ANNEX VIII

SAFETY DESIGN FEATURES OF THE 4S-LMR

Central Research Institute of Electric Power Industry and Toshiba Corporation, Japan

VIII-1. Description of the 4S-LMR concept

The Super-Safe Small and Simple Liquid Metal cooled Reactor (4S-LMR) is a concept of small sodium cooled fast reactor developed in Japan by the Central Research Institute of Electric Power Industry (CRIEPI) and Toshiba Corporation and for long operation without on-site refuelling. This concept is described in detail in ANNEX XV of [VIII-1].

The 4S-LMR is being developed to meet needs of certain segments of the diverse global energy market [VIII-1]. An economic disadvantage is pointed out to be the principal obstacle to realize small reactors. Higher safety level is also needed, because the number of nuclear power plants would increase in case small reactors are deployed around the world. Improved economic performance tends to be incompatible with the enhanced safety level, as shown by the experience of nuclear power reactors of previous generations. Stronger reliance on passive safety design options is expected to establish certain synergy between economic performance and safety. To facilitate such a synergy, the 4S-LMR is being designed to ensure simple operation, simplified maintenance including the refuelling, high safety level, and improved economic performance. More specific design policy for the 4S-LMR could be summarized in the following 9 design objectives:

1. No refuelling over 10 – 30 years;
2. Simple core burn-up control without control rods and without control rod driving mechanisms;
3. Reactors control and regulation executed by systems and components not belonging to the reactor system;
4. Quality assurance and short construction period based on factory fabrication of the reactor unit;
5. Minimum maintenance and inspection of reactor components;
6. Negative reactivity coefficients on temperature; negative sodium void reactivity;
7. No core damage in any conceivable initiating events without the reactor scram;
8. Safety system independent on the emergency power and not incorporating active decay heat removal systems,
9. Complete confinement of radioactivity under any operational conditions and in decommissioning.

Items from 1 through 5 are related to simplification of the systems and maintenance. Items from 6 through 9 are related to safety design.

Based on abovementioned design objectives, the 4S-LMR concept was attributed with multiple passive safety design features. Such an approach could help realize a high safety level and simultaneously reduce the number of auxiliary systems otherwise required to support safety functions of the safety system. The resulting reduction in the number of systems and system simplification may, in turn, reduce the required scope of maintenance works.

Small reactors are to be installed closer to the end users. In order to allay public fears, "a sense of security" is essential, which means that a transparent safety concept, a proven or easily demonstrable technology, and a small number of systems are cumulatively preferable. A fully passive heat removal system is employed in the 4S-LMR so that the auxiliary support systems can be eliminated. Safety of the 4S-LMR can easily be demonstrated in full-scale tests, because of its small size. Design status and passive safety features of the 4S-LMR are described in reference [VIII-1]. This reference also presents safety performance of the reactor in anticipated transients without scram and combinations thereof, based on the performed safety analyses.

The 4S-LMR incorporates a load following capability provided by a simple control of the feed water rate in the power circuit. The analyses have shown that the reactivity of core thermal expansion, which is one of the passive reactivity feedbacks, is important to realize this option. Core thermal expansion feedback also helps to secure the reactor safety. Specifically, analytical results predict that the presently selected cladding material HT-9 is compatible with the mechanism of the core expansion reactivity feedback. It is also shown that a flow rate control of the secondary pump would enhance the power range of reliable reactor operation due to an improved stability of the steam generator at steam-water side. As the irregular load following operation affects schedule pre-programming, the plant control systems of the 4S-LMR would be reconsidered in case the reactor is assumed to operate at partial power.

The 4S-LMR is a pool type sodium cooled fast reactor with steam-water power circuit. The power output is 50 MW(e), which corresponds to 135 MW(th). The refuelling interval for the variant considered in this description is 10 years. Major specifications of the 4S-LMR are listed in Tables VIII-1 and VIII-2.

TABLE VIII-1. MAJOR DESIGN PARAMETERS OF THE 4S-LMR

ITEMS	SPECIFICATIONS
Reactor:	
Diameter [m]	3.0
Height [m]	18.0(*1)
Reactor vessel thickness [mm]	25
Guard vessel thickness [mm]	15
Inner cylinder:	
Inner diameter [m]	1.84
Thickness [mm]	15
Reflector:	
Material	Graphite
Height [m]	2.1
Thickness [mm]	300
Core barrel:	
Inner diameter [m]	1.33
Thickness [mm]	10
Primary electromagnetic (EM) pump	
Rated flow [m^3/min.]	50
Head [MPa]	0.08×2

