POSITION PAPER ON FLEXIBILITY OF GEN IV SYSTEMS

2019 November

Economic Modelling Working Group

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TABLE OF CONTENTS

SECTION **PAGE**

FIGURES

TABLES

1. BACKGROUND

In October 2016, the Economic Modelling Working Group (EMWG) was asked to work collaboratively with the Senior Industry Advisory Panel (SIAP) to assist the Policy Group's (PG) initiative on market issues, looking specifically at the challenges and opportunities for deployment in low carbon energy systems. In response to the PG's request, the EMWG produced a position paper on the impact of increasing the share of renewables on the deployment of Generation IV energy systems. An executive summary of this report is available on the GIF public website. Subsequently, the EMWG mandate was revised in October 2018 to include studies related to flexibility requirements for Generation IV systems for integration with renewable resources and the opportunities for reducing the capital costs for competitiveness with other energy sources. Development of variable renewable electricity sources means that the Generation IV systems will need to be more flexible compared to the current reactors for deployment in the low carbon energy systems. Electric Power Research Institute (EPRI) was enlarging the concept of flexibility and defines three-fold flexibility for Generation IV reactors – namely the operational, product and deployment flexibility. There are several studies looking at the cost reduction opportunities for advanced reactors. Both the flexibility and cost reduction requirements involve considerations during the development stage of the Generation IV systems and the corresponding research and development (R&D) to support these requirements.

A questionnaire was developed to submit to the System Steering Committees (SSCs) to gather information on the flexibility aspects of the respective Generation IV systems and to learn how these flexibility requirements are addressed through the R&D. The questionnaire also included questions related to the opportunities for cost reduction. The questionnaire was sent to the SSCs in January 2019. All six SSCs responded to the questionnaire by May 2019. The extent of the responses varied among the SSCs; the SSCs with systems at higher technological readiness level provided more detail responses compared to the others.

A (1/2 day) workshop with joint participation of SSC representatives, SIAP and EMWG members, was held in Vancouver, Canada on May 29, 2019. This workshop focused on the flexibility requirements and opportunities for cost reduction for Generation IV systems. The workshop was opened with presentations from the SIAP and EMWG setting the tone for the workshop and invited presentations from Massachusetts Institute of Technology (MIT) and Electric Power Research Institute (EPRI). SSCs made presentations on the flexibility and cost reduction aspects of their respective system designs. The presentations were followed by discussions and possible path forward with enabling flexibility of Gen IV systems during the development stage.

2. WHAT IS FLEXIBILITY?

Various definitions of power system flexibility can be found in the literature. The International Energy Agency (IEA) [1] defines power system flexibility as all relevant characteristics of a power system that facilitate the reliable and cost-effective management of variability and uncertainty in both supply and demand. Driven in many contexts by the integration of variable renewable energy (VRE) in daily operations and a growing intensity and frequency of high-impact events, power system flexibility is an increasingly important topic for policy makers and system planners to consider. National Renewable Energy Laboratory (NREL) defines power system flexibility as the ability of a resource, whether any component or collection of components of the power system, to respond to the known and unknown changes of power system conditions at various operational timescales [2].

These definitions relate to the requirements of entire power system for "keeping the lights on" across all timescales with varying demand and supply conditions. Nuclear Energy Agency (NEA) [3] has identified five different technological options for power system flexibility:

1. *Flexibility from the conventional power plants:* Conventional power plants include various technologies including fossil, nuclear and hydroelectric generation. Currently, most of the flexibility services are provided by the conventional plants. Although many nuclear plants operate in base load mode; they are capable of providing flexibility services. Advanced reactors are being designed to be more flexible. This aspect will be discussed in more details later in this chapter.
2. *Grid integration and Network development:* Larger networks have less variable residual load.
3. *Energy Storage:* Energy storage is important for balancing the system against fluctuations in VRE generation and demand. The pumped-hydro energy storage has been deployed successfully, and several technologies are under development for thermal and electrical energy storage.
4. *Demand-side response (DSR):* provides flexibility by allowing electricity users to redistribute their consumption in response to the changes in the system.
5. *Operational flexibility from VRE*: Includes curtailment of VRE or control of VRE generation. Renewables are being given priority when connecting to the grid; in which case, dispatchable generation sources are required to load follow to meet the residual demand.

As the SSCs are directing the development of Generation IV system; the focus of this initiative was the flexibility of the reactor systems; albeit taking into consideration its deployment in the future energy markets having significant share of VRE resources, energy storage and potential co-generation applications.

The utilities in the Europe and the USA issued requirements for the advanced light water reactors (Gen III+) [4], [5] to ensure that new nuclear plants are capable of providing flexibility services to the system. These utility requirements are mainly focused on operational flexibility of the nuclear plants.

The advanced Generation IV reactors are significantly different compared to Gen III pressurized water reactors (PWR) reactors and use different fuels and coolants and operate at higher temperatures; making it suitable for applications beyond electricity production. Therefore, to evaluate the flexibility of Generation IV type reactors, EPRI proposed expanded flexibility criteria [6]. EPRI's expanded flexibility criteria consists of a set of three sub-criteria or attributes, each having specific attributes as follows:

- Operational Flexibility
- Deployment flexibility
- Product flexibility

The sub-attributes for each of the above sub-criteria/attribute and their benefits are summarised in Table 1 below.

Table 1
EPRI Attributes of Advanced Reactor Flexibility and Benefits

Attribute	Sub-Attribute	Benefits
Operational Flexibility	Maneuverability	Load following
	Compatibility with Hybrid Energy Systems and Polygeneration	Economic operation with increasing penetration of intermittent generation, alternative missions
	Diversified Fuel Use	Economics and security of fuel supply
	Island Operation	System resiliency, remote power, micro-grid, emergency power applications
Deployment Flexibility	Scalability	Ability to deploy at scale needed
	Siting	Ability to deploy where needed
	Constructability	Ability to deploy on schedule and on budget
Product Flexibility	Electricity	Reliable, dispatchable power supply
	Process Heat	Reliable, dispatchable process heat supply
	Radioisotopes	Unique or high demand isotopes supply

Therefore, due to the comprehensiveness of the criteria, the flexibility questionnaire was framed around the EPRI criteria for flexibility of advanced reactors and included sixteen questions based on three EPRI attributes of flexibility shown in Table 1. The questionnaire also included additional four questions on opportunities for cost reduction. The questionnaire template is attached as Appendix A and responses to the questions are compiled in Appendix B. The Sodium Fast Reactor (SFR) and the Very High Temperature Reactor (VHTR) SSCs provided detail responses for all reactor concepts being developed under those SSCs. EPRI also proposed the technology readiness level (TRL) and availability of technical information to assess the systems against flexibility criteria, which is summarized in Figure 1 [6].

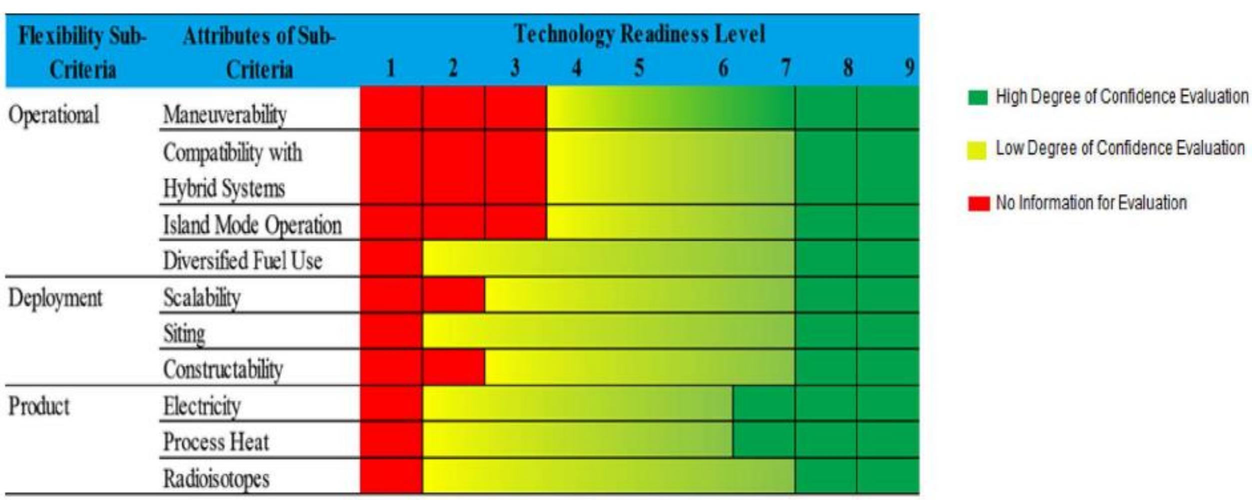

Figure 1: Technology readiness levels thresholds for evaluating flexibility of advanced reactor technologies (reproduced from reference [6]).

3. OPERATIONAL FLEXIBILITY

Four attributes of operational flexibility proposed by EPRI are as follows:

1. *Maneuverability*: The ability of the advanced reactor system to match the grid demand, including load following, meeting the ramping requirements for the grid and providing frequency control
2. *Compatibility with Hybrid Systems*: The ability is considered important particularly for integration with

VRE resources through hybrid energy systems which may include energy storage and other energy applications. The advanced reactor system needs to be capable of operating in concert with other energy-related technologies such as topping cycles and energy storage.
3. *Diversified Fuel Use*: The ability to operate using different types of fuel
4. *Island Mode Operation*: The ability of the advanced reactor system to operate in isolation from electricity distribution networks. This attribute of flexibility is particularly important for the advanced reactors in remote locations that are not served by the regional grid.

The questions around maneuverability focused on ramp rates, minimum power level and duration, automatic primary frequency control, power modulation and secondary frequency control. The operational flexibility requirements for Gen III+ reactors, shown in Figure 3 of Appendix A, were given as a guide for comparison. As seen in Figure 3, the operational flexibility criteria can be assessed for systems at TRL levels of four or greater. SFR and VHTR systems have equal or better maneuverability compared to Gen III+ systems as can be seen from detailed responses in Appendix B. The operational flexibility of these reactors has been validated through physics calculations. Existing water-cooled reactors are capable of providing full flexibility services for about 2/3rd of the fuel cycle, with limited or no flexibility at the beginning or near the end of the fuel cycle. Extended period of operation at low load factor could also lead to xenon poisoning of fuel. Advanced fast reactor concepts will not have xenon limitations. In case of gas-cooled advanced reactors, the thermal fluctuations can be avoided by controlling the coolant flow with the required power fluctuations, thus preventing aging of components due to thermomechanical stresses. Improved control systems and high degree of automation would also improve operational flexibility and facilitate integration with VRE resources through hybrid energy systems. Responses from other SSCs were less detailed or incomplete possibly because of lower TRL, although the SSCs generally think that these Gen IV systems will be more flexible than Gen III+ systems. Operational flexibility of lower TRL systems has not been validated yet through multi-dimensional physics calculations.

Some of the limitations on flexible operation could be attributed to steam cycles. Brayton CO_2 cycle being considered for higher temperature reactor would be more suited for flexible operations.

SFR, VHTR, Super Critical Water Reactor (SCWR), and Lead Fast Reactor (LFR) SSCs indicated capability of island mode operation. The capability of island mode of operation allows the reactor to be operated in a remote location of energy demand, connection to the grid with poor reliability and unacceptable interruptions in offsite power supplies.

All systems also indicated fuel flexibility. Liquid fuels for Molten Salt Reactor (MSR) provide more flexibility compared to the PWR fuels due to the absence of Xenon poisoning. TRISO fuels could have kernels of plutonium, thorium or uranium oxides. MOX fuels and TRU fuels are also being considered for Gen IV systems. Generally, Gen IV systems claim to have better fuel flexibility compared to Gen III+ systems.
Overall the preference seems to be to operate the reactor at full power through coupling with energy storage or intermittent industrial customers of thermal energy.

Some specific R&D needs have been identified for greater TRL system like SFR to address thermal degradation of materials, however no specific R&D was indicated for VHTR flexible operation. There may be an opportunity for cross cutting R&D for flexible operation of power generation, and thermal energy transport section of the plant.

4. DEPLOYMENT FLEXIBILITY

The deployment flexibility is the ability of an advanced nuclear reactor to be licensed, financed, sited, and built under a range of external conditions. EPRI describes three attributes of deployment flexibility; scalability, siting and constructability [7].

