INL/CON-22-68692-Revision-0

MODULARITY-AT-SCALE FOR COST COMPETITIVE DEPLOYMENT OF NUCLEAR ENERGY

October 2022

Changing the World's Energy Future

Efe G Kurt, David E Shropshire

INL/CON-22-68692-Revision-0

MODULARITY-AT-SCALE FOR COST COMPETITIVE DEPLOYMENT OF NUCLEAR ENERGY

Efe G Kurt, David E Shropshire

October 2022

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

MODULARITY-AT-SCALE FOR COST COMPETITIVE DEPLOYMENT OF NUCLEAR ENERGY

E.G. Kurt[1], and D.E. Shropshire[1]

[1]Idaho National Laboratory, Idaho Falls, ID, USA

efe.kurt@inl.gov, David.Shropshire@inl.gov

Abstract

Modularity options have been limited for traditional nuclear energy deployment due to the conventional light water reactor (LWR) safety requirements, such as high pressure retaining heavy and robust containment structures. However, a relatively new regulatory approach called 'Functional Containment' has potential to allow less expensive and more flexible designs for non-LWRs. Functional containment provides flexibility in design and deployment based on risk-informed and performance-based criteria, so that reactors are not over-designed. Non-nuclear industry has successfully used modular design approaches in automotive, aerospace, chemical processing, building construction, and ship building. These industries have shown that modular construction reduces construction time by around 30% - 50% compared to the conventional stick-built approach. The nuclear industry can use similar approaches to reduce construction time and costs, balanced with safety requirements, using the functional containment approach. This paper discussing the background of modularity in nuclear energy, examples of less learned, modularity approaches in non-nuclear industries and the potential of cost and schedule savings through the emerging regulatory design flexibilities potentially enabling combination of modular deployment at different scales.

1. Introduction

Recent nuclear power plant builds around the world, especially in the US and the West, have not been cost-competitive with other energy sources. They suffered from cost overruns that are multiples of their initial estimates and schedule delays spanning over a decade. LWR plants have large, heavy, and costly pressure-retaining concrete containment structures, in addition to passive and active safety systems, to prevent the release of fission products in case of a severe accident. From the regulatory perspective, the excellence in quality and imposing ASME requirements on these types of structures are critical for the safety of public. This statement also holds true for the non-LWR Generation IV (GEN-IV) reactors, however non-LWR nuclear energy options come with inherent safety features that enable new approaches on the design of the plants. Some of the components of the GEN-IV reactors may become more costly relative to the LWR type plants, such as fuel costs. Alternatively, more flexible regulations, which may be applicable to different reactor physics of Generation IV concepts, provides the opportunity for innovative and lower-cost alternatives to the entire traditional containment structure system while maintaining (or ideally improving upon) plant, public, and environmental safety. Advantages of modularization [1], include relatively shorter construction schedules due to increased productivity and better quality-control, reduced costs through higher on-site efficiency, repeatability and learning by standardization of the design and re-use of equipment, and broader availability of skilled laborers working in nuclear projects at remote locations. From an investment perspective, increased construction efficiency through modularity enables robust mitigation against uncertain market conditions. It is argued that modularity may be preferred over non-modular approaches, even if the cost is higher for the former [2]. Such a preference can also be attributed to the ability to defer investment costs for future reactor modules and enable self-financing of future deployments with revenues produced by the earlier units. This statement becomes more valuable for uncertainties in the market and at the deployment stages, if the project is one large-sized plant with high capital requirements.

The Generation IV International Forum (GIF) Economic Modeling Working Group (EMWG) [3] credit the benefits of modularization for large GENIV reactor concepts to learning effects, parallel production, parallel construction, site productivity, cost of money, capital at risk and future technology benefits. US Nuclear Regulatory Commission has been releasing information on a technology-inclusive, risk-informed and performance-based approach, that may be alternatively called functional containment. Functional containment refers to the set of barriers designed to prevent any release of radioactive material to the environment. Existing light-water reactor (LWR) plants have large, heavy, and costly pressure-retaining concrete containment structures to prevent the release of fission products in case of a severe accident. The U.S. Nuclear Regulatory Commission (NRC 2018) describes a "functional containment" approach to the overall design scheme of an advanced nuclear power plant (NPP). The NRC describes functional containment as the full set of barriers designed to prevent any release of radioactive material to the environment. Hence, functional containment approach can shift the nuclear plant design from satisfying rigid LWR-style prescriptive requirements toward considering multiple possible solutions in a technology-inclusive, risk-informed, and performance-based (TI-RIPB) manner. The approach also enables the combining of innovative alternatives to prevent release of radioactive materials, protecting against external hazards, and producing site-independent designs such as seismic isolators, underground embedment, accident-tolerant fuels, and passive safety systems. Functional containment provides more latitude on engineering decisions and technology selection as long as safety requirements are satisfied. This flexibility can lead to significant cost reductions for nuclear plants, as discussed below. The functional containment approach enables a broad strategy that would be applicable to all nuclear plant categories—Gen III+, SMRs, microreactors, and Gen IV concepts—to varying degrees. For example, in some circumstances, the enveloping structures could be thinner or lighter, or they could be constructed more easily with advanced concrete and other innovative materials. For SMRs and microreactors, functional containment would involve scaling down containment for smaller reactor sizes and their particular risk profiles. As another example, advanced reactors, such as modular high temperature gas cooled or very high temperature reactors, provide safety features that do not exist in the traditional LWRs. The possible internal hazards associated with these non-LWR reactor designs are also different from traditional LWRs. The necessary pressure-related containment boundary for LWR design is not required for these types of designs. Because the safety features and the release environment are different from traditional LWRs, they provide the basis of functional containment. Figure 1 shows a possible application of structural design arising from the beneficial aspects of the functional-containment approach to an advanced-reactor concept.