(*1) from bottom to coolant free surface

TABLE VIII-2. MAJOR DESIGN SPECIFICATIONS OF THE 4S-LMR

ITEMS	SPECIFICATIONS
Thermal output [MW]	135
Electrical output [MW]	50
Primary coolant condition [°C] (outlet/inlet)	510/355
Secondary coolant condition [°C] (outlet/inlet)	475/310
Steam condition [°C/MPa]	453/10.8
Core diameter [m]	1.2
Core height [m] (inner/outer)	1.0/1.5
Number of fuel sub-assemblies (inner/outer)	6/12
Number of reflector units	6
Reflector thickness [m]	0.3
Core lifetime [years]	10
Plant lifetime [years]	30
Number of fuel pins	469
Fuel pin diameter [mm]	10.0
Cladding thickness [mm]	0.59
Smear density [%TD]	75
Pitch/Diameter	1.15
Duct thickness [mm]	2
Duct gap [mm]	2
Bundle pitch [mm]	258
Assembly length [mm]	4800
Average burn-up [GW day/t]	70
Pu enrichment [weight %] (inner/outer)	17.5/20.0
Maximum linear heat rate [kW/m]	25
Conversion ratio (middle of cycle)	0.71
Coolant void reactivity (end of cycle) [%]	~0
Burn-up reactivity swing [%]	~9
Core pressure drop [MPa]	~0.1

Figure VIII-1 shows vertical layout of the reactor, including the primary heat transport system (PHTS). The PHTS consists of the containment vessel (guard vessel), the reactor vessel, the intermediate heat exchanger (IHX), the electromagnetic (EM) pumps, the reflectors, the internal structures, the core, and the shielding.

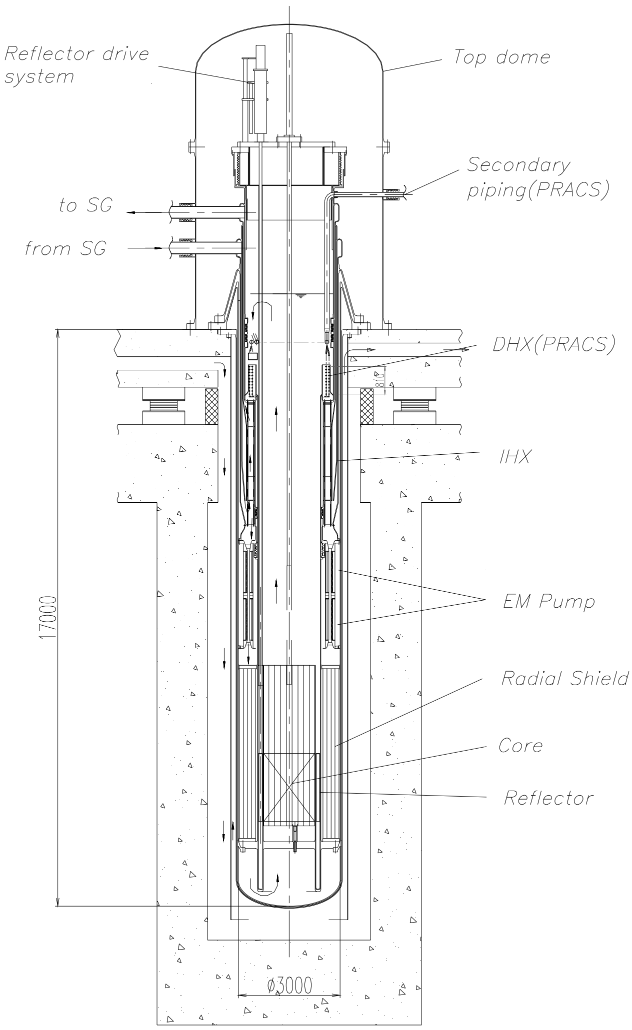

FIG. VIII-1. Vertical view of the 4S-LMR layout.

The reactor vessel is 3 m in diameter and 18 m in height and is divided into the inner part of a coolant riser plenum and the outer part of a coolant down-comer by the inner cylinder of 1.8 m diameter. The inner cylinder accommodates the core and the reflector. It also accommodates the reflector drivelines and the ultimate shutdown driveline. In the outer part, there are the direct heat exchanger (DHX) of a primary reactor auxiliary cooling system (PRACS), the intermediate heat exchanger (IHX), the electromagnetic (EM) pumps, and the radial shield assemblies, from top to bottom. As a design option, PRACS can be replaced by the intermediate reactor auxiliary cooling systems (IRACS), which removes shutdown heat via the secondary sodium in an active 9normal operation) or passive (postulated initiating events) mode. The primary coolant gets from the riser into the down-comer and then gets back into the coolant plenum underneath the core. There is no moving parts inside of the reactor vessel except for the reflector, which moves very slowly at 1~2 mm per week.

The guard vessel covers the reactor vessel to prevent a loss of the primary coolant. The guard vessel also forms the containment boundary, together with the top dome. A natural draught air cooling system between the guard vessel and the cavity wall, the so called reactor vessel auxiliary cooling system (RVACS), is designed as a passive decay heat removal system. The PRACS (or IRACS) mentioned above is then the second passive decay heat removal system. These two systems are redundant and diverse.

The primary pump system consists of the two EM pumps arranged in series. Each EM pump is of a sodium immersed self-cooled type and has an annular single stator coil. The total rated flow is 50 m^3/min, and each pump has a 0.08 MPa head. Such system of pumps arranged in series provides a favourable inherent response in the case of a single pump seizure, when it is necessary to mitigate to decrease of the core flow by a still working pump, “using” its Q-H (flow-head) curve. At the same time, the reverse flow may occur at a failed pump in a parallel-arranged pump system.

