LEAD-BISMUT EUTECTICS COOLED LONG-LIFE SAFE SIMPLE SMALL PORTABLE PROLIFERATION RESISTANT REACTOR (LSPR)

1. General information, technical features and operating characteristics

1.1. Introduction

The design philosophy behind the LSPR concept is as follows.

Past trend of nuclear power development and associated issues

Conventional nuclear power reactors have almost reached a power size limit after pursuing the economies of scale by building larger plants. Future directions in which nuclear power can be effectively developed are unlikely to be toward larger sizes. Currently it is almost impossible to find new sites for larger plants in the developed countries; larger plants also pose a large economic risk that might be unbearable even for large companies or governments.

Small reactors [1]

Small reactors can be built on less than ideal land such as small and less stable areas; therefore, it is much easier to find a proper site for a small reactor.

Small reactors can also be utilized for several purposes other than electricity production, such as heat generation, seawater desalination, etc. The transport of heat and pure water for long distances requires high costs and encounters energy and material losses. For such purposes, a local reactor is appropriate; the power required of a local reactor is small and, therefore, the reactor should be small.

Potential power-plant customers generally hesitate to build large reactors due to a high investment risk. Even a delay in construction may incur a considerable economic penalty; therefore, a smaller reactor may be preferable, if economically feasible.

Innovative nuclear reactors

Innovative nuclear reactors are expected to solve future problems such as global warming and other environmental issues, resource shortages, proliferation and security concerns, etc.

Innovative reactors are also required for purposes other than electricity production, such as fuel breeding, hydrogen production and high temperature process heat applications, motive power, etc. Small reactors provide an attractive domain for the innovations needed to address the abovementioned problems.

Economical performance

The disadvantage of scale is a considerable factor degrading the economic performance of small reactors. However, there are many factors pertaining to small reactors that might be used to improve economic performance. These are discussed in section 1.6.1.

Small reactors for developing countries

Smaller reactors pose less radiological hazard because the total quantity of contained radioactive material is smaller. Furthermore, certain small reactors can incorporate inherent safety characteristics, where safety function relies more on natural phenomena and less on human actions or mechanical devices.

If a reactor is small enough to be transportable and has a sufficiently long core lifetime, it can be built at a factory and shipped to a site. When such reactor is designed to be sealed, the discharge of any fuel becomes impossible outside the factory, and this would enhance its proliferation resistance.

In the 21st century, global warming caused by the carbon dioxide emissions might become an urgent problem. The carbon dioxide emissions from developing countries would be especially important, and nuclear reactors could be deployed to minimize their scope.

However, in developing countries, the infrastructure and technical skills are often insufficient to realize a full-scale nuclear power development programme. Furthermore, some developing countries are politically unstable. The energy demand is in many cases local and small. As mentioned before, a small reactor could be made simple and easy to operate and maintain; it may incorporate inherent safety features and enhanced proliferation resistance. Therefore, small reactors may have a good potential to solve global warming problems resulting from carbon emissions in developing countries.

Targeted features and their interrelation

Based on the abovementioned considerations, the features targeted for a small reactor include long-life core, design simplicity (resulting in easy maintenance and operation), small size and transportability, strong reliance on inherent safety features, and enhanced proliferation resistance achieved through the operation with a sealed reactor vessel.

However, some of these features are tightly interrelated. For example, transportability requires a small size and, therefore, these two features are essentially similar. By examining all these characteristics from a viewpoint of similarity, it appears that only long core lifetime and small reactor size are basic characteristics and all others can be derived from these two.

With these two features being achieved, a scenario is that a long-life small reactor is built at a factory in a developed country, shipped to a site in a developing country, installed there and operated over a certain period without reloading and shuffling of fuel in the core, and replaced with a new reactor after its operational life is completed. A barge-mounted reactor is an alternative; it can be shipped to a site and operated as a power plant in an appropriate port.

In these scenarios, the procedures requiring high technical skills, such as fuel replacement, are not required. The maintenance of such reactor becomes simple; and heat produced in accidents escapes easily from the core surface due to a favourable core surface-to-volume ratio; in addition to this, the power shape is more stable. For fast reactors, it is especially important that void coefficients in small reactors are shifted toward the negative side.

From the abovementioned considerations, it appears that both long core life and small reactor size are tightly related to enhanced safety and design simplicity.

In the scenarios outlined, the reactor is always sealed during transportation and operation and measures are taken to prevent the access to fuel located inside the reactor vessel. Therefore, it could be assumed that such reactors incorporate enhanced proliferation resistance.

Small reactor with a long-life core

From the arguments presented above it appears that the features of long-life core and small reactor size are basic to realize the concepts of long-life, safe, simple, small, portable, and proliferation-resistant reactors. However, these two basic features are generally in conflict because small sized reactors usually show poor neutron economy, also resulting in the impossibility to achieve a high fuel burn-up. The neutron economy or, in other words, the requirement of reactor criticality, provides restrictions for both the size and lifetime of the reactor core.

This discussion leads to a conclusion that a long-life safe simple small portable proliferation-resistant reactor requires excellent neutron economy. It is well known that fast reactors show much better neutron economy than thermal or epithermal ones.

Lead-bismuth eutectics cooled fast reactor

The abovementioned arguments suggest that small fast reactors should be investigated.

At present, sodium is considered the best coolant for fast reactors due to its superior cooling ability, which can help to increase the core power density and shorten the doubling time. Short doubling time was an indispensable requirement in the early phases of development and construction of fast breeder reactors from 1960s through 1980s. It is reported that for safety reasons, the lead-bismuth eutectic (LBE) cooled fast reactor was originally considered [2].

As previously mentioned, the neutron economy is very important to realize long-life small reactors. For these, it is expected that LBE coolant has better performance in neutron economy than sodium coolant because of a larger elastic and smaller inelastic scattering cross section. It is reported that the LBE cooled long-life small fast reactor shows better performance for neutron economy, burn-up reactivity swing and void coefficient [3].

However, in the Western world for a long time it has been considered that LBE cannot be used as a reactor coolant due to negative experimental results on corrosion. Opposite to this, in the Russian Federation this problem has been solved by control of the oxygen concentration and LBE was employed as a submarine reactor coolant. It is reported that 8 nuclear submarines with LBE coolant were constructed and operated for about 80 reactor-years [2]. After the Russian research results have been opened, many research works targeting corrosion experiments were started worldwide. The corrosion problem is considered solvable by choosing proper materials, temperature, and fluid velocity and oxygen concentration.

Characteristics of LBE

The most important merit of LBE compared to sodium is chemical inertness; the LBE does not react violently with water or air.

The boiling temperature of sodium is 1156 K and it is not easy to prevent boiling in severe accidents. If the void coefficient is positive, sodium boiling may lead to a core destruction accident. By contrast, the boiling temperature of LBE is 1943 K with which the possibility of boiling is negligible. Furthermore, as mentioned before, the void coefficient for LBE is more negative than for sodium.

The density of LBE is about 12 times the sodium density; the viscosity of LBE is large and the pressure drop is expected to be large; the Prandtl number is about 3 times the sodium value. These characteristics lead to a poor cooling ability of the LBE; therefore, the power density of a LBE cooled reactor should be lower and, for corrosion protection, the flow rate must be lower too.

Since the power density of a small reactor is usually restricted by the requirement of criticality preservation under fuel burn-up [4], the power density of some very small fast reactors, even with sodium coolant, is very low. Therefore, the poor cooling ability of LBE may be not so important for long-life small reactors.

For natural circulation capability, LBE-cooled reactors can offer better potential through larger equivalent hydraulic diameter of the core [5]; it also improves the reactor response in accidents.

As mentioned before, the LBE cooled long-life small fast reactor shows better performance for neutron economy, burn-up reactivity swing and void coefficient due to a larger elastic scattering cross section. The LBE also exhibits a better shielding effect against neutrons and gamma rays, which facilitates a reduction of the total reactor size.

The radioactive materials produced in the coolant during operation are also important. For sodium, ^{24}Na should be considered with the half-life of 15 hours, which emits high-energy gamma rays (2.8 MeV and 1.4 MeV). Therefore, the primary loop of a sodium cooled reactor shows a very high dose rate. On the other hand, LBE does not produce so many gamma ray emitters, although polonium, an alpha ray emitter, is produced. Altogether, the expected dose rate around the primary loop of a LBE cooled reactor is much lower than for sodium cooled reactor.

LSPR

To achieve a long-life safe simple small portable proliferation-resistant reactor, a lead-bismuth-eutectic (LBE) coolant was selected as the best candidate. The original concept of a long-life small LBE cooled fast reactor was proposed more than 10 years ago [3], which was the world’s first trial of this kind. The name of this reactor, the LBE cooled long-life safe simple small portable proliferation-resistant reactor (LSPR) distinguishes it from similar reactors proposed by other institutes.

