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NUCLEAR POWER | AN ENERGY OF THE FUTURE?

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The author | A Belgian national with a Master's degree in Electrical and Mechanical Engineering, a degree in Physics and Nuclear Chemistry and a baccalaureat in Economics from the Louvain University (Belgium), Jean-Pierre SCHAEKEN WILLEMAERS began his career as a Lecturer at the faculty of applied sciences of this University. He thereafter joined the Tracetebel and Suez-Tracetebel group. Within this group, he was Head of Trade and Marketing and a member of the Tracetebel Engineering Executive Committee. He was thereafter appointed Executive Vice President and member of the executive committee of Suez-Tractebel EGI (Electricity and gas international), and Director of Powerfin. He was in charge of investments in Europe, Russia and the Middle East in the fields of electricity production, transmission and distribution as well as the transportation and distribution of natural gas by acquisition or project development. In this capacity, he was appointed Chairman or Director of several subsidiaries of this group in Europe and Central Asia. He was also Vice President of the Brussels Chamber of Commerce and Judge at the Brussels Commercial Court. In 2000, he founded a centre for high technology start-ups of which he is still a board member. Today, he is a board member of several industrial companies. He is Chairman of the Energy, Climate & Environment Department of the Thomas More Institute a also member of its Advisory Board.

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The demand for energy will continue to increase in the decades to come, more than 33% by 2035 according to IEA, and fossil fuels will remain the main sources at least during that period of time.

In such circumstances, can the world back down from nuclear? The hasty decisions of some European governments to phase out completely or partially their nuclear production, after the Fukushima disaster, have been taken under emotional pressure.

"It is useful to stress that all analyses of what happened in Fukushima, conclude that the disaster (results from) the underestimation of the risks posed by tsunamis and (is) not a nuclear power plant problem… One thing is for sure: the Fukushima disaster reinforced the need for a policy of safety and security at many levels and among all nuclear players."[1]

Anyway, many countries worldwide continue to invest in nuclear energy or are reconsidering their moratorium on nuclear power generation.

According to the UN atomic agency (IAEA), at the end of 2012, there were 437 operating nuclear power reactors in the world, two more than in 2011. They had a total generation capacity of 372.5 GW, up 3.7 GW from 2011. The latest IAEA anticipations, which are based on Member States declarations, indicate that this number could increase in the next 20 years, with the possibility even to double. There are 67 new reactors under construction.

New nuclear reactors under design or construction are 3d generation which have, inter alia:

- higher availability and longer operating life, typically 60 years;
- further reduced possibility of core melt accidents;
- resistance to serious damage that would allow radioactive release from an aircraft impact;
- higher burn-up capabilities to use fuel more fully and efficiently and reduce the amount of waste;
- substantial grace period, so that following shutdown, the plant requires no active intervention for (typically) 72 hours.

Among other features it is worth mentioning that**:**

More and more nuclear power plants will be designed for load following. While most French reactors today are, to some extent, operational in that mode, the French 3d generation EPR offers better performances in that respect. It will be able, for instance, to maintain output at 25% for period of time ranging from some hours to few days and then ramp up to full output at a rate of 2.5% of rated power per minute up to 60% output and at 5% per minute up to full capacity. This means that, potentially, such a power plant can go from 25% to 100% capacity in less than 30 minutes though this may be at the expense of wear and tear.

"European regulators are increasingly requiring large new reactors to have some kind of core catcher or similar device, so that in a full core melt accident there is enhanced provision for cooling the bottom of the reactor pressure vessel or simply catching any material that might melt through it. The French EPR and Russian VVER-1200 have core catchers under the pressure vessel and the AP-1000 (Westinghouse) and APWR (Mitsubishi) have provision for enhanced water cooling".[2]

[1] Emmanuel Goût, *European Voice*, November 29, 2012.
[2] *Advanced nuclear power reactors*, November 2012, .on www.world-nuclear.org/info,

1 | Fourth generation nuclear reactors

A | Preliminary remarks

Major international initiatives have been launched to develop reactors and fuel cycle technology of the future. The next step is the fourth generation of nuclear reactors which is based on five main criteria featuring the technology of the future:

- sustainability: saving natural resources[3], and environmental friendly design (plutonium recycling, transmutation[4] of minor actinides[5] and so on);
- competitiveness: in terms of investment costs per installed kW as well as fuel and operation costs and consequently, cost per kWh which must be competitive with respect to other power production;
- safety and reliability;
- resistance to diversion of materials for weapons and security from terrorist attacks;
- providing process heat next to electricity for industrial processes like water desalination and hydrogen production.

To meet these objectives, an international forum, called the Generation 4 International Forum (GIF) was initiated in 2000 and formally chartered in 2001. It deals with an international collective representing government of following countries: USA, Argentina, Brazil, Canada, China, France, Japan, Russia, South Korea, South Africa Switzerland and the EU (Euratom).

B | Six reactors technologies featuring the future shape of nuclear power

Late in 2002, GIF announced the selection of six reactor technologies which they believe represent the future shape of energy.

VHTR, Very High Temperature Reactor

It deals with an helium cooled, graphite moderated, high efficiency (more than 50%) thermal neutron spectrum reactor with a coolant outlet temperature up to 1000°C or above and using coated fuel particles (see footnote 7). However there is a trade-off between high efficiency (linked to the outlet temperature) and the cost of the reactor. The higher the outlet temperature, the higher the efficiency. For each point of efficiency increase, there is a 2% cost reduction per kWh delivered for a given investment. But higher temperatures require more expensive materials. Research programs are under way, among others, to improve the materials properties subject to very high temperatures/high neutron fluxes and to evaluate the potential of the graphite use in the core.

