C. R. Physique 13 (2012) 352–358

Contents lists available at SciVerse ScienceDirect

Comptes Rendus Physique

www.sciencedirect.com

Science of nuclear safety post-Fukushima

Third generation nuclear plants

Les réacteurs nucléaires de troisième génération

Bertrand Barré[1]

INSTN, point courier 35, centre CEA de Saclay, 91191 Gif-sur-Yvette cedex, France

ARTICLE INFO

Article history:
Available online 23 April 2012

Keywords:
Nuclear plants
Safety
Accident prevention
Accident mitigation
EPR

Mots-clés :
Réacteur nucléaire
Sûreté
Prévention des accidents
Mitigation
EPR

ABSTRACT

After the Chernobyl accident, a new generation of Light Water Reactors has been designed and is being built. Third generation nuclear plants are equipped with dedicated systems to insure that if the worst accident were to occur, i.e. total core meltdown, no matter how low the probability of such occurrence, radioactive releases in the environment would be minimal. This article describes the EPR, representative of this “Generation III” and a few of its competitors on the world market.

RÉSUMÉ

L’accident de Tchernobyl a conduit à concevoir une nouvelle génération de réacteurs à eau ordinaire, dont plusieurs exemplaires sont en cours de construction. Ces réacteurs de troisième génération sont équipés de dispositifs et de dispositions dédiés à assurer que s’il se produit l’accident maximum que constitue la fusion totale du cœur, et aussi faible que soit le risque d’un tel accident, les relâchements de radioactivité dans l’environnement soient minimes. Cet article décrit l’EPR, archétype de cette « Génération III » ainsi que certains de ses concurrents sur le marché mondial.

1. Nuclear plant “generations”

It is only since 1999, when the US Department of Energy took the initiative which led to the Generation IV International Forum GIF that we classify the nuclear power plants and, more widely, the nuclear power systems including the NPP and the associated fuel cycle, in terms of successive “generations”:

Generation I covers the plants of the pioneer era, a succession of various prototypes of rapidly increasing power ratings, without any standardization or series effect. Almost all those plants are now shut down and at various stages of decommissioning.

Generation II is made of the 400 or so nuclear power plants in operation throughout the world, which generated together in 2010 slightly less than 14% of the world electricity. As shown in Fig. 1, two thirds of these plants belong to the Pressurized Water Reactor (PWR) type, including the Russian version called VVR. A quarter of the plants are Boiling Water Reactors BWR and the remaining gathers British gas-graphite reactors, Russian RBMKs of the Chernobyl

---

E-mail address: bcbarre@wanadoo.fr.
URL: http://www.bertrandbarre.com.

[1] Scientific Advisor to AREVA.

1631-0705/$ – see front matter
http://dx.doi.org/10.1016/j.crhy.2012.03.002

family and, in a "niche" position, Pressurized Heavy Water Reactors of Canadian origin. Within the fleet of plants under construction, Light Water Reactors and notably PWRs are even more dominant.

Generation III nuclear plants, described in the present article, are still under construction. They are either PWRs or BWRs of a technology close to that of the previous generation, but upgraded to take full advantage of the lessons learned from the Three Mile Island (TMI2) and Chernobyl accidents.

And while "Gen I" plants are being decommissioned, "Gen II" plants are generating power and "Gen III" plants are under construction, a number of countries gathered within the GIF co-operate to develop future *Generation IV* nuclear *systems*, optimized to fit the constraints anticipated for the second half of the XXIst century. This new generation of nuclear systems will probably not be deployed until the world fleet of operating nuclear plants has reached a size such as to question the possibility of feeding with uranium new reactors over their full anticipated lifetime (a date impossible to forecast with a degree of certainty today).

This classification appears simple, but the border between generations II and III depends upon the precise definition of the latter – and there is no universally accepted definition for it. Commercial competition induces vendors to keep the border fuzzy by introducing concepts like generations II+, III, III+ or even III++ without any objective basis. In the present article, we shall only use the term generation III with the following criterion: a nuclear plant belongs to this generation if it is equipped with dedicated systems to insure that if the worst accident were to occur, i.e. total core meltdown, no matter how low the probability of such occurrence, radioactive releases in the environment would be minimal, so that no people around would have to be durably evacuated nor any agricultural land durably condemned.

This constitutes a distinct difference with generation II systems which are dimensioned to resist a Design Basis Accident DBA that is not the worst possible accident.