The LSPR concept is being developed at the Research Laboratory for Nuclear Reactors of the Tokyo Institute of Technology (RLNR TITech, Japan).

1.2. Applications

The LSPR is a long-life small reactor, in which the thermal power output is 150MW and the coolant output temperature is nearly 800 K. It can be used for many applications. Current plans are to use it for electricity generation and co-generation including district heating, seawater desalination, hydrogen production, process steam production, or a combination thereof.

1.3. Special features

As it was already mentioned, the LSPR has a long-life core, incorporates many inherent safety features, has a simple design with easy maintenance and operation, has a small size core, is transportable and designed to operate with a sealed reactor vessel.

The LSPR is a factory fabricated and fuelled reactor designed to operate without on-site refuelling, i.e., without reloading or shuffling of the fuel during the whole reactor lifetime.

1.4. Summary of major design and operating characteristics

A summary of major design and operating characteristics of the LSPR is given in Table 1.

Figure 1 gives a general view of the reactor vessel and internals. An integral type reactor design is employed in which steam generators are installed within the reactor vessel, which is possible since severe reaction between the LBE reactor coolant and steam generator water coolant is not anticipated. Nitride fuel with a high thermal conductivity is chosen as a principal fuel candidate because of compatibility with the LBE coolant. The application of metal fuel, which has a potential for higher performance, is left for future studies to be concerned with material compatibility issues. A simplified schematic diagram of the LSPR plant is shown in Fig. 2. The integral type primary circuit incorporates 2 steam generator sets; a mechanical pump; a coolant-purifying unit and an oxygen concentration control unit. Serpentine tube type steam generators are employed for the reason of compactness.

Selection of the driving devices for the heavy metal coolant is one of the key issues in the reactor design. In this design, the mechanical centrifuge pumps were selected assuming that further studies would address long-life cores, possibly with a higher pressure drop, and because of versatility in the ability to assure adequate pump coastdown times. The natural circulation potential of the primary circuit is arranged to constitute from 30 % to 40 % of the nominal primary flow at the nominal heat balance level.

As shown in Fig. 2, re-circulation in the secondary system is arranged with a free surface in the water drum (in power operation); which is to ensure passive heat removal by natural circulation through the steam generators. The steam generator auxiliary heat removal system (SGAHRS) is adopted, in which the decay heat is removed by natural convection through the steam generators to air coolers, without auxiliary cooling systems in the reactor vessel. In this, the reactor vessel auxiliary cooling system (RVACS) is installed as a backup system to the SGAHRS. To control the thermal conductivity and enhance the function of the RVACS, the reactor wall is designed to stay at a cold leg temperature in power operation but to encounter the hot leg temperature brought by the coolant overflow in accident conditions.

Natural uranium or depleted uranium based fuel assemblies are placed at the centre of the core as an inner blanket, whereas plutonium fuel assemblies are settled outside of the inner blanket. In such core composition, the burn-up of fuel progresses from the outer core into the inner blanket region, which is beneficial for sustaining the reactivity for long-term burn-up with a small reactivity swing [6].

TABLE 1 SUMMARY TABLE OF MAJOR DESIGN AND OPERATING CHARACTERISTICS OF LSPR

General characteristics	
Installed capacity: - Thermal; - Electric.	 150 MW(th) 53 MW(e)
Load factor (target)	95 %
Major design characteristics	
Type of fuel	Nitride
Fuel enrichment	10 – 12.5 %
Type of coolant	Lead-bismuth eutectics (LBE)
Type of structural materials	HT-9
Core type / characteristic dimensions: - Core diameter; - Core height.	 1.65 m 2.0 m
Major design characteristics (continued)	
Reactor vessel type / characteristic dimensions:	

- Reactor vessel diameter; - Reactor vessel height.	5.2 m 15.2 m
Number of circuits	2
Thermodynamic cycle efficiency	35 %
Neutron-physical characteristics	
Void reactivity effect	< - 0.8 % δk/k (total void)
Burn-up reactivity swing	< - 0.1 % δk/k
Power peaking factor	1.64
Reactivity control	
Reactivity control mechanism	Secondary coolant flow rate
Number of independent active reactor control and protection systems	2
Thermal-hydraulic characteristics	
Circulation type	Forced
Pump type	Centrifugal
Core coolant temperatures: - Inlet; - Outlet.	 360^{o}C 510^{o}C
Primary coolant flow rate	12 300 t/hour
LBE velocity in the core	0.9 m/s
Pressure in primary circuit: - Vessel bottom static pressure; - Total pressure drop.	 15 kg/cm^{2} 0.7 kg/ cm^{2}
Secondary coolant system: - Feedwater temperature; - Feedwater flow rate; - Steam temperature at steam generator (SG) outlet; - Steam pressure at SG outlet.	 210^{o}C 294 t/hour 280^{o}C 6.47 MPa
Temperature limits: - Fuel; - Cladding; - Coolant (boiling point).	 2780^{o}C 700^{o}C 1670^{o}C
Maximum fuel temperature	630^{o}C
Maximum cladding temperature	510^{o}C
Fuel burn-up characteristics	
Maximum burn-up of discharged fuel	9 % FIMA
Fuel lifetime / period between refuellings	4 200 effective full power days
Design basis lifetime of reactor vessel and structures	
Reactor core	12 years
Reactor vessel	> 12 years
Structures	> 12 years

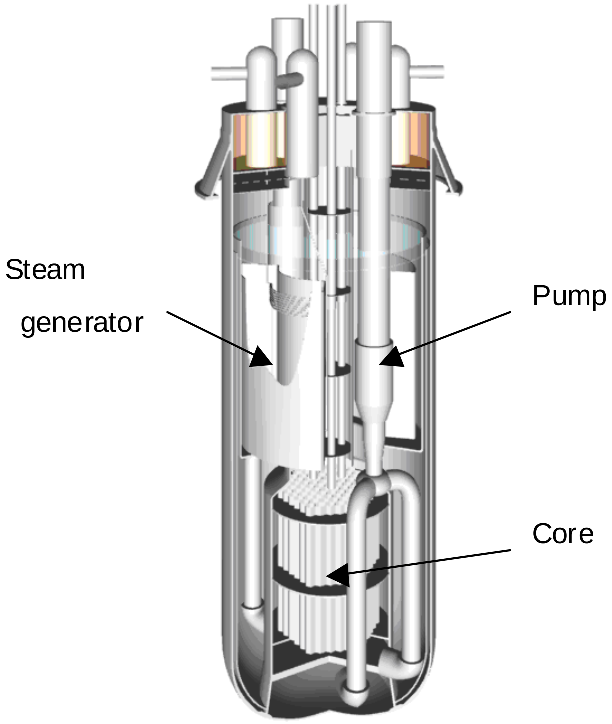


FIG. 1. General view of LSPR vessel and internals.

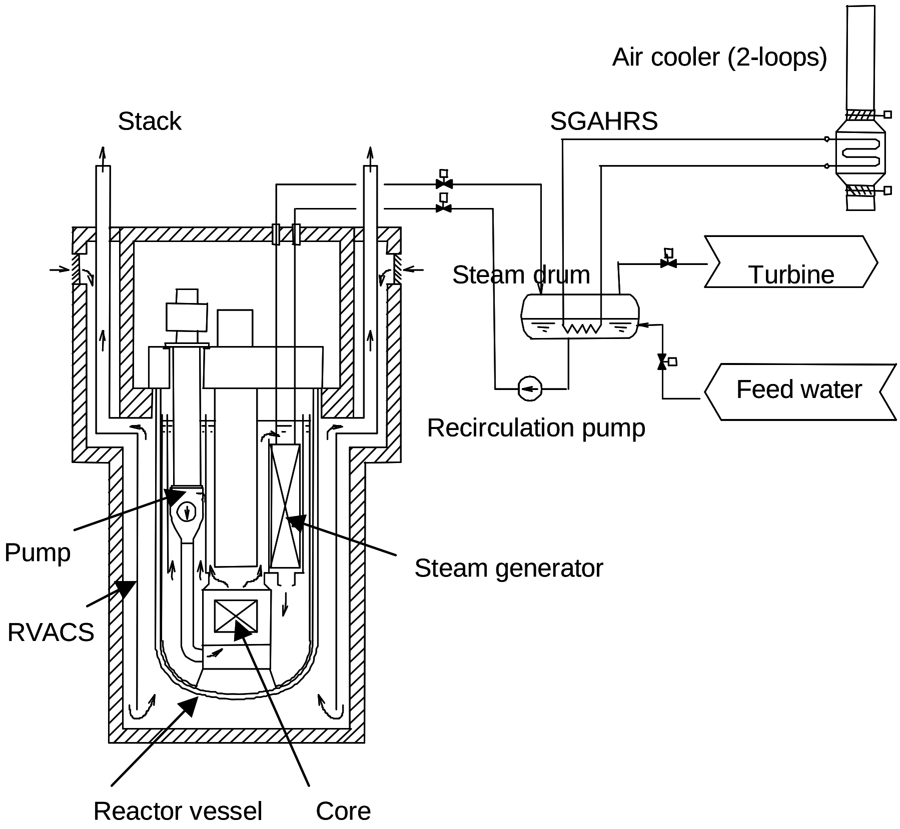
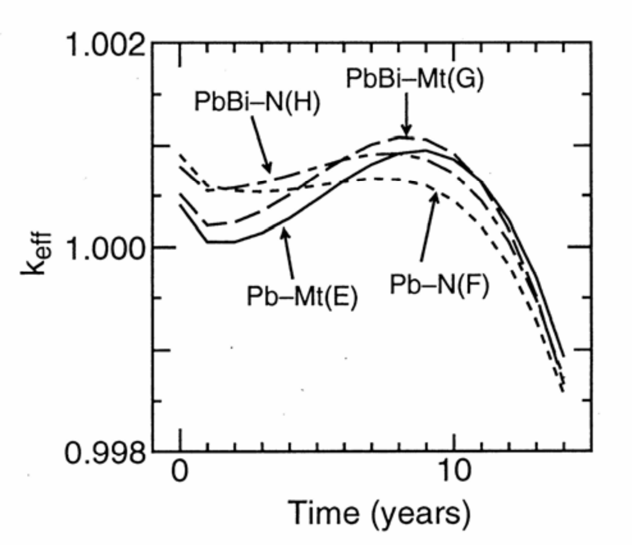