The annular reflector, divided into six segments, controls reactivity in the reactor core and compensates the burn-up reactivity swing. Any stuck event or malfunction of the reflector driving systems will eventually result in a subcritical state of the reactor, when negative reactivity due to fuel burn-up will not be compensated by a slow upward movement of the reflector. Dropping the reflector down will make the reactor subcritical from any operational state, due to the resulting increase of neutron leakage from the core.

The intermediate heat transport system (IHTS) consists of one EM pump, one steam generator (SG), the piping, and a dump tank. The EM pump is integrated in the SG.

The 4S-LMR core is designed for a lifetime operation without on-site refuelling and provides for negative reactivity coefficients and a reduced pressure drop at a relatively large core height. The requirement of 10-year core lifetime could reduce the maintenance works and contribute to non-proliferation [VIII-1]. The negative reactivity coefficients and a reduced pressure drop could enhance safety by providing intrinsic protection against loss-of-flow (LOF) events. The selection of core height was also limited by the available choices for performing full-core irradiation tests, in view of the existing facilities.

Figure VIII-2 shows the 4S-LMR core configuration. There are 6 inner sub-assemblies and 12 outer sub-assemblies. The ultimate shutdown rod is arranged at the centre of the core. It is a back-up shutdown system; the primary shutdown system provides for dropping down the reflector. The active height of the inner core is shorter than that of the outer core. This 0.5 m sodium region above the inner core helps to decrease the coolant density reactivity coefficient over the entire core. The coolant void reactivity is kept below zero during the core lifetime and is nearly zero at the end of the core life.

The average core outlet temperature was selected from the condition of not exceeding the minimum liquefaction temperature 650°C, at which a (metallic) fuel-steel eutectics starts to be formed. The hottest interface temperature between the outer fuel surface and the inner cladding surface was evaluated using the hot channel factor of ~1.9 (including the engineering safety factor), which is a conservative assumption. The safety design criteria for the cladding were also evaluated in consideration of the cladding thinning due to this metallurgical effect.

Reactivity feedback coefficients on temperature integrated over the core region are summarized in Table VIII-3. Reactivity feedback coefficients on density of the fuel, the coolant and the structures (cladding and duct) were derived from a diffusion calculation in R-Z geometry based on the perturbation theory. The density coefficients multiplied by thermal expansion rates of the fuel and structures make the temperature coefficients. The thermal expansion rate of the cladding was used to describe fuel axial expansion. Because the expansion rate of the cladding is smaller than that of the fuel, such an approach produced conservative results. The safety analyses performed considered spatial distributions of reactivity coefficients and expansion effects.

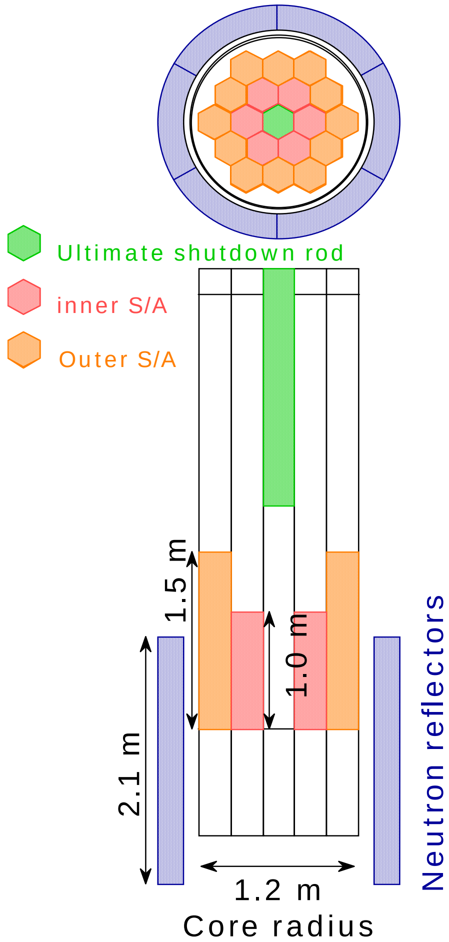

FIG. VIII-2. Core configuration of the 4S-LMR (ANNEX XV [VIII-1]).

TABLE VIII-3. REACTIVITY FEEDBACK COEFFICIENTS ON TEMPERATURE INTEGRATED OVER THE CORE VOLUME

CORE DESIGN		PREVIOUS DESIGN	CURRENT (MODIFIED) DESIGN
Doppler	$\left(T\frac{dk}{dT}\right)$	-2.80×10^{-3}	-7.07×10^{-3}
Fuel	$\left(\frac{\Delta k/kk'}{^{o}C}\right)$	$-7.29\times10^{-6\times}$	-2.68×10^{-6}
Coolant	$\left(\frac{\Delta k/kk'}{^{o}C}\right)$	-3.23×10^{-6}	~0
Structure	$\left(\frac{\Delta k/kk'}{^{o}C}\right)$	-0.50×10^{-6}	-8.94×10^{-8}

VIII-2. Passive safety design features of the 4S-LMR

The design philosophy of the 4S-LMR is to put an emphasis on simple, passive and inherent safety features as a major part of the defence in depth strategy. The ultimate objective in the 4S-LMR safety design is to eliminate the requirement of population evacuation as an emergency response measure.