2. Lessons learned from TMI2 and Chernobyl

From the early days of nuclear power, nuclear safety relies upon "defense in depth" against the risks of an accident or a simple incident. This defense is notably based on the redundancy and the diversity of safety relevant components and systems in order to mitigate material failures.

The main lesson learned from Three Mile Island was that designing and building a safe plant is not enough: it is the couple "plant + operator" which must be safe. If both do not communicate well with each other, the consequences may be catastrophic.

In fact, the plant operators were fooled by ambiguous information in their control room: a light was signaling that the automatic control system had ordered the closure of a power operated relief valve located on top of the pressurizer, after having triggered its opening to relieve a pressure peak in the primary circuit. The operators interpreted this signal as meaning that the valve was physically closed and that, therefore, the primary circuit was leaktight again. For the next two hours, the operators fought against the automatic emergency system to prevent sending water in the primary circuit which was losing its cooling water through the open valve. Less and less cooled, the reactor core overheated because of the decay heat generated by the decay of fission products, until meltdown occurred.

As a result, the TMI2 accident taught us to take into account the human factor in the defense-in-depth assessment:

- New control room design (ergonomy, presentation on screens of unambiguous data, alarms hierarchization);
- Periodic training of plant operators on full-scale simulators;
- No interference with the automatic emergency systems during the first phase of a potential accident;
- "*Approche par états*": rather than attempting to identify the accident scenario, with the risk of mistake, identify the main parameters of the facility (temperatures, pressure, water levels, etc.) before taking the control to bring it to safe shutdown;
- Creation in the EDF production centers of the specialized job "Safety Engineer";
- Definition of "ultimate procedures" to limit the consequences of a severe accident;
- Introduction of hydrogen recombiners in the containment building and of sand filters to trap radioactive aerosols before any release to the exhaust stack;
- In the USA, creation of INPO, Institute of Nuclear Power Operators to establish and promote "best practices".

The TMI2 accident did also underline the risks associated with a "small breach LOCA" in the primary circuit, more insidious than the large breach LOCA that was the basis used to design and dimension the emergency core cooling systems. It was at the origin of the constitution in France of a "plural" expertise (EDF, CEA, IPSN and Framatome) on the thermal hydraulics of accidents in PWRs.

The Chernobyl accident was too specific of the RBMK family of reactors for any lesson to be drawn to prevent this kind of accident in light water reactors, but it taught nevertheless three major lessons:

1. The containment building is a major element to limit the environmental and sanitary consequences of a severe accident. It is therefore necessary to protect it against the various aggressions due to the accident itself: hydrogen explosion,

steam explosion, overpressure, corrosion of the concrete basemat by the "corium" and progressive loss of mechanical properties of the concrete when submitted to heat for a long period;

2. No matter how low its probability of occurrence, a massive radioactivity release is unacceptable: preventing severe accidents is not enough, on must guarantee the limitation of its consequences outside the plant ("mitigation");
3. The use in neighboring countries of different safety and radiation protection norms had a very detrimental effect on the acceptance of nuclear power by disoriented citizens.

The first two lessons from Chernobyl are really at the origin of the "generation III" of nuclear power plants: Their Design Basis Accident is now total core meltdown, and this accident must not make it necessary to relocate neighboring populations or to durably condemn agricultural productions around.

The third lesson induced the French and German Safety Authorities to get together and issue in 1993 joint directives, while all the European electrical companies did jointly develop the EUR, European Utilities Requirements document. Based on these directives and these requirements, Framatome, Siemens, EDF and a few German utilities jointly designed the EPR, the archetype of Gen III nuclear power plants.

3. The generation III models

Gen III reactors belong to both LWR families.

The PWR branch comprises the EPR of AREVA, the AP 1000 of Toshiba–Westinghouse, the VVR AES 92 of Rosatom, the APWR of Mitsubishi and the ATMEA jointly developed by AREVA and Mitsubishi. Whether the Korean APR1400 is Gen III is debatable because its proposed management of a molten core is not fully convincing.

The BWR branch is shorter: the ABWR of General Electric and Hitachi, GE's ESBWR and AREVA's Kerena.

APWR, ATMEA, ESBWR and Kerena have not yet been ordered; the others have units under construction: 2 ABWR in Taiwan, 2 APR1400 in South Korea, 2 AES 92 in India, 4 AP 1000 in China and soon 2 more in the USA, and 4 EPR in Finland, France and China.

