Alliance Nationale de Coordination de la Recherche pour l'Énergie

Decarbonization Wedges Exercise

December 2015 – www.allianceenergie.fr

GENERATION 4 NUCLEAR REACTOR TECHNOLOGIES

1. State of the art and current development in different world regions

Gen-4 fast neutron reactors can convert U238 —which makes up 99.3% of natural uranium— into plutonium, which is a fissile element. This is why Gen-4 fast neutron reactors with a multiple recycling of plutonium are considered a key technology for a durable development of nuclear power worldwide. Fast neutron reactors with a closed nuclear fuel cycle also have the capability to burn transuranic elements (plutonium and minor actinides which make up a few 0.1% of the spent fuel content and bear most of the medium- and long-term burden of radwaste decay heat and radiotoxicity), thus enabling to minimize the high level radioactive waste to be ultimately disposed of.

Gen-4 nuclear systems include three types of fast neutron reactors with a closed fuel cycle:

- **Sodium Fast Reactors (SFR)**, which are the most mature and best available technology among fast neutron reactors today: almost all experiments and prototypes of fast neutron reactors that have been built so far (in Europe, in Russia, in the U.S.A., etc.) are based on this technology;
- **Gas Fast Reactors (GFR)**, which inspired large projects in Europe (Gas Breeder Reactors (GBR) and in the U.S.A. (Gas-Cooled Fast Reactors (GCFR): there are no built reactors; it is considered as a long term option;
- **Lead Fast Reactors (LFR)**, which are based upon the experience of Lead-Bismuth cooled reactors for the Alpha —class submarines in Russia are also considered a long term option.

Gen-4 nuclear systems encompass three other types of reactors that may pave the way to the nuclear future in the 21st century and beyond:

- **Very-High-Temperature Reactors (V/HTR)** that build upon the experience of High Temperature Reactors gained in Europe and in the U.S.A.: the goal is to enable electricity generation with a high energy conversion efficiency and to supply high temperature heat for industrial processes;
- **SuperCritical Water Reactors (SCWR)**, which are tentatively based on the extended experience acquired on Light Water Reactors (LWR): the goal is to improve their performance in terms of compactness and efficiency;
- **Molten Salt Fast Reactor (MSFR)** and other molten salt-based reactors that operate at high temperature and low pressure and may allow for an online on-site processing of the fuel salt.

Among these systems, only the SFR and the V/HTR may be broadly deployed enough to play a sizeable role in cutting CO_2 emissions by 2050: SFRs should supplement LWRs to use uranium more efficiently, and V/HTR should displace fossil fuels currently used to supply process heat to the industry. Russia, India and China currently have the most aggressive plans for developing fast neutron reactors. Other Gen-4 concepts are too prospective in this respect to really have a foreseeable impact. However it is important that research keeps on focusing on all those systems to achieve durable CO_2 emissions reduction through nuclear power over centuries and expandable beyond the sole generation of electricity.

2. Maturity level and technological perspectives

Maturity of elementary technologies associated with Gen-4 reactors

Methodological information:

The maturity level is the TRL, reduced to 5 levels with market deployment enclosed in the higher TRL classes; maturity level scaling: 0 = none; 1 = fundamental research; 2 = R&D; 3 = demonstrator; 4 = low deployment; 5 = large deployment.

	2015	2020	2030	2040	2050
SFR	3	3	3	4	5
GFR	2	2	3	3	4
LFR	2	2	3	3	4
V/HTR	3	3	3	4	5
SCWR	1	2	2	3	3
MSFR	1	1	2	2	3

The timescale for a progressive deployment of Gen-4 fast neutron reactor technology and a worldwide commercial deployment of this Gen-4 technology will be mostly driven by the rise of natural uranium price generated by the expansion of the world nuclear capacity, possibly around the middle of the 21st century. Such reactors are expected to be marketed only in major nuclear countries that master all steps of the nuclear fuel cycle. When this technology is ready to be marketed, a limited number of fast neutron reactors (i.e. 10% to 20% of total nuclear capacity) may be deployed to manage actinides and to minimize the decay heat and radiotoxicity of high-level radioactive waste from existing LWR fleets.

Medium-term deployment —first commercial prototypes are scheduled for 2035-2040 onwards— can be achieved with SFRs. Other Gen-4 fast neutron reactors require longer lead-times so that their commercial deployment is not expected to occur before 2050. Other than that, GFRs and LFRs need innovations in the research field, so that their time to market is likely to be at least 20 years longer than that of SFRs.

Unlike fast neutron reactors, which benefit from institutional support for research and development as they are expected to durably support nuclear power, high temperature reactors (V/HTR) are seen as dedicated to meet market needs and therefore are required to have their research and development partly cofounded by potential user industries.

Potential development of technologies associated with Gen-4 reactors

Methodological information:

Potential development is measured as the percentage of the technology's contribution to environmental protection. This means evaluating, in terms of carbon emissions and of carbon emissions reduction, to what extent this new technology can contribute to limiting temperature increase to 2°C above pre-industrial level according to the time horizon considered in this study. Potential development scaling: 0 = not significant; 1 = significant (i.e. more than 1% of global emissions reduction) in some countries; 2 = significant on the global scale; 3 = very significant on the global scale (i.e. up to 3% of global emissions reduction); 4 = major technology vs. climate change (i.e. more than 3% of global emissions reduction).

	2020	2030	2040	2050
Gen-4	0	0	0	1

The overall impact of Gen-4 reactors for cutting CO_2 emissions is not expected to become significant before 2050.