All SSCs, except Gas Fast Reactor (GFR) SSC responded to the questions on deployment flexibility. A range of sizes, ranging from micro reactors to small modular reactors and large scale reactors are being developed as Gen IV systems. One of the goals for Gen IV systems is to eliminate the need for offsite emergency response and thus reduce or eliminate the emergency planning zone. The improved safety of Gen IV systems is attributed to intrinsic safety features such as passive decay heat removal systems, underground siting and seismic isolation. System developers are also considering modular skids fabrication in factories, particularly for smaller reactors, to reduce on-site work. These deployment flexibility aspects make Gen IV systems attractive for industrial applications.

5. PRODUCT FLEXIBILITY

Product flexibility refers to ability of the advanced reactor systems to be used for multiple missions. Most of the current nuclear plants produce electricity, although over seventy reactors world-wide have been used in cogeneration mode for various applications including district heating, providing industrial steam and for water desalination. Cogeneration is the term used for simultaneous production of electricity and thermal energy or heat; and is also called as combined heat and power (CHP) mode of operation of a power plant. In the case of nuclear power plants, the thermal energy use currently only accounts for a small fraction (<1%) of the cumulative output of the nuclear power plants. Nonetheless; the individual thermal energy applications varied from 5 to 240 MWth. It is also worth noting that a 750 MWth sodium cooled-fast reactor, BN-350; one of the types being developed as Generation IV systems, has already been used for desalination of water in Aktau, Kazakhstan in 1973 to 1999 [9].

There is growing interest in nuclear cogeneration to address two issues:

- to provide flexibility for integration with increasing share of VRE resources on the grid while improving economics of nuclear operations, and,
- to combat climate change through application of carbon-free production of nuclear energy for industrial applications.

All Gen IV systems have higher outlet temperatures compared to current operating reactors and are thus are amenable to provide thermal energy for multiple industrial applications as shown in Figure 2. VHTR SSC has a project to develop water-splitting processes for hydrogen production using high-temperature thermal energy.

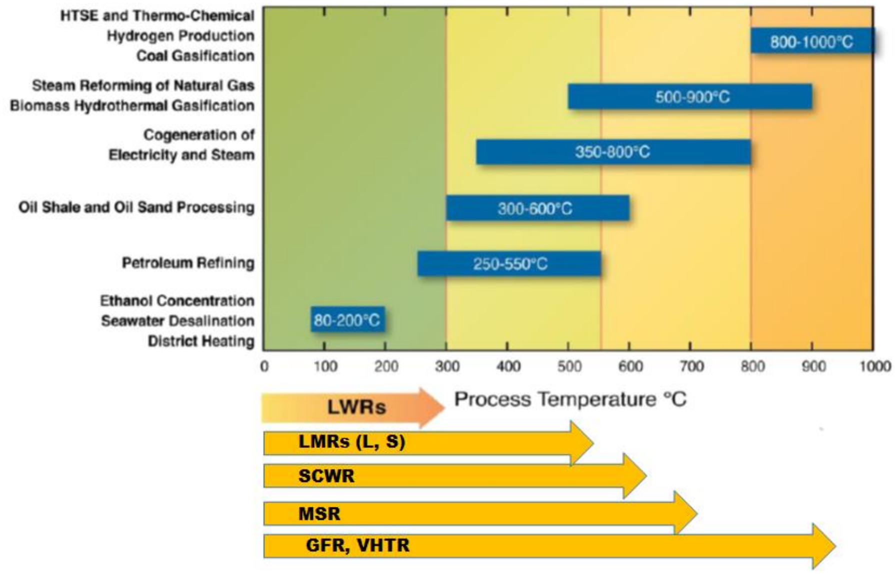

Figure 2: Potential cogeneration applications of Gen IV systems.

6. COST REDUCTION OPPORTUNITIES

The questionnaire on flexibility also included four questions on design considerations for cost reduction, since the cost of Gen IV systems would be critical for potential deployment in the future energy markets. Recent study [8] showed that the cost reduction efforts should focus on how the overall plant is constructed and on the ways to accelerate the construction. The design of the nuclear reactor and power conversion system also play a part in reducing cost through improved fabrication techniques. The responses from Gen IV systems at lower TRL level were not specific, however, they would consider cost reduction opportunities during development. SFR and VHTR systems envisage the following cost reduction opportunities.

- Compact reactor system and containment (e.g. reduced number of loops for SFR)
- Improved operation and maintenance, advanced diagnostics (under-sodium repairs), advanced reactor materials
- Advanced energy conversion system with compact machinery and improved efficiency (CO_2 Brayton Cycle)
- Modular design, factory fabrication of road-transportable skids and modules, reduced on-site construction and assembly

7. SUMMARY

Increasing the share of VRE resources on the grid requires additional flexibility of dispatchable energy sources to meet the variable and at times unpredictable residual load demand. Nuclear generation, typically characterized by high capital cost and low variable cost is most economic when operated at high capacities rather than in a modulating mode. Nonetheless, most nuclear plants are capable of flexible operation and in particular the plants in France and Germany are operating in a flexible mode. Utilities require new build nuclear plants to provide flexibility services to the grid. However, to increase economic viability, the nuclear plants can produce alternate energy products to achieve high capacity factors, in addition to providing flexibility services to the grid. EPRI proposed expanded criterion for flexibility of advanced reactors, which extends beyond the operational flexibility to include deployment flexibility and product flexibility.

Based on the questionnaire survey and the discussions during the workshop, the Gen IV systems that are under development within GIF are considered to have greater flexibility compared to the existing reactors. Existing water-cooled reactors are capable of providing full flexibility services for about 2/3rd of the fuel cycle, with limited or no flexibility at the beginning or near the end of the fuel cycle. Extended period of operation at low load factor could also lead to xenon poisoning of fuel. Advanced fast reactor concepts will not have xenon limitations. In case of gas-cooled advanced reactors, the thermal fluctuations can be avoided by controlling the coolant flow with the required power fluctuations, thus preventing aging of components due to thermomechanical stresses. Reactor developers are already taking into consideration the flexible operation requirements during the design and development phase. Many advanced reactor concepts are also being developed as small modular reactors which have potential for better constructability and deployability compared to current generation reactors.

Although many nuclear reactors have been used for low-temperature co-generation applications, such as district heating, water desalination and process steam, such applications account for a small fraction of cumulative energy output of nuclear plants. Gen IV systems will be more suited for cogeneration applications because of higher outlet temperatures which are suitable for replacing fossil fuel for thermal energy in many process applications. Simultaneous development of high-temperature water-splitting processes presents opportunities for economical hydrogen production using high-temperature advanced reactors to enable hydrogen as energy carrier. Advanced reactors, together with large-scale energy storage technologies will also be more suited for the hybrid energy systems which are proposed for improving the reliability and economics of integrated nuclear-VRE systems.

Gen IV systems with higher TRL have already considered some flexibility aspects in their design; whereas those at lower TRL level are ideally suited for incorporating flexibility aspects in their System Research Plans. There may be opportunities for cross-cutting R&D across the systems; for example control systems for dynamic balancing of heat and electricity output, materials resistant to thermal cycling and improved energy conversion systems.

The flexibility attributes for each system should be evaluated at appropriate TRL as recommended by EPRI [6] and summarized in Figure 1.

8. RECOMMENDATIONS

Flexibility is not included in the current goals for the development of Gen IV systems. However, considering the importance of flexibility for deployment of Gen IV systems in the future energy markets, SSCs need to ensure that flexibility aspects are part of the R&D. This may be done through identifying specific R&D in the System Research Plans.

The opportunities for cross-cutting R&D across the Gen IV systems should be identified through focused surveys. From the discussions during the workshop, some of the opportunities for cross-cutting R&D could include advanced materials resistant to thermal fatigue, advanced instrumentation and control for dynamic balancing of electrical and thermal outputs and efficient and flexible energy conversion system such as CO_2 Brayton cycle.

9. REFERENCES

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[3] Nuclear Energy Agency (NEA), “The Cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables”, NEA Report 7299, 2019

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[8] Massachusetts Institute of Technology (MIT), “The Future of Nuclear Energy in a Carbon-Constrained World”, Chapter 2, 2018.

[9] International Atomic Energy Agency (IAEA), “Opportunities for Cogeneration with Nuclear Energy”, Report No. NP-T-4.1, 2017.

APPENDIX A EMWG ADDENDUM TO SIAP QUESTIONNAIRE

D1: Background

Economics Modeling Working Group (EMWG) was mandated to develop methodologies to assess Generation IV systems against the two economic goals;

1. Generation IV nuclear energy systems will have a clear life-cycle cost advantage over the other energy sources, and,
2. Generation IV nuclear energy systems will have a level of financial risk comparable to other energy projects.

The EMWG published its cost estimating guidelines in 2007 (available on GIF external website https://www.gen4.org/gif/jcms/c_9260/public) along with an Excel-based software, G4ECONS v2.0, for economic assessment of Generation IV systems. Several papers on the assessment of Generation IV systems have been published. An improved version of the software, G4ECONS v3.0 (available on CD from the GIF Secretariat NEA), was released for use in August 2018.

In October 2016, the EMWG was asked to work collaboratively with the Senior Industry Advisory Panel (SIAP) to assist Policy Group's (PG) initiative on market issues, looking specifically at the challenges and opportunities for deployment in low carbon energy systems. In response to the PG's request, the EMWG produced a position paper on the impact of increasing share of renewables on the deployment of Generation IV energy systems. An executive summary of this report is available on the GIF public website (see the link above). Subsequently, the EMWG mandate was revised in October 2018 to include studies related to flexibility requirements for Generation IV systems for integration with renewable resources and the opportunities for reducing the capital costs for competitiveness with other energy sources.
Initial studies found that the Generation IV systems will have to be more flexible compared to the current reactors for deployment in the low carbon energy systems. EPRI defines three-fold flexibility for Generation IV reactors – namely the operational, product and deployment flexibility. There have been several studies looking at the cost reduction opportunities for advanced reactors. Both the flexibility and cost reduction requirements require considerations during the development stage of the Generation IV systems and the corresponding R&D to support these requirements.

A workshop (1/2 day) with joint participation of SSC representatives, SIAP and EMWG members is planned in the margins of the GIF EG and PG meetings in Vancouver, Canada on May 29, 2019. This workshop will be focused on the flexibility requirements and opportunities for cost reduction for Generation IV systems. SSCs will be invited to present the flexibility and cost reduction aspects of their system designs at this workshop. In the meantime, SSCs are requested to provide information about their systems as requested in this questionnaire. There are three categories of flexibility and one for cost reduction opportunities. In each category, the first question is open-ended to allow freedom of describing the system aspects. The other questions are specific but are meant to promote thinking while answering the first open-ended question. These questions also provide the basis for the SSC presentations at the Vancouver workshop on May 29, 2019.

D2: Flexibility

Reference Document: "Program on Technology Innovation: Expanding the Concept of Flexibility for Advanced Reactors: Refined Criteria, a Proposed Technology Readiness Scale and Time-Dependent Technical Information Availability" EPRI Technical Report 3002010479, November 2017.

D2.1: Operational Flexibility: Defined as the ability of the power plant to adjust to the grid conditions and support power quality via load following and grid frequency control.

