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FUTURE GENERATION IV SMR REACTORS: ASSESSMENT AND POSSIBILITY OF INTEGRATION IN CLOSED NUCLEAR FUEL CYCLES

PRIHAJAJOČA IV. GENERACIJA SMR REAKTORJEV: EVALVACIJA IN MOŽNOST INTEGRACIJE V ZAPRTE JEDRSKE GORIVNE KROGE

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Keywords: small and medium size reactors, generation IV reactors, investment cost, value analysis methodology, review and evaluation process, modular design, advanced nuclear fuel cycle, energy transition, sustainability

Abstract

Over the previous decade, many economic, strategic, technical, and other arguments in favour of Small and medium-size reactors (SMR), present in the nuclear industry since the beginning of its use for peaceful purposes, have become prominent. The Generation IV SMR is a next-generation design excelling in its considerable contribution to sustainability. Most favourable concepts impose high coolant temperatures and high breeding ratios and represent progress in the design of future GEN IV SMRs. This paper presents a new review and evaluation process of SMR GEN IV reactors, which seem most suitable for early implementation. Evaluation presented in this paper was performed on the basis of the Value Analysis methodology, indicating the most economically interesting technologies with the shortest time to commercial availability. The SMR GEN IV reactor integration in advanced closed nuclear fuel cycles could an play important role in the energy transition to sustainable oriented

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low-carbon energy future. Mass balance and material flow for nuclear fuel cycles involving SMRs were established with the NEA 1767 SMAFS model and through the webKORIGEN software. The advantages of SMRs attract embarking countries to look towards use of nuclear as domestic energy source, especially when the paradigm of energy independence is becoming strategically important.

Povzetek

V preteklem desetletju se pojavljajo številni ekonomski, strateški, tehnični ter ostali razlogi, ki kažejo na določene prednosti Majhnih in srednjih reaktorjev (SMR), sicer prisotnih od pričetka uporabe jedrske energije za miroljubne namene. Četrta generacija jedrskih elektrarn med katere spadajo tudi SMR GEN IV je vključena v napredne zaprte gorivne kroge in omogoča velik napredek v trajnostnem razvoju ter proizvodnji energije. Najobetavnejši SMR koncepti stremijo k visoki temperaturi hladila na izstopu iz sredice ter visokem oplodnem razmerju ter predstavljajo velik napredek v zasnovi SMR GEN IV reaktorjev prihodnosti. Ta članek predstavlja sodoben pristop k procesu pregleda in evalvacije SMR GEN IV reaktorjev, ki so glede na današnje vedenje in informacije najugodnejši za zgodnjo implementacijo. V tem članku predstavljena evalvacija bazira na metodologiji vrednostne analize ekonomsko najzanimivejših tehnologij z najkrajšim časom do njihove komercialne uporabe. Vključevanje SMR GEN IV reaktorjev v sodobne zaprte gorivne cikle predstavlja velik potencial pri energetski tranziciji v nizkoogljično prihodnost. Masne bilance in tok materiala v izbranih gorivnih ciklih, primernih za implementacijo SMR reaktorjev, so bile določene s pomočjo NEA 1767 SMAFS modela ter v nadaljevanju s pomočjo webKORIGEN programskega paketa. Predstavljene prednosti SMR reaktorjev so zanimive tudi za države, ki razmišljajo prvič o uporabi jedrske energije, saj postaja energetska samozadostnost ter neodvisnost strateško zelo pomembna.

1 INTRODUCTION

Small and Medium Reactors (SMR) have been present in nuclear industry since the beginning of its use for electricity or heat generation in the 1950s (Figure 1).

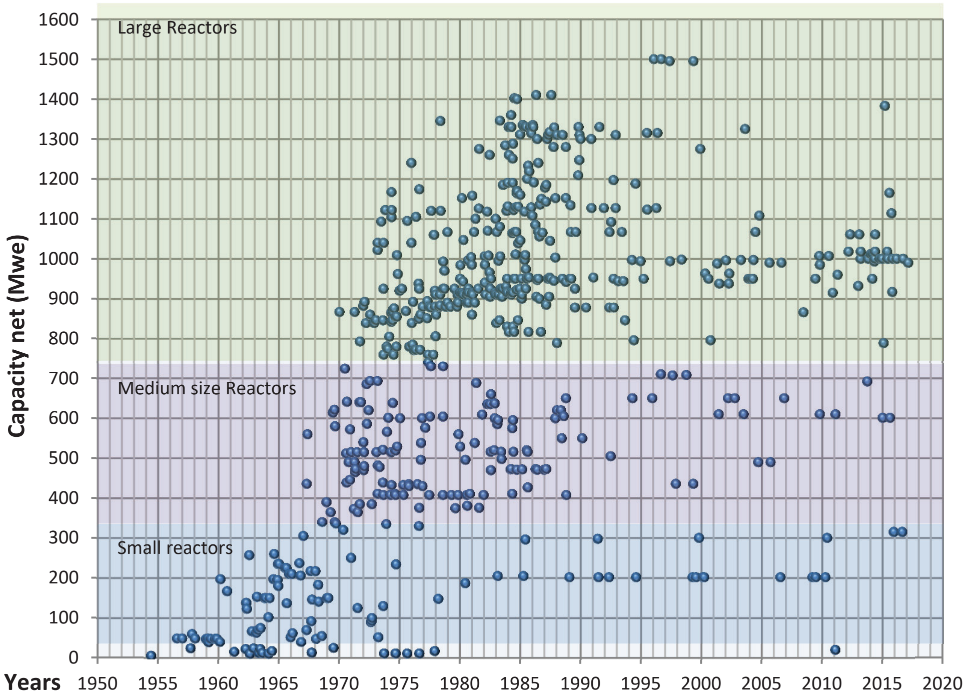


Figure 1: *Size of operating Nuclear Power Plants including SMRs, data source, [28]*

1.1 SMR implementation goals

SMR units are designed as single units that can also be accommodated as multiple SMR modules sequentially on single sites to optimize site investment costs. Economics of smaller units is planned as increasing the factory assembly manufacturing of units, shorter construction times, optimized supply chains and as mass production impact at manufacturing equipment modules could reduce construction costs and further overnight costs.

SMR investment costs include the engineering, procurement and construction (EPC) costs and the owner's costs. The total capital investment cost (TCIC, defined in *[2]*) is equal to the sum of overnight costs, contingency and the cost of financing, *[1]*. According to available data for SMR overnight costs, the prices of electricity predicted per installed kW (USD/kWe) are in range from 1200 to 4000 USD/kWe, *[4]*. This is a rough estimate and involves many volatile factors.

1.1.1 SMR general design features

SMRs are intended to fill market niches with implementation in smaller grids, or where heat production or desalinization in addition to electricity is foreseen. SMR is expected to have simpler design, optimized manufacturing costs and due to its size optimized TCIC in comparison with large ALWRs. SMRs are mainly designed with high levels of passive safety. For instance, a SMR reactor vessel with smaller thermal power (P_{therm}) and higher thermal inertia can be by its design narrow and high, thus enabling more intensive natural recirculation with higher thermal dissipation with higher coolant flows along the fuel channels. With higher secondary coolant parameters, more advanced thermodynamic cycles with higher turbine efficiency rates can be implemented. It can be concluded from an American Nuclear Society report, that a major part of the active safety systems and support systems implemented in large ALWRs ($P_{electr} > 600\ MWe$) is redundant for SMRs and can be effectively replaced by passive approaches, *[5].*

1. 1. 2 General GEN IV reactors classification

Among next-generation design reactors, Generation IV (GEN IV) reactors generally excel in sustainability, minimal environmental impacts, better economy, and further reduced proliferation issues.

