GIF/EMWG/2021/001

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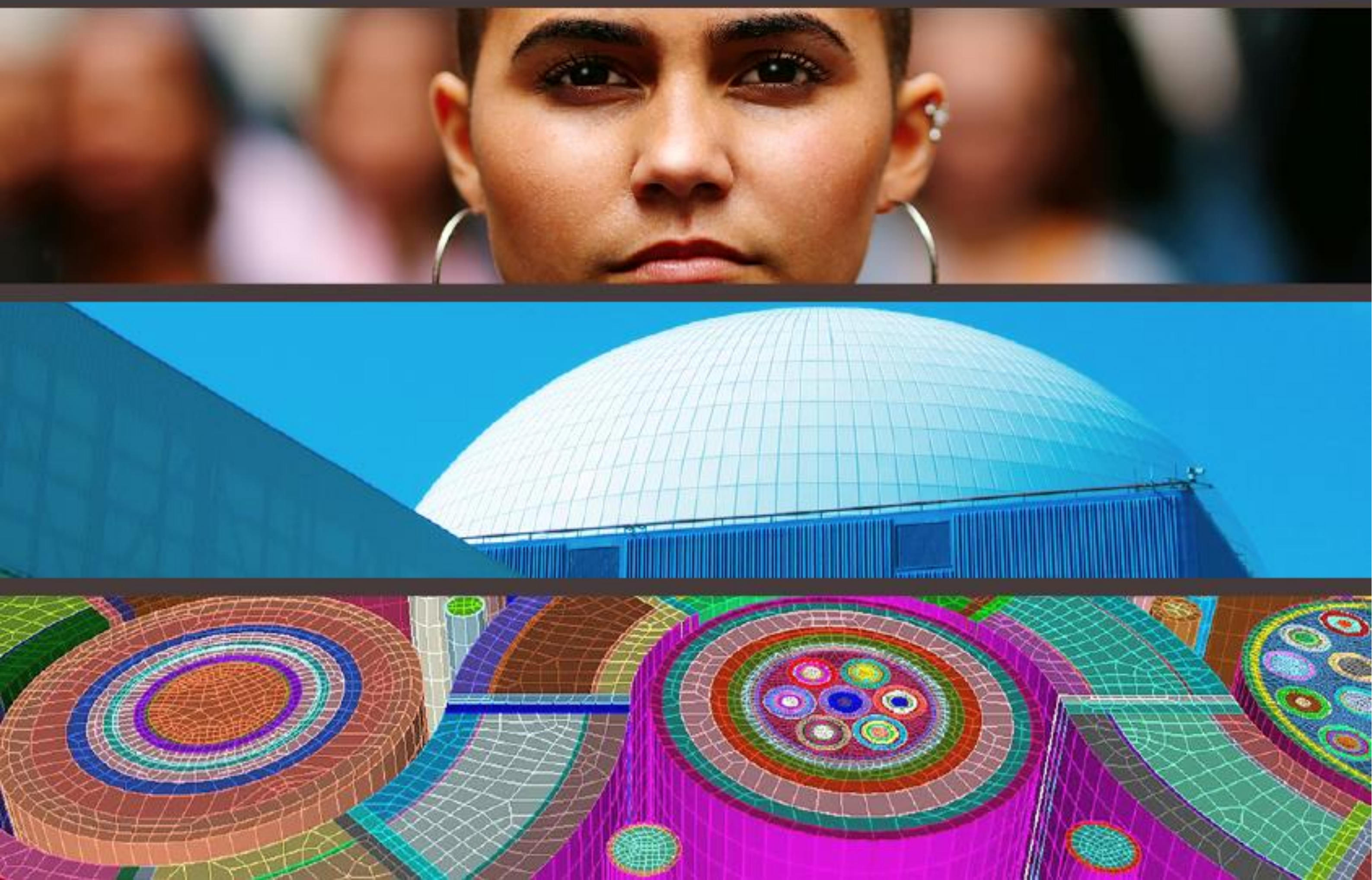
ADVANCED NUCLEAR TECHNOLOGY COST REDUCTION STRATEGIES AND SYSTEMATIC ECONOMIC REVIEW

September 2021



Foreword and acknowledgements

The present study was written by David Shropshire, Andrew Foss, and Efe Kurt from the Idaho National Laboratory in the United States under the guidance of the Generation IV International Forum (GIF) Economic Modelling Working Group (EMWG) chaired by Fiona Reilly (United Kingdom), Megan Moore (Canada) and David Shropshire (USA). The authors wish to thank Jeetesh Keshaw, Atsushi Kato, Gilles Mathonniere, and Antoine de la Chevrotière for their insightful reviews and comments that improved the quality of the report.

This study was developed with three goals in mind; first, to create a methodology for creating impactful cost reduction strategies that crosscut a broad set of advanced nuclear reactor technologies; second, to generate an example cost reduction strategy using the methodology; and third, to provide a path forward to improve the methodology and produce additional cost reduction strategies. The EMWG can lead future cost reduction strategy studies, but the range and impact of this body of work is greatly enhanced by the direct contributions from the GIF methodology working groups, task forces, system steering committees for the six Generation IV reactors and the industry panel.

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List of abbreviations and acronyms

ASME	American Society of Mechanical Engineers
ADS	Automatic depressurization system
ANTSER	Advanced Nuclear Technology Cost Reduction Strategies and Systematic Economic Review
AOO	Anticipated operational occurrence
ASME	American Society of Mechanical Engineers
ATWS	Anticipated transient without SCRAM (system)
BDBE	Beyond design-basis events
BWR	Boiling water reactor
D&D	Decommissioning and demolition
DA	Design alternative
DBA	Design-basis accident
DBE	Design-basis event
DOE	Department of Energy (United States)
ECSS	Emergency core cooling system
EMWG	Economic Modelling Working Group (GIF)
EPRI	Electric Power Research Institute (United States)
ETWG	Education and Training Working Group (GIF)
FHR	Fluoride salt-cooled high-temperature reactor
GEN III/GEN IV	Generation III/Generation IV (reactors/concepts)
GFR	Gas-cooled fast reactor
GIF	Generation IV International Forum
HALEU	High-assay low-enriched uranium
HPCI	High pressure coolant injection (system)
HTGR	High temperature gas reactor
IAEA	International Atomic Energy Agency
INL	Idaho National Laboratory (United States)
KWe	Kilowatt electric
LBE	Licensing-basis events
LFR	lead-cooled fast reactor
LPCI	Low pressure coolant injection (system)
LMP	Licensing Modernization Project
LOCA	Loss-of-coolant accident
LOFA	Loss-of-flow accident
LWR	Light water reactor
MCDM	Multi-criteria decision making
MIT	Massachusetts Institute of Technology (United States)
MSR	Molten salt reactor
MWt	Megawatt thermal
NEA	Nuclear Energy Agency
NIA	Nuclear Industry Association
NPP	Nuclear power plant
NQA	Nuclear quality assurance (levels)
NRC	Nuclear Regulatory Commission (United States)
NUREG	Nuclear Regulatory report
O&M	Operation and maintenance
PB	Performance-based
PWR	Pressurized water reactor
R&D	Research and development

RD&D	Research, development and demonstration
RI	Risk-informed
SCWR	Supercritical-water-cooled reactor
SFR	Sodium-cooled fast reactor
SIAP	Senior Industry Advisory Panel (GIF)
SMR	Small modular reactor
SSC	Structures, systems and components
TI	Technology-inclusive
TRISO	Tristructural-isotropic (fuel)
TRL	Technology readiness level
VHTR	Very-high-temperature reactor

Executive summary

Advanced Nuclear Technology Cost Reduction Strategies and Systematic Economic Review describes a process to produce a methodological framework for evaluating nuclear cost reduction strategies. Actions, the timeline, anticipated products and outcomes are all outlined in the present report. Key areas for nuclear cost reduction strategies and technologies are categorized under design, construction/production and project management. Application of the framework is illustrated on reactor designs that are based on cost reduction through "functional confinement," followed by a presentation of a more rigorous application of the methodology in Appendix A.

Purpose

The report refines advanced nuclear power plant cost reduction strategies and develops a systematic economic-review process — applicable to Generation III+ (Gen-III+), small modular reactor (SMR) designs, microreactors, and Generation IV (Gen-IV) concepts — to: 1) identify opportunities and conditions for cost reduction on the reactor design, emphasizing the costs of the balance of the plant; 2) provide a methodology to review progress in designs towards reducing costs; and 3) inform and provide training on cost reduction strategies for reactor designers and other stakeholders.

Methodology

Alternative cost reduction strategies are assessed based on past and current lessons learned, along with an assessment of the readiness levels of technologies and the potential for cost reductions. The Generation IV International Forum (GIF) Economic Modelling Work Group (EMWG) is developing a systematic economic review process called Advanced Nuclear Technology Cost Reduction Strategies and Systematic Economic Review (ANTSER), consistent with the GIF EMWG Cost Estimating Guidelines.[1] The results and the methodology being developed can inform the design and selection of future cost reduction demonstration projects. Information and updates on cost reduction strategies and the study outcomes will be posted in an online repository.

Actions/timeline

The GIF EMWG:

1. Defines key areas for nuclear energy cost reduction possibilities by compiling references to current state-of-the-art literature concerning nuclear cost reduction opportunities (e.g., by the Massachusetts Institute of Technology [MIT],[2] Electric Power Research Institute [EPRI],[3] Nuclear

1. Generation IV Economic Modelling Working Group (EMWG, 2007), *Cost Estimating Guidelines for Generation IV Nuclear Energy Systems*, Rev. 4.2, GIF/EMWG/2007/004. For more information, see www.gen-4.org/gif/upload/docs/application/pdf/2013-09/emwg_guidelines.pdf.
2. *The Future of Nuclear Energy in a Carbon-Constrained World: An Interdisciplinary MIT Study* (2018), http://energy.mit.edu/research/future-nuclear-energy-carbon-constrained-world/.
3. EPRI (2019) *Advanced Nuclear Technology: Economic-Based Research and Development Roadmap for Nuclear Power Plant Construction*, Product ID 3002015935, www.epri.com/research/products/000000003002015935.

Energy Agency [NEA],[4] Nuclear Industry Association [NIA][5]) and linking them to related ongoing program activities.[6]

2. Reviews and revises the GIF EMWG "Cost Estimating Guidelines for Generation IV Nuclear Energy Systems" to incorporate nuclear cost reduction strategies (future).
3. Categorizes key areas for nuclear energy cost reduction and for the enabling of technologies (see list of priorities below):
   a) Separates cost reduction opportunities by design, construction or production, and by project management;
   b) Defines life-cycle cost reduction strategies (e.g., construction, fuel cycle, operation and maintenance [O&M], decommissioning and demolition [D&D]);
   c) Categorizes opportunities to help inform new areas for research and development (R&D).
4. Presents a paper at the International Atomic Energy Agency (IAEA) Cost Workshop on Advanced Nuclear Technologies (2Q 2021).
5. Prepares guidelines on how to conduct an ANTSER and training package for cost reduction strategies (2021–2022).
6. Conducts GIF Education and Training Working Group (ETWG) Initiative webinar on nuclear economics, with a focus on cost reduction strategies (September–December 2021).
7. Conducts initial ANTSER reviews with GIF technology developers, preparing findings and a recommendation report (2022).
8. Creates an online GIF repository with comprehensive and up-to-date information on cost reduction strategies and results from ANTSER reviews (2021–2022).
9. Ensures that the ANTSER methodology is an ongoing EMWG activity to identify and assess future cost reduction strategies for advanced nuclear power technologies (ongoing).

Anticipated products

The GIF EMWG members will prepare in 2021–2022, and thereafter on an annual basis:

- Cost reduction strategy assessments (design, construction, project management);
- Periodic papers containing findings from cost reduction strategy assessments;
- Training and presentations on best economic practices for advanced reactor design;
- Review reports based on ANTSER reviews;
- Updates to the GIF EMWG Cost Estimating Guidelines;
- Strategies to be listed in the online repository.

4. The 2020 NEA report *Unlocking Reductions in the Construction Costs of Nuclear: A Practical Guide for Stakeholders*, NEA-7530, www.oecd-nea.org/ndd/pubs/2020/7530-reducing-cost-nuclear-construction.pdf.
5. The 2020 NIA report *Nuclear Sector Deal: Nuclear New Build Cost Reduction,* www.niauk.org/wp-content/uploads/2020/09/New-Build-Cost-Reduction-Sector-Deal-Working-Group.pdf.
6. The NEA 2021-2022 Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (or the Nuclear Development Committee [NDC]) Programme of Work 8.3.1.

