Nuclear Fission, today and tomorrow: from renaissance to technological breakthrough (Generation IV)

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This paper addresses two major questions:
- What are the chief challenges to nuclear fission in a world of energy policies aiming at sustainability, competitiveness and security of supply? (needs of society and industry).
- What sort of international research in nuclear fission is necessary to meet these challenges? (with emphasis on Generation IV systems, whose deployment is planned for 2040).

En este trabajo, se analizan dos cuestiones importantes:
- *¿Cuáles son los retos principales de la fisión nuclear en un mundo donde las políticas energéticas van dirigidas a la sostenibilidad, competitividad y seguridad del suministro? (las necesidades de la sociedad y la industria).*
- *¿Qué tipos de investigaciones internacionales sobre la fisión nuclear son necesarios para responder a estos retos? (centrándose en los sistemas de Generación IV, cuyo despliegue está previsto para el año 2040).*

"Yes, my friends", says Cyrus Smith, "I believe that, in the future water will be used as fuel, that hydrogen and oxygen, which constitute it, will provide, separately or together, an inexhaustible source of energy and light, of an intensity that coal is not able of, and that when coal resources are exhausted, we will heat ourselves using water. Water will be the coal of the future. "The Mysterious Island", (1874), Jules Verne [1].

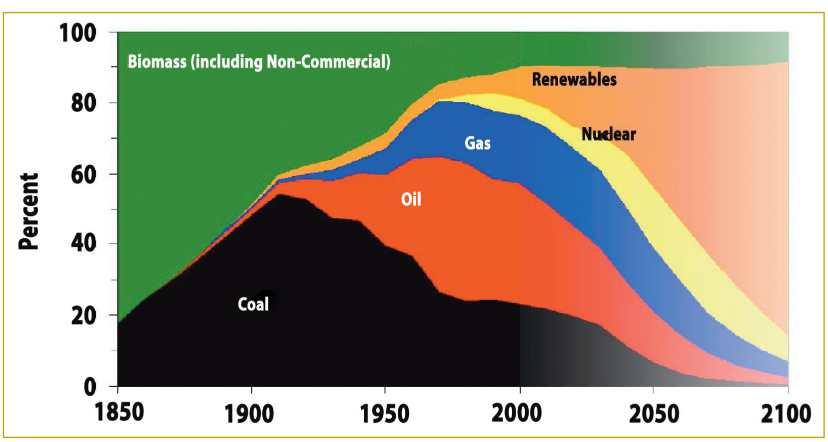

Figure 1: Trend in the overall demand for primary energies: fossil (coal, oil and gas), fissile (nuclear power) and renewable over 250 years (Marchetti, IIASA, 1985) [2].

INTRODUCTION

Two types of instruments are usually needed to produce technological breakthroughs: political instruments, to provide guidance for research and innovation with ambitious and long-term objectives; and financial instruments, to fund the relevant research and training programmes, based on synergies between private and public sectors.

The past several decades have shown that nuclear fission plays an important role in the mix of primary energies. The "Climate and Energy" policy of the European Union (EU) addresses all primary energies (clean fossil, fissile or renewable), with special attention to energy saving (Objectives 20/20/20 for 2020, fixed by the EU Council of March 2007). Nuclear fission is likely to maintain its place in creating a low-carbon economy, even though, in the very long term (around the year 2100), an entirely new generation of renewable energies

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may begin to dominate. Figure 1 shows the energy mix scenario envisioned by a famous research institute 25 years ago: it was an early warning about the rapid exhaustion of the natural energy resources in a world-wide business-as-usual scenario.

One of the principal problems likely to confront mankind is the continuing strong growth of energy consumption throughout the world. A new generation of energy vectors will be needed in a not too far future, to replace or improve the current electricity and hydrocarbon fuels (for example, hydrogen: see the above quotation of Jules Verne). They will be produced "cleanly" (that is, without emission of greenhouse gases (GHG)), by using electricity and high-temperature heat, whenever possible.

This paper describes briefly the major scientific and technological challenges related to the very innovative nuclear fission reactor systems to be deployed at the horizon 2040 (called Generation IV). The paper focuses on the benefits of the Generation IV systems, according to criteria or Technology Goals established at the international level (Generation IV International Forum (GIF)). These Goals are drastic improvements in four areas: sustainable development, industrial competitiveness, safety and reliability, and proliferation resistance. The focus is on the design objectives and associated research issues that have been agreed upon internationally to meet these four ambitious Goals.

EU COMMUNITY RESEARCH AND INNOVATION FOR "SUSTAINABLE, COMPETITIVE AND SECURE ENERGY"

Energy played a key role in the construction of the European Union. Two of its founding treaties deal directly with energy: the European Coal and Steel Community (ECSC) created in 951 by the Paris Treaty, and the European Atomic Energy Community (Euratom), created in 1957 by the Treaty of Rome.

Today, with its 27 Member States, the EU is home to 492 million consumers and approximately 25 million companies, and represents the world's second-largest energy market. The EU, however, must import 50% of its energy needs with an annual bill of 240 billion Euros, and its primary energy consumption continues to increase by 2% each year. If no basic changes are made, the imported quantity of primary energies (primarily from fossil origin) could reach 70% in 2030.

These hard facts show that energy problems cannot be taken for granted in the EU, and demand a Community-wide approach. The European Commission (EC) has been mandated to create the political and financial framework to deal with these challenges. In March 2006, the Commission published a Green Paper (COM 2006 105) entitled "A European strategy for sustainable, competitive and secure energy" [3]. The proposed strategy should lead to a low-carbon economy, based on a balance between sustainable development, industrial competitiveness and security of supply.

The Knowledge Society, promoted by the EU since the early 2000's, is intended as a natural support of the new energy economy. It entails substantial research, innovation and training efforts to foster the new technologies needed for the future low-carbon economy (figure 2).