Figure 2 presents six GEN IV technologies, according to their breeding ratios and coolant temperatures at reactor core exit. The most favourable concepts impose high coolant temperatures and high breeding ratio, thus most effectively implementing three fields of progress in the design of future reactors:

- higher coolant temperatures when exiting reactor core enabled with the use of new materials and advanced thermodynamic cycle’s higher turbine efficiency rates,
- high neutron flux with 100 times better UO fuel efficiency, less radioactive waste and use of reprocessed fuel from LWRs,
- favourable breeding ratio; fissile material obtained to spent fissile material after the use of a fuel mixture of fissile and fertile material in a reactor or ratio between fission and capture in actinides.

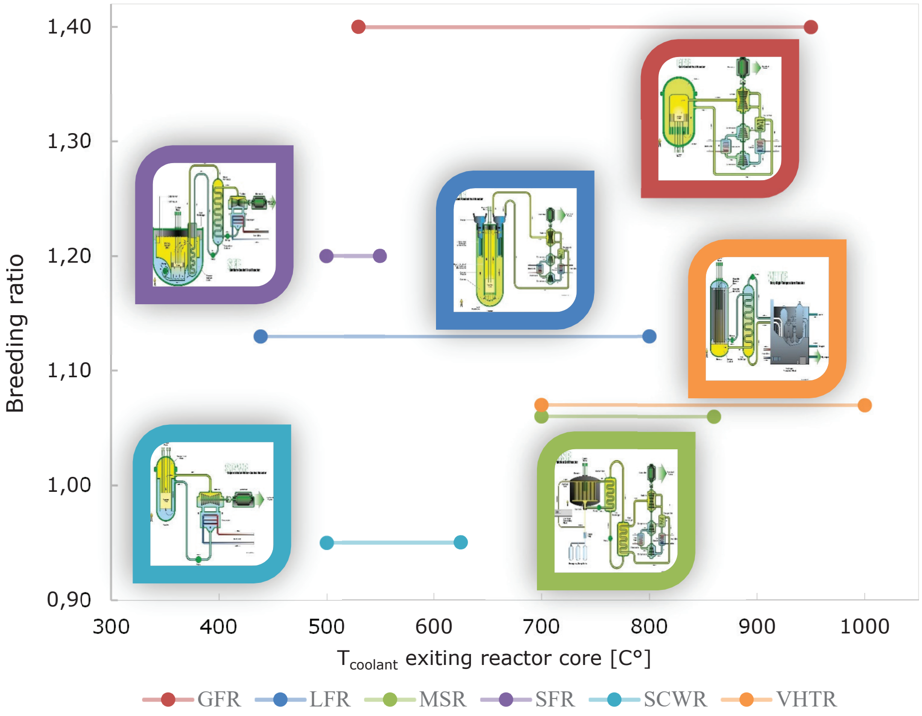


***Figure 2**: six most promising GEN IV SMR technologies as suggested by Generation IV International Forum, data sources: [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16]*

2 GENERAL APPROACH TO SMR MODULARITY

A common approach to most SMR reactor designs, especially GEN IV designs is based on the elimination of postulated initiating events (PIE) and the prevention of severe accident consequences, mainly by passive means. A combination of passive and active safety systems is often used for other accident prevention approaches, similar as in today's GEN III ALWRs, such as AP1000, VVER-1000, ESBWR, etc.

According to many SMR designers, general features contributing to the efficient implementation of inherent and passive safety design are:

- larger surface to volume ratio at reactor vessel for larger decay heat removal, especially in case of a single-phase coolant,
- solutions for a more compact Reactor Coolant System (RCS) as for instance integral compact RCS pool, suppressing certain initiating events,
- reduced power density of reactor core, simplifying implementation of passive safety systems,
- reduced potential hazard results from lower source term due to lower fuel inventory, lower heat and pressure energy stored in the reactor, and lower integral decay heat rate, *[19]*.

2. 1 Modularization process and improvement possibilities

Customer requirements, the existence and further development of modularization at construction or manufacturing are triggered and preserved by the requirements of a short construction schedule, cost reduction, higher quality and safety at the construction site and in exploitation phase (nuclear safety). Those factors emerging mostly from market demands like investor requirements at NPP construction or vendors requirements to achieve more competitive position on market. They are integrated within the whole product lifecycle; in this case, the lifecycle of Systems Structures and Components (SSC) and for the whole NPP project from construction to decommissioning (Figure 3).

In the case of SMRs, modularity is present on two levels: an SMR unit, as a whole, represents a module designed to fit and operate within multi-unit site; modules within an SMR are compatible and interchangeable within unit or within units from different vendors.

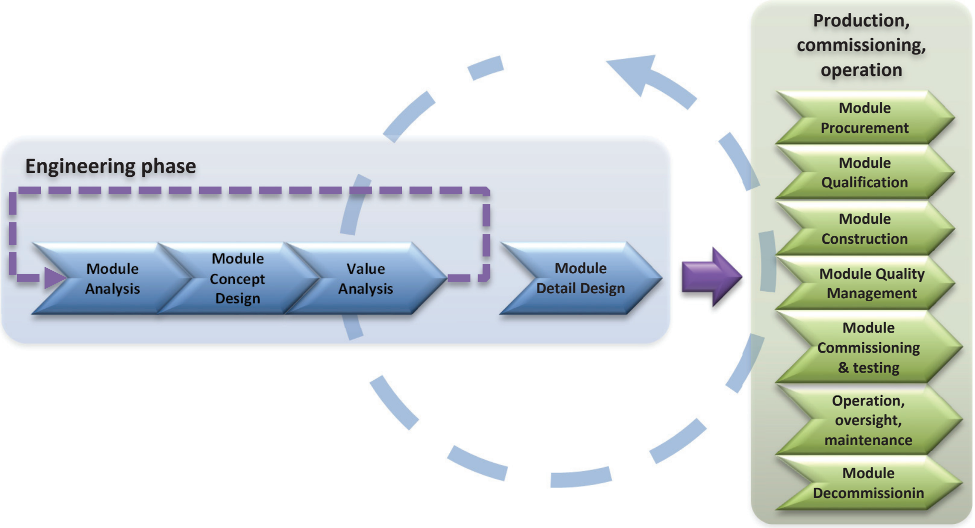


***Figure 3**: Modularization process integrated within module lifecycle*

2. 1. 1 SMR SSC Modularity from the designer's point of view

Since SMRs are in various design phases, it is difficult to predict to what extent particular SSCs will be interchangeable within various vendor types of SMR, as has been the case for many decades in other industries like automotive, aerospace, naval, robotics, etc. At such a modularity stage, where common SSCs were developed and licensed, a designer would have easier task to make system integration of those SSC. In the nuclear industry, in addition to functionality requirements, there is additional requirement for nuclear safety, which is distinct from other industries and of great importance in setting design basis for the plant.

