batteries Be Economically Competitive in Large Markets?," *Energies 2021, Vol. 14, Page 4385*, vol. 14, no. 14, p. 4385, Jul. 2021, doi: 10.3390/EN14144385.

[13] F. Fakhry, J. Buongiorno, S. Rhyne, B. Cross, P. Roege, and B. Landrey, "A central facility concept for nuclear microreactor maintenance and fuel cycle management," *Nuclear Engineering and Technology*, Oct. 2023, doi: 10.1016/j.net.2023.10.016.

[14] D. Shropshire, G. Black, and K. Araújo, "Global Market Analysis of Microreactors DOE Microreactor Program," Idaho National Laboratory, 2021. Accessed: Oct. 02, 2022. [Online]. Available: http://www.inl.gov

[15] E. Germonpré and J. Buongiorno, "Feasibility Study of Decentralized Hydrogen Production using Nuclear Batteries," Massachusetts Institute of Technology, CANES report MIT-ANP-TR-199, Jan. 2024.

[16] M. Voldsund *et al.*, "Low carbon power generation for offshore oil and gas production," *Energy Conversion and Management: X*, vol. 17, p. 100347, Jan. 2023, doi: 10.1016/j.ecmx.2023.100347.

[17] L. Wilhoit and C. Supan, "2011 Deepwater Solutions & Records for Concept Selection: Going Deeper with Production Technology," May 01, 2011. Accessed: Apr. 03, 2024. [Online]. Available: https://www.offshore-mag.com/resources/maps-posters/whitepaper/14034320/2011-deepwater-solutions-records-for-concept-selection

[18] W. Cui, S. Fu, and Z. Hu, Eds., “FPSO (Floating Production Storage and Offloading),” in *Encyclopedia of Ocean Engineering*, Singapore: Springer Nature, 2022, pp. 638–638. doi: 10.1007/978-981-10-6946-8_300299.

[19] “Internal Communication with the Project Sponsors Shell, Equinor, and ExxonMobil,” 2023.

[20] “FPSO/FSO | Floating Production Systems | FPSO Business| MODEC.” Accessed: Apr. 11, 2024. [Online]. Available: https://www.modec.com/business/service/floater/fpso/

[21] “Sevan Piranema, the first Sevan circular-shaped FPSO. | Download Scientific Diagram.” Accessed: Apr. 11, 2024. [Online]. Available: https://www.researchgate.net/figure/Sevan-Piranema-the-first-Sevan-circular-shaped-FPSO_fig1_281705036

[22] “FPSO Topside Module Laser Scan To 3D Modeling,” Rishabh Engineering Services - Quality Engineering Solutions. Accessed: Apr. 11, 2024. [Online]. Available: https://www.rishabheng.com/project/fpso-topside-module-laser-scanning-to-3d-modeling/

[23] C. Adolphe, “Commissioning the Heating and Cooling Systems on an FPSO (Floating Production Storage and Offloading facility),” KTH, 2015. Accessed: Apr. 21, 2024. [Online]. Available: https://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-172775

[24] D. Grainger, A. U. Bindingsbø, O. Brekke, G. De Koeijer, O. R. Nilssen, and J. Pettersen, “Reducing CO2 emissions from offshore oil and gas production,” Mar. 2021. [Online]. Available: https://ssrn.com/abstract=3820726

[25] R. R. Brown, “FPSO Electrical Systems: Lessons Learned,” *IEEE Industry Applications Magazine*, vol. 10, no. 2, pp. 18–23, Mar. 2004, doi: 10.1109/MIA.2004.1270797.

[26] H. Fang and M. Duan, *Offshore Operation Facilities: Equipment and Procedures*. Gulf Professional Publishing, 2014.

[27] “IEC 61892-1:2019 | Mobile and fixed offshore units - Electrical installations - Part 1: General requirements and conditions.” International Electrotechnical Commission, 2019.

[28] “IEC 61892-3:2019 | Mobile and fixed offshore units - Electrical installations - Part 3: Equipment.” International Electrotechnical Commission, 2019.