3.1. APR1400 [1]

The APR1400 is a large (1450 MWe) evolutionary PWR modernized by South Korea from the System 80+ of Combustion Engineering (now absorbed within Toshiba–Westinghouse). The primary circuit comprises two loops, each of them being equipped with one large steam generator, one hot leg and two cold legs and two primary pumps connected to the cold legs. In one of the loops, a large pressurizer is connected to the hot leg. There are four emergency core cooling trains, each of which has only a 50% capability to insure safe shutdown. The single concrete containment building is equipped with an internal steel liner. The nuclear plant is made of two twinned units which share a number of auxiliary buildings. This setup saves on investment but is not immune from the risks of human error during maintenance. In case of full core meltdown, the corium would supposedly be solidified in situ through the pressure vessel by flooding the vessel pit: this may be doubtful for a reactor of this size.

3.2. AP 1000 [2]

The AP 1000 is an extrapolation in size (1200 MWe) of the AP 600, designed by Westinghouse during the 1980s to be a "revolutionary" reactor, relying much more on passive safeguard systems than on active ones.

The primary circuit (Fig. 1) comprises two "mixed" loops as does the APR1400, but the primary pumps, wet canned, are directly connected to the bottom end of the stream generators. The containment is made of a single steel shell located within a concrete chimney. This chimney is topped by a large annular water tank which gives to the plant a characteristic profile. Within the containment is a large in-containment refuelling water storage tank IRWST, two core makeup tanks and two accumulators (there is no emergency injection pump).

If a breach develops on a primary pipe (LOCA), the water from all these tanks would flood automatically the bottom of the containment shell, creating a kind of pool, and the water level would reach the bottom part of the steam generators. As a result, the breach would be under water. The core would therefore be cooled, under natural convection, via the breach itself and the decay heat would be transferred to the "pool" (Fig. 2). The water of the pool would then evaporate, but the steam would condense on the wall of the steel shell and the condensed water would flow back into the pool, thus compensating the evaporation. During the first hours after the accident, the shell would be externally cooled by water flowing by gravity from the tank atop the chimney. The time needed to empty the tank is enough for the decay heat of the core to decrease to the point where it can be evacuated by the air flowing between shell and chimney by natural circulation. The whole sequence would happen passively with a minimum of action from the operators and without the need for power beyond the batteries.

In case of core meltdown, the corium would be solidified back in situ by flooding the vessel pit.

The designers of AP 1000 have especially endeavored to limit on-site construction time: some 250 large modules are pre-fabricated in the factory and set into the shell "open top" by powerful cranes. The shell itself is raised, section after section during the assembly. The vendor hopes to limit on-site construction time to 36 months from first concrete to fuel load.

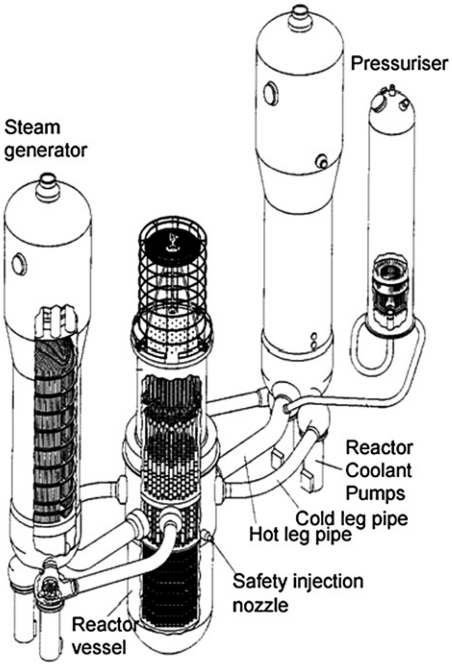

Fig. 1. AP 1000 primary circuit.