FIG. 2. Simplified schematic diagram of LSPR.

For the reactor lifetime of 12 years the expected burn-up reactivity swing is around 0.1% (see Fig. 3) and, therefore, the possibility of a prompt criticality is eliminated.

In a long-life core it is not easy to achieve high power density but the LSPR design provides that of 60 MW/m^3, which is reasonably acceptable compared with about 100 MW/m3 averaged over the core and blankets in typical fast reactors. Three control rods are placed within the core region. An option not to use these control rods for power regulation, except for the reactor start-up and shutdown, is being examined, to take advantage of very small excess reactivity.



Mt – metallic fuel; N – nitride fuel

FIG. 3. Effective neutron multiplication factor vs. fuel burn-up with Pb and Pb-Bi coolants being applied.

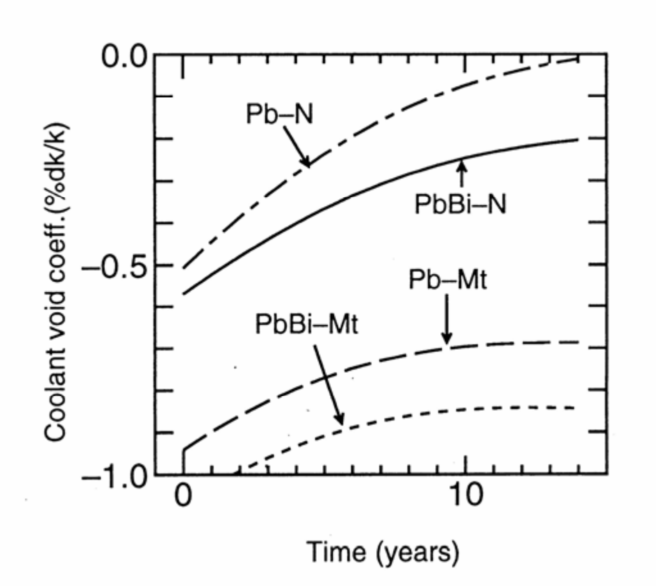
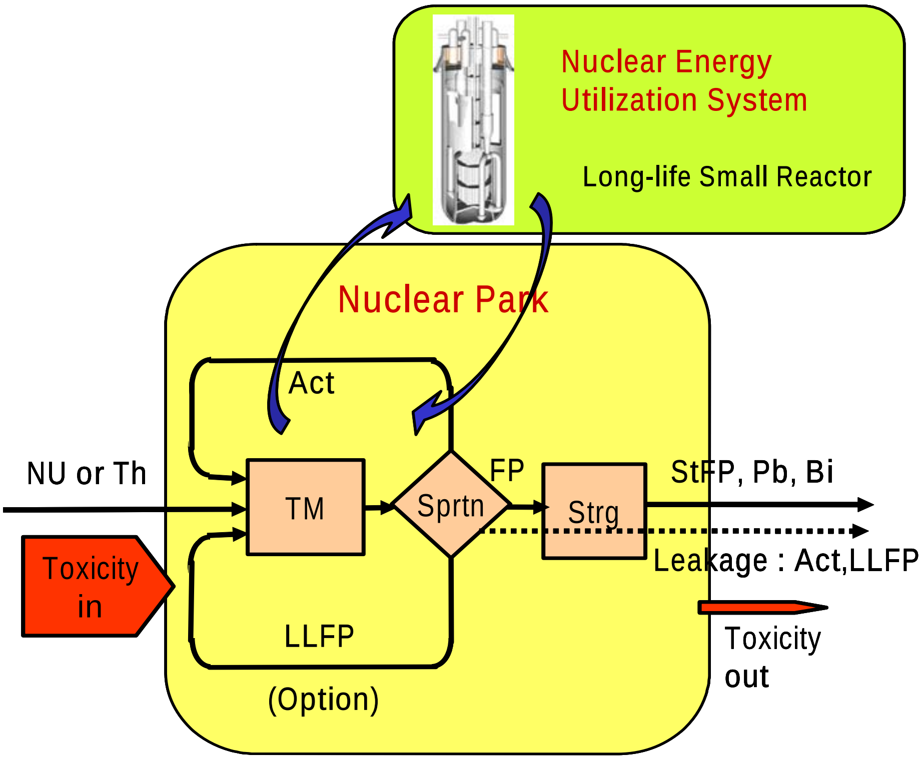


FIG. 4. Coolant void coefficient versus fuel burn-up.

The changes in coolant void coefficient for the whole core during its lifetime are shown in Fig. 4, where the coefficients for lead coolant and metal fuel are also shown for comparison [6]. In all cases the coolant void coefficient remains negative. It could be noted that it becomes positive, if the coolant is changed to sodium.

1.5. Outline of fuel cycle options

The fuel cycle concept for LSPR is shown in Fig. 5.



TM – transmutation
Sprtn – separation
Strg – storage
LLFP – long-lived fission products
StFP – stable fission products
Act – actinides
Toxicity in - inflow of radiotoxicity
Toxicity out - outflow of radiotoxicity
NU – natural uranium

FIG. 5. Nuclear park concept.

All operations with fuel are performed in a centralized way within a nuclear park. A closed nuclear fuel cycle where separation and transmutation are performed to ensure an acceptable balance between the inflow and the outflow of radiotoxicity (see Fig. 5) is applied.

The LSPR is a factory fabricated and fuelled reactor designed for operation without on-site refuelling. Therefore, there are no operations with fuel on the utility site and during transportation.

1.6. Technical features and technological approaches that are definitive for LSPR performance in particular areas

1.6.1. Economics and maintainability

Small reactors do not benefit from economy of scale; however, several approaches in design and construction might contribute to improving their economy.

The LSPR can be produced complete in a factory and, if it is produced in series, that could considerably reduce the reactor cost. For a given rated power, the number of small reactors is larger than the number of large reactors and, therefore, more experience can be gained from the construction and operation of small reactors. The terms for licensing and construction could be shorter for small reactors and the amount of interest on the investment would be also smaller. Small reactors can be used to build modular plants of larger capacity with predicted good economic performance.

Long-life reactor core is also associated with an economic disadvantage related to a higher upfront premium or a higher interest rate on fuel cost (in case the reactor or fuel are leased). For a core with very long lifetime the corresponding effect in cost increase could be quite substantial. Other approaches to improve economic characteristics of small reactors should be used to compensate for this disadvantage.

Refuelling systems installed in conventional reactors are eliminated in the LSPR, contributing to a reduction of maintenance costs. High fuel burn-up reduces the fuel cycle cost and contributes to increased plant availability.

1.6.2. Provisions for sustainability, waste management, and minimum adverse environmental impacts

The LSPR is a transportable factory fabricated and fuelled reactor, providing for no handling of spent fuel or any other waste on the utility site.

The LSPR has a good neutron economy, resulting in a breeding ratio of about unity and an enhanced transmutation capability. When operated in a closed fuel cycle with a nuclear energy park (see Fig. 5), the total system is fissile self-sustainable and ensures that the radiotoxicity of disposed waste is comparable to that of the extracted natural uranium. Moreover, the transmutation requirements to a nuclear energy park can be reduced because all actinides could be effectively recycled in the LSPR.

Polonium produced by neutron absorption on bismuth will not be hazardous because the reactor vessel is sealed and not opened for regular fuel handling as in conventional reactors. If the reactor vessel is opened soon after the shutdown, however, the high radioactivity is no doubt very hazardous but may be beneficial from the viewpoint of proliferation resistance.

