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“Systems of the future”

CEA 31-33, rue de la Fédération 75752 Paris cedex 15 - Tel. : +33 (0)1 40 56 10 00

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The energy context and the challenges for future systems

Today's energy context calls for crucial adaptations to face up to the new socio-economic and international geo-strategic realities. There will be heavy pressure on global energy and electricity demand as a result of population growth. At the start of this century the world had over 6 billion inhabitants and this figure is set to rise to about 8 billion in the 2020's.

Use of the world's energies will have to be readjusted during the 21st century to cope with the combined effect of the expected drop in oil and gas reserves, the need for universal access to inexpensive energy – essential for development – and the growing concern for environmental protection.

There should be room for nuclear energy in this readjustment as its fuel (uranium) does not suffer from the same limitations as oil or gas. It has richer stocks (250 years' worth of consumption in stock with the current systems used and several millennia when new technologies are harnessed), and their availability does not suffer from the same geo-political vagaries. It does not contribute to global warming in the way that the main greenhouse gas emitters, coal, oil and gas, do. The waste it produces is managed using today's best available technologies. Technical solutions have been devised to supplement the current mechanisms and the decision to implement them could be taken in the next few years.

The international community is aware of the challenges facing nuclear energy at the 2020-2030 dateline. Some ten countries have decided to pool their efforts to rise to the challenge of developing a new generation of nuclear systems[1] capable of contributing to a high-growth energy supply to meet the expected energy requirements for the next twenty years and beyond. The Generation IV International Forum is the key initiative working towards this.

Reactors used all over the world to generate electricity have witnessed constant improvements and technological breakthroughs since the beginning of the civilian nuclear industry in the 1950s. These breakthroughs are known as reactor "generations": today's working installations are "second generation" reactors. The main reactors are light (PWR) or boiling (BWR) water reactors in the United States, Europe and Japan, VVER (analogous to REP) and RMBK (boiling water in pressurised pipes) reactors in Eastern Europe and Candu reactors (heavy water reactors) in Canada and India.
A third generation of reactors is ready to take over by 2015 or even earlier for some (the Franco-German EPR, and the American AP1000 and ESBWR…). The "future systems" refer to the fourth generation that have yet to be designed, and aim to come on stream by 2040. CEA's research workers are working on developing these new systems in an international context, characterised by enhanced safety levels and cost-effectiveness and recycling capability of all fuels to recover the fissile materials (uranium, plutonium) and minimise the production of long-lived waste (minor actinides) by transmutation.

Against this background, research into future nuclear systems is being conducted:

- in a short-to-medium-term perspective on developing innovations for pressurised water reactors (REP), and
- in a medium-to-long-term perspective on developing new systems within an international framework (essentially the Generation IV Forum).

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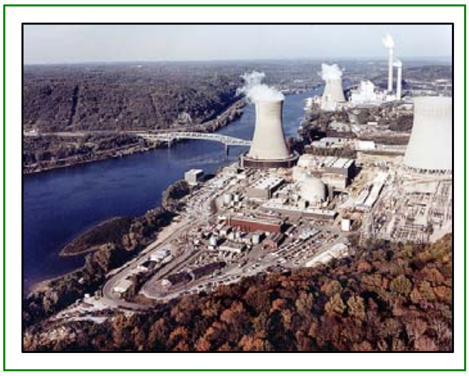
[1] The reactors and their associated fuel cycles are covered by the term system.

Nuclear energy's potential for generating electricity became apparent after the 2nd World War. Naturally the reactor designs adopted and used to meet these needs over the course of the years, were governed by the technologies available at the particular time, but the immediate priorities and constraints of the context played a large role in decision-making. Within these contexts that have changed considerably with time, four generations of reactors that have already been designed and developed or have yet to be designed, can be distinguished over a timescale of about a century.

From Generation I to Generation IV

Generation I includes the first prototype reactors (UNGG, Shippingport, Magnox, Fermi I), that were commissioned prior to 1970.
Generation II corresponds to the first commercially operated reactors from 1970 - 1995 using various technologies: PWR, BWR, VVER and Candu.
Generation III corresponds to the advanced reactors: ABWR, AP600, EPR, AP1000 and even the modular HTR. This generation is likely to come on stream before 2015.
Generation IV comprises the future systems: most of the design work on the reactors and the fuel cycle is still ahead of us, and should be deployable by the 2040 dateline.