Early on, the Euratom Treaty (1957) [4] called on the EU to "promote research in particular and ensure the dissemination of information" (Title 1: Tasks of the Community). More recently, the Sustainable Nuclear Energy Technology Platform (SNE-TP, begun in 2007) [5] was given the mission of providing broad guidelines for EU research. Education and training activities are dealt with more specifically by the European Nuclear Education Network (ENEN) [6].

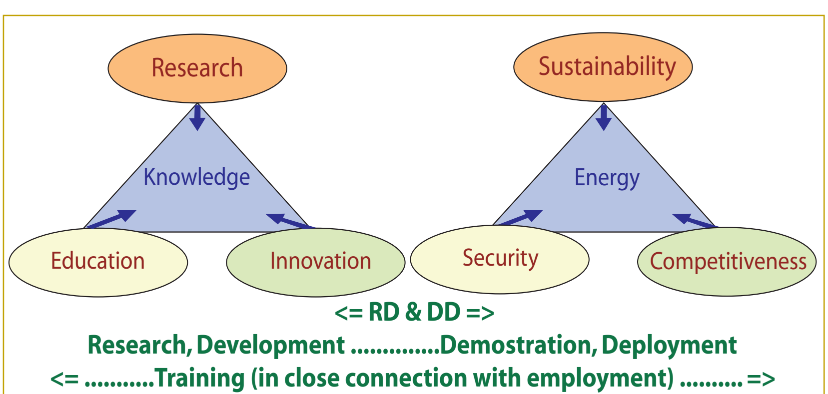

Figure 2. Cycle of innovation (RD&DD) / "Triangle of Knowledge" (Research and Development) and "Triangle of Energy" (Demonstration and Deployment).

The generation of electricity through nuclear fission is now a fact of life in the EU. Currently, there are a total of 145 reactors in 15 Member States. In 2006, in computing EU electricity production by primary energy source, nuclear power arrived on top (29.5%), followed by coal (28.6 %), natural gas (21.1%), oil (3.9%), hydropower (1.1%), renewable energy (14.6%) and other sources (1.2%). Still, that means that more than half of the EU's electricity production (53.6 %) today continues to use technologies emitting CO_2.

NUCLEAR ENERGY IN THE WORLD: 50 YEARS OF INDUSTRIAL EXPERIENCE

Four generations of fission reactors: a continuous technological development

To better understand the context, it is necessary to consider the two preceding Generations II and III: GEN II (yesterday): safety and reliability of nuclear facilities and energy independence (in order to ensure security of supply in an unstable context worldwide); GEN III (today): continuous improvement of safety and reliability, and increased industrial competitiveness in a growing, highly diversified energy market; and GEN IV (tomorrow): optimal utilization of natural resources and waste minimization (integral recycling) to meet the sustainable development target, and proliferation resistance (figure 3).

- *Generation I (period 1950-1970, USA, Soviet Union, France and the United Kingdom)*

This category designates the prototype power reactors of the 1950s and 1960s (built at the time of the Atoms for Peace conference, 1953). They use mainly natural uranium [U] as fuel (uranium oxide UOX), graphite as moderator and CO_2 as coolant. The period 1950-1970 saw also the first developments of sodium-cooled breeders with fast neutron spectrum: Enrico Fermi (USA), Rapsodie (France), BOR-60 1968 (Soviet Union), and PFR 1974 (UK, Scotland). The pioneer breeder reactors paved the way for Generation IV. They provided the first historical attempt to introduce what is now called "sustainable development in nuclear fission" (in particular, through the optimal utilization of natural resources and the reprocessing of used fuel to recover U and Pu).

- *Generation II (period 1970-2000, 30 countries throughout the world)*

The commercial reactors deployed since the 1970s, following the OPEC-related first oil crisis in 1974, are still in operation today. These are mainly light water reactors (LWR), divided into two large families: boiling water reactors (BWR) and pressurized water reactors (PWR).

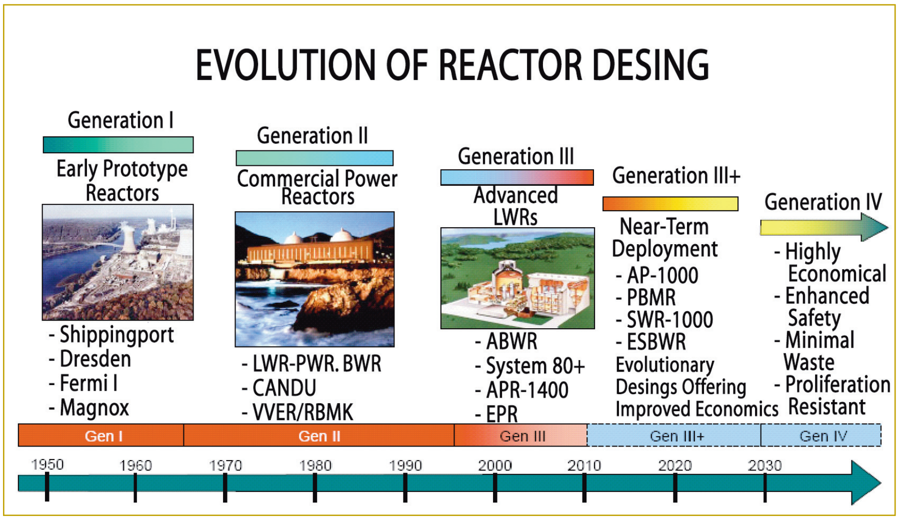

Figure 3. Evolution of Generation I to III and technological breakthrough to GEN IV [8].