3. Technological, economic and social bottlenecks

Methodological information:

The following table ranks the bottlenecks according to their impact on the development of the technology. A bottleneck ranking at 6 on the scale will hinder or stall the deployment of the technology compared with bottlenecks ranking at 1; conversely, a bottleneck ranking at 1 will hinder the deployment of the technology much less than bottlenecks ranking at 6. Note that the ranking is relative, meaning that a bottleneck ranking at 6 is not necessarily hard to remove; conversely, a bottleneck ranking at 1 is not necessarily easy to remove. Technologies rank according to: research, finance, regulations, resources & environment, security and acceptability. The table also contains keywords associated with each bottleneck.

It must be stressed that the ranking of such different factors must be considered with caution; as an expert's judgement, not a quantitative assessment.

Technology		**Research & technological bottlenecks**	**Economy and financial bottlenecks** (investment, risks)	**Regulation & institutional environment**	**Resources & environmental impacts** (including scarcity of raw materials, water, land, climate)	**Safety & security** (impacts on health, people and security assets)	**Socio-technical feasibility**
Sodium Fast Reactor (SFR)	Rank	2	3	4	1	5	6
	Key-words	Research for enhanced safety and commercial viability	Moderate (based on proven technology but still subject to tightening of safety rules)	Nuclear regulations on safety and security (physical protection & non-proliferation)	No need for uranium mining	Specific safety case	Specific manufacturing capabilities Possible focus on opposition to nuclear power
Very/High Temperature Reactor (V/HTR)	Rank	1	2	4	3	6	5
	Key-words	Research for a new generation of V/HTR with heat supply capabilities and commercial viable	Moderate (based on proven technology)	Nuclear regulations on safety and security	Comparable to LWRs with regards to natural Uranium consumption	Specific safety case	Specific manufacturing capabilities

Considerations on financial aspects are closely dependent on the economic system: 'free' market or 'centralized' economy. First fleets of fast neutron reactors are expected to deploy in centralized economy countries: e.g. Russia, China, India, etc.

Gen-4 reactors require specific manufacturing capabilities as they use distinct materials and services from those implemented for LWRs: spent fuel reprocessing and actinide bearing fuels manufacturing plants for fast neutron reactors, graphite and 10-20% enriched uranium production for high temperature reactors, etc.

4. Potential radical and incremental innovations

Methodological information:

The following table lists the nature of innovations needed to overcome the bottlenecks mentioned earlier. There are two types of innovations: I stands for 'incremental innovation' (i.e. improving existing products and processes) and R stands for 'radical innovation' (i.e. developing new products and processes).

Technology		**Research & technological innovations**	**Economy and financial bottlenecks** (investment, risks)	**Regulation & institutional environment**	**Resources & environmental impacts** (including scarcity of raw materials, water, land, climate)	**Safety & security** (impacts on health, people and security assets)	**Socio-technical feasibility**
Sodium Fast Reactor (SFR)	I or R	I-R	I	I-R	I-R	I-R	I-R
	Key-words	Incremental & Targeted innovations (Core design, power conversion, instrumentation…)	Moderate (reactor type mainly based on proven or incrementally improved technologies)	Safety and security regulations subject to incremental & potentially breakthrough innovation	No need for uranium mining Deployment subject to availability of plutonium from LWR spent fuels Dedicated plants required for used fuel reprocessing and fresh actinide fuel manufacturing	Incrementally improved & Innovative safety features Closed fuel cycle with appropriate non-proliferation provisions	Incrementally evolved manufacturing techniques
Very/High Temperature Reactor (V/HTR)	I or R	I-R	I-R	I-R	I-R	I-R	I
	Key-words	Incremental & Targeted innovations (Fuel, passive safety systems…) New materials	Moderate (reactor type mainly based on proven or incrementally improved technologies) Innovative business model for heat users	Safety and security regulations subject to incremental & potentially breakthrough innovation	Dedicated plant required for Uranium enrichment (10-20%) Specific front-end workshop for used fuel reprocessing	Incrementally improved & Innovative safety features Specific safety case of collocated reactor and heat user industry	Incrementally evolved manufacturing techniques

A broader recognition by governments of the long-term benefits of Gen-4 reactors —fast neutrons for enhanced Uranium use and actinide management, high temperature supply for process heat, etc. —, together with an enhanced political and financial support of the R&D needed to advance the required reactor and fuel cycle technologies could speed-up the building of demonstrators, prototypes with associated fuel cycle facilities, and thus accelerate the market readiness. Creating public-private partnerships between governments and industry is also essential to fund these graduated demonstration facilities.

International cooperation is key to share costs of R&D and potentially also costs of technology demonstrators with selected industrial partners. Furthermore promoting internationally harmonized codes and standards, as well as licensing rules, together with sharing costs of R&D on novel safety and security features would also contribute to speed-up the access to the worldwide market.

The linkage and complementarity between Gen-3 advanced LWRs and Gen-4 fast neutron reactors should be better acknowledged both in terms of timeline and complementarity of nuclear fuel cycle. Gen-3 LWRs will bridge the gap between operating reactors (Gen-2) and Gen-4 reactors because of the lead time to develop radical technologies; Gen-4 fast neutron reactors with a closed fuel cycle will enable recycling actinides from LWRs (Gen-2&3) used fuels. Both types of reactors will then be capable to operate synergistically and sustainably in a mixed generating fleet.