[3] To obtain electrical energy corresponding to an output of I GW over one year, an ordinary water reactor (PWR for instance) requires some 140 tons of natural uranium whereas with a breeder system 1.4 ton of fertile nuclei would suffice. See *Clefs du CEA*, CEA, N° 55-Autumn 2007.
[4] Transmutation: conversion of hazardous waste into stable substances or radioactive substances with short half-lives. The technology is still under development.
[5] Besides fission products, other elements contribute to the radioactivity in the core of a nuclear reactor: the actinides. Those elements have atomic numbers ranging from 89 (actinium) through 103 (lawrencium). They are all radioactive. In addition to the fissile Pu239, reactors produce other actinides in much lesser quantities, called for this reason minor actinides, such as neptunium 237, americium 241/242 and curium 244/245. Waste from a PWR consists of about 94% of uranium (about 93% of U238 and about 1% of U235), 0.1% of minor actinides and 4 to 5% of fission products.

The high outlet temperature of the VHTR affords the use of nuclear power for potential heat applications, specifically carbon-free hydrogen production.

In the US[6], a mid-size reactor with a thermal power of about 600-800 MWth and a coolant outlet temperature of 1000°C or above, using coated fuel particles[7] in a once-through low-enriched uranium fuel cycle capable of very high burn-up, is being developed. The reactor is designed to guarantee passive decay heat removal during accidents in order to preclude radioactive release.

In Japan, Fuji Electric is advancing research and development with the goal of achieving the practical application of a modular HTGR on a commercial scale aimed at realizing thermal power of 600 MWth and an outlet temperature of 950°C.

Modular HTGRs have the following features:

- Natural cooling during an accident. Thanks to its rather small size, the decay heat of this type of reactor can be removed adequately by natural cooling, even during accident. For example, even in the case of the loss of helium coolant due to, for example, rupture of the main cooling pipe (a loss of coolant accident), heat will be removed from the reactor building naturally through the soil and atmosphere (reactor cavity cooling system: passive cooling by ventilation with natural draft air);
- Passive shutdown of reactor at the time of an accident. In general, a reactor using low enriched uranium or plutonium fuel has a characteristic whereby, as the temperature of the core rises, negative reactivity feedback acts so as to mitigate nuclear reactions naturally (capture of neutrons by U238 or any other matrix such as thorium or inert matrix, is enhanced with temperature).
- Radioactive materials are retained in fuel particles after an accident. The integrity of the fuel will be maintained solely by natural physical phenomena. Accordingly, radioactive materials accumulated in the core will be reliably contained in the fuel, and there is no need for a pressure and leak proof containment vessel as in the LWR."[8]

GFR, Gas cooled Fast Reactor (helium)[9]

This technology "associates the advantages of fast spectrum systems for long term resources sustainability, in terms of use of uranium, and waste minimization (through fuel multiple reprocessing and fission of long lived actinides) with those of the high temperature (high thermal cycle efficiency and industrial use of the generated heat for hydrogen or industrial processes).[10]

The components of the reactor core are simultaneously exposed to very high temperatures and very strong radiation, essentially from neutrons, and consequently must have the required mechanical characteristics to resist such very hard operation conditions to avoid brittleness, swelling or creep.

This competitive and efficient reactor can generate as much fissile material as it consumes and is recycling all actinides.

Reference concept: 1,200 MW_e with a cycle efficiency of more than 45%. "The fuel compound is made of pellets of mixed uranium-plutonium-minor actinide carbide. A leak tight barrier made of a refractory metal or of a Si-based multi layer ceramics is added to prevent fission products diffusion through the clad."[11]

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[6] *The Very High Temperature Reactor: A technical Summary*, MPR Associates Inc., June 2004.

[7] The particle is composed of a kernel of fuel and several coating layers. A traditional four layer particle, for instance, consists of a buffer layer (surrounding the kernel of fuel) of low density carbon that acts as an expansion space to collect the released gases; the inner pyrocarbon layer that provides a smooth surface for the silicon carbide layer; the silicon carbide SiC) layer itself and the outer pyrocarbon isolating the SiC layer from the matrix that binds the particles together, limiting differences in the thermal expansion of the particles.

[8] Fotoshi Okamoto et al., *Fuji Electric Review*, Vol. 56 N°4.

[9] Reactor using little or no moderator, fission being caused by fast neutrons i.e. neutrons which have lost little energy by collision.

[10] P. Anzieu et al., *Gas-cooled fast reactor (GFR): overview and perspectives*, GIF Symposium, 9-10 September, 2009.

[11] *Ibid*.

Some advantages of helium as a coolant:

- Good chemical compatibility with structural materials;
- totally inert coolant;
- optically transparent;
- low positive void effect and hence low risk of core disruptive accident;
- hard neutron spectrum which increases the breeding potential of the reactor;
- potentially high temperature (850°C) heat delivery for industrial processes;
- passive devices intended to assure shutdown under accidental conditions when all other active control systems have failed.[12]

Some disadvantages of helium as a coolant:

- Need to maintain high pressure in the system, typically around 7 MPa;
- higher pumping power compared to liquid coolants;
- high coolant flow velocity can lead to significant vibrations of the fuel pins;
- decay heat extraction from the high power density core is difficult, becoming more so following a depressurization event;
- small thermal inertia of the core which requires a specific safety approach.

SCWR, Supercritical Water cooled Reactor[13]

The SCWR is a nuclear reactor cooled with light water in its supercritical state i.e., temperature and pressure being respectively above 374°C and 22.1 MPa[14] (the critical point): up to 600°C and 250 kg/cm^2.

Under such physical conditions, the water is always in a single fluid state, in other words the distinction between liquid and gaseous phases disappears. It is featured by a direct once-through cycle whereby the supercritical water from the core is used directly in a steam turbine.

The SCWR concept (with its many synergies with the basic Candu-Canada Deuterium Uranium- design) allows much higher efficiency (up to 45%) than PWR reactors because of high temperature, high specific heat which enables greater heat transfer per unit volume (higher power density) and consequently lower flow rate, and improves the economics through simplification of the balance-of-plant (among others: no steam generator and no steam separator) and smaller pumps, piping and associated equipment.

However, there is a large density difference along the coolant course through the core which is expected to induce flow instabilities. These latter can be mitigated by increasing the pressure loss of the core inlet orifices adjusting the flow to each assembly.