The following list covers some potential SSCs that might be common for sodium-cooled fast Reactors of various vendors. SSCs of various manufacturers could be compatible, having the same functionality and operating parameters; all could be used in the same SFR or one SSC that is functionality compatible with the required operating parameters of SFRs from different vendors:

- Steam Generator (SG), with which modularity/similarity is achieved with adequate heat transfer surface, SG design remains unchanged and covers wider group of this SMR type with different power outputs, e.g. with one or more same SGs;
- Electromagnetic Reactor Coolant Pumps (RCP), controlled with frequency converters, enabling pre-set, project-defined optimum coolant flow through various operating states, as a single RCP or multiple-mounted, similar to AP1000 design;
- RCS piping, forged according to unified codes and standards with appropriate multiple sizes, covering the range of reactors, according to safety requirements, forged as a monobloc; standardisation lowers the manufacturing costs;
- Auxiliary reactor vessel cooling systems could be unified and pre-licensed for the whole range of FSR SMRs; various power ranges are handled with multiple, yet redundant systems;
- Fuel Handling Building (FHB) could be assembled from the same or similar modules, varying according to requirements with modular support equipment;
- Seismic resilience, small and compact dimensions at SMRs with higher eigen-frequencies are more favourable for consideration on siting in more demanding geological, geotechnical and seismic locations, with additional implementation of appropriate seismic isolators, it should be viable that site properties would not exist as limiting factor even when considering those reactors on the most demanding sites.

Other equipment, such as intermediate heat exchangers, reactor protection system modules, sodium reservoirs, steam and other pipelines, and equipment for transformation to electric energy, can be similarly optimized, modularized, and unified.

Experiences with the modularization process show that not many efforts in this direction have been successful, especially when the process itself has been the responsibility of developers or suppliers, without clear and strong support and collaboration from investors/operators with high requirements and particularly regulatory bodies, which may have to expand their scope and participate more proactively in order to promote the safe and peaceful use of atomic energy.

3 REVIEW AND EVALUATION OF PROMISING SMR GEN IV REACTORS

A review and evaluation process of SMR GEN IV reactors that seem most suitable for early implementation is divided into two phases: preliminary elimination and secondary elimination selection. Evaluation methodology is qualitative with elements of value analysis (VA), *[20]*, according to the methodology of Small Modular Reactor Strategic Assessment, *[21]*, and is divided into five steps within those phases:

1. collecting relevant information on assessed technologies,
2. preliminary elimination,
3. determination of important functions and properties,
4. properties and relative variant value assessment,
5. optimal technology selection.

The intermediate result based on VA is a ranked list of SMRs. The selection of a technology group is made among those reactors according to the most collected points for suggested ranking factors and characteristics for the most promising technology, (1st part of 4th phase). The goal of the review process by assessing the economy of different technologies is to define, by VA (2nd part of 4th phase), the group of technologies that meets the set threshold of ranking factors and characteristics (5th phase).

3. 1 Technology relevant data acquisition

Data from 27 SMR GEN IV technologies (reactor designs from specific vendor) being in various design phases were gathered for the assessment:

- 7 types of Gas-cooled fast reactors (GFR),
- 1 very-high-temperature reactor (VHTR),
- 9 types of lead-cooled fast reactors, cooled with Pb or Pb-Bi eutectic (LFR),
- 3 types of molten-salt reactors (MSR),
- 7 types of sodium-cooled fast reactor (SFR).

The listed technologies are in development in the US, Russian Federation, Japan, China, India, South Korea, Czech Republic, and South Africa. Most R&D institutions or companies do not publish or reveal their progress regularly; therefore, this assessment is based on publicly available articles, industry societies, conferences, NRC or IAEA evaluations, interviews with design engineers or other available sources, referenced at the end of the paper.

3. 2 Preliminary elimination

Preliminary elimination evaluates each of the 27 technologies according to following parameters:

- commercial operation is viable only after 2030,
- complex process of fuel fabrication; remark: this parameter is important, but has less influence in this preliminary evaluation due to different design phases of assessed technologies,
- unreliable or non-existent sources for R&D financing, high risk for financing termination,
- FOAK technology, proof-of-concept working prototype is required before final prototype,
- technology in early R&D phase.

Any technology fulfilling any of the above parameters is excluded (✘) as an unsuitable candidate for further assessment. An exception is made when, within the whole technology group (GFR, VHTR, etc.) there is no suitable technology, in which case one technology is conditionally (☑)

selected, having the best result within the group. According to these rules, the following technologies were selected and presented in Table 1.

Table 1*: SMR GEN IV reactor overview [1], [2], [4], [19], [21]*

Technology designation	Selection	Power (MWe)	Designer	Origin	Parameters, Remarks
GFR (Gas-cooled Fast Reactor) group					
Adams Engine	✗	1 to 100	Adams Atomic Engines, Inc.	USA	a, b, e
EM2	✗	240	General Atomic	USA	a, b
GT-MHR	✗	150	General Atomic, OKBM Afrikantov, Fuji	USA, Russian Federation, Japan	a, b, e, *igt*
ALLEGRO	☑	75 (MWt)	ÚJV Řež, a.s., MTA EK in VUJE a.s., CEA, EURATOM	Europe	a, b, c, d, e
MTSPNR	✗	2	NIKIET	Russian Federation	a, b, c, double reactor unit
PBMR	✗	150	PBMR, Pty.	South Africa	a, c
GTHTR-300	✗	280	JAERI	Japan	a, b
VHTR/AHTR (Very High Temperature Reactor) group					
Antares	✗	~288	Areva, Fuji	France, Japan	e, b, d
HTR-PM	✓	211	INET, Tsinghua University	China	
LFR (Lead-cooled Fast Reactor) group					
ANGSTREM (Pb-Bi)	✗	n/p	TES-M		*noinf*
BREST-OD-300	✗	300	Gidropress	Russian Federation	e
ENHS	✗	50	University of California, Berkley	USA	a
HPM(Pb-Bi)	✗	25	Hyperion Power Generation, Inc.	USA	e single or multiple reactor unit
LSPR(LBE)	✗	53	RLNR TITech	Japan	a
SSTAR (Pb-Bi)	✗	20 10 to 100	Argonne National Lab & Lawrence Livermore Laboratory, Toshiba	USA,	e
STAR-LM, STAR-H2 Hydrogen production	✗	180	Argonne National Lab & Lawrence Livermore Laboratory	USA, Japan	e
SVBR-100 (Pb-Bi)	✓	100	Gidropress	Russian Federation	*dd*
TWR	✗	300	Lawrence Livermore Lab (DOE), Terrapower	USA	a, b, d, e
ALFRED	✗	300	Ansaldo nuclear with 16 European organizations	Europe	a, b, e
MSR (Molten Salt Reactor) group					
Fuji MSR (LFTR)	☑	100	IThEMS	Japan, Czech Republic	a, d, e

Technology designation	Selection	Power (MWe)	Designer	Origin	Parameters, Remarks
LFTR	✗	20 to 50	Flibe Energy	USA	a, b, *noinf*
PB-AHTR	✗	410	UC Berkley, ORNL	USA	a, b, d, e
SFR (Sodium-cooled Fast Reactor) group					
4S	✓	10	Toshiba	Japan	*dd*
ARC-100	✗	100	Advanced Reactor Concepts, LLC	USA	e
CEFR	✓	20	CNEIC	China	*op*
KALIMER-600	✗	600	KAERI	South Korea	a, b
PFBR-500	✓	500	IGCAR	India	*const*
PRISM	✓	155	GE, Hitachi	USA, Japan	*dd*
Rapid-L	✗	0.2	Toshiba, CRIEPI, JAERI	Japan	a, b, *igt*
Astrid	✗	600	CEA with industry consortium	International	a, b, e

Remarks: *igt*-integral gas turbine poses great technological challenges, *noinf*-non-existent or poor information on technology, *dd*- reactor in detail design phase, *const*-reactor in construction phase, *op*-reactor in operation phase.

Technologies are conditionally selected for secondary elimination based on larger development potential, are recognized as interesting for potential investors in FOAK technologies or have broad international support on financing and R&D and have large potential for niche markets.