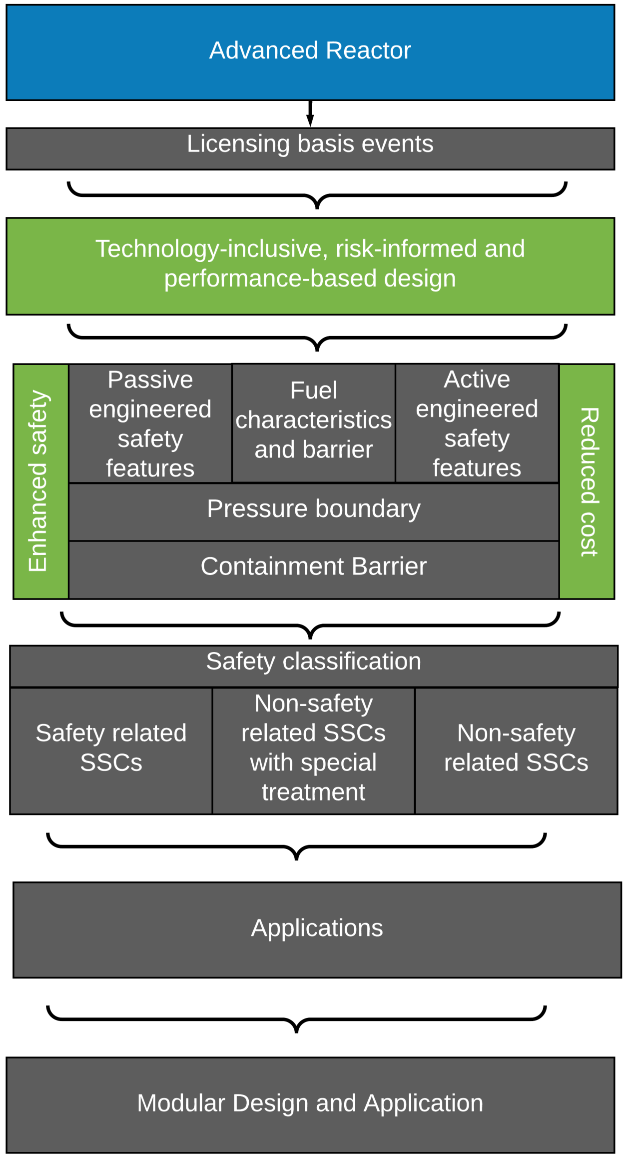

Figure 1: Functional Containment Approach for Modular Design and Applications

This study is based on the GIF EMWG Advanced Nuclear Technology Cost Reduction Strategies and Systematic Economic Review (ANTSER) framework. The 2021 cost reduction strategy was based on Functional Containment [4] and was expanded upon in the second strategy focused on cost reduction through modularity. This paper summarizes key findings from the 2022 GIF report on Modularity-at-Scale [5].

2. Modularity at scale

Modularity can be applied to different scales of nuclear energy deployment. Not all modularity approaches, such as modular reactors or modular balance-of-plant, are applicable or meaningful at every scale. Below is a brief discussion related to applicability and combability of modular approaches for different scales: large NPPs, SMRs and microreactors.

2.1 Modularity for large NPPs

The ability to break down structures, systems, and components into transportable modules for assembling them together at a site is an important parameter of modularity. Road transportability is constrained by the weight and size of modules, depending upon the final deployment location. Large NPPs have a disadvantage over smaller sized plants due to limits on module transportability, e.g., power plants above 600 MWe may become too large to be road transported. From a constructability perspective [6], recommended a maximum of three modules for each component and structural element. Increasing the number of modules also starts to increase the number of connections to construct the equipment or structural elements. This results in (1) time spent connecting the modules, (2) increased workmanship, and (3) increased complexity of the work. As an example, a structural module can be assembled much quicker than the same unit divided into 20 modules that would require connecting them together. Module subdivision may not be feasible for all machinery and equipment, for instance the moisture-separator reheater units in a turbine building cannot be subdivided. Large-size plants have not benefited from modular approaches both at the reactor and construction stages. The scalability is constrained through an increase in power outputs. For example, AP1000 designs have a higher output than a former AP600 reactor. Modularity discussions for large scale plants are usually restricted to BOP, specifically for construction. In the early 2000s, a U.S. company attempted to modularize construction of a large-scale nuclear plant using steel-plate composite (SC) walls. SC walls are concrete walls sandwiched between steel plates. The modular steel portions of the SC walls would be built in fabrication shops, transported to the reactor site where the modules are welded together, and concrete is poured inside the modules. A ICONE 9 conference paper [7] describes this approach as follows:

