Development of Next-Generation Light Water Reactor in Japan

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Abstract. The Next-Generation Light Water Reactor development program was launched in Japan in April 2008. The primary objective of the program is to cope with the need to replace existing nuclear power plants in Japan after 2030. The reactors to be developed are also expected to be a global standard design. Several innovative features are envisioned, including a reactor core system with uranium enrichment above 5%, a seismic isolation system, the use of long-life materials and innovative water chemistry, innovative construction techniques, safety systems with the best mix of passive and active concepts, and innovative digital technologies to further enhance reactor safety, reliability, economics, etc. In the first 3 years, a plant design concept with these innovative features is established and the effectiveness of the program is reevaluated. The major part of the program will be completed in 2015.

1. INTRODUCTION

Nuclear power is an important source of energy for Japan. At present, 53 commercial power reactors are in operation, serving approximately 30% of the country's electricity demand. The Framework for Nuclear Energy Policy, announced in October 2005, established a policy to "maintain the share of nuclear power in the total electricity supply at the level of about 30-40% or more if necessary starting from 2030." Many of the commercial power reactors in service today were built in the 1970s or 1980s. From around 2030, the decommissioning of these reactors will begin to produce a major demand for their replacement. Moreover, in these years of "nuclear renaissance," there is a global trend towards rediscovering the value of nuclear power as a promising energy source that may contribute to the strengthening of energy security and the reduction of greenhouse gas emissions.

Against this background, and in anticipation of the demand for reactor replacement that is expected to grow from around 2030, the national government, electric power utilities and plant venders agreed to join hands in a national program for the development of next-generation light water reactors (LWRs). Development activities within the framework of this program started in April 2008.

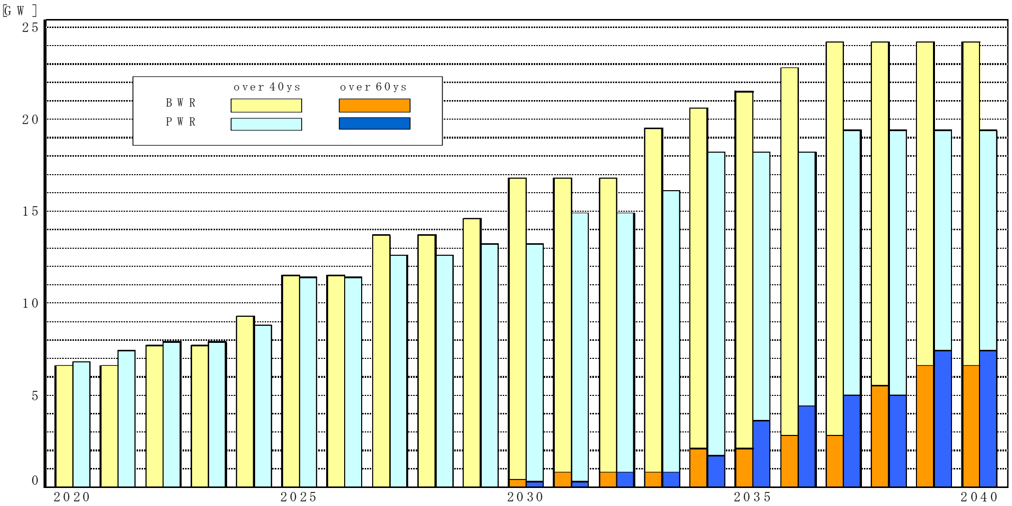


Fig. 1. Total generation capacity from plants aged 40/60 years or more in Japan[3]

2. CONCEPT OF THE NEXT-GENERATION LWR

In the interest of plant safety and economic efficiency, it is beneficial to both plant manufacturers and electric power utilities to share their licensing, building and operating experience with each reactor type. Since these reactors are going to be released onto the market beginning around 2030, they should not only have considerably better performance than the latest reactors of today, but should also be able to compete successfully with other reactors in the market in the 2030 timeframe. In view of these requirements, a two-year feasibility study was initiated in 2006 to consider the issues surrounding electric power generation in Japan and the relative performance of reactors from overseas manufacturers.