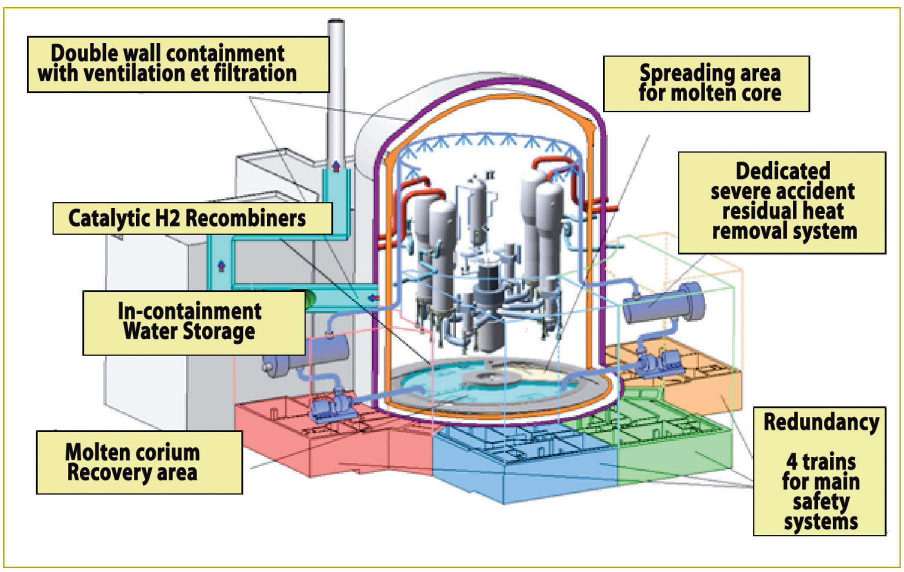

Figure 4. EPR: a Generation III reactor with advanced safety systems (AREVA NP) [7].

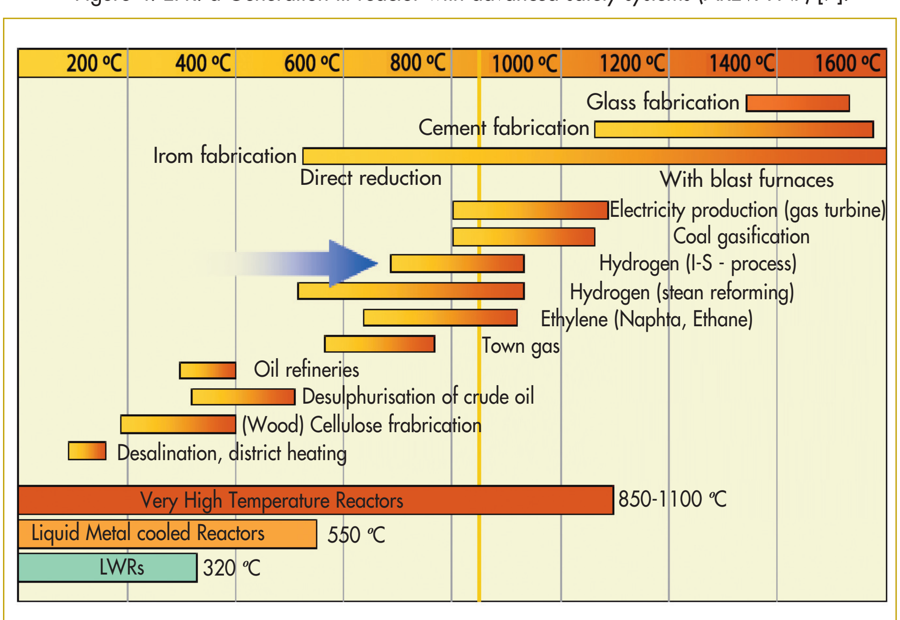

Figure 5: Applications of nuclear combined heat and power (Generation IV) [8].

- *Generation III (today, reactors of evolutionary type for the Renaissance of nuclear power)*

Although second-generation LWRs have an excellent safety record, efforts continue to improve both their safety and performance, while reducing the already very low radioactivity they release in the environment. Generation III reactors were designed for the first time in the 1990s. Some are already under construction: they are generally LWRs. For example: EPR (European Evolutionary Pressurized Reactor, AREVA, figure 4), in Finland, France and China; AP-1000 of Toshiba-Westinghouse (Advanced PWR), in China; VVER-1200 (AES-2006 of OKB Gidropress), in Russia (planned to start operation in 2012-13), and APR-1400 of KEPCO (Advanced Power Reactor), in Abu Dhabi, following a deal concluded in December 2009).

- *Generation IV (2040, technological breakthrough for nuclear fission systems and fuel cycles)*

With Generation IV, the term "reactor" gives way to the more appropriate term "system", thereby including both the reactor and the processing/recycling of its fuel. These new nuclear systems must show they can out-perform the previous generations in sustainable development, industrial competitiveness, safety and reliability, and proliferation resistance (thus justifying the term "technological breakthrough"). Some systems will produce electricity, while others will also create heat at high temperatures (400-900 °C) for numerous industrial applications such as: petro-chemistry, synthetic fuel production, gasification of the biomass, hydrogen production from water or production of glass or cement. Applications at lower temperatures will include desalination of sea water and fertilizer production (temperatures needed: 100-300 ° C), figure 5.

Some Generation IV systems are characterized by a fast neutron spectrum. Their inherent breeding capacity, associated with advanced partitioning and transmutation (P&T) technologies, offers many advantages. Their nuclear fuel will be highly heat-resistant and is designed to contain all actinides. As a result, the fuel cycle will be entirely closed. Hence these new systems will be particularly efficient in terms of sustainable development because of the minimisation of nuclear waste production (incineration of all actinides).

On the eve of a technological breakthrough (Generation IV)

Thorough research and innovation programmes are needed at the international level to develop the Generation IV systems. Today there is a broad international consensus in both society and industry endorsing GIF technology goals. Principal stakeholders are: research organisations, systems and energy suppliers, nuclear regulatory bodies, civil society (decision makers and opinion leaders), NGOs, etc., and international institutions such as the IAEA (Vienna) and the OECD/NEA (Paris), which have a long tradition of collaboration with Euratom in the field of nuclear fission research and training.

a) Sustainable development

— Optimal utilization of natural resources which is also related to security of supply

A weak point in current technologies is their limited capacity to extract the potential energy of the uranium fuel. Thermal reactors of Generation I and II use a U isotope that accounts for less than 1% of the total quantity of U in nature. Breeder reactors (FR) benefit from a major part of the energy not used in the thermal LWRs, increasing the quantity of energy extracted from the same quantity of uranium by a factor of approximately 50. They can convert fertile U-238 into fissile Pu-239 at faster rates than their consumption (breeding). In addition, they may also make use of very low U ore concentrations and perhaps even of U present in the oceans (natural concentration of 0.0032 mg/liter). On the other hand, it is worth noting that the MOX technology enables Pu to be used in the current Generation II reactors as well as in FRs.