The *inherent safety features* of the 4S-LMR are:

- Low power density in the core;
- Good thermal characteristics of the metallic fuel bonded by sodium;
- Negative reactivity coefficients on temperature;
- Negative sodium void reactivity coefficients;
- Large coolant inventory;
- Elimination of active or feedback control systems operating inside the reactor vessel;
- Elimination of components consisting of the rotating parts (application of static devices such as EM pumps);
- Limitation of the radioactivity confinement area (no on-site refuelling and no systems for fuel loading/unloading and shuffling, no fuel storage facilities in the reactor or on the site);
- Multiple barriers against fission product release, including:
  - The fuel cladding;
  - The reactor vessel, the upper plug and the IHX tubes;
  - The top dome and the guard vessel as containment;
- Relatively small radioactive inventory of a small power reactor;
- To prevent a sodium leakage and to mitigate the impact or influence if it occurs – double boundaries for sodium with a detection system for small leakage occurring by one boundary failure:
  - The reactor vessel and guard vessel for primary sodium;
  - Double piping, tubes and vessels for secondary sodium, including heat transfer tubes of the SG.

Passive safety systems of the 4S-LMR are the following:

- An automatic sodium drain system from the SG to the dump tank – if a sodium-water reaction occurs, an increase in cover gas pressure in the SG causes the secondary sodium to drain rapidly to the dump tank located beneath the SG (without rapture disks);
- Two diverse and redundant passive shutdown (residual) heat removal systems operating on natural convection of the coolant and natural air draft (PRACS or IRACS and RVACS);

For the shutdown (residual) heat removal, two independent passive systems are provided RVACS and IRACS (or PRACS, see Section VIII-1). The reactor vessel auxiliary cooling system (RVACS) is completely passive and removes shutdown heat from the surfaces of the guard vessel using natural draught of air. There are no valves, vanes or dampers in the flow path of the air; therefore, RVACS is always working, even in normal (rated) operation. Two stacks are provided to obtain a sufficient draft.

The IRACS removes shutdown heat via the secondary sodium. In normal shutdown, heat is removed by forced circulation of air with a blower driven by normal electric power; the

IRACS can also remove the required amount of heat solely through natural circulation of both air and sodium in the case of postulated initiating events.

The 4S-LMR incorporates no *active safety systems*. However, there are several active systems providing normal operation of the reactor at rated (or derated) power. In normal operation heat removed from the core by forced convection of sodium driven by EM pumps. The compensation of burn-up reactivity swing is performed by very slow upward movement of the reflector. An advanced driving mechanism for such movement is being considered [VIII-1].

No information was provided on whether certain systems of the 4S-LMR are safety grade.

VIII-3. Role of passive safety design features in the defence-in-depth

Some major highlights of the passive safety design features in the 4S-LMR, structured in accordance with the various levels of defence in depth [VIII-2, VIII-3], are brought out below.

Level 1: Prevention of abnormal operation and failure

(A) Prevention of transient over-power:

- Elimination of feedback control of the movable reflectors,
  - ➢ A pre-programmed reflector-drive system, which drives the reflector without feedback signals;
  - ➢ The moving speed of the reflector is approximately 1mm/week;
- The limitation of high-speed reactivity insertion by adopting the electromagnetic impulsive force (EMI) as a reflector driving system;
- The limitation of reactivity insertion at the start-up of reactor operation;
- Negative whole core sodium void worth;
- Power control via pump flow rate in the power circuit (no control rods in the core);

(B) Prevention of loss of coolant:

- Double boundaries for primary and secondary sodium in SG tubes and leak detection systems of continuous operation;

(C) Prevention of loss of flow:

- Primary EM pumps are arranged in two units connected in a series where each single unit takes on one half of the pump head;
- A combined system of the EM pumps and the synchronous motor systems (SM) ensures a sufficient flow coastdown characteristics;

(D) Prevention of loss of heat sink:

- Redundant and diverse passive auxiliary cooling systems (RVACS and IRACS or PRACS) with natural draught of the environmental air acting as a heat sink;

(E) Prevention of sodium – water reaction:

- A leak detection system in the heat transfer tubes of the SG using wire meshes and helium gas, capable of detecting both:
  - ➢ An inner tube failure (water / system side of the boundary); and
  - ➢ An outer tube failure (secondary sodium side of the boundary).

Level 2: Control of abnormal operation and detection of failure

The inherent and passive features contributing to such control are:

- All negative temperature reactivity feedback coefficient;
- Negative whole core sodium void worth;
- Effective radial expansion of core (negative feedback);
- Large thermal inertia of the coolant and the shielding structure;
- Two redundant power monitoring systems, the primary and the secondary; balance of plant temperature monitoring system; EM pump performance monitoring system, cover gas radioactivity monitoring system, etc.

Level 3: Control of accidents within the design basis

The inherent and passive features contributing to such control are:

- Metallic fuel (high thermal conductivity, low temperature);
- Low liner heat rate of fuel;
- Negative whole core sodium void worth;
- All negative temperature reactivity feedback coefficient;
- Low pressure loss in core region;
- Effective radial expansion of core (negative feedback);
- Redundant and diverse passive auxiliary cooling systems (RVACS and IRACS or PRACS) with natural draught of the environmental air acting as a heat sink;
- Increased reliability of the reactor shutdown systems achieved by the use of two independent systems with each of them having enough reactivity for a shutdown, including:
    - ➢ The drop of several sectors of the reflector;
    - ➢ Gravity-driven insertion of the ultimate shutdown rod;
- Increased reliability of the sodium-leakage prevention systems achieved by the use of double-wall SG tubes with detection systems for both inner and outer tubes.