A number of other challenges must be addressed. Let’s mention two of them:

- The feasibility of the SCWR depends on whether materials can be found that can withstand high temperature, pressure and radiation;
- High operating temperature and pressure can induce heavy stresses on the structures. Creep (slow plastic deformation of materials under constant stress) is a cause for concern. Indeed, creep that accumulates over the years is a limiting factor for the operating life time of the reactor.

The single most important variable that is likely to impact the practical operation of the SCWR is the chemistry of supercritical water in the presence of radiation and in particular the radiolysis of the water in the presence of radiative flux and the thermal decomposition of the water due to the high operating temperature. The situation will be exarcerbated in a fast spectrum fuel cycle environment, where higher

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[12] For instance, an absorber could be stored in a sealed storage tank. When the seal melts due to overheating, the absorber is released into the core.

[13] Most of the technical details relating to the SCWR concept are taken from Satyen Baindur, "Materials challenges for the supercritical water-cooled reactor", *Bulletin of the Canadian Nuclear Society*, Vol.29 N°.1, March 2008, 32-38 pp.

[14] 1 MPa (megapascal) = 10.197 kg/cm^2.

radiative flux will likely radiolyse more water, changing the equilibrium concentrations of the transient and stable species. The chemical potentials of oxygen and hydrogen peroxide that are formed in this process also affect the corrosion potential of the water.

An extensive testing and evaluation program is required to assess the effects that the above factors have on the properties of potential SCWR materials, as no nuclear reactor has yet been built using supercritical water as the coolant.

It is also worth mentioning that a fast SCWR could be a breeder reactor and could burn the long-lived actinide isotopes.

SFR, Sodium cooled Fast Reactor and LFR, Lead cooled Fast Reactor

The requirement of a fast neutron spectrum for an efficient breeding and TRU (transuranic) incineration implies the usage of coolants with low moderating power, such as sodium, lead, lead/bismuth or helium. The helium scheme has been discussed above. In this section, the focus is on sodium (sodium-cooled fast reactors have already been built- Phenix, BN-600, JOYO and BOR-60-, and can be further improved) and lead.

"Sodium features a reasonably low melting temperature (98°C), but also a low boiling point (883°C)[15], which raises safety concerns regarding unprotected transients leading to a coolant heat up. Sodium exhibits high chemical activity with water, water vapor and air; a limited sodium leak and fire has stopped the operation of the Japanese MONJU reactor since 1995.

The choice of lead and lead-alloys as coolants is motivated on the one hand by their high boiling temperature (1,740°C)[16] and high melting point (327°C), which avoids the risk of boiling. On the other hand, lead and lead alloys are compatible with air, steam, CO_2 and water and thus no intermediate coolant loop is needed as in the sodium-cooled system… The neutron mean free path in sodium is larger than that of lead. Therefore, the leakage of neutrons and their contribution to overall neutron balance in the system is more significant for sodium… the lead-alloy cooled systems would be better than for sodium-cooled counterparts having the same geometry…

Considering the typical core lattice design configurations, the LFR showed to have advantages over SFR regarding behavior in severe accidents, Unprotected Loss of Flow-ULOF-and Total Loss of Power-TLOP. This is due to better natural circulation behavior of LFR design and the much higher boiling temperature of lead. Moreover, chemical inactivity of lead excludes possibility of fires or other strongly exothermic reactions with air, water and water vapor. The LFR appears to have also an economic advantage since it does not need an intermediate coolant circuit and the number of reactor outages can be limited."[17]

However lead at high temperatures is relatively corrosive towards structural materials which requires a careful control of lead purity and accurate choice of structural materials. In any case, temperature must be maintained above 350°C because lead's high boiling point.

Corrosion and material characteristics of steels need further investigations under irradiation conditions.

Lead like sodium is opaque, so that in service, inspection remains to be properly addressed.

A lead-bismuth eutectic (LBE) coolant could also be used. "However LBE has two major drawbacks. The first one is represented by bismuth transmutation into highly radioactive α-emitter polonium210 by neutron capture, which limits the access to the reactor and requires extensive use of robotic systems. The second

[15] Compared to other coolants such as lead (Pb or Pb-Bi).

[16] High boiling point has a beneficial impact on the safety of the system whereas the high melting point requires technical solutions to prevent freezing of the coolant, especially at reactor shutdown and refueling.

[17] Comparison of sodium and lead-cooled fast reactors regarding severe safety and economical issues, Kamil Tucek et al., *Joint Research Centre of the European Commission*, May 2005.

one deals with recrystallization: LBE undergoes expansion in the solid state which damage the mechanical structures in case of freezing."[18]

Lead is considered as a more attractive coolant than lead-bismuth eutectic mainly due to its higher availability, lower price and lower amount of induced polonium activity.

MSR, Molten Salt Reactor

In a molten salt[19] reactor (MSR), the fuel is dissolved in a fluoride salt coolant, such as uranium tetrafluoride (UF4). Fluoride salts are favored because fluorine has only one stable isotope (F-19) and it does not easily become radioactive under neutron bombardment. Earlier, MSRs were thermal-neutron-spectrum reactors. Currently, fast spectrum MSRs are being developed to extend fuel supplies and to burn minor actinides. Decisions on minor actinides burning may have major impacts on the preferred methods to ensure fuel sustainability. The 1st rule of waste management is to limit the generation of waste.

"Two fertile materials (Th232 and U238) can be converted to fissile materials and form the basis of long term sustainable closed fuel cycle. Th232 plus a neutron yields fissile U233 and U238 plus a neutron yields fissile Pu239. The uranium-PU239 fuel cycle generates large quantities of transuranic (TRU) actinides. The Th233-U fuel cycle generates much less TRU, because it takes many neutron captures to convert U233 to TRU isotope.. If society requires that actinides be destroyed to assist waste management, serious consideration must be given to fuel cycles to minimize both the production of actinides and the cost associated with actinide destruction".[20]

In the core, fission occurs within the flowing fuel salt, which then flows into the primary heat exchanger, where the heat is transferred to a secondary liquid salt coolant. The fuel salt is purified and then flows back to the reactor core.