[29] “10 CFR Part 50 | Domestic Licensing of Production and Utilization Facilities.” U.S. Nuclear Regulatory Commission, 1998. [Online]. Available: https://www.nrc.gov/reading-rm/doc-collections/cfr/part050/full-text.html

[30] “10 CFR Part 52 | Licensing, Certifications, and Approvals for Nuclear Power Plants.” U.S. Nuclear Regulatory Commission, 2007. [Online]. Available: https://www.nrc.gov/reading-rm/doc-collections/cfr/part052/index.html

[31] N. Guaita, “Uncovering hidden market opportunities for advanced nuclear reactors,” Idaho National Laboratory (INL), Idaho Falls, ID (United States), INL/MIS-23-74499-Rev000, Nov. 2023. doi: 10.2172/2278791.

[32] C. Forsberg, A. Foss, and A. Abou-Jaoude, “Fission battery economics-by-design,” *Progress in Nuclear Energy*, vol. 152, Oct. 2022, doi: 10.1016/j.pnucene.2022.104366.

[33] K. Schroeder, “Microreactor Regulations Put Alaskan Communities at Forefront of Energy Innovation,” Mike Dunleavy. Accessed: Mar. 28, 2024. [Online]. Available: https://gov.alaska.gov/microreactor-regulations-put-alaskan-communities-at-forefront-of-energy-innovation/

[34] S. E. Aumeier *et al.*, “Microreactor Applications in U.S. Markets: Evaluation of State-Level Legal, Regulatory, Economic and Technology Implications,” Idaho National Laboratory (INL), Idaho Falls, ID (United States), INL/RPT-23-71733-Rev000, Mar. 2023. doi: 10.2172/1964093.

[35] “Gateway for Accelerated Innovation in Nuclear - MicroreactorProgram.” Accessed: Mar. 28, 2024. [Online]. Available: https://gain.inl.gov:443/SitePages/MicroreactorProgram.aspx

[36] “Advanced Reactor Development,” Energy.gov. Accessed: Apr. 29, 2024. [Online]. Available: https://www.energy.gov/ne/articles/infographic-advanced-reactor-development

[37] P. Gordon, R. Lighty, J. Sanders, S. Clausen, and W. Pearson, "Inflation Reduction Act of 2022 Boosts Nuclear Power with Tax Credits and Funding," Morgan Lewis. Accessed: Jan. 14, 2023. [Online]. Available: https://www.morganlewis.com/pubs/2022/08/inflation-reduction-act-of-2022-boosts-nuclear-power-with-tax-credits-and-funding

[38] K. Martin, "Bonus Tax Credits and the Inflation Reduction Act | Project Finance NewsWire," Norton Rose Fulbright. Accessed: Jan. 14, 2023. [Online]. Available: https://www.projectfinance.law/publications/2022/october/bonus-tax-credits-and-the-inflation-reduction-act/

[39] J. Tirpak, "Lawmakers Push for More Nuclear Microreactors in INDOPACOM," Air & Space Forces Magazine. Accessed: Apr. 21, 2024. [Online]. Available: https://www.airandspaceforces.com/lawmakers-nuclear-microreactors-indopacom/

[40] T. E. Fairbanks KUAC-, "Work on Eielson microreactor project may resume this summer," Alaska Public Media. Accessed: Mar. 28, 2024. [Online]. Available: https://alaskapublic.org/2024/03/26/work-on-eielson-microreactor-project-may-resume-this-summer/

[41] R. Weinmann-Smith *et al.*, "Material Control and Accounting Regulatory and Technical Considerations for Microreactors," Los Alamos National Laboratory (LANL), Los Alamos, NM (United States), LA-UR-22-21265, Dec. 2021. doi: 10.2172/1845245.

[42] "U.S. Department of Energy Establishes High-Assay Low-Enriched Uranium Consortium," Energy.gov. Accessed: Apr. 21, 2024. [Online]. Available: https://www.energy.gov/ne/articles/us-department-energy-establishes-high-assay-low-enriched-uranium-consortium

[43] A. Huning, S. Arndt, and J. A. Christensen, "An Introduction to Microreactor Licensing Basis Events," Oak Ridge National Laboratory (ORNL), Oak Ridge, TN (United States), Jun. 2023. Accessed: Apr. 21, 2024. [Online]. Available: https://www.osti.gov/biblio/1993692

[44] A. Le Person and J. Mangin, "Consequence-Based Analysis of a Sodium-Cooled Graphite-Moderated Thermal Microreactor (SGTR)," Massachusetts Institute of Technology, Aug. 2023.

[45] "Discussion of Prof. Buongiorno with the eVinci development team," 2024.