Level 4: Control of severe plant conditions, including prevention of accident progression and mitigation of consequences of severe accidents

The inherent and passive features contributing to such control are:

- Redundant and diverse passive auxiliary cooling systems (RVACS and IRACS or PRACS) with natural draught of the environmental air acting as a heat sink;
- Inherent safety features of a metal fuelled core, such as excellent thermal conductivity and low accumulated enthalpy;
- Low linear heat rate of fuel;
- Negative whole core sodium void worth;
- Large inventory of primary sodium to meet the requirements for increased grace periods;

- The rapid system of sodium drain from the SG to the dump tank as a mitigation system for sodium-water reaction.

Level 5: Mitigation of radiological consequences of significant release of radioactive materials

The inherent and passive safety features of the 4S are capable to eliminate an occurrence of fuel melting in any accident without scram (AWS) or anticipated transient without scram (ATWS), see ANNEX XIV and ANNEX XV in [VIII-1].

VIII-4. Acceptance criteria for design basis and beyond design basis accidents

VIII-4.1. List of design basis and beyond design basis accidents

For the safety analysis of the 4S, design basis events (DBEs) have been selected and identified systematically with consideration of the 4S operation cycle and the events postulated for the MONJU and DFBR (Japan), and for LWRs. A broad variety of events have been considered in the following categories [VIII-1]:

- Power transients;
- Loss of flow;
- Local fault;
- Sodium leakage;
- Balance of plant (BOP) failure and loss of off-site power;
- Multiple systems failure.

Beyond design basis events (BDBEs) have been selected and identified in a similar manner [VIII-1]. On a broad scale, the beyond design basis accidents are divided into two big groups, which are anticipated transients without scram (ATWS) and accidents without scram (AWS). The ATWS comprise the sequences in which one of the active reactor shutdown systems does not work for any reason. The AWS groups the sequences more severe that ATWS, which include failures of more than one redundant system, such as failures of both pumps, both shutdown systems, and failure of one or both decay heat removal systems.

The examples of ATWS are [VIII-1]:

- Loss of on-site power without scram;
- Failure of the reflector drive system in rated power operation without scram.

The examples of AWS are [VIII-1]:

- Sudden loss of head in all primary pumps without scram (AWS event);
- Failure of the reflector drive system in a start-up without scram;
- Failure or IRACS and RVACS with the collapse of both of the two stacks (an event more severe than AWS).

VIII-4.2. Acceptance criteria

A general objective of the 4S-LMR safety design is to secure the capability of the plant to withstand a wide range of postulated initiating events and the scenarios resulting thereof without exceeding the pre-set limits for temperature of the fuel, the cladding, and the coolant, thereby maintaining the fuel pin and the coolant boundary integrity.

The criteria for DBE are based on the experience with conventional light water reactors (LWRs) and a previous design experience with the sodium cooled fast reactors; specifically, it incorporates the requirements used in the Clinch River Breeder Reactor project [VIII-4]. Table VIII-4 shows the acceptance criteria for DBE. The frequency ranges are similar to those recommended by the ANS standards for LWRs [VIII-5, 6].

TABLE VIII-4. ACCEPTANCE CRITERIA FOR DBE

DESIGN BASIS EVENT CATEGORY	FREQUENCY RANGE (F) (/RY)	EVALUATED POINT AND CRITERIA			
		CDF*	Primary coolant boundary	Radiation exposure to plant personnel	Offsite radiological dose
Normal operation	-	CDF<0.05	ASME Service level "A" limits	10 CFR 20 limits	10 CFR 50 Appendix I limits
Anticipated event	$F>10^{-2}$	Σ CDF all anticipated events + CDF max. unlikely event 1<0.1	ASME service level "B" limits	10 CFR 20 limits	10 CFR 50.34
Unlikely event	$10^{-2}>F>10^{-4}$		ASME service level "C" limits	10 CFR 20 limits	10 CFR 50.34
Extremely unlikely event	$10^{-4}>F>10^{-6}$	CDF<0.5	ASME service level "D" limits	10-CFR 20 limits	10 CFR 50.34

CDF: Cumulative Damage Fraction

The criteria for ATWS and AWS are as follows:

- ATWS events:
  - Maximum cumulative damage fraction (CDF) is less than 0.5;
  - Maximum fuel temperature is lower than the melting point;
  - The coolant boundary limit does not exceed the service level D in ASME [VIII-5, 6]
- AWS events:
  - Maximum coolant temperature is lower than the boiling point;
  - Maximum fuel temperature is lower than the melting point;
  - The coolant boundary limit does not exceed the service level D in ASME [VIII-5, 6].