3. 3 Secondary elimination

Eight SMR designs entered the secondary phase: Allegro, HTR-PM, SVBR-100, Fuji SMR, 4S, CEFR, PFBR-V and PRISM. The second elimination step consists of the following phases of VA: 3) determination of important functions and properties, 4) properties and relative variant value assessment (USD/kW $_{\text{installed}}$), and 5) optimal technology selection.

3. 3. 1 Determination of important functions and properties

In this phase, the functions, properties and properties influence of SMR technologies enabling evaluation are selected. Results of 8 SMR technologies evaluated in greater detail on the design, licensing and construction with characteristics are:

1. Design maturity and status of development, *[22]*, *[23]*,
2. Designer, manufacturer experiences, *[22]*, *[23]*,
3. Licensing challenges, regarding current GEN III challenges at licensing, *[22]*, *[23]*,
4. Simplicity of design and constructability, *[22]*,
5. Technical and technology challenges,
6. Level of participation in closed fuel cycle, HLW amount in fuel elements, possibility for the use of reprocessed nuclear fuel from other technologies like PWR, BWR, *[22]*, *[24]*,
7. Maturity levels for supply chain, and infrastructure for components and heavy component manufacturing and supply.

At VA, product properties, in this case technologies (variants), are evaluated. Because most of the assessed technologies are in various phases (e.g. R&D, construction, etc.), it is necessary not to assess only properties, which may be changed during process, but also the effects and influence due to conditions at project development over certain aspects, such as design or economics, etc. Instead of specific properties, the combination of group of properties as a whole (influenced properties field) are important and therefore evaluated.

3. 3. 2 Properties and relative variant value assessment

3. 3. 2. 1 Variant properties assessment

Technologies are evaluated by assessing the fulfilment level of factor K of selected group of properties for technology and influenced properties field, varying from factor value from:

- 0.00 – inadequate, influence on assessment field gives unacceptable results,
- e.g. 0.50 – appropriate, without significant influence on assessment field,
- 1.00 – most suitable, influence on assessment field exhibits excellent results.

Since all assessment fields may not be equally important to the assessor, they can be weighted with a ponder value. The sum of denominated ponder relative values for assessment fields evaluated with K represents 100%; therefore, change in one ponder changes the influence of all other ponders for specific variants.

Variant properties assessment was conducted on the basis of pre-prepared assessment sheets by a group of five nuclear technology experts, three of them with doctorates in nuclear technology and two with more than five decades of experience in SSC design since the deployment of GEN II NPPs. Table 2 summarizes their evaluations of selected variants. The number of points of selected property group at variant is arithmetic mean of assessor's evaluations:

$$\bar{T} = \frac{1}{n}\sum_{i=1}^{n} T_i \ , \ for\ n = N^o\ of\ assessors \tag{3.1}$$

Table 2: Variant properties and influenced properties field assessment results [22]

N°	Property / Influenced Properties Field	Ref.	Allegro			HTR-PM			SVBR-100			Fuji MSR		
			$\Sigma p_i/n$ [%]	$\Sigma K_i/n$	$\Sigma T_i/n$	$\Sigma p_i/n$ [%]	$\Sigma K_i/n$	$\Sigma T_i/n$	$\Sigma p_i/n$ [%]	$\Sigma K_i/n$	$\Sigma T_i/n$	$\Sigma p_i/n$ [%]	$\Sigma K_i/n$	$\Sigma T_i/n$
1	Design maturity and status of development	*[22]*	18.2	0.6	9.9	18.2	0.8	14.9	18.2	0.9	15.3	18.2	0.3	5.9
2	Designer, manufacturer experiences	*[22]*	13.4	0.6	7.8	13.4	0.7	8.4	13.4	0.8	11.1	13.4	0.3	3.7
3	Licensing challenges	*[22]*	14.2	0.5	7.0	14.2	0.7	9.2	14.2	0.8	11.5	14.2	0.3	4.4
4	Simplicity of design and constructability	*[22]*	14.4	0.5	7.9	14.4	0.5	6.6	14.4	0.7	9.3	14.4	0.5	7.5
5	Technical and technology challenges	*[22]*	12.1	0.7	7.8	12.1	0.8	10.5	12.1	0.9	10.8	12.1	0.5	5.7
6	Level of participation in closed fuel cycle	*[24]*	14.4	0.7	9.4	14.4	0.3	4.8	14.4	0.7	9.7	14.4	0.3	4.0
7	Maturity of supply chain and manuf. infrastr.		13.3	0.7	9.3	13.3	0.9	11.6	13.3	0.9	11.7	13.3	0.5	5.9
			Eval. Sum all fields ΣT		59.18	Eval. Sum all fields ΣT		66.00	Eval. Sum all fields ΣT		79.30	Eval. Sum all fields ΣT		37.21
				Rank	**VII**		**Rank**	**VI**		**Rank**	**I**		**Rank**	**VIII**

N°	Property / Influenced Properties Field	Ref.	4S			CEFR			PFBR-500			PRISM		
			$\Sigma p_i/n$ [%]	$\Sigma K_i/n$	$\Sigma T_i/n$	$\Sigma p_i/n$ [%]	$\Sigma K_i/n$	$\Sigma T_i/n$	$\Sigma p_i/n$ [%]	$\Sigma K_i/n$	$\Sigma T_i/n$	$\Sigma p_i/n$ [%]	$\Sigma K_i/n$	$\Sigma T_i/n$
1	Design maturity and status of development	*[22]*	18.2	0.7	12.8	18.2	0.8	14.4	18.2	0.8	14.8	18.2	0.8	13.8
2	Designer, manufacturer experiences	*[22]*	13.4	0.8	10.4	13.4	0.7	8.9	13.4	0.8	9.9	13.4	0.8	10.1
3	Licensing challenges	*[22]*	14.2	0.6	8.4	14.2	0.7	9.7	14.2	0.8	11.0	14.2	0.6	8.6
4	Simplicity of design and constructability	*[22]*	14.4	0.6	8.0	14.4	0.5	7.5	14.4	0.5	7.1	14.4	0.6	7.8
5	Technical and technology challenges	*[22]*	12.1	0.7	9.0	12.1	0.8	10.8	12.1	0.8	10.9	12.1	0.8	10.8
6	Level of participation in closed fuel cycle	*[24]*	14.4	0.6	8.5	14.4	0.6	8.5	14.4	0.6	8.8	14.4	0.6	8.9
7	Maturity of supply chain and manuf. infrastr.		13.3	0.7	9.1	13.3	0.8	11.0	13.3	0.8	10.5	13.3	0.7	9.7
			Eval. Sum all fields ΣT		66.20	Eval. Sum all fields ΣT		70.90	Eval. Sum all fields ΣT		72.85	Eval. Sum all fields ΣT		69.67
				Rank	**V**		**Rank**	**III**		**Rank**	**II**		**Rank**	**IV**