The first generation of reactors was largely limited by fuel cycle constraints, particularly in the 1950s-60s, firstly because uranium enrichment technology did not exist on an industrial scale, and secondly because a number of nations wanted to arm themselves with nuclear deterrent capability that called for the production of fissile materials. Accordingly reactors had to operate fuelled by natural uranium (unenriched), which entailed using moderators such as graphite or heavy water. This is how the technology known as Natural Uranium Graphite Gas (UNGG) came to be developed in France. The first three reactors (G1, G2 and G3) were geared to plutonium production, followed by six others to generate electricity (on the Saint Laurent, Bugey and Chinon sites). CEA was very highly involved in developing this technology, as the process licenser. The UK's Magnox reactors are part of the same generation. While these reactors offered useful characteristics for development on a broader scale (thermodynamic output, optimum uranium utilisation in the reactor core, etc.), they suffered from technology-related limitations: higher capital cost, safety improvement difficulties and extrapolation difficulties to higher outputs. This all had a generally adverse effect on their cost-effectiveness when compared to water reactors (PWR or BWR).



During this first phase, concerns about the **fuel cycle** considerations in terms of rational and sustainable use of natural resources (recycling the energy materials) and waste management were raised. As a result, fuel cycle back end processes and installations to reprocess spent fuel and recycle plutonium (i.e.: separation and recycling in the reactors) were developed. Thus from the outset France adopted the reprocessing-recycling-based fuel cycle, that improved resource usage and reduced the amount and long-term harmfulness of ultimate waste. The waste is conditioned in such a way as to ensure that the radionuclides are safely and durably confined. The first reprocessing plant, UP1 at Marcoule, for reprocessing UNGG fuel, was commissioned in 1958, followed by the UP2 plant at La Hague in 1966, which acquired a new shop (HAO) in 1976 for reprocessing spent fuel from pressurised water reactors. They have now been replaced by two plants at La Hague, UP3 (1989) and UP2-800 (1994). MOX (Mixed Oxide) fuel manufacturing facilities have also been developed and brought on stream: CFC at Cadarache (1968-2003), Dessel in Belgium (MOX fuel manufactured since 1986) and Melox at Marcoule (1995).

From the early days, the challenge to conserve natural fuel resources and optimise their use over the long term was taken up by the development of sodium-cooled fast neutron reactors, primarily in the United States (the Enrico Fermi reactor[2] in 1963), Russia (BOR 60 in 1968, BN 350 in 1972 and BN 600 in 1980[3]), and France (Rapsodie in 1967).

The second generation of reactors, that accounts for most of the world's current nuclear electricity generating capability, arose from the need to make nuclear energy more competitive and reduce energy dependence in certain countries in the 1970s when major tensions on the fossil energy market were making themselves felt.

Fissile material production for defence purposes was no longer a priority and the development of uranium enrichment by gaseous diffusion was completed and ready to be rolled out industrially on a wide scale (the EURODIF plant in France). During this period pressurised water (PWR) and boiling water (BWR) reactors were deployed. They make up over 85% of the world's current electricity-generating nuclear capability (about 450 reactors).
Industrial feedback over the last decades has borne out the economic and environmental performance of nuclear energy production with a per kWh cost that competes very keenly against fossil energies. Constant progress is being made on discharges that are already well down below the statutory limits. The accumulated global operation of over 10,000 reactor years proves that this technology has reached industrial maturity.
CEA has been a major player in Frenchifying Westinghouse's PWR technology in partnership with EDF and Framatome-ANP. The French nuclear electricity generating capability is entirely equipped with these reactors. Since then CEA, along with EDF and Framatome-ANP, have been working on R&D to support these plants, primarily to optimise operation by increasing installation availability and service life, and the burnup rate of the fuels used: UO_2 and MOX.

Alongside this effort, natural resource conservation concerns have prompted the pursuit of sodium-cooled fast neutron reactor development, mainly in Russia (BN 350 in 1972 and BN 600 in 1980[4]), France (Phénix in 1973, Superphénix in 1985) and Japan (Joyo in 1978 and Monju in 1994). Now India and China are also developing demonstrators of this design.

Although the forecasts for rapid industrial deployment of nuclear power did not materialise in the second half of the 20th century, fast neutrons' advantages for regeneration and minimising

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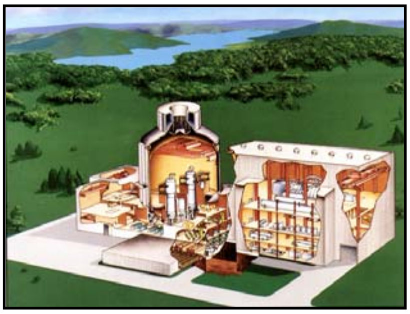
[2] 60 MWe
[3] BOR 60: 12 MWe.
[4] BN 350 = 350 MWe. BN 600 = 600 MWe.

the long-term radiotoxicity of waste are still valid for a new generation of nuclear systems that will contribute to sustainable energy policy. These aims are enshrined in the 4th generation system specifications, and therefore, the technological and industrial know-how acquired on the Phénix and Superphénix installations are vital for the development of fourth generation nuclear systems.