2.1. Concept for the next-generation LWR

These reactors should provide the world's best safety and economy in the 2030 timeframe, and should comply with the global standard, thus encouraging public acceptance of nuclear power plants while simplifying their operation and maintenance.

2.2. Reactor Types for the next-generation LWR

One PWR design and one BWR design

2.3. Electric output

1,700 to 1,800 MWe class
(Key technologies should be developed for 800 to 1,000 MWe class plants within the framework of the standardization of designs for the 1,700 to 1,800 MWe class)

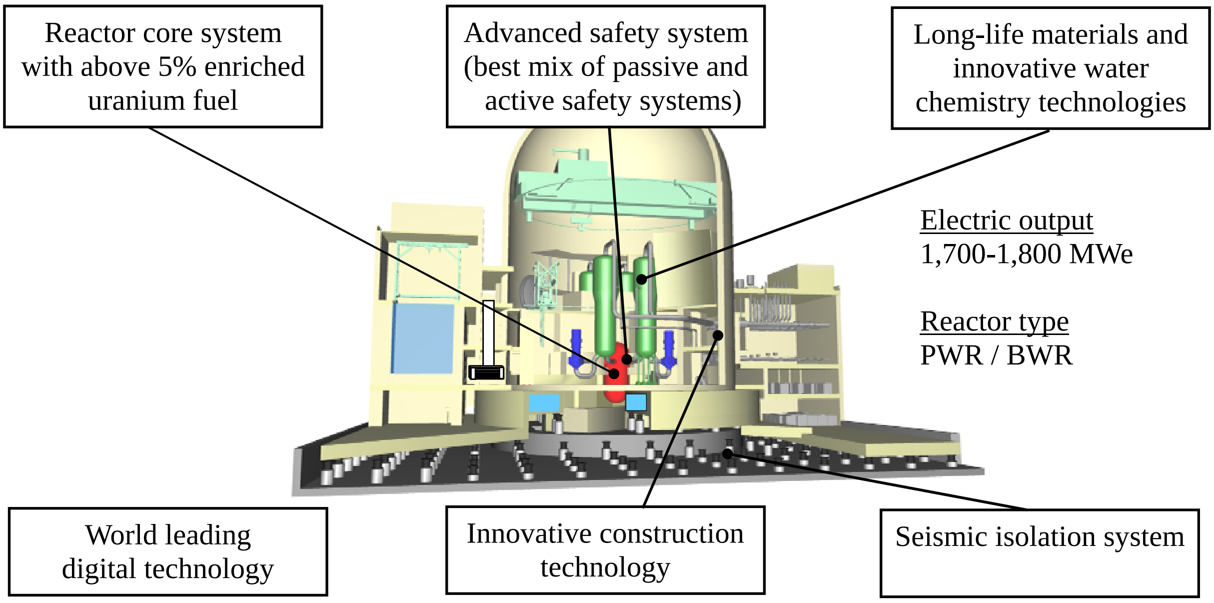
Table 1. Major user requirements in Japan

Items	Requirements	
Electric output	1,700–1,800 MWe Key technologies are available for 800-1,000 MWe plant.	
Safety	Core damage frequency	10^{-5}/reactor year
	Containment failure frequency	10^{-6}/reactor year
	Countermeasure against severe accident	yes

Economy	Construction cost	[TBD]
	Capacity factor	97% (average throughout plant life)
	Operating cycle	24 months
	Plant lifetime	80 years
	Construction period	Less than 30 months
Public acceptance	Evacuation frequency (short term)	10^{-6}/reactor year
	(long term)	10^{-7}/ reactor year
	External accident	Earthquake, Tsunami, Airplane crash
Operation & maintenance	Core design	70 GWd/t (average assembly burn-up)
	Maintainability	High reliability and easy maintenance
	Quantity of maintenance work	50% reduction from the maintenance required in the latest plant

3. TECHNOLOGY DEVELOPMENTS

The feasibility study mentioned above included the reviewing of specific subjects that will have to be addressed by technological development activities to ensure the realization of the design concept. This led to the identification of six essential design features as targets of technological development. FIG. 2 below illustrates these six design features.