> *"Its designers made a concerted effort to simplify systems and components to facilitate construction, operation, and maintenance."*
>
> *"It has been designed to make use of modern modular construction techniques. To the maximum extent possible, the design is based upon parallel construction activity paths. This is done through the extensive use of modules."*
>
> *"...concrete to fuel load is 36 months. This duration has been verified by experienced construction managers through 4D (3D models and time) reviews of the construction sequence."*

Unfortunately, the advantages of modular construction were not realized in actual practice. Difficulties in maintaining the quality of the on-site nuclear grade welding and discrepancies in the tolerances between approved engineering drawings and on-site implementation, resulted in cascading effects on the cost and schedule of the projects. However, this does not imply that modular construction is not suitable for nuclear energy, but it shows the importance of decision making at early stages that aligns with potential challenges of nuclear-grade construction.

Although the SC modular systems were promising, the technology's high reliance on on-site work, including high volumes of nuclear grade welding or on-site concrete pouring, quality control, and inspection, decreased the effectiveness of the modular approach. If AP1000s did not face with such issues and they been successfully deployed in series, the costs would be expected to be below $3000 per kilowatt.

2.1.1 Modularity for SMRs

Contrary to conventional large size NPPs, which are typically monolithic plants, the integral layout and reduced size of SMRs [8] may benefit from factory fabrication of components which are transported to and assembled into super-modules in an on-site assembly area and eventually lifted and installed in the designated location. This construction strategy is called modularization. The nuclear industry is still in its early stages to fully understand the merits and challenges in modularization due to a lack of experience in production scale deployment of SMRs. The transition from stick-built to modular construction in nuclear industry still requires further research to realize benefits experienced by other industries [9]. Based on experience from other sectors (e.g., oil, gas, high rise, etc.), modular construction results in schedule compression because of simultaneous design and procurement, higher productivity off-site and parallel production [10] and cost savings achieved by economy of scale in production, lower cost of labor, tools, supervision, training, quality control, etc. in a shop environment compared to on-site and increased competition in potential fabricators. Conversely, there is an increase in cost associated with engineering design, project management and transportation of fabricated units. In the case of a new modular technology, such as in the case of Westinghouse's SC modular construction, the cost of building a specific factory or finding appropriate factory lay-outs can potentially increase the cost of the modular units. Thus, it is important to rely on existing, established, and proven supply chains and production environments to realize the effectiveness benefits of modular construction. Considering all factors, past studies based on chemical process industry, high-rise building [11], modular power plant [12], and shipbuilding industries [13] have shown that modular construction reduces construction time by around 30 to 50% compared to conventional stick-built approach.

2.1.2 Modularity for Microreactors

Microreactors are considered as a unique class due to their unique compact design, transportability, and their potential for mass factory production make their deployment inherently effective and modular. The characteristics of microreactors include: (i) modular and rapid deployment capabilities, (ii) ability to provisionally add adjacent reactor units to scale up in size, (iii) lower capital overnight costs compared to large reactors, and (iv) self-contained, minimizing transport of separate auxiliary systems [14]. The current financial premise for microreactors is different than large size NPPs, where initial estimations and business case for microreactors is to compete with diesel generators and serve as an energy source at remote locations, such as remote communities and mines. There are several developers of microreactors for commercial use [15-17], or defense purposes [18] and also for demonstration and research [19]. One of the biggest advantages of microreactors is their size, which enables manufacturing the complete unit in a controlled factory environment and repeat-and-iterate the production procedures in future deployments to increase efficiency and reduce costs. A U.S. DOE study [20] on the economics of heat pipe microreactors identified that modularity could provide cost savings through rapid installation and deployments, and simplified decommissioning. Modularity further enables economies of multiple when vendors are able to scale their production units to reap efficiencies from learning and streamlining. Learning rates for capital related expenses were assumed to benefit from learning rates estimated at 15%, resulting in cost reductions in the range of 20–60% over the build of 100-200 units [20]. The DoM increases as the power source shifts from a large-scale plant to a microreactor. This is mainly due to sizes of relatively smaller nuclear energy sources being more suitable for factory fabrication. However, the limitation to making smaller units profitable is the need for large orders and sufficient demands to mass-manufacture and reduce the cost of individual units. The U.S. Microreactor Program global market study on microreactors showed that to be competitive in future profile markets, costs need to decrease from $0.50-$0.60/kWh for initial deployments (2020-2030) to $0.20-$0.35/kWh (2035-2050) through factory scale-ups and producibility improvements in designs [14].