VIII-5. Provisions for safety under external events

In the 4S-LMR design, the reactor building is isolated horizontally by seismic isolators. The design standard already exists for such isolators for NPPs in Japan. The 'tiny' reactor shape has a higher characteristic frequency; therefore, the 4S-LMR reactor could be rigid against vertical shock. The reactor vessel is located in a shaft under a ground level (see Fig. VIII-3), which together with the relatively small footprint of the plant contributes to an increased protection against aircraft crash. The capability of the plant to survive all postulated accidents relying only on the inherent and passive safety features without the need of the operator intervention, the emergency team actions, or the external power and water supplies is rated as an important feature contributing to the plant protection against impacts of external events.

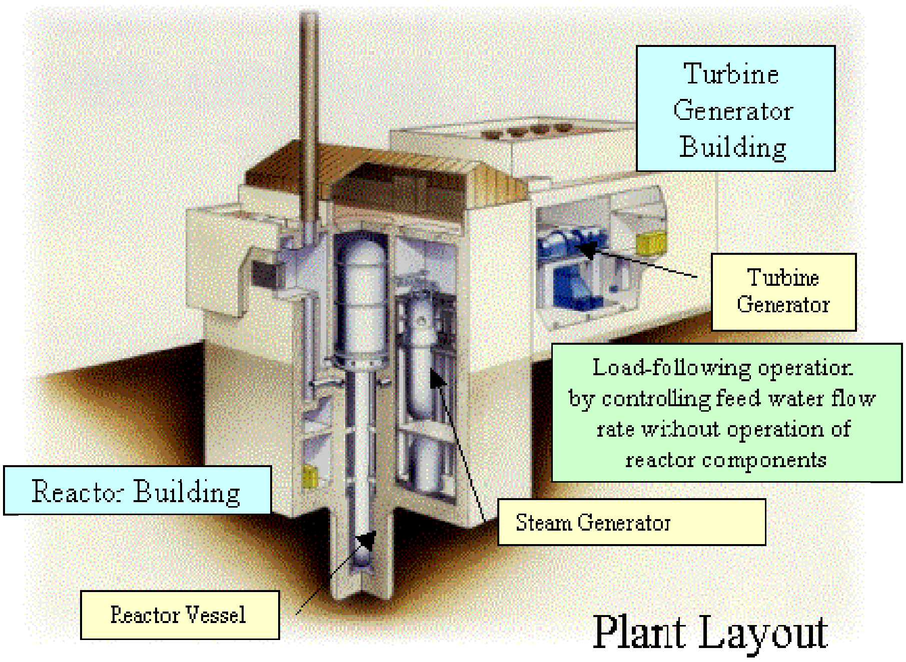

FIG. VIII-3. Reactor building of the 4S-LMR (1991 design) [VIII-1].

VIII-6. Probability of unacceptable radioactivity release beyond plant boundary

For the 4S-LMR it has been shown, that fuel never melts under any hypothetically postulated conditions such as ATWS or AWS (see ANNEX XIV and ANNEX XV of [VIII-1]). Some fuel pins with maximum cladding temperature might fail in more severe AWS events. The analyses have been performed for a hypothetical condition when all fuel element claddings fail (ANNEX XIV of [VIII-1]). The analytical results show that the dose equivalent in this case is 0.01 Sv at a distance of 20 m from the reactor. It means that only 20 m are required as a site boundary for the 4S-LMR.

VIII-7. Measures planned in response to severe accidents

One of the most important design objectives of the 4S is to enhance the level of safety so as to eliminate the need for population evacuation beyond the plant boundaries as a consequence of any postulated accident.

VIII-8. Summary of passive safety design features for the 4S-LMR

Tables VIII-5 to VIII-9 below provide the designer's response to the questionnaires developed at an IAEA technical meeting "Review of passive safety design options for SMRs" held in Vienna on 13 – 17 June 2005. These questionnaires were developed to summarize passive safety design options for different SMRs according to a common format, based on the provisions of the IAEA Safety Standards [VIII-2] and other IAEA publications [VIII-3, VIII-7]. The information presented in Tables VIII-5 to VIII-9 provided a basis for the conclusions and recommendations of the main part of this report.