The reactor has a built-in thermostat. If it starts to heat up, the salt expands, spreading out the fuel and slowing the reactions which allows the mixture to cut off. In the event of a power outage, a stopper at the bottom of the reactor melts and the fuel and salt flow into a holding tank, where the fuel spreads out for the reactions to stop. The salt cools and solidifies, encapsulating the radioactive materials.

Thanks to their high boiling points molten salt and particularly suited for very high temperature reactors (VHTR).

There are two constraints on MSR operating temperatures. The minimum temperature is determined by the temperature required to have good physical properties as a coolant. This temperature is typically 50 to 100°C above the melting point of the salt. The peak operating temperature of a MSR is limited by the materials of construction because the boiling point of these salts are all above 1,200°C, even above 1,400°C for most of them, above the limits of current materials of construction.

A major challenge is that molten salts are highly corrosive, all the more so when the temperature of the coolant rises. Therefore, for the primary cooling loop of the MSR, a material is needed that can withstand corrosion at high temperatures and intense radiation. Carbon composites appear to be suitable. Long-term experience with production scale reactors has still to be gained.

[18] "Lead-cooled fast reactor (LFC) development gaps", M. Tarantino et al.

[19] The melting points of molten salts are comprised between 350 and 500°C whereas the boiling points of most molten salts being considered are ≥ 1,400°C.

[20] Thermal-and-Fast-Spectrum Molten Salt Reactors for Actinide burning and Fuel Production, Charle W. Forsberg, Oak Ridge National Laboratory.

C | Small Modular Nuclear reactors

Small modular reactors offer the advantage of lower initial capital investments (due to modular components and factory fabrication), scalability and siting flexibility at locations unable to accommodate more traditional larger reactors. They also have the potential for enhanced safety and security.

The term modular refers to the ability to fabricate major components of the nuclear steam supply system in a factory environment and ship to the point of use.

SMRs are envisioned to require limited on-site preparation and substantially reduce the lengthy construction times that are typical of the larger units.

Some advanced SMR designs can produce a higher temperature process heat for either electricity generation or industrial applications. Some will be designed to operate for extended periods without refueling. These SMRs could be fabricated and fueled in a factory, sealed and transported to sites for power generation or process heat, and then returned to the factory for defueling at the end of the life cycle.

To date, none of the existing SMR concepts have been designed, licensed or constructed. The US department of energy (DOE) believes that SMRs may play an important role in addressing the energy economic and climate goals of the US if they can be commercially deployed within the next decade.

On April 15, 2013, the Babcock&Wilcox mPower, Inc. (B&W mPower), and the Us department of Energy have signed a cooperative agreement for funding made available through DOE’s SMR Licensing Technical Support Program for the development and licensing of B&W’s mPower technology.

The mPower America team includes B&W, the Tennessee Valley Authority (TVA) and Generation mPower. Commercial demonstration of the B&W mPower SMR is scheduled by 2022.

The B&W reactor is a 180 MW_e advanced integral pressurized water reactor. The reactor incorporates technology innovations with the advanced state-of-the-art in nuclear plant safety, security and economics.

D | Alternative fuel

Thorium is another possible feedstock. Its deposits are well distributed worldwide, most probably in much larger quantities than uranium and it produces less waste. However for its use in nuclear reactors, it must be converted into a fissile product: U233. Because of this additional process and other difficulties linked to the thorium nuclear properties, the generation of electricity with thorium as a fertile material, is more complex than that from U235.

Operating nuclear reactors with thorium (using molten salt as a coolant mixed with the fuel) is much safer and much cleaner from radioactive substances than current reactors and produces very little plutonium.[21] Moreover the use of thorium can make the nuclear production costs cheaper by 20-30%, needs ten times less fissile products for start up and produces thousand times less minor actinides than current reactors.

However a number of obstacles have still to be overcome. For example, the physical and chemical properties of the molten salt are not yet fully understood and the evacuation and treatment of the fission products are still being studied.

Today India is the most advanced country in the development of the thorium line although far from industrial maturity. The owner of the widest resources of natural thorium in the world, it already chose the site where the first reactor of this kind (with a capacity of 300 MW) will be installed. Building the reactor will last 6 years.

The Canadian Candu and molten salt reactors appear to be particularly fit for this type of fuel. However the latter type of reactor is still at the R&D stage.

[21] The amount of plutonium is about 80% less than the quantity produced in a reactor with the same power operating on uranium.

Israel is also very active in the development of this technology and in particular the nuclear engineering department of the Ben Gurion University.

E | General remarks

Temperatures of new generation reactors coolant range from about 500 to 1000-1200°C compared to less than 330°C for today's light water reactors.

It is significant that to address non-proliferation concerns, the fast neutron reactors are non-conventional fast breeding i.e. they do not have a blanket assembly where Pu239 is produced. Instead plutonium production takes place in the core where burn-up is high and the proportion of plutonium isotopes other than Pu239 remains high. In addition new reprocessing technologies will enable the fuel to be recycled without separation of the Pu.

With 4th generation reactors, all U238 (99% of the ore) and U235 (0.7% of the ore) will be used while in the reactors currently in operation, the chain reaction is sustained by thermal neutrons (slow neutrons) and the energy produced result from the fission of U235, the only uranium isotope directly fissile. As in the today reactors only a few slow neutrons can transmute U238 into Pu 239 (which is fissile) only a tiny proportion of the uranium ore is used.

According to the French CEA[22], with the 4th generation reactors, the world uranium reserves will secure 100 times[23] more nuclear power production than the current nuclear technology.

Moreover the ultimate nuclear waste restricted to fission products with minor actinides largely transmuted, would be much more easily stored.

Reactors of the 3d and 4th generation could be operated together from 2050 on (or earlier?). Indeed when the 4th generation will be operational, the third generation will still be performing well because they are designed for a 60 year lifetime and will not suffer a lack of fuel supply.[24]

Moreover 3d and 4th generation are complementary in terms of fuel: generation 3 produces Pu necessary for generation 4. Generation 4 burns Pu and spent fuel (minor actinides) from generation 3.