[46] "eVinci Microreactor: Advanced Solutions | Virtual Tour," Westinghouse Navigator. [Online]. Available: https://navigator-voyantstudios.com/evinci.html

[47] "Load-following capabilities of NPPs - Nuclear Engineering International." Accessed: Apr. 29, 2024. [Online]. Available: https://www.neimagazine.com/features/featureload-following-capabilities-of-npps

[48] "Principal Design Criteria Topical Report," Westinghouse, ML23179A199, 2023. Accessed: Apr. 21, 2024. [Online]. Available: https://www.nrc.gov/docs/ML2317/ML23179A199.pdf

[49] "Technology Inclusive and Risk-Informed Reviews for Advanced Reactors:Comparing the US Licensing Modernization Project with the Canadian Regulatory Approach," U.S. Nuclear Regulatory Commission and Canadian Nuclear Safety Commission, ML21225A101, Aug. 2021.

[50] "Pre-Licensing Vendor Design Review." Accessed: Feb. 13, 2024. [Online]. Available: https://www.cnsc-ccsn.gc.ca/eng/reactors/power-plants/pre-licensing-vendor-design-review/#R3

[51] "Saskatchewan government provides C$80 million for eVinci demonstration." Accessed: Apr. 03, 2024. [Online]. Available: https://www.ans.org/news/article-5568/saskatchewan-government-provides-c80-million-for-evinci-demonstration/

[52] W. E. Company, "First Canadian eVinci™ Microreactor Targeted for Saskatchewan." Accessed: Apr. 03, 2024. [Online]. Available: https://info.westinghousenuclear.com/news/first-canadian-evinci-microreactor-targeted-for-saskatchewan

[53] Westinghouse, "Presentation: eVinci Microreactor Overview for MIT," Nov. 2023.

[54] X-Energy, "X-energy's Next-generation Integrated Transportable High-temperature Microreactor Plant | Flyer Shared with Prof. Buongiorno," 2022.

[55] H. Gougar, “Market-driven Optimization of the XENITH Microreactor.” U.S. Department of Energy Office of Nuclear Energy.
[56] “Project Pele in context: An update on the DOD’s microreactor plans.” Accessed: Mar. 13, 2024. [Online]. Available: https://www.ans.org/news/article-5308/project-pele-in-context-an-update-on-the-dods-microreactor-plans/
[57] E. Nygaard, “Private communication with Mr. Erik Nygaard, the director of Product Development for BWXT Advanced Technologies, LLC.”
[58] “Advanced Nuclear Reactor Technology | A Primer,” Nuclear Innovation Alliance, Mar. 2023. [Online]. Available: https://nuclearinnovationalliance.org/sites/default/files/2023-03/NIA%20Primer%20-%20March%202023_0.pdf
[59] “Offshore nuclear power concept under development by BWXT and Crowley.” Accessed: Feb. 14, 2024. [Online]. Available: https://www.ans.org/news/article-5397/offshore-nuclear-power-concept-under-development-by-bwxt-and-crowley/
[60] *International Convention for the Safety of Life at Sea (SOLAS), 1974*. London: International Maritime Organization, 1974.
[61] “International Convention for the Safety of Life at Sea (SOLAS), 1974.” Accessed: Apr. 13, 2024. [Online]. Available: https://www.imo.org/en/About/Conventions/Pages/International-Convention-for-the-Safety-of-Life-at-Sea-%28SOLAS%29,-1974.aspx
[62] I. A. E. Agency, “Quality Assurance for Safety in Nuclear Power Plants and other Nuclear Installations: Code and Safety Guides Q1-Q14,” International Atomic Energy Agency, Text, 1996. Accessed: Apr. 16, 2024. [Online]. Available: https://www.iaea.org/publications/5131/quality-assurance-for-safety-in-nuclear-power-plants-and-other-nuclear-installations-code-and-safety-guides-q1-q14
[63] “Nuclear Quality Assurance (NQA-1) Certification.” Accessed: Apr. 16, 2024. [Online]. Available: https://www.asme.org/certification-accreditation/Nuclear-Quality-Assurance-NQA1-Certification
[64] UK Government, *The Merchant Shipping (Nuclear Ships) Regulations 2022*.
[65] UK Government, *Explanatory Memorandum to the Merchant Shipping (Nuclear Ships) Regulations 2022*.
[66] “Maritime Guidance Note Nuclear Ships,” Maritime Coastguard Agency, MGN 679 (M).
[67] “Defence Nuclear Safety Regulations of the Defence Nuclear Enterprise,” Defence Safety Authority, DSA02-DNSR, May 2021.
[68] “Defence Nuclear Safety Regulations of the Defence Nuclear Enterprise -Guidance,” Defence Safety Authority, DSA03-DNSR, May 2021.
[69] C. Sleight Crawford, “Conceptual Design of a Nuclear Microreactor Transportation Cask,” Massachusetts Institute of Technology, 2024.
[70] “Communication with Paul Sclavounos, Professor of Mechanical Engineering and Naval Architecture at MIT,” 2024.
[71] S.-H. Lee, M.-I. Roh, M.-J. Oh, and K.-S. Kim, “Optimal Layout Design of a Liquefied Natural Gas FPSO: A Case Study,” *Journal of Offshore Mechanics and Arctic Engineering*, vol. 142, no. 041403, Feb. 2020, doi: 10.1115/1.4046012.
[72] *Double-Hull Tanker Legislation: An Assessment of the Oil Pollution Act of 1990*. Washington, DC: The National Academies Press, 1998. doi: 10.17226/5798.
[73] K. Terhune, “Limitations of double hulls,” Living Oceans Society, Mar. 2011. Accessed: Mar. 24, 2024. [Online]. Available: https://policycommons.net/artifacts/1192052/tanker-technology/1745176/
[74] A. Papanikolaou, *Ship Design: Methodologies of Preliminary Design*. Springer, 2014.
[75] M. Mohammed, “Mechanical design and State of the Art for Unmanned Surface Vehicle (USV) or Autonomous Surface Craft (ASC).,” 2018. doi: 10.13140/RG.2.2.31764.55681.
[76] “Container ship,” *Wikipedia*. Apr. 04, 2024. Accessed: Apr. 17, 2024. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Container_ship&oldid=1217286616