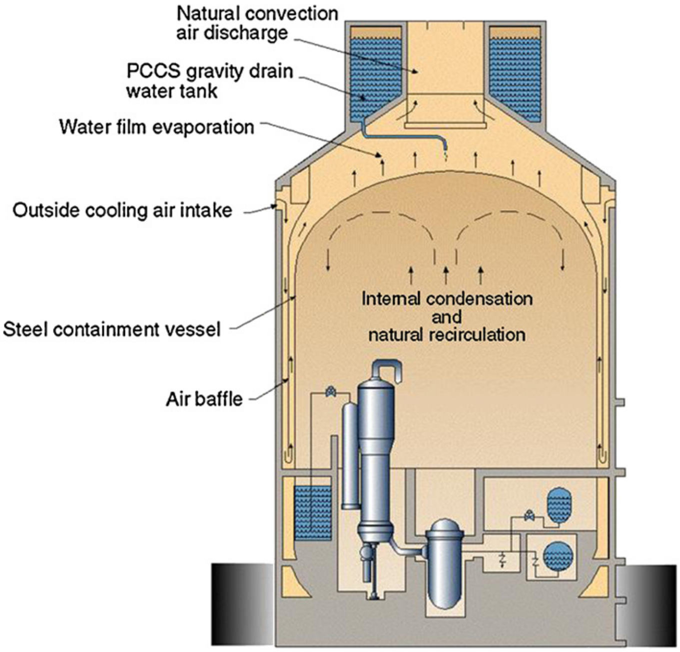

Fig. 2. Passive evacuation of the decay heat after a LOCA.

3.3. *AES 92 [3]*

L'AES 92 is a 1000 MWe VVR, the Soviet/Russian version of the PWR. Its design is somewhat similar to EPR's and it is equipped of a passive containment cooling through six air-cooled heat exchangers. It has two different sets of accumulators (one set under pressure and the other, gravity driven) and, like the EPR, four 100% emergency core cooling trains. In case of core meltdown, the molten corium would be gathered in a core-catcher located below the pressure vessel pit. The design of this "ashtray" is cruder than the EPR design (Fig. 3).

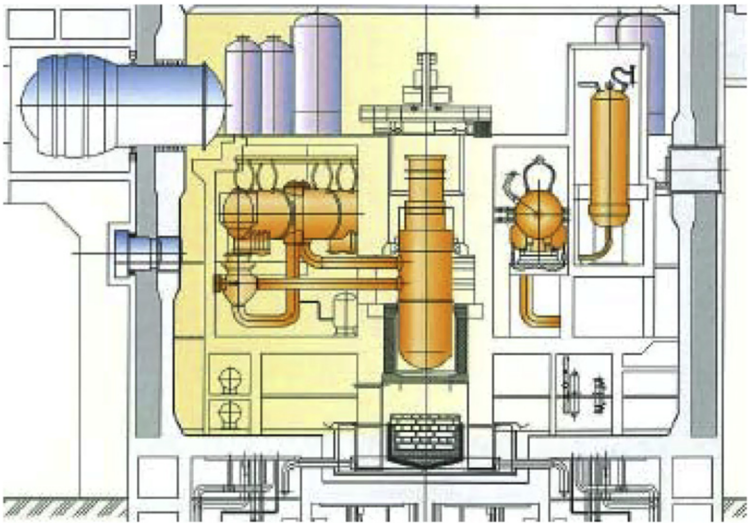

Fig. 3. Cross section of AES 92 showing the VVR-specific horizontal SG and the location of the "ashtray" below the pressure vessel pit.

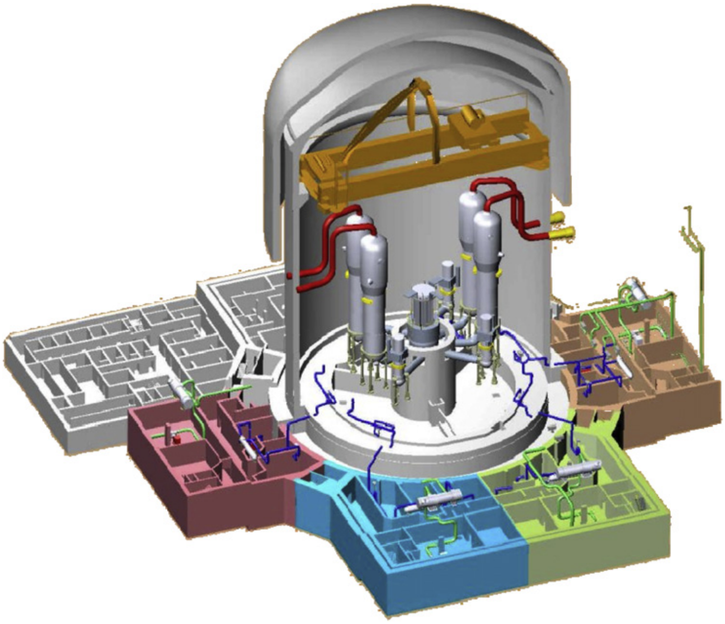

Fig. 4. Open view of EPR's nuclear island.