3. Modularity Experience Outside Nuclear Industry

The ANTSER analysis includes novel modular designs and applications from on non-nuclear industries. Energy, aerospace industry, construction, data centers, and software development are among businesses using modular approaches in achieving scalability, cost savings, quality control, and rapid iterations of future products. Google, LLC, developed modular data centers housed inside standardized shipping containers for rapid and cost-competitive deployment [21]. Sun Microsystems also developed turn-key modular data centers that are reported to be operational for 1% of the cost of building traditional data centers [22]. Tesla, the largest electric vehicle company by sales, has applied modular and efficient methods to build and expand their lithium-ion battery factory, Gigafactory.45 The methods used in constructing the Gigafactory are different from the conventional construction practices, where the facility is composed of minimum viable products of units that are operational and functional as soon as they are deployed. Such an approach allows revenue generation and satisfies the supply need for their business, even before the facility is 100% complete. An additional advantage of their modular approach is that the company could rapidly expand their factories around the world, such as in China and Germany. The potential modular applications in the nonnuclear construction industry can be collected under three topics: (1) conventional non-modular construction (in-place construction), (2) SC modular construction, and (3) precast concrete modular construction.

As mentioned earlier, AP1000 construction was planned to be achieved through a SC-type modular design. The SC-type of construction is being used in nonnuclear construction in the structural core design and construction of Rainer Tower in Seattle, Washington, USA. The construction method provided fast-paced deployment of the second tallest structure in the Pacific Northwest of the United States. Precast concrete was used during the construction of Tesla's Gigafactory and Apple Park Office for speeding up the deployment process and compressing the schedules. Precast concrete structural elements are produced in factories and transported to the construction site for assembly. Precast concrete elements have been recognized as a competitive alternative to other methods of construction for both simple and complex structures [23]. Three main reasons for this cost competitiveness are: (1) ability to repetitively use molds for concrete casting, thus reducing material cost, (2) high quality of workmanship, thus reducing iteration time at the construction site, and (3) factory fabrication, thus reducing workmanship, schedule, and cost for the construction site operations. A conventional nuclear energy option has not benefited from precast modular construction at the critical paths of the projects, such as in the construction of large safety-critical containment structures. This was mainly related to satisfying the safety requirements of the conventional high-pressure light water reactors (LWRs). Aeronautics and space industries have historically been challenged with budget overruns and schedule delays on multiple projects for a myriad of reasons. However, this trend may be changing. A new company named Planet, formed by the NASA's ex-employees, developed a relatively compact and modular satellite unit, called Dove, that is easy to iterate on the previous designs. They have successfully launched several of their satellites faster than any company or government [24]. Innovative construction systems are being deployed by SpaceX for the Falcon 9 reusable rocket. The Falcon 9 pieces are mated in SpaceX's custom-build Horizontal Integration Facility, a large hangar in Florida, with most of the rocket's modular components including fuselages and engines being shipped from a factory in California and other locales to various test stands before final assembly. After use, Falcon 9's first stage is returned to the Horizontal Integration Facility where it is checked out, refurbished, and readied for another launch. Reusing the stage is much cheaper than building a new one for every launch [25].

4. Lessons Learned from Modularity Attempts in Nuclear Energy

The ANTSER analysis continued by evaluating the lessons-learned from using modularity. The nuclear energy industry pursued and has been pursuing modular approaches for decades. The modularity attempts have mainly focused on reducing the schedule and cost at the BOP, with the most potential for positive financial impact at the relatively large safety-critical containment buildings. Modular reactors have been discussed and pursued in a few cases [26], but none have matured or been sustained in the industry. However, SMRs have gained substantial attraction [27] in the last decade, due to their promise to reduce the initial capital costs, and the ability to expand the capacity by adding a series of modular reactors based on customer needs. SMRs are also viewed as a new entry point to revive the nuclear energy industry. As summarized and discussed in the earlier sections, the challenges observed for the SC-type of modular construction cannot be directly attributed to the modularity idea in general. It is more related to selecting a suitable modular technology under nuclear energy and regulatory standards. In more detail, it can be argued that the SC-type of modular construction was not an optimal choice due to still requiring a list of demanding nuclear grade on-site activities including: (1) attaching of the plates with tight tolerances at the site, (2) conducting nuclear grade welding for the connections under various site and geometric conditions, (3) pouring considerable amounts of high-quality controlled concrete at the site, and (4) lack of visibility of concrete surfaces increasing the amount of time for regulatory inspections and approval. It is important to emphasize that when the choice of modular technology is combined with the lack of experience and capabilities in manufacturing modular steel-plates, the work at the site is continuously delayed and supply-chain is adversely affected. SMRs and microreactors are still early in their development. Therefore, it is not possible to have an in-depth discussion on how modularity affected the associated nuclear energy deployments. However, modularity at the reactor level for SMRs has been an ongoing discussion. One of the most prominent proposals for building an SMR-based NPP were constructing the entire plant with a limited number of reactor modules, with a single reactor capacity around 50 MWe. In case the customer needed additional capacity over time, they could add more reactor modules and produce more electricity with the existing BOP. Some of the microreactor developers are promoting their technology as modular microreactors that are functional by themselves with minimal on-site work. In the U.S. there are approximately ten microreactors, sometimes referred to as a fission batteries, under development. All vendors plan to incorporate some amount of modularity in their designs.