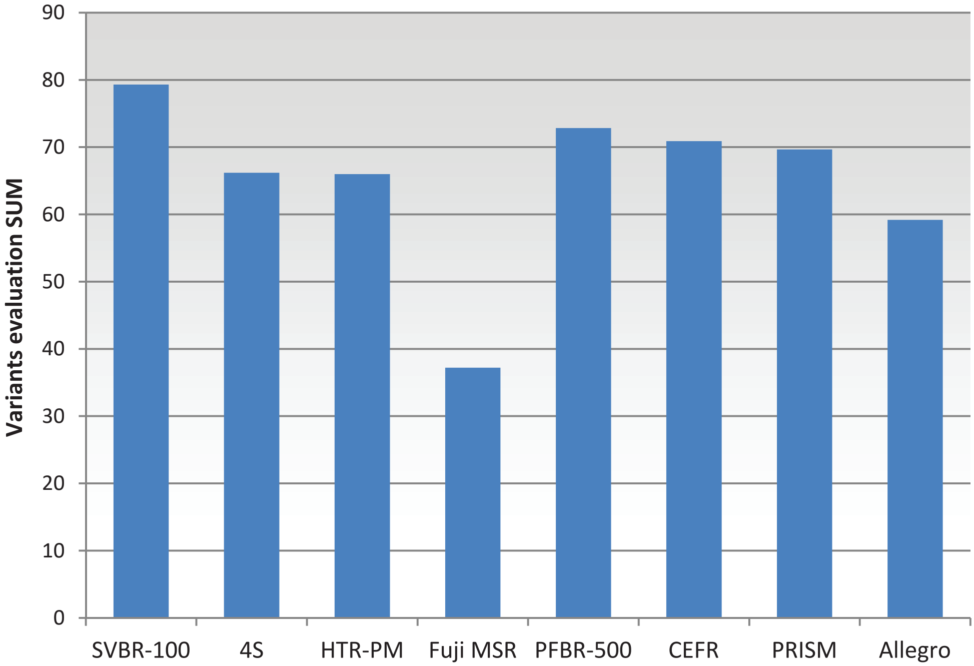


Figure 4: Variant assessment results' ranking, *[22]*

3. 3. 2. 2 Relative value at assessed variants

Collecting information on technology implementation (investment) costs is an essential part of the comprehensive assessment, although it is focused on a niche industrial field prone to ever-changing competition conditions. Collected information originates from publicly available information, *[4]*, or from discussion with leading experts in nuclear, SMR technology-related fields. Regardless of the source of information, it can be concluded with certainty that the information is more reliable than cost calculations executed for particular SMR SSC, especially when experience shows that even partial costs given to recognized reliable investors by vendors in bidding phases for NPPs may vary from the final costs. Equipment costs may also vary according to investors requirements, since investors can prefer specific equipment suppliers due to fleet/equipment standardization and maintenance optimization, even if not recognized as standard OEM by vendors. Power generation plant costs also depend and vary on specific investor requirements, such as desalinization, hydrogen production, heat cogeneration, etc., and are not included due to multiple variants emerging from those requirements. Further costs that should be recognized in assessment are contingency, project engineering, licensing costs, various compensations costs to local community, municipality or state etc.

Cost are presented separately in Table 3, ranking is conducted according to Levelized Unit Electricity Cost (LUEC) and to overnight capital costs of each technology, *[4].*

When assessing variant suitability, relative values are calculated, *[20]*:

$$V = {}^{F}/_{C} = {}^{P}/_{C} = {}^{T}/_{C} = {}^{properties}/_{costs} \qquad (3.2)$$

Where V represents relative value, F function, P property (group), costs (LUEC and overnight capital costs separately) and T variant properties value. Calculated V (Figure 5) provides information on property group assessment with variants relative value under costs consideration, where higher value represents better results, having lower costs.

Table 3*: Relative value according to LUEC and to overnight capital costs*

	HTR-PM	SVBR-100	Fuji MSR	4S
Overnight Capital Costs (OCC)	1500 USD	1200 USD	4500 USD	1500 USD
Relative tech. value/OCC	0.0440	0.0661	0.0083	0.0441
Levelized Unit Electricity Cost (LUEC)	51 USD/MWh	42 USD/MWh	29 USD/MWh	290 USD/MWh
Relative tech. value/LUEC	1.2940	1.8882	1.3056	0.2283

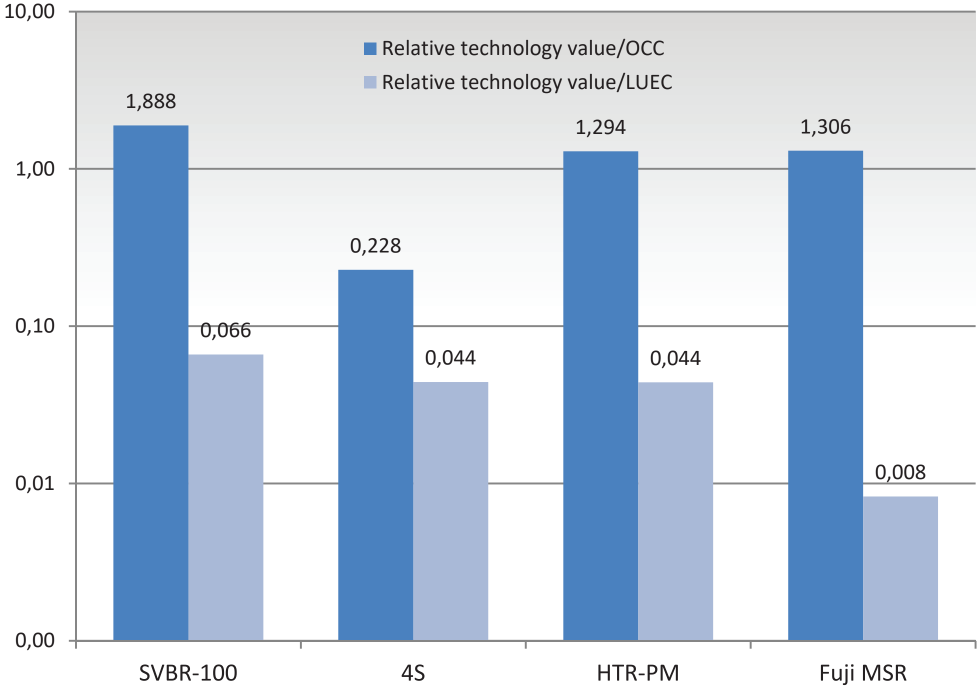


Figure 5*: Relative value ranking from Table 3*

Assessment approach with Value Analysis is reasonable and useful in case of strategic investor decisions, especially when dealing with larger lifecycles of investment, such as with NPPs. Assessment results indicate the most economically interesting technologies with the shortest times to commercial availability.

4 SMR GEN IV INTEGRATION IN ADVANCED NUCLEAR FUEL CYCLES

Suitable for SMR GEN IV integration are examples of advanced, fully closed, nuclear fuel cycles (NFC, FC), in which all actinides are continuously recycled in fast reactors. Only two fuel cycle schemes were studied in this paper (out of several different fuel cycles possible) and are indicated as FCA and FCB.

A fuel cycle based on PWR reactor and integral fast reactor concept (Fuel Cycle A (FCA)), featuring partitioning & transmutation (P&T) option, results in small waste quantities without actinides, containing only material from reprocessing losses and fission products (FP). In FCA, proliferation possibility is disabled, since there is no Pu separation from other actinides (Figure 6).

A fuel cycle based on GCR concept (Fuel Cycle B (FCB)), capable of burning all actinides (U, Pu, Am, Cm, etc.) results in minimising actinides loss in process and maximizing use of uranium resources. Waste is trans-uranium elements from reprocessing efficiency losses and FP. Due to the small consumption of depleted uranium, FCB can be recognized as a sustainable energy source (Figure 8).