4. The EPR [4]

In their joint 1993 directives, the French and German Safety Authorities had made clear the importance they gave to the return of experience as an insurance of safety. They said in essence: "*if your new model is so innovative that the cumulative experience of both the French and German operating fleets is no longer fully relevant, be prepared for some serious discussions during the safety analysis procedure*". This message was well understood by the designers: *EPR is purposely evolutionary* and its only significant innovations are dedicated to enhance its safety to Gen III level.

With this proviso, EPR is an accomplished marriage between the most recent PWR models from both side of the Rhine river, N4 and Convoy. Similarly, it is a 4-loop PWR, but its rating is somewhat higher (1650 MWe).

It has four emergency core cooling trains, each with a 100% capability to bring the reactor to safe shutdown. These four trains are located in four separate safeguard buildings to combine functional redundancy with geographical separation, thus avoiding common mode failures.

The auxiliary buildings are built close to the reactor building and share with it the same extra-thick basemat, a very seism-resistant setup (Fig. 4).

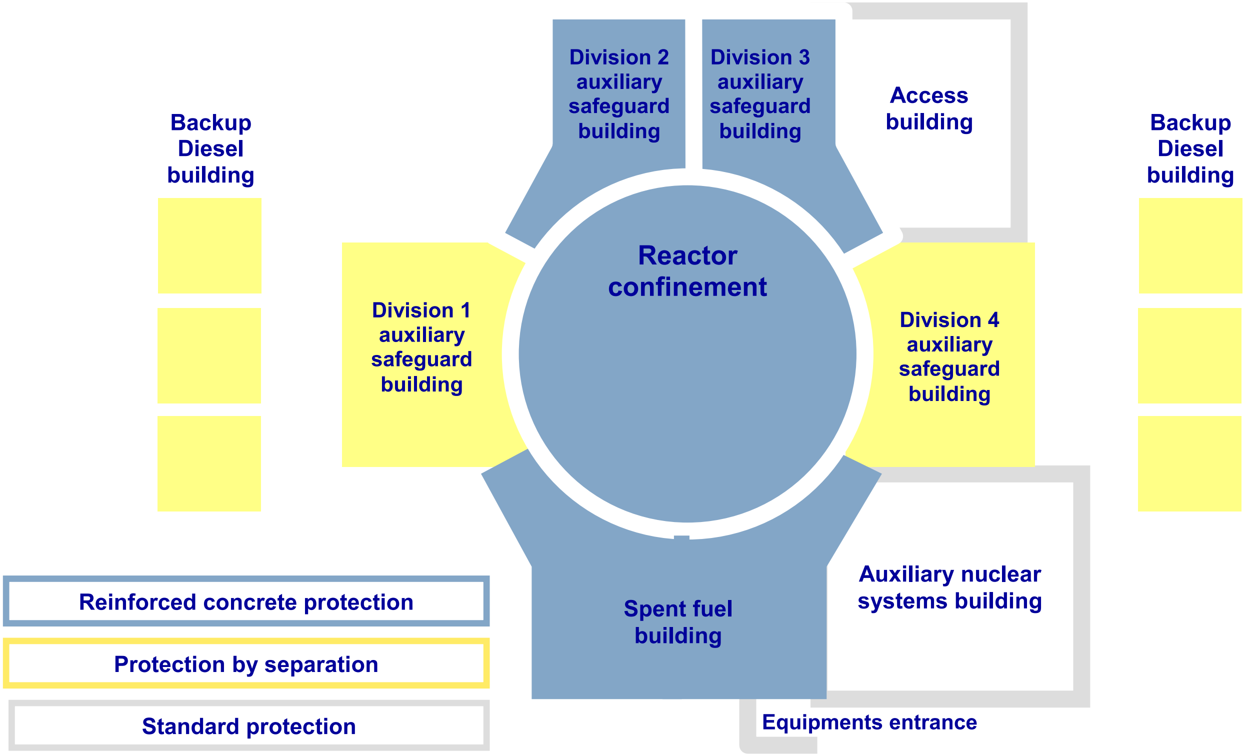

Fig. 5. Schematics of EPR's protection against external aggressions.

EPR has a double containment: inner thick hull made of prestressed concrete with an internal steel liner, and outer hull made of heavily reinforced concrete. A similar hull is also protecting the fuel building as well as two of the four safeguard buildings, the other two being located on each side of the reactor building (Fig. 5). Such a disposition guarantees an outstanding protection against external aggressions, be they natural or malevolent.