Canada scientists are studying modular reactors, particularly for remote mining as a replacement for diesel generators [28-30].

5. Involvement and Compatibility of Modular Approaches in the Nuclear Industry

Nuclear industry has stringent regulations and rules that require regulatory inspectors to devote significant time and resources to verify the licensee's completion of the requisite inspections, tests, analyses, and acceptance criteria [31]. This on-site inspection inherently makes nuclear energy deployment relatively slower than a comparable infrastructure project. Additionally, any divergence from the regulatory requirements will end up with rework at the site, such as remanufacturing of an out of compliance component or constructing the shielding wall elements again with predefined tolerances. Thus, the conventional nuclear energy deployment can be classified as monolithic (non-modular) and time-consuming in general, rather than modular and efficient. Several recent examples of non-modular and time-consuming deployment environments exist, such as Flamanville [32] or Olkiluoto [33]. Non-modular designs are custom built, imposing difficulties to achieving the benefits of standardization, such as learning [34], and prevents ease of iterations in future deployments. As discussed earlier, the methods used in constructing the Gigafactories of the Tesla Company are different from the conventional construction practices, where the facility is composed of minimum viable products of units that are operational and functional as soon as they are deployed. Such an approach allows the revenue generation and satisfies the supply needs for their business, even before the facility is 100% complete. Conversely, a 99% finished commercial NPP project has had zero output or revenue. Non-modular approaches also make it difficult for the nuclear energy to scale, either up or down. As an example, additional capacity cannot be easily added when needed with a monolithic build. This also caps the business expansion and potential profitability of nuclear energy. The earlier sections of the study discuss how the nuclear industry has tried to use modularity using different approaches. SMRs are reactor-level modularity attempts and SC construction such as in Vogtle and VC Summer are at the BOP level. Moving toward modularity in deployment can be considered a positive indication in making nuclear energy cost-competitive, based on the several examples from other industries. However, the technology selection and approach for achieving modularity and the compatibility of them in nuclear is important. The challenges and hardship of the recent modularization of the BOP is discussed earlier sections. Additionally, challenges in the selected modular technology and supply chain issues resulted in inefficient management of the deployment site. The figure below shows construction cost performance index (CPI) (hours spent/hours earned) during an approximately 1-year time frame at the Vogtle site [35]. If the CPI was above 1.0, the project was spending more hours than planned to complete tasks. The Vogtle site was experiencing a cumulative direct CPI of approximately 20% more than planned at the time of the report. Hence, the choice of modularity approach and the compatibility of the technology are highly important for the success of the projects. It can be argued that an inefficient modular deployment approach produces similar results as a monolithic and time-consuming approach.

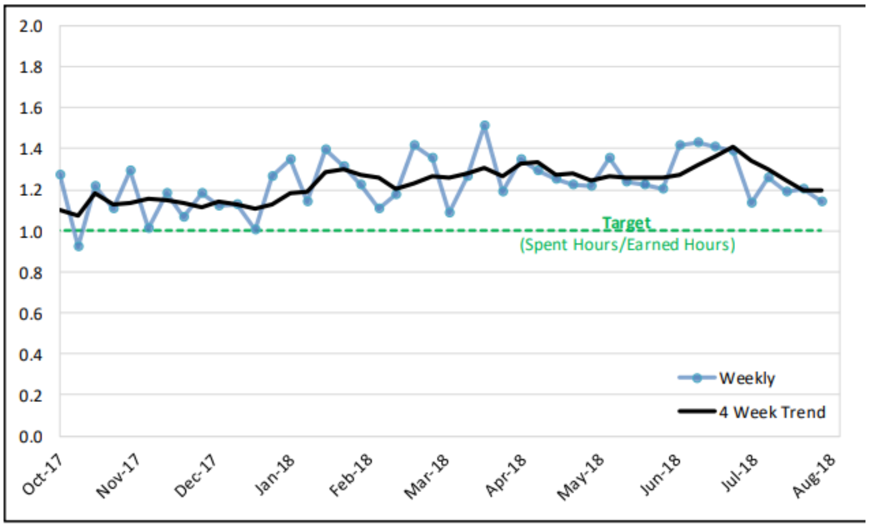

Figure 2. Direct CPI at Vogtle site during 2017–2018.

Global nuclear energy markets have favored large-scale LWRs, usually in the order of 600–1200 MWe output. LWRs have supplied clean energy all over the world since their inception. However, hardship in delivering and deploying such plants has been observed in the last few decades, especially in the West.