—Waste minimisation

A weakness in the current open-cycle strategy (disposal of spent nuclear fuel (SNF), without reprocessing) is the quantity, the radio-toxicity and the heat released by the spent fuel. Worldwide as of 2008, more than 250.000 metric tons of high-level radioactive waste and spent fuel from reactors currently operating will require disposal (including a separated civil plutonium reserve estimated at 200 tons). The amount of spent nuclear fuel accumulated in Europe, is estimated as 55.000 tons for the year 2008 with additional 2500 tons of spent fuel being produced every year. Rather conservative projections indicate that world-wide by the year 2060, almost 1,5 million tons of discharged fuel might require disposal. Although there is general agreement that geological disposal of high level waste in deep layers is the best available solution from a safety point of view, such facility doesn't exist yet.

Projection estimates for the coming decades indicate that by year 2060, the amount of this type of waste requiring disposal could become almost unbearable for society at large. This problem, however, has been partially solved in countries that have chosen to apply Pu reprocessing on an industrial scale (closed cycle strategy with partial recycling); these include France, the United Kingdom, the Russian Federation, Japan and India. Belgium, too, has been outstanding in the development of nuclear fuel management techniques, both at the front end and at the back end of the fuel cycle.

Whether the back end of the cycle is closed (reprocessing of SNF) or open (direct disposal of SNF), the ultimate phase of the fuel cycle is the geological disposal of the remaining high-level radioactive waste in deep stable layers, as it has been mentioned earlier. This ultimate phase will happen after some storage in the power plant (SNF pool or dry storage containers) or in interim near-surface storage facilities, for 40 to 150 years.

Advanced partitioning and transmutation technologies are the subject of numerous research projects under Generation IV. Nuclear chemistry makes it possible to separate, or partition, the spent fuel into different components according to its final use or disposal requirements.

— Environmental protection:

An analysis of the nuclear energy cycle shows that its production of greenhouse gases is equivalent to that of hydroelectric energy, that is to say: extremely low. The EU produces a third of its electricity by nuclear power, thus avoiding a quantity of CO_2 emission equal to that of the EU vehicle fleet (approximately 200 million vehicles or 900 million tonnes of CO_2 per year). This has also a positive impact on the cost of the nuclear MWh.

b) Industrial competitiveness

It is worth noting that most external costs of nuclear power production (e.g., insurance and provisions for waste management and dismantling of the facilities) are internalised, contrary to what occurs in power plants using other types of primary energy. The fixed costs of nuclear energy are rather high (large initial investment), but the variable costs are low due to the low fuel price. The price of uranium has little impact on the final cost of electricity, and the overall cost of the nuclear MWh is much lower than other energy sources, especially when the cost of the CO_2 is included (figure 6).

Light-water reactors of Generation II and III have relatively low core-exit temperatures, approximately 300° C, which limits their thermal efficiency (roughly 30 % for a traditional LWR). Generation IV reactors should attain much greater thermal efficiency. Using other coolants, far higher temperatures are reachable: 400-600° C for CO_2, 500-700° C for liquid metals (sodium, lead) and 700-900° C for helium. Reminder: A core-exit temperature of 900 ° C results in thermal efficiency up to 44 %, approximately a third more than a traditional LWR.

Co-generation of heat and power (CHP) —beyond mere electricity generation— for industrial process heat applications or for CO_2-free production of hydrogen is a major innovation and a major challenge for Generation IV. Process heat applications are used in refineries and petro-chemical industries (including, for example, hydrogen generation for upgrading of heavy sour crude oil), in metallurgical processes and in the production of synthetic hydrocarbon fuels (figure 5). It requires

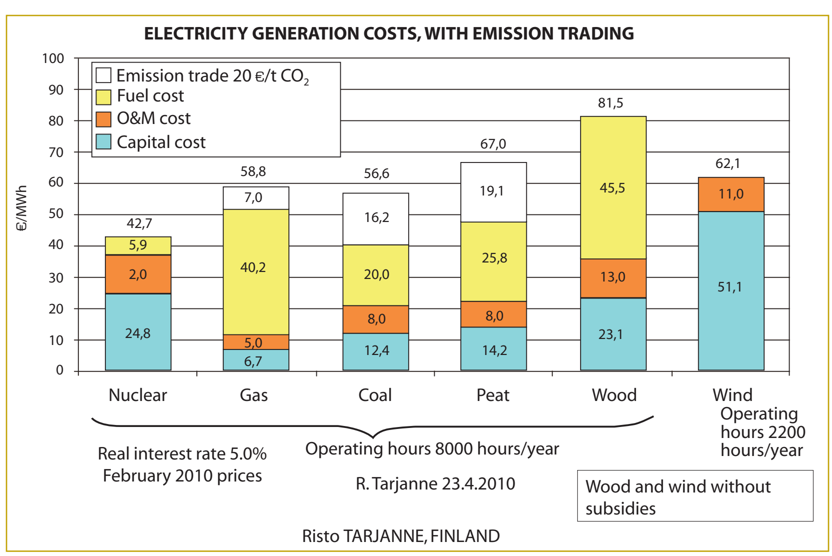

Figure 6: Comparison of the electricity costs for fossil, fissile and renewable sources (Tarjanne Risto et al., Lappeenranta University, Finland, 2010) [9].

not only to develop an appropriate nuclear heat source, but also to develop coupling technologies and to adapt industrial processes to the coupling.