TABLE VIII-5. QUESTIONNAIRE 1 – LIST OF SAFETY DESIGN FEATURES CONSIDERED FOR/INCORPORATED INTO THE 4S-LMR DESIGN

#	SAFETY DESIGN FEATURES	WHAT IS TARGETED?
1.	Low linear heat rate of fuel	A large margin to fuel melting
2.	Metallic fuel with high thermal conductivity	Decrease of fuel centreline temperature and temperature gradients in a fuel pin
3.	Double boundaries for primary and secondary sodium	Prevention of loss of coolant
4.	Secondary sodium coolant loop (intermediate heat transport system)	Prevent sodium – water reaction from affecting the core
5.	Increased reliability of the sodium-leakage prevention systems achieved by the use of double-wall SG tubes with detection systems for both inner and outer tubes	Prevention of sodium-water reaction
6.	All temperature reactivity feedback coefficients are negative	Accomplish passive shutdown and prevent accidents with core disruption
7.	Negative whole-core sodium void reactivity	Accomplish passive shutdown and prevent DBE from progressing into severe accidents
8.	Effective radial expansion of the core (with a negative feedback on reactivity)	Passive insertion of negative reactivity in transients with temperature rise; simple reactor control in load following mode
9.	Simple flow path of the coolant in the primary loop.	Enhance natural convection of the primary sodium coolant
10.	Low pressure loss in the core area	Enhance natural convection of the primary sodium coolant
11.	Electro-magnetic pump.	Prevent immediate pump trips due to a pump shaft stuck
12.	Two electro-magnetic pumps in series	Prevent loss of flow or limit its consequences
13.	Two redundant and diverse passive auxiliary cooling systems (RVACS and IRACS or PRACS) with natural draught of the environmental air acting as a heat sink.	Assure reliable removal of decay heat
14.	Two diverse passive shutdown systems with each of them having enough reactivity for a reactor shutdown	Assure reliable reactor shutdown in normal operation and in accidents
15.	No control rods used in the core – power control executed via feedwater flow rate control in the power circuit	Enhanced power range of reliable reactor operation; elimination of accidents with control rod ejection; simplified reactor design and operation
16.	Burn-up reactivity compensation with a reflector moving upward at a very low speed (1 mm per month) in a pre-programmed mode, with no feedback control	Prevention of transient over-power accidents

TABLE VIII-6. QUESTIONNAIRE 2 – LIST OF INTERNAL HAZARDS

#	SPECIFIC HAZARDS THAT ARE OF CONCERN FOR A REACTOR LINE	EXPLAIN HOW THESE HAZARDS ARE ADDRESSED IN SMR
1.	Prevent unacceptable reactivity transients	- No control rods in the core, reactor power control via feedwater flow rate in the power circuit; - All negative temperature reactivity feedbacks; - Negative whole-core sodium worth; - Prevention system of reflector insertion accident.
2.	Avoid loss of coolant	- Vessel pool configuration with a surrounding guard vessel; - Double boundaries for primary and secondary sodium; - Double-wall SG tubes with detection systems for both inner and outer tubes; - Because all temperature reactivity feedback coefficients are negative, coolant boiling will not occur.
3.	Avoid loss of heat removal	- Decay heat transport by natural circulation with the diverse IRACS and RVACS using environmental air as an ultimate heat sink; - Relatively large volume of sodium in the interconnected primary and secondary coolant systems of a pool type reactor.
4.	Avoid loss of flow	- The flow rate of natural convection sufficient to remove decay heat, boosted by simple flow path of the primary sodium and low pressure drop in the core; - Local blockage of flow pass in the core is prevented by inlet geometry of a fuel assembly, providing an axial and a radial barrier to the debris; - Two primary electromagnetic pumps arranged in series.
5.	Avoid exothermic chemical reactions (sodium-water and sodium-air reactions)	- Secondary sodium coolant loop (intermediate heat transport system); - Double-wall SG tubes with detection systems for both inner and outer tubes; - Because all temperature reactivity feedback coefficients are negative, coolant boiling and consequent high pressure generation, which may lead to a disruption of the coolant pressure boundary, will not occur.
6.	Prevent radiation exposure of public and plant personnel	- Low linear hear rate of fuel; - Because all temperature reactivity feedback coefficients are negative, temperature of the cladding inner surface will not increase up to the eutectic temperature; - Progression to core melt is prevented by the inherent and passive safety features.

TABLE VIII-7. QUESTIONNAIRE 3 – LIST OF INITIATING EVENTS FOR ABNORMAL OPERATION OCCURRENCES (AOO) / DESIGN BASIS ACCIDENTS (DBA) / BEYOND DESIGN BASIS ACCIDENTS (BDBA)

#	LIST OF INITIATING EVENTS FOR AOO / DBA / BDBA TYPICAL FOR A REACTOR LINE (SODIUM COOLED FAST REACTORS)	DESIGN FEATURES OF THE 4S-LMR USED TO PREVENT PROGRESSION OF THE INITIATING EVENTS TO AOO / DBA / BDBA, TO CONTROL DBA, TO MITIGATE BDBA CONSEQUENCES, ETC.*	INITIATING EVENTS SPECIFIC TO THIS PARTICULAR SMR
1.	Loss of flow	- Two primary electromagnetic pumps arranged in series with each capable of handing 05 of the nominal coolant flow rate; - Passive reduction of the reactor power by all negative temperature reactivity coefficients; - Heat transport by the flow rate of natural convection sufficient to remove decay heat, boosted by simple flow path of the primary sodium and low pressure drop in the core.	
2.	Transient over-power	- All temperature reactivity feedback coefficients are negative; - Whole-core sodium void reactivity is negative; - No feedback control of a moveable reflector; - No control rods in the core (power control via pump flow rate in the power circuit); - Limitation of high-speed reactivity insertion by adopting the electromagnetic impulsive force (EMI) as a reflector driving system; - Limitation of reactivity insertion at the start-up of reactor operation; - High thermal conductivity of metallic fuel.	- Failure in insertion of the ultimate shutdown rod; - Failure in the operation of a pre-programmed moveable reflector.
3.	Loss of heat sink	- Environmental air draught is used as an ultimate heat think, with two redundant and diverse passive decay heat removal systems (RVACS and IRACS) being provided; - Relatively large volume of sodium in the interconnected primary and secondary coolant systems of a pool type reactor; - Passive reduction of the reactor power by all negative temperature reactivity coefficients; - Whole-core sodium void reactivity is negative.	
4.	Local fault	- High thermal conductivity and low centreline temperature of metallic fuel; - Local blockage of flow pass in the core is prevented by inlet geometry of a fuel assembly, providing an axial and a radial barrier to the debris.	