1.6.3. Safety and reliability

Safety concept and design philosophy; provisions for simplicity and robustness of the design

The philosophy behind the LSPR safety concept is maximum reliance on the inherent and passive safety features incorporated in the original design concept, and reliance of passive systems for decay heat removal.

One of the important advantages of LBE cooled reactors is the possibility to reduce the number and complexity of engineered safety systems by effectively mitigating the impact of a reactor coolant leakage accident with a simple guard vessel.

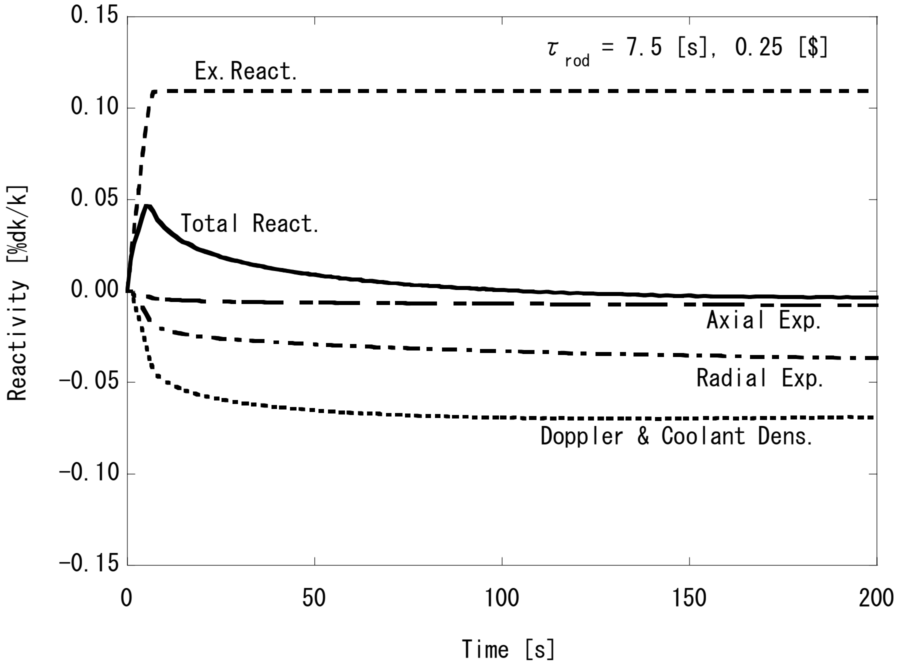
Active and passive systems and inherent safety features; design basis and beyond design basis accidents

In safety analysis of the LSPR, several uncontrolled transients and combinations thereof have been considered. The categorization of these transients into design basis and beyond design basis accidents has not been applied.

As a representative initiating event of an anticipated transient, the loss of external power is commonly postulated, in which a diesel generator is expected to start up and supply electricity for safety demands in a conventional design. Different from this, the LSPR incorporates a fully passive system of decay heat removal without diesel generators - the decay heat can be removed by steam generator auxiliary heat removal system (SGAHRS) through the SGs to the air coolers by natural circulation.

The transient overpower (TOP) due to a control rod withdrawal, the loss of primary flow (LOF) and the loss of heat sink (LOHS) due to a loss of the heat removal capability of the secondary system are commonly postulated as accident scenarios for power reactors. Even though the loss of external power is commonly superposed on these events, this does not lead to any serious problem if the reactor is safely tripped. Severe accidents, where the failure of a scram system is superposed on the abovementioned accidents, are surveyed below, for the LSPR. The analytical methods employed are described in [7].

In an uncontrolled transient overpower (UTOP), the power returns to a stable state without scram by virtue of a negative reactivity coefficient, since the maximum reactivity insertion is limited by 0.25 $ due to a very low burn-up reactivity swing. The changes of reactivity, normalized power and hot spot temperature in this scenario are shown in Figures 6 to 8. In all cases, maximum temperatures reached are much lower than the corresponding temperature limits.



Ex – external	Exp – expansion	Dens – density
React. – reactivity	0.25$ are inserted in 7.5 s	

FIG. 6. Reactivity changes in UTOP.

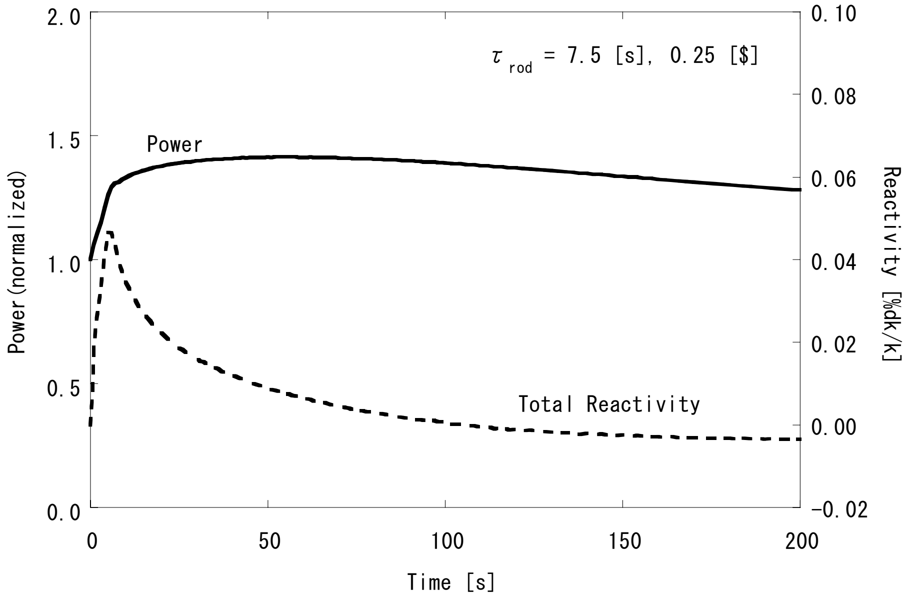


FIG. 7. Normalized power and total reactivity changes in UTOP.

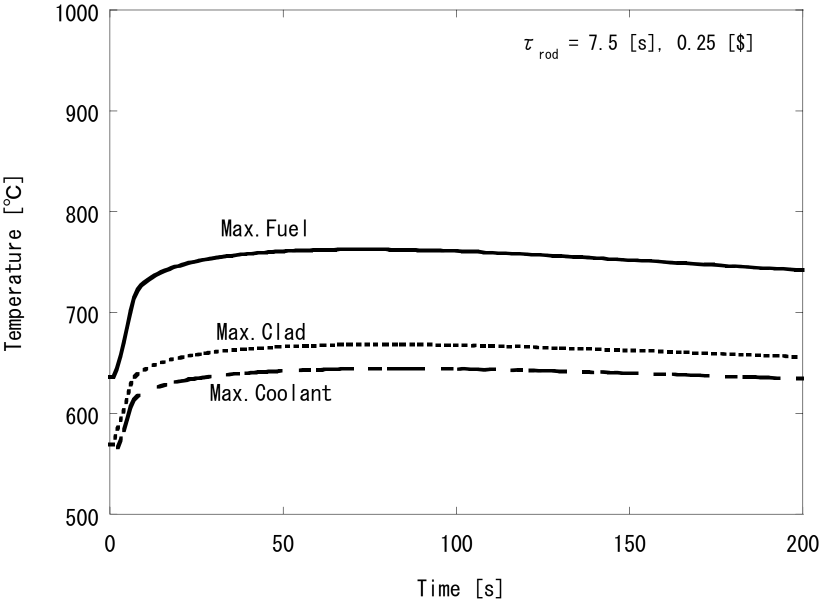


FIG. 8. Hot spot temperature changes in UTOP.

In an uncontrolled loss of flow (ULOF), all primary pumps are postulated to stall without scram, and the total coolant mass flow rate along the core and SG changes, as shown in Fig. 9, where the coastdown half time of the primary pump is set to 6 sec. The changes of reactivity, normalized power and hot spot temperature for this scenario are shown in Figures 10 to 12. In all cases, maximum temperatures reached are much lower than the corresponding temperature limits.