[77] "Panamax," *Wikipedia*. Apr. 03, 2024. Accessed: Apr. 22, 2024. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Panamax&oldid=1217054520
[78] C. N. Team, "VesselsValue: Newbuild Report 2021," Container News. Accessed: Apr. 17, 2024. [Online]. Available: https://container-news.com/vesselsvalue-newbuild-report-2021/
[79] "Appendix S to 10 CFR Part 50 | Earthquake Engineering Criteria for Nuclear Power Plants." U.S. Nuclear Regulatory Commission, 1998. [Online]. Available: https://www.nrc.gov/reading-rm/doc-collections/cfr/part050/part050-apps.html
[80] "10 CFR Part 100 | Reactor Site Criteria." U.S. Nuclear Regulatory Commission, 1998. [Online]. Available: https://www.nrc.gov/reading-rm/doc-collections/cfr/part100/index.html
[81] Haoyu X., Yizhou Z., Wengang Z., Guangwu T., and Yongcheng X., "Generation Method of Target Power Spectral Density for Seismic Design of Nuclear Power Plant Equipment," *hdlgc*, vol. 42, no. 5, pp. 128–133, Sep. 2021, doi: 10.13832/j.jnpe.2021.05.0128.
[82] "Vogtle, Units 3 and 4, Updated Final Safety Analysis Report Section 2.5," Westinghouse, ML122490612, Sep. 2012. Accessed: Apr. 21, 2024. [Online]. Available: https://www.nrc.gov/docs/ML1224/ML122490612.html
[83] "Vogtle, Units 3 and 4, Updated Final Safety Analysis Report Section 3.7," Westinghouse, ML122490612, Sep. 2012. Accessed: Apr. 21, 2024. [Online]. Available: https://www.nrc.gov/docs/ML1224/ML122490612.html
[84] "Final Safety Evaluation Report Related to the Certification of the Economic Simplified Boiling-Water Reactor Standard Design," General Electric-Hitachi, ML14100A304, Apr. 2014. Accessed: Apr. 21, 2024. [Online]. Available: https://www.nrc.gov/docs/ML1224/ML122490612.html
[85] Y. Zhang, J. Buongiorno, M. W. Golay, and N. E. Todreas, "Safety Analysis of a 300-MW(electric) Offshore Floating Nuclear Power Plant in Marine Environment," *Prof. Buongiorno via Chris Sherratt*, Mar. 2018, Accessed: Apr. 22, 2024. [Online]. Available: https://dspace.mit.edu/handle/1721.1/118919
[86] V. Kindfuller *et al.*, "Overview of Security Plan for Offshore Floating Nuclear Plant," in *24th International Conference on Nuclear Engineering*, 2016.
[87] J. Conway *et al.*, "Physical security analysis and simulation of the multi-layer security system for the Offshore Nuclear Plant (ONP)," *Nuclear Engineering and Design*, vol. 352, p. 110160, Oct. 2019, doi: 10.1016/J.NUCENGDES.2019.110160.
[88] "Radiation shielding concrete." Accessed: Feb. 14, 2024. [Online]. Available: https://www.concrete.org.uk/fingertips-nuggets.asp?cmd=display&id=786
[89] "Spirit™ 5 – Gas Turbine Power Generation System | Combustion Associates Inc.," Combustion Associates, Inc. Accessed: Apr. 09, 2024. [Online]. Available: https://cai3.com/spirit-5-mw/
[90] "Communication with Gyutae Park who is continuing work on the MIT NB," 2024.

