SUPER-SAFE, SMALL AND SIMPLE REACTOR (4S, TOSHIBA DESIGN)

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

Overview

Full name	Super-Safe, Small and Simple Reactor
Acronym	4S
Reactor type	Pool Type Reactor
Coolant	Sodium
Moderator	No Moderator
Neutron spectrum	Fast Neutrons
Thermal capacity	30.00/135.00 MW(th)
Electrical capacity	10.00/50.00 MW(e)
Design status	Conceptual Design
Designers	Toshiba
Last update	03-06-2013

1. Introduction

The 4S (super-safe, small and simple) is a small sodium cooled reactor without on-site refuelling. Being developed as distributed energy source for multi purpose applications, the 4S offers two outputs of 30 MW(th) and 135 MW(th), respectively. These energy outputs have been selected from demand analyses [1].

Japan has a long-term national plan to introduce sodium-cooled fast breeder reactors (FBRs) for effective utilization of natural uranium. To provide their initial fuel load, plutonium will be extracted from the spent fuel of existing light water reactors (LWRs).

To accomplish this plan, the sodium cooled experimental reactor JOYO has been constructed and being used in the Japan Atomic Energy Agency (JAEA), an organization combining the former Japan Nuclear Cycle Development Institute (JNC) and Japan Atomic Energy Research Institute (JAERI) in 2005.

The prototype FBR MONJU was constructed by former JNC to demonstrate electricity generation by FBRs and build sufficient experience with sodium cooled power plants, aiming at their commercialization in Japan in the future. The technologies gained through these experiences support the base of the 4S design as a sodium cooled reactor.

Apart from the prototype FBR MONJU, much research and development (R&D) has already been performed to complete the design of the Demonstration FBR, sponsored by nine Japanese utilities, Electric Power Development Co., Ltd., and the Japan Atomic Power Company (JAPC). The R&D included the development of new types of equipment for sodium cooled reactors such as highly reliable electromagnetic pumps and double-walled tube steam generators with leak detection systems for both sodium and water/steam. This new equipment is considered to become more important for the commercialization of sodium cooled reactors, and the 4S is adopting these technologies in its design.

Since 2002, Central Research Institute of Electric Power Industry (CRIEPI), JAERI, Osaka University, and the University of Tokyo had performed the R&D focussed on the technologies of the 4S reactor core, fuel and reflectors, sponsored by the Japan Ministry of Education, Culture, Sports, Science and Technology (MEXT). Critical experiments for the 4S had been performed at the Fast Critical Assembly (FCA) in Tokai-mura (former JAERI). The Argonne National Laboratory (ANL) and the Idaho National Laboratory (INL, former ANL-West) have developed the metal fuel technology, which is a keystone to achieving the desired features the 4S, and much experience with the metal fuel has been gained through the operation of the EBR-II reactor in the USA.

Licensing activities for the 4S design initiated with the U.S. Nuclear Regulatory Commission (U.S.NRC) in 2007. In pre-application review, four meetings were held. In the first meeting, high level overview was discussed. In the second meeting, system design and long-life metallic fuel which is used in 4S were discussed. In the third meeting, safety design and regulatory conformance were discussed. In the fourth meeting, 4S Phenomena Identification and Ranking Table (PIRT) [2] and design conformance to policy statement [3] were discussed.

Since 2008, Toshiba had performed the R&D focussed on the technologies of electromagnetic pump (EMP) and steam generator, sponsored by the Japan Ministry of Economy, Trade and Industry (METI).

The 4S project has been conducted by Toshiba Corporation, CRIEPI, Westinghouse Electric Company (WEC), and ANL.

ENHS and STAR-LM are SMR concepts similar to the 4S [4, 5].

2. Description of Nuclear Systems

2.1 General Design of 4S

The 4S is a sodium-cooled reactor; therefore, its neutron spectrum is fast. However, the 4S is not a breeder reactor since blanket fuel, usually consisting of depleted uranium located around the core to absorb leakage neutrons from the core to achieve breeding of fissile materials, is not provided in its basic design.

The 4S is a reactor without on-site refuelling in which the core has a lifetime of approximately thirty years. The movable reflector surrounding the core gradually moves, compensating the burn-up reactivity loss over the thirty-year lifetime.

The reactor power can be controlled by the water/steam system without affecting the core operation directly. The capability of power self-adjustment makes the reactor applicable for a load follow operation mode.

Table 1 shows major design and operating characteristics of 4S.

A vertical cross-section of the 4S is shown in Fig. 1; a simplified schematic diagram of the 4S based electric power plant is given in Fig. 2. Although the 4S has two designs, those of 10 MW(e) and 50 MW(e), both of these figures show the 10 MW(e) design.

The reactor is a pool type (integral type) as all primary components are installed inside the reactor vessel (RV). Major primary components are the Intermediate Heat Exchanger (IHX), primary EM pumps, moveable reflectors which form a primary reactivity control system, the ultimate shutdown rod which is a back-up shutdown system, radial shielding assemblies, core support plate, coolant inlet modules and fuel subassemblies.

TABLE 1. MAJOR DESIGN AND OPERATING CHARACTERISTICS OF 4S

ATTRIBUTES	DESIGN PARTICULARS	
Thermal rating	30 MW(th)	135 MW(th)
Electric output	10 MW(e)*	50 MW(e)*
Mode of operation	Base load or load follow	
Load factor/ availability (targets)	> 95 %	
Reactor type	Pool type (integral type)	
Fuel material	Metal fuel (U-Zr alloy) based on enriched uranium	
Coolant	Sodium	
Neutron energy spectrum	Fast	
Core and fuel lifetime	30 years (no refuelling during the whole lifetime)	
Reactivity control system	Axially movable reflectors / Fixed absorber	
Reflector type	Cylindrical type; divided into 6 sectors	
Primary shutdown system	Axially movable reflectors of 6 sectors	
Back-up shutdown system	A single ultimate shutdown rod	
Inherent shutdown system	Inherent characteristics based on reactivity feedbacks	
Type of primary pump	Two electromagnetic (EM) pumps in series	
Reactor vessel diameter	Approximately 3.5 m	Approximately 3.6 m
Shutdown heat removal system (1)	Reactor vessel auxiliary cooling system (RVACS)	
Shutdown heat removal system (2)	Intermediate reactor auxiliary cooling system (IRACS)	Primary reactor auxiliary cooling system (PRACS)
Boundary for primary sodium	Double boundary: reactor vessel (RV) and guard vessel (GV)	
Containment system	GV and top dome	
Secondary cooling system	One sodium loop: heat transport from intermediate heat exchanger (IHX) to steam generator (SG)	
Type of secondary pump	EM pump	
Number of steam generators (SGs)	1	
Type of SG	Helical type	
Type of tubes in SG	Double wall tubes with leak detection system	

* In the case when all thermal output is used for electricity generation in the balance of plant (BOP).

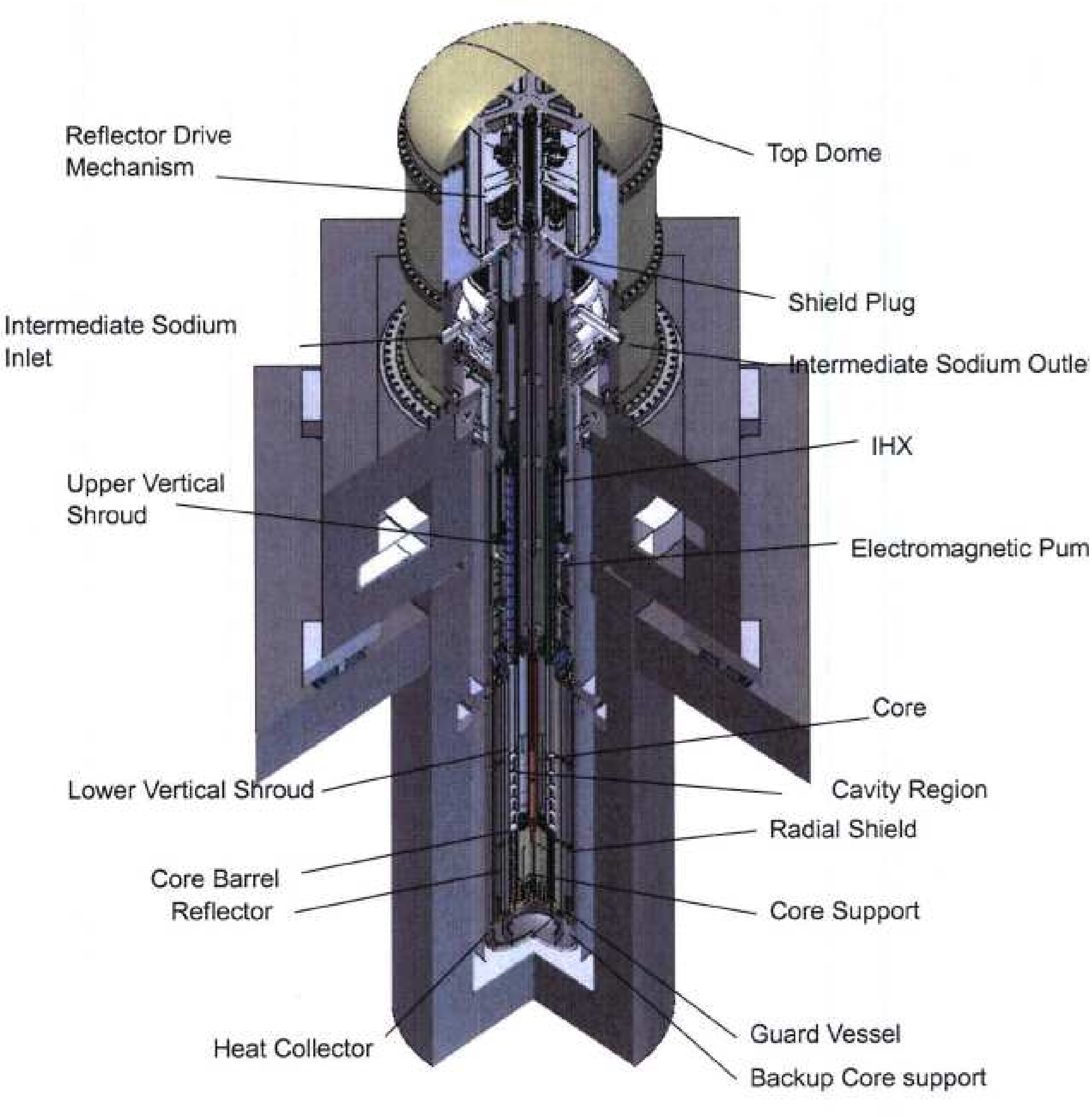


FIG. 1. Vertical section of the 4S plant of 10 MW(e).