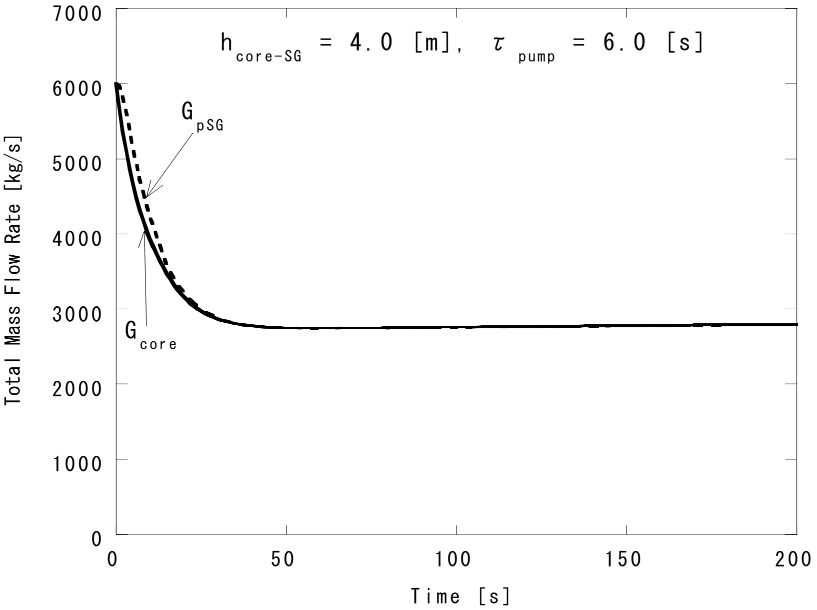
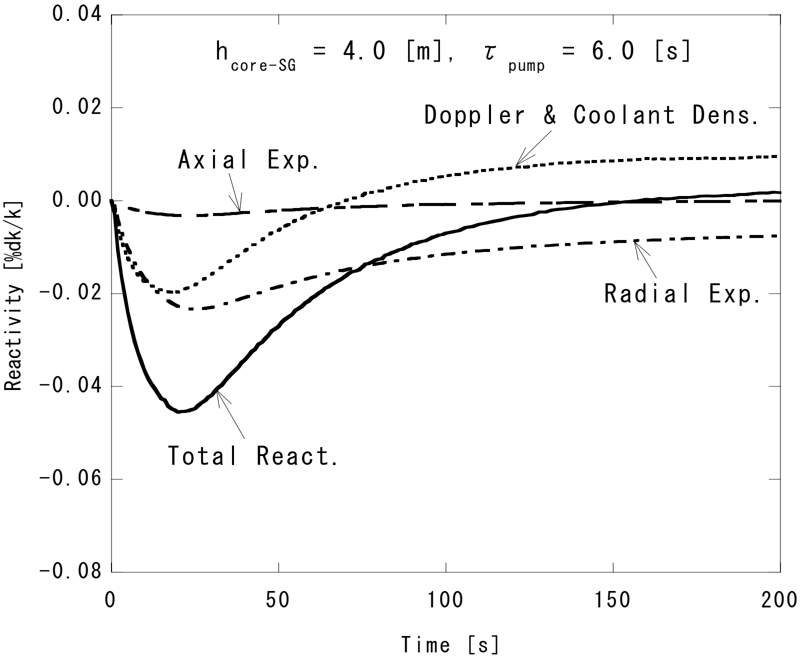


FIG. 9. Change of total coolant mass flow rate along the core and SG in ULOF (thermal centre elevation difference between the core and the SG is 4.0 m).



Ex. – external; Exp. – expansion; Dens. – density; React. – reactivity

FIG. 10. Reactivity change in ULOF.

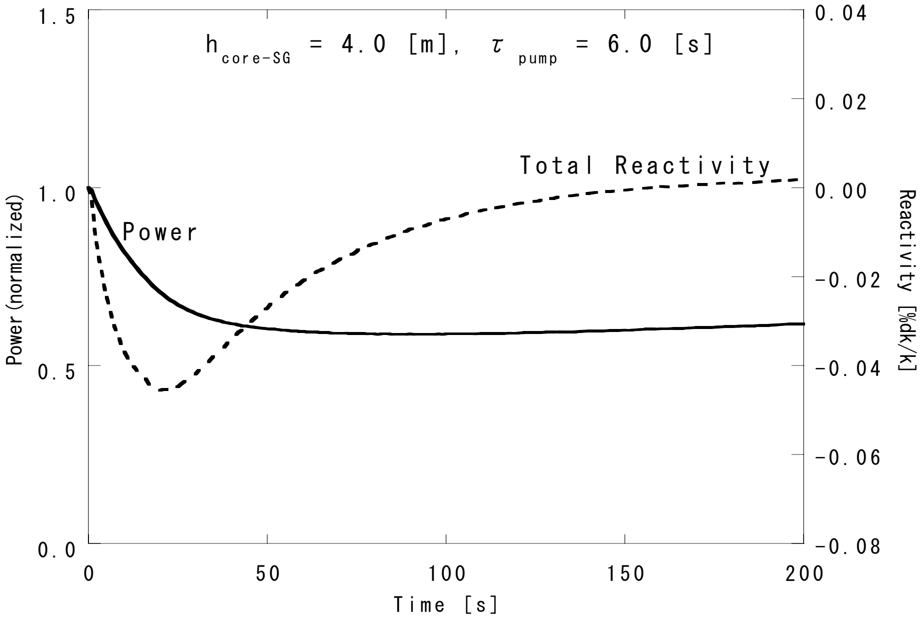


FIG. 11. Normalized power and total reactivity change in ULOF.

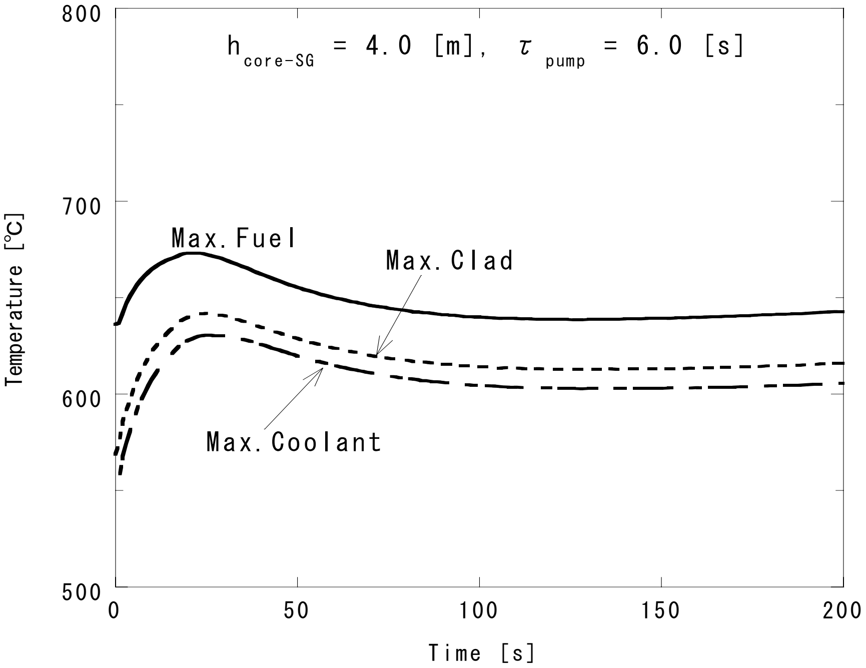
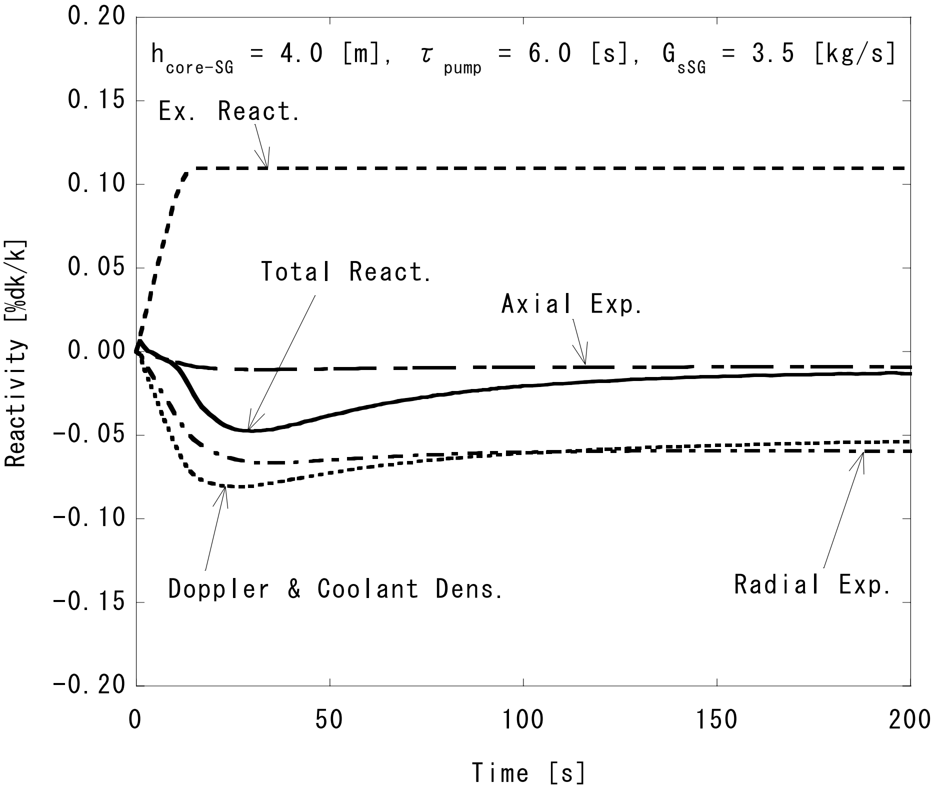


FIG. 12. Hot spot temperature changes in ULOF.

