

New trends for future reactors. A R&D review.

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ABSTRACT

Third generation reactors proposed to the market are mostly LWR, pressurized or boiling, with confirmed competitiveness. A special effort to increase the safety level is sensible and should be improved. At least, solutions are studied to better use plutonium. The development of a new generation of NPP's offers opportunity to have another step towards more safety, for example in being fail-safe, and towards a minimization of ultimate waste produced. In this field, CEA dedicates its main effort to the development of a gas cooled reactor and constraint on safety, waste minimization are indicated. At least some examples of progression in the safety level of a plant are shown from an existing one to an hypothetical future reactor.

Introduction

The growth in world energy demand and future prospects of decommissioning of existing nuclear plants stimulate the development of a new generation of nuclear energy systems. Those systems intend to be more competitive, safer and more sustainable. Public acceptance of nuclear energy depends strongly on safety, and on public's perception of safety. Consequently, a major challenge for next generations of nuclear systems is to improve the safety and the robustness of the technology, but also the public confidence in safety.

New trends in Light Water Reactors (LWRs)

At present time, 17% of the world electricity is produced using some 400 light water reactors, pressurized (PWR) or boiling (BWR), in operation in approximately 20 countries. Their design, developed some forty years ago, has gradually evolved towards units of increasing size, according to a scaling economy factor, but also with increasing complexity as they were required to meet more and more stringent safety criteria.

Those reactors, fuelled with little enriched uranium, are of moderate cost and very reliable. Their competitiveness will further increase in years to come, with an increase

in the service lifetime, from 40 years today to 50 and maybe 60 years, and with anticipated improvements in fuel performances by increasing the burn up from 52 GWd/t today to 70 GWd/t at the end of the decade.

The satisfactory efficiency achieved with this technology have logically led the manufacturers to design a new generation of reactors of similar type, so-called Generation III. The joint French/German pressurized water reactor EPR, the Korean pressurized water reactor APR 1400, the Americans BWR 90+ and CE 80+ or the American/Japanese boiling water reactor ABWR, belong to the same category. For some of them, a large electric output, i.e. around 1400 MWe was adopted. These reactors benefit from all the experience accumulated in the present generation, and a special effort of development has been done on safety, specially to limit the consequences of severe accidents. Also regarding safety, these large reactors increase grace periods for operator actions by designing components (e.g. pressurizer or steam generators) with larger water inventories in order to smoothen transients.

Another tendency, is to design projects of lower power, i.e. 600 to 1000 MWe, in order to make it easier to use passive safety features to recover easily from accidental situations. It is the case of ABB/Westinghouse projects AP600 and AP1000 or the Framatome/ANP SWR-1000. However, no industrial plant construction has yet been achieved out of those projects, whereas these passive reactors concepts seem very attractive.

A selected comparative table is given which shows the real tendency of safety features to increase on third generation systems compared to the present ones (See Table 1).

Nuclear industry worldwide has for a long time put as a priority the strict management of nuclear waste. However, even if the amounts of radioactive waste are very small compared to other toxic industrial waste (for instance in France : 600 kg/year of long lived high activity waste per TWhe), their faultless management remains an important issue for public acceptance, more especially for the long term. In particular plutonium, which is both a highly energetic element and the main contributor to the long-life radio toxicity of spent fuel, is regarded by nuclear opponents as a waste, even if this element will provide the fuel of tomorrow.

It could be recycled in the present PWR and in the future EPR for instance, in order to stabilize the plutonium inventory and to avoid the deep geological storage of significant quantities of this element. Complementary studies are being carried out to illustrate the ability of the EPR reactor to consume plutonium, and potentially, certain minor actinides.

The development of new plutonium assemblies, CORAIL and APA (*Advanced Plutonium Assembly*), will make plutonium recycling in LWR possible. The new CORAIL assembly, made of UOX and MOX standard rods, could be, after conception studies and qualification in a reactor, rather quickly industrialized by 2010. APA could enable the consumption of even more plutonium. Its implementation will require fuel development, neutronic and thermal-hydraulic detailed qualification. These Advanced Plutonium Assemblies could be ready for industrialization by 2020.

Company	Type	Power, MWe	Severe core damage frequency	Molten core recovery	Passive systems	Containment	Operating exposure, man.Sv/y
-	Current PWR	900	10^{-4}	no	no	Simple pre-stressed concrete	>2
FRA-ANP	EPR	1550	5.10^{-7}	External core catcher	no	Double, reinforced	0.5
GE	ABWR	1350	10^{-7}	In vessel	no	Reinforced	<1
ASE	VVER 91/99	1050	-	Basement crucible	no	-	-
ABB/Westing.	AP1000	1000	-	In vessel	important	-	-
ABB/Westing.	BWR 90+	1500	5.10^{-7}	External core catcher	no	Reinforced	
FRA-ANP	SWR-1000	980	5.10^{-8}	In vessel	Combined with active ones	Highly reinforced, cooled	<0.5
GE	ESBWR	1190	-	Large spreading area	important	Water cooled	-
RDIPE	VK-300	250	2.10^{-7}	External refractory container	Natural circulation	Underground, reinforced	-

Table 1 : Example of some generation III LWR safety characteristics
(values from open literature)

Goals for future nuclear energy systems

Nuclear energy has unique advantages to meet requirements for a sustainable development in terms of economical competitiveness, safety, environmental friendliness and natural resources saving. Whereas progress towards these goals can only be achieved for existing reactors through optimizing the fuel cycle, some flexibility is available to make substantial progress on future systems while developing promising technologies for reactors, fuels and the fuel cycle.