As mentioned earlier, nuclear industry attempted to reduce the costs of large-scale projects through several avenues including modularization of the BOP. The modularity of large LWRs has a limited set of choices due to the inherent safety requirements of the reactor technology. The containment building structures that house the reactor need to be designed against technology-specific accidents, such as high internal pressure events, making them heavy and expensive buildings. This causes the deployment of the large-scale LWR NPPs an immediate challenge with supply chain management, and high and sustained on-site quality control and management.

With the transition to non-LWR reactor technologies and their unique safety requirements, new regulations and approaches to design cost-efficient BOP are emerging. Functional containment design and regulations permitting risk-informed, performance-based, and technology-inclusive design approaches could potentially allow flexible designs and new technologies used for the cost competitive deployment of nuclear power energy [4]. The functional-containment concept makes possible a reduction in the cost of the nuclear power plant project by decreasing the amount of nuclear-grade construction (imposing American Society of Mechanical Engineer N-stamp requirements on the design and implementation in real life). Within the functional-containment approach, candidate technologies or approaches used by industry help to reduce the risk and design requirements of structures or components accompanying advanced reactors. These candidate technologies (such as seismic protective systems) or approaches (such as deeply embedding the structures) can make risk-informed, performance-based, and technology-inclusive design of structures meet their functional requirements at reduced cost.

Functional containment could be applied at different scales:

- Mid to large size Gen-IV reactors, such as modular high temperature gas reactors (HTGRs) or very high temperature reactors, may not need costly and heavy containment structures. The possible internal hazards associated with these non-LWR reactor designs are also different from traditional LWRs. The necessary pressure-related containment boundary for LWR design is not required for these types of designs. Because the safety features and the release environment are different from traditional LWRs, they provide the basis of functional containment. New technologies, engineering approaches, and combinations of them may be considered. These include modular deployment approaches used by the non-nuclear industries, seismic isolators, deeply embedded and relatively small footprint structures and tristructural isotropic (TRISO) fuel. These technologies and approaches will allow engineers and designers to optimize their overall plant designs to satisfy the safety and functional requirements while maintaining cost competitive design.
- Similarly for advanced small modular reactors and microreactors, functional containment would involve scaling down containment for smaller reactor sizes and their particular risk profiles. Functional containment could be implemented by embedding the reactor underground or modifying the design of the containment structure. The enveloping structures could be thinner or lighter, or they could be constructed more easily with advanced concrete and other innovative materials.

Although functional containment can provide flexibility in the design and use of new engineering approaches in nuclear energy, not all of the technologies can be expected to have same level of economic impacts. The modular technologies both at the reactor level and BOP discussed in the previous sections are expected to have positive cost impacts; however, not all reactors can benefit from some modularity concepts (e.g., reactors requiring high pressure resistant containment).

To illustrate the concepts described in this paper, the potential compatibility of reactor technologies with modular construction technologies applied to the balance of plant as described in Table 1. LWRs need high robust containment structures due to their safety requirements. As shown in the red cells, modular precast construction is not compatible with large- and medium-sized LWRs. On the other side, modular SC-type construction is compatible with LWRs, although the data on their deployment show extreme challenges during their deployment. Modular precast construction is potentially compatible with HTGRs and sodium-cooled fast reactors (SFRs). This can be attributed to the operational environment and containment at the fuel, which are discussed in more detail below. Modular precast construction is a more mature technology compared to modular SC-type technologies, has widespread availability through global suppliers, and is less dependent upon site services such as requiring high volumes of concrete or nuclear grade welding.

Table 1. Illustration of compatibility of different modular reactor technologies to modular BOP.

	Modular Precast Construction			Modular SC-type Construction		
	Large-size plants	Medium-size plants	Micro-reactors	Large-size plants	Medium-size plants	Micro reactors
LWR						
HTGR						
SFR/Thermal Micro reactor						

Legend: Red=not compatible, Green=compatible, Yellow=marginally compatible

Potential modularity concepts for reactors and their BOP are assessed in terms of their (1) applicability to the different plant sizes, (2) potential cost implications, (3) technology readiness level for nuclear applications, (4) transportability, and (5) further research, development, and demonstration needs in Table 2.

- LWRs are mostly applicable to mid- and large-sized plants; however, their high-pressure environment has and will hinder cost-effective modular approaches at the BOP level.
- HTGR and SFRs operate at lower pressures compared to LWR reactors. Additionally, the new fuel technologies, such as TRISO fuel, may enable new modular approaches at the BOP level for these type of reactors through newly developed regulation of functional containment approach. These reactor technologies have been deployed at relatively smaller scales, but the fuel development and investigations into their safety performance are still being conducted.
- Modular precast construction has not been applied for the costly safety significant structures or systems in the nuclear domain due to the lack of performance of connections under high-pressure environments and high-intensity seismic events. However, with the safety features of GEN-IV reactors and functional containment approach, precast modular systems are potential candidates for reducing costs, if it is shown that their designs satisfy the risk-informed and performance-based approaches.
- Modular SC systems have been used in nuclear applications. Their codes and standards have been fully developed and the technology is ready to be deployed for every reactor type. However, due to their high on-site activity demand, it is still uncertain whether they will be able to bring down costs and schedule for the next-generation plants.