- *Describe the maneuverability of the reactor design(s) being pursued in your System Steering Committee to match the external conditions? Please refer to Figure 1 for a concept of flexible operation over a 24-hour cycle.*

- *What are the ramp-rates (%/min) being considered for the designs?*

- *What is the minimum power level (% power) achievable? How long (hours) can it be sustained?*

- *Is the system capable of providing primary frequency control (automatic power modulation based on external frequency control signal)?*

- *What is the extent of power modulation (e.g. 5% in Figure 1) for secondary frequency control?*

- *Is the operational flexibility validated through multi-dimensional physics calculations?*

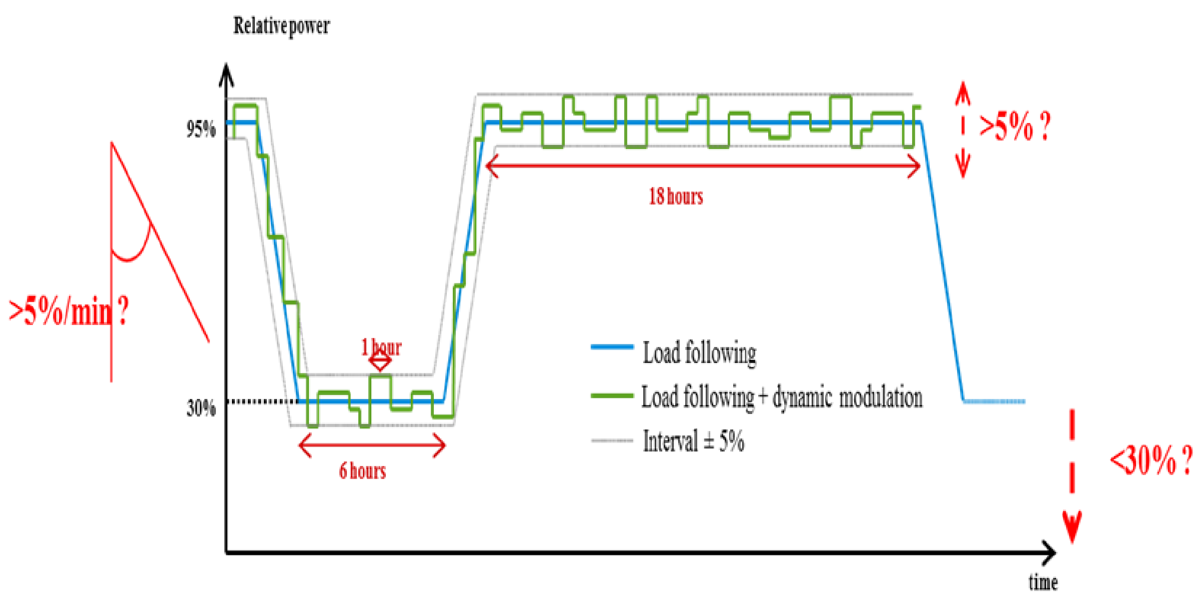


Figure 3: Concept of Flexible Operation for Advanced Reactors.

- *Are the reactor designs in your SSC, compatible for integration with hybrid systems with energy storage, topping cycles and/or co-generation using thermal energy? Are there any analyses performed for dynamics of power conversion system?*

- *Are there specific R&D being done to address material and component degradation resulting from flexible operation of reactor and power conversion system?*

- *Describe fuel flexibility aspects of reactor designs in your SSC. Are alternate fuels being considered?*

- *Are the reactors capable of operation in island mode; isolated from regional grid network?*

D2.2: Deployment Flexibility: Defined as the ability of the advanced reactors to be licensed, financed, sited and built under a range of external condition.

- *Describe the deployment flexibility aspects of reactor designs in your SSC. Specific questions to consider while describing your systems are as follows.*

- *How scalable are the reactor designs? What is the minimum feasible size and maximum size in terms of power output?*

- *Are there any specific siting requirements, considering emergency planning zone, improved safety (underground construction, passive cooling etc.)?*

- *Are the reactor components, systems amenable to factory fabrication to reduce on-site construction/assembly work?*

D2.3: Product flexibility: Defined as ability to fulfil more than one mission

- *Describe the product flexibility of the reactors designs under development within your SSC?*

- *Does the reactor design enable additional process heat applications that are not possible with currently deployed reactors?*
  What is the maximum temperature at which the process heat can be supplied to potential industrial user? Are the equipment for heat transfer included in the R&D/design effort? Are there any specific process heat applications (e.g. hydrogen production) already identified. Are the reactors capable of producing specific medical or industrial isotopes based on the neutron flux in the reactor core?

D3: Opportunities for Cost Reduction of NPP

Reference Document: "The Future of Nuclear Energy in a Carbon-Constrained World", Chapter 2, Massachusetts Institute of Technology, 2018.

As stated in the GIF economic goals, the Generation IV reactors will have to cost competitive with alternate energy systems if these reactors are deployed for electricity or process heat applications in the future low carbon energy systems. Recent experience of construction of Generation III /(+) reactors in western countries have shown unplanned significant cost increases through the project life, adversely affecting the economic viability and making nuclear less attractive for investment. Although the policies imposing carbon constraint of energy use would create opportunities for nuclear, the costs could be impediment for deployment of Generation IV systems. Therefore, opportunities for cost of nuclear plants should be explored from early development stages.

Recent studies show that cost reduction efforts should be focused on how the overall plant is constructed and on the ways to accelerate the construction. The design of the nuclear reactor and power conversion system also play a part in reducing the cost by making it more amenable to fabrication techniques that reduce cost.

- *Describe the cost reduction aspects on the reactor designs being pursued in your SSC.*

- *Are there any modularization opportunities? Are the components and systems amenable for factory production ad assembly? Are there features that reduce on-site assembly/construction of components and systems?*

- *Are there design features that reduce equipment costs – including advanced instrumentation and control technologies, advanced construction materials (steel, concrete), advanced power conversion cycle etc?*

- *Are there advanced siting options to reduce construction and licensing costs – including seismic isolation, below grade construction etc.?*

APPENDIX B RESPONSES TO EMWG ADDENDUM TO SIAP QUESTIONNAIRE

GFR
D2: Flexibility
D2.1: Operational Flexibility
Describe the maneuverability of the reactor design(s) being pursued in your System Steering Committee to match the external conditions? Please refer to Figure 1 for a concept of flexible operation over a 24-hour cycle.
Most of the questions - not applicable at the moment, no GFR concept is developed enough to answer such detailed questions. However, general observations can be made despite that fact. Reference solution of the power conversion system of the GFR 2400MWTh reactor is to use combined cycle, with gas turbines in the three secondary circuits and, using the remaining heat, a steam R-C cycle in the tertiary circuit. This fact, alongside with very low thermal inertia of the primary circuit (compared to other reactor types) is favouring operational flexibility of the reactor. Moreover, modern gas turbines retain reasonably high efficiency even at fraction of nominal load. Very low thermal efficiency brings also one significant drawback connected to changes in the power level – in case core outlet temperature is kept constant, coolant mass flow rate must be changed, which can lead to possibly dangerous situation in case of sudden power increase. Keeping core mass flow rate constant leads to fast decrease of coolant temperature and, subsequently, the core internals and other heat structures of the primary circuit. This can lead to their damage.
What are the ramp-rates (%/min) being considered for the designs?
No response.
What is the minimum power level (% power) achievable? How long (hours) can it be sustained?
No response.
Is the system capable of providing primary frequency control (automatic power modulation based on external frequency control signal)?
No response.
What is the extent of power modulation (e.g. 5% in Figure 1) for secondary frequency control?
No response.
Is the operational flexibility validated through multi-dimensional physics calculations?
No.
Are the reactor designs in your SSC, compatible for integration with hybrid systems with energy storage, topping cycles and/or co-generation using thermal energy? Are there any analyses performed for dynamics of power conversion system?
Generally, GFR is suitable for co-generation, because the final waste heat still has good enough parameters.
Are there specific R&D being done to address material and component degradation resulting from flexible operation of reactor and power conversion system?
No.
Describe fuel flexibility aspects of reactor designs in your SSC. Are alternate fuels being considered?
No response.
Are the reactors capable of operation in island mode; isolated from regional grid network?
No response.
D2.2: Deployment Flexibility
Describe the deployment flexibility aspects of reactor designs in your SSC. Specific questions to consider while describing your systems are as follows.
No response.
How scalable are the reactor designs? What is the minimum feasible size and maximum size in terms of power output?
Not yet applicable.

Are there any specific siting requirements, considering emergency planning zone, improved safety (underground construction, passive cooling etc.)?
Not yet applicable.
Are the reactor components, systems amenable to factory fabrication to reduce on-site construction/assembly work?
Not yet applicable.
D2.3: Product Flexibility
Describe the product flexibility of the reactors designs under development within your SSC?
GFRs are suitable both for very high efficiency electricity production through the combined power conversion cycle or high-potential process heat production.
Does the reactor design enable additional process heat applications that are not possible with currently deployed reactors? What is the maximum temperature at which the process heat can be supplied to potential industrial user? Are the equipment for heat transfer included in the R&D/design effort? Are there any specific process heat applications (e.g. hydrogen production) already identified? Are the reactors capable of producing specific medical or industrial isotopes based on the neutron flux in the reactor core?
Very high temperature hydrogen production processes. Maximum core outlet temperature is around 900°C, it can be reasonably assumed that the process heat can be supplied at temperatures above 800°C. The equipment for heat transfer is not yet included in the R&D/design effort. Hydrogen production is a heat application. With fast neutron scpectrum and enough neutron flux, GFR is theoretically capable of producing any isotope than can be possibly produced in a nuclear reactor. However, there are some inherent features of the technology that would make it complicated, for example necessity to keep the primary circuit pressurized even during outages and fuel handling.
D.3: Opportunities for Cost Reduction of NPP
Describe the cost reduction aspects on the reactor designs being pursued in your SSC.
Not yet applicable.
Are there any modularization opportunities? Are the components and systems amenable for factory production ad assembly? Are there features that reduce on-site assembly/construction of components and systems?
Not yet applicable.
Are there design features that reduce equipment costs – including advanced instrumentation and control technologies, advanced construction materials (steel, concrete), advanced power conversion cycle etc?
Not yet applicable.
Are there advanced siting options to reduce construction and licensing costs – including seismic isolation, below grade construction etc.?
Not yet applicable.

LFR
D2: Flexibility
D2.1: Operational Flexibility
Describe the maneuverability of the reactor design(s) being pursued in your System Steering Committee to match the external conditions? Please refer to Figure 1 for a concept of flexible operation over a 24-hour cycle.
The LFR-pSSC, taking into account the present state of the LFR system development, regards such considerations as somewhat early for a system that is still in a demonstration phase. However, it is anticipated that from a technical point of view the LFR can present substantial advantages in terms of operational flexibility, although such considerations are not forming the basis of the present design development. Phenomenologically, load following operations are considered to be strongly favoured by the fast neutron spectrum (limiting the xenon effect).
What are the ramp-rates (%/min) being considered for the designs?
This will strongly depend on the design solutions of the specific system. In principle at least the 5% / min is achievable. Higher performance can be however considered in the future.
What is the minimum power level (% power) achievable? How long (hours) can it be sustained?
Minimum power level may be as low as 30% of the nominal. However, as for other reactors, it does not seem to be economically viable without any additional market incentives to operate a reactor at a so low power level (considering the high capital intensity of the nuclear power plants). For a given reactor design, the duration of licensing is also usually independent from the power at which the reactor is operated. It can be noted that the implementation of integrated energy storage (e.g., heat storage or electrical storage) or intermittent auxiliary energy product production (e.g., water desalination, hydrogen production, etc.) could further improve economic performance by allowing diversion of produced power rather than operating at a very low level.
Is the system capable of providing primary frequency control (automatic power modulation based on external frequency control signal)?
These aspects are not yet considered in design.
What is the extent of power modulation (e.g. 5% in Figure 1) for secondary frequency control?
These aspects are not considered in design, yet.
Is the operational flexibility validated through multi-dimensional physics calculations?
These aspects are not considered in design, yet.
Are the reactor designs in your SSC, compatible for integration with hybrid systems with energy storage, topping cycles and/or co-generation using thermal energy? Are there any analyses performed for dynamics of power conversion system?
The LFR is in general compatible with energy storage. The expected temperatures are compatible with solar thermodynamic cycles and co-generation can indeed be an option. This will not depend strongly on the reactor design itself but on the implemented Balance-of-Plant (BOP) solutions. Some industrial developments already include energy storage at least as an option. In the short-term, the generated electricity could for example be used for hydrogen production through low-temperature electrolysis process.
Are there specific R&D being done to address material and component degradation resulting from flexible operation of reactor and power conversion system?
Not at this stage. Note that if the primary side pumps are operated at variable speed one may minimize thermal transients at primary side and only secondary and BOP operation may consequently be affected from flexible (load-following) operation. In case energy storage or multiple tightly coupled products (e.g., electricity and heat) are considered, the operational flexibility is provided through polygeneration or switching between the energy storage and production of different energy products.
Describe fuel flexibility aspects of reactor designs in your SSC. Are alternate fuels being considered?
The pSSC considers at present MOX and Mixed Nitrides.
Are the reactors capable of operation in island mode; isolated from regional grid network?
Yes, some projects are analyzing the use of small grids integrating LFRs as well as intermittent energy sources on the same distribution system to assure power availability. Especially for small (micro) LFRs, this possibility is already considered. Some LFR designs are also specifically being developed by industry considering deployment in insular (local) grids and at remote locations.