The goals for future nuclear energy systems are a matter of active debate internationally, and especially in the framework of the Generation IV International Forum under the auspice of US-DOE. The French vision of these goals are especially ambitious for those regarding sustainability; they can briefly be summarized as the following:

- reinforce economic competitiveness compared to other available energy generation supply, with a special emphasis put on reducing the investment cost;

- enhance passive safety, especially through an increased resistance to core damages during severe accidents and through limitation of potential hazards generated for workers, for the public and for the environment;
- minimize production of long lived radioactive waste;
- save resource through an optimized utilization of the available resources of fissile and fertile materials (*natural and depleted uranium, thorium*)
- develop potentialities for other applications than electricity supply, hydrogen production and sea water desalination.

Significant progress towards these objectives and also for opening new applications to nuclear power, call for breakthroughs beyond light water reactors, towards hardened neutron spectra and high temperatures of the coolant. Moreover, spent fuel processing and nuclear materials recycling are recognized as essential technologies for minimizing long-lived radioactive waste and for making an efficient utilization of all available fissile and fertile nuclear fuels.

For the sake of consistency of the reflection on future nuclear energy systems, the reactor, the fuel and the associated fuel cycle are addressed as integral parts of a nuclear system to be optimized globally.

Trends for future systems

In the field of future nuclear systems, which brings together the whole international nuclear community, there is already a very good consensus about the criteria which the future systems will be expected to meet. These criteria are stated here in the order which appear at this time to be the order of importance. That is the order we should use when assigning priorities :

- The first criterion is competitiveness, with the objective of meeting the world's energy needs at reasonable cost.
- The second criterion relates to system safety. To expand widely nuclear energy applications, future systems will have to be fail-safe (or even accident free) so as to eliminate risk, even in those cases when they are operated under difficult conditions.
- The third and the fourth criterion respectively relates to minimization of ultimate waste for a given produced energy and to optimization of the energy extracted from the fuel for a given amount of it. Future systems should also be as proliferation-proof as feasible.

Future systems will also have to answer new demands :

- Hydrogen will play a major role in transportation in the future more for reasons of limiting pollution than for long-term concerns for resources. Moreover, nuclear production of hydrogen would avoid the production of carbon dioxide while saving oil reserves.
- The challenge of drinking water for major urban areas around the world will also inevitably lead to a reassessment of ways for the desalination of sea water.

- The direct use of heat, new systems compatible with unsophisticated networks, which were, so far, the subject of only limited or experimental applications, could open new fields for future nuclear energy systems.

Prospects for future gas cooled systems

Gas coolants, specially helium, and the high temperature reactors technology appear promising for the development of a new generation of Gas Cooled Reactors, GCR. They offer attractive characteristics consistent with the criteria assigned to the next generation of systems to be brought out by industry in the years 2020-2030 :

- Economics : with the simplicity of a single performance with a gas that goes directly to the turbo-alternator, standardised construction in factory with elementary modules of several hundreds MWe and fast construction which means less capital outlay.
- Safety and security : with conducting, refractory and highly confining fuel which could enable a very robust behaviour in the case of accidental transients, with little interaction with the coolant.
- Environmental protection : with minimisation of radioactive waste and optimised use of resources which lead, by the way, to fast spectrum core design.
- Last but not least, high temperature gas cooled reactors will be suitable for other applications such as hydrogen production for transport or desalination. It could be the two major stakes for humankind and environment in the decades to come.

The potential of gas coolants in these areas must be confirmed and several international R&D programmes are already under way. The GCR technology range covers a variety of applications and it can be developed step by step :

- On the short term, direct cycle HTRs, as for instance the GT-MHR or the PBMR, could be implemented. These concepts are resulting from developments made in the 70's-80's, and from modern gas turbine technology.
- On the medium term, specialised CGR could be developed such as :
 - A very high temperature GCR for high thermodynamic efficiency and hydrogen production through a thermo-chemical cycle or through a high efficiency electrolysis,
 - A robust GCR model for countries without experience and/or infrastructure in the field of nuclear power production.
 - An optimised GCR for transmutation of radioactive waste could also be considered.
- On the long term, GCRs with fast spectrum for an optimum use of fuel resources, and with an integrated cycle for transmuting all the actinides, could be implemented for a sustainable nuclear power production.

Coming back to the tendency indicated in Table 1 for safety trends, we can add now the challenge that Generation IV systems would have to accept (see Table 2).

Company	Type	Power, MWe	Severe core damage frequency	Molten core recovery	Passive systems	Containment	Operating exposure, man.Sv/y
-	Current PWR	900	10^{-4}	no	no	Simple pre-stressed concrete	>2
-	GEN III	1000-1400	5.10^{-7}	Core catcher	no	Reinforced	0.5
-	GEN IV	300-1000	$<10^{-7}$	Yes, for in depth defense	important	Highly reinforced	<0.5

Table 2 : a possible tendency for safety trends on future systems.

Comments have to be done on this tendency. First there is a competition between power and safety as it is easier to use passive features with a restricted core power. But available studies are showing that the investment cost per kWe is raising while the total power is decreasing. Appropriate answers will come from more and more simplified design and geometry of the system taking advantage of the most recent technologies.

Severe core damage will be eliminated as far as possible by an appropriate design, using for instance refractory materials for internal structures and a high global thermal conductivity to avoid core melt down.

Passive systems will be developed and used, with active ones when needed, within the objective of simplified safety demonstrations.

External and internal hazards related to severe accidents, as for instance generalized fire, major earthquake, explosion or impact will be taken into account to design the containment.

Conclusion

Future nuclear systems intend to be more competitive, safer and more sustainable. Concerning the second point, while looking at the general tendency of advanced LWR to address severe accidents in their design and to reduce potential hazard, one can extrapolate the challenge that next generation of reactors will have to accept. A lot of R&D is needed to get significant progress for this new generation. Among it, gas cooled reactors offer attractive characteristics and are already being studied in France.