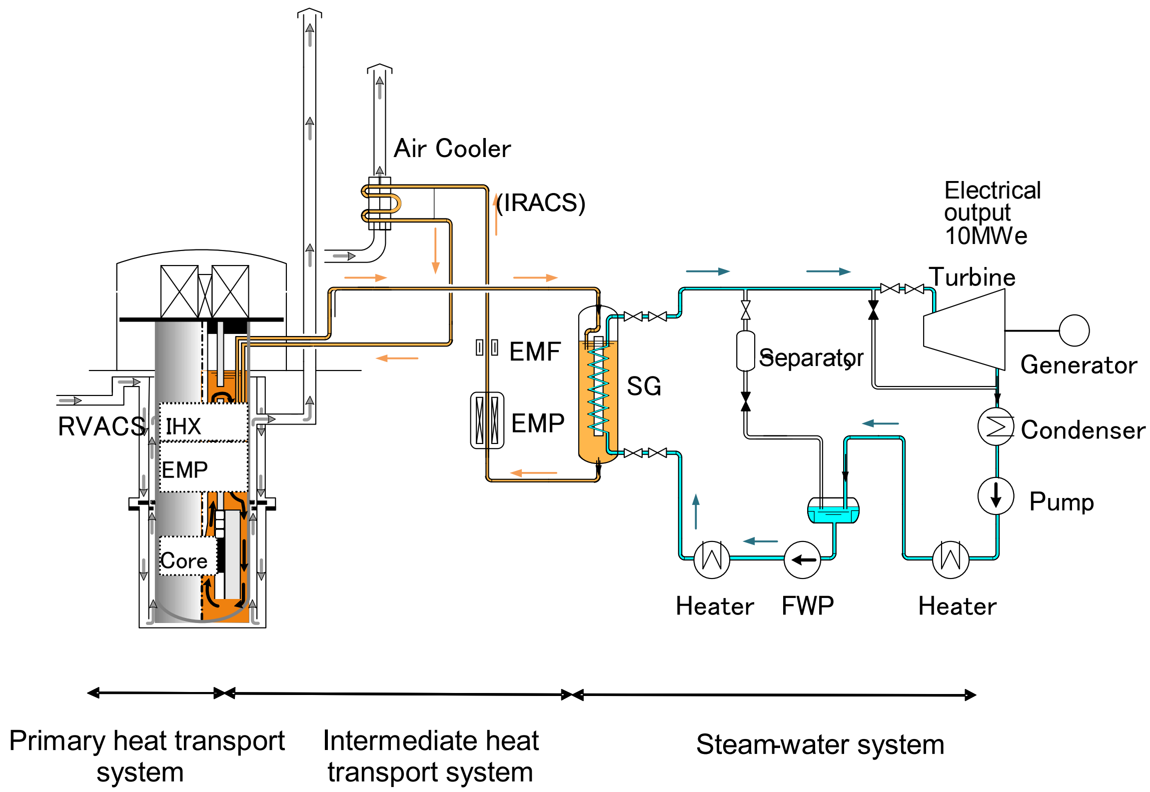


FIG. 2. Simplified schematic diagram of the 4S plant of 10 MW(e).

The IHX is located at the upper position inside the RV. Heat produced in the core is transferred from the primary sodium to the secondary sodium through the IHX. The primary EM pump system, located beneath the IHX, consists of two units arranged in series to insure redundancy for the circulation capability of primary sodium in case of one pump failure. Each EM pump unit produces a half of the head needed to circulate sodium in the reactor primary coolant system. A shielding plug seals the RV at the top. The cover gas (argon) fills the region between the surface of the primary sodium and the bottom of the shielding plug. The guard vessel (GV) provides a second boundary for the primary sodium at the outer side of the reactor vessel (RV). The containment system consists of the GV and the top dome, which covers the upper region of the RV, a shielding plug and the equipment located on the shielding plug. Horizontal seismic isolators are adopted for the reactor building.

The primary sodium circulates from the EM pumps downward, driven by pump pressure, and flows through radial shielding assemblies located in the region between the RV and the cylindrical dividing wall. The coolant flow changes its direction at the bottom of the RV and then goes upward, mainly into the fuel subassemblies and partly into the movable reflectors.

The coolant flow is distributed appropriately to fuel subassemblies of each type and to the movable reflectors. Here, the core barrel separates the core and reflector regions. Heat produced in the core is transferred to the coolant while it flows through the fuel pin bundles. Reflectors are also cooled so that the temperature becomes sufficiently low and the temperature distribution is flattened to maintain integrity through 30 years. The coolant gathers at the hot plenum after flowing through the fuel subassemblies and the reflectors. The heated primary sodium then goes into the IHX to transfer heat to the secondary sodium.

The secondary sodium loop acts as an intermediate heat transport system and consists of the IHX, piping, dump tank, EM pump, and steam generator (SG). Secondary sodium coolant heated in the IHX flows inside the piping to the SG where heat is transferred to water/steam of the power circuit to be supplied to the steam turbine generator.

The heat transfer tubes of the SG are double wall tubes. Between the inner and outer tube, wire meshes are provided, which are filled with helium and act as a detection system for a one side tube failure.

For heat removal from a shutdown reactor, two independent passive systems are provided, which are RVACS and IRACS. The RVACS is completely passive and removes shutdown heat from the surfaces of the guard vessel using natural circulation of air. There is no valve, vane, or damper in the flow path of the air; therefore, the RVACS is always in operation, even when the reactor operates at rated power. 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 sodium circulation and natural air convection with normal electric power supply; the IRACS can also remove the required amount of heat solely through natural circulation of both air and sodium in case of postulated accidents.

Figure 3 shows a general view of the 4S reactor for a 50 MW(e) plant.; Although the size and dimensions differ from those of the reactor for a 10 MW(e) plant, nearly all basic concepts are the same, except that PRACS is used in the 50 MW(e) design instead of the IRACS in the 10 MW(e) design.

Figure 4 gives a general view of the 4S core.

The neutronic design of the 4S has been optimized to achieve the following design targets:

- Improvement of the public acceptance and safety: all reactivity feedback by temperature and void reactivity of core are zero or negative;
- Minimization of fuel cost and operation and maintenance (O&M) cost; ensuring enhanced proliferation resistance (fuel costs are affected by the burden of fuel transport and storage problems in rural areas): no refuelling incurred during the whole 30- year core lifetime,
- Ensuring public acceptance; taking into account certain political circumstances such as non-proliferation regime and early deployment option: use of uranium fuel with the enrichment by ^{235}U less than 20 % (by weight);
- Minimization of fuel cost and securing fuel integrity under long-life operation of the core: adequate fuel burn-up;
- Minimization of construction costs: reduction of core size.

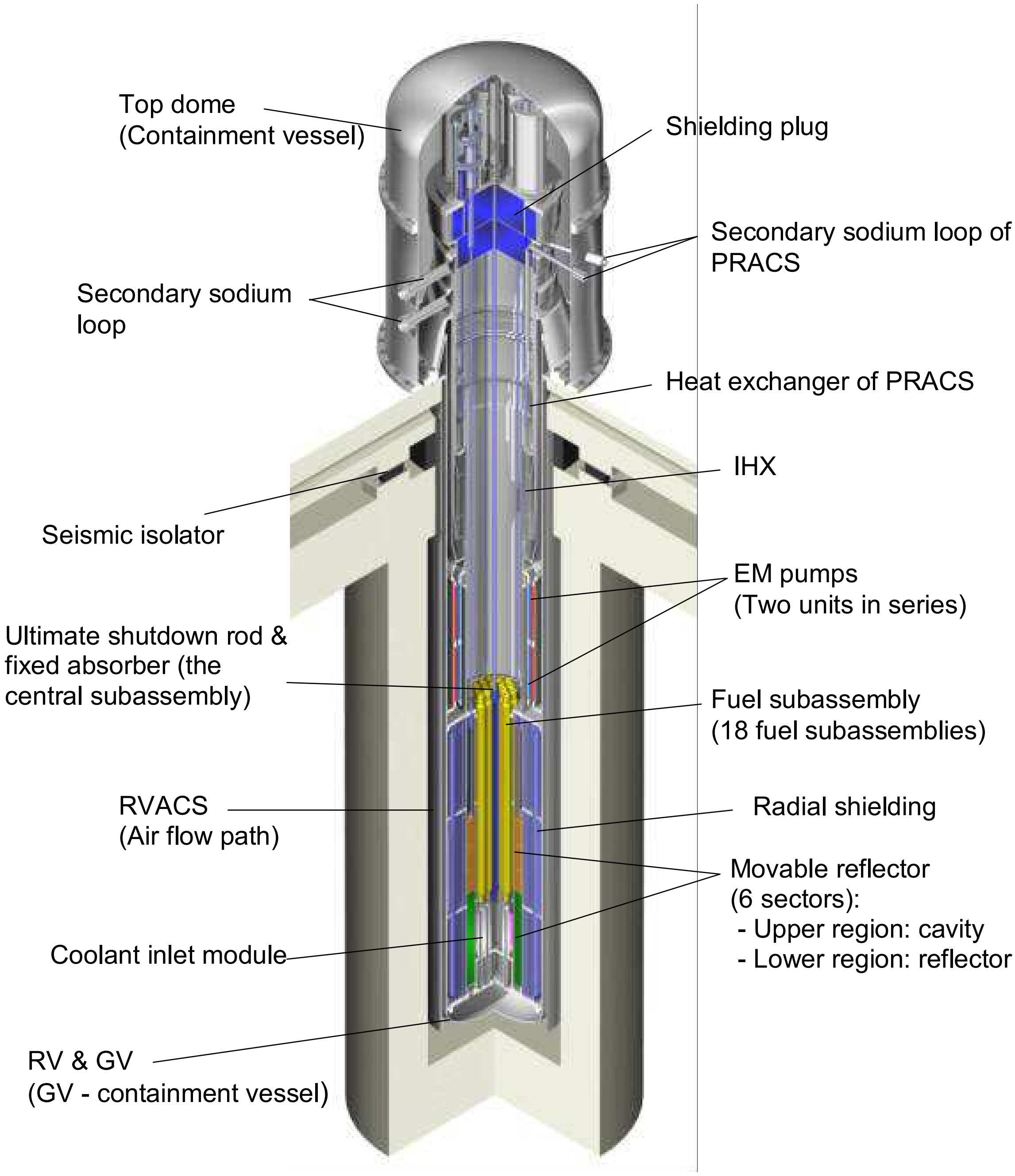


FIG. 3. General view of the 4S reactor for a 50 MW(e) plant.

The abovementioned design targets were defined after deliberations regarding the actual needs or demands at each site in rural areas and taking into account the factors of acceptability to the public, early deployment option, regulation policies, and (international) political circumstances including non-proliferation, cost competitiveness, etc.

A summary of the neutron-physical characteristics of the 4S reactor is provided in Table 2.

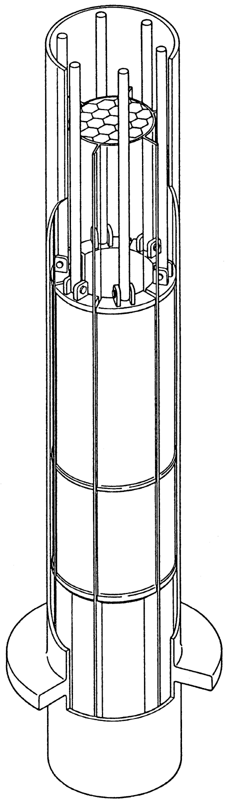


FIG. 4. General view of the 4S core.

TABLE 2. NEUTRON-PHYSICAL CHARACTERISTICS OF THE 4S

Electric output	10 MW(e)	50 MW(e)
Number of uranium enrichment zones	2 (inner / outer core)	2 (inner / outer core)
Uranium enrichment	17.0 / 19.0 wt%	12.0 / 18.0 wt%
Average linear heat rate	39W/cm	110 W/cm
Conversion ratio	0.45	0.53
Average burn-up	34 GWd/t	90 GWd/t
Burn-up reactivity swing	8 %dk/kk’	10 %dk/kk’
Coolant void reactivity	0 %dk/kk’	0 %dk/kk’

The drive mechanism of the reflectors carries them upward to conform to the predicted or pre-adjusted curve to give the core a constant reactivity-worth (Fig. 5).

A mismatch between reactivity added by the reflectors and the reactivity lost via fuel burn-up is adjusted by the feedwater control of the water/steam system. Therefore, the reactivity control is unnecessary at a reactor side and this is an important factor to simplify the reactor operation.