#	List of initiating events for AOO / DBA / BDBA typical for a reactor line (sodium cooled fast reactors)	Design features of the 4S-LMR used to prevent progression of the initiating events to AOO / DBA / BDBA, to control DBA, to mitigate BDBA consequences, etc.*	Initiating events specific to this particular SMR
5.	Loss of on-site power	- Gravity driven insertion of ultimate shut-down rod; - Gravity driven drop of reflector parts to shut down the reactor; - With moveable reflector being stuck, the reactor would operate for some time and then become subcritical because burn-up reactivity loss will not be compensated by slow upward movement of the reflector; - All temperature reactivity feedback coefficients are negative; - Whole-core sodium void reactivity is negative; - Natural convection in the primary circuit sufficient to remove decay heat; - Environmental air draught is used as an ultimate heat think, with two redundant and diverse passive decay heat removal systems (RVACS and IRACS) being provided.	
6.	Sodium leak	- Secondary sodium coolant loop (intermediate heat transport system); - Double-wall SG tubes with detection systems for both inner and outer tubes.	

* The analyses performed have shown that all postulated designs basis and beyond design basis accidents can be terminated without core melting relying only on the inherent and passive safety features of the plant [VIII-1].

TABLE VIII-8. QUESTIONNAIRE 4 - SAFETY DESIGN FEATURES ATTRIBUTED TO DEFENCE IN DEPTH LEVELS

#	Safety design features	Category: A-D (for passive systems only), according to IAEA-TECDOC-626 [VIII-5]	Relevant DID level, according to NS-R-1 [VIII-2] and INSAG-10 [VIII-3]
1.	Secondary sodium coolant loop (intermediate heat transport system)	A	1, 4
2.	Double-wall SG tubes with (active) Na leak detection system for each wall	A	2
3.	Electromagnetic pump	B	1
4.	Two electromagnetic pumps in series	A	2
5.	Simple flow path in the primary loop	A	2, 3
6.	Low pressure loss in the core	A	2, 3
7.	Reactor vessel auxiliary cooling system (RVACS, IRACS or PRACS) with the environmental air as an ultimate heat sink	B	3, 4

#	Safety design features	Category: A-D (for passive systems only), according to IAEA-TECDOC-626 [VIII-5]	Relevant DID level, according to NS-R-1 [VIII-2] and INSAG-10 [VIII-3]
8.	Two redundant and diverse passive decay heat removal systems (PRACS or IRACS and RVACS)	A	2, 3
9.	Metallic fuel (high thermal conductivity)	A	1, 3
10.	Low linear heat rate	A	1, 3
11.	Relatively large volume of sodium in the interconnected primary and secondary coolant systems of a pool type reactor	A	3, 4
12.	A whole core sodium void worth is negative.	A	1, 3
13.	All temperature reactivity feedback coefficients are negative	A	1, 3
14.	Fuel assembly inlet geometry providing axial and radial barriers to the debris	A	1, 2
15.	Radial expansion of the core	B	2, 3
16.	Two redundant and diverse gravity-driven reactor shutdown systems (drop of the reflector and ultimate control rod insertion)	C	1, 2, 3
17.	No feedback control of the reflector movement	A	1
18.	No control rods in the core	A	1

TABLE VIII-9. QUESTIONNAIRE 5 - POSITIVE/ NEGATIVE EFFECTS OF PASSIVE SAFETY DESIGN FEATURES IN AREAS OTHER THAN SAFETY

Passive safety design features	Positive effects on economics, physical protection, etc.	Negative effects on economics, physical protection, etc.
Positive / negative effects of passive safety design features on economics, physical protection, etc. have not been investigated yet.		

References

[VIII-1] INTERNATIONAL ATOMIC ENERGY AGENCY, Status of Small Reactor Designs without On-site Refuelling, IAEA-TECDOC-1536, Vienna (2007).

[VIII-2] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Nuclear Power Plants: Design, Safety Standards Series, No. NS-R-1, IAEA, Vienna (2000).

[VIII-3] INTERNATIONAL ATOMIC ENERGY AGENCY, Defence in Depth in Nuclear Safety, INSAG-10, Vienna (1996).

[VIII-4] Clinch River Breeder Reactor Project Preliminary Safety Report, Clinch River Breeder Reactor Plant Project -Clinch River Breeder Reactor Plant Project Office, April 1978, Clinch River, USA.

[VIII-5] American National Standards Institute / American Nuclear Society Standard – ANSI/ANS-51.1-1983, Nuclear Safety Criteria for the Design of Stationary Pressurized Water Reactor Power Plants.

[VIII-6] American National Standards Institute / American Nuclear Society Standard – ANSI/ANS-52.1-1983, Nuclear Safety Criteria for the Design of Stationary Boiling Water Reactor Power Plants.

[VIII-7] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Related Terms for Advanced Nuclear Plants, IAEA-TECDOC-626, Vienna (1991).