Anticipated outcomes

The benefits that the studies are expected to net to GIF:

- GIF reactor developers are made aware of cost reduction opportunities for nuclear designs, construction, O&M and D&D through training and reference to best economic practices for advanced reactors;
- Specific research activities are identified to reduce advanced nuclear reactor costs;
- Trends in nuclear industry supply chains for standardized cost reduction processes are influenced;
- International practices that reduce nuclear costs are shared within the nuclear community.

Key areas for nuclear cost reduction strategies and technologies

Potential, specific cost strategies are organized under design, construction/production, and project management. Strategies are listed in the order of descending potential for cost reduction based on expert judgement, with enabling sub-technologies defined when applicable.

Design[1]

- Functional containment;
- Fuel engineering and margin capturing to increase power density given same-size civil structures (in consideration of electric and heat applications);
- Systems engineering;
  - Enabling technologies: digital engineering and integrated numerical tools — e.g., role of simulation on behalf of experimental or demonstration facility.
- Modularity, advanced manufacturing — e.g., analysis of the fabrication process of the system and its components, as well as its loads — and standardization (includes decoupling from the nuclear island);
- Innovative seismic protection;
  - Enabling technology: seismic isolators
- Open source/open architecture for balance of plant;
- Intrinsic design and technology readiness levels (TRLs);
  - Enabling technologies: accident tolerant fuels
  - Dominant factors for different reactor (coolant) types
  - Direct auxiliary cooling system
- Optimization of margins and tolerances.

Manufacturing/production

- Advanced manufacturing (inclusive of additive manufacturing, 3D printing);
- Lean production.

Construction[2]

- Advanced concrete;
  - Enabling technologies: steel composite, modular construction, prefabrication, alternative and advanced formwork

1. Cost drivers may be very different from one reactor technology to the next. For microreactors, see Abou Jaoude et al. (2021), *An Economics-by-Design Approach Applied to a Heat Pipe Microreactor Concept.*
2. The latest advances in construction technologies are provided by the National Reactor Innovation Center. For more information, see https://nric.inl.gov/act/.

- Open-top placement of civil-structure modules;
- Other advanced construction materials;
  - Enabling technologies: advanced rebar, composites (e.g., Nicalon), high-strength materials (e.g., oxide-dispersion alloys)
- Advanced reactor materials.

Project management[3]

- Construction schedule optimization and planning (modularization of civil structures);
- Supply chain (e.g., innovative quality-assurance and export-control processes);
- Productivity enhancements;
  - Enabling technologies: building-information modeling; wearable technologies; virtual reality for crew training; automated inspection for welds; machine learning and other artificial intelligence
- Sensory enhancements;
  - Enabling technologies: digital engineering, digital instrumentation and control; robotics and drones; and the industrial Internet of Things.

3. For a review of "lessons learned" from past nuclear projects, see Biegel et al. (2019), *Cost Drivers for Construction of DOE Large-Scale Nuclear Facilities*.

Table 1. Summary table template for cost reduction strategy assessments

Strategies	Applicability	Cost reductions	Technical readiness	Further RD&D	Additional metrics
Design (with illustration)					
Strategy 1: functional containment	Applicable to most Gen-IV reactor designs, including reactors with a low-pressure salt coolant and gas cooled reactors, with TRISO fuel	Flexibility in design through non-prescriptive engineering approaches could net ~5-15% cost savings in the overall design, implementation and construction of the plants	Most of the discussed technologies have high readiness levels (TRL 6-8)	Individual cases require further RD&D such as seismic isolations and their performance for component isolation and performance under high temperature environments	[Design strategies may be cross-referenced to impacts on construction and project management]
Strategy 2					
Manufacturing/Production					
Strategy 3					
Strategy 4					
Construction					
Strategy 5					
Strategy 6					
Project management					
Strategy 7					
Strategy 8					
Etc…					

In Reference to Table 1, please note the following definitions:

EMWG members: on an annual basis, members of the Generation IV International Forum (GIF) Economic Modelling Working Group (EMWG) may research one or more of the strategies of their choice listed in Table 1, under design, manufacturing/production, construction, or project management. Each strategy will include information under the appropriate column heading, and the findings can be reported at EMWG meetings. Members can also help to compile pertinent information for training and publication purposes. Strategies may be developed in collaboration with the technology specific GIF System Steering Committees. Members with limited time could contribute as technical reviewers of new cost reduction strategy papers.

Strategies: each cost reduction strategy within the three categories occupies a row in the table.

Applicability: this column will contain assessments of each strategy's applicability to various types of nuclear plants. For example, some strategies may be applicable to all types of plants, including Gen III/III+, while other strategies may be applicable only to Gen-IV plants.

Cost reduction: this column will contain estimates of the potential cost reductions from current generation technologies or other relevant concepts with similar features (whether as point values or ranges) for construction cost components (e.g., equipment, materials, labor, or indirect), fuel cycle, O&M or D&D.

Technical readiness: this column will indicate each strategy's TRL, which will range from 1 to 9, according to the US Department of Energy's (DOE) TRL system.[4]

Further research, development and demonstration (RD&D): this column will indicate recommendations on further RD&D to advance each strategy, if deemed promising, towards market deployment. This could include collaboration with other GIF working groups, such as the Risk and Safety Working Group.

Additional metrics: in addition to the four items mentioned above, other measures could also be used to evaluate the strategies. The additional metrics column may thus be used to show cross linkages (e.g., design strategies linked to impacts on construction, or project management).

4. See the DOE (2011) *Technology Readiness Assessment Guide* at: www2.lbl.gov/DIR/assets/docs/TRL%20guide.pdf.

Methodology illustration: Functional containment

To illustrate the process of assessing nuclear cost reduction opportunities using the framework outlined in the previous chapter, the following preliminary case study has been prepared on the design strategy that is considered of the highest priority, based on cost reduction potential – functional containment. The case study begins with a description of functional containment and its applicability to various categories of nuclear plants. Estimates of potential cost reductions are then presented based on currently available information. The case study concludes with assessments of technical readiness and the most useful areas for further research, development and demonstration.

This example case study is both brief and preliminary because its purpose is simply to provide a high-level overview of the envisioned approach. The actual assessment of the functional containment approach and other strategies in the 2020–2022 Economic Modelling Work Group (EMWG) activities outlined above will address issues in significantly more depth than is the case of this example.

Description

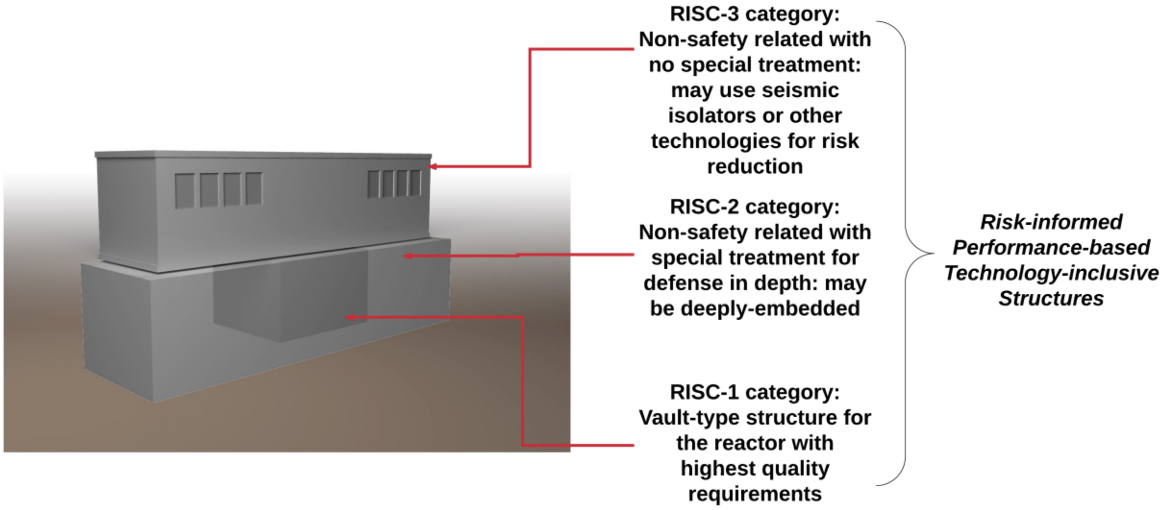
Functional containment refers to the set of barriers designed to prevent any release of radioactive material into the environment. Existing light water reactor (LWR) plants have large, heavy and costly pressure-retaining concrete containment structures to prevent the release of fission products in the case of a severe accident. The functional containment approach provides an opportunity for innovative alternatives to the traditional containment structure while maintaining (or ideally improving upon) safety performance. Such a gain in design and cost reduction is enabled by the inherent advantages of advanced designs. The approach also allows for a combination of innovative alternatives to prevent the release of radioactive materials, protect against external hazards, and produce site-independent designs such as seismic isolators, underground embedment, accident tolerant fuels and passive safety systems. Hence, functional containment can shift the nuclear plant design from satisfying rigid prescriptive requirements towards considering multiple possible solutions in a risk-informed and technology-inclusive manner. 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 (see the discussion below).

Applicability to nuclear plant categories

The functional containment approach enables a broad strategy that would be applicable to all nuclear plant categories — Gen III+, small modular reactors (SMRs), microreactors, and Gen-IV concepts — to varying degrees. For Gen-III+ reactors, functional containment could involve embedding the reactor underground or modifying the design of the containment structure while satisfying the same safety requirements (or perhaps achieving even better safety levels). 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.

Advanced reactors, such as modular high temperature gas-cooled or very high temperature reactors, provide safety features that do not exist in traditional light water reactors (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, for example, 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 below shows a possible application of structural design arising from the beneficial aspects of the functional containment approach to an advanced reactor concept.

Figure 1. Risk-informed, performance-based, technology-inclusive structures



Source: INL, 2021.

Potential cost reductions

Opportunities for cost reductions may be identified from the historical records of nuclear power projects experiencing cost overruns during construction for balance-of-plant technologies (see ETI, 2018). 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 allow the risk-informed, performance-based, and technology-inclusive design of structures to meet their functional requirements at reduced costs.

EMWG members performing the functional containment case study can review available literature on the potential cost reductions from this set of strategies. Examples of references with pertinent information include the Electric Power Research Institute (EPRI) study (2019) and the Champlin study (2018).

Technology readiness

Many elements of functional containment are already available. The US Nuclear Regulatory Commission (NRC) addressed functional containment performance criteria for non-LWRs in its 2018 study on functional containment performance criteria. These approaches would need to be further incorporated into civil engineering codes and nuclear standards, however. EMWG members performing the functional containment case study can review available literature on the technology readiness of this set of strategies. Examples of references with pertinent information, in addition to the 2018 NRC document, include Idaho National Laboratory (INL) study (2012).

Areas for further research, development and demonstration

Although the expectation for the functional containment approach is to decrease the nuclear-grade requirements without compromising necessary functional safety, no systematic approach allows evaluation of the capability to deploy and construct different technologies in the nuclear domain. EMWG members performing this case study will identify useful RD&D activities to advance functional containment strategies towards deployment.

Regulatory acceptance costs are inherently included in further RD&D, including the cost of the ensuing capacity-building required for regulators to license a technology (in addition to longer regulatory timelines). *Please note that these costs should be weighed in importance when compared to the costs of the actual plant design, construction and operations.*

Individual ANTSER strategies will be appended to this introductory report. Strategy 1 represents functional confinement. Subsequent strategies will be ordered sequentially.

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Appendix A – ANTSER strategy number 1: Design – Functional containment

Generation IV International Forum (GIF) Economic Modelling Working Group (EMWG) advanced nuclear technology cost reduction strategies

Strategy #1: Functional containment

Recent nuclear power plant builds around the world, especially in the United States and the West, have not been cost competitive with other energy sources. They have suffered from cost overruns that are multiples of their initial estimates, as well as schedule delays spanning over a decade. These challenges have been observed for light water reactors (LWRs). 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 requirements of the American Society of Mechanical Engineers (ASME) on these types of structures are critical for the safety of the public. This statement also holds true for non-LWR Generation IV (Gen-IV) reactors; however, advanced nuclear energy options come with inherent safety features that enable new approaches on the design of the plants. Some of the components of Gen-IV reactors may become more costly relative to LWR-type plants, for example in the case of fuel costs. Alternatively, the functional containment approach, which may be applicable to the different reactor physics of Gen-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. The US Nuclear Regulatory Commission (NRC) describes a "functional containment" approach to the overall design scheme of an advanced nuclear power plant (NPP) in a 2018 study. It characterizes functional containment as the full set of barriers designed to prevent any release of radioactive material into the environment. Hence, the functional containment approach can shift the nuclear plant design from satisfying rigid LWR-style prescriptive requirements towards considering multiple possible solutions in a technology-inclusive, risk-informed and performance-based (TI-RIPB) manner (Moe, 2018). The present GIF report describes functional containment as a regulatory strategy and introduces a comprehensive framework for assessing the potential cost reductions for Gen-IV designers, following the ANTSER framework described in the main body of the report.