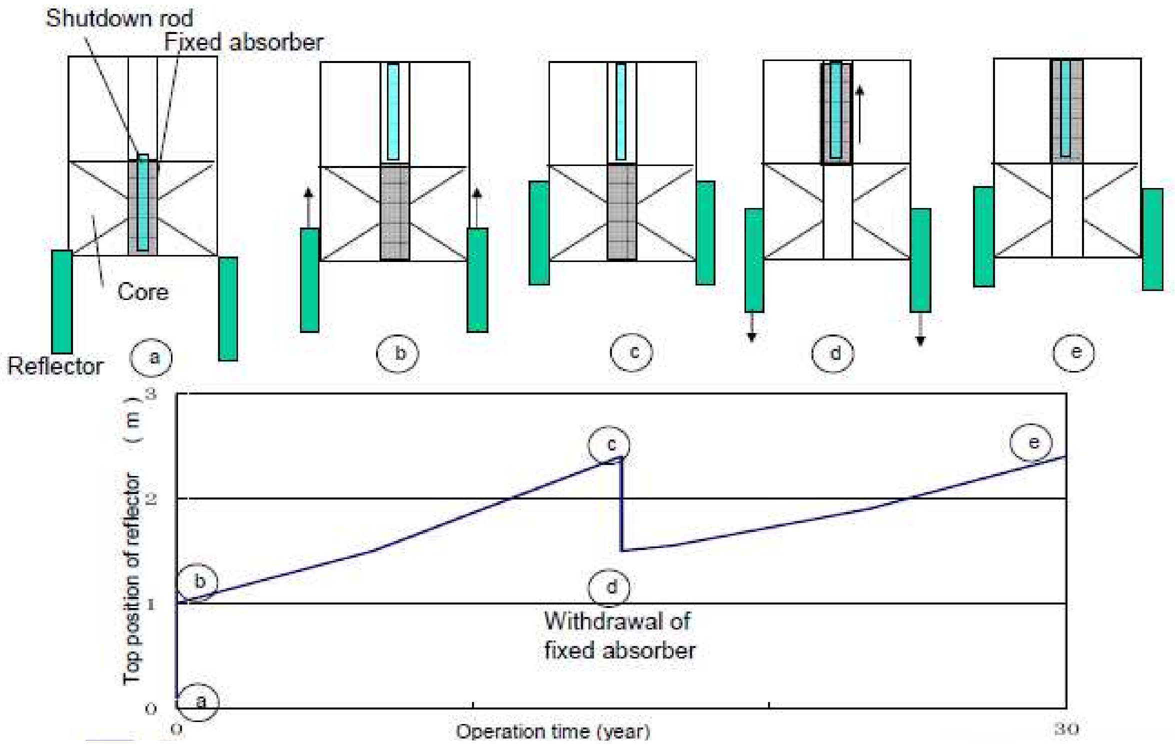


FIG. 5. Axial position of the top of the reflector versus operation time.

In addition to the inherent safety features, there are two independent systems for reactor shutdown. The primary shutdown system provides for a drop of several sectors of the reflector, and the back-up shutdown system provides for insertion of the ultimate shutdown rod, located as a central subassembly on a stand-by in a fully "out" condition.

The 4S is sodium-cooled reactor; therefore, an intermediate heat transport system is employed to avoid a reaction between the primary (radioactive) sodium and water/steam of the power circuit. The 4S has three heat transport systems: the primary sodium system located inside the RV, the secondary sodium system in which sodium is sufficiently non-radioactive to define it as an "uncontrolled area", and the water/steam turbine system.

The thermodynamic efficiency is approximately 33 % for the 30 MW (th) plant and 37 % for the 135 MW(th) plant.

The main thermal-hydraulic characteristics of the 4S are shown in Table 3.

The 4S operation without on-site refuelling is one of the keystones for the reactor application in rural areas, for a variety of reasons. The core and fuel lifetime as well as the plant lifetime would be approximately 30 years; the fuel in the 4S does not need to be reloaded or shuffled during the plant lifetime. The fuel is just installed when the 4S is constructed at a site. Therefore, the concept of "annual flow of fuel and non-fuel materials" is of somewhat limited meaning for the 4S.

The material balances for the 4S are given in Table 4. The major part (more than 95%) of the discharged minor actinides (MA) is neptunium.

The design lifetime of the core and fuel as well as the reactor vessel and components is 30 years. The reactor building including the concrete silo can be used for more than 60 years.

TABLE 3. THERMAL-HYDRAULIC CHARACTERISTICS OF THE 4S

Electric output	10 MW(e)	50 MW(e)
Primary circulation: - Normal operation - Unprotected loss of flow (ULOF)	Forced circulation (two EM pumps in series) Flow coastdown with motor generation set, then natural circulation	The same as for the 10 MW(e) plant
Primary coolant system: - Coolant temperature - Pressure - Pressure loss in the fuel subassembly	355 / 510°C (inlet / outlet). Non-pressurized Less than 0.1 MPa	The same as for the 10 MW(e) plant Less than 0.2 MPa
Maximum temperature of fuel cladding	610°C (hot spot)	The same as for the 10 MW(e) plant
Secondary cooling system: - Coolant temperature - Pressure	310 / 485°C Non-pressurized (slightly higher pressure than in the primary system)	The same as for the 10 MW(e) plant
Steam/water system: - Coolant temperature - Pressure	210 / 453°C 10.5 MPa	The same as for the 10 MW(e) plant

TABLE 4. MASS BALANCES OF FUEL MATERIALS FOR THE 4S

Electric output	10 MW(e)	50 MW(e)
Heavy metal (U) inventory	9.23 t	16.2 t
Fissile (^{235}U) inventory	1.69 t	2.58 t
Average annual flow* of: - Heavy metals (U) - Fissile materials (^{235}U)	308 kg/y 56 kg/y	539 kg/y 86 kg/y
Average annual flow per MW(e)* of: - Heavy metals (U) - Fissile materials (^{235}U)	31 kg/y/MW(e) 6 kg/y/MW(e)	11 kg/y/MW(e) 2 kg/y/MW(e)
Average burn-up of discharged fuel,	34 GWd/t	90 GWd/t
Inventory of materials discharged after 30 years: - Heavy metals total - U - ^{235}U - Pu - MA	8.90 t 8.75 t 1.36 t 0.15 t 2 kg	14.7 t 14.1 t 1.36 t 0.65 t 17 kg
Natural uranium requirements**: - For fabrication of fresh enriched uranium fuel load - Average specific flow of natural uranium	320 – 400 t 1070 – 1320 kg/y/MW(e)	500 – 620 t 330 – 410 kg/y/MW(e)

* Total inventory is divided by 30-years.

** It is assumed that ^{235}U content in depleted uranium is in the range between 0.2 % and 0.3 % (by weight); reprocessing/recycle of fissile materials remaining in the fuel is not taken into consideration in this calculation.

Two kinds of systems for non-electric applications have been incorporated in the 4S; they are:

- Seawater desalination system; and
- Hydrogen and oxygen production system.

Combinations of these systems and the turbine generator system as balance of plant (BOP), including the capacity of each system, would be determined to meet the actual needs at each site.

To be a viable option for power generation in remote areas, the 4S must provide competitive cost of electric power determined as busbar cost. "Busbar cost" is that required to generate a kilowatt-hour of electricity as measured at the plant busbar, i.e., the conducting boundary in the plant where the generated electricity is transferred to the external grid.

A preliminary effort to estimate the 4S busbar cost has been conducted under the following assumptions:

- A levelling period of 30-years;
- An assumed construction period of 12 months under normal site conditions;
- An assumed house load factor of 8% for the 4S plant operation;
- A mass production phase, i.e., N^{th}-of-a-kind plant.

2.2 Reactor Core Design

Figure 6 shows a cross section of the 4S core.

The core and fuel are designed to eliminate the need for refuelling during approximately thirty years and to make all reactivity temperature coefficients negative. Metal fuel, which has an excellent thermal conductivity, is applied. The core is shaped as a cylinder; its main dimensions are given in Table 5. The core can be operated during thirty years by axially moving reflectors installed at the outside of the core, upward from the bottom. No reloading or shuffling of fuel is required during the whole core lifetime.

Figure 7 shows the fuel subassembly of the 4S. The fuel element (fuel pin) consists of fuel slugs of U-Zr alloy, bonding sodium, cladding tube, and plugs at both ends. A gas plenum of an adequate length is located at the upper region of the fuel slugs.

In the fuel subassembly, fuel pins are assembled with grid spacers and a top shield is installed to prevent activation of the EM pumps and the secondary sodium in the IHX. Coolant inlet modules located beneath the fuel subassembly provide a lower shielding for the reactor internal structures including the core support plate and air in the RVACS.

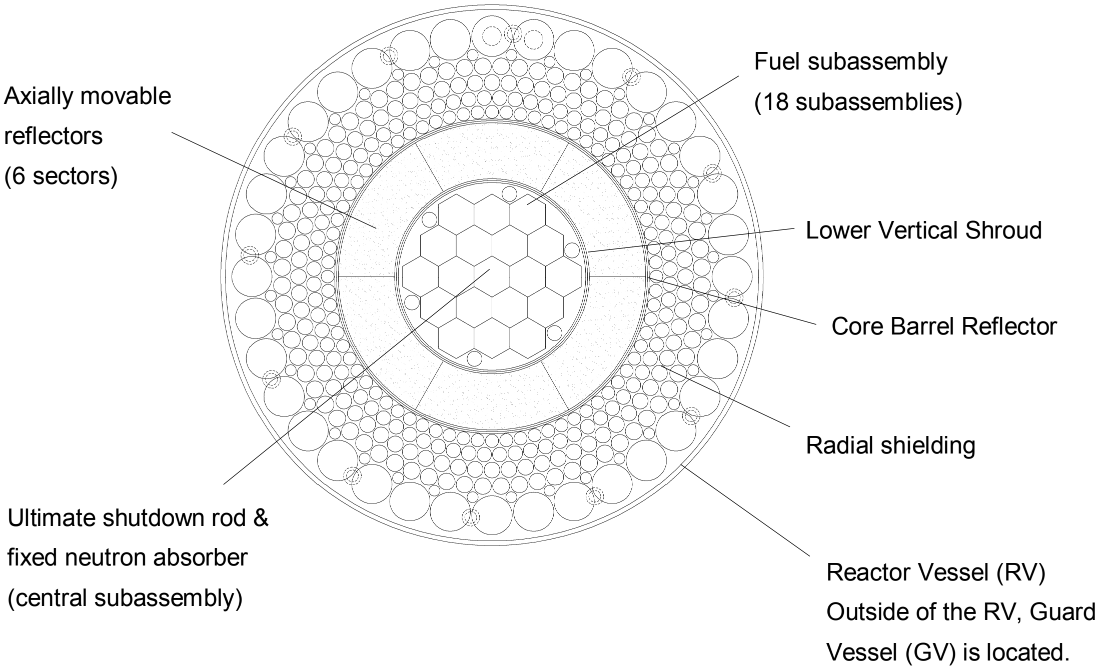


FIG. 6. Cross-section of the 4S core (10 MW(e) plant).