When mature, 4th generation reactors can sustain itself once it has been "lighted" thanks to the plutonium generated in thermal reactors and replaced by new one generated in the fast reactor itself.

[22] Commissariat à l'Energie Atomique, French government funded technological research organization.
[23] Or even more according to other sources.
[24] Transition to 4th generation is secured because proven reserves can cover more than 50 years expected consumption.

2 | Nuclear power strategies in some key countries

Nuclear power strategies are very different between countries and as a rule between Europe and the rest of the world. Whereas public opinion in a number of European countries and consequently their governments are anti-nuclear, most countries in the rest of the world are more pragmatic and less emotional in their approach to nuclear. To illustrate this, let us briefly review the situation in some key countries.

A | The United States

Despite a near halt in new constructions of more than 30 years, US reliance on nuclear power has continued to grow. The nuclear industry has also achieved remarkable gains in power plant utilization through increase of operating efficiency, maintenance and safety systems at existing plants.

In 1980, nuclear power plants produced 250 TWh (250 billion kWh) accounting for 11% of the country's electricity generation. In 2008, that output has risen to 809 TWh and nearly 20% of electricity. Much of the increase came from 47 reactors, all approved for construction before 1977.

The USA is the world's largest producer of nuclear power accounting for more than 30% of the world nuclear generation of electricity with 104 reactors totaling more than 100,000 MW_e.

It was scheduled that up to 6 new units may come on line by 2020. However lowest gas prices since 2009 have put the economic viability of some of these projects in doubt. Actually no more than 4 new units (AP 1000[25], 1200 MW_e) will come on line by that date.

In 2011, US electricity generation was 4,344 TWh gross, of which, essentially, 1,874 TWh (43%) from coal-fired plants, 1,047 TWh (24%) from gas, 821 TWh (19%) from nuclear, 351 TWh (8%) from hydro and 121 TWh (2.8%) from wind.

There are 69 PWRs (pressurized water reactors) with combined capacity of 67 GW_e and 35 BWRs (Boiling water reactors) with a combined capacity of 34 GW_e. Almost all the US nuclear generating capacity comes from reactors built between 1967 and 1990. There have been no new construction since 1977 because of cheap gas and Three Miles Island accident in 1979.

In all, about 90 reactors are likely to have 60 years lifetimes.

Today government R&D funding for nuclear energy is being revived with the objective of rebuilding US leadership in nuclear technology. In an effort that brings together government research laboratories, industry and academics, the Federal government has significantly stepped up R&D spending for future plants that improve or go well beyond current design. There has been particular attention to the Next Generation Nuclear Power Plant (NGNP) project (a generation4 high temperature gas cooled reactor). The DEO (Department Of Energy) has stated that its goal is to have a pilot plant ready at is Idaho national laboratory by 2021.

A high priority of the US Department Of Energy (DOE) is the deployment of Small Modular Reactor (SMR) technologies through the SMR Licensing Technical Support program.

SMRs offer the advantage of lower initial capital investment, scalability and siting flexibility at locations unable to accommodate more traditional large reactors.

The term "modular" refers to the ability to fabricate and assemble major components of the plant in factory and ship them then to the point of use. SMRs are designed to require limited on-site preparation and substantially reduce the lengthy construction times.

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[25] This passive (passive safety system) pwr reactor is the only generation 3+ reactor to receive Design Certification from the US NRC (Nuclear Regulatory Commission). It is also certified by the British ONR (Office for Nuclear Regulation).

Some SMRs will be designed to operate for extended periods without refueling. They could be fabricated and fueled in a factory, sealed and transported to sites for power generation or process heat and then returned to the factory for defueling at the end of the life cycle.

Babcock& Wilcox mPower, Inc and the US Department of Energy (DOE) have signed, in April 2013, a Cooperative Agreement for funding made available through DOE's Small Modular reactor (SMR) Licensing Technical Support Program for the development and licensing of B&W's mPower technology.

The signing of this agreement formalizes B&W's cost-share agreement with DOE, following the selection of the mPower America team- B&W, the Tennessee Valley Authority and Generation mPower (mPower and Bechtel) - as the winner of DOE's bid funding opportunity, in support of commercial demonstration of the B&W mPower SMR by 2022.

Transatomic Power, an MIT spinoff, is developing a nuclear reactor that it estimates will cut the overall cost of a nuclear power plant in half. It is an updated molten-salt reactor, a type highly resistant to meltdowns. The new reactor is expected to save money not only because it can be built in a factory rather than on site but also because it adds safety features- which could reduce the amount of steel and concrete needed to guard against accidents- and because it runs at atmospheric pressure rather than he high pressures required in conventional reactors.

B | South Korea

Korea's generation capacity of 80.5 GW in 2010 is expected to grow to 101 GW in 2022. In 2010, nuclear capacity was 17.7 GW (about 22% of total), supplying 30% of total.

Today 23 reactors totaling 20,700 MW_e supply about one third of South Korea's electrical energy.

The Korean government is firmly committed to nuclear. Four new reactors, currently under construction, are expected to be completed between 2014 and 2017, three of them being of APR 1400[26] design. The Ministry for Knowledge Economy announced plans for 59% of domestic electricity to be from nuclear by 2030.

It also declared its intention to be one of the major nuclear power reactors exporters.

"A South Korean consortium signed a contract to provide four commercial nuclear reactors to the United Arab Emirates (UAE)[27], signaling a new role for South Korea in the world nuclear energy market. The USD 20 billion deal indicates that South Korea has completed the transition from passive purchaser of turn-key nuclear plants in the 1970s to major nuclear technology supplier, capable of competing with the largest and most experienced nuclear technology companies in the world. The South Korean government reportedly has established a goal for South Korea to capture 20% of the world nuclear power plant market during the next 20 years".[28]

Korea Power Engineering Company (KOPEC) is the main designer and Dodsan, the main manufacturer. Kopec is developing an APR 1400-EUR for the European market, having double containment, core catcher and extra safety train.