Six diesel groups housed in two separate building located on either side of the reactor buildings supply the emergency electric power supply when required. Each heavily built and waterproof diesel building houses two "normal" diesel groups, each with a 100% capability, and another group of a different technology dubbed "SBO" which stands for station black-out. SBO diesel would be called if a common mode failure were to affect simultaneously all four normal diesel groups. Fuel tanks for the diesel groups are also located within the buildings.

With respect to the previous models, a series of systems have been added to manage severe accidents while guaranteeing the containment of radioactivity.

In case of severe accident with full core meltdown and corium escaping from the reactor pressure vessel:

- The corium spreads itself into the refractory spreading zone where it is cooled down, first by the water flowing passively from the large In-reactor water storage tank (1800 m^3) around it, then by the aspersion system located at the containment ceiling;
- This aspersion system:
  - is powered by the emergency diesel groups or by the SBO diesels;
  - is cooled by a dedicated system in addition to the safety-grade cooling system;
- Pressurized core meltdown is prevented by opening dedicated valves on top of the pressurizer (2×900 t/h).

The risk of hydrogen explosion is prevented trough some sixty passive catalytic recombiners located within the inner containment. This inner hull can resist a pressure around 10 bars. Residual leakages through the inner containment penetrations would gather in the inter-containments annular space and filtered before release to the stack.

EPR
In case of full core meltdown, no need for short term evacuation of people beyond the close proximity of the plant (according to ICRP 63 limits).
No need for any long term relocation (same dose limits).
No loss of agricultural product beyond one growth season (EC dose limits on food consumption).

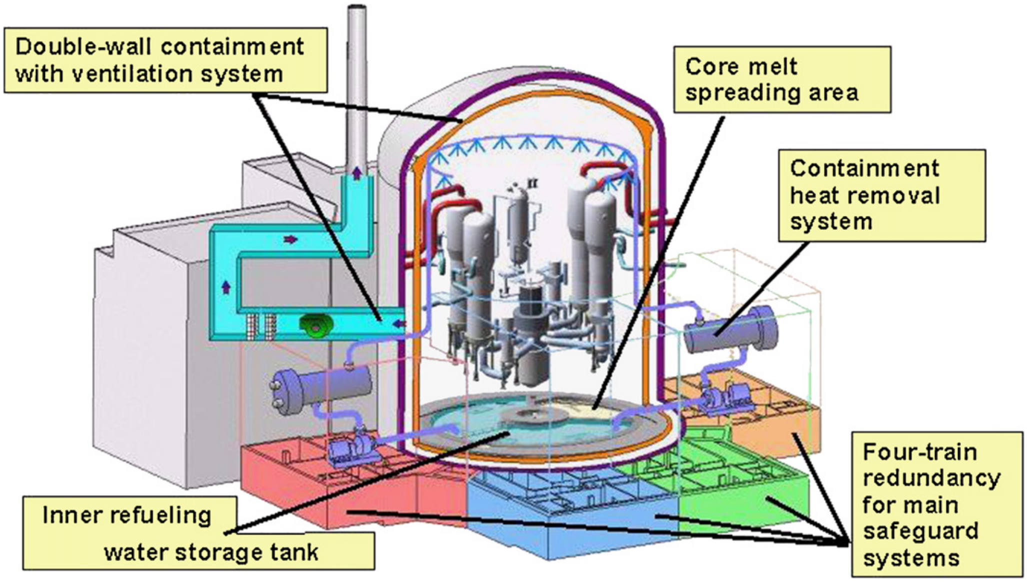

Fig. 6. EPR main specific safety features.

Fig. 6 summarizes the EPR main safeguard systems.

It is well known that the first two EPR plants under construction at Olkiluoto (Finland) and Flamanville have largely exceeded both provisional construction times and costs. That is typical of prototypes almost everywhere: Boeing's Dreamliner, a beautiful plane headed for commercial success, has just experienced quite similar delays and cost overruns. But we are quite confident that series reactors shall be built quicker and shall be less expensive than the prototypes: it may well be already the case for EPR 3 and 4 presently under construction in Taishan (China).

References

[1] Jon Tae Seo, Experience on APR1400 construction, in: IAEA TWG-LWR, Vienna, July 26–28, 2011.
[2] Final safety evaluation report related to certification of the AP 1000 standard design, in: NUREG-1793, September 2004.
[3] S.K. Agrawall, et al., The VVERs at KandanKulam, Nuclear Engineering and Design 236 (2006) 813–835.
[4] F. Bouteille, Assessment of the standard EPR reactor against the European Utilities Requirements, in: ICAPP, Nice, May 2–5, 2011.