Appendix A **Footprint and Weight Estimation**

The size and weight of the reactor systems crucially determine the attractiveness of the NBs as an offshore power source. However, they are not publicly available. So, in this appendix, the "total minimal" footprint and weight of the reactor system are estimated using renderings and other information. "Total" means that not only the reactor module but also the essential auxiliary systems and structures (i.e., the reactor bay) are considered. These systems are assumed to be unoptimized for offshore use – mainly the reactor bay, which could likely be downsized. In that way, the estimates are conservative.

And "minimal" in the sense that only systems are considered that are absolutely needed for operation. Non-essential elements – in a technical sense – such as a security perimeter and checkpoint, buildings to shelter the turbine and reactor bay from weather, and working space for operators are omitted. Many of these elements are important, so accepting their omission in offshore use is optimistic.

A.1 eVinci

The eVinci modules' sizes were determined based on a site rendering provided in Westinghouse's NRC report [1] and the eVinci navigator [46]. The green lines in Figure 34 draw a rough estimate of a rectangular area on the building floor, which is, in turn, used to rescale the image to a top-down perspective. After the rescaling, the floor coincides with the plane of the image, and distances can be measured as usual using an orthogonal basis. However, the horizontal and vertical scales are not equal.

The calibration process starts with the assumption that the person in the image is 1.8 m tall, which puts the bay height at 12 m (yellow lines). Moreover, the person's height can be used to estimate the width of the door as 1.65 m (red line). The door width is then used to calibrate distances in the horizontal direction. This allows us to estimate the turbine width to be 3.7 m, the reactor width (including reflectors) to be 4.2 m, the bay width to be 10m, and the bay wall thickness to be 1.25 m.

The vertical calibration relies on the assumption that the turbine support struts have equal spacing in the horizontal and vertical directions. Given the four windows between the struts in the lengthwise directions compared to two along its width, the turbine length is estimated at 7.4 m, which provides vertical calibration and puts the bay length at 15 m.

For simplicity, the cross-sectional dimensions of the air intakes are taken to equal the width of the turbine, 3.7 m, which also roughly matches the dimensions of the air intakes for the gas turbines of the LNG platform studied by Lee et al. [71]. Moreover, the dimensions of the I&C modules and load-following batteries are approximated to match those of standard 20 ft CONEX shipping containers.

Equipment is stacked as much as possible on FPSOs to save on deck area. Neglecting weight considerations for the deck strength and assuming that the auxiliary I&C and turbine modules can be placed on the reactor bay, the minimum footprint for a single eVinci module is about 150 m^2. A more reasonable approach will spread out the modules, as is done in the design of the floating barge, in which case the per-unit footprint roughly doubles to 343 m^2. Note that the footprint of an onshore facility including the security exclusion area is 1.5 acres – 6 070 m^2.