For the future low-carbon economy in the so-called *post-petroleum society*, hydrogen seems indeed very promising. Hydrogen is not a primary energy source, such as fossil, fissile or renewable energy. Hydrogen is an energy vector, like electricity and hydrocarbon fuels. It could become essential as an alternative, providing mankind with true security of energy supply and the broadest possible environmental protection. There are, however, several problems to solve before a hydrogen-based economy becomes a reality. One of them is its production in large quantities by technologies with low-carbon emissions. Some Generation IV systems (especially those with core exit temperatures higher than 900 °C) could offer the only clean technologies with sufficiently high energy density to create abundant quantities of hydrogen from water, while at the same time producing electricity. There exist two such technologies today: the thermo-chemical water splitting cycles (TCWSC, minimum 750 °C required) and the high-temperature electrolysis of steam (HTES, minimum 700° C required).

Competition among the three energy vectors (electricity, hydrocarbon fuels and hydrogen) will probably be very stiff in the future; they could continue coexisting in the 21st century, but in very different proportions compared to today.

c) Safety and reliability

For Generation IV, the defense-in-depth strategy with its large safety margins remains the natural safety basis (IAEA standards). This strategy is of the deterministic type, that is to say: based on the systematic investigation of initiating events and respective accident sequences (so-called "Design Basic Accidents"). But to better cope with the uncertainties inherent in the innovative GEN IV designs, a safety approach of a mixed deterministic-probabilistic kind has proven necessary, thereby providing assurance of the overall homogeneity and consistency of the design.

Public confidence in safety remains fragile, and any severe accident, even without victims, would have a very unfavorable impact on the future of nuclear energy. One of Generation IV's aims is to eliminate as far as possible the technical need for an off-site emergency response, whatever the causes and the gravity of the accident inside the power station.

In the current nuclear industry, the safety systems are in general active, based on the electric and mechanical active control of equipments such as probes, valves, pumps, accumulators, heat exchangers and auxiliary energy systems. Generations III and IV have simpler and more efficient safety systems. Some use passive safety systems (in particular, to deal with decay heat removal that require no active control or manual intervention in the management of an accident situation. They rely simply on gravity, natural convection, spring- or compressed gas-supported systems, or resistance to high temperatures. Passive safety should prove more efficient, reliable and economic. Finally, a number of innovative techniques for man-technology-organisation (MTO) interfaces are being developed to take better into account the human factor.

Industrial reliability goes together with safety, as it is shown by the WANO performance indicators [10]. EU Member States have never before produced as much nuclear power as today (almost a third of the total electricity is produced by nuclear power). Nuclear energy's capacity factor is 90%, far exceeding all other means of electricity production. That makes it a remarkably reliable energy source for electricity production at any time throughout the year.

d) Proliferation resistance and physical protection

The Treaty on the Non-Proliferation of Nuclear Weapons (NPT) encapsulates, in its spirit at least, the noble wish, vision and mission of Eisenhower. It is the legal basis of the IAEA's international nuclear safeguards system and consists of three pillars: disarmament, peaceful utilization of nuclear energy and non-proliferation. As far as non-proliferation is concerned, the IAEA imposes technical and legal regulations and ensures that a maximum of measures are implemented in the nuclear facilities under its jurisdiction. These measures are also aiming at the physical protection against theft or unauthorized diversion of nuclear material and against the sabotage of nuclear facilities. The IAEA non-proliferation objectives focus on two international threats: 1) the possible development of nuclear weapon programmes in other than the five states officially possessing them under the Non-Proliferation Treaty (NPT); and 2) the possible acquisition of fissile material by terrorist organisations anywhere in the world.

One important proliferation risk, and a weak point in current nuclear reactor technologies, could be the transportation of pure plutonium (e.g., needed for the production of MOX fuel) from reprocessing facilities to power plants. A solution also has to be found for the reserves of nuclear material of military origin.

Today, to remove civilian or military plutonium, one can "transmute" it in relatively small quantities, by using MOX fuel either in LWRs or in breeder reactors. Tomorrow, the fast systems of Generation IV and the ADS will transmute large quantities not only of plutonium but also of minor actinides (in particular, those that might be used for non-peaceful purposes).

This will be done by excluding pure plutonium-states throughout the system flow. The inclusion of minor actinides in the innovative fuels, in particular, will lower its attractiveness and the possible use of on-site reprocessing in some Generation IV systems will indeed make highly impracticable any illegitimate diversion of fissile matters. But that will still not eliminate the need for international non-proliferation arrangements (framed by the IAEA), or of national and regional systems (such as the Euratom Security Control in the EU).

In conclusion, the proposed Generation IV strategy will thus enable to extract the maximum energy from natural resources (breeding), while optimising the waste treatment (integral recycling of all actinides) and minimising the proliferation risks (minor actinides bearing fuel).

GENERATION IV (YEAR 2040): TECHNOLOGICAL BREAKTHROUGH TO MEET NEW NEEDS

Some EU countries are actively committed to make Generation IV become a reality. In January 2006, French President Jacques Chirac announced "the immediate launching of a CEA programme on a prototype reactor of fourth generation, with operation planned in 2020."

In mid 2009 it was recommended that the sodium-cooled system should be a high priority in R&D on account of its actinide-burning potential. A decision was taken in France about the demonstrator "Astrid" (Advanced Sodium Technological Reactor for Industrial Demonstration). The CEA is seeking support under the EC's European Sustainable Nuclear Industrial Initiative (ESNII, an outcome of the SNE-TP [5]) and partnerships with other GIF countries interested. With this innovative sodium-cooled breeder reactor, France and the EU launch a clear signal that they intend to remain world leaders in nuclear energy.