D2.2: Deployment Flexibility
Describe the deployment flexibility aspects of reactor designs in your SSC. Specific questions to consider while describing your systems are as follows.
As discussed above, the LFRs are considered for deployment as small (mini) reactors in insular grids and at remote locations. Larger units are intended for central station power generation.
How scalable are the reactor designs? What is the minimum feasible size and maximum size in terms of power output?
As usual, different design solutions are used depending on the power level. The envisaged power ratings for LFRs range from 1-2 MWe to up to 600 MWe with a possibility to increase the maximum power to 1000-1200 MWe in the future.
Are there any specific siting requirements, considering emergency planning zone, improved safety (underground construction, passive cooling etc.)?
One of the goals of LFR designers has been to eliminate the need of emergency planning zone (EPZ) benefiting from the intrinsic physical and chemical characteristics of lead coolant, the extensive use of passive safety systems, improved redundancies, etc., strengthening together the Defence-in-Depth. Underground siting of LFRs is considered as well at least for small/medium-size units.
Are the reactor components, systems amenable to factory fabrication to reduce on-site construction/assembly work?
Yes, they are in general. For large-size units, it may not be the case for very large components like main and safety vessels, but this remains indeed a possibility for most of the other reactor components.
D2.3: Product Flexibility
Describe the product flexibility of the reactors designs under development within your SSC?
As discussed above, in the short-term, generated electricity could be used for the production of hydrogen. A capacity of LFRs for polygeneration of multiple tightly coupled products (e.g., electricity, heat, desalination, dystric heating etc.) is planned to be assessed in near future.
Does the reactor design enable additional process heat applications that are not possible with currently deployed reactors? What is the maximum temperature at which the process heat can be supplied to potential industrial user? Are the equipment for heat transfer included in the R&D/design effort? Are there any specific process heat applications (e.g. hydrogen production) already identified? Are the reactors capable of producing specific medical or industrial isotopes based on the neutron flux in the reactor core?
The steam outlet temperatures presently envisaged are around 450°C, which is not achievable by LWR technology. Higher temperatures are under consideration and complete compatibility with solar plant is reached practically at 520°C (not so far away). Industrial use of steam is one possibility and covers the range of temperatures needed for most of the industrial applications. The reactor is capable, inside dedicated channels, to produce industrial isotopes. I must be noted that the above cited temperatures refer to the present status of the LFR technology. As improved corrosion resistant materials are developed and qualified, even higher output temperatures can be envisioned which would enable further improvement in efficiency and permit improved application of other energy products such as hydrogen.
D.3: Opportunities for Cost Reduction of NPP
Describe the cost reduction aspects on the reactor designs being pursued in your SSC.
Modularization, mini-serial production, standardisation, design simplification, inherent safety characteristics related to use of lead, and high safety margins are expected to be the main factors influencing cost reduction aspects. In particular, lead primary coolant can be maintained at near atmospheric pressure benefitting from low partial vapor pressure of molten lead, eliminating the need for complex / expensive structures to provide pressure boundaries (as in LWR). Finally, LFR's capability of long-burning without refueling can eliminate refueling equipment, fuel cost, spent nuclear fuel storage cost, reduce safeguards cost.
Are there any modularization opportunities? Are the components and systems amenable for factory production ad assembly? Are there features that reduce on-site assembly/construction of components and systems?
Yes, cf. above
Are there design features that reduce equipment costs – including advanced instrumentation and control technologies, advanced construction materials (steel, concrete), advanced power conversion cycle etc?
Yes. Supercritical CO_2 Brayton cycle is envisaged / possible. Some designs have already developed new concepts innovative multi-layer concrete construction and so on.

Are there advanced siting options to reduce construction and licensing costs – including seismic isolation, below grade construction etc.?
Yes. Seismic isolation is considered as an option for some designs. Below grade as well, but it is expected to translate in a very high cost. A very small emergency planning zone (EPZ), would also allow their deployment less controversial and hence less expensive, especially in densely-populated areas.

MSR
D2: Flexibility
D2.1: Operational Flexibility
Describe the maneuverability of the reactor design(s) being pursued in your System Steering Committee to match the external conditions? Please refer to Figure 1 for a concept of flexible operation over a 24-hour cycle.
The first MSR concepts were designed to power aircrafts. To prove this concept, the HTRE projects were established. The absence of Xenon poisoning allows high levels of flexibility in the primary circuit. Most of the flexibility limits from an operational point of view come from the steam cycle. Data on flexible operation over a 24-hour cycle is not available at this stage of design.
What are the ramp-rates (%/min) being considered for the designs?
Around 10 %/min.
What is the minimum power level (% power) achievable? How long (hours) can it be sustained?
Around 20%. This operational limit is imposed by the steam cycle.
Is the system capable of providing primary frequency control (automatic power modulation based on external frequency control signal)?
In principle, yes.
What is the extent of power modulation (e.g. 5% in Figure 1) for secondary frequency control?
This information is not available at this stage of design.
Is the operational flexibility validated through multi-dimensional physics calculations?
No.
Are the reactor designs in your SSC, compatible for integration with hybrid systems with energy storage, topping cycles and/or co-generation using thermal energy? Are there any analyses performed for dynamics of power conversion system?
The MSR is compatible with hybrid system (e.g. thermal storage of the salt) however, given the early stage of the design, dynamic analyses of power conversion have not been performed yet.
Are there specific R&D being done to address material and component degradation resulting from flexible operation of reactor and power conversion system?
Not for now but it could be planned.
Describe fuel flexibility aspects of reactor designs in your SSC. Are alternate fuels being considered?
Liquid fuels provide inherent flexibility capabilities, especially due to the absence of Xenon poisoning. Many different types of fuels cycles can also be considered.
Are the reactors capable of operation in island mode; isolated from regional grid network?
Not for now but it could be planned.
D2.2: Deployment Flexibility
Describe the deployment flexibility aspects of reactor designs in your SSC. Specific questions to consider while describing your systems are as follows.
Deployment flexibility can be achieved thanks to different reactor sizes and power outputs.
How scalable are the reactor designs? What is the minimum feasible size and maximum size in terms of power output?
MSR concepts range from 1 MW to 300 MW. The minimum feasible size is 1 MW.
Are there any specific siting requirements, considering emergency planning zone, improved safety (underground construction, passive cooling etc.)?
MSR have similar siting requirement than other Gen IV concepts. Not specific requirements for MSR have been identified.
Are the reactor components, systems amenable to factory fabrication to reduce on-site construction/assembly work?
Yes, as any other SMR concept, it has potential for improved constructability.

D2.3: Product Flexibility
Describe the product flexibility of the reactors designs under development within your SSC?
Yes, as any other SMR concept, it has potential for improved constructability.
Does the reactor design enable additional process heat applications that are not possible with currently deployed reactors? What is the maximum temperature at which the process heat can be supplied to potential industrial user? Are the equipment for heat transfer included in the R&D/design effort? Are there any specific process heat applications (e.g. hydrogen production) already identified? Are the reactors capable of producing specific medical or industrial isotopes based on the neutron flux in the reactor core?
MSR is the Gen IV concept with the highest exergy which means that it can provide high quality heat for industrial application and hydrogen production (i.e. IMSR). The output temperature ranges 600-700°C. Heat transfer components are part of the R&D effort. MSR can also be used for radioisotope production or even as a burner depending on the neutron spectrum (i.e. thermal or fast).
D.3: Opportunities for Cost Reduction of NPP
Describe the cost reduction aspects on the reactor designs being pursued in your SSC.
Design development of MSR is not mature enough to provide detail cost figures. Nevertheless, cost reduction opportunities may arise from improved constructability thanks to simplification of design and enhanced modularisation. Both higher fuel and plant efficiency also improve the overall economics of the plant. Furthermore, low-pressure systems such as MSR offer additional opportunities on cost reduction.
Are there any modularization opportunities? Are the components and systems amenable for factory production ad assembly? Are there features that reduce on-site assembly/construction of components and systems?
Design development of MSR is not mature enough to provide detail cost figures. Nevertheless, cost reduction opportunities may arise from improved constructability thanks to simplification of design and enhanced modularisation. Both higher fuel and plant efficiency also improve the overall economics of the plant. Furthermore, low-pressure systems such as MSR offer additional opportunities on cost reduction.
Are there design features that reduce equipment costs – including advanced instrumentation and control technologies, advanced construction materials (steel, concrete), advanced power conversion cycle etc?
Design development of MSR is not mature enough to provide detail cost figures. Nevertheless, cost reduction opportunities may arise from improved constructability thanks to simplification of design and enhanced modularisation. Both higher fuel and plant efficiency also improve the overall economics of the plant. Furthermore, low-pressure systems such as MSR offer additional opportunities on cost reduction.
Are there advanced siting options to reduce construction and licensing costs – including seismic isolation, below grade construction etc.?
Design development of MSR is not mature enough to provide detail cost figures. Nevertheless, cost reduction opportunities may arise from improved constructability thanks to simplification of design and enhanced modularisation. Both higher fuel and plant efficiency also improve the overall economics of the plant. Furthermore, low-pressure systems such as MSR offer additional opportunities on cost reduction.

SCWR
D2: Flexibility
D2.1: Operational Flexibility
Describe the maneuverability of the reactor design(s) being pursued in your System Steering Committee to match the external conditions? Please refer to Figure 1 for a concept of flexible operation over a 24-hour cycle.
In principle, SCWR as an evolution of BWR should have similar flexibility / load following capabilities as BWRs (Germany). Steam temperature remains constant, mass flow rate would increase proportionally with power.
What are the ramp-rates (%/min) being considered for the designs?
See ISSCWR-9 papers on "start up" times. Papers from XJTU. Also BWR characteristics (see NEA report) **Ramp rates HPLWR from 20% load to 100%:** 1 ½ hour **Running down 100% to 20%:** 1 hour **Cold start up:** 4 hours (Ref. HPLWR Design & Analysis, T. Schulenberg)
What is the minimum power level (% power) achievable? How long (hours) can it be sustained?
Typically 20%.
Is the system capable of providing primary frequency control (automatic power modulation based on external frequency control signal)?
Yes.
What is the extent of power modulation (e.g. 5% in Figure 1) for secondary frequency control?
See BWR.
Is the operational flexibility validated through multi-dimensional physics calculations?
Calculations performed (Canada, Europe, China, Japan – see Oka's book) but not "validation calculations".
Are the reactor designs in your SSC, compatible for integration with hybrid systems with energy storage, topping cycles and/or co-generation using thermal energy? Are there any analyses performed for dynamics of power conversion system?
Yes – for example, H2 generation (Canadian SCWR coupled to H2 generation pb, Copper Chlorine Cycle). Reference: Armando to provide Canadian reference (see Montreal IEM paper).
Are there specific R&D being done to address material and component degradation resulting from flexible operation of reactor and power conversion system?
Specific R&D on this topic not identified as priority.
Describe fuel flexibility aspects of reactor designs in your SSC. Are alternate fuels being considered?
Uranium fuel, thorium fuel, MOX fuel.
Are the reactors capable of operation in island mode; isolated from regional grid network?
Yes.
D2.2: Deployment Flexibility
Describe the deployment flexibility aspects of reactor designs in your SSC. Specific questions to consider while describing your systems are as follows.
Deployment flexibility because several sizes from very small SCWR to large SCWR. Reference: Canadian SCWR design studies.
How scalable are the reactor designs? What is the minimum feasible size and maximum size in terms of power output?
10 MWe to 1200 MWe (Canada) – 1725 MWe (Japan).
Are there any specific siting requirements, considering emergency planning zone, improved safety (underground construction, passive cooling etc.)?
Water for cooling, similar to Gen III LWR.
Are the reactor components, systems amenable to factory fabrication to reduce on-site construction/assembly work?
Same as LWRs and fossil BoP components.

D2.3: Product Flexibility
Describe the product flexibility of the reactors designs under development within your SSC?
H2, desalination, process steam, space heating.
Does the reactor design enable additional process heat applications that are not possible with currently deployed reactors? What is the maximum temperature at which the process heat can be supplied to potential industrial user? Are the equipment for heat transfer included in the R&D/design effort? Are there any specific process heat applications (e.g. hydrogen production) already identified? Are the reactors capable of producing specific medical or industrial isotopes based on the neutron flux in the reactor core?
More applications than current reactors (steam at higher temperatures) 625 deg C max. Temperature (Canadian design) R&D on heat exchangers (TH&S PMB scope) H2 work (Canadian participation in VHTR HP applicable to SCWR).
D.3: Opportunities for Cost Reduction of NPP
Describe the cost reduction aspects on the reactor designs being pursued in your SSC.
Main advantage of SCWR over other Gen IV – cost reduction compared to BWRs (20% cost advantage). Ref is HPLWR book. Cost reduction essentially fewer components, higher temperature (higher power at same component cost). Less concrete & steel. Experience of operating BWR & supercritical fossil power plants. Application of GIF EMWG methodologies to Canadian SCWR.
Are there any modularization opportunities? Are the components and systems amenable for factory production ad assembly? Are there features that reduce on-site assembly/construction of components and systems?
Yes, in principle. SMR type designs exist (concepts).
Are there design features that reduce equipment costs – including advanced instrumentation and control technologies, advanced construction materials (steel, concrete), advanced power conversion cycle etc?
Yes. Advanced power cycle of SCWR compared to BWR/PWR. (Savings in plant costs not in fuel costs.)
Are there advanced siting options to reduce construction and licensing costs – including seismic isolation, below grade construction etc.?
Not yet addressed.