The FCA fuel cycle features a PRISM reactor, and FCB features an ALLEGRO reactor. Material flow and mass balances originate from the characterization of advanced nuclear fuel cycles and the determination of HLW quantity for final disposal, *[24]*, with the consideration of the Slovenian case on used nuclear fuel inventory, *[27].* Mass balance and material flow for the beginning of fuel cycle was determined for each NFC through the NEA 1767 SMAFS model. With an iteration approach through webKORIGEN software, final mass balances of Used Nuclear Fuel (UNF) were established. The activity, toxicity, residual heat power, and mass balance of final high-level waste (HLW) for final disposal were also established with the same approach through webKORIGEN. Quantities in both NFCs were normalized on 1MWe year/FC, *[24].*

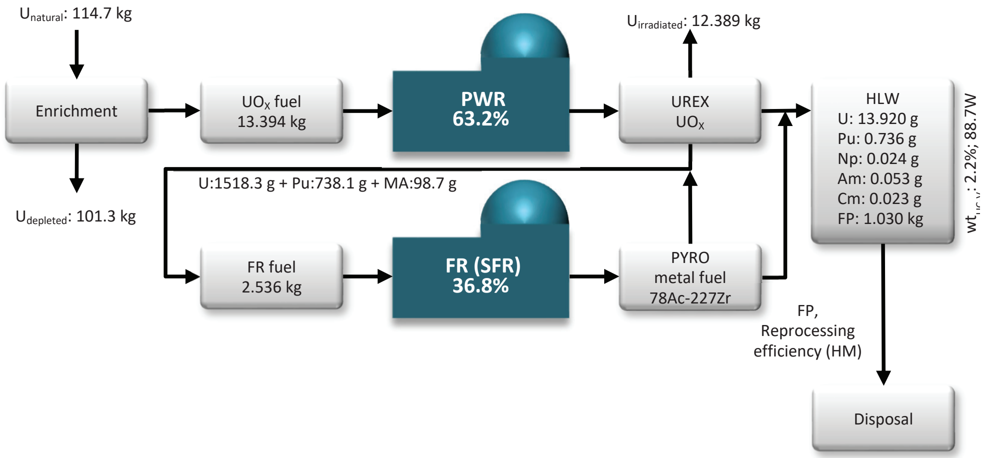


***Figure 6**: FCA fuel cycle, UOX (UREX) reprocessing, Pyrochemical reprocessing of metal fuel (PYRO)-TRU partitioning and homogenic transmutation, [24]*

SMR GEN IV reactors could play an essential role in the energy transition to sustainable oriented low-carbon energy future. Combining reprocessing within closed or semi-closed FCs minimizes the quantity (volume) of material entering NFC and waste. In addition, there is notable improvement with minimizing relative residual heat generation and radioactivity reduction in comparison with open FC (Figure 7 for FCA, Figure 9 for FCB and Figure 10 for FCA, FCB, FCO comparison). All features combined contribute to reducing necessary volume in final disposal and its decay time to natural background level. Since economy of smaller HLW disposals is worse than of larger, the idea of establishing regional HLW disposal, accommodating fuel from many international reactors could be more attractive, especially when disposing of reprocessed HLW, for which the radiotoxicity timespan down to natural background could degrade under 1000 years.

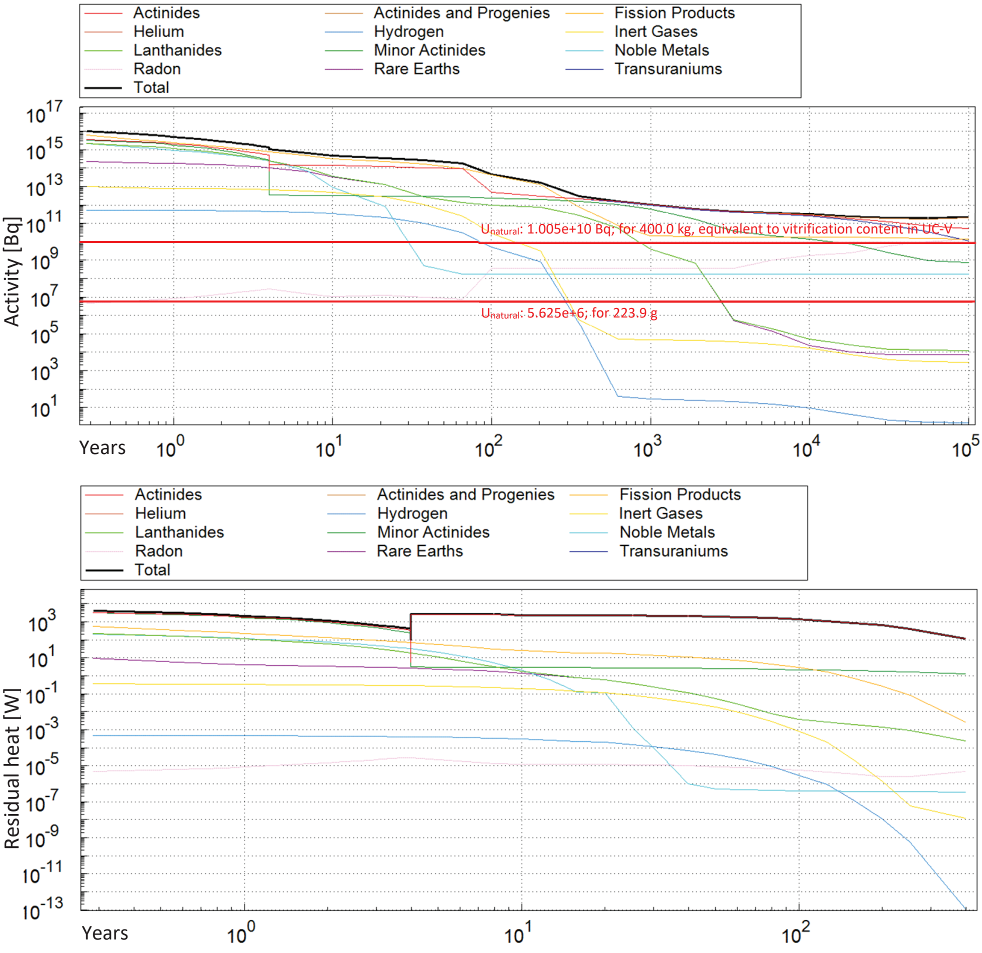


Figure 7*: Activity and residual heat decay over time for FCA fuel cycle after disposal, [24]*

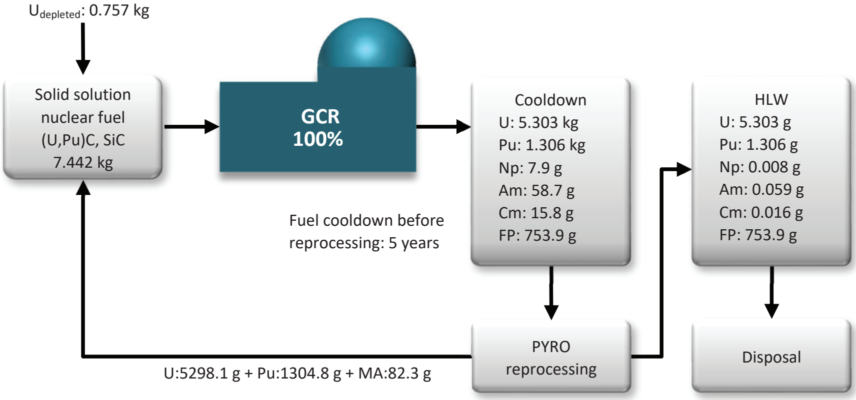
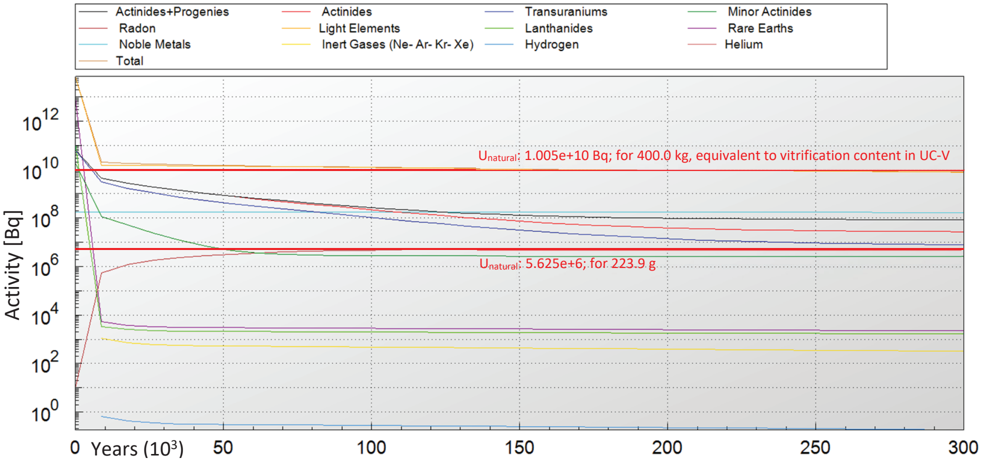