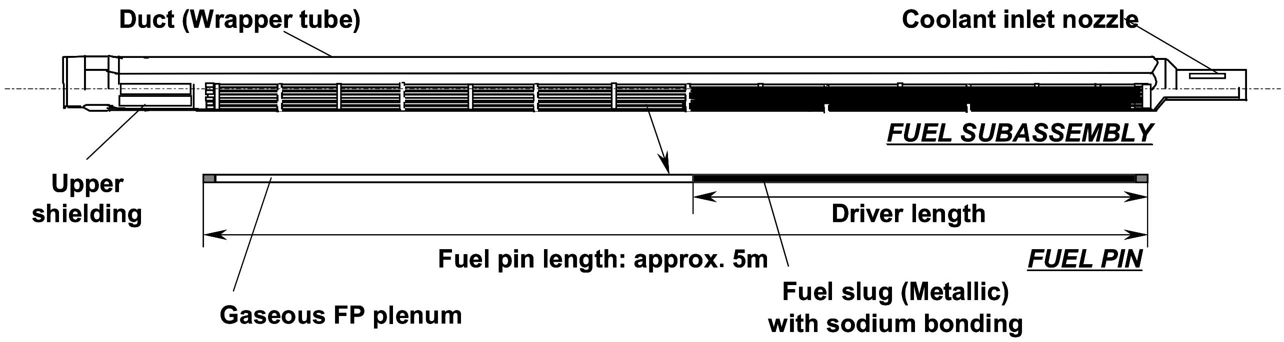


FIG. 7. 4S fuel subassembly (10 MW(e) plant).

TABLE 5. MAIN DESIGN PARAMETERS OF THE 4S CORE AND FUEL

ATTRIBUTES	DESIGN PARTICULARS	
Thermal rating	30 MW(th)	135 MW(th)
Active core height	2.5 m	2.5 m
Core equivalent diameter	0.95 m	1.2 m
Core configuration	Cylindrical shape	
Number of fuel subassemblies	18	
Type of fuel subassembly	Triangular fuel pin arrangement (Hexagonal cross section)	
Number of fuel pins per subassembly	169	271
Fuel assembly arrangement pitch	206 mm	259 mm

Main heat transport system

A schematic of the 4S main heat transport system with specification of heat removal path in normal operation and in accidents is given in Fig. 8; a brief explanation of this scheme is provided below.

Normal operation

The primary system is enclosed inside RV; sodium coolant is circulated by two EM pump units arranged in series. The heat generated in the reactor is transferred to the coolant of secondary sodium via the IHX located at the upper region in the RV. The secondary sodium is circulated by one EM pump unit. The heat is transferred to the water/steam system via heat transfer tubes in the SG. Water/steam is circulated by the feedwater pump.

The RVACS is a system for shutdown heat removal; however, to keep the fully passive features, it is continuously operating even at normal operation of the reactor. The IRACS is a sodium loop with an air cooler for shutdown heat removal, arranged in series with the secondary sodium loop (see Fig. 2).

Shutdown heat removal

The RVACS removes shutdown heat with natural circulation of air. In the IRACS operation for shutdown heat removal, dampers are adjusted for the required capacity of heat removal. In case of a long-term operation for decay heat removal, the IRACS is directed into a natural circulation mode via the adjustment of the dampers.

The water/steam system is also available for normal shutdown heat removal.

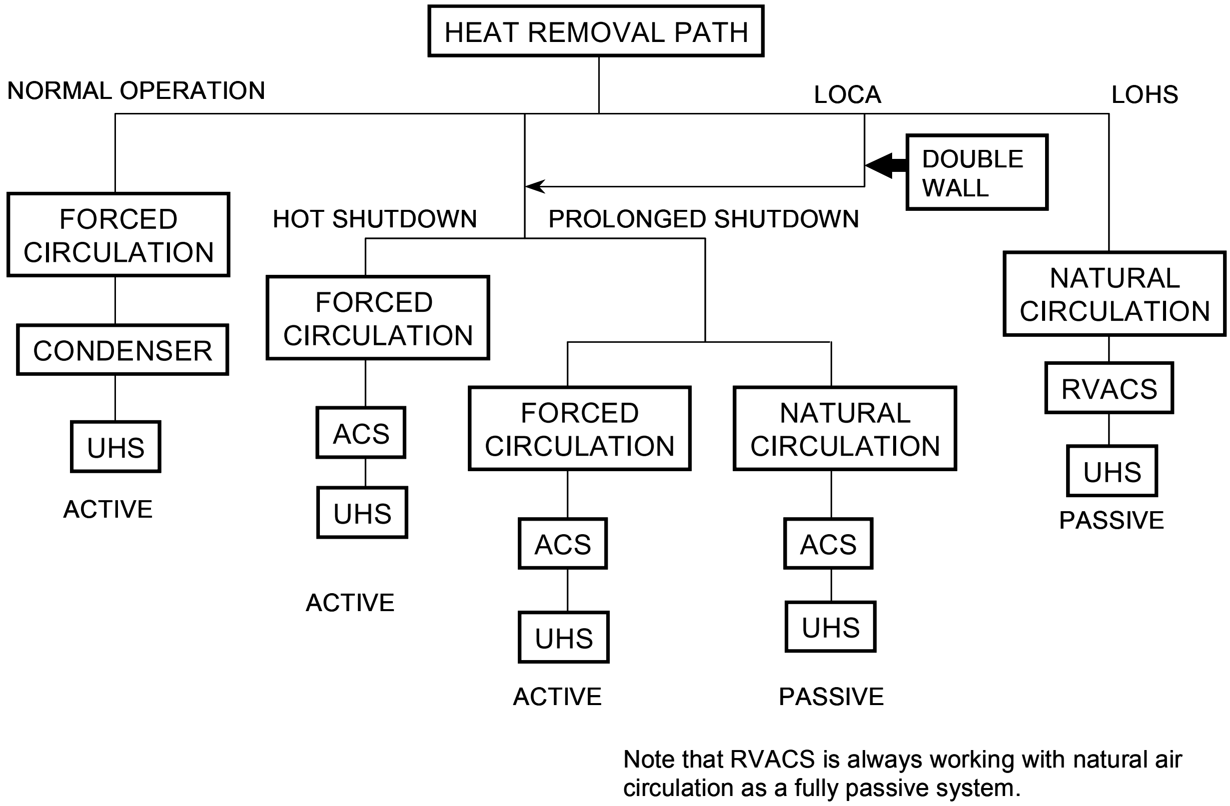
Loss of coolant accident (LOCA)

The 4S is a sodium cooled reactor; therefore, its primary system is “non-pressurized”. Hence, if sodium leakage occurs, the leak rate is quite small and the leaked sodium is retained by the second boundary, i.e., by the guard vessel, in all cases provided by the design; therefore, the core is always immersed in sodium. In case of a failure of the first boundary, both shutdown and normal shutdown heat removal systems operate.

Loss of heat sink (LOHS)

In case of a failure of the IRACS start-up, which is a failure of dampers, the dampers should be opened manually to provide for the removal of heat. If opened manually, the IRACS would act as a heat sink, in a natural circulation mode.

If the IRACS fails completely, the RVACS is able to remove shutdown heat as a fully passive system of air convection.



ACS – auxiliary cooling system: RVACS, or RVACS + IRACS

LOHS – Loss of heat sink UHS – Ultimate heat sink

FIG. 8. Heat removal paths of the 4S.

2.3. Applications

As it was already mentioned, the 4S concept offers two different thermal outputs, which are 30 MW(th) and 135 MW(th). When all thermal energy produced is converted into electric power, the 4S will generate 10 MW(e) and 50 MW(e) respectively.

The plant can be configured to deliver not only electricity but also hydrogen and oxygen using the process of high temperature electrolysis (HTE). The HTE is a technology that can produce both hydrogen and oxygen from steam and electricity; the latter are produced by the 4S without environmentally disadvantageous by-products, such as carbon dioxide. The plant can also be configured to produce potable water using a two-stage reverse osmosis system for seawater desalination. They are discussed in Section. 11.

2.4. Special features

Figure 9 shows birds-eye view of 4S plant. The 4S is a land-based nuclear power station with the reactor building basically embedded underground for security reasons, to minimize unauthorized access and enhance inherent protection against externally generated missiles. The BOP including a steam turbine system and the HTE units or desalination system is located at ground level.

To assure high quality of the reactor building and reactor components, they are shop-fabricated and transported to a site. Taking the advantage of small size and light weight design, the reactor building with major components like steam generators can be transported by barge. The transportability offers the advantage of a short on-site construction period.

Finally, the 4S is a reactor without on-site refuelling designed to operate for 30 years without reloading or shuffling of fuel in the core.

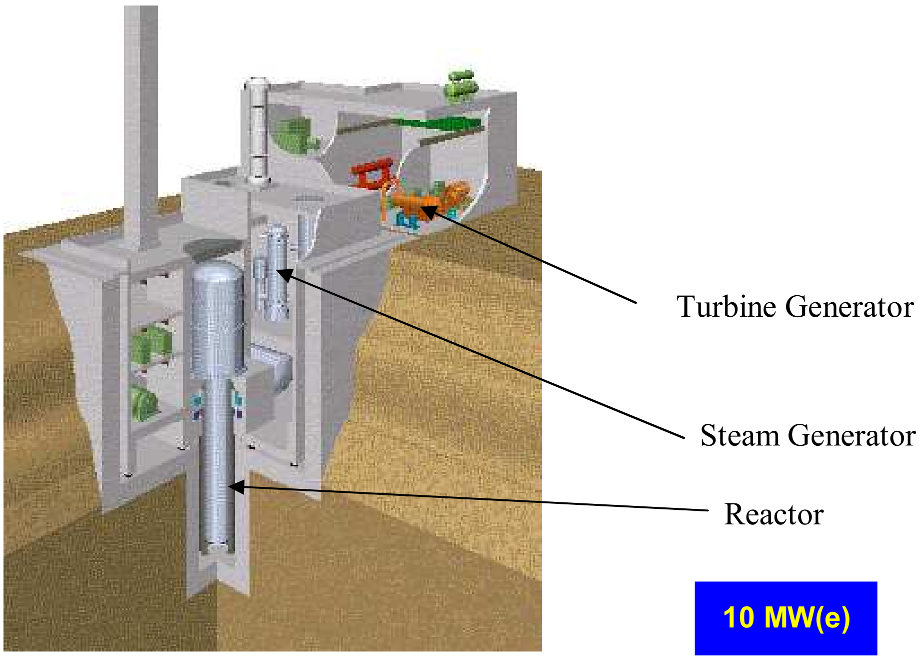


FIG. 9. Earth-sheltered reactors of the 4S plants.

3. Description of Safety Concept

Safety concept and design philosophy

The philosophy behind the 4S safety concepts is to put an emphasis on simplicity achieved by strong reliance on passive and inherent safety features as a major part of the defence in depth strategy. The ultimate objective of the 4S safety concept is to eliminate the requirement of evacuation as an emergency response measure. The 4S safety concept provides for three functions to be shouldered by the defence in depth in each phase of the abnormal operation or an accident; these three functions are the following:

- Prevention;
- Mitigation;
- Confinement of radioactive material.

Provisions for simplicity and robustness of the design

Incorporation of several passive and inherent safety features, such as low power density in the core, good thermal characteristics of the metal fuel bonded by sodium, negative reactivity coefficients by temperature, passive shutdown heat removal by both natural circulation of the coolant and natural air draft, and a large coolant inventory are some important provisions for simplicity and robustness of the 4S design.