Electric output
1,700-1,800 MWe

Reactor type
PWR / BWR

Fig. 2. Overview of the next-generation light water reactor

3.1. Reactor core system with uranium enrichment above 5% for significant reduction of spent fuel discharge and notably higher availability

Attaining a higher capacity factor (increased availability) is an important economic goal. Next-generation LWRs should support a longer operation cycle of 24 months (vs. 13 months with conventional reactors in Japan), which will achieve the world's best capacity factor by almost halving the frequency of refueling outages. For efficient and economical operation with this longer operation cycle, reactors must use fuel with a uranium enrichment level greater than 5% to increase the burnup from the conventional level of around 50 GWd/t to around 70 GWd/t. This will have the additional benefit of reducing the spent fuel volume by roughly 30-40%.

The cladding of fuel assemblies used in conventional LWRs is only good enough to withstand a burn-up of 50 GWd/t (average discharge burn-up) with fuel having a uranium enrichment level of less than 5%. Therefore, the current plan is to develop innovative cladding materials with higher resistance to corrosion and irradiation so that next-generation cladding will withstand a 70 GWd/t burn-up.

3.2. Seismic isolation technologies to standardize plant design independent from site conditions

Each existing nuclear power plant built around a LWR employs a unique seismic design to address site-specific conditions. This prevents the standardization of plant design (strength design, in particular) and results in higher construction costs. Next-generation LWRs should employ seismic isolation technologies that support the standardization of plant design, as well as using standardized and simplified designs for the reactor building and equipment, so as to increase the safety margin against beyond-design-base earthquakes.

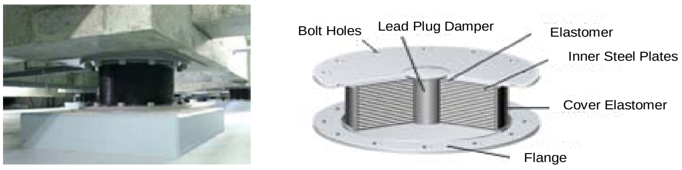


Fig. 3. Seismic isolation system

3.3. Long-life materials and innovative water chemistry technologies for an 80-year plant lifetime and significant reduction of occupational dose

While conventional plants have a life of about 40 to 60 years, next-generation LWRs should greatly extend the plant life to 80 years. Another goal is to significantly decrease radiation exposure doses from maintenance activities. Over the long plant life of 80 years, components and materials should have improved durability in spite of severe conditions such as neutron irradiation and the corrosive water environment caused by high temperatures. Therefore, plans call for the development of new materials and the optimization of water chemistry and solid surface durability.

3.4. Innovative construction techniques for significant shortening of construction period

It is important to assure that plants can be built in a short construction period. The planned next-generation LWRs are going to employ construction techniques such as steel-plate reinforced concrete (SC) and allow the expanded use of large modular blocks of pre-assembled pipes and components. These will greatly reduce the scale of construction, piping and electrical machinery installation work at the plant construction site, significantly shortening the construction period from the present level.

An SC structure allows the preparation of reinforced building walls as prefabricated modules of steel plates, which are transported to the plant construction site, installed and filled with concrete. The SC structure thus eliminates the most time-consuming procedures in the setting-up of reinforced concrete structures: installing reinforcement rods and preparing/removing concrete molds. As a result, material handling at the plant construction site will be reduced and the construction period will be shortened. With the next-generation LWRs, an SC structure is expected to be used even for the reactor containment, which is presently a critical bottleneck in construction, preventing any further shortening of the construction period. Thus, these next-generation LWRs are expected to permit a significant shortening of the construction period.

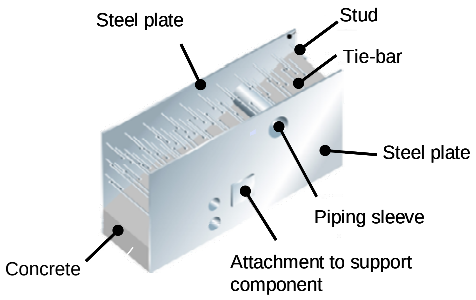


Fig. 4. Structure of steel-plate reinforced concrete

3.5. The best mix of passive and active safety systems to realize economy and safety

Next-generation LWRs should be as safe as, or safer than ABWRs and APWRs, which presently boast the world's highest safety level. They should simultaneously achieve the high level of economy expected from reactors that are scheduled for debut in or around 2030. To achieve this, the plans include the optimum combination of active systems[1] that are well proven through operating experience, and passive systems[2] that are used in the latest reactors. New systems configured in this manner are expected to ensure safety and reliability while enabling major reductions in construction costs and major improvements in serviceability.