Research conducted on **third generation reactors** is mainly geared to optimising the economics and safety of water-cooled reactors to improve on the performance levels offered by reactors currently in operation. The main innovations relate to the safety architecture, with primarily, additional resort to "passive" systems and strengthened confinement.



Experience drawn from current reactor operations forms the basis for optimising their design. Considerable improvements are sought for in the following areas:

- safety, with, for example, a metal-lined double-wall concrete containment vessel, a core catcher under the reactor core;
- economic competitiveness by increasing standardisation and simplifying the architecture;
- the fuel cycle with enhanced burnup and thus better use of the fuel;
- waste reduction.

The EPR (European pressurised water reactor), an Areva/Framatome-ANP project, is one of the third generation reactors. Research work on it at CEA it is geared to optimising fuel for multi-recycling of plutonium and reducing the production of radioactive waste.

Virtual view of the EPR reactor (European Pressurized water Reactor) circuits. (*Framatome-ANP)*

Several countries debated the new types of reactor at the end of the 1990s. The Generation IV International Forum, launched on the initiative of the United States, was the main initiative to pool these efforts, with the inclusion of main players France, Japan, the United Kingdom, Canada and South Korea. This forum has set itself the aim of selecting and developing a small number of nuclear systems (reactor and associated fuel cycle) that offer the most promising technologies to meet the requirements of the international market by the 2040 dateline. These **fourth generation** systems not only aim to produce electricity but also other applications such as hydrogen production from water, synthetic fuel production for transport, heat production for industry and desalinating water.

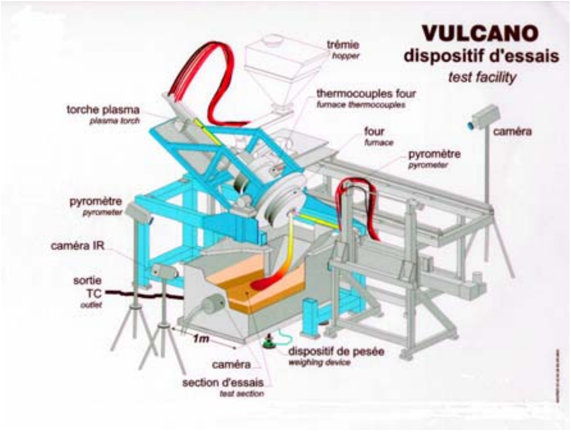
R&D on 3rd generation reactors

The notion of safety is central to the design of 3rd generation reactors. The Three Mile Island accident that occurred in the United States in 1979, caused major damage to the reactor core but had relatively minor radiological consequences for the environment. Research workers all over the world drew lessons from this accident, and have been working on improving safety with four main objective that have structured their research:

- minimising dose rates during operation;
- using passive systems to make safe from accidental situations;
- reducing the probability of core meltdown;
  - by reducing the probability of initiating events occurring,
  - by improving the reliability of backup systems,
- limiting the consequences outside the site in a serious accident situation, primarily by strengthening containment.

Thus CEA research workers are studying both the potential initiators and the phenomenology of the most serious accidents that could occur in order to improve the safety of third generation reactors, even if the probability of their occurrence is very low or hypothetical. The hypothesis retained for PWR reactors is core cooling failure leading to temperatures likely to damage the fuel element. "Corium", a mixture of fuel and materials, could then form, and flow through the internal structures to the bottom of the reactor vessel, and eventually cross it and spread onto the reactor building floor.

CEA has embarked on a major programme to characterise corium and its behaviour to study and limit the consequences of its phenomenology. The ultimate aim is to control core cooling in any condition to guarantee its long-term containment. Research workers are using dedicated facilities for these studies, primarily the Vulcano facility comprising a furnace that can rise to 3000°C.



They are also studying the best solutions to guarantee nuclear material containment integrity and prevent the release of radioactive products into the environment. These studies cover hydrogen production and transport phenomenology, and deflagration risks and conditions. Hydrogen recombiners and containment spray circuits are used in the research vessel to reduce pressure and avoid the loss of integrity.

The Generation IV International Forum and INPRO

The objectives set out for future systems and the choice of key technologies to achieve them are actively discussed in the international arena, particularly through the Generation IV International Forum.