The uncontrolled loss of heat sink also terminates safely if the SGAHRS holds the safety passive function. The reactor vessel auxiliary coolant system (RVACS), which removes heat through the reactor wall to the chimney, serves as a passive system to back up the function of the SGAHRS in accident conditions.

Since the results for each of the abovementioned accidents show considerable safety margins, investigation of a combined UTOP+ULOF+ULOHS accident is being performed, though it is the case not necessarily to be considered in conventional safety analysis. The changes in reactivity, normalized power and hot spot temperature in this scenario are shown in Figures 13 - 15. No fuel damage is anticipated though the cladding temperature is slightly over the safety temperature limit (700^{o}C) for a short period. It might be possible to restart the reactor even in these circumstances, if causes of the accidents can be removed.

The reactor performance can be improved by changing design parameters. The effects of changing the pump coastdown half time and the thermal centres elevation difference on maximum cladding temperature are shown in Figures 16 and 17, respectively.



Ex. – external Exp. – expansion Dens. – density React. – reactivity

FIG. 13. Reactivity change in UTOP+ULOF+ULOHS.

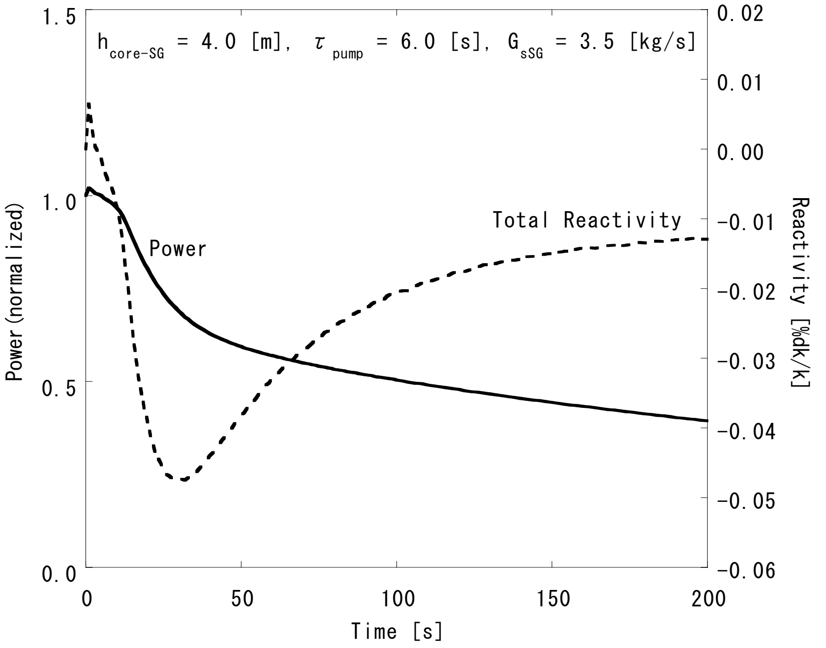


FIG. 14. Normalized power and total reactivity change in UTOP+ULOF+ULOHS.

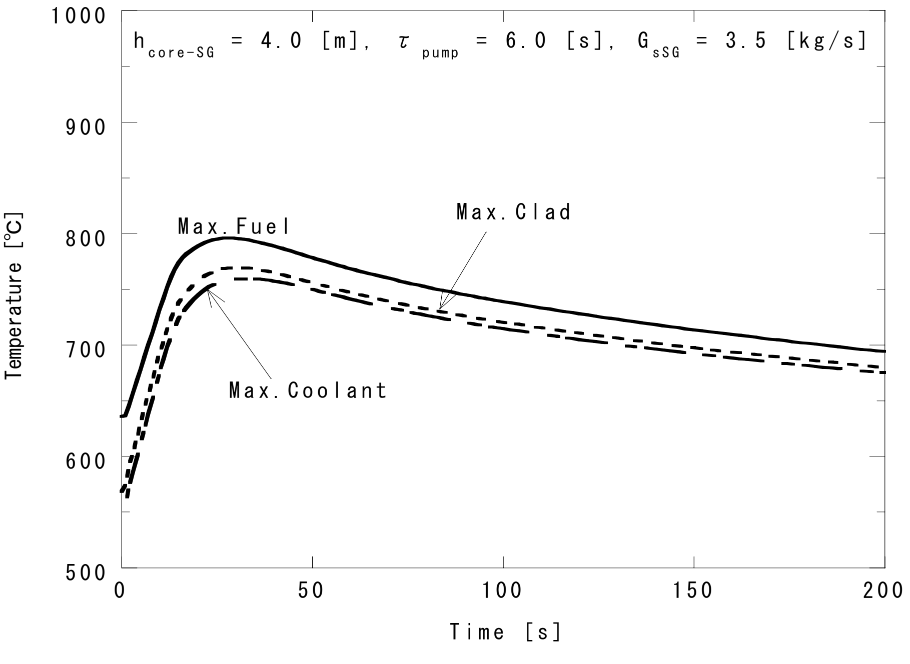


FIG. 15. Hot spot temperature changes in UTOP+ULOF+ULOHS.

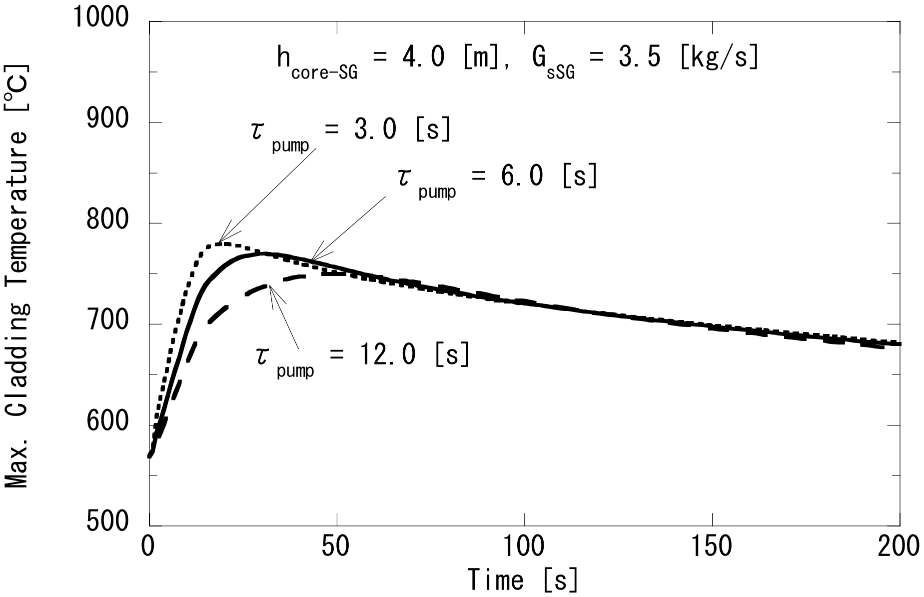


FIG. 16. Maximum cladding temperature change in UTOP+ULOF+ULOHS for different pump coastdown half times.

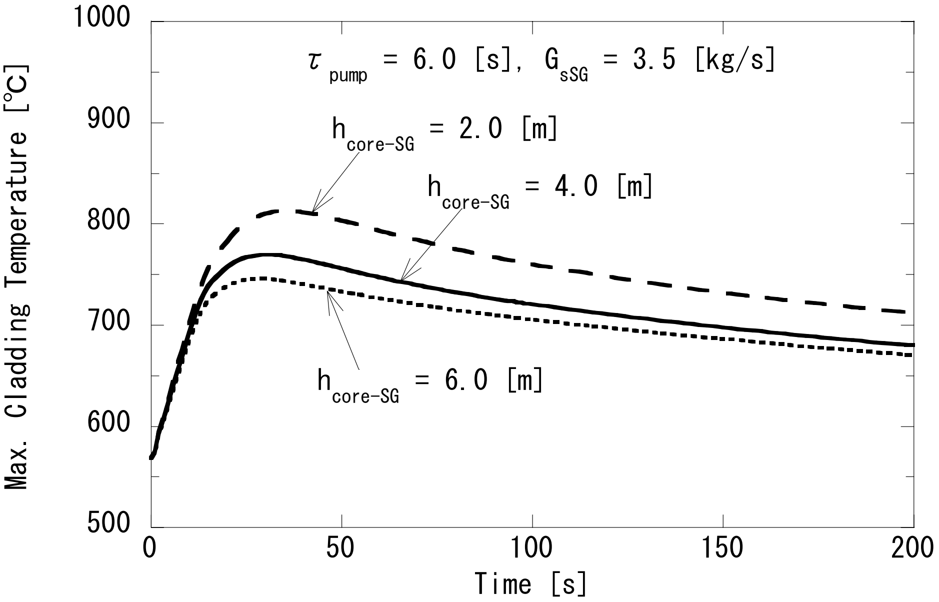


FIG. 17. Maximum cladding temperature change in UTOP+ULOF+ULOHS for different thermal centres elevation difference.