[26] Advanced Power Reactor 1400 (APR1400) is a 1450 MW evolutionary PWR based on well proven Korean Standard Power Plant design derived from the System 80 of the US firm Combustion Engineering. It has a 60 year life time. The first two APR1400 nuclear power plants, currently under construction in South Korea, will be completed in 2013. The US-Korean nuclear energy cooperation is concluded under a "123 agreement" required by section 123 of the atomic Energy Act of 1954. The current agreement was signed in 1973 and will expire on March 19, 2014. As with most US 123 agreement, the existing US-Korean agreement requires US consent for any reprocessing or enrichment activities related to US-supplied materials and technology. Korea is requesting that the new 123 agreement includes US advance consent Korean future civilian reprocessing and enrichment activities. The US has opposed the idea on grounds of general non-proliferation policy (US congressional research service)

[27] The South Korean consortium headed by Kepco includes Pittsburgh-based Westinghouse Electric Company, which currently owns the US design on which the Korean design is based, and the Japanese Toshiba, which now owns most of Westinghouse. Because the APR-1400 is based on US design, US export controls will continue to apply

[28] Mark Holt, Congressional Research Service, January 28, 2013.

South Korea fuel cycle does include neither enrichment nor reprocessing, following the terms of its 1974 nuclear agreement with the USA which is to be renewed in 2014.

Recent reports suggest that a Korean enrichment plant, under international control, is a possibility with reprocessing being done in a third country such as Japan.

As far as radioactive waste management is concerned, used fuel is stored on the reactor site pending construction of a centralized interim storage facility with 20,000 t capacity.

After the Fukushima accident, each nuclear site safety was assessed. A number of measures were initiated such as raising of coastal barriers, watertight doors fitted to emergency diesel generator buildings, battery power supplies, vehicles with portable diesel generators, passive hydrogen removal systems non-dependent on electricity, and so on.

C | Japan

In July 2011, the Energy & Environment Council (ENECAN or EEC) was set up by the cabinet office as part of the National Policy Unit to recommend on Japanese' energy future to 2050.

METI has estimated that power generation costs would rise by over USD 37 billion per year, an equivalent of about 0.7% of GDP, if utilities replaced nuclear energy with thermal power generation. In February 2012, METI's Minister said that electricity costs would need to increase up to 15% while nuclear plants remained shut.

ENECAN "Innovative Energy and Environment Strategy" was released in September 2012, recommending a phase-out of nuclear power by 2040. In the short term, reactors currently operable but shut down would be allowed to restart once they gain permission from the incoming Nuclear Regulatory Authority, but a 40 year operating limit would be imposed.

ENECAN's energy policy framework focused on burning imported gas (LNG) and coal, along with expanded use of intermittent renewables provoked a strong and wide reaction from industry with a consensus that 20-25% nuclear was necessary to avoid very severe economic effects, not to mention high domestic electricity prices. The Keidanren (Japanese Business Federation) said the ENECAN phase-out policy was irresponsible and the head of the Liberal Democratic Party agreed.

Four days after indicating general approval of the ENECAN plan, the cabinet backed away from it, relegating it as a "reference document", and the prime minister explained that the flexibility was important in considering energy policy. The timeline was dropped. Reprocessing used nuclear fuel would continue and there is no impediment to continuing construction of two nuclear plants. A new basic energy plan will be decided after further deliberation and consultation, especially with municipalities hosting nuclear plants.

In any case, Japan's new Prime Minister, Shinzo Abe, taking office in December 2012, declared that nuclear energy is absolutely necessary for his country's economic development. However it will take time to restart the nuclear power plants because of testing procedures and for convincing the Japanese citizens.

D | France

France concentrates on two of the above selected systems: GFR and SFR.

A prototype of a 600 MW fast neutron, sodium cooled reactor is expected to be built by 2020 under a consortium made up of EDF, Areva, Alstom Power Systems, Comex Nuclear, Jacobs France, Toshiba and Rolls Royce. This project is named ASTRID[29]. This project benefits from a EUR 650 million French government loan for the period 2010-2017.

[29] Advanced Sodium Technological Reactor for Industrial Demonstration.

The purpose of this project is to commercialize, by 2040, a new type of nuclear reactor generating more energy at a lower cost with a reduced impact on the environment and a far smaller production of nuclear waste.

Besides this prototype, France is also working on the gas cooled reactor under an European consortium which will lead to the building of a small scale prototype called ALLEGRO in another country than France.

E | The United Kingdom

UK's office for nuclear regulation (ONR) is processing the Areva[30] EPR (European Pressurized Reactor) and Westinghouse AP 1000 for Generic Design Assessment (GDA).ONR and the environment agency jointly issued an interim design acceptance confirmation (IDAC) and interim statements on design acceptability (ISODA) for EPR and AP 1000 in mid-December 2011.

ONR issued on December 13, 2012, the DAC for the UK EPR nuclear reactor which remains valid for a period of 10 years from the date of issue. The provision of a DAC by ONR means that it is fully content with the security and safety of the generic design. The next step is the obtaining from ONR of a site specific license and any necessary consents for construction of that installation.

Plans for new nuclear power stations in the UK are going on in spite of setbacks resulting from withdrawal of E.ON, RWE and Areva from the Horizon project[31].

This leaves bids by a consortium led by Westinghouse and one by Hitachi whose nuclear technology is not yet licensed in the UK.

Nugen, owned by Spain's Iberdrola and France's GDF Suez are considering new reactors in Cumbria and are reported to make a decision by 2015.

Negotiations are underway between the UK government and EDF for the construction of two EPR reactors. The guaranteed electricity selling price is at stake, EDF offering a much higher price than UK government is prepared to grant.

F | Poland

To support its economic growth, Poland needs to secure power supply at an acceptable price. To assure energy independence from Russia and to meet EU targets, Poland is seeking to develop alternatives to coal (which currently is the fuel for 90% of the electricity production): nuclear and shale gas.

However for now, Poland is focusing on meeting its energy needs with fossil fuels. The final decision on nuclear energy is expected to be made by late 2014 or early 2015.