There was also a significant U.S. initiative in January 2006, this one addressed to the world. After consultation with the United Kingdom, France, the Russian Federation, Japan and China, the U.S.A. launched the Global Nuclear Energy Partnership (GNEP). Its chief aims were to limit access to sensitive technologies (primarily fuel production with enrichment and fuel reprocessing) and to strengthen international safeguards within the framework of an increased use of nuclear energy, while still ensuring a sufficient supply of nuclear fuel for partners. GNEP also sought to solve the problem of highly radioactive waste in the U.S.A. by allowing spent fuel reprocessing and the construction of breeder reactors (in particular, advanced breeder reactors). This entailed abandoning the prohibition of recycling Pu established under the presidency of Jimmy Carter (U.S.A.-1976-1980).

Research, Development, Demonstration and Deployment Programme for GEN IV (ten GIF members)

In 1999, a group of nine countries, led by the U.S. Department of Energy, launched an international project to select a series of nuclear systems of a "revolutionary" type that would deploy industrially around 2040. The countries involved were the USA., Argentina, Brazil, Canada, France, Japan, South Africa, the Republic of South Korea, and the United Kingdom. They all signed the GIF Charter in 2001, thereby creating the Generation IV International Forum (GIF [8]), with the aim to implement the four GIF Technology Goals, mentioned in Section 3.2. In 2002, Switzerland too became a forum member, followed in 2003 by the European Atomic Energy Community (Euratom) which represents the 27 EU Member States.

To fix the rules of collaboration, the GIF proposed an intergovernmental Framework Agreement. In 2009, the GIF had ten active members, i.e. members who have signed the Charter and signed, ratified or acceded to the Framework Agreement and are effectively contributing to GIF work: USA, Canada, France, Japan, South Africa, the Republic of South Korea, Switzerland, Euratom, China and the Russian Federation. The technical secretariat of the GIF, entrusted to the Nuclear Energy Agency (OECD/NEA), manages the coordination of the international research through various committees associated with each nuclear system.

Six innovative nuclear systems (including innovative fuel cycles) were selected in 2002 after the evaluation of more than 100 different designs by more than 100 experts from a dozen countries. In 2002, the GIF members also agreed upon individual roadmaps for each of the six systems, consisting of three phases extending over a period of several decades:

In 2002, the GIF members also agreed upon individual roadmaps for each of the six systems [11], consisting of three phases extending over a period of several decades:

- the viability phase (pre-conceptual design): 5 to 15 years needed
- the performance phase (conceptual design): 5 to 10 years needed
- the demonstration phase (preliminary design in view of the engineering design for the industrial phase): 3 to 6 years needed.

It should be noted that only the above phases 1 (viability) and 2 (performance) are covered by the GIF collaboration agreements. The execution of the last phase (demonstration) is left to specific arrangements among GIF members, because it is considered to be too close to commercial exploitation. For the time being, in most GEN IV systems, GIF members are still busy with the viability phase (pre-conceptual design).

Another international initiative, complementary to the GIF's, is worth mentioning: the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), launched by the IAEA in 2000 (with a view to completion by 2050). This project was proposed at the United Nations Millennium Summit and confirmed by the UN's General Assembly in 2001. As of February 2010, INPRO counted 31 members. INPRO focuses on the needs of the "end-users" of innovative systems (focus on demand side), while GIF organises the relevant international technological RD&DD (focus on supply side).

List of Generation IV systems and innovative fuel cycles: design objectives and research issues

In 2002, the GIF began organising scientific collaboration among interested signatory states in six nuclear systems. The selection included three systems with fast neutron spectrum (SFR, LFR and GFR), one system with thermal neutrons (VHTR) and two systems that can be either fast or thermal (SCWR and MSR). A budget of approximately one billion U.S. dollars per system was planned for this international scientific collaboration through 2020. The EU laboratories, in particular through Euratom, work on all six GIF systems and on the associated fuel cycles (see FISA-2009 conference [12]).

Here below is a very brief summary of the main design objectives and research issues for the six GIF systems with the list of members that signed up to the respective system agreements.

1) Sodium fast reactor (SFR) / Japan, USA, France, Euratom, Korea, China (+ Russia observer)

Electricity production with integral recycling as main design objective; core exit temperature of 550 °C with efficiency of 42%; fast neutron spectrum; three major reactor options (large size "loop" type of 600-1500 MWe; intermediate-to-large size "pool" type reactor of 300 – 1500 MWe; small size modular-type reactor of 50-150 MWe); demonstration around 2020 (Astrid in France), SFR it is the reference technology of the ESNII in the SNE-TP [5].

2) Lead fast reactor (LFR): Euratom and Japan in negotiation (+ U.S.A. and Russia observers)

Electricity production with integral recycling as main design objective; fast neutron spectrum; two major design options (ELSY = "European Lead Cooled System" of 600 MWe for central station power generation and nuclear waste transmutation; SSTAR = U.S.A. battery concept for remote siting "Small Secure Transportable Autonomous Reactor" of 20 MWe with natural circulation at power and very long refueling interval, 10 to 30 years); both options are of the pool type and use pure lead as coolant; core exit temperature of 480 °C in ELSY and 570 °C in SSTAR, with efficiency of 42% in both options; breakthrough in the design and simplicity of operation; fuel enrichment max of 19 % (LEU); demonstration around 2025 (LFR Technology Pilot Plant MYRRHA and LFR Demonstrator) – LFR it is the alternative technology of the ESNII in the SNE-TP [5].

3) Gas fast reactor (helium, GFR) / France, Euratom, Japan, Switzerland

Cogeneration of electricity and heat at very high temperature with integral recycling as main design objective; fast neutron spectrum; core exit temperature of 850 °C with efficiency of 45% ; the GFR associates the advantages of fast neutron spectrum and high temperature systems (efficient electricity production using a Brayton gas turbine in a direct helium circuit); high reference power of 1000 MWe; fuel enrichment max of 15% wt HM; demonstration around 2025 (ALLEGRO demonstrator of 75 MWth proposed in the EU, foreseen to demonstrate the viability of the GFR system design, no reactor of this type having been ever built before) – GFR it is the alternative technology of the ESNII in the SNE-TP [5].