The first section of this chapter introduces the regulatory approaches, required plant components and costs for nuclear plant safety for Gen III/III+ (i.e., LWRs) and Gen-IV concepts. The second section presents a systematic assessment framework for estimating potential cost reduction opportunities related to functional containment, determining technical readiness, and further research, development and demonstration (RD&D) to apply to the strategies in future nuclear plants. The next sections apply the assessment framework to case studies related to functional containment. As a conclusion, the last section summarizes possible, further applications of the assessment framework by other member countries.

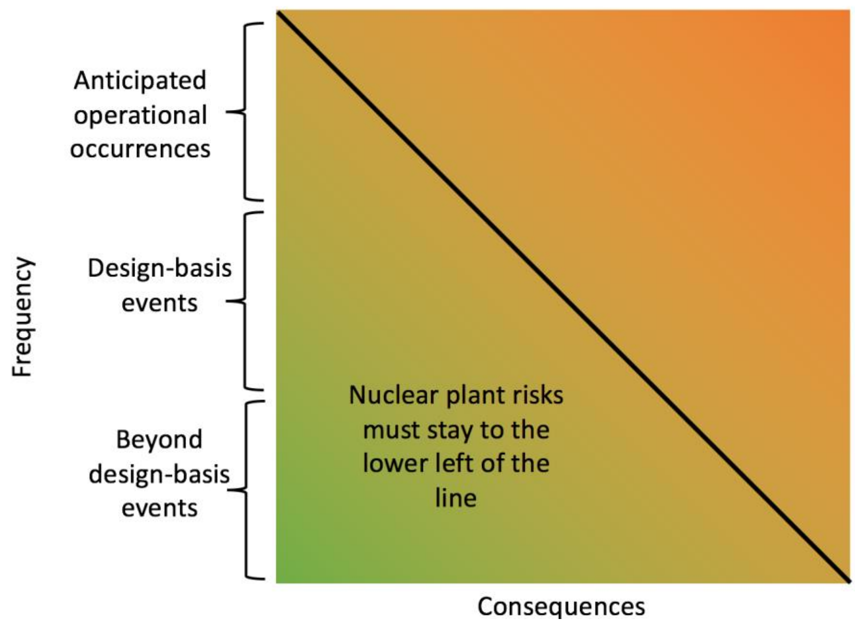
It is important to highlight that non-prescriptive engineering solutions applicable to GIF reactors through a functional containment design approach <u>provide the opportunity to design structures, systems and components that are more cost-competitive design alternatives compared to those for conventional nuclear reactors</u>. At the same time, although the potential in cost savings exists, the global cost estimation with design, construction and operation may not be viable until the plants are designed, built and operated in real life.

Note that the focus of this report is on nuclear plant safety during normal operations and accident scenarios. Issues of physical security and non-proliferation lie outside the scope of this report.

Nuclear safety through functional containment

Nuclear safety involves minimizing risks to plant workers, the broader public, and the environment based on detailed analyses of the probabilities and adverse impacts of possible scenarios. In the context of nuclear modeling and simulation, the probabilities of possible scenarios are referred to as frequencies (usually on the order of 10^{-3} to 10^{-7} per simulated reactor-year of operation) by the NRC, and the impacts are referred to as consequence. With this terminology, the risk inherent in each possible scenario can be calculated by multiplying the frequency by the consequence. Therefore, minimizing nuclear safety risks involves minimizing the frequency (probability) of possible scenarios, minimizing the consequence, or minimizing both frequency and consequence. Figure 2 below illustrates the conceptual basis for nuclear safety requirements.

Figure 2. Nuclear safety risk based on frequency and consequence



Source: INL, 2021.

Although technologies and approaches such as fuel or seismic isolators can be applicable to both LWRs and non-LWRs, the benefits of functional containment can only be maximized under non-prescriptive requirements. As long as LWRs have prescriptive requirements, the value of making improvements in inherent safety features like better fuel performance will not result in considerable cost savings for the rest of the plant. Examples of functional containment designs — including fuel layers, pressure containment and embedment of structures and seismic isolators — are discussed in later sections.

Safety structures, systems and components for LWRs

National, nuclear regulatory agencies ensure public safety and environmental protection by requiring associated risks with structures, systems and components (SSCs) at plants so as to remain within the lower left (green) area of the frequency/consequence (see Figure 2 above). The three fundamental safety functions for nuclear SSCs are: 1) reactivity control; 2) decay-heat removal using the primary cooling system; and 3) radionuclide containment. For conventional

LWRs (currently Gen III/III+), many SSCs are essential to ensure safety, and these SSCs provide layers of protection through defense in depth from the fuel cladding to the pressure vessel, reactor-room shield, building walls, the containment structure and plant site. In the United States, many of these SSCs require vendor certification under nuclear quality assurance level 1 (NQA-1) as defined by the ASME. The numerous SSCs in LWRs are summarized in Table 2.

Table 2. LWR safety SSCs

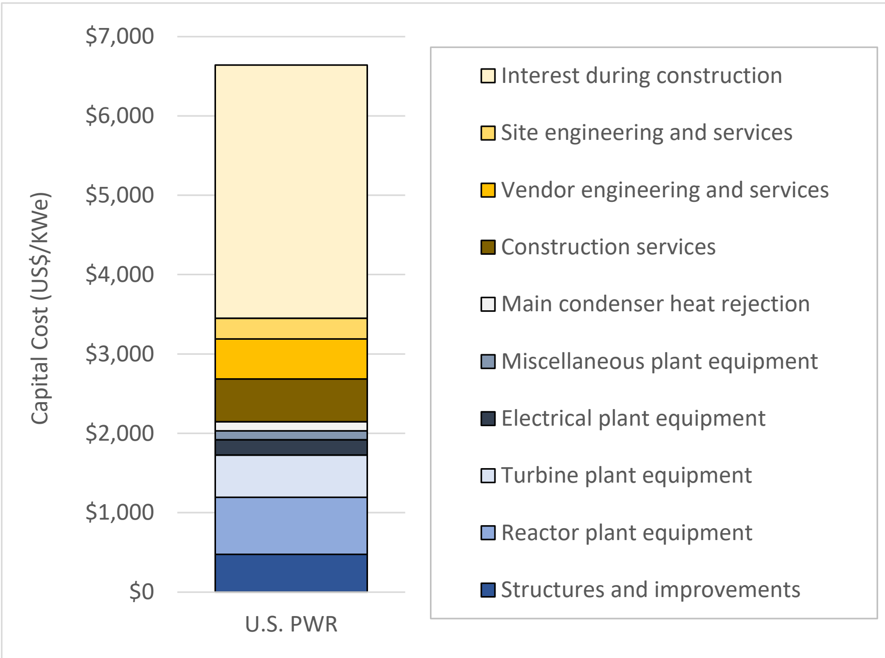
Safety function	Situational status	LWR safety structures, systems and components
1. Reactivity control	**Normal operation and transients**	Selection of fuel isotopes, enrichment, geometry
		Moderator / coolant
		Control rods and drives
	Accident scenarios	Boric acid / neutron poison
		Shutdown / SCRAM*
		Anticipated transient without SCRAM (ATWS) system
2. Decay heat removal	**Normal operation and transients**	Primary cooling system (pumps and pressure)
		Ultimate heat sink
	Accident scenarios	Emergency core cooling systems (ECSS) High pressure coolant injection (HPCI) system Low pressure coolant injection (LPCI) system Automatic depressurization system (ADS) Core flood tanks Core spray system (boiling water reactors [BWRs]) Containment spray system
		Auxiliary feedwater system
		Emergency service water system
		Emergency and off-site power (diesel, batteries)
		Core catchers (corium retention)
3. Radionuclide retention	**Normal operation and transients**	Fuel cladding (“first” layer of radionuclide retention)
		Pressure vessel
	Accident scenarios	Primary concrete containment structure
		Secondary concrete containment structure (for BWRs)
		Concrete basement for seismic protection
		Plant site and exclusion zone
		Transmission through air, soil, water

* A SCRAM (or reactor trip) is an emergency shutdown of a nuclear reactor effected by immediately terminating the fission reaction.

Source: INL, 2021.

A precise calculation of the costs for LWR safety SSCs, whether individually or collectively, is difficult to carry out using publicly available information. An additional difficulty is that the costs for ensuring nuclear plant safety depend on the local setting for each plant project with respect to regulatory requirements, equipment and concrete prices, labor wages, management practices, vendor consortia, etc. Representative capital cost components for US pressurized water reactors (PWRs), using data from the Massachusetts Institute of Technology (MIT, 2018) and based on analysis of US nuclear construction projects in the 1970s and 1980s, appear in Figure 3. Direct construction costs for the reactor, turbine and other plant systems are in blue and gray, while indirect costs for engineering, construction management services and interest are in gold and yellow. The direct construction expenses represent only 32% of the total capital costs. The indirect costs and interest represent 68%, primarily because the many safety SSCs for LWRs require extensive attention and many person-hours of work throughout the construction project, ranging from engineers, construction managers, inspectors and other technical professionals. Interest is a large cost component, according to the MIT study (2018), based on US experience, because gigawatt-scale construction projects have taken such an extended period of time to be completed (e.g., over ten years for Vogtle Units 3 and 4, currently ongoing in the United States), and high interest rates or other capital costs reflect the substantial financial risks borne by funders. The MIT analysis uses a representative interest rate of 7.86%. If non-LWRs with inherent safety features can be designed and built with fewer, simpler and smaller SSCs than LWRs, based on functional containment and other strategies, with fast construction schedules and lower project execution risk, then the large indirect costs for LWRs shown in Figure 3 below can potentially be reduced significantly for non-LWRs.

Figure 3. Representative capital cost components for US PWRs



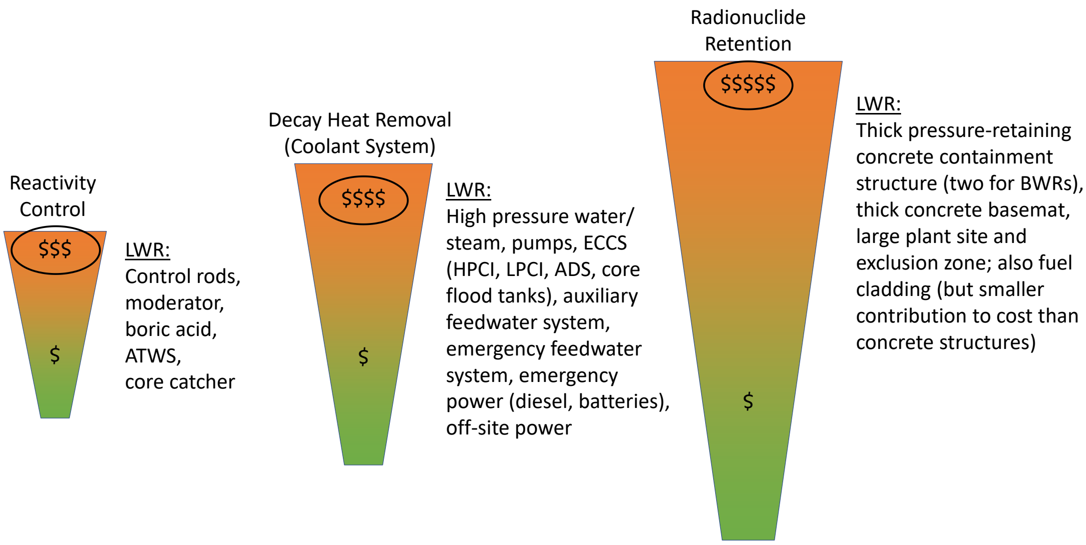
Note: The figure uses data for the US PWR best experience set of construction projects in the 1970s and 1980s, as discussed in the source study, and costs are expressed in 2018 US dollars.

Source: Figure is based on data from MIT, 2018.

On the costs of containment structures for LWRs, Champlin (2018) calculates the cost of the AP1000 containment and shield building as USD100 million. As discussed below, strategies that avoid the need for such structures could achieve cost savings around this same amount, assuming the strategies do not impose significant additional costs of their own.