3.6. Innovative digital technologies to improve availability and safety

Improved safety, reliability and serviceability require the development of technologies not only for hardware (plant components, equipment, materials, etc.) but also for software in areas pertaining to plant operation, maintenance and management. Our next-generation LWRs will make extensive use of advanced digital technologies to support sensing and monitoring plant status, information analysis and evaluation, information presentation, information transfer and information security. Using such technologies, a system for integrated plant control will be configured, contributing to the prevention of human factor errors, the simplification of maintenance and material-handling activities, and the improvement of the utilization factor.

4. DEVELOPMENT SCHEDULE AND ORGANIZATION

The goal is to complete the basic development activities in approximately eight years. In the following period, irradiation tests and other tests that require a long time will continue, leading to the production of detailed and site-specific designs in time for the scheduled commissioning in or around 2030.

In the first three years, the plant design concept described above will be consolidated and basic specifications established, based on the design features that were also mentioned earlier. In the process of technological development, irradiation tests and other tests would consume a great deal of time and money if performed on full-scale specimens. Therefore, for the first three years, basic test activities will be the focus, with the goal of determining the feasibility of target technologies. Such tests will include tests for the screening of materials and tests to gather basic data on feasibility. In the third year, a comprehensive evaluation of the results and progress of these activities will be conducted and the conclusions used to plan or modify the subsequent years' activities.

The total cost of the development program is expected to be about 60 billion yen. However, the program will be reviewed in the third year to ensure that important development tasks are supported by sufficient investment.

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[1] i.e. systems that rely on the operation of active devices such as pumps
[2] i.e. systems that are designed to operate with natural forces or phenomena such as gravity and boiling

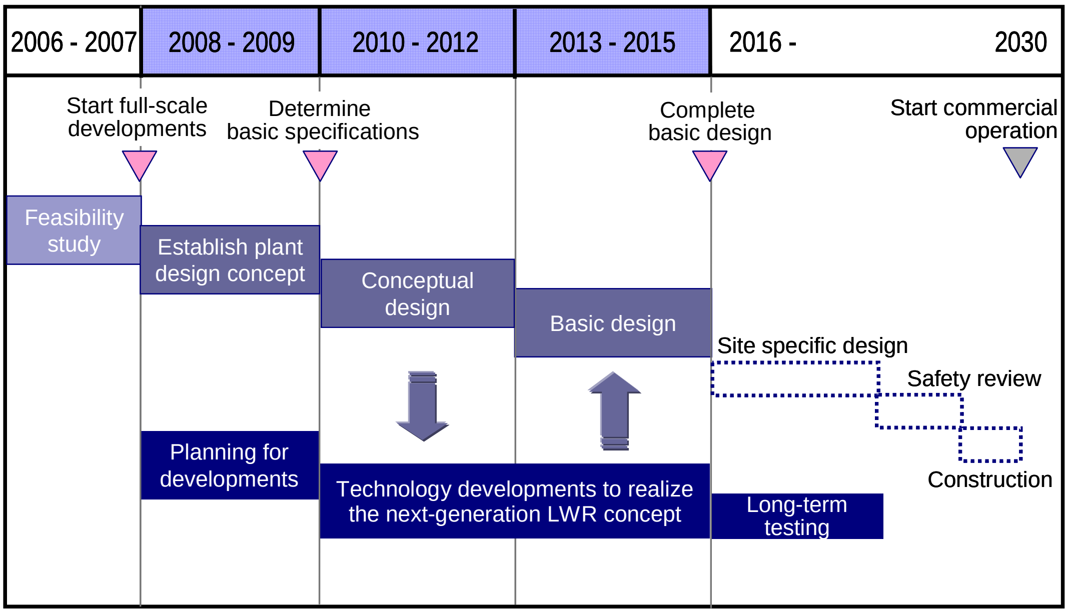

Fig. 5. Schedule of development of the next-generation LWR

Governmental organizations, utilities and plant vendors will be involved in development activities. The Institute of Applied Energy(IAE), therefore, will undertake overall management of the development program, while three plant vendors in Japan (Hitachi-GE Nuclear Energy, Mitsubishi Heavy Industries and Toshiba) undertake a substantial amount of the technological development activities. Nuclear fuel manufacturers and construction companies, as well as research institutions in Japan and in overseas, will provide support to the development program.