A steam generator (SG) tube rupture accident, which brings water of the steam generator tubes into the LBE coolant, is one of the most serious postulated events. The high pressure steam ejected in the reactor coolant is relieved through relief valves to a steam relief tank located above the reactor vessel, keeping the pressure in the reactor vessel below a specified level. The resulting impact on the hydrodynamic behaviour of the primary coolant and the behaviour of steam bubbles due to a steam generator tube rupture as well as the possibility of production of the oxides of lead and bismuth must be fully investigated.

1.6.4. Proliferation resistance

The LSPR is a factory fabricated and fuelled reactor designed for operation without on-site refuelling. During the whole period of reactor operation and transportation to and from the site, the reactor vessel is always closed (sealed) and the fuel is confined in the vessel. Because of very small operation reactivity margin in the core, the fuel inside the reactor vessel cannot be removed and fertile materials cannot be inserted in the reactor to produce fissile materials. No refuelling equipment is provided in the reactor or at the site during the whole period of reactor operation, including its transportation to and from the site.

1.6.5. Technical features and technological approaches used to facilitate physical protection of LSPR

The LSPR strongly relies on inherent and passive safety features to achieve a high level of safety in a variety of uncontrolled accidents or combinations thereof, which secures an enhanced level of protection against human actions of malevolent character.

Even the reactor is highjacked, it would not be easy to open the reactor vessel for a certain period after shutdown of the reactor because of the high polonium activity in the coolant.

1.7. Non-technical factors and arrangements that could facilitate effective development and deployment of LSPR

As it was mentioned before, the LSPR may be a good choice for developing countries with small electricity grids and insufficient infrastructure; in particular, through operation without on-site refuelling, it could facilitate making a decision to skip the development of the indigenous fuel cycle. To realize these potential benefits of the LSPR, an infrastructure framework for nuclear power plant leasing needs to be created.

In the 21st century, global warming caused by the carbon dioxide emissions may become an urgent problem and the carbon dioxide emissions from developing countries would then become important.

More countries joining the Kyoto protocol and other international conventions targeted at greenhouse effect prevention would objectively facilitate the progress of nuclear power and, specifically, increase the deployment opportunities for small reactors without on-site refuelling, such as the LSPR.

1.8. List of enabling technologies relevant to LSPR and status of their development

The enabling technologies, relevant for the LSPR, that require further development are the following:

(1) Structural materials compatible with lead-bismuth coolant; the major trends of further research and development (R&D) are:

- Development of instrumentation and control techniques and equipment to effectively control oxygen concentration in the LBE coolant;
- Development of new material to increase coolant output temperature and velocity;

(2) Polonium treatment technology;

(3) Countermeasures for accidents with a SG tube break;

(4) Cost reduction methods;

(5) Design approaches to reduce in-vessel coolant inventory (as a anti-seismic design measure).

Based on the LSPR concept fundamentals, several concepts of innovative small LBE cooled reactors are under development in RLNR TITech, incorporating:

(a) A lift-up pump concept, described in [8];

(b) A “Constant Axial shape of neutron flux, nuclide densities, and power shape During Life of Energy producing reactor” (CANDLE) burn-up concept, described in [9, 10].

1.9. Status of R&D and planned schedule

In Japan, the R&D for technology development in areas specified in section 1.8 are underway in the Tokyo Institute of Technology (TITech), being funded by the Japan Ministry of Education, Culture, Sports, Science and Technology (MEXT).

Sufficient data to support implementation of the LBE coolant technology is expected to be available within the next 10 years and, then, another 10 years may be necessary to design and construct a prototype reactor.

The presented conceptual design study of the LSPR has been carried out conservatively and the primary coolant velocity was selected low compared with the other designs, in consideration of the ambiguity of material corrosion data with respect to the LBE coolant. The height of the reactor vessel was chosen to be high enough to give a sufficient natural circulation head with ambient margins.

One option of further R&D option might be to consider mounting a reactor compartment on a barge, which might facilitate installation and dismantling operations at a site.

Alternatives to the present centrifuge mechanical pumps, such as natural circulation without pumps, the application of lift-up pumps providing the introduction of gas bubbles into the coolant to increase the buoyancy force, would be further investigated in the future. The present development, however, makes an emphasis on a simple and feasible reactor concept with the requested functions being performed only with the use of conventional and reliable devices.

The plans for future R&D, targeted at further improving of the LSPR safety and economy, include studies of the core design incorporating the CANDLE burn-up concept [9, 10], simplification of passive decay heat removal systems, identification of measures to cope with a steam generator tube rupture, and development of simplified maintenance techniques for in-vessel devices.

1.10. Justification of why a demonstration prototype or a significant amount of demonstrations will be needed

There is no experience in commissioning and operation of small lead or lead-bismuth cooled reactors with long-life cores in civil nuclear power and, therefore, a prototype plant would be required to test and demonstrate the innovative technologies of the LSPR outlined in sections 1.8 and 1.9.

1.11. List of other similar or relevant SMRs for which the design activities are ongoing

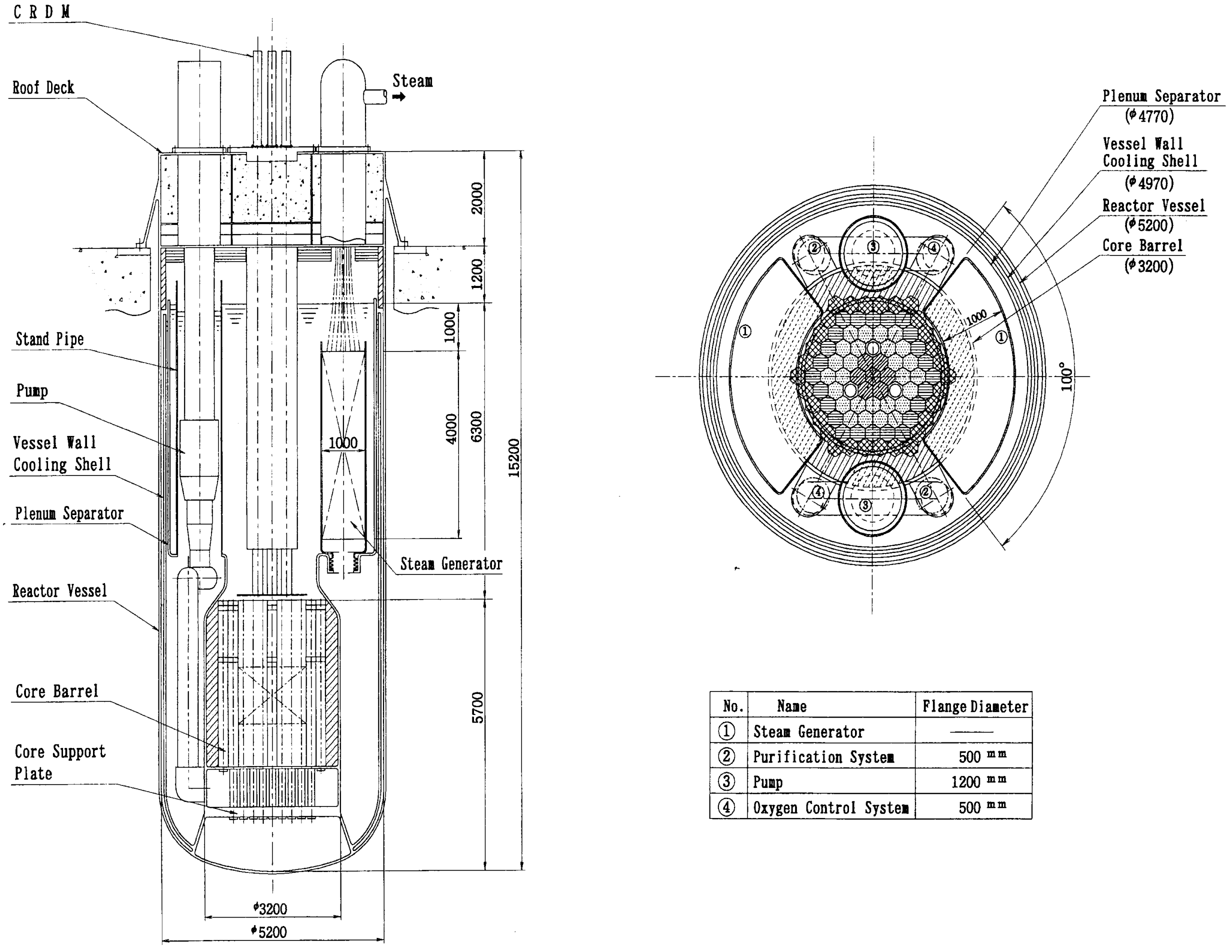
Several similar design studies for small lead or lead-bismuth cooled reactors with long-life cores are being performed at Experimental Design Organization (EDO) “Gidropress” and Institute of Physics and Power Engineering (IPPE) in the Russian Federation [11 to 13]; at the

Bandung Institute of Technology (ITB) in Indonesia [14]; at the University of California in Berkeley and Argonne National Laboratory (ANL) in the USA [15, 16]; and at the TITech and JNC in Japan [8].