4) Very high temperature reactor (VHTR, using helium gas)/ USA, Japan, France, Canada, Korea, Switzerland, Euratom, China (+ South Africa expected in 2010)

Cogeneration of electricity and heat at very high temperature (CHP) as main design objective: thermal neutron spectrum (graphite moderated); open fuel cycle; fuel enrichment max 19% (LEU);

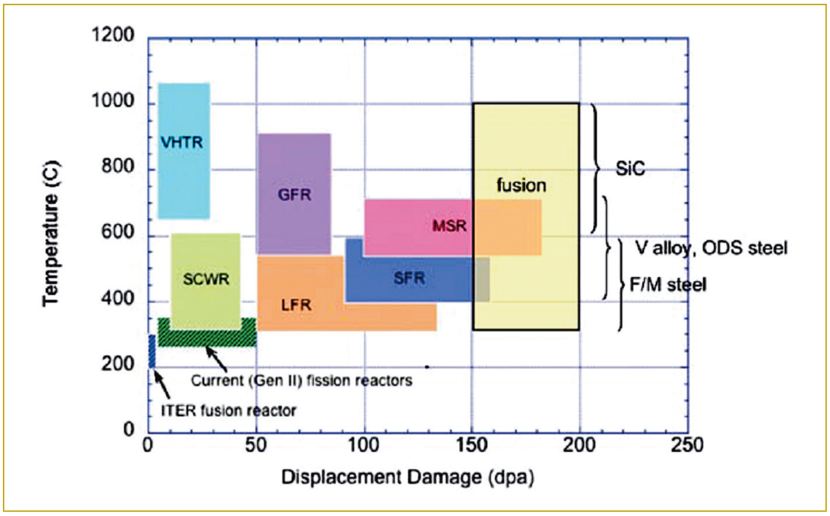

Figure 7: Operating temperature ranges and irradiation damage for different reactor concepts (dpa: displacement per atom) (KIT) [5].

core exit temperature up to 1000° C with efficiency of 50%; direct or indirect Brayton cycles; reference power of 400 to 600 MWth; potential for hydrogen production (up to 200 tons/day); demonstration around 2020 (NGNP in USA, HTR-PM in China, GTH-TR-300C in Japan, NHDD in Korea, PBMR in South Africa).

5) Supercritical water reactor (SCWR) / Euratom, Canada, Japan (+ Korea observer)

Electricity production as main design objective (actually an evolutionary development of GEN II); thermal neutron spectrum; open fuel cycle; core exit temperature up to 625 °C (pressure of 25 MPa) with efficiency of 45%; experience feedback from the commercial supercritical water-cooled, fossil-fuel-fired plants /SCW FFP /; two major options (pressure vessel in the EU as a development of LWR and pressure tube in Canada EU as a development of CANDU); fuel based on UO2; reference power up to 1700 MWe; demonstration around 2025.

6) Molten salt reactor (MSR) / Euratom, France and USA in negotiation (+ Russia observer)

Electricity production with integral recycling as main design objectives (at least in the EU concept of MSFR); core exit temperature up to 800° C with efficiency of 45%; two major design options (fast neutron spectrum concept without graphite in the EU (molten salt fast reactor or MSFR, 3000 MWth) and high temperature reactor with molten salt as a primary coolant in the USA (Molten Salt cooled High Temperature Reactor, also called MS-HTR or Advanced HTR, 2400 MWth); the MSFR is a breeder of fissile U-233 from fertile thorium-232 with a large negative temperature and void reactivity coefficient; the AHTR could be a thorium fuel cycle thermal breeder reactor characterized by an inherently safe neutron regulation (thermal spectrum); reference power = 1600 MWe; demonstration around 2035.

Innovative nuclear materials: extreme radioactive, chemical and thermal conditions

The extreme radioactive, chemical and thermal conditions, generally met by Generation IV and transmutation systems, necessitate especially strong structural materials for the reactor core components (e.g. fuel subassemblies, cladding and wrapper tubes) and primary coolant components. These conditions are far from those of existing reactors and include, in particular: high temperatures, aggressive coolants (especially liquid metals), high energy neutron exposure (fast spectrum), and high "displacement per atom" (dpa), all resulting in complex thermo-mechanical loadings (figura 6). Some of these innovative nuclear materials are also applicable for Fusion energy systems: there are actually many commonalities between the materials research programmes of Fission and Fusion.

Innovative nuclear fuels: transmutation performances under extreme conditions

The fuel of Generation IV and Transmutation systems is very innovative because of its content of transuranium elements [TRU]. In addition, it is submitted to extreme radioactive, chemical and thermal conditions for nuclear materials (in particular, fuel cladding). In the design of the fuel-cladding-coolant system, particular attention is devoted to the mechanical and chemical interactions. Wherever transmutation is an objective, the fuel cycle study should cover the range from the traditional breeder role to an incinerator of plutonium and minor actinides, including economics of fuel cycle technology (e.g. minimization of fuel inventory, simple and compact spent-fuel treatment and refabrication for recycling).

EURATOM EDUCATION AND TRAINING IN THE CURRENT "NUCLEAR RENAISSANCE"

Keeping the nuclear option open means maintaining an adequate skills base to ensure sufficient personnel in research organizations and in nuclear installations. Nuclear education and training is a concern shared not only by all EU Member States but also by the OECD/NEA and by the IAEA. As far as the EU is concerned, it is worth recalling that " maintaining and further developing expertise and skills in nuclear safety" is one of the subjects of the recent "Nuclear Safety Directive" [13].

The Euratom approach to nuclear education is well in line with the so-called Bologna process (European Area of Higher Education), based on the European Credit Transfer and accumulation System [ECTS], also known as ERASMUS exchanges.