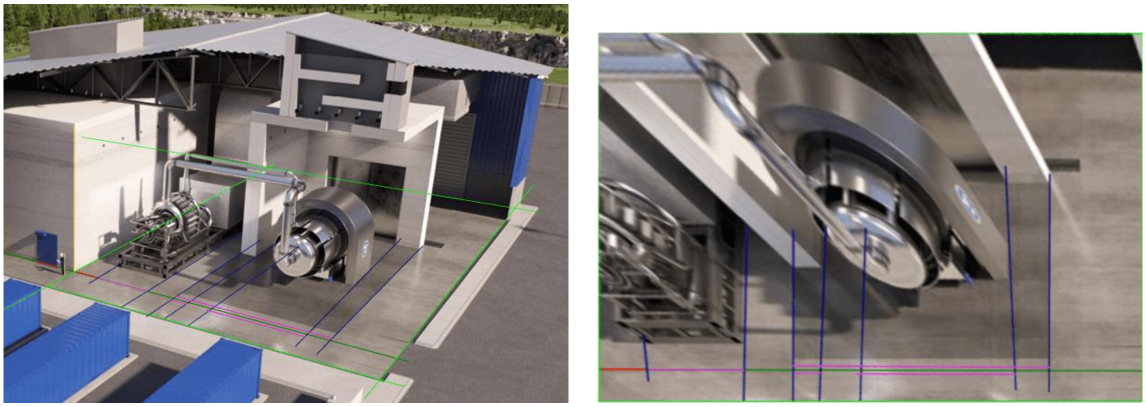


Figure 34 Left: a rendering of the eVinci site with an overlay of lines used to estimate component sizes. Right: a digitally rescaled image that shows a top-down projection

The total concrete volume of the bay is 980 m^3 assuming that the floor of the reactor bay on an FPSO is the same thickness as the walls and roof – which might not be needed given that the floor does not need to provide protection against intruders and airplane impact. Using the average density of radiation protection concrete of 3 700 kg/m^3 [88], that puts the reactor bay weight follows as 3 625 MT.

Moreover, the reactor module is estimated to weigh 100 MT [5]. The turbine weight – with generator set, air intakes, etc. – is approximated to be the same as that of the commercial 5 MW Spirit 5 gas turbine [89], i.e., 60 MT. Finally, the weight of the I&C modules and load-following batteries are approximated as twice the weight of an empty CONEX container, putting their weight at 4.1 MT – although the battery bank might be significantly heavier.

Table 16 summarizes the size and weight estimates of the different modules of the eVinci system. The reactor bay accounts for the majority of the total weight, with the weight of all other systems accounting for only 4 % of the total weight.

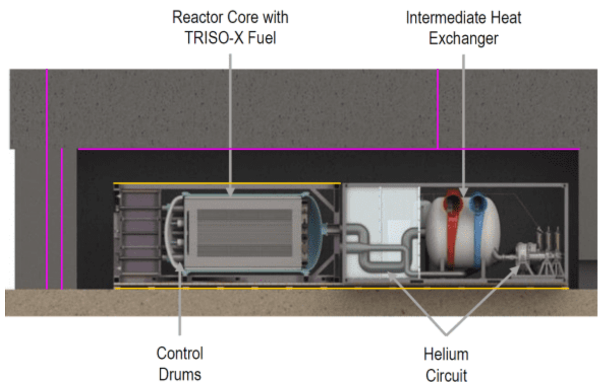
Table 16 Summary of the eVinci dimensions and weight

	L [m]	W [m]	H [m]	T [m]	Weight [MT]
Reactor bay	15.0	10.0	13.3	1.25	3 625
Reactor w. reflector	7.8	4.2			100
Turbine	7.4	3.7			60
Air intake	3.7	3.7			
I&C modules	6.1	2.4	2.6		4
Total weight [MT]					3 788
Minimum footprint [m^2]					150

A.2 XENITH

Much like the eVinci plant, the XENITH reactor module is placed inside a thick concrete bay without the I&C module and turbine, which are outside the bay – shown in Figure 21. The XENITH reactor module, the intermediary heat exchanger, and the I&C module are all the same size as standard 20-ft CONEX shipping containers [54]. Their length, width, and height are thus 6.1 m, 2.4 m, and 2.6 m, respectively.

The thickness of the concrete bay, as well as the inner height and length, can be determined using the known dimensions of the reactor module (Figure 35). Furthermore, the internal width of the bay can be estimated using the known width of the site, Figure 35. The outer length, width, and height of the reactor bay are 18 m, 11 m, and 6 m, respectively, which is similar to the dimensions of the eVinci reactor bay. Yet, with a thickness of 2.2 m, the XENITH reactor bay is significantly thicker than the eVinci reactor bay, which is only 1.25 m thick. The minimal footprint of the XENITH reactor – once more assuming that the turbine and I&C modules are stacked on top of the bay – is 198 m^2. The onshore exclusion area, on the other hand, is much larger at 1 338 m^2.