In October 2012, four leading Polish companies led by PGE joined forces to work on plans to create a 3000 MW nuclear facility by 2024 costing EUR 9-12 billion.

[30] Areva was created on September 3, 2001 by merging Framatome (now Areva NP), COGEMA (now Areva NC) and Technicatome (now AREVA TA). Its main shareholder is the French CEA (a public-sector company) owning 78,9%.

[31] Horizon nuclear power was formed in January 2009 with the aim of developing new nuclear capacity to help meet the UK's need for stable and sustainable low carbon energy.

G | Germany

Until 2011, 25% of German electricity production came from 17 nuclear power reactors (about 20,000 MW) which represented about 15% of the installed capacity.

This picture changed in 2011with the shutdown of 8 reactors, the remaining 9 nuclear power plants (about 12,000 MW) being scheduled to be closed by 2022.

This decision was taken in spite of the May 2011 report of the German reactor safety commission (RSK) concluding that all 17 reactors were basically sound and safe." It had reviewed all reactors and evaluated their robustness with respect to natural events affecting the plants, station blackouts and failure of cooling system, precautionary and emergency measures as well as man-made events affecting the plant, e.g. plane crashes…

Both houses of parliament approved construction of new coal and gas-fired plants despite retaining its carbon dioxide reduction targets, as well as expanding wind energy… France, Poland and Russia (Kaliningrad) are expecting to increase electricity exports to Germany, mostly from nuclear sources, and Russia is expected to export significantly more gas… Apart from contesting the fuel tax, all the nuclear generators are seeking compensation for the effective confiscation of generating rights from the 8 reactors ordered shut after Fukushima, despite safety assurances from the regulator…*Already* in 2007, Deutsche Bank warned that Germany will miss its carbon dioxide emission targets by a wide margin, face higher electricity prices, suffer more blackouts and dramatically increase its dependence on gas imports from Russia as a result of its nuclear phase-out Policy… If Germany were to proceed with its nuclear phase-out policy and maintains carbon reductions, by about 2020 it would need to import 25,000 MW of electricity as base-load. The country already has significant interconnection with France, the Netherlands, Denmark, Poland, Czech Republic and Switzerland. Connection With Russia's Kaliningrad where 2,400 MW Russian nuclear plant is being built, is envisaged and Russia expects to export half the output of that plant to Germany… This would put Germany in 2020 in much the same position as Italy today, being dependent on neighbours for electricity (which would mostly be nuclear)…Germany's decision to shut its nuclear plants will, despite its massive investment in new renewables, create an extra 300 million tonnes of CO_2 to 2020 from increased fossil fuel use… The Bundesnetzagentur on 30 September said that 25 new power plants with total 12,000MW were under construction, 67% powered by black coal and 17% by brown coal. While gas plants fit better as back-up for expanded renewables, they are less economic and gas supplies are uncertain".[32]

According to RWE, nuclear phase-out would cost EUR 250 to 300 billion to 2030 (without power station dismantling) and EUR 50 billion to extend nuclear power plant lifetime to 60 years.

3 | Nuclear fusion power

Fusion powers the sun and stars as hydrogen atoms fuse together to form helium thanks to massive gravitational forces. This reaction converts matter into energy.

When heated at a sufficient temperature, the hydrogen gas is ionized and turns into a plasma consisting of positive ions (hydrogen nuclei) and negative electrons. Normally, the fusion of hydrogen ions is not possible because of the strongly repulsive electrostatic forces preventing those positively charged particles to get close to each other. However, at very high temperatures (more than 100 million °C) ions are reaching speeds high enough to bring them close enough together so that the attractive nuclear force (active at short distances) outweighs the repulsive force. The nuclei can then fuse with a release of energy.

"With current technology, the reaction most readily feasible is between the nuclei of the two heavy forms

[32] World Nuclear Association, updated Report, January 2013.

(isotopes) of hydrogen-deuterium (D) and tritium (T). Each D-T event releases 17.6 MeV… Deuterium occurs naturally in seawater (30 grams/cm^3)… Tritium does not occur naturally and is radioactive, with half life of around 12 years. It can be made in a conventional nuclear reactor, or in the present context, bred in a fusion system from lithium.

Lithium is found in large quantities (30 parts/million) in the earth's crust and in weaker concentrations in the sea.

In a fusion reactor, the concept is that neutrons generated from the D-T fusion reaction will be absorbed in a blanket containing lithium which surrounds the core. The lithium is then transformed into tritium and helium. The blanket must be thick enough (about 1 meter) to slow down the high energy (14 MeV) neutrons. The kinetic energy of the neutrons is absorbed by the blanket, causing it to heat up. The heat energy is collected by the coolant (water, helium or Li-Pb eutectic) flowing through the blanket and, in a fusion power plant, this energy will be used to generate electricity by conventional method. If insufficient tritium is produced, some supplementary source must be employed such as using a fission reactor to irradiate heavy water or lithium with neutrons… While the D-T reaction is the main focus of attention, long term hopes are for a D-D reaction, but this requires much higher temperatures… At present, two main experimental approaches are being studied: magnetic confinement and inertial confinement. The first method uses strong magnetic fields to contain the hot plasma. The second involves compressing a small pellet containing fusion fuel to extremely high densities using strong lasers or particle beams…

The most effective magnetic configuration is toroidal, shaped like a doughnut, in which the magnetic field is curved around to form a closed loop. For proper confinement, this toroidal field must have superimposed upon it a perpendicular field component. The result is a magnetic field with force lines following spiral (helical) paths that confine and control the plasma (tokamak, stellarators and reversed field pinch (RFP) devices)…

In inertial confinement fusion, which is a newer line of research, laser or ion beams are focused very precisely onto the surface or target, which is a pellet of D-T fuel, a few millimiters in diameter. This heats the outer layer of the material, which explodes outwards generating an inward-moving compression front or implosion that compresses and heats the inner layers of material. The core of the fuel may be compressed to one thousand times its liquid density, resulting in conditions where fusion can occur. The energy released then would heat the surrounding fuel, which may also undergo fusion leading to a chain reaction (known as ignition) as the reaction spreads outwards through the fuel. The time required for these reactions to occur is limited by the inertia of the fuel (hence the name), but is less than a microsecond…