The Euratom approach to nuclear training is aimed at continuously increasing the level of nuclear competences, while achieving the desired "free movement" of nuclear experts across the EU (internal market policy). A number of Euratom Fission Training Schemes (EFTS) are carried out in specific areas where a shortage of skilled professionals has been identified (e.g. safety culture in general or Generation III challenges or Generation IV design).

The EFTS is an ambitious programme, spread over many years and relying on the active participation of stakeholders. The aim is to transfer knowledge (know what, know how and know why) in a number of nuclear areas during a couple of years. An EFTS consists usually in training modules addressing different "publics" (e.g., higher level education, PhD student coaching, mentoring of professionals, customer training) and using different techniques (e.g., regular versus virtual classroom training, face-to-face versus distance learning).

Wherever appropriate, as an outcome of an EFTS project, a series of "Learning Agreements" and "Personal Transcripts" will be established in collaboration with the employers. A "Learning Agreement" is an individualised document which sets out the conditions for a specific mobility period. Information on the EU approach for continuous professional development (in particular ECVET) is available on the DG EAC website [14].

In order to ensure the highest quality in nuclear education and training across

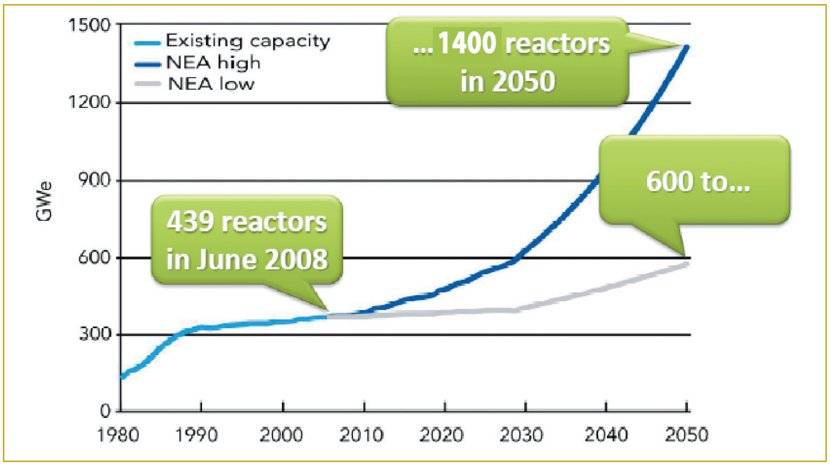

Figure 8: Projections of world nuclear power (OECD/NEA- 2008).

the EU, a non-profit making association was formed in September 2003 under the French Law of 1901. This legal entity (located at CEA-INSTN Paris) is the European Nuclear Education Network (ENEN). As of March 2010, the ENEN association had 56 members in 20 countries (19 EU members and Switzerland). The ENEN is also open to international collaboration: it has signed external Memorandums of Understanding (e.g., with South Africa, Russia and Japan) and partnership agreements (e.g., with ENS, IAEA/ANENT, Canada and WNU. The above mentioned education and training activities (in particular, the EFTS) are described in the website of ENEN [6].

CONCLUSION: GENERATION IV IS BENEFICIAL, RESPONSIBLE AND SUSTAINABLE

This paper has described briefly the major scientific and technological challenges related to the very innovative nuclear fission reactor systems to be deployed at the horizon 2040 (called Generation IV).

In 2008, the OECD/NEA carried out world-wide projections for nuclear power through 2050, following high and low scenarios (Nuclear Energy Outlook, 2008, [15] and figure 8). The results: Between now and 2050, installed nuclear power should increase by a factor between 1,5 and 3,8. Some countries with no present nuclear power reactors still intend to build a nuclear fleet. These projections of a "nuclear Renaissance" substantially agree with those of other international organisations. In the following decades, reactors will principally be of the Generation III type. The commercial deployment of Generation IV systems should start only around 2040.

"The Stone Age came to an end not for a lack of stones and the oil age will end, but not for a lack of oil" was the famous prediction made in September 2000 by Sheikh Zaki Yamani, a Saudi Arabian who served as his country's oil minister from 1962 to 1986 (i.e., during the Arab oil embargo of the 1970s and OPEC crisis). It is perhaps also worth recalling here the prediction of Jules Verne, the inventor of the science fiction novel, in his *The Mysterious Island* (1874) [1].

In the future low-carbon economy, nuclear fission will certainly be an important part of the solution, especially because of its envisioned co-generation capacity (e.g., production of combined heat and power for process heat or hydrogen generation without GHG). Fission will thus remain an essential component in the mix of sustainable, competitive and secure energy technologies that is proposed by the EU (Objective 20/20/20 for 2020).

Fission technologies, however, can be transmitted to the next generations only within the framework of a responsible strategy regarding waste management and recycling of fissile and fertile matters. This is in line with the IAEA: "*any use of nuclear energy should be beneficial, responsible and sustainable, with due regard to the protection of people and the environment, non-proliferation, and security*" [16].

At horizon 2040, Generation IV represents a real technological breakthrough and therefore a challenge to today's research. One will have to produce not only electricity at lower costs but also heat at very high temperature (figure 5), while exploiting a maximum of fissile and fertile matters, and recycling all actinides. The ultimate phase of commercial deployment is planned for 2040, but no one can predict accurately when industry and investors will make firm, often difficult decisions regarding Generation IV. They depend not only on scientific and technological innovations but also on economic and political contexts.

At all events, whether one thinks of the renaissance of today or of the technological breakthrough of Generation IV tomorrow, the public must be informed and reassured. In all research and innovation for Generation IV, one must never forget that those activities are guided by strict criteria: sustainable development, industrial competitiveness, safety and reliability, proliferation resistance. Last but not least, nuclear competences have to be maintained at a very high level. Within the EU, that is made possible through the Euratom education and training programmes.

In conclusion, it is believed that Generation IV is not only a challenge for R&D organizations world-wide (GIF) but also a promising power generation technology that will be beneficial, responsible and sustainable for society and industry at large.

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