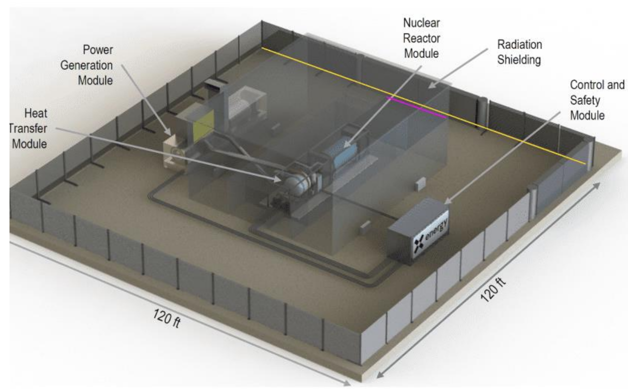


Figure 35 Renderings of the XENITH reactor bay and site layout with known lengths represented by yellow lines and estimated lengths shown with pink lines

By again assuming that the bay floor is the same thickness as the walls and roof, the bay concrete volume comes down to 1 261 m^3 with a weight of 4 665 MT – assuming a 3 700 kg/m^3 concrete density [88]. However, the vastly greater wall thickness might point to the use of regular concrete rather than high-density concrete. If a typical concrete density of 2 400 kg/m^3 [88] is used, the reactor bay weight comes down to 3 043 MT. Other factors may well be at play. For example, the XENITH reactor might have higher radiation leakage and need a thicker shield, or the bay may be designed with more stringent security requirements in mind – XENITH is a commercial spin-off of X-energy's Project Pele reactor for the Department of Defense, after all. So, for the purpose of this study, the more conservative 4 665 MT is used.

In addition, the weight of the reactor module is mentioned to be less than 50 MT in Ref. [54]. To be conservative, we use the upper limit of 50 MT and assume that the intermediary heat exchanger weighs as much as the reactor module itself. Finally, the turbine and I&C module weights are chosen the same as for the eVinci reactor, which again puts the total system weight at 164 MT – 3.4 % of the total system weight.

Table 17 Summary of the XENITH dimensions and weight

	L [m]	W [m]	H [m]	T [m]	Weight [MT]
Reactor bay	17.8	11.1	8.1	2.2	4 665
Reactor module	6.1	2.4	2.6		50
Intermediary heat exchanger	6.1	2.4	2.6		50
Turbine	7.4	3.7			60
Air intake	3.7	3.7			
I&C modules	6.1	2.4	2.6		4
Total weight [MT]					4 829
Minimum footprint [m^2]					198

A.3 MIT NB

Most of the sought-after dimensions can be taken directly from the work of Shirvan et al. [5] – see Figure 36. However, information about the heat rejection system is missing. To be conservative, we assume that the heat rejection system is so large that it occupies almost all space above the reactor bay and turbine. As a result, the minimal footprint of the stacked equipment is not simply the floor area of the bay but the floor area of the bay and turbine, i.e., 159 m^2.

In the work of Jérémy Mangin and Amaury Le Person on the security analysis of the MIT NB bay (Ref. [44]), the reactor bay thickness is 2 m – whereas it is only 1 m in the work of Shirvan et al. [5]. Here, we also assume a 2 m thickness, resulting in a concrete volume of 715 m^3 and a bay weight of 2 645 MT. The bay is much smaller than those of the XENITH, eVinci, and BANR designs, and likely misses key design features due to the early design stage. As a result, it may not be representative of the final design.

Finally, the reactor module is relatively light at 76 MT [90]. With the same turbine and I&C module weights, that puts the total system weight at 140 MT – i.e., 5 % of the total weight.