The origin of the Forum

After the American Department of Energy (DOE) informed its government of the risks of shortages and medium-term energy reliance, the Government has embarked on an effort to reactivate the electricity-generating resources. Its commitment breaks down into two complementary initiatives in the field of nuclear energy:

- the first, purely American, the Nuclear Power 2010 program (NP2010),aims to make new reactor construction easier in the short term (2010) in the United States. An ad hoc group, the Near-Term Deployment Group (NTDG) has assessed the reactors likely to be built by 2010, identified any technical, statutory or administrative problems to be solved, and suggested initiatives to ease short-term deployment of these third generation nuclear reactors.
- The second is the Generation IV International Forum (GIF). Its guiding principle is that its ten member countries acknowledge the advantages that nuclear energy offers for meeting the world's growing energy requirements, mindful of sustainable development and preventing climate change-induced risks. This principle is enshrined in the Forum’s Charter and is expressed as the common wish to create an international R&D framework. The community of Euratom member states are also members of this Forum. Other countries and international bodies may eventually join in on this research effort.

Technological orientation selection methodology

A Policy Group presides over the Forum’s activities. Today high-level representatives from the ten member countries are included in this organisation. It supervises all the projects and guides them in keeping with its political vision. The following stages have already been completed:

- the assessment, based on highly coded methodology, of the designs proposed by the participating countries (completed between April 2001 and April 2002).
- the selection of a few designs founded on technologies deemed particularly promising during the assessment (completed in May 2002).
- the drawing up of a development plan for these technologies, published in October 2002, in preparation for a subsequent international cooperation phase (the main purpose of the Forum since October 2003).
- The signing of system-agreements between the main countries in 2005 defining the intellectual property right rules applicable for future developments.

From the outset strong convergence was reached on the main Generation IV programme goals and approach. Each country remains free to choose its own options and programmes for future systems. Four main goal areas were defined to characterise future systems. They will have to be simultaneously:

- sustainable: that is sparing with natural resources and environmentally-friendly (by minimising waste production in terms of radiotoxicity, mass, residual output, etc.);

- economical: in terms of the investment cost per installed kWe, fuel cost, installation operating cost, and consequently, the per kWh production cost which must be competitive in relation to other energy sources;
- safe and reliable: with research for progress over current reactors, and by eliminating as much as possible the need to evacuate the population outside the site regardless of the cause or gravity of the accident;
- proliferation resistant and likely to be easily protected against external attack.

Some one hundred engineers and research workers took part in the first phase of the Forum's work, which resulted in the publication of a development plan, for the technologies deemed the most promising in October 2002. The plan is poised to serve as the basis for international cooperation between the member countries of the Forum and beyond.

For each technology being considered (water-, gas-, liquid metal-cooled reactors…) technical groups were assigned to assess the fitness of the various designs put forward to the adopted goals and criteria, and to draw up R&D plans for the designs once selected. A specific working group developed and refined the assessment methodology, allotting some thirty or so basic criteria to the four targeted progress areas described above. A co-ordination group supervised all the technical groups in their work and ensured that the findings were incorporated into the stage documents and final summary.

The Forum's choices

The selection of the most promising designs for future systems was finalised during a Policy Group meeting in May 2002 in Paris.

Six nuclear systems were selected, that will enable considerable advances to be made on sustainable energy development, economic competitiveness, safety and reliability, and resistance to proliferation and external attacks. These systems also support other applications besides electricity generation, such as hydrogen production and water desalination.
The reason why there is no one single Generation IV system, but a range of solutions on which the R&D efforts of the Forum's member countries are now focused is that the needs to be covered and the international contexts are diverse.

⇨The six selected systems

- VHTR - Very High Temperature Reactor (1000°C/1200°C), helium-cooled, dedicated to hydrogen production or hydrogen/electricity cogeneration;
- GFR Gas-Cooled Fast Reactor system - helium-cooled fast reactor;
- SFR Sodium-Cooled Fast Reactor system - sodium-cooled fast reactor;
- LFR Lead-Cooled Fast Reactor system - lead alloy-cooled fast reactor;
- SCWR (Super-critical Water-Cooled Reactor system) – super-critical water-cooled reactor;
- MSR Molten Salt Reactor system – molten salt fuel reactor.

France has expressed its primary interest to the Generation IV International Forum, in the advanced very high temperature gas-cooled (VHTR) systems or fast neutrons with complete actinide recycling (GFR) systems, for sodium-cooled fast neutron reactors (SFR) and secondary interest, resulting in reduced commitment, to the supercritical water-cooled (SCWR) and the molten salt reactor (MSR) system.

INPRO

In 2002, the International Atomic Energy Agency (IAEA) launched the **INPRO** (International Project on Innovative Nuclear Reactors and Fuel Cycles) project, which aims to promote the development of innovative nuclear systems that will meet future energy requirements to be met while upholding the aims of economic competitiveness, safety, environmental-friendliness, proliferation resistance and acceptance by the public.

The point of this project is to guide and supplement technological developments such as those being carried out under the Generation IV framework, wherever the IAEA may have specific input, for example by enabling many countries to take part, primarily developing countries that have not started using nuclear energy, but are interested in doing so, or through its non-proliferation competences and international monitoring.