Figure 4 below presents a conceptual summary of the relative cost additions to LWR plant designs for reactivity control, decay-heat removal (i.e., the cost of the coolant system), and radionuclide retention. The tapering at the bottom of the wedges, green color and single dollar sign denote the region of low costs, whereas the wider top of the wedges, red color and multiple dollar signs denote the region of high costs. The oval within each wedge qualitatively reflects the approximate placement of high, medium or low costs. Similar figures for cost reduction strategies related to non-LWRs with the functional containment design are presented in subsequent subsections.

Figure 4. Conceptual summary of costs for reactivity control, decay-heat removal and radionuclide retention for LWRs



Source: INL, 2021.

Comparing LWR and Gen-IV safety profiles

The six reactor families selected by the Generation IV International Forum for further research and development comprise a wide variety of concepts: 1) the molten salt reactor (MSR); 2) the sodium-cooled fast reactor (SFR); 3) the lead-cooled fast reactor (LFR); 4) the very-high-temperature reactor (VHTR); 5) the supercritical-water-cooled reactor (SCWR); and 6) gas-cooled fast reactor (GFR). The six reactor families, with their associated nuclear physics and fuel cycles, differ from LWRs in terms of inherent passive safety and other aspects of reactor physics and plant design. Performance-based regulations account for these differences in Gen-IV reactors relative to LWRs through functional containment analysis, rather than relying on prescriptive LWR-based requirements. In addition, future nuclear plants could embed reactors underground and use seismic isolation as strategies to take further advantage of the functional containment approach with the ensuing cost reductions. These advantages may not be obvious with the prescriptive LWR-based requirements (e.g., minimum thickness for structures). The following items summarize the uniqueness of Gen-IV reactor designs and innovative approaches relative to LWRs. The items are examples as not all Gen-IV designs incorporate each of these items.

Inherent passive safety;

- Negative void coefficients
- Coolant boiling points > maximum potential reaction temperatures
- No core melt (high temperature gas reactor [HTGR])
- Specific design features -> loss-of-flow accident (LOFA) risk elimination

Other safety aspects of reactor physics and plant design;

- Lower power density (large vessel and large building)
- Lower core damage frequencies (probabilities)
- Integrated primary loop -> loss-of-coolant accident (LOCA) risk elimination
- Coolant pools (whether as enclosed reactor vessels in pools or pool-based designs)
- Reactors in pools (including integrated PWR, as well as pool-type sodium and lead)
- Larger water inventories
- Smaller fuel inventory

- Fission product retention in layered fuels (e.g., tristructural-isotropic [TRISO] fuel as discussed below)
- High heat capacity in salts
- High thermal conductivity for metal coolants
- Hydrogen passive autocatalytic recombiner
- Inert containment
- Low-pressure design and piping (e.g., sodium-cooled fast reactors)

Additional cross-cutting strategies (Gen-IV, as well as LWR);

- Embedment
- Seismic isolation

The passive safety characteristics of non-LWRs are provided in Table 3 below and are based on the views of MIT researchers (MIT, 2018). Detailed assessments of the characteristics of non-LWRs are also available from the Generation IV International Forum's Risk and Safety Working Group (GIF, 2021). Non-LWRs also carry certain risks and concerns relative to LWRs, however, such as combustion with air for sodium-cooled reactors and leakage of helium for high-temperature gas reactors. The MIT report also notes (in Appendix K) that the cost differences for non-LWRs relative to LWRs may be small, especially if regulatory requirements and project management needs are similar.

Table 3. Passive safety characteristics of non-LWRs

Coolant	Passive Safety Characteristics
Helium	**Modular HTGR:** Inherent and passive safety because of lower power density coupled with high heat capacity of graphite and passive heat removal from core and reactor vessel. Passive shutdown from negative reactivity feedback in anticipated transients without scram and other transients has been demonstrated on existing smaller versions of HTGRs.
	GFR: Claims to be passively safe but demonstration will be required. Historically GFRs have had difficulty attaining high degrees of passive decay heat removal given high power density, low thermal capacity in the core, and poor conductivity of the helium coolant.
Liquid Metals	**Small SFRs:** Low pressure pool design to eliminate loss of coolant. Through a combination of reactivity feedbacks[a] from enhanced neutron leakage, this design achieves a negative power reactivity feedback, which helps to control the system under all postulated unprotected (no scram) transients without operator intervention. Passive safety of these concepts has been demonstrated in tests done at EBR-II. A variety of passive decay heat removal systems exist that can provide a connection to an ultimate heat sink for the long term.
	Large SFRs: Designing for overall negative reactivity feedback is more challenging for larger systems given the lower neutron leakage and positive reactivity void coefficient of these types of reactors. Passive heat removal is also more difficult given the decay heat load and lower surface-to-volume ratio of the reactor vessel compared to small SFRs.
	LFR: Lead provides a large heat sink, especially in unprotected events. Reactivity feedbacks prevent severe accidents, similar to SFR approach. However, because the Russian LFR was built for submarine service, testing of passive safety systems that is representative of commercial designs would be required.
Molten Salt	**FHR:** Combines passive safety features of HTGR with the large heat capacity and natural circulation capabilities of molten salt to obtain excellent safety profile. No integral testing of passive safety has been conducted but will be required.
	MSR: To provide passive safety, drain tanks with a passive fuel plug that will melt if high temperatures occur under off-normal conditions are incorporated into the design. Drain tanks will have to be designed to avoid criticality events and to remove decay heat. Integral testing has never been performed to confirm the safety benefits. Heat content of the off-gas system containing noble gases and volatile fission products needs to be considered in design. Holdup of highly radioactive molten salt in reactor piping might severely limit operator access even after molten salt draining. Fast-spectrum MSRs have large negative temperature and void coefficients because liquid fuel is expelled from the core if voids are formed or if the temperature increases. Criticality might occur under accident conditions if the fissile materials were to leak from the primary system and come near neutron moderators, such as concrete.

[a] The combination of reactivity feedbacks for liquid metal-cooled fast reactors is discussed in MIT, 2018.
Source: Table 3.4 from MIT, 2018.

NRC performance-based approach for Gen-IV concepts

The Licensing Modernization Project (LMP), led by industry and supported by the US Department of Energy (DOE) and Idaho National Laboratory (Moe, 2018), addresses challenges arising from the transition from licensing requirements of traditional LWRs to the newer generation NPPs. The new-generation plants include advanced non-LWRs such as molten-salt, liquid-metal fast, and gas-cooled reactors. The advanced reactors possess safety features that are unique and different from LWR designs. The LMP helps achieve these benefits and better aligns licensing requirements for advanced reactors respective to their unique designs. Hence, the LMP was conducted with the goal of reducing regulatory uncertainties in the deployment of non-LWR reactors. The balance between the deterministic and probabilistic approaches has been considered for risk-informed decisions throughout the life cycle of advanced reactors.

Using the outcomes of the LMP, the NRC (2020) approved guidance for the licensing, certification, and approval of non-LWR reactors. The guidance is based on a methodology that is technology-inclusive (TI), risk-informed (RI), and performance-based (PB). The TI part of the methodology provides a common approach in selecting the licensing-basis events (LBEs), classification of SSCs, and assessing the defense in depth for different non-LWR technologies. However, the applicability of specific technical regulatory requirements related to the unique safety features of different non-LWR technologies is determined on a case-by-case basis.

The US DOE (2020) describes the general layout for the licensing process of advanced non-LWR reactors, as shown in Figure 5. The process relies on TI characteristics of different non-LWR reactors. Next, the LMP framework is initiated for a systematic and reproducible evaluation and selection of LBEs, classification of SSCs, and determination of defense-in-depth adequacy. Acceptable accident event sequences are identified using frequency-consequence (F-C) target curves under the LMP framework. The F-C curve indicates the acceptable risks of event sequences, and the LBE is the frequency of occurrence of the event sequences. The LBE categories are defined as: design-basis accidents (DBAs), anticipated operational occurrences (AOOs), design-basis events (DBEs), and beyond design-basis events (BDBEs). If the F-C target is not met, the overall design is iterated until the target values are achieved.

Figure 5. Streamlined advanced reactor licensing process

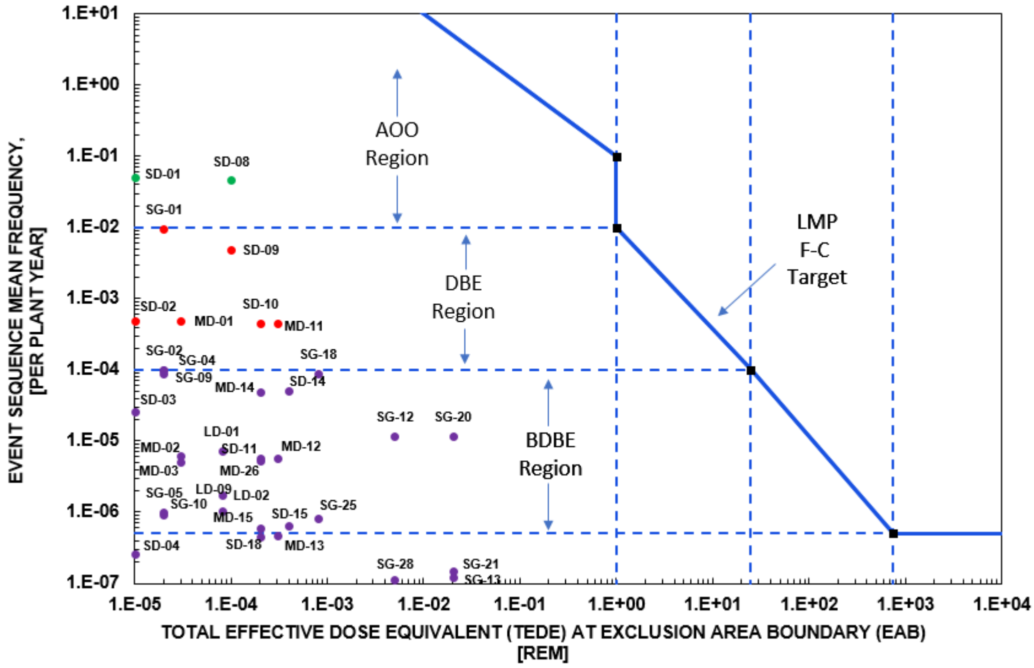
Source: US DOE, 2020.

According to filings with the NRC and supporting documents, the following non-LWR designs have completed, begun or are planning to use the LMP process:

- High-temperature gas reactor (HTGR): X-energy;
- Sodium-cooled fast reactor: GEH PRISM;
- MSR: Oak Ridge National Laboratory's MSR Experiment;
- Fluoride salt-cooled high-temperature reactor: Kairos;
- Heat pipes: Westinghouse eVinci.

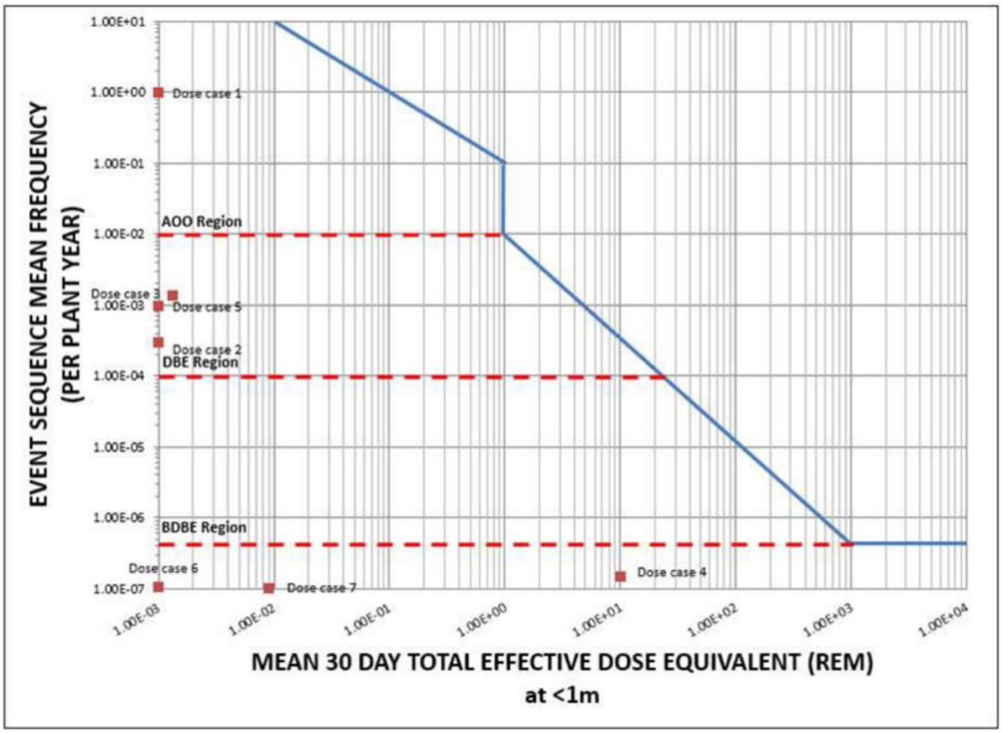
For example, Figures 6 and 7 below show the preliminary frequency/consequence (F-C) analyses for the X-energy X-100 HTGR (Southern Company, 2018) and the Westinghouse eVinci (Southern Company, 2019) heat pipe reactor. In both figures, the risks associated with the analyzed scenarios (represented by small points on the diagram) are far below the target level.