Active and passive systems and inherent safety features

The active and passive systems and inherent safety features of the 4S are applied with the following main objectives:

- To reduce the probability of component failure; the inherent features of the 4S design supporting such a reduction are the following:
  - By-design elimination of active systems and feedback control systems from the reactor side;
  - By-design elimination of components with rotating parts (use of static devices such as EM pumps);
  - By-design limitation of the radioactivity confinement area (no refuelling during the whole reactor lifetime and no systems relevant for fuel reloading or shuffling);
- To prevent core damage in accidents; the active and passive systems and inherent safety features of the 4S supporting such prevention are the following:
  - Two independent active shutdown systems, including:
    - The actively-initiated drop of several sectors of the reflector;
    - Active insertion of the ultimate shutdown rod;
  - Enhancement of inherent safety features via the use of metal fuel in the core (lower accumulated enthalpy of fuel);
  - All-negative reactivity coefficients by temperature (an inherent safety feature);
  - A higher capability for natural circulation of sodium after a pump trip enabled by low pressure loss in the fuel subassemblies and a simple flow path inside the reactor (an inherent safety feature);
  - Two fully passive shutdown heat removal systems, including:
    - The RVACS, based on natural circulation of primary sodium and natural air draft around the guard vessel; and
    - The IRACS, based on natural circulation of secondary sodium and natural air draft through the air heat exchanger;
  - A large inventory of primary sodium (an inherent safety feature);
- To confine the radioactive materials; the design features of the 4S supporting this objective are as follows:
  - Multiple barriers against fission product release, including:

    - The fuel cladding;
    - The reactor vessel, upper plug and the IHX tubes;
    - The top dome and the guard vessel as a containment;
  - The small radioactive inventory typical of a small sized power reactor;
- To prevent sodium leakage and to mitigate the associated impact if it occurs; the design features of the 4S supporting this objective are the following:
  - A by-design double boundary for sodium in the primary system and in the important parts of the secondary system with a detection system for small leakages occurring via a one-boundary failure, including:
    - The reactor vessel and guard vessel boundary for primary sodium;
    - The heat transfer tubes have double walls in both the SG;
  - A passive 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 would cause disk rupture and make secondary sodium to drain rapidly to the dump tank located beneath the SG.

Structure of the defence in depth

Some major highlights of the 4S design and systems, structures and components corresponding to various levels of the defence in depth are brought out as follows:

Level 1: Prevention of abnormal operation and failure:

(A) Prevention of loss of coolant:

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

(B) Prevention of loss of flow:

  - Primary EM pumps are arranged in two units connected in 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;

(C) Prevention of transient overpower:

  - 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 very low speed driving system;
  - The limitation of reactivity insertion at the start-up of reactor operation;

(D) 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/steam side of the boundary); and

- An outer tube failure (secondary sodium side of the boundary).

Level 2: Control of accidents within the design basis.

The design features of the 4S supporting Level 2 of the defence in depth are as follows:

- 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;
  - Insertion of the ultimate shutdown rod;
- Increased reliability of the shutdown heat removal systems achieved by the use of two passive systems based on natural convection;
- 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 3: Control of severe plant conditions, including prevention of accident progress and mitigation of the consequences.

The design features of the 4S supporting Level 3 of the defence in depth are as follows:

- Inherent safety features of a metal fuelled core, such as excellent thermal conductivity and low accumulated enthalpy;
- All-negative reactivity coefficients by temperature;
- The fully passive shutdown heat removal system (RVACS) based on natural air draft and natural circulation of sodium;
- 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 4: Mitigation of radiological consequence 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 anticipated transient without scram (ATWS).

A preliminary evaluation has been conducted where failure of all fuel element claddings (approximately 3000 fuel pins) was hypothetically assumed to calculate site suitability source term (SSST). The status of major nuclides defining the source term and their behaviour are as follows:

- Plutonium (Pu) is retained in the metal fuel slug because fuel melting never occurs;
- Caesium (Cs) could be solidified and retained in a lower temperature area using a leakage path from the coolant to the reactor vessel, including the upper plug and the IHX, and then to the containment;
- Iodine (I) is retained in the sodium coolant within NaI compound because fuel melting never occurs; therefore, iodine migration does not occur also.

It was assumed that 100 % of the noble gases including krypton and xenon are released from the sodium coolant to the cover gas. Further migration of noble gases was considered as follows:

- At a leak rate of 1 %/day from cover gas through the reactor vessel, upper plug and IHX and then to the top dome, during 30 days;
- At a leak rate of 1 %/day from the top dome to the reactor building;
- Noble gases in the reactor building were assumed to be released off-site.

The analytical results obtained show that the dose equivalent in this case is 0.01 Sv at a distance of 50 m from the reactor. It means that only 50 m are required as a site boundary for the 4S.

Design basis accidents and beyond design basis accidents

A major objective of the 4S design is to ensure the capability of withstanding a wide range of postulated events without exceeding the specified temperatures of fuel, cladding, and coolant boundaries, thereby maintaining the fuel pin and coolant boundary integrity. For the safety analysis of the 4S, design basis events (DBEs) ,which are include anticipated operational occurrence (AOO) and design bases accident (DBA), have been selected and identified systematically with consideration of the 4S operation cycle and the events postulated for MONJU, DFBR (Japan), and LWRs. A broad variety of events have been considered in the following categories:

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

For the safety analysis of the 4S, beyond design basis events (BDBEs) have been selected and identified in a similar manner. The criterion for ATWS is as follows:

- ATWS events:
  - Maximum CDF (Cumulative Damage Fraction) less than 0.1;
  - The coolant boundary limit does not exceed the service level D in American Society of Mechanical Engineers (ASME)

For the ATWS event, when upper side of 95 percent probability at a 95 percent confidence level is within the acceptance criterion, the 4S design is validated. The basic analysis procedure for ATWS was derived from [6]. Code Scaling, Applicability and Uncertainty Evaluation (CSAU) are adopted for analyzing ATWS. Representative analytical results which are AOO, DBA, and ATWS are summarized below.

Loss of Offsite Power (AOO event)

The loss of offsite power leads to simultaneous trip of the primary circulation pumps, the intermediate-loop circulation pump, and the feedwater pump. The power supply for the primary and intermediate-loop circulation pumps is switched to the coastdown power supply from the individually independent motor-generator (MG) sets. The flow rates of the primary and intermediate coolant will then coast down in response to the reduction of the circulation pump head.

A reactor scram is caused by a low signal in the normal bus voltage signal of the reactor protection system. With the occurrence of a scram signal, the reflectors descended and the shutdown rod is inserted and the reactor power drops rapidly. A signal of the reactor protection system also triggers the IRACS residual heat removal start-up, whereby the air-side damper of the air cooler (AC) installed in the intermediate loop is opened and residual heat removal commences. The residual heat of the reactor core is removed by natural circulation in both the primary and intermediate-loop coolant, using both the IRACS AC and the RVACS. The blower associated with the AC and the intermediate-loop circulation pump is then started up by the emergency power supply shortly after the occurrence of the event. This results in the forced circulation of both air flowing into the AC and intermediate-loop coolant, rapidly cooling the reactor to the cold standby state.

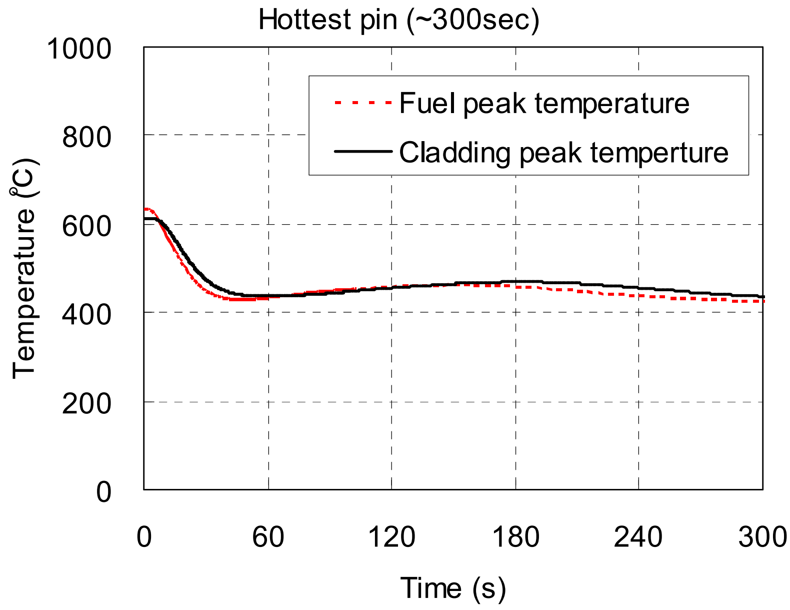
The fuel and cladding peak temperature and CDF for 300 seconds are shown in Fig. 10, respectively. The fuel peak temperature and the fuel cladding peak temperature of the hottest pin rises to 635°C and 613°C at a maximum, meaning there is a sufficient margin to the fuel melting point, thus meeting the “no fuel melting” safety acceptance criterion. The CDF value of the hottest pin is 5.7×10^{-9}, which means there is sufficient margin for the safety acceptance criteria specified by the inequality $\Sigma CDF < 0.1$, with multiple occurrences considered.

Failure of a Cavity Can (DBA event)

If a cavity can is damaged during reactor operation, positive reactivity is inserted and increases reactor power, resulting in a reactor power high signal from the power-range monitor to the safety protection system.

This results in a scram signal and causes the power supplies of the primary and intermediate loop circulation electromagnetic pumps to switch to the MG-set coastdown power supply. The reflectors descend and the shutdown rod is inserted, resulting in a rapid decrease in reactor power.

Fuel and cladding peak temperature and CDF for 300 seconds are shown in Fig. 11 respectively. The fuel peak temperature and the cladding peak temperature of the hottest pin, which provides a sufficient margin to the fuel melting point for the safety acceptance criteria. The CDF value for the hottest pin is $1.7\text{x}10^{-8}$ in this event, which provides a sufficient margin to $\Sigma CDF < 0.1$ of the acceptance criterion, even with one occurrence time considered. Thus, the 4S design meets the acceptance criterion for core coolable geometry.



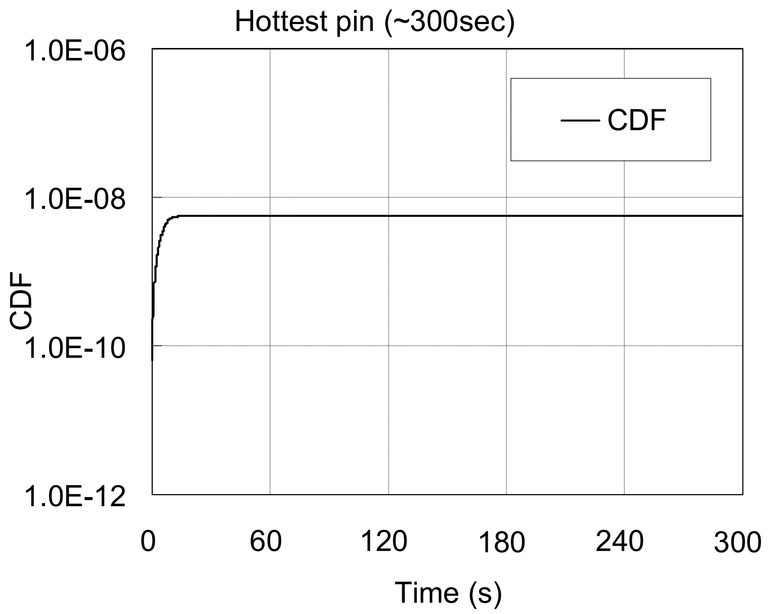


FIG. 10 Fuel and cladding peak temperature (upper) and CDF (bottom) for 300 seconds (LOSP).