Firstly (phase 1), the project's technical aims are to:

- identify, over a very broad base, the countries' needs and objectives given their diverse situations, and to specify how innovative nuclear systems can contribute to meeting them;
- define the criteria and methodologies for analysing and comparing the various innovative reactor designs.

Secondly (phase 2), the Agency envisages that the project will expand on the criteria definition and the assessment methodology for new reactor designs or projects and fuel cycles to assist the Agency's member countries in their own analyses of the nuclear systems that best meet their requirements. The project does not aim to embark on technical R&S or reactor and innovative system development initiatives, in contrast to the Generation IV Forum.

It has 14 member countries (Argentina, Brazil, Canada, China, France, Germany, India, the Netherlands, Russia, South Korea, Spain Switzerland, Turkey, United States plus the European Commission. It has been funded to date by voluntary contributions from these countries and does not draw on the IAEA's ordinary budget.

Bilateral co-operation

Bilateral co-operation initiatives with the United States, Japan and Russia were redefined in 2001 to make more allowance for common studies and developments on sodium- and gas-cooled fast neutron reactor technologies, high temperature nuclear technologies for hydrogen co-generation and recycled fuel processing and refabrication procedures.

Co-operation with the United States since 2002 has led to work on fifteen common projects co-financed on these topics (NERI-International initiatives as part of CEA-DOE co-operation). In time, four of these five projects could eventually involve Generation IV co-operation.

Co-operation with Japan enables the research and development on sodium- and gas-cooled fast neutron reactors, specific technological developments (fuels, materials) on high or even very high temperature reactors, refining certain processes (hydrogen production), and the possibilities of experimenting on the HTTR experimental reactor to be shared with the JAEA agency.

France’s R&D strategy for nuclear energy in the future

Background

Allowance is made for several elements specific to France’s background in the strategic orientations for future nuclear systems . These include in the medium-to-long-term:

- **Making the most of the potential progress on water-cooled reactors**, resulting from:
  - the possible gains in cost-effectiveness, safety or plutonium management in EPR using new fuels,
  - gains in new projects likely to interest the international market for the low and medium (300-600 MWe) or very high (> 2000 MWe) output ranges, or
  - gains for a new generation of post EPT water-cooled reactors capable of offsetting the consequences of natural uranium enrichment through more efficient use of this resource.

- **Optimising the opportunities offered by the renewal of working nuclear installations:**
  - Renewal of the nuclear power plants envisaged by EDF with the replacement of at least half the current capacity by EPRs from 2020 onwards, and the possible introduction of fast neutron reactor technology from 2030-2040 to finish the renewal.
  - Upgrading or renewal of the reprocessing plant at La Hague from 2040,

- **Incorporating the consequences of implementing optimised radioactive waste management strategy** on the basis of French research findings in application of the 30 December 1991 Act. This primarily involves on-going R&D into reducing the amount and harmfulness of ultimate waste.

- **Research for however long is needed to make progress on establishing nuclear energy as one of the energies capable of meeting energy requirements in a sustainable and environmentally-friendly manner.** This advancement targets two additional areas to constant economic and safety improvements, that differ from those of water-cooled reactors:
  - Saving natural resources and minimal production of long-lived radioactive waste, through fast neutrons and fuel recycling.
  - The broadening of the scope of applications beyond electricity production, primarily fuel production such as hydrogen for transport, which, on the basis of current knowledge, uses very high temperature processes (>850°C) efficiently to break down water thermochemically or electrochemically.

These long-term objectives fall in line with those of the Generation IV International Forum, launched in 2000. France has actively contributed to their orientation, with CEA involvement along with some one hundred international experts. These long-term objectives should also take into account French and European experience of sodium-cooled reactors and to a lesser extent high-temperature gas-cooled reactors.

International consolidation of nuclear players, and likewise the resources that can be harnessed by all countries for new technology development costs, make it essential that any national strategy falls in line with the international context.

France's strategy for future systems

An R&D strategy balanced between the medium and longer terms (>2040) has been put forward for future systems that targets three complementary objectives based on forward-looking research conducted by CEA and its industrial partners:

- Research for **innovations in water-cooled reactors**,
- **Fast neutron systems with a closed fuel cycle** to support sustainable energy development through fast breeding, and manage all the actinides in the French nuclear power industry in time *(plutonium in critical reactors, and minor actinides in critical or sub-critical systems (ADS) as an option),*
- **Key technologies for nuclear hydrogen production** or the supply of very high temperature heat for industry *(very-high temperature thermal or fast neutron reactors, and water disassociation processes).*

The last two objectives clearly relate to the prospect of CEA and its industrial partners' becoming involved in the Generation IV Forum's international R&D programme on technologies that break away from water-cooled reactors, and bilateral co-operation with Russia. French R&D efforts for these innovations and co-funding possibilities of major research facilities or prototype reactors in France or Europe need to be redoubled.