5. DEVELOPMENT PLAN FOR THE FIRST THREE YEARS

5.1. Reactor core system with uranium enrichment above 5%

To achieve a major reduction in spent fuel volume together with the world's highest utilization factor, it is necessary to use fuel with a uranium enrichment level of greater than 5%. Such operation, however, is not yet commercially practical anywhere in the world. Therefore, before starting serious development activities, it is vital to study the feasibility and validity of associated technologies. Anticipated tasks include the assessment of impacts on the core design, impacts on the integrity of fuel materials and implications for different facilities for nuclear fuel cycling, the identification of regulatory requirements that require revision, and negotiation with concerned agencies.

In the first three years, a quantitative assessment will be conducted of the flow-on effects of the use of uranium fuel enriched beyond the 5% level, hoping to confirm the absence of any insoluble technological issue and to demonstrate the large advantages that can be expected from the use of such fuel. To facilitate the introduction of fuel enriched beyond 5%, a summary of the required modifications of existing infrastructure and regulatory schemes will be prepared. Regulations and standards that may require modification will be reviewed, and negotiations will be undertaken with concerned agencies.

New materials with higher performance (zirconium alloy materials and stainless steel materials) will be developed for use as cladding materials. Activities in the first three years will include out-of-pile testing of promising materials to identify the best candidates. From the fourth year, irradiation testing of chosen materials will be conducted to demonstrate their long-term integrity.

5.2. Seismic isolation system

In non-nuclear fields, seismic isolation systems have already been used in many buildings. In Japan, the Japan Electric Association has produced design guideline[4] for use in the nuclear field. However, the Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities[5], after its amendment in September 2006, contains new provisions on additional review procedures such as the evaluation of the potential damage from simultaneous inputs of horizontal and vertical seismic motions and the evaluation of existence of the "Residual Risks"[3].

In the first three years, data on the basic characteristics of seismic isolation systems will be collected to address the above-mentioned requirements in the Regulatory Guide. In parallel, assessments will be made of ways that seismic isolation systems may improve safety margins and also how they may increase the plant cost, in the hope of justifying their use because of their advantages. In the subsequent period, data will be collected on full-scale models with a view to proposing updates of regulations in the light of collected data.

5.3. Long-life materials and innovative water chemistry

To ensure that plants maintain a high utilization factor throughout their 80-year life, the need for major repair activities must be decreased. To achieve a plant life of 80 years, BWRs must be well protected against stress corrosion cracking (SCC) and irradiation-assisted stress corrosion cracking (IASCC) of in-core structures, while PWRs must be well protected against corrosion of steam generator heat transfer tubes on the secondary side.

For use with next-generation LWRs, new materials will be developed that excel conventional materials in terms of resistance against SCC and corrosion. In the first three years, the best materials for in-core structures and steam generator heat transfer tubes will be identified. Efforts will also be made to reduce the elution of materials and improve the water purification system to minimize exposure, and to examine the feasibility of incorporating relevant ideas into water chemistry technologies to be developed from the fourth year.

5.4.Innovative construction techniques

The most critical restriction on the plant construction period is imposed by the time required for the construction of reactor containment vessel. The reactor containment vessel is designed to contain radioactive materials in the event of an accident. In a loss-of-coolant accident(LOCA), high temperature and high pressure prevail inside the reactor containment. This condition is likely to continue for a prolonged period if the plant relies on passive safety systems.

If an SC structure is used for the primary containment vessel of BWR plant with the aim of shortening the plant construction period, major technical challenges will include the buckling of steel plates on the surface due to thermal expansion and the degradation of the concrete. It will be essential to assess, for example, how well a reactor containment with SC structure withstands the high temperature and high pressure caused by accidents, and how well it may maintain its integrity when hit by an earthquake after an accident.