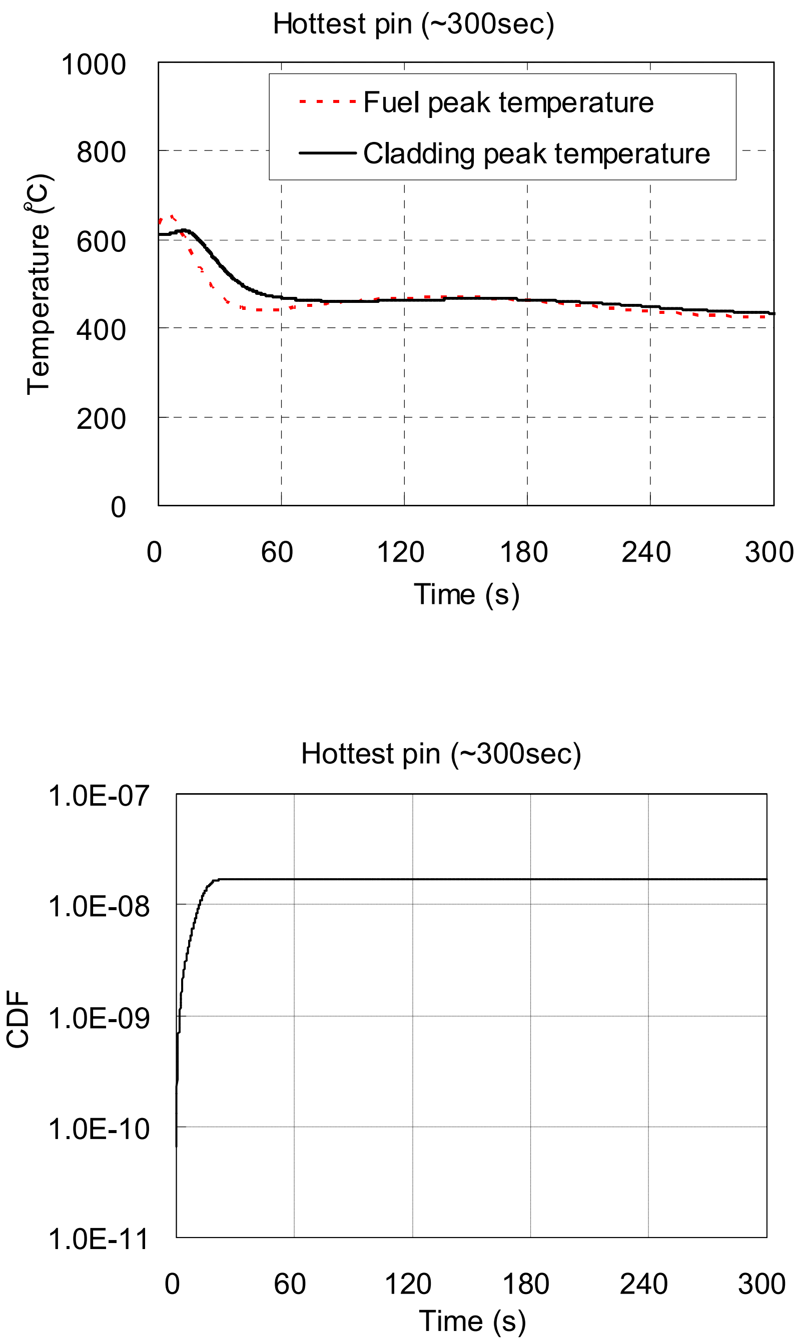


FIG. 11 Fuel and cladding peak temperature (upper) and CDF (bottom) for 300 seconds (FCC).

Loss of Offsite Power without Scram (ATWS event)

ULOF event is selected as a typical ATWS case [7]. After a metric concerned with safety design is defined as performance factor, a Phenomena Identification Ranking Table (PIRT) is produced in order to select the plausible phenomena that affect the metric. Then a sensitivity analysis is performed for the parameters related to the selected plausible phenomena. Finally the metric is evaluated with statistical methods whether it satisfies the given safety acceptance criteria.

Cladding peak temperature and CDF in ATWS statistical analysis are shown in Fig. 12, respectively. The CDF for the cladding is defined as a metric, and the statistical estimation of the one-sided upper tolerance limit of 95 percent probability at a 95 percent confidence level in CDF is within the safety acceptance criterion; CDF < 0.1. In this result, upper tolerance limit of 95/95 level of cladding temperature and CDF are $T_{c95/95}$ = 798℃ and $CDF_{95/95}$ = 0.01, respectively. The result shows that the 4S safety performance is acceptable in the ULOF event.

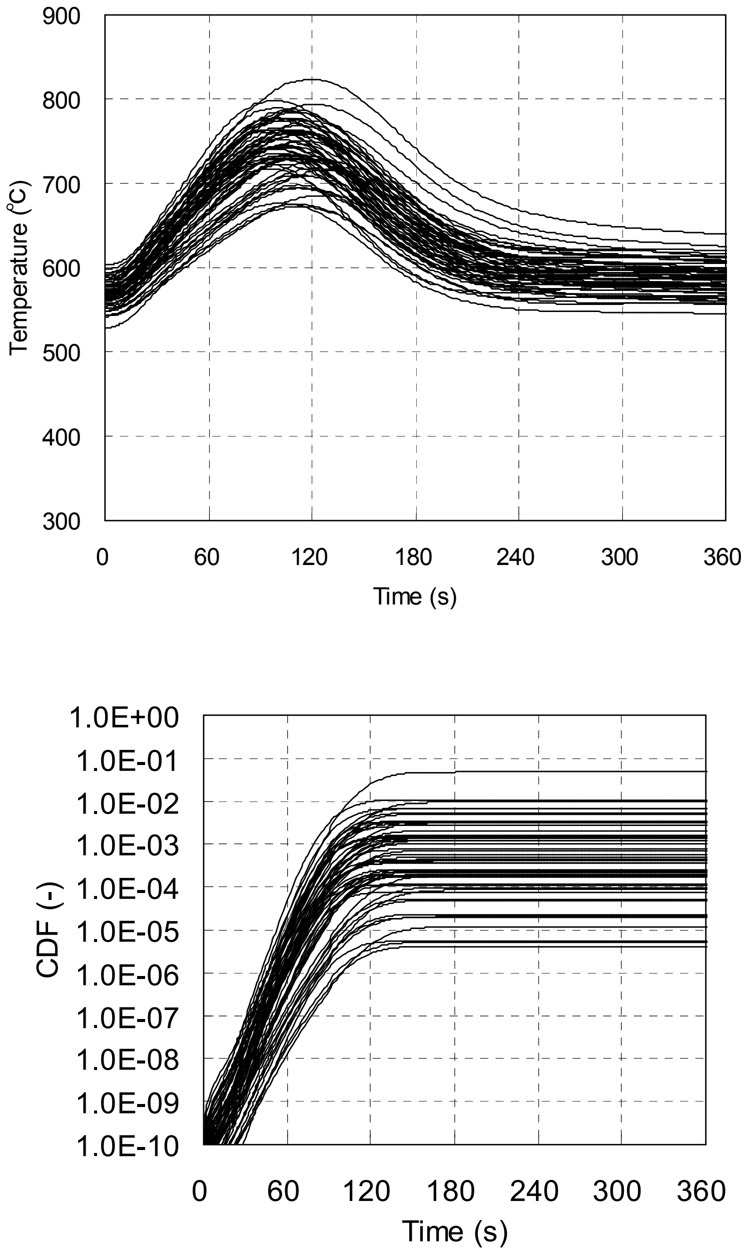


FIG. 12 Cladding peak temperature and CDF (ATWS statistical analysis).

Safety feature related to Fukushima-Daiichi Accident

4S has safety feature related to Fukushima-Daiichi Accident as follows,

Station black out (SBO)

Core damage is avoidable without any emergency power supplies by passive decay heat removal system with natural circulation, not necessary the pump. There is no limitation for duration time.

Spent fuel pool

No need for spent fuel pool due to long-term cooling (about 1 year) after the long-term operation (i.e., 30 years) and then stored in dry cask for the 10MWe-4S.

Final heat sink in emergency situations

Air is the final heat sink (RVACS and/or IRACS), not depends on water and any emergency power (passive decay heat removal system).

Containment system reliability

Containment system is consisted of top dome and guard vessel.

Earthquakes

Reactor building is supported by seismic isolator.

Tsunami / Flood

4S has redundant shutdown system and passive decay heat removal system without external power supply and emergency power system. Reinforced reactor building can be protected from massive water invasion by keeping its water-tightness.

Aircraft Hazard

4S is constructed underground.

4. Proliferation resistance

Technical features of the 4S contributing to a high level of proliferation resistance are:

- Uranium based fresh fuel with the ^{235}U enrichment less than 20 % by weight;
- Low plutonium content in the spent fuel, less than 5 % by weight;
- The reprocessing technology available for metal (alloy) fuel, such as U-Zr or U-Pu-Zr, ensures that plutonium is always recovered together with the accompanying minor actinides, which include highly radioactive and radiotoxic nuclides.

Absence of refuelling during the whole core lifetime and low maintenance requirements resulting from continuous operation of a sealed reactor in the course of 30 years provide a substantial physical protection of nuclear material. There is no opportunity for fuel to come out of the thick reactor vessel except for the period of loading at the beginning of the 30-year lifetime and discharge at the end of the lifetime. The number of fuel subassemblies is small (only 18 subassemblies), which makes it easy to monitor and scrutinize all of the subassemblies.

The 4S is designed in a way that there are no facilities or equipment to discharge the fuel subassemblies, or to disassemble the fuel subassemblies into fuel pins and extract nuclear material from the metal fuel slugs. The fuel-handling machine is temporarily provided to discharge spent fuel subassemblies after 30-year operation and only following adequate cooling inside the reactor. The spent fuel subassemblies are then encased in a cask and transported to a geological storage site (in the first phase) or to a recycle centre (in the next phase). Therefore, it would be difficult to perform an undeclared production of fissile material in the 4S just because there is no facility or apparatus available to enable such production.

As for unauthorized use of the fuel-handling machine, this kind of machine is a temporary system for the 4S and would be shared among several 4S sites. There would be no available machine for fuel assembly handling during the operation.

5. Safety and Security

Below-grade siting helps to protect the reactor building from external hazard such as missile or airplane impact (see Fig. 9).

The designers of the 4S consider embedding the whole reactor underground as one of the most natural and substantial methods of physical protection against unauthorized access and external missiles. Other features of the 4S contributing to an enhanced physical protection are as follows:

- No refuelling during the whole reactor lifetime of 30 years;
- The reactor operates completely sealed;
- The operation is automatic without the need of operator actions.

The fundamental concept of the 4S is that of “continuous monitoring” rather than “active operation”. The reactor operates using a system of pre-programmed movable reflectors. The plant and component conditions and/or unauthorized access could be continuously monitored.

6. Description of Turbine Generator System

The steam and power conversion system converts the heat produced in the reactor to electrical energy. The 4S plant consists of one reactor and one turbine generator system.

Figure 13 shows a simplified flow diagram for the turbine-generator system. Superheated steam is supplied from the steam generator to the turbine. The steam is exhausted to a condenser. Condensate from the condenser is pumped by one of two 100-percent capacity condensate pumps through a low-pressure feedwater heater train consisting of two heaters in series, and is discharged to a deaerator. From the dearator, feedwater is pumped by one 100-percent capacity feedwater booster pump in series with one 100-percent capacity feedwater pump. After passing through a single high-pressure feedwater heater, it is returned to the steam generator.