The concentration of efforts in these three areas, results firstly from a strategic and technical analysis bearing in mind the specific elements of the French context, and secondly from the resolve to acquire the maximum number of intellectual property rights during the R&D phases.

Regardless of whether they involve reactors, fuel or fuel cycles, the contribution of basic research is essential for the achievement of the advances and breakthroughs sought for in the processes and technologies of future systems. The CNRS and universities that have been contributing to innovation and the analysis of forward-looking options for radioactive waste management for 15 years, are already providing significant input to the research for the future systems presented in this document. Over and above the on-going co-operative work on the physics of reactors, separative chemistry and materials for waste conditioning (as part of the CNRS PACE programme), CEA with its industrial partners and the CNRS have undertaken to extend the field of their co-operation to other key areas for future nuclear systems such as materials resistant to very high temperatures, the use of molten salts, primarily as coolants, high temperature electrolysis, thermal transfers…

There follow the major R&D issues motivated by the three strategic objectives, the allocation of financial resources and the main milestones and decisions to be taken.

R&D strategy by theme

Priority is very clearly given to **fast neutron systems with a closed fuel cycle (SFR and GFR)**.

At a lower, but significant level, there are the **very high temperature systems, capable of producing hydrogen (VHTR)**

The research effort will be increased in line with the demand by industrial partners on **water-cooled reactor innovations** and the exploratory effort on **molten salt reactors** will be pursued.

Fast neutron systems with a closed fuel cycle

- Fast neutron strategy

Against a background characterised both by:

- considerable feedback on sodium-cooled fast neutron reactors (Phénix, Superphénix), whose strengths and outstanding difficulties are well documented, and
- the confirmed interest, during the Generation IV International Forum's technological orientation phase of gas as another potential fast neutron reactor coolant with robust fuel technology,

CEA and its industrial partners have agreed to devise an R&D programme on fast neutrons along two parallel paths:

- research into innovations to solve the outstanding technological difficulties surrounding **sodium-cooled fast neutron reactors**, and
- basic developments on the specific technological obstacles of the **gas-cooled fast neutron system** (essentially fuel).

This strategy paves the way for:

- participating in the development of key technologies, with the available means, for a number of systems, that will primarily enable the choice of a rapid neutron system for the 2nd renewal phase of the French nuclear power plant base to be delayed until about 2015 (rather than having to prematurely take a stand on this issue), and

- making full use of Generation IV members' R&D potential for the next 10-15 years before having to select a technology.

The R&D strategy implemented on fast neutron systems also aims to:

- Enhance the expertise acquired in France and Europe on sodium fast reactors primarily to guide research for innovation and specify the objectives for a demonstrator by 2015-20,
- In co-operation with the various European, American and Japanese partners, remove the technological obstacles to gas fast reactors and create an international project of its technical demonstrator, the REDT.
- Similarly enhance the experience gained in research into advanced partitioning of minor actinides in the development of processes that will enable the overall management of French power plant actinides and ultimate waste and proliferation risk management to be optimised.

The R&D on 4th generation fast neutron systems also includes the development of **new processes for reprocessing** the **spent fuel** of the relevant systems involving at the least uranium and plutonium recycling and optionally all the actinides (uranium, plutonium and minor actinides). This last development underlies the development of fuels containing minor actinides, and grouped partitioning and co-management processes for minor actinides (such as the Ganex process derived from French research into advanced partitioning).

The dedicated application of fast neutron systems (critical or sub-critical) for transmutation calls for additional R&D requirements including:

- Technologies for fuels and/or targets with high minor actinide concentrations,
- Appropriate treatment processes for these fuels and/or targets, and
- The development of high-intensity, high-reliability proton accelerators and spallation targets for neutron production in the case of sub-critical systems.

All these requirements are covered by various 5th and 6th European RTD Framework Programme (FP5 & FP6) initiatives with extensions provided for in FP7.

- Sodium-Cooled Fast Reactor System (Sodium Fast Reactor (SFR))

The SFR benefits from considerable industrial reactor experience. The French partners aim to make the most of this experience and the R&D effort that they can muster for this purpose to provide guidelines for the research for innovations and define the objectives for an international prototype by the 2015-20 dateline.