Table 2. Assessment to potential modular approaches.

Technology	Scale Applicability	Cost Implications	Tech. Readiness in Nuclear	Transportability	Further RD&D
LWR	Mid- to large-sized plants	Hinders cost-effective modularization of the BOP.	TRL 8–9	Transportable as single units to the deployments site.	Ready to use.
HTGR	Micro- to medium-size plants	Enables high DoM at the reactor and BOP levels. Allows creating standardized units.	TRL 8–9	Transportable as single units to the deployment site.	Needs further RD&D on fuel certification.
SFR	Micro- to medium-size plants	Enables high DoM at the reactor and BOP levels. Allows creating standardized units.	TRL 8–9	Transportable as single units to the deployment site.	Needs further RD&D on safety and performance.
Precast Construction	Micro- to large-size non-LWRS	Enable standardization of structures, such as containment buildings. Requires on-site assembly.	TRL 6	Highly transportable but limited to the weight of individual modular units depending on road and site regulations and equipment.	Requires research on their performance satisfying regulatory requirements against external hazards.
Steel Plate Composite Construction	Micro- to large-size reactors	Enable standardization of structures, such as containment buildings. Requires welding, high volumes of concrete casting, workmanship and assembly on-site.	TRL 9	Only the steel portions of the modules are transportable.	Has been approved, developed, and demonstrated in real nuclear energy applications.

6. Conclusions and Further Discussions

This study evaluates cost-reduction opportunities for Gen IV nuclear concepts, based on modularity at different scales and types of advanced reactors. This cost strategy is intended to inform the GIF and other international stakeholders on the potential uses of modularity to reduce advanced reactor costs. The greatest potential for cost savings on advanced reactors may be achieved through design strategies that employ proven modularity concepts along with a functional containment to create flexible designs. Further alignment of modularity concepts successfully deployed by the non-nuclear industry is encouraged. The outcome of this strategic cost reduction activity is to increase information sharing within the GIF and other stakeholders to accelerate progress toward global deployments of cost-competitive nuclear plants.

7. References

1. Lloyd, C. A., T. Roulstone, and R. E. Lyons, "Transport, constructability, and economic advantages of SMR modularization," *Progress in Nuclear Energy* 134:103672, 2021. https://doi.org/10.1016/j.pnucene.2021.103672.
2. C. Gollier ,D. Proult, F. Thais and G. Walgenwitz, "Choice of nuclear power investments under price uncertainty: Valuing modularity," *Energy Economics* 27(4):667-685, 2005. https://doi.org/10.1016/j.eneco.2005.04.003.
3. Generation IV International Forum (GIF), "Economic Modeling Working Group (EMWG), Cost Estimating Guidelines for Generation IV Nuclear Energy Systems, Revision 4.2," 2007.
4. D.E. Shropshire, A. Foss and E. Kurt. 2021. "Advanced Nuclear Technology Cost Reduction Strategies and Systematic Economic Review," Generation IV International Forum (GIF) Economic Modeling Working Group (EMWG), GIF/EMWG/2021/001.
5. E. Kurt, D.E. Shropshire. 2022. "Advanced Nuclear Technology Cost Reduction Strategies and Systematic Economic Review, Cost Reduction Strategy #2: Design – Modularity-at-Scale," Generation IV International Forum (GIF) Economic Modeling Working Group (EMWG), GIF/EMWG/2022/001.
6. C.A. Lloyd., "Modular Manufacture and Construction of Small Nuclear Power Generation Systems," (Doctoral thesis, University of Cambridge), 2020. https://doi.org/10.17863/CAM.46941.
7. J.W. Winters, M. M. Corletti and M. Thompson, "AP1000 construction and operating costs," 9 International Conference on Nuclear Engineering, France, 2001.
8. M.D. Carelli, P. Garrone, G. Locatelli, M. Mancini, C. Mycoff, P. Trucco and M. E. Ricotti, "Economic features of integral, modular, small-to-medium size reactors," *Progress in Nuclear Energy* 52(4):403-414, 2010. https://doi.org/10.1016/j.pnucene.2009.09.003.
9. B. Mignacca, G. Locatelli, M. Alaassar and D. C. Invernizzi, "We Never Built Small Modular Reactors (SMRs), but What Do We Know About Modularization in Construction?" Proceedings of the 2018 26th International Conference on Nuclear Engineering (Vol. 51432, p. V001T13A012). London, England. https://doi.org/10.1115/ICONE26-81604, 2018.
10. M.L. De La Torre, "A review and analysis of modular construction practices," (Thesis presented to the Graduate and Research Committee of Lehigh University). https://preserve.lib.lehigh.edu/islandora/object/preserve%3Abp-3100780, 1994.

11. R.M. Lawson, R. G. Ogden and R. Bergin, "Application of Modular Construction in High-Rise Buildings," *Journal of Architectural Engineering* 18(2):148-154. https://doi.org/10.1061/(ASCE)AE.1943-5568.0000057, 2012.