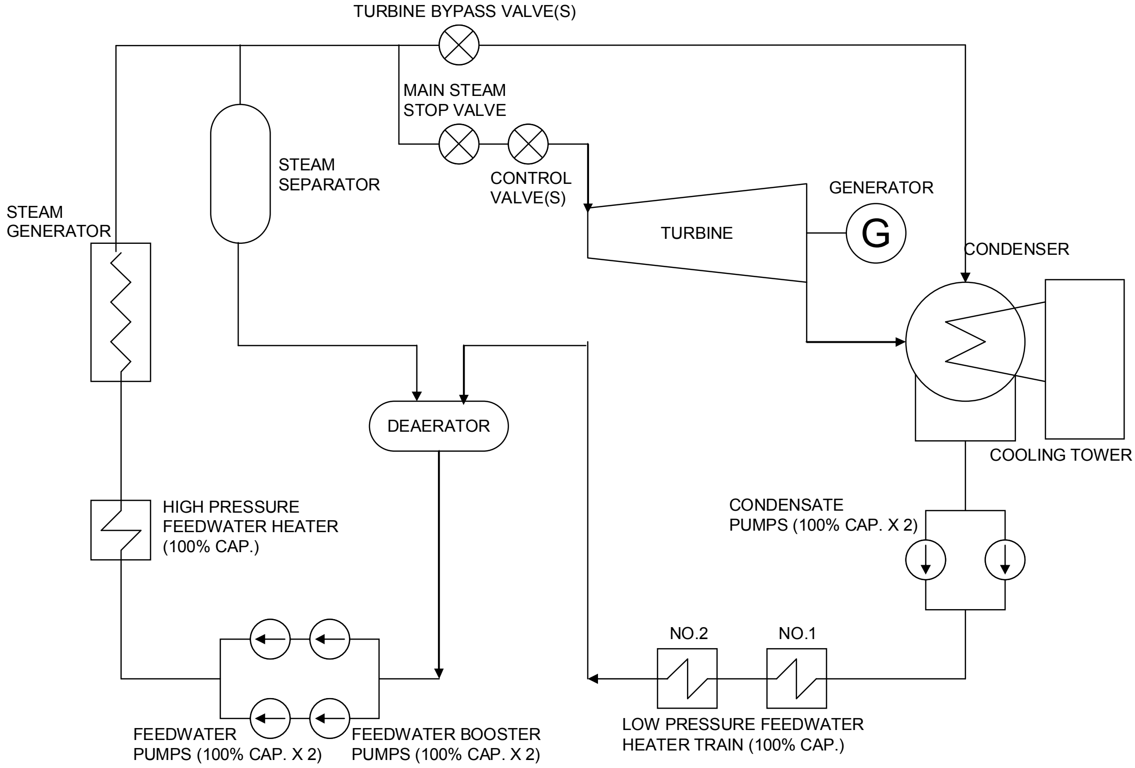


FIG. 13. Heat removal paths of the 4S

7. Electric and I&C System

The instrument and control system is composed of system related to safety and the system related to non-safety. The system related to safety includes reactor protection system (RPS), engineering safety feature actuation system, remote shutdown system and other instrumentation system required for safety. As for RPS, the two out of three voter logic is adopted. Sensor, cable and actuator switching breaker associated with RPS are grouped into three groups and they are electrically and physically separated. These systems have the safety class 1E instrumentations. The instrumentation and control system related to non safety system consists of plant control system and interfacing reactor system.

The reactor protection system is actuated when a threshold is attained by any one of the safety-function parameters as follows:

- Reactor core neutron flux
- Liquid sodium level of the reactor vessel
- Supply voltage/current of primary EM pumps
- Primary outlet temperature of IHX
- Voltage of power line
- Seismic acceleration

Figure 14 shows reactor protection system sensors for above parameters. All sensors are located in the primary system.

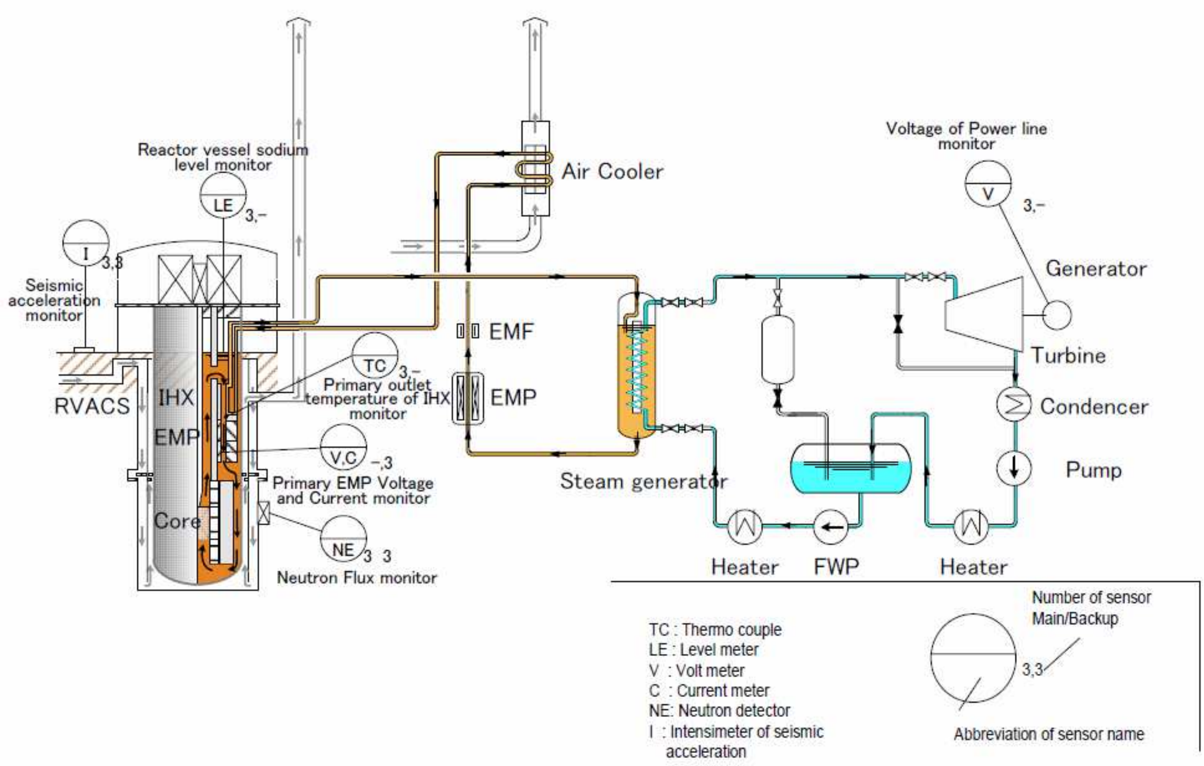


FIG. 14. Reactor protection system sensors

8. Spent Fuel and Wastage Management

A metal uranium fuel is used for the 4S. Viewed from the current situation regarding the capacity of actual reprocessing facilities for metal fuel, in the first phase of the 4S spent fuel would be stored/cooled and then preserved geologically in medium or long-term storage. In other words, a once-through fuel cycle is assumed for the first phase of the 4S.

In the next phase, spent fuel from the 4S or other reactors including LWRs could be reprocessed using pyro-process technology developed at ANL (USA) and/or CRIEPI (Japan). In this phase, plutonium and MA recovered from spent fuel could be used as fresh fuel for the 4S. To put it short, in the next phase, the 4S would be operated in a closed nuclear fuel cycle.

The 4S can be configured for a variety of alternative fuel cycle options to meet actual demands of its users. These include a plutonium or Trans-uranium (TRU) burner option using a metal fuel such as a U-Pu-Zr alloy or using inert materials to avoid further production of plutonium from the installed ^{238}U [8, 9].

9. Plant Layout

The plant layout of the 4S is optimized to meet various functional needs; the requirements for safety, radiation zoning, and piping and cabling; construction requirements; and access and security considerations. The general philosophy of the 4S plant layout is as follows:

- Efficient space utilization and minimization of volume of the buildings;
- Horizontal seismic isolation for the reactor building;
- An embedded reactor building, securing that the reactor is earth-sheltered;
- Lightweight buildings to assure a high degree of transportability in construction;

- The secondary sodium loop area is categorized as a "non-controlled area"; to achieve this, a sufficient shielding of the IHX is to be provided.

Vertical cross-sectional view of the 4S plant is given in Fig. 15.

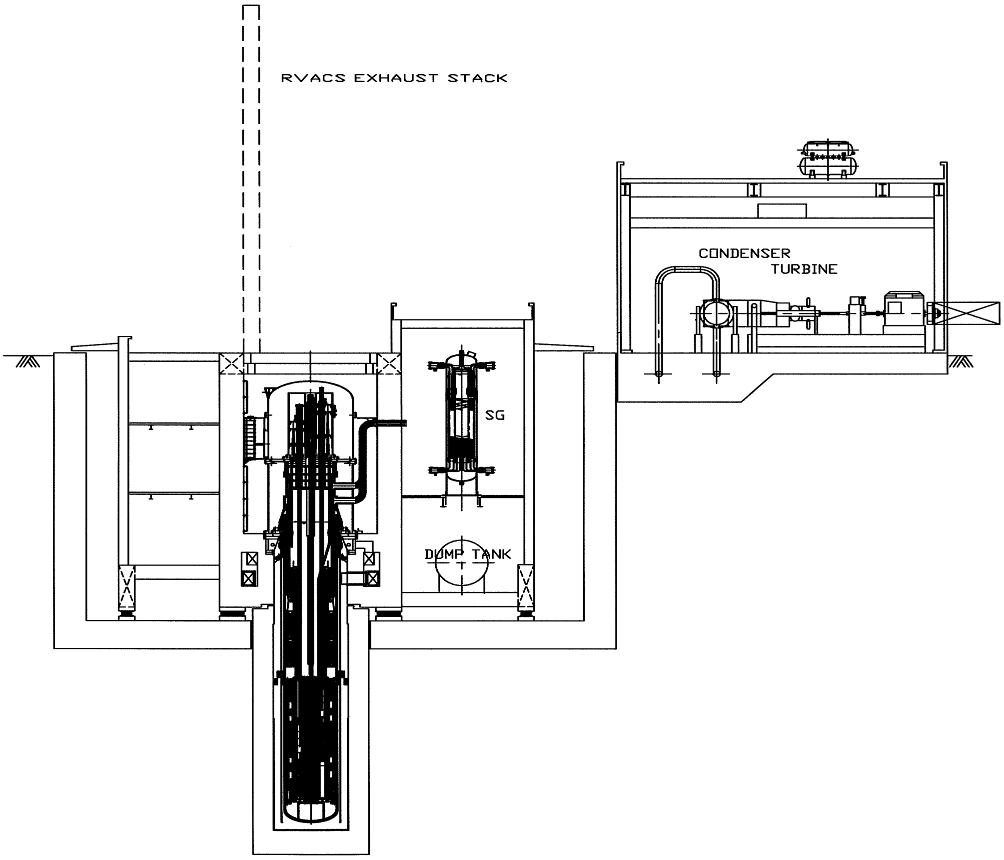


FIG. 15. Vertical cross-section of the 4S plant of 10 MW(e).

10. Plant Performance

10.1. Economics and maintainability

The inherent and passive safety features, the operation without on-site refuelling, lower projected maintenance and operating requirements, plant transportability in construction scheme and projected lower busbar costs of the 4S could facilitate its deployment in developing countries with limited technological resources. However, as the first step, the 4S design should be approved and certified for production in series by a regulatory body in a developed country.

The main design features of the 4S supporting a reduction of its capital cost is as follows:

- Reduced volume and weight of materials achieved by the use of simple systems and structures (the concepts of simple operation, simple inspection and strong reliance on inherent safety features are supported by the use of simple systems and structures);

- Passive principles of reactor operation; the operation of almost all systems of the 4S is based on natural phenomena, taking the advantage of small reactor size;
- Shop fabrication and transportability of the reactor building including the SG and the reactor, resulting in a reduced site construction load and a shorter construction period of approximately 12 months.

For example, the absence of a necessity of fuel reloading and shuffling (for a period of 30 years) eliminates the need of a permanent fuel handling system, which could be substituted by a demountable temporary system, which would be shared among several 4S plants. Therefore, the 4S reactor has no control rods, drive mechanisms or upper internal structure (UIS). The RVACS and IRACS are a completely passive system using air naturally circulated around the guard vessel and is a final heat sink in one of the shutdown heat removal systems. In heating, ventilating, and air conditioning (HVAC), there is no need to use systems with seawater as an ultimate heat sink; a system of heat release to the air will be sufficient for this purpose because of the small thermal output of the plant.