Priority is accordingly given to:

- **design studies** to simplify the system and reduce the capital cost,

- fine-tuning more efficient **in-service inspection, maintenance and repair techniques**
- improving **serious accident prevention and the associated criticality risks**,

- developing **cycle processes** that make for co-management of at least uranium and plutonium if not all actinides (U, Pu and minor actinides) for increased resistance to proliferation risks, so that all actinides can be recycled, which calls for:
    - remotely operated "all actinide" **fuel manufacturing processes** on a shielded process line,
    - **spent fuel reprocessing** involving co-management of all actinides and re-manufacturing on a shielded process line (R&D comprising a major common core with those of other Generation IV Forum fast neutron cycles).

- Gas Fast Reactor (GFR)

The GFR is a highly innovative system that combines fast neutrons with high temperature. So far no demonstrator for this system has been constructed. A number of technological obstacles need to be removed and specific safety demonstrations provided to make it feasible including:

- **the fuel** technology that aims to transpose HTR fuel design functionalities to particle (confinement of fission products, resistance to very high temperatures, thermal conduction…),
- **the development of structural materials for the core** that will resist high temperatures and damage caused by fast neutrons,
- **accident situation management**, with active or short-term semi-passive systems, and passive systems using natural convection in the medium term,
- **the fuel cycle** whose processes must make for co-managed recycling of at least uranium and plutonium if not all actinides (uranium, plutonium and minor actinides) for increased resistance to proliferation risks, and co-managed total recycling of all actinides. This area of R&D has a major common core with those of other Generation IV Forum fast neutron cycles

and a common core with the R&D on the VTHR:

- **the technology of very high temperature helium circuits** and components such as exchangers (manufacture, performances and service reliability…)
- **the** gas turbine **conversion system technology** for electricity production (when direct cycle conversion is involved).

GFR’s feasibility also partly depends on a major R&D core in common with the VHTR involving materials and high temperature components for the coolant circuit, the helium circuit technology and the conversion system. The development efforts on these technologies will simultaneously benefit the VHTR system which will probably be the first to mature for the international market and the GFR which requires other innovations.

Once the fuel’s feasibility has been established, the GFR development plan provides for testing the system-specific principles and technologies in a 30-50 MW **research and technological development reactor (REDT)**, due to be commissioned around 2017.

Active co-operation is going on in the Laboratoire des Composites Thermostructurés *(a joint venture between CNRS, CEA, Snecma and Université Bordeaux 1)* on the technology and manufacturing processes for GFR fuel. Another co-operative project is being set up between CEA and the CNRS on the development of materials resistant to high temperatures for the GFR fuel and core materials, and also plastic ceramics for structural elements (excluding the core) of the GFR and VHTR (as part of the bilateral CEA/CNRS co-operation within the Gedepéon research group).

Work on the GFR will also benefit from specific action (CGFR) as part of the European FP5 and FP6 R&D programmes, which will back up co-operation on the GFR principally with the United States, Japan and Euratom under the aegis of the Generation IV Forum.

The fuel developed for the GFR may turn out to be a robust fuel that can be applied to other technologies, particularly sodium fast reactors.

Hydrogen production and gas-cooled very high temperature thermal neutron system (Very High Temperature Reactor (VHTR))

Hydrogen production with the water disassociation processes currently anticipated as being the most efficient, as well as the supply of very high temperature energy for industry, are an additional R&D area for meeting energy requirements on a global scale.

This objective involves **very high temperature reactors** and a gas coolant with a target core output temperature of 1000°C. It has a major common R&D core with Areva's **Antares** development programme devoted to high temperature reactors (850-950°C).

This shared effort by CEA and its industrial partners aims to develop a reactor project associated with the Antares programme and place the French nuclear industry in the position of being major R&D partners in nuclear hydrogen production, in particular in the Generation IV Forum very high temperature systems, and also in the American NGNP project whose Idaho National Laboratory should provide a first demonstrator of this type around 2017.

Over and above the development of key technologies to extend nuclear energy applications to hydrogen production, CEA also wishes to make the most of the R&D on very high temperature thermal neutron reactors as a resource in common core for the gas-cooled fast systems (primarily in connection with helium circuit materials and technology, conversion systems and hydrogen production and the computing system), which enables the R&D specific to these systems to be limited in the first place to fuel development which is the main technological obstacle, as well as safety demonstrations. Gas-cooled fast reactors that combine high temperature and fast neutrons for their part, offer durable prospects for VHTR applications (including hydrogen production) beyond the 21st century.