12. G. Ondrey, "Modular design would shorten construction times for nuclear plants," *Chemical Engineering* 116(10), pp.16-18. Gale Academic OneFile, link.gale.com/apps/doc/A210441029/AONE?u=anon~c6c762d0&sid=googleScholar&xid=f7118978, 2009.

13. J.W. Abbott, and S. Garver, 2014. "Embracing change: Reducing cost and maximizing mission effectiveness with the flexible warship," *Marine Technology* 51(3):22-28, 2014.

14. D.E. Shropshire, G. Black and K. Araújo, "Global Market Analysis of Microreactors," INL/EXT-21-63214-Rev 0, Idaho National Laboratory, Idaho Falls, ID, 2021.

15. https://www.westinghousenuclear.com/Portals/0/new%20plants/evincitm/GTO-0001%20eVinci%20flysheet.pdf

16. U.S. NRC, "Aurora – Oklo Application," Application for a custom combined license for a compact fast micro-reactor. Accessed August 13, 2022 https://www.nrc.gov/reactors/new-reactors/col/aurora-oklo.html.

17. MMR®. n.d. "MMR® Energy System Micro Modular Reactor Energy System," Accessed August 13, 2022 https://usnc.com/mmr-energy-system.

18. U.S. Department of Defense, "Strategic Capabilities Office Selects Two Mobile Microreactor Concepts to Proceed to Final Design," Accessed August 13, 2022 https://www.defense.gov/News/Releases/Release/Article/2545869/strategic-capabilities-office-selects-two-%20mobile-microreactor-concepts-to-proce/, 2021.

19. US Office of Nuclear Energy, "New MARVEL Project Aims to Supercharge Microreactor Deployment," Accessed August 13, 2022 https://www.energy.gov/ne/articles/new-marvel-project-aims-supercharge-microreactor-deployment, 2021.

20. A. Abou-Jaoude, A. Foss, Y. Arafat, B. Dixon, "An Economics-by-Design Approach Applied to a Heat Pipe Microreactor Concept", Idaho National Laboratory, INL/EXT-21-01201, 2021.

21. Google, "Google container data center tour," YouTube video, https://www.youtube.com/watch?v=zRwPSFpLX8I, 2009.

22. Wikipedia, s.v. "Sun Modular Datacenter," last modified January 27, 2022, 11:56, https://en.wikipedia.org/wiki/Sun_Modular_Datacenter.

23. National Precast Concrete Association, "Why Precast Cost Less," Accessed August 13, 2022 https://precast.org/2010/05/why-precast-costs-less/, 2010.

24. Planet. n.d. "Our Approach," Accessed August 13, 2022 https://www.planet.com/company/approach/

25. Science Focus, How does SpaceX build its Falcon 9 reusable rocket? https://www.sciencefocus.com/space/how-does-spacex-build-its-falcon-9-reusable-rocket/

26. M.V. Ramana., "The Forgotten History of Small Nuclear Reactors," IEEE Spectrum, 52(5), pp.44-58, 2015.

27. IAEA., "Advances in Small Modular Reactor Technology Developments, A Supplement to: IAEA Advanced Reactors Information System (ARIS) 2020 Edition," Accessed August 13, 2022 https://aris.iaea.org/Publications/SMR_Book_2020.pdf, 2020.

28. Canadian National Laboratory, Canada's Small Modular Reactor Action Plan. https://smractionplan.ca/, 2022.

29. SaskPower et al, "Feasibility of Small Modular Reactor Development and Deployment in Canada," March 2021.

30. Ontario Power Generation et al, "Small Modular Reactor (SMR) Economic Feasibility and Cost-Benefit Study for Remote Mining in the Canadian North: A Case Study," May 2021.

31. U.S. NRC. 2021, "Construction Inspection Program for New Reactors," Accessed August 13, 2022 https://www.nrc.gov/reactors/new-reactors/oversight/cip.html.

32. Nuclear Newswire. 2022, "Another delay, cost bump, for Flamanville-3," Accessed August 13, 2022 https://www.ans.org/news/article-3573/another-delay-cost-bump-for-flamanville3/

33. YLE News. 2019, "Olkiluoto 3 delayed yet again, now 12 years behind schedule," Accessed August 13, 2022 https://yle.fi/news/3-11128489.

34. World Nuclear News. 2016, "The benefits of standardization for nuclear projects," Accessed August 13, 2022 https://www.world-nuclear-news.org/RS-The-benefits-of-standardisation-for-nuclear-projects-22091601.html

35. Letter from Kyle Leach with Georgia Power to Reece McAlister with Georgia Public Service Commission, RE: Georgia Power Company's Nineteenth Semi-Annual Construction Monitoring Report for Plant Vogtle units 3 and 4; Docket No. 29849. August 31, 2018. Accessed August 13, 2022 https://assets.sourcemedia.com/a0/5b/de057dbb4d6dab264cfc857a7008/gpc-19th-construction-mon.%20report.pdf