SFR

D2: Flexibility

D2.1: Operational Flexibility

Describe the maneuverability of the reactor design(s) being pursued in your System Steering Committee to match the external conditions? Please refer to Figure 1 for a concept of flexible operation over a 24-hour cycle.

Many of the countries do not have specific request for network following for nuclear plants. As a consequence, most of the SFR design tracks have not applied a strong constraint to take into account these requirement even if some of them have top level requirements for network following. Some examples of the high level requirements applied to Generation-IV SFR Concepts:

JSFR

- daily load following
- 0-100% manual operation
- 30-100% automatic operation
- 10% step load change
- 5%/minutes ramp load change
- automatic operation after 95% load loss

ESFR

ESFR has to comply French request at least, that means:

- Self- sustaining capacity (house load) during an incident in order to replenish it rapidly;
- Ability of load following: daily load following between 20% to 100% nominal power;
- Automatic frequency control to keep the grid frequency as close to the nominal value of 50Hz, 9% load change and 5%/minutes ramp load change.

KALIMER

Top level requirement of KALIMER for flexible operation are as follows:

- Self-sustaining capacity only with house load during an incident at full power.
- Load following capability was not considered yet. But KALIMER is designed to accommodate 10% step load change within 10 seconds and ramp change of 5%/min.
- Frequency control capability to follow grid frequency was not considered yet in KALIMER.

BN1200

For BN-1200, the top-level requirements for operation flexibility are:

- Self- sustaining capacity (house load) during an incident in order to replenish it rapidly;
- Some investigations on operation of the BN-1200 at different power levels in accordance with request of energy system to regulate load and frequency are carried out, nevertheless, now BN-1200 is oriented to operate in base mode at steady power level.

CFR1200

Based on the deployment of nuclear energy in China now, the operation flexibility of CFR1200 may be considered as follows:

- Self- sustaining capacity (house load) during an incident in order to replenish it rapidly;
- Ability of load following: daily load following between 50% to 100% nominal power;
- Automatic frequency control to keep the grid frequency as close to the nominal value of 50Hz, 10% load change and 2%/minutes ramp load change.

In addition, to the specific responses to the operational flexibility questions given below, France contributed a System Integration and Assessment (SIA) trade study regarding this topic with respect to the ASTRID design: "How to comply with grid regulation for SFR in FRANCE?"

SIA Contribution: Grid Network regulation in France

In FRANCE, the reactor needs to comply with French regulations to be authorized to be connected to the grid. Regulations issued from the French electricity network company RTE, that request to the main mode of production (80% of electricity in France comes from nuclear power) both to ensure an adaptable power production in order to maintain the stability of the network frequency at 50 Hz and its self-sustaining capacity (house load) during a widespread incident on the network in order to replenish it rapidly. From these requirements, the plant "house load" is regulatory together with the primary and secondary frequency control imposed for production facilities with output power higher than 120 MWe.

Load frequency control

The grid frequency varies depending on the balance between production and consumption and must therefore be continuously controlled and regulated. The frequency control keeps the grid frequency as close to the nominal value of 50Hz required for proper operation of electrical systems of consumer processes. For that purpose, the main means of electric production must be flexible enough to lower or raise the power they supply to the grid. This power adjustment is divided into a primary control which represent a first adjustment required and in addition a secondary control with characteristics explained hereafter.

a. Requirements for the primary frequency control

In case of increase in the grid frequency, the power plant needs to reduce its power and be able to reach any point of operation beyond a minimum plant power level Pmin and below the maximum plant power Pmax. It corresponds to the ability to increase or decrease by 2.5% of the Pmax in less than 30 seconds, half in less than 15 seconds and be capable to maintain the new level for at least 15 minutes. This setting (automatically controlled by the inner turbo-machine regulation) is used in priority for a network frequency deviation from 20 mHz to 200 mHz which is necessary on an average of 2 times per hour.

b. Requirements for the secondary frequency control

The secondary control of the frequency is complementary to the primary control and must be possible from any operating point between Pmin and Pmax. The control must be possible within a band equal to +/- 4.5% of the Pmax with a gradient up to 9% Pmax in 133 second. The secondary control half band can be added to that of the primary control to provide a total reserve on the rise at least of 7% Pmax. The power plant must be able to contribute to the secondary control of the frequency by controlling its active power according to a control signal coming from RTE. The unit must have equipment capable of receiving the control signal and change its power supplied to the grid.

House load procedure

The house load procedure corresponds to an automatic power decrease to 50% Pmax in power order to quickly recover the full.

The ability of SFR to perform a house load procedure must be demonstrated for two main reasons:
- It is regulatory for the network security in case of a major failure of the electricity transmission network that need immediate available power reserve to participate in its reconstruction.
- In case of a short duration loss of the plant supply voltage of about one second, the house load procedure is initiated to avoid a reactor shutdown procedure.

Load following procedure

The load following procedure has the objective to match the plant power to big changes in electricity consumption (typically day/night sequences). This request is not yet regulatory in France but very probably in a next future due to the increase of the renewable energy production in the electricity mix.

Feedback from existing power plants

To our knowledge none of Fast Neutron Reactors in the world has been or is operated with a full grid frequency control and/or load following.

In France:
PHENIX was only operating with the primary frequency control which is a passive control (no dedicated regulation) due to the natural coupling between the turbomachinery rotating velocity and the grid frequency (statism).

SUPERPHENIX has been considered for:
- Frequency control, but was not authorized due to the lack of fuel cladding interaction demonstration under frequent power fluctuations;
- House-load, but was not authorized by Safety Authority due the risk of non-detection of unexpected drop of control rod;
- Load-following, issues due to progressive distortion of the inner vessel due to thermal gradient through the gas/sodium interface.

SFR challenges for operational flexibility

Frequency control challenges:

- High kinetic transfer of power changes from primary to tertiary circuit to cope with regulation requirement: ~5% Pmax/mn
- Fuel rod cladding mechanics must cope with local frequent power changes: ~2/hour
- The impact of unexpected regulation control rods withdrawal
- Potential fatigue of control rods mechanism and steam generators tubes due to boiling zone spatial fluctuations

Load following challenges:

- Accommodate the free Na level of emerged internal vessel integrity with time

House load Challenges:

No particular challenges identified

Maneuverability of SFR design(s) to match the external conditions

Korean SFR does not have explicit requirement of load following capability because primary role of Korean SFR is not the electricity generation but the transmutation of toxic element of spent nuclear fuel. However, a metal fueled SFR has a high performance of following the external load change owing to its unique reactivity feedback effects, i.e., small fuel temperature coefficient. The load following could be done only with the change of flow rate, which is also proved during EBR-II operation.[1]

SFR benefits for operational flexibility

Advanced reactors designed for load following provide an attractive alternative to the demand leveling strategies of energy storage and hybrid energy systems of light water reactors. Many of the factors limiting light water reactor technology for flexible operation are not limiting for advanced reactors. These include the effect of xenon inventory on reactivity control during load changes, the degree of axial power peaking during transients, the simplicity of operability for meeting power changes, and thermal stresses on structures[2]. One might expect certain design features and capabilities for a U.S. SFR operating in the electric grid of tomorrow where the fraction of renewables has increased, and gas generation needs to be displaced. While the specifics are electricity market dependent, ramp rates greater than 5%/min will be needed to service the reserve market. Preliminary techno-economic analyses indicate rates as great as 20%/min can coffer cost advantages. This will require a next-generation plant-wide control system for managing the potential temperature variations that can occur at these rates. This entails a high degree of automation and it also happens to align with interest in the use of automation to reduce staffing for operations and maintenance tasks.

What are the ramp-rates (%/min) being considered for the designs?
In France, The ramp-rates considered for SFR is 5%Pmaw/min to match with the regulatory request. This rate is very challenging for SFR with Steam/Water Rankine Power Conversion System because of low kinetic transfer of power changes from primary to tertiary circuit. To achieve higher ramp-rates, it is need to studies innovative Power Conversion System. Korean SFR has the design requirement to accommodate 10% step change within 10 seconds and ramp change of 5%/min.
What is the minimum power level (% power) achievable? How long (hours) can it be sustained?
In France, the minimum power level achievable for SFR is 20% Pmax. There is no duration challenges for this operation procedure. The power operation range of Korean SFR is 30 to 100% of full power.
Is the system capable of providing primary frequency control (automatic power modulation based on external frequency control signal)?
In France, Studies have been done for SFR design tracks to demonstrate the capability of these reactors to provide automatic modulation power. The reference option is that output electrical power is tuned by the core power. The feasibility has been confirmed with a specific regulation on outlet core temperature and secondary pump for the right kinetic of thermal energy transfer between the core and turbine. Dedicated Control Rods architecture is needed. For example, for ASTRID cases, three rods (called "regulation rods") from 18 control rods would be dedicated to this regulation. Korean SFR does not have a design requirement of frequency control capability.

1 Korean KALIMER-600 was designed to be a commercial power plant to reduce the spent nuclear fuel toxicity and to enhance the uranium resource utilization. The PGSFR is a technology demonstrator for KALIMER-600 design and safety. Followings are the case of PGSFR because Korean activities has been concentrated on the PGSFR rather than KALIMER-600. The design requirement and features will be very similar between PGSFR and KALIMER-600.

2 Vilim and Passerini, "Evaluation of Design Variants for Improved inherent Regulation of Advanced Small Modular Reactors," Proceeding of ICAPP 2015, May 2015.

What is the extent of power modulation (e.g. 5% in Figure 1) for secondary frequency control?

In France, Primary frequency: +/- 2.5% Pmax
Secondary frequency: +/- 4.5% Pmax
A cumulative reserve of both frequencies types: +/- 7% Pmax

Is the operational flexibility validated through multi-dimensional physics calculations?

The operational flexibility is validated with system code calculation like CATHARE in France.

Are the reactor designs in your SSC, compatible for integration with hybrid systems with energy storage, topping cycles and/or co-generation using thermal energy? Are there any analyses performed for dynamics of power conversion system?

Sodium Fast Reactor, like PWR, are compatible for hybrid systems. Nevertheless, all the design tracks in SFR SSC are designed to produce electricity with a power conversion system without storage or co-generation using thermal energy. Most of the design used Rankine Steam/water PCS and R&D is done on innovative Gaz PCS using Brayton cycle with Supercritical CO2 or Nitrogen.For ASTRID project, studies have been investigated to maintain the reactor to full power whatever the grid load demand is, and energy excess to be stored or used as a by-product (vapor or electricity) for industrial processes (H2; power to gas….).

Are there specific R&D being done to address material and component degradation resulting from flexible operation of reactor and power conversion system?

The material and component degradation resulting from flexible operation of the reactor can be considered as an acceleration of the material and component ageing of the reactor. Therefore, we can consider that all R&D on material and component ageing can be used for the flexibility purpose.
Other R&D on design of the reactor have been considered to limit the degradation of the material and component like:

- Re-design of the inner vessel to avoid thermal gradient
- Insert a back-pressure to avoid the free level difference for operation
- Removal of inner structures by design

Describe fuel flexibility aspects of reactor designs in your SSC. Are alternate fuels being considered?

In France, interaction between fuel and clad is one of the main limitation of the number of cycle that can be considered for fast reactor. Different type of fuel are considered in SFR SCC (oxide, metal, carbide,…). At that time, no top level requirements are considered in Advnaced Fuel Project for flexibility aspects.
Korean SFR was designed to accommodate various flexible scenarios of fuel managements. As a TRU burner design, high contents (over 30%) of TRU fuel was considered, while low contents of TRU fuel (less than 20%) was considered as a breakeven core design. Korean SFR also has a capability of long-life operation with low enriched uranium fuel.