VHTR derives from high temperature reactor prototypes (HTR at 850-950°C) that operated in Europe and the United States in the 1960s-1980s. The following are the major technological obstacles to the feasibility of a VHTR System with a core output helium temperature of 1000°C exist:

- **very high temperature-resistant materials** (>950°C) for the coolant circuit and its components (particularly the intermediate exchanger if it exists),
- **the technology of very high temperature helium circuits** and components such as exchangers (manufacture, performances and service reliability…)
- **particle fuel** for which research for an additional margin of at least 200°C on the operating temperature has led to replacing the SiC fission product buffer layer with a ZrC buffer layer,

and a common core with the R&D for the GFR:

- **the technology of the** gas turbine **conversion system** for electricity production (when for direct cycle conversion is involved),
- **the hydrogen production processes** by thermochemical or electrochemical disassociation of water *(Iodine-Sulphur cycle, hybrid Sulphur-electrolysis and high temperature electrolysis cycle).*

Research into innovations to improve the performance levels of VHTR fuel benefits from active co-operation in the Laboratoire des Composites Thermostructurés *(a joint venture between CNRS, CEA, Snecma and Université Bordeaux 1*]. Many French and European industrial concerns are consulted and closely associated in developing high temperature-resistant steels and super alloys for the primary coolant, developing the various heat exchanger technologies, and composite refractory materials (C/C, SiC/SiC) for the internal core structures (control rod sleeves in particular)

French R&D on the VHTR has had the benefit of European support since FP5. This is because since the 1990s, the European Framework for Technological Research and Development section devoted to new nuclear system designs has concentrated on HTR technologies, which had development input from many European countries in the 1960s to 1980s.

Transmutation-dedicated sub-critical systems

The specific R&D requirements for transmutation-dedicated sub-critical systems are covered by a number of FP5 and FP6 R&D initiatives:

- The MUSE programme headed by CEA and the CNRS on the Masurca model to validate the calculation of neutron transport in a sub-critical environment,
- The MEGAPIE programme that consists of creating a PbBi eutectic-cooled spallation target and testing it on the PSI accelerator,
- The international TRADE, RACE, SAD and MYRRHA programmes.

Furthermore the design of an eXperimental ADS demonstrator (XADS) has been subject to a brief outline plan, "PDS-XADS". Lastly the integrated EUROTRANS project should enable the technical and financial elements to be gathered by 2008 to judge the viability of a full-power ADS for transmutation.

This work, like the work that contributes to the development of a high intensity, highly reliable proton accelerator, benefits from strong involvement by the CNRS.

Other nuclear systems

CEA together with the CNRS and its industrial partners are also researching into more forward-looking technologies such as **molten salt reactors**, **lead-cooled reactors** and **supercritical water reactors**. Their aim is to bring their assessments up to date while providing input to a number of R&D sticking points on these technologies.

The main interest for **molten salts** is to assess an innovative technology, in addition to their use in pyrochemical processing of spent fuel. Given the technical obstacles that need to be removed, this is very long-haul research.
More recently, the interest in molten has been extended to their use as an unpressurised high temperature coolant (>600°C), primarily for coupling nuclear systems and a few applications such as hydrogen production.

Work on molten salt reactors, which is mainly receiving input from the CNRS, primarily covers all the aspects that will make it possible to assess the feasibility of regenerating fissile fuel (neutron design, salt treatment strategy and processes), and in the second place, the technology of the circuits that will contain the molten salt (materials, corrosion). These studies have been included in the European framework research programme since FP5 (MOST initiative), which have been extended to the Generation IV Forum through contributions to the ***Molten Salt Reactor (MSR)*.**

In continuation of its own work that CEA carried out in the 1990s, current activity on **lead-cooled reactors** basically consists of following up the Russian studies on the subject. There is limited interest in this technology because for reasons of weight, corrosion and the maintenance and in-service inspection conditions, lead is recognised as having a major handicap as a coolant for reactors with unit power of the order of one GWe.

Work on **super-critical water reactors** basically consists of feasibility studies and performance assessments (conversion output at 550°C, conversion ratio in the uranium/plutonium cycle). These studies are supplemented by corrosion tests on the materials being considered for the internal structures of the core, that must withstand the super-critical water in the presence of hydrolysis. CEA's Material Sciences Division is providing its expertise on the hydrolysis phenomenon. These studies have been included in the European framework research programme since FP5 *(HPLWR initiative)*, which have been extended to the Generation IV Forum through contributions to the ***Super-Critical Water reactor (SCWR).***

The European dimension

A fully-dedicated European research programme on future systems is now in sight with funds of at least €50M (EU funds) earmarked in the FP7. This is the logical result of the Euratom treaty signatory countries' admission to the Generation IV Forum as its 11th member. Since FP6, the integrated VHTR and CGFR project structures have been running parallel to those of their counterpart Generation IV Forum projects (VHTR and GFR). The proposed FP7 programme is open to initiatives of the technological platform type for reactor technologies (very high temperature, fast neutrons, cycle closure) and their applications (hydrogen production). The challenges are both to gain a better grasp of the strategic technologies for the nuclear systems likely to interest European countries (which have operated several high temperature and fast neutron reactors), and the pledge of more even-handed co-operation with major partners such as United States and Japan.