Figure 6. X-Energy's Xe-100 HTGR preliminary F-C analysis



Source: Southern Company, 2018.

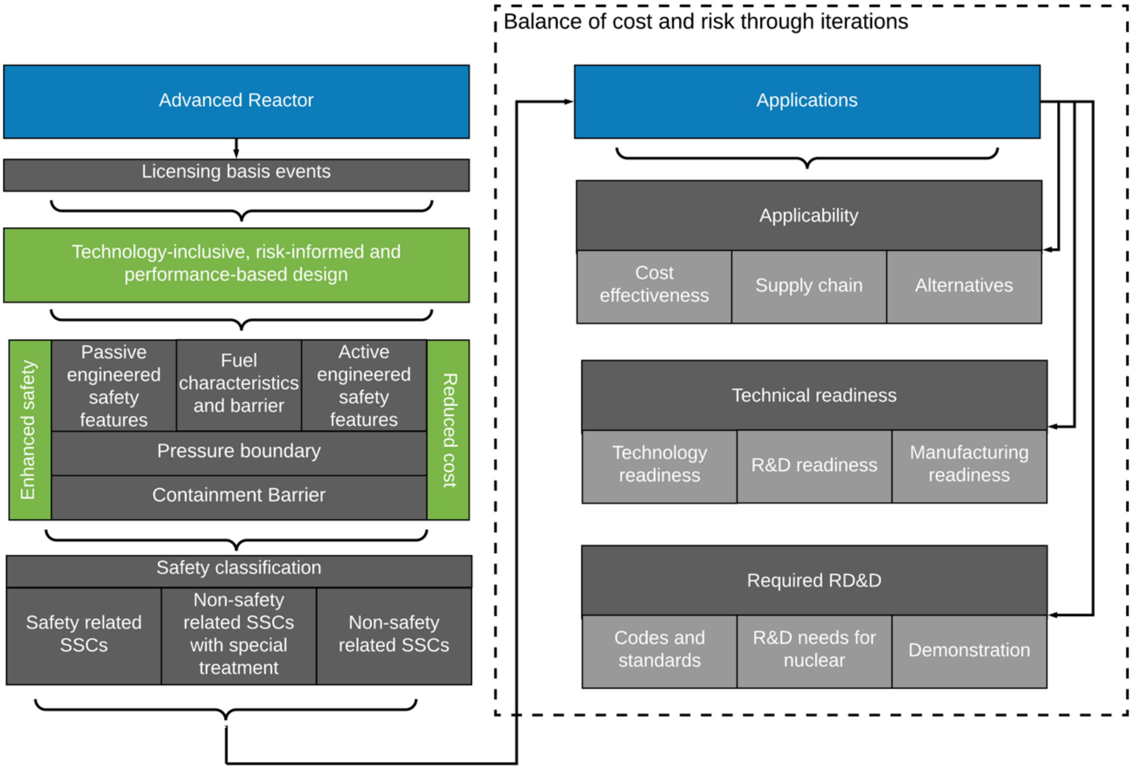
Figure 7. Westinghouse eVinci heat-pipe reactor, preliminary F-C Analysis



Source: Southern Company, 2019.

The TI-RIPB framework provides a comprehensive safety assessment for advanced nuclear reactors that can result in a combination of different fuel and SSCs in the design, as shown in Figure 8 below. The core design and related safety features are collected as: 1) fuel characteristics and barriers; 2) passive engineered safety features; and 3) active engineered safety features. These safety features and benefits are usually the outcome of the reactor or fuel design, such as that of using TRISO fuel, and are the basis for the design of the rest of the plant. The safety and comparably reduced cost of non-LWR designs start at this stage. The pressure boundary for advanced designs is also usually different from the conventional high-pressure reactor designs, which enables a more flexible containment barrier. As a result of these safety features and the defense-in-depth approach, advanced reactors have the potential to be sited near industrial complexes, making them more cost-efficient than conventional reactors.

Figure 8. The overall schematic of the TI-RIPB framework for cost-effective advanced nuclear



Source: INL, 2021.

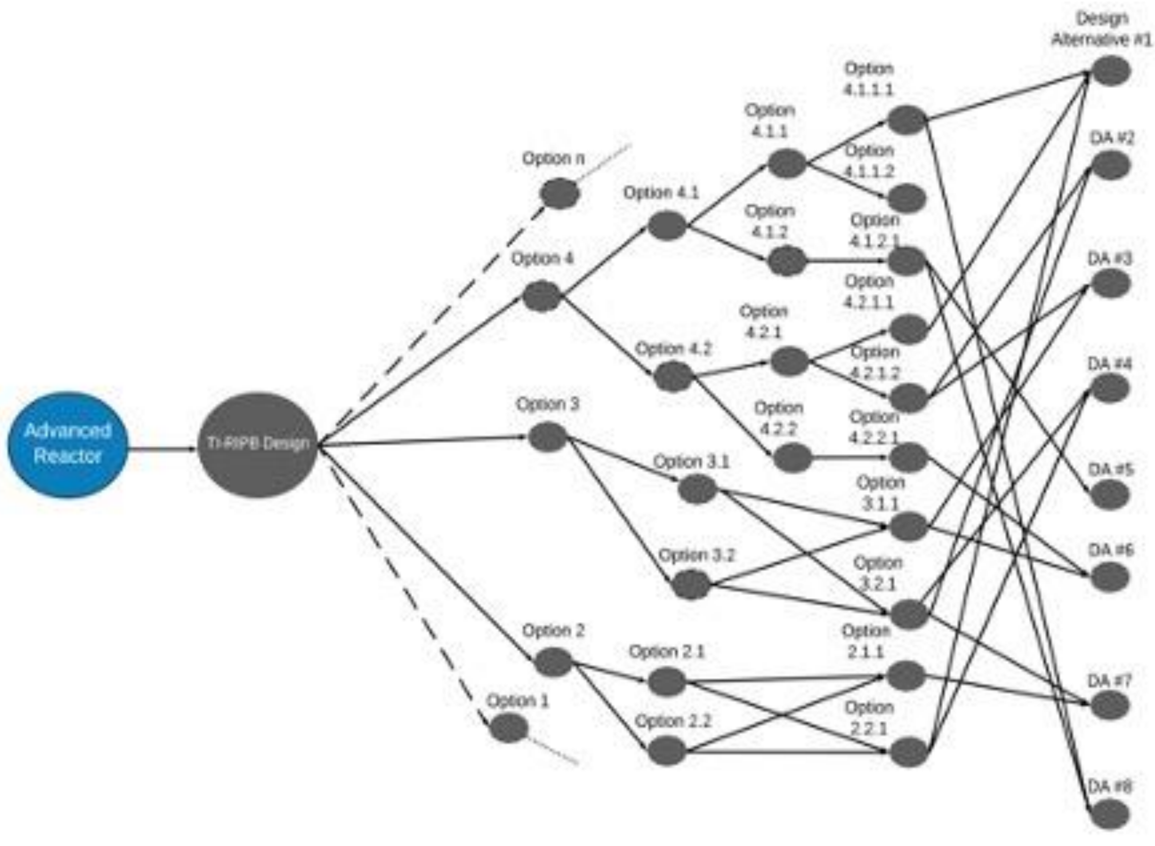
Different safety classifications may be assigned to SSCs based on LBEs and the design of the safety components. The different classifications are based on how large a contribution to safety is desired from the SSCs. These classifications are: 1) safety related SSCs; 2) non-safety related SSCs with special treatment; and 3) non-safety related SSCs. At this stage of the process, different design strategies may be evaluated with a potential to reduce the cost of the overall plant design while balancing acceptable risk. It is possible to integrate different technologies or approaches in the design iterations of a plant. These technologies and approaches are evaluated based on their functionality — for example: 1) installing seismic isolators to reduce the seismic loads on the safety-critical components or the reactor building; 2) deeply embedding reactor buildings to protect them from external accident initiators; or 3) employing modular structural systems to maintain geometry under severe events.

Functional containment design for nuclear plants

This study covers the potential technologies and approaches under three categories: 1) applicability; 2) technical readiness; and 3) required RD&D. In short, the applicability is based on cost effectiveness compared to the preceding technologies in nuclear energy or alternatives. The supply chain maturity of individual technologies or approaches for advanced nuclear energy is also evaluated at this stage. Technical readiness is evaluated with the existing R&D, enabling technologies and technical studies on their deployment, and allowing established manufacturing capabilities to be deployed at the present time. The representative R&D category links to the need for: 1) development of codes and standards; 2) nuclear energy deployment; and 3) demonstration projects to gain practical experience.

The TI-RIPB framework approach for advanced reactors enables a combination of different options in design, which can lead to different costs and overall associated risks. Figure 9 below illustrates a combination of selections that may result at different risk levels and the associated overall cost for the plant. For example, designers could develop a design that includes seismic isolators for the reactor vessel and heat exchangers, bury the reactor building, and reduce the safety classification for the rest of the plant. Alternatively, a preferable design could site the plant on the surface, use seismic isolators as base isolators and use robust modular shielding walls for the reactor building. Designs could be developed iteratively, which include SSCs with different safety classifications, costs and safety features. The selection of these options is highly dependent on the regulatory scheme and inherent safety features of the reactor design, such as use of TRISO fuel. The objective is to optimize each design for the best safety at the least cost. In the terminology of decision analysis, trade-offs between plant risk and cost can be weighed by selecting a design alternative from the Pareto efficient frontier (i.e., for possible combinations of plant risk and cost that are superior to other combinations, see Figure 10).

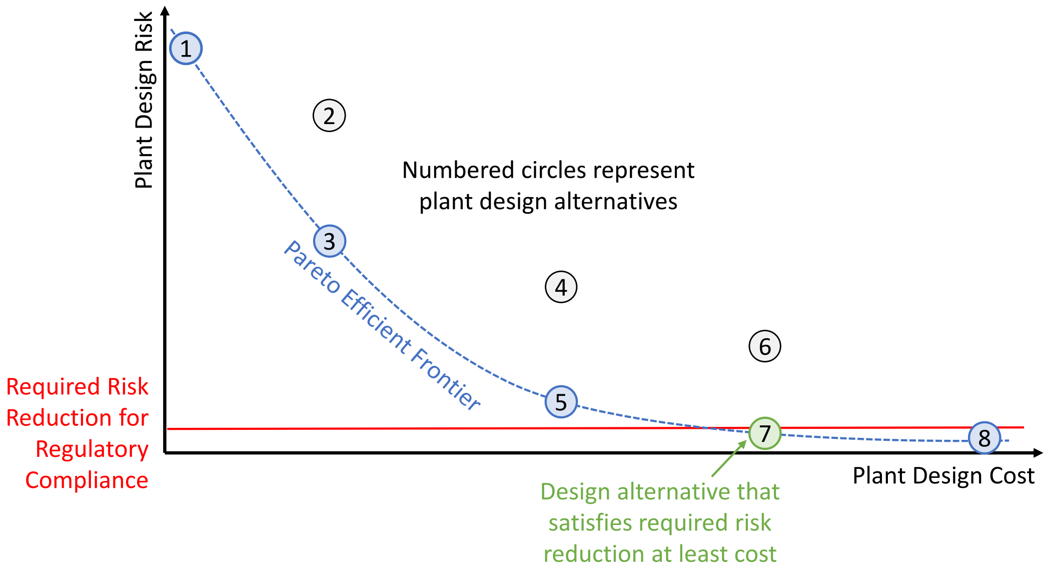
Figure 9. Process for developing and refining design options and alternatives for advanced reactor concepts



Source: INL, 2021.