In the first three years, preliminary assessments will be conducted of the ability of an SC structure to withstand accidents and earthquakes without losing integrity, using scaled-down models, with the aim of demonstrating the feasibility of developing reactor containers with an SC structure. From the fourth year, demonstration tests will be conducted using models that more closely resemble a real reactor containment in terms of scale and geometry, with the aim of collecting data required for the design stage. At the same time, analysis methods and design standards will be established.

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[3] Existence of the "Residual Risks" may cause serious damages to the Facilities by the ground motion exceeding the formulated design basis ground motions, or massive radioactive release from the Facilities, or cause as a consequence radiological exposure hazards to the public in the vicinity of the Facilities.

5.5. Safety system with the best mix of passive and active concepts

A major goal is to achieve the best mixture of active and passive concepts to build a simple safety system that is as reliable as, or more reliable than safety systems of conventional reactors. The safety system will be evaluated by comparing target levels of core damage frequency, containment failure frequency, economic efficiency, and so on. The outcome of the evaluation will be examined during the review of conceptual design. From the fourth year, R&D activities will focus on developing the technical seeds required for the realization of the safety system and for confirming the validity of the system as a whole through demonstration tests.

5.6. Innovative digital technologies

It is essential to improve plant operability over the total life span while ensuring that safety and reliability are maintained. As there is a need to manage a great variety and amount of information pertaining to nuclear power plants, efforts are being made to compile such information into a database for each distinct phase in a plant's total life span. For example, information pertaining to design and manufacturing is stored mostly in databases managed by plant manufacturers, while information pertaining to operation and maintenance is stored mostly in databases managed by electric power utilities. However, the task remains to develop, with the help of advanced digital technologies, a system that enables integrated control of information pertaining to all life stages including design, manufacturing, construction, operation, maintenance and decommissioning, and that allows the sharing of all such information between plant vendors and electric power utilities.

In the first three years, work processes that take place in the total life span of a nuclear power plant will be analyzed and categorized, along with a variety of information and data used in these work processes, and areas to which digital technologies may effectively be applied will be identified. In parallel, research will be conducted on technical seeds for advanced digital technologies as the overall concept of a total management system is developed, scheduled for debut in or around 2030. In addition, the conceptual designing of subsystems will be conducted, including a maintenance support system that supports the minimization of components that require maintenance, and an operation support system that helps prevent human factor errors committed by operation crews. From the fourth year, new technical seeds found to be required by the system on the basis of our activities in the first three years will be developed and verified.

6. REGULATORY DEVELOPMENT

For our next-generation LWRs, highly innovative technologies will be prepared that should develop into global standards in the future. Development of regulations and codes and standards for the innovative technologies is essential to realize the next-generation LWRs, to utilize their performance and to market them worldwide.

Particular attention is required for those technologies that do not fit with present regulatory frameworks or codes and standards, for which it is important that a roadmap is produced for regulatory development, and that work is undertaken to ensure that concerned organizations agree upon their roles and schedules.

Therefore, our group will produce a roadmap for regulatory development, and hold discussions with regulatory authorities and with institutions and associations that are in control of codes and standards. Moreover, the types of research required for regulatory development will be identified to ensure that they are addressed within the framework of the next-generation LWR development program.

In view of the need to support the consistency of safety regulations worldwide, attention must be paid to global trends in regulatory requirements and these must be incorporated appropriately into the design of reactors under development. Simultaneously, efforts will be made to promote the expanded use of the next-generation LWRs that will achieve high levels of safety because of their design, which will be based on the latest findings and operating experience acquired by Japan. Therefore, using the multinational design evaluation programme (MDEP) and other opportunities for international discussions provided by international organizations such as IAEA and OECD/NEA, our group will participate in activities dedicated to the harmonization of safety regulations around the world.

7. CONCLUSION

The next-generation LWR development program is now underway as the first major development program for commercial light water reactors since the Improvement and Standardization for LWRs Program Phase-III of about 20 years ago in Japan. The technologies being developed as essential parts of the concept of next-generation LWRs could be made ready for practical use in the near future. We are determined to make steady progress in the development of these technologies and to move toward the realization of the next-generation LWRs that embody a global standard, hoping that our development efforts may contribute to the sustenance and advancement of nuclear power technologies in Japan and in the rest of the world.

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