Are the reactors capable of operation in island mode; isolated from regional grid network?

Sodium Fast Reactors can operate house load procedure and no particular challenges are identified.
In principle, Korean SFR is operated with external grid network. However, Korean SFR has a capability to switch operation mode only with in-house load without reactor and turbine trips in case of complete loss of external power.

D2.2: Deployment Flexibility

Describe the deployment flexibility aspects of reactor designs in your SSC. Specific questions to consider while describing your systems are as follows.

See the response to the next question.

How scalable are the reactor designs? What is the minimum feasible size and maximum size in terms of power output?

The Generation-IV SFR designs cover a wide range of power levels to address different deployment missions and markets. As shown in Table 3, current design tracks range from 100 MWe to 1500 MWe to address. Furthermore, many of the design tracks can be adapted to different power levels with similar design features and approach.
For example, the minimum feasible size of Korean SFR will be 150 MWe, same size of PGSFR. The most of KALIMER-600 design features could be kept as similar to that of PGSFR. The maximum feasible size of Korean SFR will be 1,200 MWe, double of KALIMER-600. In this case, some of design features of KALIMER-600 should be revised for steam generator, reactor head and its support concepts, etc.

Table 3
Key Design Parameters of Generation IV SFR Concepts

Design Parameters	JSFR	KALIMER	ESFR	BN-1200	AFR-100
Power Rating, MWe	1,500	600	1512	1220	100
Thermal Power, MWt	3,570	1,500	3600	2800	250
Plant Efficiency, %	42	40	42	43.5	40
Core Outlet Coolant Temperature, oC	550	545	545	550	550
Core Inlet Coolant Temperature, oC	395	390	395	410	395
Main Steam Temperature, oC	503	503	490	510	517a
Main Steam Pressure, MPa	19.2	16.5	18.5	17.0	20a
Cycle Length, years	1.5–2.2	1.1	1.35	1.0	30
Fuel Reload Batch, batches	4	5	5	Up to 6	1
Core Diameter, m	5.1	4.2	4.72	4.18	3.0
Core Height, m	1.0	0.89	1.0	0.83/1.0	1.1
Fuel Type	MOX	Metal	MOX	MUPN/	Metal
	(TRU bearing)	(U-TRU-10%Zr Alloy),		MOX	(U-10%Zr Alloy),
Cladding Material	ODS	HT9M	ODS	AAS/FMS/ODS	HT9
Fuel FissileEnrichment (Pu/HM), %	13.8	25.2	15.7	Up to 20	13.5[b]
Burn-up, GWd/t	150	139	100	Up to 100/125 (average)	100
Breeding Ratio	1.0-1.2	0.74	1.0-1.2	1.35/1.2	0.8

[a]Energy conversion medium is supercritical CO_2, not steam
[b]Uranium enrichment (U-235/HM), %

Are there any specific siting requirements, considering emergency planning zone, improved safety (underground construction, passive cooling etc.)?

The Generation-IV Safety and Reliability-3 goal states that Generation IV nuclear energy systems will eliminate the need for offsite emergency response. Thus, all of the Generation-IV SFR design tracks have superior safety performance and utilize passive decay heat removal systems. Korean SFR has specific siting requirements for improved safety.
Korean SFR has passive ex-vessel cooling system for keeping reactor vault temperature below certain value and reactor and auxiliary building is seismically isolated.

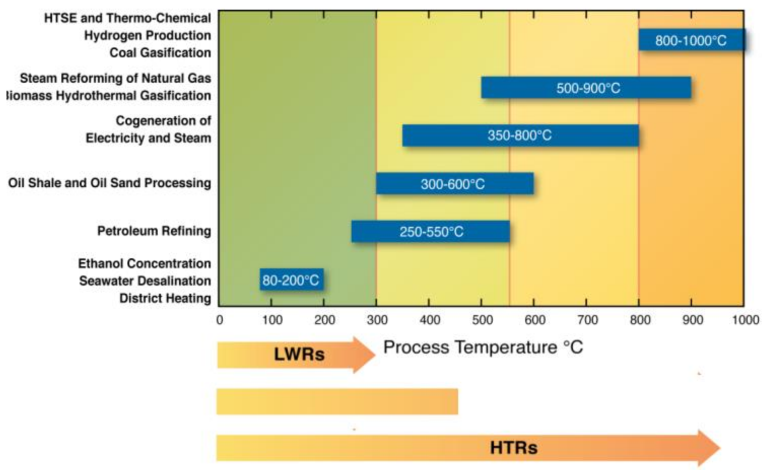
Are the reactor components, systems amenable to factory fabrication to reduce on-site construction/assembly work?

All of the Generation-IV design tracks target factory fabrication to reduce the capital costs. Modular construction techniques are utilized for both large components (e.g., reactor vessel) and smaller repeated components (e.g., fuel assemblies). Specific applications are design specific.
Korean SFR consider the factory fabrication of large size components, but on-site assembly work of reactor vessel internal is still necessary.

D2.3: Product Flexibility

Describe the product flexibility of the reactors designs under development within your SSC?

See the response to the next question.

Does the reactor design enable additional process heat applications that are not possible with currently deployed reactors? What is the maximum temperature at which the process heat can be supplied to potential industrial user? Are the equipment for heat transfer included in the R&D/design effort? Are there any specific process heat applications (e.g. hydrogen production) already identified? Are the reactors capable of producing specific medical or industrial isotopes based on the neutron flux in the reactor core?
With an outlet temperature of 500-550oC, the Generation-IV SFR can be utilized for a vary of heat applications that extend beyond electricity production. Figure 1 shows some of the potential missions for this particular temperature range: 

D.3: Opportunities for Cost Reduction of NPP

Describe the cost reduction aspects on the reactor designs being pursued in your SSC.
For the commercialization of the SFR system, it is important to achieve a level of economic competitiveness that enables system installation in accordance with market principles. For this purpose, an important goal is to achieve energy costs (unit cost of power generation) competitive with alternate future energy sources. For this purpose, the reduction of the plant capital costs is crucial. A number of innovative SFR design features have been proposed to improve SFR capital costs including: - Configuration simplifications. These include reduced number of coolant loops by improving the individual loop power rating, improved containment design, refined (and potentially integrated) component design, and possibly elimination of the intermediate coolant loop. - Improved Operations & Maintenance (O&M) technology. Innovative ideas are being considered for in-service inspection and repair. Remote handling and sensor technology for use under sodium are being developed, including ultra-sonic techniques. In addition, increased reliability for sodiumwater steam generators (e.g., by using double tube configuration with leak detection) is being pursued by advanced detection and diagnostic techniques. - Advanced reactor materials. The development of advanced structural materials may allow further design simplification and/or improved reliability (e.g., low thermal expansion structures and greater resistance to fatigue cracking). These new structural materials need to be qualified, and the potential for higher temperature operation evaluated. - Advanced energy conversion systems. The use of a supercritical CO2 Brayton cycle power generating system offers the potential for surpassing 40% efficiency; a more compact design may also be possible. Cost and safety implications must be compared to conventional Rankine steam cycle balance-of-plant design. - Fuel Handling. Techniques and components employed in previous fast reactors were reliable, but very complicated and expensive. Recent design innovations may simplify the fuel handling system, but require the development and demonstration of specialized in-vessel handling and detection equipment. - The total cost of electricity also includes the plant operation cost. This can be reduced by enhancing the plant load factor by making the reactor cycle length longer and capacity factor higher (e.g., by robust materials and improved system reliability). The fuel cycle cost can also be reduced by increasing the fuel burn-up. For this purpose, advanced cladding materials together with high-burnup transuranic fuel will be crucial.

Are there any modularization opportunities? Are the components and systems amenable for factory production ad assembly? Are there features that reduce on-site assembly/construction of components and systems?
Korean SFR consider the factory fabrication of large size components, but on-site assembly work of reactor vessel internal is still necessary.
Are there design features that reduce equipment costs – including advanced instrumentation and control technologies, advanced construction materials (steel, concrete), advanced power conversion cycle etc?
The reduction of equipment cost is realized to utilize passive safety features in safety grade system. The passive system contribute to the cost reduction by reducing the number of safety equipment of latter part of safety grade system.
Are there advanced siting options to reduce construction and licensing costs – including seismic isolation, below grade construction etc.?
Korean SFR is design to be seismically isolated, which reduce total building and component mass required for integrity of the reactor system during earthquake.

VHTR (FRAMATOME (SC-HTGR))

D2: Flexibility

D2.1: Operational Flexibility

Describe the maneuverability of the reactor design(s) being pursued in your System Steering Committee to match the external conditions? Please refer to Figure 1 for a concept of flexible operation over a 24-hour cycle.

Framatome Steam Cycle HTGR is a medium temperature (core outlet at 750°C) HTGR. Its primary purpose is production of high temperature steam (@560°C) for industrial applications. The reference SC-HTGR is a modular reactor, 625 MWth per module coproducing electricity and process heat. The dual product (steam and electricity) allows load switching between electricity and steam while the reactor operates at 100% power.
In addition the plant can increase/decrease power between 20% and 100% (reactor power) if total demand for electricity plus steam is less than 100%. This is expected to be a rare situation if the plant is connected to the national grid.
The load switching between electricity and steam at any reactor power level is performed by standard secondary side digital electronics. The reactor power level on the other hand is adjusted (fine tuning) either by turbine frequency control or primary system circulator speed control. In addition, gross power level adjustment is achieved by control element movements.

What are the ramp-rates (%/min) being considered for the designs?

In the dual (steam-electricity) operating mode the reactor is at constant 100% power and the ramp-rate for switching between steam and electricity is as fast as the customer requires.
When the overall module power demand is less than 100% the control system can achieve a 5%/min ramp rate between 20% and 100% power.

What is the minimum power level (% power) achievable? How long (hours) can it be sustained?

Each SC-HTGR reactor module can operate indefinitely at 20% power; however, such operation is not economical. The reference SC-HTGR plant has four modules; therefore demand can be optimized between the modules.

Is the system capable of providing primary frequency control (automatic power modulation based on external frequency control signal)?

The SC-HTGR is capable of providing primary frequency control. However, load following and flexible operation is best economically achieved by load switching capability of the SC-HTGR.

What is the extent of power modulation (e.g. 5% in Figure 1) for secondary frequency control?

Fast and responsive power level modulation is best performed by load switching. Note that the primary purpose of the SC-HTGR is production of high temperature steam for industrial application. Electricity generation is added income stream to increase the flexibility of plant operations and economics.

Is the operational flexibility validated through multi-dimensional physics calculations?

The design of the SC-HTGR is based on previous HTGR design experience and operating history. The flexibility calculations have not yet been performed but the designers are confident that both fast load switching and gross module power level modulation is possible.

Are the reactor designs in your SSC, compatible for integration with hybrid systems with energy storage, topping cycles and/or co-generation using thermal energy? Are there any analyses performed for dynamics of power conversion system?

Yes – A recent study sponsored by the US Department of Energy, MIT, Framatome, and University of Texas (Austin) provided technology evaluation and configuration assessments of integrating SC-HTGR with a variety of intermittent energy sources (solar and wind) with a variety of thermal energy storage concepts.
The study concluded that the load switching and load following flexibility of the SC-HTGR is the key to the round-the-clock (24/7) production of lowest cost electricity and/or high temperature process steam.

Are there specific R&D being done to address material and component degradation resulting from flexible operation of reactor and power conversion system?

No such R&D is needed for SC-HTGR.

Describe fuel flexibility aspects of reactor designs in your SSC. Are alternate fuels being considered?

The SC-HTGR will use TRISO coated particle fuel with UCO kernel. This fuel form is being qualified for SC-HTGR use in the U.S.A. under the DOE AGR fuel qualification program. Any other TRISO coated fuel form including PuO_2, ThO_2, and UO_2 have been used in the past and can be used again after successful completion of an appropriate qualification program.