The potential trade-offs between risk and cost for nuclear plant designs – using eight alternatives – are represented by numbered circles in the Figure 10 below. The vertical axis shows the risk inherent in each design alternative (defined as risk = simulated frequency multiplied by the consequence), with a red line representing the required risk reduction for regulatory compliance, and the horizontal axis showing the necessary cost for each design alternative, accounting for O&M costs in addition to construction capital costs. The trade-offs between risk and cost for design alternatives are an example of Vilfredo Pareto's efficient frontier mentioned above, which is now widely used in economics, engineering and other fields, incorporating optimization analysis across multiple competing objectives (Chong and Zak, 2013). The Pareto efficiency frontier is the set of feasible options forming the envelope of potentially optimal strategies, provided the bounding constraints are satisfied. Any deviation from the Pareto efficiency frontier would worsen one or more of the objective variables.

Figure 10. Illustration of trade-offs between risk and cost for nuclear plant design alternatives



Source: INL, 2021.

Design alternatives (DAs) – in blue circles in Figure 10 – lie along the Pareto efficient frontier because no other alternatives would reduce risk to equivalent levels at lower cost. For example, DA 1 (in this purely hypothetical illustration) would entail high risk, but low cost; it would not be approved by regulators because it does not achieve the required risk reduction. DA 2 would reduce the risk relative to 1, but it would also require larger costs. DA 3 would reduce the risk further, at the same costs as DA 2. Thus, DA 3 is superior to DA 2, and it would not make economic sense to choose DA 2 (unless other factors are relevant besides the risks and costs shown here). DAs 4 to 8 have lower risks and higher costs than 3, but 5 is superior to 4, and 7 is superior to 6. DA 8 has the lowest risk, but also the highest cost. DAs 1, 3, 5, 7, and 8 define the Pareto efficient frontier, and any design alternatives to the upper right of them would be worse. Assuming the required risk reduction for regulatory compliance shown in the figure, DA 7 best satisfies the regulatory requirements at a lower cost than 8. Note as well that in this figure, with a shallow slope of the Pareto efficient frontier for low levels of plant design risk, relatively small changes in the required risk-reduction level could significantly change the necessary costs. For example, DAs 5 and 8 are both close to the required reduction level (beyond and within the boundary respectively), but DA 8 would cost approximately twice as much as DA 5, assuming a linear scale for the horizontal axis denoting plant design cost (in reality, the costs could be exponential). Although the following assessments of functional containment case studies do not directly apply the framework of the Pareto efficient frontier, the case studies highlight opportunities for plant risk reduction with minimal increase in plant design and construction cost (as well as the potential implications on O&M and D&D costs). Future studies could use the Pareto efficient frontier to study trade-offs for multi-criteria decision making (MCDM).

Functional requirements are the statements of the high-level tasks, actions or activities that the system or its component must do. These requirements do not indicate how these statements can be achieved; i.e., they do not go into detail on how to implement the associated functions. “Maintain control of radionuclides” can be a system-level functional requirement. To achieve this function, sub-functions, such as “preserve geometric integrity” of the components or structures may be needed. There are complimentary aspects to the functional requirements, including performance requirements for the components to function as intended. These performance requirements are usually quantitative, such as temperature or displacements. The business and economic success of a system – such as an HTGR NPP – are accomplished by successful implementation of the required functions and the desired performance of the aggregated subsystems. A designer can select different SSCs to satisfy the performance levels and achieve the required functions. The variety of approaches in designing and selecting these components or structures has a considerable impact on the overall cost of the NPP. Safety features and associated risks of the selected technologies and their performance eventually affect the overall performance and risk of the NPP. A system could undergo several cycles of iterations under the TI-RIPB framework approach in order to find a satisfactory design that meets business, cost, regulatory, public safety and environmental requirements.

Assessment framework for cost reduction strategies

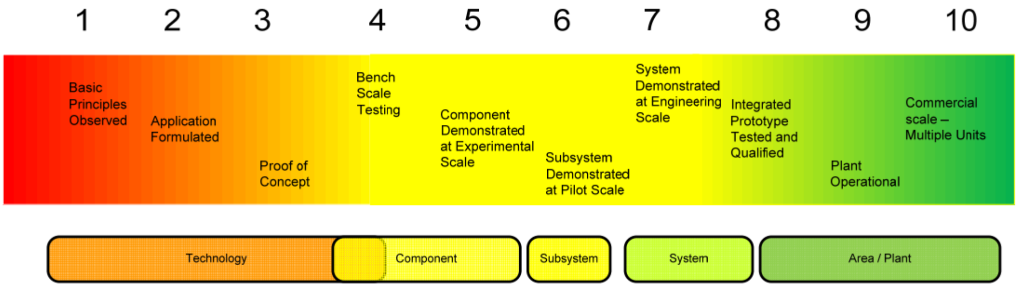
The assessment methodology follows multiple steps for each functional containment strategy:

1. *Description, benefits, applicability, and performance-based regulation.* The functional containment strategies are first described and linked to Gen-IV concepts based on their particular reactor physics and risk profiles. The benefits of each strategy are identified relative to conventional LWRs with high costs for containment SSCs so as to comply with prescriptive regulations. The functional containment strategies are applicable to most or all of the Gen-IV concepts, and some strategies could be relevant for Gen-III/III+ LWR designs as well. The details of reactor physics and risk profiles for Gen-IV concepts, however, could make certain functional containment strategies more or less applicable. This assessment of applicability draws on existing materials, such as public submittals to the NRC, addressing the potential use of functional containment for Gen-IV concepts and their benefits relative to traditional LWR prescriptive requirements. The integration of each functional containment strategy into performance-based regulation is also discussed in this step.

2. *Cost reduction.* In this step, estimates of functional containment costs are presented from existing public sources. Representative costs for LWR-style prescriptive requirements from past or ongoing nuclear construction projects have been collected to calculate illustrative cost reductions from functional containment strategies. The cost assessment takes a holistic perspective across the plant life cycle, spanning construction-cost components (equipment, materials, labor, or indirect, and interest during construction), fuel cycle, O&M and D&D. This step also accounts for aspects of the Gen-IV concepts and functional containment strategies that introduce additional costs relative to LWRs. It is important to emphasize that all cost information in this initial assessment rests on various assumptions and particular drivers that may differ between plant designs, construction locations, and other project-specific circumstances. For these reasons, all quantitative estimates of functional containment costs and potential cost reductions relative to LWR-style prescriptive requirements are only illustrative, and further work is necessary by members of the GIF Economic Modelling Work Group (EMWG) or by the Senior Industry Advisory Panel (SIAP) to develop more precise cost estimates for their own contexts, as discussed in the final section of this report.

3. *Technical readiness*. Functional containment strategies are assessed in terms of their technical readiness. This assessment uses the standard levels of 1 to 10 and their respective criteria from the US DOE, as shown in Figure 11. This step also highlights gaps and obstacles on the path towards commercial deployment.

Figure 11. Technology readiness levels from the US DOE



Source: Reitsma, 2020.

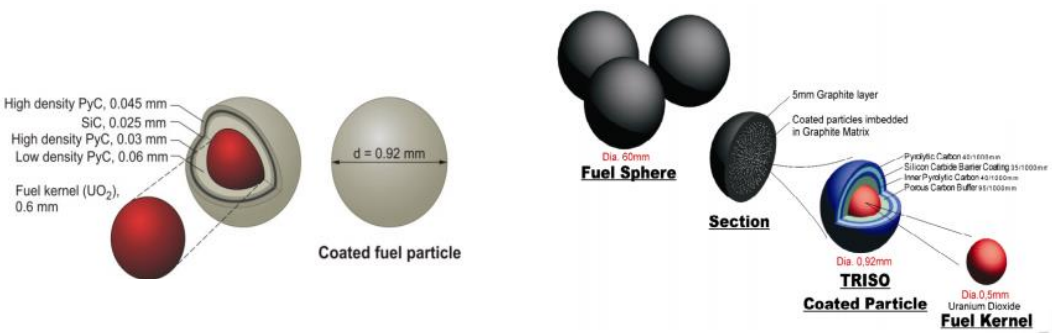
4. *Further RD&D*. Based on the technical-readiness assessment above, further needs for RD&D are identified for each functional containment strategy. This step involves planning technical work to demonstrate technologies, establishing regulatory criteria and improving the precision of cost reduction opportunities. The most promising strategies receive the most attention in this part of the assessment so that RD&D resources can be put to their best use by member countries and by associated organizations. Opportunities for collaboration with other GIF working groups, such as the Risk and Safety Working Group, are also summarized in the case studies.

The following sections present case studies of the assessment framework for functional containment strategies.

Case study 1: Enhanced micro fuel layers in functional containment design

In the current fleet of LWRs with conventional fuel assemblies, the cladding around fuel rods contributes to the defense-in-depth strategy for compliance with regulatory safety requirements. Some concepts for new nuclear plants would use TRISO particle fuels with layers of carbon materials that retain fission products as an enhanced form of functional containment within the fuel assembly. Figure 12 below shows TRISO fuel particles for two types of HTGRs. On the left, representing fuel particles for prismatic-block HTGRs, the fuel kernels containing uranium dioxide (UO_2) are enclosed within several layers of pyrocarbon and silicon carbide to form coated fuel particles that are 0.92 mm in diameter, which are then assembled within larger fuel compacts, rods, blocks and columns. On the right, representing pebble-bed HTGRs, the coated fuel particles are inserted into fuel spheres that are 60 mm in diameter, and are stacked within the reactor, descending one at a time through the core. Petti et al. (2013) argue that both approaches with TRISO particles provide functional containment directly around the fuel sources of radioactive nuclides, thereby reducing the need for other SSCs around the reactor and plant. Collins (2009) quantifies the reduction in source term achieved with TRISO. In addition to the two varieties of HTGR, the fluoride-salt-cooled high-temperature reactor (FHR) will also use TRISO and leverage its functional containment advantages.

Figure 12. TRISO particles for HTGR prismatic-block design (left) and pebble-bed design (right)



Source: Collins, 2009.

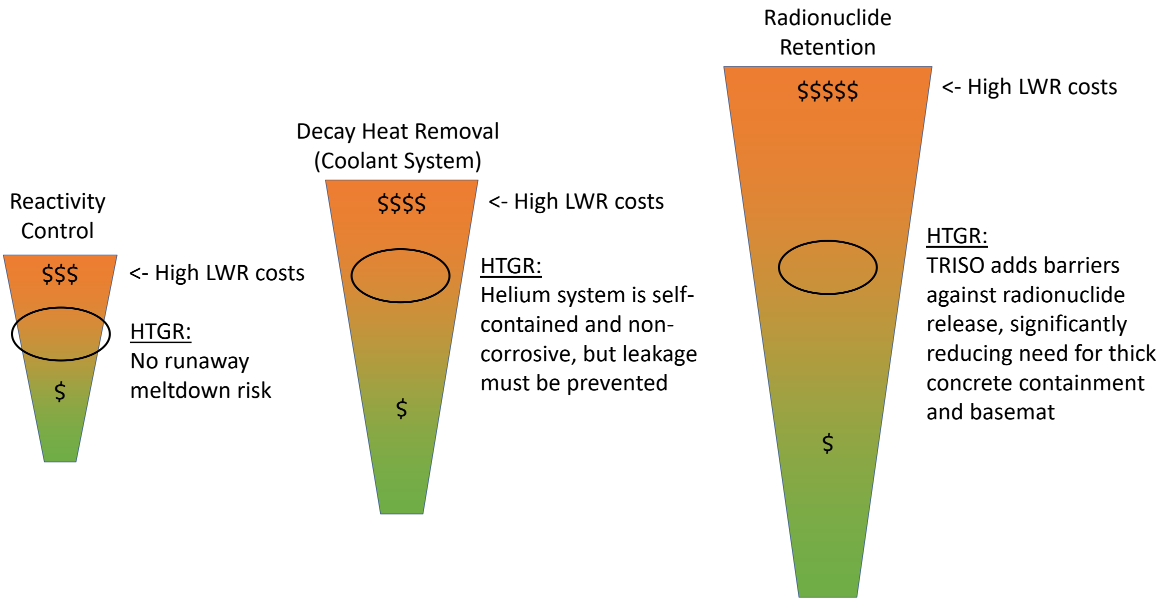
Cost reduction

A fuel strategy using TRISO is expected to reduce costs for nuclear plants with by reducing or eliminating the need for some of the SSCs identified in Table 1. Summary table template for cost reduction strategy assessmentsbecause the layers of pyrocarbon and silicon carbide prevent radionuclide release within accident scenarios and temperature ranges relevant for HTGRs and FHRs. In the functional containment design approach, the layers around the fuel kernel contribute towards defense in depth: therefore, fewer SSCs are necessary around the reactor and plant to stay within the allowable risk range.