2. Design description and data for LSPR

2.1. Description of the nuclear systems

A vertical and a horizontal cross-section of the LSPR core arrangement in the reactor vessel is shown in Fig. 18.



No.	Name	Flange Diameter
①	Steam Generator	——
②	Purification System	500 mm
③	Pump	1200 mm
④	Oxygen Control System	500 mm

(a) Vertical cross section (b) Horizontal cross section

FIG. 18. LSPR core arrangement in reactor vessel.

Summary description of the core and fuel design and primary circuit design is provided in section 1.4; summary of the specifications is in Table 1; and the outline of heat removal paths is given in section 1.6.3. No further details were provided.

2.2. Description of the turbine generator plant and systems

No information was provided.

2.3. Systems for non-electric applications

No information was provided

2.4. Plant layout

The plant layout of a LSPR plant is shown in Figures 19 and 20. The conventional fuel handling system is not available for a long life core. However, maintenance handling machines and maintenance spaces are accommodated and the pullout space necessary for mechanical pump impellers and purifying units is provided. When the reactor vessel lifetime expires, the current assumption is to comply with the need to exchange the reactor vessel with a new one.

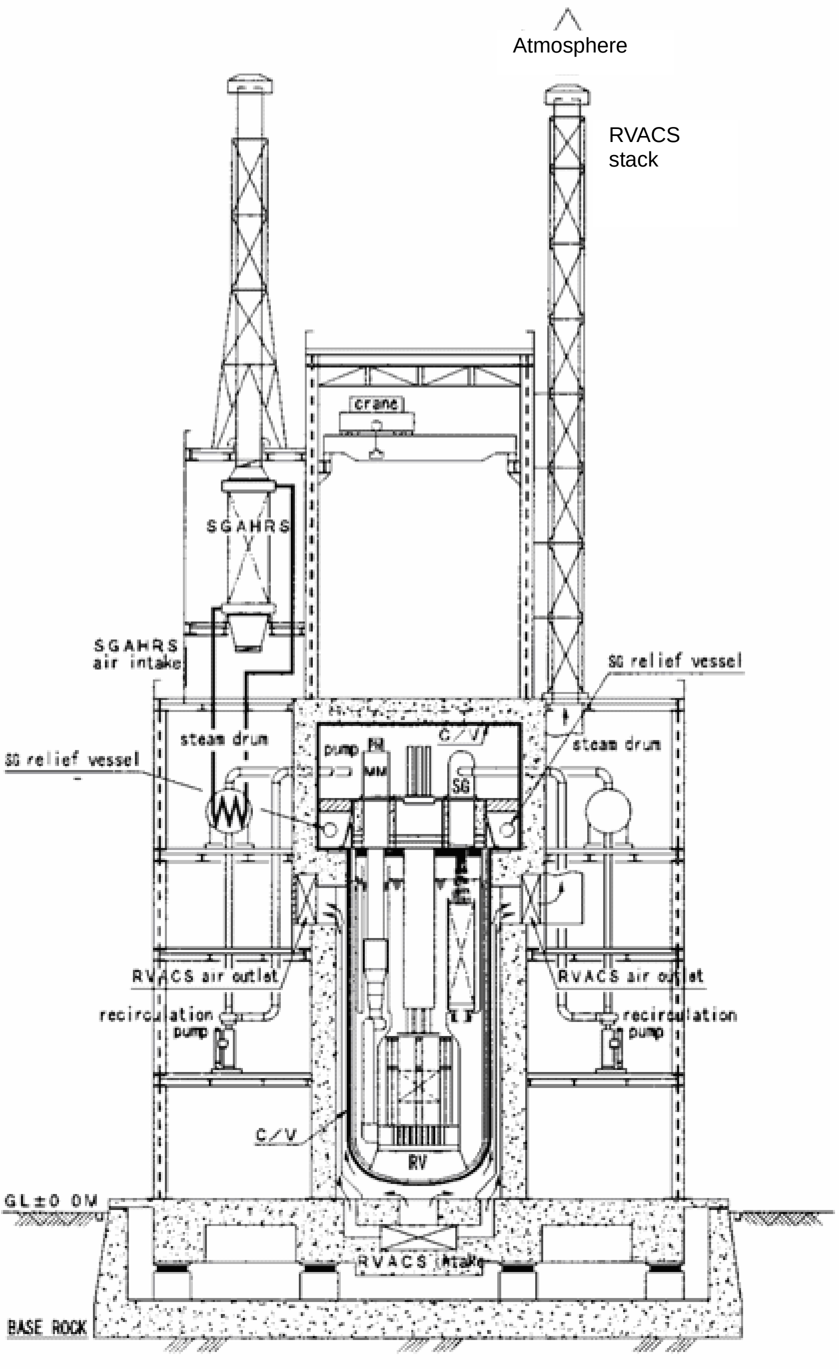


FIG. 19. LSPR plant layout (vertical section).

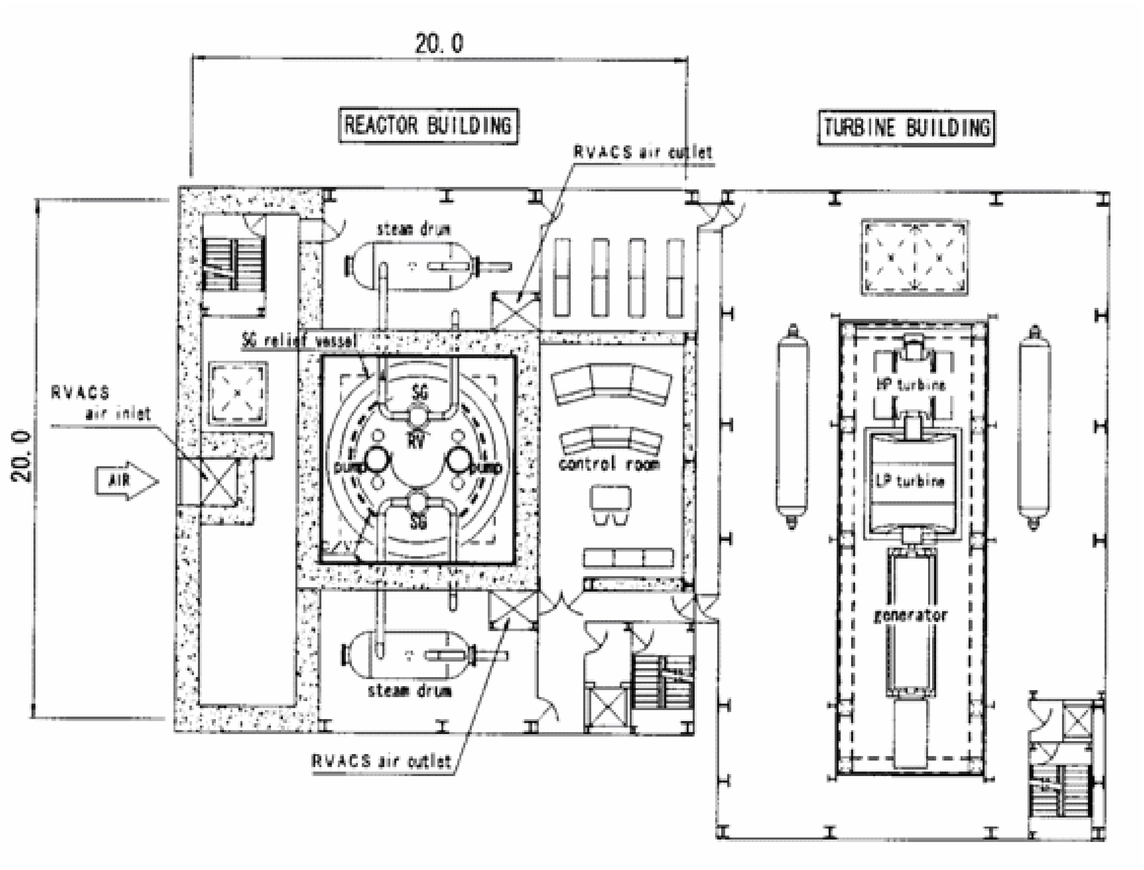


FIG. 20. LSPR plant layout (horizontal section).

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