Are the reactors capable of operation in island mode; isolated from regional grid network?
Yes – SC-HTGR can operate in the “island” mode totally disconnected from outside power supply or feed. In addition, a “black-start” variance of the SC-HTGR is also available that does not require external power source to start.
D2.2: Deployment Flexibility
Describe the deployment flexibility aspects of reactor designs in your SSC. Specific questions to consider while describing your systems are as follows.
No response.
How scalable are the reactor designs? What is the minimum feasible size and maximum size in terms of power output?
SC-HTGR is not only benefits from modular design it is highly scalable. The reference plant consists of four 624MWth modules. However, Framatome have conceptualized several scaled models including a) 350 MWth single loop module, b) 180 MWth steam only module, c) 54 MWth remote site module, and d) 2MWth micro module. All designs use the same basic prismatic fuel block. It must be noted that as power level decrease the unit cost of electricity and/or steam increases. Therefore, if demand exists the most economical SC-HTGR is our reference 625MWth module.
Are there any specific siting requirements, considering emergency planning zone, improved safety (underground construction, passive cooling etc.)?
Framatome’s reference plant (4 x625MWth plant) has a 400m EPZ (emergency planning zone). No public evacuation or environmental disturbance beyond the 400 meter plant site boundary is required. The SC-HTGR reference plant is designed to be co-located near an industrial complex that will use its high temperature steam. Framatome is working with the US-NRC to modernize siting requirements of the US licensing rules scalable to accident plant’s source term.
Are the reactor components, systems amenable to factory fabrication to reduce on-site construction/assembly work?
Yes - Most components and subcomponents of the SC-HTGR will be factory built and site assembled. However the reference SC-HTGR reactor vessel must be site assembled from three factory built subassemblies. The scaled variances of the reference plant are all factory built and site assembled. The remote site and the micro variances of the SC-HTGR are totally factory built with minimal site construction requirements.
D2.3: Product Flexibility
Describe the product flexibility of the reactors designs under development within your SSC?
Framatome’s reference SC-HTGR is in its conceptual design phase. Our current design focus is on key systems’ and components’ testing and validation. Once Framatome engages an “early-adopter” or the first commercial scale reactor the design and licensing activities will begin. As described before dual product stream of the SC-HTGR makes it extremely cost efficient.
Does the reactor design enable additional process heat applications that are not possible with currently deployed reactors? What is the maximum temperature at which the process heat can be supplied to potential industrial user? Are the equipment for heat transfer included in the R&D/design effort? Are there any specific process heat applications (e.g. hydrogen production) already identified? Are the reactors capable of producing specific medical or industrial isotopes based on the neutron flux in the reactor core?
Yes – Current operating reactors cannot produce process steam beyond 275°C. The SC-HTGR can produce up to 560°C process steam. This opens up a large sector of process heat industry that is currently captive to the use of fossil fuel. All process heat equipment and hardware are currently available. No R&D is necessary for the entire non-nuclear side of the SC-HTGR. There are a variety of industrial application for high temperature process heat including but not limited to, petro-chemical, fertilizer, refinery, hydrogen generation, and pharmaceutical. Any reactor is capable of producing industrial or medical isotopes. It is a matter of designing and placing a target material in the core and retrieving it at the appropriate time for processing. Core access is available in all SC-HTGR variances for radio-isotope production.

D.3: Opportunities for Cost Reduction of NPP
Describe the cost reduction aspects on the reactor designs being pursued in your SSC.
There are several key elements of cost-reduction features that can be implemented to make SC-HTGR or its scaled variances economically more viable. Of course the Framatome's reference plant is most cost effective plant with the lowest unit end-product cost. This is due to the ever present "economy of scale". Other key element of the cost reduction is "order-book". It is not economical to build one plant at a time many years apart (this has been the main reason for cost over-runs in the western societies). We are essentially building FOAK plants over and over. Factory building is cost reduction measure which requires a "order-book" that could financially substantiate building of the factory. Additive-Manufacturing is also becoming widely used on larger and larger components and a variety of materials. ASME or ESPN code qualification is necessary to use such technologies in nuclear applications. Modular construction techniques and seismic isolation techniques have been in use throughout large construction projects. Adoption of such techniques in nuclear industry could save construction time and money. Finally, regulatory oversite during construction is a major cost factor. Modifying and streamlining regulatory oversite during construction is actively being considered by Framatome and other advanced reactor designers in the U.S.A.
Are there any modularization opportunities? Are the components and systems amenable for factory production ad assembly? Are there features that reduce on-site assembly/construction of components and systems?
Yes – The designers of the SC-HTGR and its scaled variances are continuously pursuing standardization and modularization to reduce site construction and assembly time.
Are there design features that reduce equipment costs – including advanced instrumentation and control technologies, advanced construction materials (steel, concrete), advanced power conversion cycle etc?
Yes – the reference SC-HTGR and its scaled variances use already available SA-508/533 material for its vessel systems. This material is widely used and well known in light water reactor industry. SC-HTGR requires minimal safety grade instrumentation. The secondary side, however, uses sophisticated non-safety grade digital instrumentation to optimize plant product distribution, load switching and flexible operations.
Are there advanced siting options to reduce construction and licensing costs – including seismic isolation, below grade construction etc.?
Yes - Framatome is actively engaged with EPRI and the University of Buffalo NY evaluating seismic isolation of the entire plant or individual components of the plant. We believe one of the best cost reduction techniques is the use of seismic isolation. The idea is to seismically design the entire plant for modest seismic characteristics and the use seismic isolation devices to build the plant at any location with any specific seismic characteristics. This is basically a cost trade-off between the cost of seismic isolator devices and the redesigning the entire plant for a specific location.

VHTR (INET (HTR-PM))
D2: Flexibility
D2.1: Operational Flexibility
Describe the maneuverability of the reactor design(s) being pursued in your System Steering Committee to match the external conditions? Please refer to Figure 1 for a concept of flexible operation over a 24-hour cycle.
As for HTR-PM design with steam cycle, the plant has the capability of 100-50-100% load following capability within each day. Actually there are no real time interval limitation. HTR-PM design has a special operation mode which can improve the operation flexibility further. The flowrate of helium and feedwater is almost proportional to power level, this means the almost same helium temperature and fuel temperature distribution for all power level, and little movement distance of control rod is required.
What are the ramp-rates (%/min) being considered for the designs?
5 %/min for HTR-PM.
What is the minimum power level (% power) achievable? How long (hours) can it be sustained?
15% of total power (30 % of one reactor) for manual operation, for unlimited time. Because HTR-PM has two reactors/steam generators to be connected to one steam turbine. One reactor/steam generator can be operated.
Is the system capable of providing primary frequency control (automatic power modulation based on external frequency control signal)?
Not clear.
What is the extent of power modulation (e.g. 5% in Figure 1) for secondary frequency control?
Not clear.
Is the operational flexibility validated through multi-dimensional physics calculations?
The operation flexibility was validated through full-scope simulator already.
Are the reactor designs in your SSC, compatible for integration with hybrid systems with energy storage, topping cycles and/or co-generation using thermal energy? Are there any analyses performed for dynamics of power conversion system?
Currently HTR-PM is designed to generator electricity through steam turbine only. Although it is very easy to extract high temperature steam for other co-generation purpose. Co-generation has no technical difficulty. 10MWt test reactor HTR-10 is operated in co-generation model already to provide district heat for INET campus.
Are there specific R&D being done to address material and component degradation resulting from flexible operation of reactor and power conversion system?
For HTR-PM, the flowrate of helium in primary circuit and feedwater in secondary circuit is almost proportional to power level, this means the almost same helium temperature, steam temperature and fuel temperature distribution for all power level. This feature reduce the challenge for the operation flexibility. No special R&D are expected.
Describe fuel flexibility aspects of reactor designs in your SSC. Are alternate fuels being considered?
Currently HTR-PM is designed with UO2 fuel in the form of TRISO coated particle. From neutronics viewpoint, TRISO coated particle fuel has the capability to use different type of fuel, such as UCO, U/Th, MOX，and etc. There are many researches on this topic. AVR/THTR/Fort St. Vrain had verified the capability of U fuel, T/Th fuel already. The on-line fuel management mode in pebble bed HTR gives more flexibility of fuel utilization even after operation of the plant. But new type of fuel can only be used in plant after complete qualification process. It takes time.
Are the reactors capable of operation in island mode; isolated from regional grid network?
Yes. HTR-PM has this capability.
D2.2: Deployment Flexibility
Describe the deployment flexibility aspects of reactor designs in your SSC. Specific questions to consider while describing your systems are as follows.
HTR-PM will start operation in 2020. The whole supply chain is ready. HTR-PM demonstrate the configuration of 2 nuclear steam supply system (NSSS) modules connected to one steam turbine. It is very easy to connect more NSSS modules to one steam turbine based on experience of HTR-PM, especially each NSSS module is exactly the same module proved in HTR-PM. Flexible configuration (1-9 NSSS modules with one steam turbine) with different power size can be easily constructed, to

meet the requirement of different utilities.

How scalable are the reactor designs? What is the minimum feasible size and maximum size in terms of power output?

The philosophy of HTR-PM is to setup different size of plant based on standardized NSSS modules.
HTR-PM has 2 NSSS modules.
HTR-PM600 with 6 NSSS modules are also designed already, just with 6 standard NSSS modules to be connected to one steam turbine.
Different power level can be easily achieved through duplication of standard NSSS modules.

Are there any specific siting requirements, considering emergency planning zone, improved safety (underground construction, passive cooling etc.)?

Because of the inherent safety features of modular HTR, HTR-PM-like plant has very wide flexibility for site selection.
Chinese Nuclear regulatory agreed already that HTR-PM technically do not need emergency plan zone.

Are the reactor components, systems amenable to factory fabrication to reduce on-site construction/assembly work?

HTR-PM has achieved standard design of the main component. The modular construction can be improved further based on the experience of HTR-PM. Design of HTR-PM600 shows better modular construction approach already.

D2.3: Product Flexibility

Describe the product flexibility of the reactors designs under development within your SSC?

Currently HTR-PM is designed to generate electricity through steam cycle.
This design can be easily extended to co-generation mode by extract the steam in different temperature range from different stages, for different purpose.
Increase of outlet helium temperature is possible with almost same reactor design, just to connect with helium turbine, IHX then to hydrogen Production facility or other process heat application facilities.
Because of the inherent safety features, HTR has the advantage to be located close to end-user, this is very important for process heat application, beside it provide very wide range of temperature output.

Does the reactor design enable additional process heat applications that are not possible with currently deployed reactors? What is the maximum temperature at which the process heat can be supplied to potential industrial user? Are the equipment for heat transfer included in the R&D/design effort? Are there any specific process heat applications (e.g. hydrogen production) already identified? Are the reactors capable of producing specific medical or industrial isotopes based on the neutron flux in the reactor core?

Taking HTR-PM as example, current technology of HTR can output temperature up to 950C, which is verified in AVR in Germany and HTTR in Japan. This temperature range can be used for many applications efficiently, including Hydrogen Production, Gas Turbine, Steam Turbine, and process application based on high temperature steam. Up to now the outlet temperature from HTR is highest, and is demonstrated already.
Outlet temperature more than 1000 C is also possible in future. This will increase the efficiency of process heat application.

D.3: Opportunities for Cost Reduction of NPP

Describe the cost reduction aspects on the reactor designs being pursued in your SSC.

Although the size of component in HTR is relatively larger than other type of reactor, but the simplification of safety system can compensate some of them.
The batch construction, the modular construction can reduce the cost.
The idea to design a large plant with many standard NSSS modules, such HTR-PM and HTR-PM600, can reduce the cost, especially the indirect cost.
Finally, regulatory oversite during construction is a major cost factor. Modifying and streamlining regulatory oversite during construction is actively being considered by Framatome and other advanced reactor designers in the U.S.A.

Are there any modularization opportunities? Are the components and systems amenable for factory production ad assembly? Are there features that reduce on-site assembly/construction of components and systems?

Modular HTR has great potential for modularization.
HTR-PM600 with 6 NSSS modules is a good example of modularization, with 6 identical NSSS modules to be connected with one steam turbine. The standardization of the NSSS module has a great opportunity for cost reduction.
The reactor building can also be constructed with modular concept. This will reduce the construction time then the construction cost.

Are there design features that reduce equipment costs – including advanced instrumentation and control technologies, advanced construction materials (steel, concrete), advanced power conversion cycle etc?
Based on experience of design and construction of HTR-PM, and experience to design new HTR-PM600, we found many chance to improve the design, to reduce the cost. Simplification, safety, standardization, multiple module, optimization on the safety classification of the component, optimization of fuel fabrication, there are many area to be optimized.
Are there advanced siting options to reduce construction and licensing costs – including seismic isolation, below grade construction etc.?
Modular HTR do not need large emergency plan zone. Modular HTR can be located near the end user center. Modular HTR can be located in formal fossil power plant. The fact that more sites can be selected also means more market opportunities and less cost.