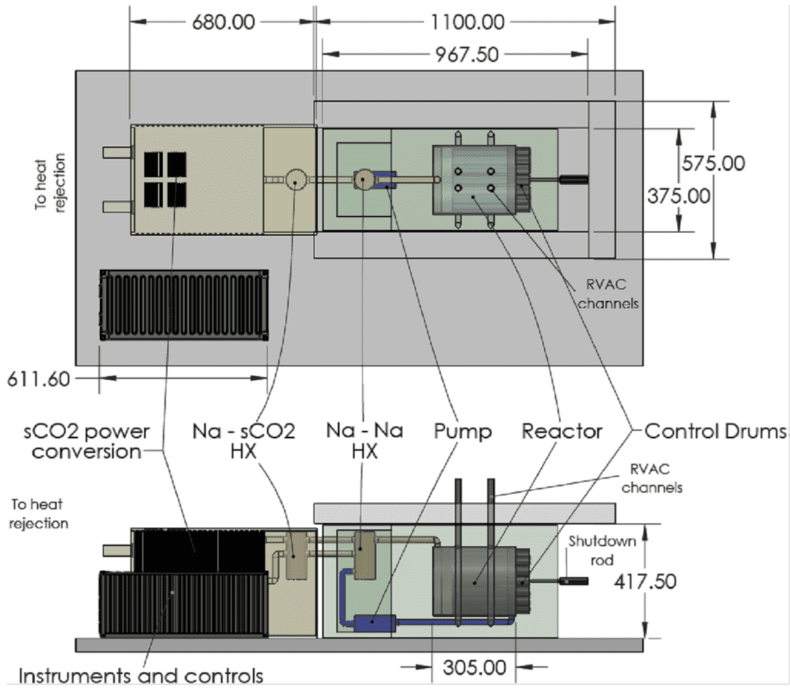


Figure 36 The site layout of the sodium-cooled NB [5]

Table 18 Summary of the MIT NB dimensions and weight

	L [m]	W [m]	H [m]	T [m]	Weight [MT]
Reactor bay	13.7	7.8	8.2	2.0	2 645
Reactor module	9.7	3.8	4.2		76
Turbine	6.8	3.8	4.2		60
I&C modules	6.1	2.4	2.6		4
Total weight [MT]					2 785
Minimum footprint [m^2]					159

A.4 BANR

The BANR reactor has a core power density of 1.8 MW/m^3 [57], which gives a total core volume of 27.8 m^3. From the core volume, the height and diameter can be calculated as 4.3 m and 2.9 m, respectively, using an approximate radius-to-height ratio from the BANR bay rendering – the yellow cross over the vessel in Figure 37. The distance between the rails on the floors can be obtained using the vessel width, which can, in turn, be used to calibrate distances in the backward plane of the bay – orange lines – and the forward plane – green rectangle and purple line.

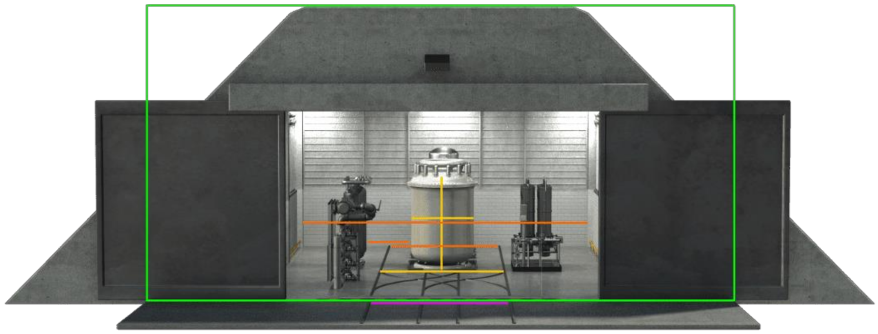


Figure 37 Rendering of the BANR reactor bunker [57] with an overlay of lines used in the estimation of the bay dimensions

The slanted walls of the BANR reactor bay, as shown in Figure 37, are designed to minimize the impact of projectiles – after all, the BANR reactor is the spinoff of BWXT's Project Pele reactor for the Department of Defense. It is unreasonable to assume that the bay will maintain this shape, in the context of FPSOs. So, instead, we assume that the bay is cut off at the green bounding box, which puts the outer width and height of the BANR reactor bay at 24.5 m and 12.3 m, respectively. The inner width of the bay is 15 m based on the separation of the rails on the back wall – orange lines in Figure 37. So, the wall thickness is 4.8 m, which is still enormous despite the cutoff provided by the green box.

In addition, the calibration on the back wall can be used to determine the length of the tiles as 0.37 m. Counting tiles on the side wall – in a different rendering – then allows us to estimate the inner length of the reactor bay as 19 m. Using the same wall thickness, we find an outer reactor bay length of 23.8 m.

No weight estimates are given for the BANR reactor given the large uncertainty in the reactor bay volume when adapted for offshore use. Furthermore, the power-to-weight ratios of the other designs already paint a clear picture: the reactor bays are too heavy for use on the FPSOs – see Section 4.1 for more discussion.

Table 19 Summary of the BANR dimensions

	L [m]	**W [m]**	**H [m]**	**T [m]**	**Weight [MT]**
Reactor bay (outer)	23.8	24.5	12.3	4.8	/
Reactor bay (inner)	19	15			
Reactor module	2.9	2.9	4.3		/
Minimum footprint [m^2]					583