Specific estimates on potential cost reductions incident to TRISO fuel are not readily available at present, and they would depend on the details of plant design (within the families of prismatic-block HTGRs, pebble-bed HTGRs and FHRs). As an approximate order of magnitude, however, Champlin (2018) indicates that the broader category of accident tolerant fuels, which includes TRISO as well as more evolutionary improvements for LWR fuels, could save hundreds of millions of dollars per reactor unit through safety-related equipment reclassification, as well as tens of millions of dollars through the elimination of current fuel-failure mechanisms, the reduction of equipment for flexible reactor control, and the reduction of the plant's evacuation planning zone. The costs of TRISO, however, should also account for the higher costs of fuel enrichment (INL, 2021).

Figure 13 below provides a conceptual summary of the cost assessment for HTGRs in order for them to comply with safety requirements based on reactivity control, decay-heat removal and radionuclide retention.

Figure 13. Conceptual cost reductions for HTGRs, with fuel layers in functional containment design



Source: INL, 2021.

Technical readiness

Coated fuel particles have already been tested in HTGR demonstrations, for example at Peach Bottom in California from 1966 to 1974 (using a simpler predecessor to TRISO with only pyrocarbon) and at Fort St. Vrain in Colorado from 1979 to 1989 (using TRISO). On this basis, Vitali (2018) assesses the TRL for TRISO at 9. Although extensive research on TRISO has been conducted over many decades, with USD 450 million in funding from the US DOE from 1999 to 2017 as calculated by Abdulla et al. (2017), Gougar (2016) assigns it a significantly lower TRL of 6 based on the lack of recent commercial plant use and different forms of fuel under current development relative to the early demonstrations.

Further RD&D

As noted above, several tests in laboratories and NPPs have been performed on TRISO and its predecessor forms of coated fuel. Further RD&D is necessary before certification of TRISO for future commercial nuclear plants, particularly for the high-assay low-enriched uranium (HALEU) in the fuel. The GIF EMWG could collaborate with the GIF Risk and Safety Working Group on the further RD&D necessary for regulatory approval of TRISO in participating countries.

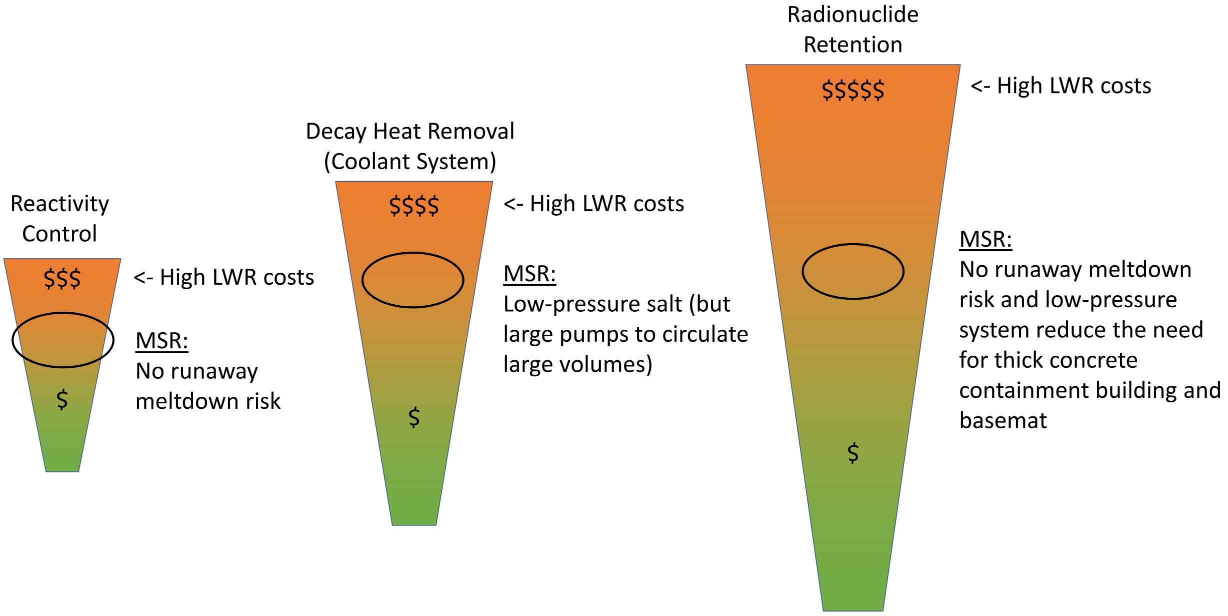
Case study 2: Low pressure containment in functional containment design

Pressure containment can be achieved in functional containment design with reactor and coolant concepts that operate at much lower pressure than LWRs. For example, MSRs remove decay heat from the reactor core by pumping liquid salt, which could contain compounds with fluoride, lithium and beryllium, as well as fuel compounds with uranium and thorium (unless the fuel for MSRs is packaged as TRISO). MSR designs would operate around atmospheric pressure (0.1 MPa, in contrast with pressures around 15–17 MPa for LWRs). Although these designs could require powerful pumps to move large volumes of molten salt (depending on salt viscosity), the low pressure would reduce or eliminate the need for thick pressure-retaining containment structures, typical of LWRs. Elsheikh (2013) summarizes the risk profile of MSRs and concludes that "the characteristics of the MSR suggest that the probability and consequences of a large accident [would] be much smaller than most solid-fuel reactors. At the same time, the processing and other operations indicate greater concerns associated with smaller accidents."

Cost reduction

Champlin (2018) calculates the cost of the AP1000 shield building as USD 100 million, based on expected concrete quantities, labor, engineering, management and time (i.e., assuming no redesign or problems leading to rework and higher-than-expected costs). The low pressure of MSRs could significantly reduce these costs by pressure containment in functional containment design. Mignacca and Locatelli (2020) summarize existing studies of MSR concepts and private-developer designs. The 1 000 MW_e MSR design from Oak Ridge National Laboratory has an estimated capital cost of USD 6 741/kilowatt electric (kWe) while published targets from three MSR private developers are significantly lower, ranging from approximately USD 1 000 to 4 000/kWe. These lower costs for MSR designs stem partly from the lower pressure of MSR systems, reducing or potentially eliminating the need for thick pressure-retaining containment structures. A conceptual summary of cost reductions relative to LWR levels for low-pressure MSR concepts is provided in Figure 14.

Figure 14. Conceptual cost reductions for MSRs with low pressure in functional containment design



Source: INL, 2021.

Technical readiness

MSRs, as the most prominent category of non-LWR system with low pressure, have been under development since the 1950s. In that decade, the United States conducted the Aircraft Reactor Experiment with a 2.5 megawatt thermal (MWt) MSR, and Oak Ridge National Laboratory created an MSR at its Critical Experiments Facility. The laboratory conducted the Molten Salt Reactor Experiment in the 1960s and 1970s. The United Kingdom and the former Soviet Union also performed research and development on MSR concepts during this period. As noted above, various private developers are now pursuing commercial deployment of MSR designs. Petti et al. (2017) assign MSRs a TRL of 3.

Further RD&D

Finan (2021) states that further RD&D for low-pressure MSRs under the US DOE has been related primarily to fundamental salt properties, reactor-system materials, models and fuel development. The circulation of molten salts in most MSR designs raises issues of material corrosion, irradiation and maintenance needs requiring further scrutiny. The GIF EMWG could collaborate with MSR researchers and the GIF Risk and Safety Working Group to plan further RD&D on low-pressure reactor concepts in the context of functional containment approaches for regulatory compliance.

Case study 3: Intrinsic protection of structures in functional containment design

Many advanced reactors are proposed with deeply embedded or buried reactor buildings. This idea stems from the expectation that deeply embedded reactor buildings are potentially less susceptible to external hazards, including earthquakes, tornados, tornado missiles and aircraft impacts. The potential cost reduction may come with reduced reactor-building wall thickness due to better resilience of underground structures to external hazards and removing the shielding building against aircraft impacts. However, the extra earthwork and securing of the excavated depth for stability may increase costs, particularly if the water table is shallow.

Cost reductions

Areva NP, Inc. (2008) conducted average cost estimations for embedding an HTGR-type reactor inside the soil at an Idaho National Laboratory (INL) site with a water table close to the ground. Table 4 below summarizes estimated costs for fully embedding a reactor building at different sites with different water table conditions. Because of the additional earth work, embedment increases the cost relative to above-grade construction. The reported estimated costs tend to increase when the water table is close to the ground surface at the plant site. However, the designer should consider possible size reductions or omissions in shielding buildings for an embedded reactor building so as to align with the functional containment approach's performance-based and risk-informed design. Gains from the functional containment approach, without having finalized the plant design for a specific site, are not easy to estimate. Overall, it is believed that deeply embedding advanced reactor buildings still has the potential to reduce costs.

Table 4. Estimated cost for embedding HTGR reactor building at different sites

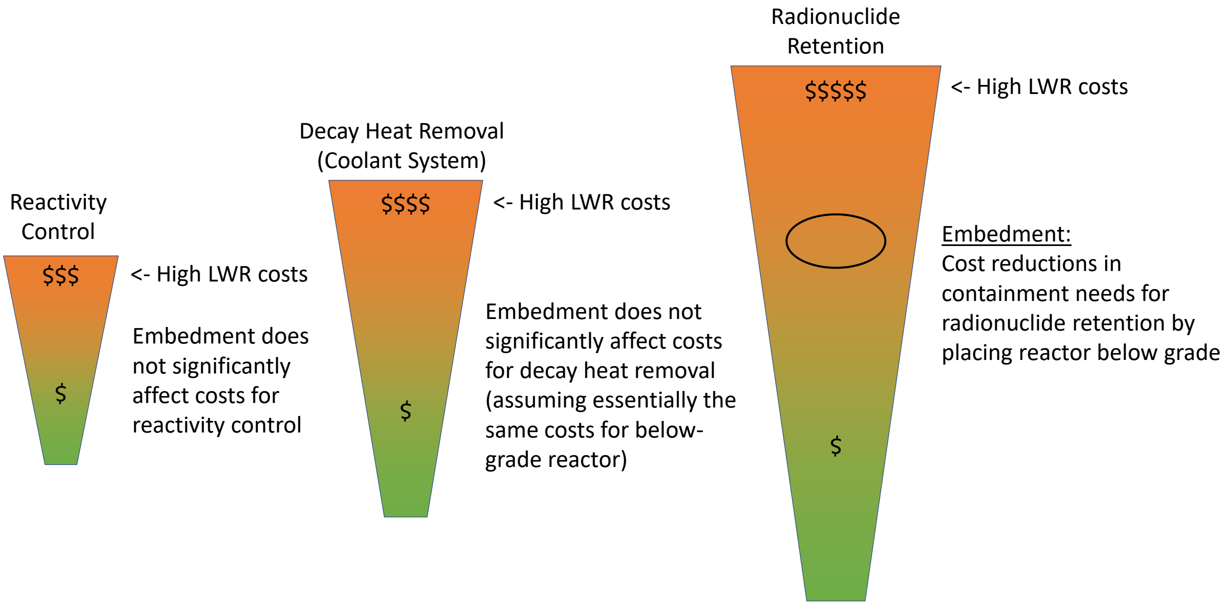
Site	Rough cost estimate (in millions of 2008 dollars)			
	Embedded			Above grade
	Slurry-wall system	Well-dewater system	Rock excavation	
INL			58	39
SRS	122	102		38

Source: Areva, 2008.

Additionally, the heavy machinery and precast modular systems for deeply embedded structures have been widely used in the construction industry. Some studies also point out that embedment with vertical excavation technologies (e.g., the vertical shaft sinking machine by Herreknecht [2021]), which excavates faster than the traditional "bathtub" approach, could cost relatively less while alleviating shielding requirements, particularly for reactor concepts such as HTGRs that use additional layers surrounding the fuel for this purpose. Cost savings have been estimated from embedment at USD 93 million (in 1990 dollars), which equates to USD 191 million in 2021 dollars. Alternatively, the cost savings could be capped at the hypothetical cost of an above-ground shield building without embedment.

A conceptual summary of cost reductions relative to LWR levels for embedment of structures in functional containment design is provided in Figure 15 below. Cost reductions relate primarily to radionuclide retention, rather than reactivity control or decay-heat removal.

Figure 15. Conceptual summary of cost reductions for embedment of structures in functional containment design



Source: INL, 2021.