VHTR JAEA (GTHTR300)
D2: Flexibility
D2.1: Operational Flexibility
Describe the maneuverability of the reactor design(s) being pursued in your System Steering Committee to match the external conditions? Please refer to Figure 1 for a concept of flexible operation over a 24-hour cycle.
The GTHTR300 is a VHTR power generation plant designed by JAEA. The GTHTR300 will vary power from 100% to 30% at constant power generation efficiency by fully utilizing the characteristics of closed cycle helium gas turbine. Dynamic modulation for ±20% variation can be accomplished by using large core thermal capacity without sacrificing efficiency and availability. The GTHTR300C is a VHTR cogeneration plant designed by JAEA. The GTHTR300C can vary power from 100% to 50% at constant reactor thermal power and power generation efficiency by assigning heat to process heat application. The reactor power will be reduced by 30% to meet the generator load of 30% without varying power generation efficiency. Dynamic modulation for ±20% variation can be accomplished by using large core thermal capacity without sacrificing efficiency and availability. The GTHTR300C can change the level of power generation rate in accordance with various types of load variations induced by intermittent renewables. Such capability is described is the following: - H. Sato, and X. L. Yan, Study of an HTGR and Renewable Energy Hybrid System for Grid Stability, Nuclear Engineering and Design, Vol.343, pp.178-186 (2019).
What are the ramp-rates (%/min) being considered for the designs?
The ramp-rates considered in the GTHTR300 and GTHTR300C are 5%/min.
What is the minimum power level (% power) achievable? How long (hours) can it be sustained?
The GTHTR300 and GTHTR300C can operate reactor thermal power of 25% without limitation on duration.
Is the system capable of providing primary frequency control (automatic power modulation based on external frequency control signal)?
Yes. The GTHTR300 and GTHTR300C can automatically regulate power by external signal using a governor with a combination of inertia of gas turbine.
What is the extent of power modulation (e.g. 5% in Figure 1) for secondary frequency control?
The GTHTR300 and GTHTR300C can accommodate ±20% variation for frequency control by using large core thermal capacity without sacrificing efficiency and availability.
Is the operational flexibility validated through multi-dimensional physics calculations?
Operability of GTHTR300C is confirmed using point kinetics model because CR rod movements during the operation is negligible and neutron flux distribution will not be distorted.
Are the reactor designs in your SSC, compatible for integration with hybrid systems with energy storage, topping cycles and/or co-generation using thermal energy? Are there any analyses performed for dynamics of power conversion system?
The GTHTR300C cogenerates electricity and second product such as hydrogen. In accordance with electricity demand variation, the second production amount is varied with fixed reactor thermal power. Dynamics of the GTHTR300C was analysed, and feasibility of operability was demonstrated. The following paper describes the detail: - H. Sato, and X. L. Yan, Study of an HTGR and Renewable Energy Hybrid System for Grid Stability, Nuclear Engineering and Design, Vol.343, pp.178-186 (2019).
Are there specific R&D being done to address material and component degradation resulting from flexible operation of reactor and power conversion system?
Specific R&Ds to enable flexible operation are not needed for the GTHTR300C.
Describe fuel flexibility aspects of reactor designs in your SSC. Are alternate fuels being considered?
All the VHTR uses coated fuel particles. VHTR can use may fuel types, e.g. UC2, PuOX, (Th, U)C2, MOX, (Th, U)O2, UO2, UCO, etc. without changing basic specification of the particles.
Are the reactors capable of operation in island mode; isolated from regional grid network?
Yes. The feasibility of operation in island mode for the GTHTR300C is validated by dynamic simulation. The results can be found in the following:

- X. L. Yan, et al., Evaluation of high temperature gas reactor for demanding cogeneration load follow, Journal of Nuclear Science and Technology, Vol.49, No.1, pp.121-131 (2012).

D2.2: Deployment Flexibility

Describe the deployment flexibility aspects of reactor designs in your SSC. Specific questions to consider while describing your systems are as follows.

No response.

How scalable are the reactor designs? What is the minimum feasible size and maximum size in terms of power output?

A single unit VHTR plant can be scalable from 10MWth to 600MWth (3MWe*1-300MWe*2).

- 1:HTR-10: H. R. Kim, GIF's Activities on Research Infrastructure, 11th GIF-INPRO/IAEA Interface Meeting, IAEA HQ, Vienna, Austria, 20 February 2017.
- 2: GTHTR300: H. Sato et al., GTHTR300 – A nuclear power plant design with 50% generating efficiency, Nuclear Engineering and Design, Vol.275, pp.190-196 (2014).

Are there any specific siting requirements, considering emergency planning zone, improved safety (underground construction, passive cooling etc.)?

There are no special requirements for VHTR siting. There are designs with inland installation, underground construction, above ground construction.

Are the reactor components, systems amenable to factory fabrication to reduce on-site construction/assembly work?

Yes. Some VHTR vendors have activities to shorten construction period by modularization of main components in factory fabrication.

D2.3: Product Flexibility

Describe the product flexibility of the reactors designs under development within your SSC?

The GTHTR300C can produce multiple products including hydrogen, high temperature steam, etc. Other cogeneration applications including district heating and desalination are possible without sacrificing the power generation by using waste heat in intrinsic cycle characteristics. The following papers describe the details:

- X. L. Yan, et al., Study of a nuclear energy supplied steelmaking system for near-term application., Energy, Vol.39, pp.154-165 (2012).
- X. L. Yan et al., Study of an incrementally loaded multistage flash desalination system for optimum use of sensible waste heat from nuclear power plant, International Journal of Energy Research, Vol.37, No.14, pp.1811-1820 (2013).

Does the reactor design enable additional process heat applications that are not possible with currently deployed reactors? What is the maximum temperature at which the process heat can be supplied to potential industrial user? Are the equipment for heat transfer included in the R&D/design effort? Are there any specific process heat applications (e.g. hydrogen production) already identified? Are the reactors capable of producing specific medical or industrial isotopes based on the neutron flux in the reactor core?

Yes. VHTR can provide heat around 900°C to process heat users which enables extend the use of nuclear heat to a wider spectrum of industrial applications.
R&Ds for heat transport system including high temperature components, e.g. intermediate heat exchangers, co-axial piping, and heat resistance materials, e.g. Hastelloy XR, etc. have been conducted and demonstrated in the HTTR, a test reactor constructed in JAEA Oarai site.
High efficiency hydrogen production is one potential application for VHTR. Temperature range of process heat is also compatible to various industrial process such as Gas-to-liquid process for production of synthetic fuels.

D.3: Opportunities for Cost Reduction of NPP

Describe the cost reduction aspects on the reactor designs being pursued in your SSC.

According to our study, recent increase in construction cost is largely due to additional requirements to quality control for component manufacturing and procurement. The level of quality control depends on safety classification of structures, systems and components. VHTR design highly relies on inherent safety features and therefore has potential to reduce excessive requirement by using risk-informed and performance-based approach for the safety classification of SSCs.

Are there any modularization opportunities? Are the components and systems amenable for factory production ad assembly? Are there features that reduce on-site assembly/construction of components and systems?
Yes. Some VHTR vendors have activities to shorten construction period by modularization of main components in factory fabrication.
Are there design features that reduce equipment costs – including advanced instrumentation and control technologies, advanced construction materials (steel, concrete), advanced power conversion cycle etc?
Yes. VHTR can use direct Brayton cycle power conversion systems. The use of the cycle offers high power generation efficiency (50.4% at 950°C TIT) and enables to reduce cost related to components required for Rankine power conversion systems, steam generators, etc. A large cost credit for power generation can be obtained by the efficient waste heat recovery of the reactor gas turbine power conversion cycle, e.g. seawater desalination. The system design and economics of GTHTR300 is described in the following: - H. Sato et al., GTHTR300 – A nuclear power plant design with 50% generating efficiency, Nuclear Engineering and Design, Vol.275, pp.190-196 (2014). - X. Yan et al., GTHTR300 cost reduction through design upgrade and cogeneration, Nuclear Engineering and Design, Vol.306, pp.215-220 (2016).
Are there advanced siting options to reduce construction and licensing costs – including seismic isolation, below grade construction etc.?
The GTHTR300 reactor system locates below grade and therefore it may contribute to reduce licensing cost. In addition, the GTHTR300C can use dry cooling efficiently and enables to site in inland area without sacrificing economics, hence the licensing cost related to water related safety events, e.g. Tsunami, flooding, etc can be reduced. The following paper describes the detail for the system design using a dry cooling system. - X. L. Yan et al., Evaluation of GTHTR300A nuclear power plant design with dry cooling, International Journal of Energy Research, Vol.38, No.11, pp.1467-1477 (2014).

VHTR (KAERI (NuH2))
D2: Flexibility
D2.1: Operational Flexibility
Describe the maneuverability of the reactor design(s) being pursued in your System Steering Committee to match the external conditions? Please refer to Figure 1 for a concept of flexible operation over a 24-hour cycle.
VHTR system is well suited for the flexibility operation in the Figure 1 due to the safety from high thermal inertia of reactor core. However, the load following operation based on co-generation such as electricity/hydrogen is recommended to increase availability and economics.
What are the ramp-rates (%/min) being considered for the designs?
The NuH2 (Nuclear Heat and Hydrogen system) is a HTGR concept developed by KAERI. The ramp-rates are considered 5%/min in the NuH2 concept.
What is the minimum power level (% power) achievable? How long (hours) can it be sustained?
The minimum power level of NuH2 concept is considered reactor thermal power of 25%.
Is the system capable of providing primary frequency control (automatic power modulation based on external frequency control signal)?
The design can be done by user's requirement. There is no obstacle to such control.
What is the extent of power modulation (e.g. 5% in Figure 1) for secondary frequency control?
It depends on the design of power conversion system. The 5% of secondary frequency control can be acceptable in a way of bypass flow control of stream in Rankine cycle or helium in Brayton cycle.
Is the operational flexibility validated through multi-dimensional physics calculations?
It will be determined using point kinetics model and/or neutronics-system coupling codes.
Are the reactor designs in your SSC, compatible for integration with hybrid systems with energy storage, topping cycles and/or co-generation using thermal energy? Are there any analyses performed for dynamics of power conversion system?
No response.
Are there specific R&D being done to address material and component degradation resulting from flexible operation of reactor and power conversion system?
Not considered yet. If co-generation is applied, degradation of material or component will be limited to power conversion system itself. But these are not critical ones for the reactor safety. Thus specific R&D is not necessary for the co-generation system of VHTR.
Describe fuel flexibility aspects of reactor designs in your SSC. Are alternate fuels being considered?
No response.
Are the reactors capable of operation in island mode; isolated from regional grid network?
No response.
D2.2: Deployment Flexibility
Describe the deployment flexibility aspects of reactor designs in your SSC. Specific questions to consider while describing your systems are as follows.
No response.
How scalable are the reactor designs? What is the minimum feasible size and maximum size in terms of power output?
The VHTR can be designed from 10MWth to 600MWth in a unit.
Are there any specific siting requirements, considering emergency planning zone, improved safety (underground construction, passive cooling etc.)?
There are no specific requirements for site of NuH2 but underground construction is recommended for a passive safety of air-cooled RCCS (natural cavity cooling system).
Are the reactor components, systems amenable to factory fabrication to reduce on-site construction/assembly work?
The VHTR can be designed for a modular concept of construction.

D2.3: Product Flexibility
Describe the product flexibility of the reactors designs under development within your SSC?
The NuH2 system considers co-generation of electricity/high temperature steam or hydrogen production.
Does the reactor design enable additional process heat applications that are not possible with currently deployed reactors? What is the maximum temperature at which the process heat can be supplied to potential industrial user? Are the equipment for heat transfer included in the R&D/design effort? Are there any specific process heat applications (e.g. hydrogen production) already identified? Are the reactors capable of producing specific medical or industrial isotopes based on the neutron flux in the reactor core?
The high temperature process heat (750~900C) can be used for LNG steam reforming for synthetic gas production and methanol production, and for the conversion of coal to hydrocarbon liquid fuel.
D.3: Opportunities for Cost Reduction of NPP
Describe the cost reduction aspects on the reactor designs being pursued in your SSC.
No response.
Are there any modularization opportunities? Are the components and systems amenable for factory production ad assembly? Are there features that reduce on-site assembly/construction of components and systems?
No response.
Are there design features that reduce equipment costs – including advanced instrumentation and control technologies, advanced construction materials (steel, concrete), advanced power conversion cycle etc?
No response.
Are there advanced siting options to reduce construction and licensing costs – including seismic isolation, below grade construction etc.?
No response.