***Figure 8**: FCB fuel cycle, Pyrochemical reprocessing of metal fuel (PYRO)-TRU partitioning and homogenic transmutation, [24]*



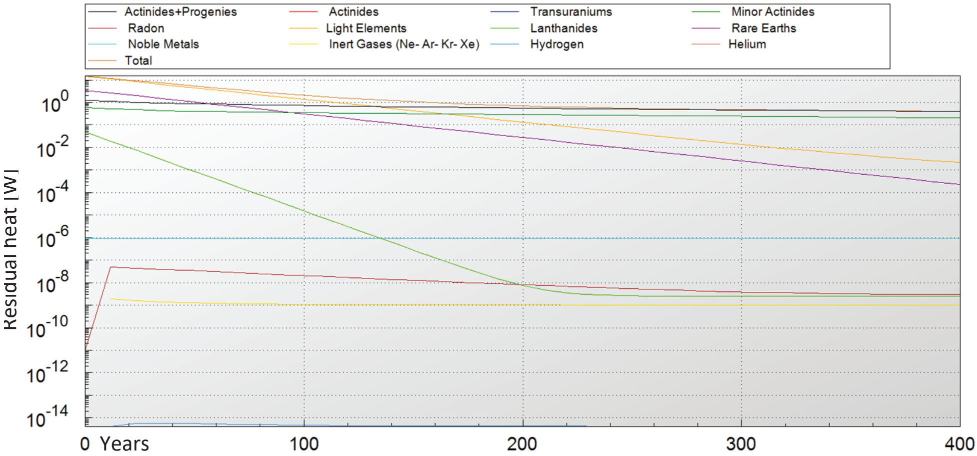
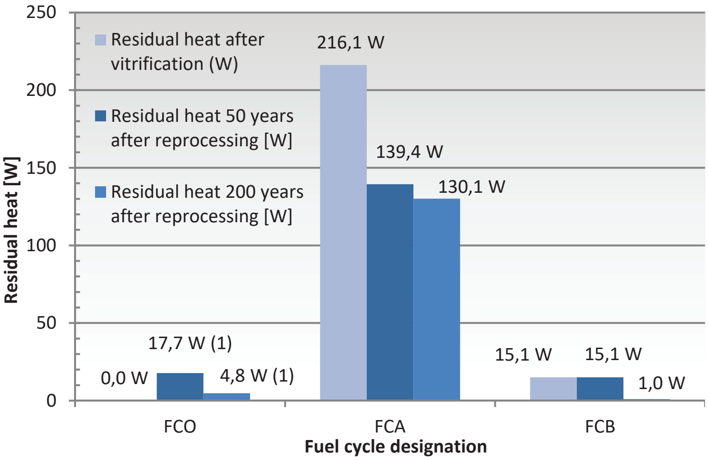


Figure 9: *Activity and residual heat decay over time for FCB fuel cycle after disposal [24]*

Figure 10 compares SMR-suitable FCA and FCB with open fuel cycle featuring the once-through use of UNF in PWRs designated FCO (Fuel Cycle – Open). Residual heat at FCO is generated in the disposed fuel element without any reprocessing. According to the disposed mass of material, the relative residual heat at reprocessed HLW is more favourable; however, at vitrification in universal canisters (UC-V), attention should be paid to the maximum allowable heat load for the glass matrix. In addition to residual heat generation, the heat load for the glass matrix is dependent on the environment contact conditions and exposure.



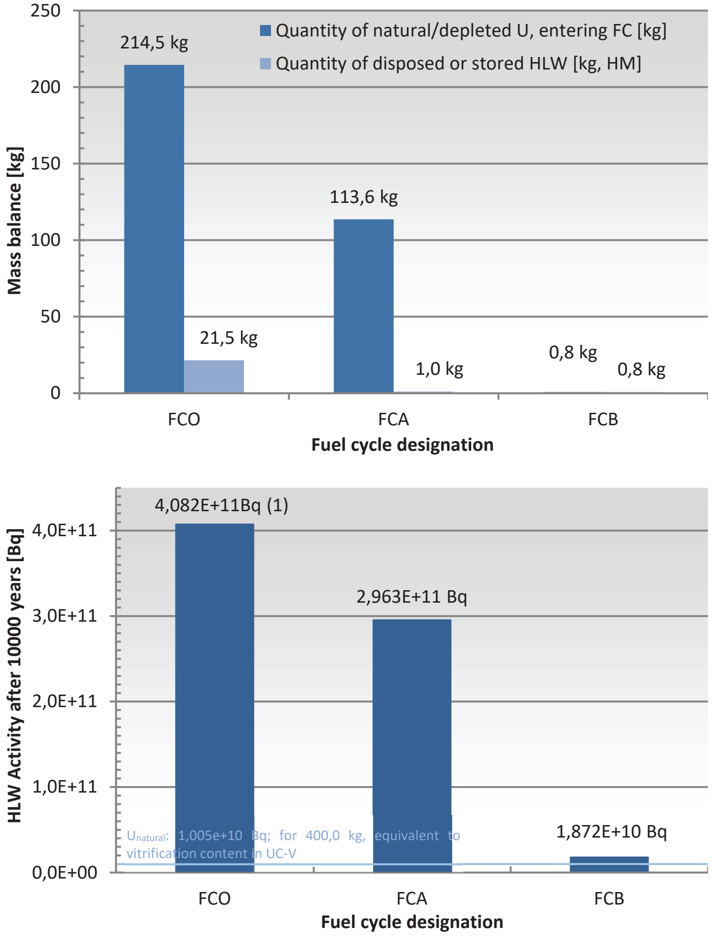


***Figure 10**: Mass balance, Residual heat decay and Activity over time, comparing open fuel cycle FCO to closed CFA and FCB, [24]*

5 CONCLUSION

The main technological advantages of SMRs over large ALWRs emerge primarily out of the size of nuclear steam supply system (NSSS) and other SSCs. Size of SMRs and their potential for modularity enables factory assembly manufacturing of SMR units. This brings shorter construction times, more effective and efficient quality assurance/quality control and optimization of the project structure and management that can reduce investment capital costs. In many cases, SMR SSCs involve FOAK technology solutions, which may be extremely innovative, such as minimizing the quantity of necessary SSCs while simultaneously maintaining safety levels in comparison with large GEN II or GEN III+ reactors. In contrast, with the FOAK approach, designers implement unproven technology and increase the risk of delayed commercial availability.