There are a number of major projects under development that may bring research to the point where fusion power can be commercialized…

Several tokamaks have been built, including the Joint European Torus (JET)… The ITER (International Thermonuclear Experimental Reactor) project currently under construction in Caradache, France, will be the largest tokomak… in Germany… the Wendelstein-7-X is under construction on the max Planck Institute's Greifwald site. Due to be completed by 2015, Wendelstein 7-X will be the largest stellarator[33] and it is planned to operate continuously for up to 30 minutes."[34]

As far as the ITER project is concerned (consortium consisting of the European Union, Japan, the USA, China, India, Russia and South Korea), the first experiment with D-T plasma is not expected before 2026. The goal is to operate at 500 MWth for at least 400 seconds continuously with less than 50 MW of input power. No electricity will be generated at ITER.

Nuclear fusion faces considerable problems. Hereafter two points in case among many others.

- Turbulence in the plasma is a major concern, causing it to escape the confinement area, and potentially touch the walls of the container. If this happens, high mass particles from the container are mixed in the fusion fuel lowering its temperature;

[33] A stellarator consists of a toroïdal vessel designed so that a plasma may be contained within it by a helical magnetic field.
[34] World Nuclear Association, Nuclear Fusion Power, October 2012.

- On the other hand, fusion reaction generates high energy neutrons. Whatever the electromagnetic confinement technique used, some of those neutrons cross the magnetic barrier to hit the vessel's wall. They ionized the atoms of this wall and produce electrons choking the fusion reaction. On top of that, those fast neutrons are bombarding the super conductive coils used for the confinement of the plasma. Hence not only the wall but also the coils are likely to be affected by the fusion reaction. These coils cannot be replaced during the project life.

4 | Conclusions

It is hard to anticipate which technology (ies) will emerge out of the six ones selected by the Generation 4 International Forum (GIF). To address people and governments concerns about nuclear hazards- especially people, because of their ever growing impact on the political decision making process- and to meet economical criteria, the reactors of the future must be:

- Safe, i.e. designed to resist:
  - Core meltdown, through a number of technical measures such as passive shutdown at the time of an accident;
  - terrorist attack;
  - diversion of materials for weapons. Fourth generation reactors are, in this respect safer than the previous generations.
- Sustainable which implies:
  - Saving natural resources;
  - to be environmentally friendly, with minimum spent fuel and radioactive waste, requiring much smaller repositories;
- Reliable and hence, among others, the extended investigation on materials resistance;
- Competitive. Extensive researches are being carried out to reduce investment costs.

Out of the six technologies selected by the GIF, the Gas cooled Fast Reactor (GFR), the lead cooled Fast Reactor (LFR) and, to a lesser extent, the Sodium cooled Fast Reactor (SFR) appear to be the most likely to meet above criteria in a not too distant future. As for the molten salt reactor (MSR), it could be a good candidate in a more distant future.

They are indeed fast reactors with closed fuel cycle which means that they contribute to sustainable development by using a much larger fraction of the uranium resources. On the other hand, the high number of excess neutrons available in fast reactors allows the transmutation of minor actinides which reduces the long term radioactivity of nuclear waste.

They both can generate as much fissile materials as they consume and are therefore potentially able to provide energy for the next thousand years with already known uranium resources.[35]

Moreover, they are recycling all actinides.

They have also developed innovative safety features, aiming to strengthen resistance to core fusion risks, such as passive anti-reactivity insertion devices or advanced core control systems.

Of course, the choice of coolant is dictated by the desire to introduce the smallest possible amount of absorption and moderation, while being able to reliably remove the heat from the high density core configuration.

Small Modular Reactors (SMRs) technologies are also being developed. They offer the advantages of lower

[35] ESNII (European Sustainable Nuclear Industrial Initiative) task force, established within SNETP (Sustainable Nuclear Energy Technology Platform), *Concept paper*, contribution to the EU low carbon energy policy.

capital investment, scalability and siting flexibility at locations unable to accommodate more traditional large reactors.

A number of European countries have already decided to proceed with nuclear power investments such as the UK, Poland, Romania, Lithuania while countries like France (that decided to reduce the nuclear share of power generation from 78% to 50% within 2025, a pure ideological decision which will increase the price of electricity and leads to important investments in infrastructures), Germany (in spite of its outstanding accumulated knowledge), Sweden and Belgium have started to phase out the existing nuclear power stations with the very negative impact on consumers bills, on competitiveness of the industry and on the stability of the power system. Spain has banned the construction of new reactors and Italy, Austria, Ireland, Luxembourg, Malta, Portugal, Norway and Latvia have no nuclear power plants.

Does it make sense to shut down existing second generation nuclear power plants and to deny oneself low cost and abundant energy whereas the European countries that took such decision, are struggling to reverse years of global manufacturing decline?[36]

Is it reasonable to ban new nuclear technologies whereas new generation reactors meet the objectives of the EU climate and energy package? Indeed, they do not emit CO_2, as nuclear power production never did by the way, they produce cheap, renewable (they will generate as much fissile materials as they consume) and sustainable energy as explained above. Moreover waste management is continuously improving through minor actinides transmutation, growing efficiencies and other technical innovations detailed in this paper. In the meantime, the US, China, India, South Korea, Russia and Mexico, to name a few, are going ahead with their nuclear investment programs. Even in Japan, where all but two of the country's 50 reactors are shut down for safety checks following the 2011 tsunami disaster, Prime Minister Shinzo Abe is backing a return to nuclear power to drive an economic revival and has made exporting nuclear technology a component of his economic plan.

Is it wise from EU "nuclear adverse" Member States to drop their unique expertise and the jobs relating to the nuclear industry for energy sources often more expensive and less sustainable?

Jean-Pierre SCHAEKEN WILLEMAERS

[36] Even Germany could face industrial decline if it does not curb its current policy of phasing out nuclear power and making simultaneously a dash at renewable (intermittent) energies.