Technical readiness

The technical readiness level for deep excavations is 10, with some challenges that need to be overcome for applicability to the nuclear domain, including:

- Technology readiness: deeply embedded structures have been mainly deployed for non-nuclear applications. There are limited-size applications in the nuclear field, with a focus mostly on waste-storage units or facilities. Although the supply chain is established for excavating to such depths, nuclear applications will likely require more in-depth control on the dimensions, settlement and quality during excavation.
- R&D readiness: embedding an advanced reactor building requires more research commitment, especially for highly nonlinear dynamic environments. The deeply embedded structures that are designed for ordinary civil or structural engineering do not consider the effects of high soil-strain events and are most relevant for stability under static conditions.
- Manufacturing readiness: no substantial innovation is necessary in manufacturing for deep excavations. The technology readiness is high for such operations.

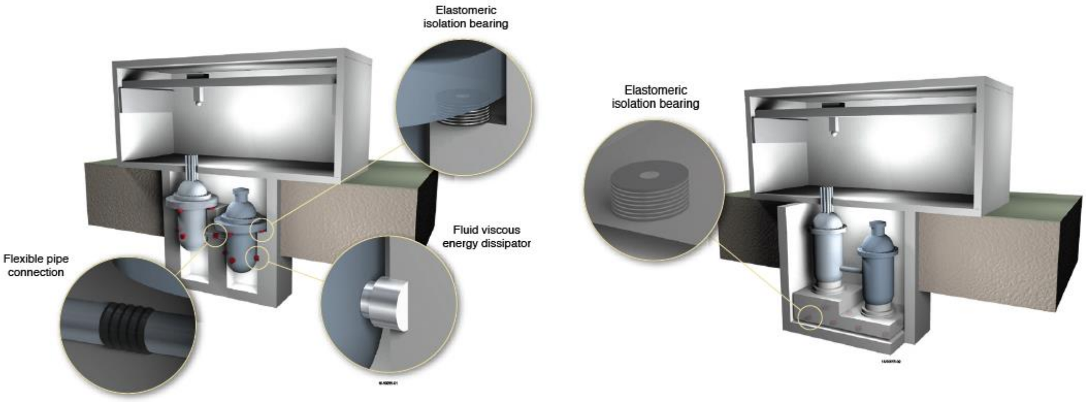
Further R&D

- Codes and standards development: the US Nuclear Regulatory report, NUREG-800 for seismic inputs, analysis and design, and Regulatory Guide, RG 1.198 for seismic soil liquefaction need to be assessed thoroughly for any possible changes or their applicability to deeply embedded advanced reactors.
- R&D needs for nuclear: the dynamic wall pressures on a buried advanced reactor building during extreme hazards, such as high-intensity or BDBE earthquakes, require the generation of experimental and numerical data. Additionally, data are required to assess the changes in the dynamic behavior of the reactor building and internal components during nonlinear soil-structure interactions events. These kinds of experiments may be costly to conduct in controlled environments. Seismic inputs are usually planar motions for conventional NPPs, whereas the consideration of inclined waves may be necessary for deeply embedded reactor buildings.
- Demonstration: after the required R&D and codes and development activities are conducted, scaled demonstration projects will increase the company and human experience to minimize potential cost overruns during deployment of advanced nuclear reactors.

Case Study 4: Seismic isolation in functional containment design

Seismic isolation, as illustrated in Figure 16 below, has been used in non-nuclear industries for ordinary structures for several decades. Whittaker (2018) discusses the past, present and future potential of seismic isolators in nuclear energy. Seismic-isolation technology is mature in terms of manufacturing capabilities, established technical data, and control over dimensions and material properties. Seismic isolation applications have mostly focused on serving as base isolation under the structures or roofs of ordinary structures to dissipate the energy at the isolator level and reduce seismic forces on the superstructure. The two common base-isolation technologies used are friction pendulums and elastomeric isolators. Figure 16 shows some potential applications of seismic isolators for advanced non-LWR reactors.

Figure 16. Examples of seismic isolator applications



Source: MIT, 2018.

Cost reduction

Base isolation may have several potential benefits, including reduced: 1) seismic forces on the superstructure, resulting in reduced structural dimensions and, thus, material and workmanship savings; 2) design and labor costs in repetitive deployments due to standardization of SSCs by only adjusting the properties of seismic isolators from site to site (site-independent design); 3) structural damage and repairs after major earthquake events; 4) insurance premiums due to relatively higher safety resulting from reduced risk; and 5) operational costs coincident with less downtime after moderate to high earthquake events. However, the cost of the seismic isolators, installing them at the site, and introducing a second basemat under the structure for their installation, must also be considered in the cost analysis.

Changes in capital costs from base isolation for non-nuclear and nuclear structures are summarized in Table 5. The non-nuclear values reflect actual experience and cost data whereas the nuclear values reflect predictions. The nuclear values suggest that base isolation for nuclear structures could reduce average capital costs by 6% on net.

Table 5. Changes in capital costs from base isolation for non-nuclear and nuclear structures

	Event/model	Initial capital cost [USD million 2018]	Added capital cost of SI	Capital cost savings from SI	Net change
Non-nuclear	(1982) Medical Building, Salt Lake City	53	+2%	-4%	-2%
	(1984) Foothills Law and Justice Center	80	+5%	-3%	+2%
	(1984) VA Hospital, Loma Linda	194	+5%	-6%	-1%
	(1986) Tandem Computers Facility		+1%	-0%	*
	(1988) Union House in Auckland, NZ				-3%
	(1989) Evans and Sutherland Facility	16	+5%		*
	(1989) Los Angeles County Fire Department				-6%
	(1989) USC University Hospital		+2%		
Nuclear	(1983) Prototype Breeder NPP	4453	+2%	-4%	-2%
	(2012) AP1000 Traditional Base Isolation**	7035	+1-5%		
	(2017) Generic Nuclear Facility	550	+2-4%	-6-9%	-2-7%
	(2017) Generic Nuclear Facility (Updated)	550	+2-4%	-11-15%	-7-13%
	(2017) NuScale Advanced Base Isolation***	7035	+3-7%		
	Non-nuclear experience average	--	+3%	-3%	-2%
	Nuclear predicted average	--	+3%	-8%	-6%

*Made little or no effort to reduce costs after incorporating isolation, citing increased safety as the deciding factor.

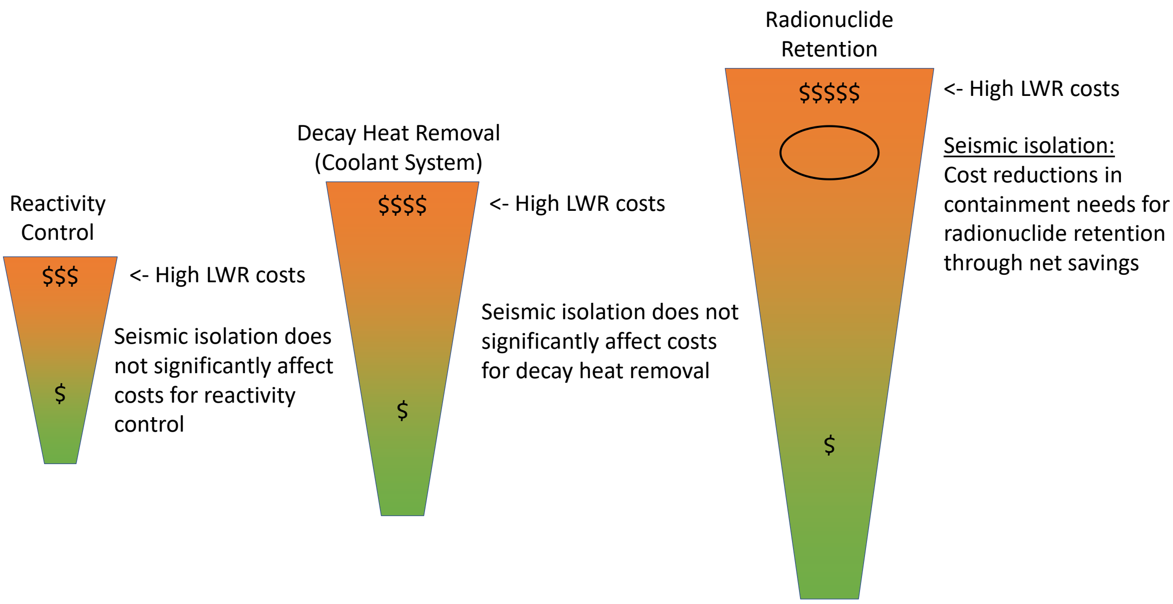
**Based on the estimate that an AP1000 requires 500-700 isolators at a material cost of USD 28-42K per non-safety grade isolator. Added cost is +1-2% for a non-safety grade system and +3-5% for safety grade.

***Based on the estimate that a NuScale plant requires 54 "advanced" isolators. This is the only entry to incorporate a seismic isolation system that mitigates both horizontal and vertical forces. Added cost is +3% for a non-safety grade system and +7% for a safety grade.

Source: Based on Champlin, 2018.

A conceptual summary of cost reductions relative to LWR levels for embedment of structures in functional containment design is provided in Figure 17. The cost reductions relate primarily to radionuclide retention rather than reactivity control or decay-heat removal.

Figure 17. Conceptual summary of cost reductions for seismic isolation in functional containment design



Source: INL, 2021.

Technical readiness

Seismic isolators have been used as base isolators in limited applications for nuclear reactor buildings: four at Cruas-Meysse in France and two at Koeberg in South Africa. The technical readiness level is high (10 based on commercial deployments), with some questions that need to be answered, especially for safety-critical component isolation. The NRC recently published NUREG/CR-7253 for technical considerations for seismic isolation of nuclear plants. The publication covers the existing literature on seismic base isolations, but lacks discussion on component isolation and isolation for a deeply embedded reactor building. Seismic base isolators are essentially ready for use with the experience obtained from non-nuclear applications; however, technical readiness needs to be improved for applicability to non-LWR reactors, including in relation to issues regarding NQA-1 certification of seismic isolators.

Further RD&D

There is high interest in deeply embedding advanced non-LWRs; therefore, comprehensive testing and studies need to be executed to increase the technical readiness level in such applications. Although it is technically possible to use seismic isolators as base isolators for deeply embedded reactor buildings, it is believed that the benefits of seismic isolation will be realized at the level of components, such as reactor vessels, heat exchangers or piping systems for deeply embedded reactor buildings. Comprehensive data will also be required to understand the fluid-structure interaction behavior for different liquid non-LWR reactor designs. Widely accepted and used seismic isolators usually do not have the capacity to dissipate energy in vertical directions. This has not been a significant concern for ordinary structures because: 1) they are mostly used for base isolation under the heavy buildings; and 2) it is usually assumed that the vertical seismic forces will not overcome the gravity loads, causing the structure to overturn. Experimental data are needed to understand the restrictions on the capability to dissipate vertical forces on the safety-critical components, especially for reactor vessels.

Conclusions and further directions

This Generation IV International Forum strategy report, *Advanced Nuclear Technology Cost Reduction strategies and Systematic Economic Review,* was developed by applying the ANTSER framework for evaluating cost reduction opportunities for Gen-IV nuclear concepts, based on functional containment approaches, which are exemplified by the NRC's ongoing development of a TI, RI, PB regulatory scheme for non-LWR designs.

This first cost strategy is intended to serve as an example for members of the GIF Economic Modelling Working Group (EMWG) and for other international stakeholders in terms of the application of the assessment framework to Gen-IV concepts and cost reduction strategies of interest, such as design standardization and modularity. The information provided in this cost reduction strategy assessment, including the four case studies, illustrates that a combination of different engineering and design approaches in functional containment could achieve substantial cost savings.

Further development of this work to include new case studies (e.g., reduced volume containment in functional design) and other original work is encouraged, and the results could be shared among members of the GIF EMWG. The desired outcome of this strategic cost reduction activity is to increase information sharing within GIF and among other stakeholders in order to accelerate progress towards the global deployment of cost competitive nuclear power plants.

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THE GENERATION IV INTERNATIONAL FORUM

Established in 2001, the Generation IV International Forum (GIF) was created as a co-operative international endeavor seeking to develop the research necessary to test the feasibility and performance of fourth generation nuclear systems, and to make them available for industrial deployment by 2030. The GIF brings together 13 countries (Argentina, Australia, Brazil, Canada, China, France, Japan, Korea, Russia, South Africa, Switzerland, the United Kingdom and the United States), as well as Euratom – representing the 27 European Union members and the United Kingdom – to co-ordinate research and develop these systems. The GIF has selected six reactor technologies for further research and development: the gas-cooled fast reactor (GFR), the lead-cooled fast reactor (LFR), the molten salt reactor (MSR), the sodium-cooled fast reactor (SFR), the supercritical-water-cooled reactor (SCWR) and the very-high-temperature reactor (VHTR).

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