The main contribution and novelty of this paper is its value analysis review and the evaluation of 27 different SMR GEN IV reactors design currently available. This value analysis gives insight into the commercially most promising technologies with strong implementation potential, which could be economically interesting in the next 10 to 15 years.

Eight out of 27 evaluated SMR designs were shortlisted in the first phase of evaluation. Those technologies went through a more detailed assessment. The most points were collected by the SVBR-100 SMR design (lead-cooled fast reactor designed in Russia). On the second and third places are PFBR-500 and CEFR SMR designs (Sodium-cooled Fast Reactor from India and China, respectively). Among the so-called “western technologies”, on the fourth place, PRISM SMR (sodium-cooled fast reactor designed by GE and Hitachi) shows potential, especially due to its multifunctionality and robust seismic design.

Based on available information, despite their unfavourable economy of scale, SMR overnight investment costs put SMRs cost of electricity production in the upper band of the price range of large reactors. Since the calculated cost of electricity production is based on predictions, actual economics is yet to be proven after first SMRs are put into operation.

When summarizing SMR technology could experience future growth under several conditions:

- similar or lower overnight investment costs and electricity production costs in comparison to large reactors,
- high level of external modularity with ability to efficiently connect several reactors on site offering several exploitation possibilities, internal modularity and standardization of SSCs of similar SMRs from different suppliers,
- flexibility at siting, with no or minimal environmental impact, seismic robustness, suitability for siting close to populated areas, smart grid and distributed supply integration possibility,
- unified international licensing approach implementation based on experience on SMR licensing conducted by world’s most recognized regulatory bodies, such as US NRC, STUK, ASN,
- large flexibility and impact at integration into existing nuclear fuel cycle schemes, consequentially leading towards closed nuclear fuel cycle,
- ultimate inherent safety against internal and internal events, with minimal or no operator intervention and relying on advanced passive safety features.

In case SMRs fail to deliver promised and expected features, especially at economic issues, they will remain interesting solely for research and for investors with high budgets, intent to solve energy supply issues at remote locations with poor infrastructure but high value. Energy supply independence is becoming more and more important in the focus of many environmental agreements, energy transitions towards electrification in heating, transportation and other demands. SMR technologies could deliver some of the answers for future energy needs.

References

[1] **OECD/NEA, Nuclear Energy Agency, Small Modular Reactors**: *Nuclear Energy Market Potential for Near-term Deployment*, OECD Publications, NEA No. 7213, Paris, France, 2016

[2] **EMWG**: *Cost Estimating Guidelines for Generation IV Nuclear Energy Systems*, Generation IV International Forum (GIF), Economic Modelling Working Group, EMWG, 2007

[3] **D. Schlissel and B. Biewald:** *Nuclear Power Plant Construction Costs*, Synapse Energy Economics, Inc., Nuclear's Tangled Economics, Business Week, 2008

[4] **OECD/NEA**: *Current status, Technical Feasibility and Economics of Small Nuclear Reactors*, OECD Publications, Paris, France, 2011

[5] **ANS**: *Interim report of the American Nuclear Society President's special committee on Small and Medium Sized reactor (SMR)*, generic licensing issues, ANS, 2010

[6] **Gen4 Energy**: *The Gen4 Module (G4M)*, http://www.gen4energy.com/technology/, accessibility check Jan 2018

[7] **Peter Líška, VUJE, Gérard Cognet**: *CEA, The ALLEGRO project – European project of fast breeder reactor*, Proc. 1st International Nuclear Energy Congress, Warsaw, 23-24 may, 2011

[8] **A. Kumar et al**: *Analysis of a sustainable gas cooled fast breeder reactor concept,* Department of Nuclear Engineering, Texas A&M University, College Station, USA, 2014

[9] **E. Greenspan**: *Fission Reactors – Options and Challenges*, Department of Nuclear Engineering, University of California, Berkley, USA, 2007

[10] **Idaho National Laboratory**: *Generation IV Nuclear Energy Systems Ten-Year Program Plan - Fiscal Year 2007*, Appendix 6.0-MSR, USA, 2007

[11] **Z. Donghui**: *Fast Reactor Development Strategy in China*, China Institute of Atomic Energy, Proc. International Conference on Fast Reactors and Related Fuel Cycles, 4.-7. march, Paris, France, 2013

[12] **C. Barton**: *Advanced High Temperature Reactor*: http://nucleargreen.blogspot.com/2010/08/advanced-high-temperature-reactor.html, 2010, accessibility check Jan 2018.

[13] **GIF, GEN IV International forum**: *Generation IV Systems*: https://www.gen-4.org/gif/jcms/c_59461/generation-iv-systems, accessibility check Jan 2018.

[14] **Idaho National Laboratory**: *Generation IV Nuclear Energy Systems Ten-Year Program Plan - Fiscal Year 2007*, Appendix 2.0-SCWR, Idaho, USA, 2007

[15] **A.I. Filin**: *Design Features of BREST Reactors and experimental work to advance the concept of BREST Reactors*, SSC RF, RDIPE, Moscow, RF, 2003

[16] **A.V. Zrodnikov**: *Multipurposed Small Fast Reactor SVBR-75/100 Cooled by Plumbum-Bismuth*, SSC RF, IPPE, Obninsk, RF, 2003

[17] **D. J. Diamond**: *Generation IV Nuclear Energy Systems*, Brookhaven National Laboratory, presented at Tennessee University, USA, 2003

[18] **M. Ragheb**: *Nuclear, Plasma and radiation Science*, Part IV, Ch. 4 High Temperature Gas Cooled Reactor, University of Illinois, USA, 2014

[19] **IAEA**: *Designs Features to Achieve Defence in Depth in Small and Medium Sized Reactors*, IAEA Nuclear Energy Series Report NP-T-2.2, Wienna, 2009

[20] **M. Pšunder**: *The economy of construction industry*, Tehniška založba Slovenije, Ljubljana, 1991

[21] **Worley Parsons**: *Small Modular Reactor Strategic Assessment*, Reading, Avgust 2011

[22] **A.Buršič, T.Žagar**: *Generation IV SMR Reactor development Forced renaissance or true need?*, PhD research seminar at subject Nuclear Power Plant Technologies, PhD Programme Nuclear Energy and Technology, University of Maribor, Faculty for Civil Engineering, April 2015

[23] **IAEA**: *Status of Small and Medium Sized Reactor Designs*, IAEA, Division of Nuclear Power, Department of Nuclear Energy, Vienna, 2011

[24] **A.Buršič, T.Žagar**: *Characterization of Advanced Nuclear Fuel Cycles and determination of HLW quantity for final disposal based on Slovenian Used Nuclear Fuel Inventory*, PhD research seminar at subject Advanced fuel cycles, PhD Programme Nuclear Energy and Technology, University of Maribor, Faculty for Civil Engineering, May 2012

[25] **OECD/NEA**: *Advanced Nuclear Fuel Cycles and Radioactive Waste Management*, NEA No. 5990, OECD Publications, Paris, 2006

[26] **T. Žagar**: *Closed fuel cycle technologies*, Jožef Stefan Institute, IJS-DP-9762, Issue 1, Ljubljana, 2008

[27] **T. Žagar, A. Buršič et al**: *Recycling as an option of used nuclear fuel management strategy*, Nuclear engineering and design, ISSN 0029-5493, vol. 241, no. 4, Amsterdam, North-Holland, 2011

[28] **World Nuclear Association**: *Reactor Database*, http://www.world-nuclear.org/information-library/facts-and-figures/reactor-database.aspx, accessibility check Jan 2018