The 4S is being designed to operate safely without active involvement of the plant operators. The design features to support such operation are as follows:

- Burn-up reactivity swing is automatically compensated by the fine motion reflectors;
- There is no need in reloading and shuffling of fuel in the course of 30 years;
- A reduction in maintenance requirements achieved by adopting static devices such as EM pumps or static devices continuously monitored by simple systems;
- Reduction of in-service inspections (ISI) achieved by taking advantage of the non-pressurized systems of a sodium cooled reactor and by applying a “continuous monitoring” process based on “leak before break (LBB)” detection to ensure safety of the 4S.

During the 4S operation, the operation personnel are required only for monitoring or checking. There might be a possibility of reducing a security effort because of the earth-sheltered embedded plant (see Fig. 9). If this would be authorized through discussion with the regulatory side, the O&M costs could be further reduced from the current estimation.

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

In the next phase of the 4S, when recovered plutonium and MA would become politically and commercially available because of the shortage of natural fissile materials, fresh fuel consisting of the reprocessed fissile materials and depleted or natural uranium could be installed in the 4S. A fast neutron spectrum of the 4S avoids the degradation of fissile materials through burn-up; therefore, the recovery process for the spent fuel of the 4S could be repeated many more times than for LWRs, resulting in a higher degree of natural uranium utilization.

Radioactive waste is mainly generated through the cleanup of equipment or those reactor internals that are used in the primary sodium (with such cleanup being performed for maintenance, repair or exchange). The absence of refuelling during 30 years and the resulting reduced maintenance requirements for a sealed reactor would facilitate a considerable reduction in the radioactive gas, liquid and solid wastes.

11. Development Status of Technologies Relevant to the NPP

In remote areas, there is a demand for a power supply technology free from the burden of fuel transportation. Also, there is an underlying request for robust energy systems and a flexible energy supply to secure the energy independence of these areas. The 4S, a fast reactor without on-site refuelling, is a concept suiting the first request; it could also suit the second one if the energy is used diversely, such as for hydrogen production.

The HTE is an appropriate method to produce hydrogen when coupled with the 4S, because HTE operates under a wide range of temperatures without emitting carbon dioxide due to the use of water as a feedstock.

The electrolysis of water is performed by introducing energy (ΔH) to a solid oxide electrolysis cell (SOEC) with high temperature steam, as shown in the equations below:

$$H_2O \dashrightarrow H_2 + 1/2O_2 - \Delta H \qquad (1)$$

$$\Delta H = \Delta G + T\Delta S$$

In these equations, ΔG is provided by electricity and TΔS is provided by heat.

Figure 16 shows a schematic drawing of hydrogen production by the HTE coupled with the 4S. The nuclear reactor of the 4S generates heat, a turbine-generator converts part of this heat to electricity, and the residual heat is transported to the HTE system. The electricity is used as power supply for the SOEC (via the rectifier) and is also delivered to the grid.

The maximum hydrogen production rate is estimated at around 14 000 Nm^3/hour with a reactor of 130 MW(th) and around 3000 Nm^3/hour with a reactor of 30 MW(th).

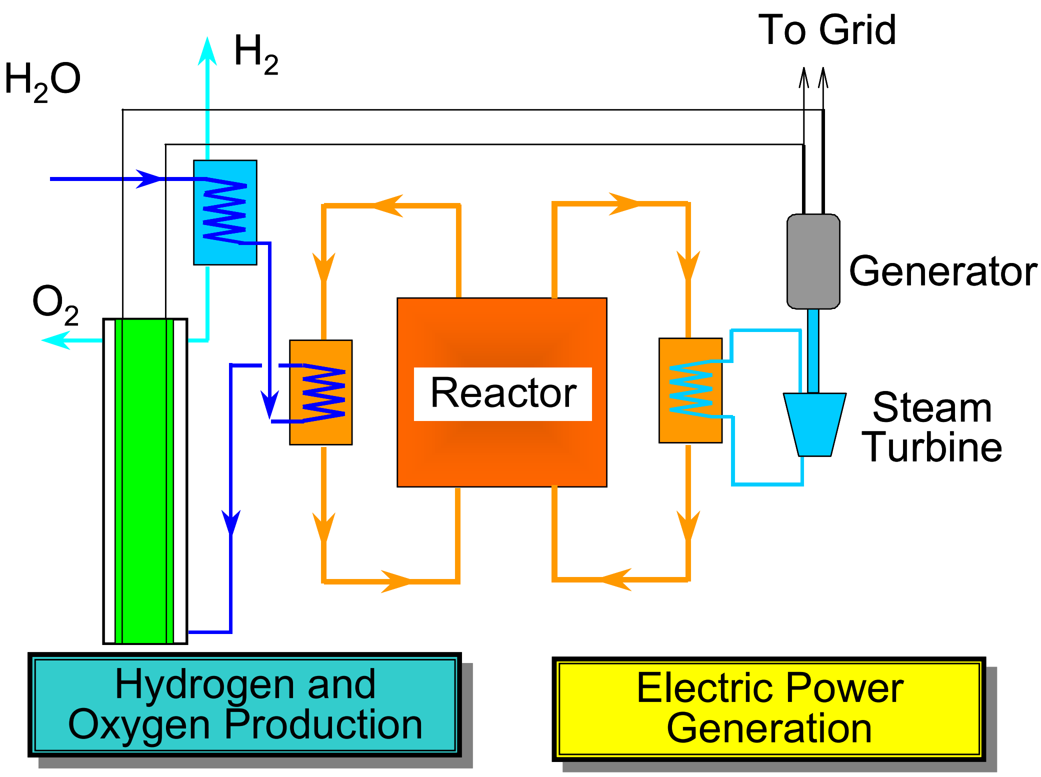


FIG. 16. Schematic of hydrogen and oxygen production by the 4S with HTE.

The plant can also be configured to produce potable water using a two-stage reverse osmosis system for seawater desalination. The amount of potable water produced could also be selected in response to demand at each site, but the maximum capabilities of two types of the 4S to produce potable water are 34 000 m^3/day and 170 000 m^3/day respectively, when all generated energy is utilized for desalination. The selected system for seawater desalination is described in detail in [10] and [11].

In the abovementioned way, the 4S can produce hydrogen and, at the same time, supply electricity to the grid. The amount of electricity supplied to the grid and the volume of hydrogen production can be easily changed to meet the demand. When electricity demand is low, more hydrogen could be produced and stored as a reserve energy source.

By using this system, the independence of energy sources in remote areas becomes possible. Also, because oxygen is produced simultaneously by the HTE, the industries making use of the oxygen could be developed in the vicinity of the 4S plants.

12. Deployment Status and Planned Schedule

A list of enabling technologies relevant to the 4S and status of their development are given in Table 6 [12]. The performance test of EM pump and test of passive back-up power system was done in 2010. SG and the relevant technology have been developed.

TABLE 6. ENABLING TECHNOLOGIES RELEVANT TO THE 4S

DESIGN FEATURE	VERIFICATION ITEM	REQUIRED TESTING	STATUS
Long cylindrical core with small diameter	Nuclear design method of reflector control core with metallic fuel	Critical experiment	Done
Reflector controlled core			
High volume fraction metallic fuel core	Confirmation of pressure drop in fuel subassembly	Fuel hydraulic test	Done
Reflector	Reflector drive mechanism with fine movement	Test of reflector drive mechanism	Done
RVACS	Heat transfer characteristic between vessel and air	Heat transfer test of RVACS	Done
EM Pump	Structural integrity Stable characteristics	Sodium test of EM pump	Done
Steam generator (Double wall tubes)	Structural integrity Heat transfer characteristic Leak detection	Sodium test of steam generator Leak detection test	Ongoing
Seismic isolation	Applicability to nuclear plant	Test of seismic isolator	Done

Toshiba is conducting the detailed design and safety analysis for design approval for 4S reactor. In parallel, Toshiba is continuing to look for customers.

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APPENDIX A

Summarized Technical Data

Summarized technical data of 4S is shown in Table A-1.

Table A-1 Summarized technical data of 4S (10MW)

General plant data	
Reactor thermal output	30 MW(th)
Power plant output, gross	10 MW(e)
Power plant output, net	10 MW(e)
Power plant efficiency, net	95 %
Mode of operation	Base load or load follow
Plant design life	30 years
Plant availability target	95 %
Seismic design, Safe Shutdown Earthquake PGA, g	0.3 g
Primary Coolant material	Sodium
Power Circuit Coolant material	Water
Intermediate Coolant material, if applicable	Sodium
Moderator material, if applicable	n/a
Type of Cycle	Indirect
Thermodynamic Cycle	Rankine
Non-electric applications:	
Potable water	1417 m^3/hour
Process steam	n/a
Heat (for district heating or industrial)	n/a
Hydrogen	3000 m^3/hour
Other	n/a
Safety goals	
Core damage frequency	-
Large early release frequency	-
Other, if Applicable	-
Occupational radiation exposure	-
Operator Action Time (Grace period)	-
Economic goals	
Mode of deployment	-
Levelized Unit Electricity Cost for n-th of a kind plant	-
Levelized Unit Cost of a non-electrical product for n-th of a kind plant	-
Reactor Core	
Active core height	2.5 m
Equivalent core diameter	0.95 m
Average linear heat rate	3.9 kW/m
Average fuel power density	3.42 kW/kgU
Average core power density	16.9 MW/m^3

Fuel material	U-10Zr
Fuel element type	Metal
Cladding material	HT-9
Outer diameter of fuel rods	14.0 mm
Lattice geometry	Triangular
Number of fuel elements in fuel assembly	169
Number of fuel assemblies	18
Enrichment of reloaded fuel in equilibrium core	17 / 19 Weight % (inner/outer)
Fuel cycle length	n/a
Average discharge burn-up of fuel	34 MWd/kg
Burnable absorber (mode of use/material)	n/a
Mode of reactivity control	Axially movable reflectors Fixed absorber
Mode of reactor shut down	Axially movable reflectors Shutdown rod
Absorber material	Hf
Soluble neutron absorber, if any	n/a
Other	n/a
Primary Coolant System	
Primary coolant flow rate	152 kg/s
Reactor operating pressure	0.3 MPa
Core coolant inlet temperature	355 ℃
Core coolant outlet temperature	510 ℃
Intermediate Coolant System	
Intermediate coolant flow rate	134 kg/s
Intermediate coolant operating pressure	0.55 MPa
Intermediate coolant minimum temperature	310 ℃
Intermediate coolant maximum temperature	485 ℃
Power Conversion system	
Working medium	Water
Working medium flow rate at nominal conditions	12.7 kg/s
Working medium pressure/temperature (Steam condition)	10.5 MPa / 453 ℃
Working medium supply[1] flow rate at nominal conditions	n/a
Working medium supply temperature	n/a
Reactor Vessel	
Inner diameter of cylindrical shell	3500 mm
Wall thickness of cylindrical shell	25 mm
Total height, inside	24000 mm
Base material	Type 304 stainless steel
Design pressure/temperature	0.3 MPa / 550 ℃
Transport weight	-

[1] *Working medium supply* = *feedwater* in case of a steam cycle

Guard Vessel, if applicable	
Inner diameter of cylindrical shell	3650 mm
Wall thickness of cylindrical shell	20 mm
Total height, inside	22643 mm
Base material	2 1/4Cr-1Mo
Design pressure/temperature	0.2MPa / 530 ℃
Transport weight	-
Steam Generator or Heat Exchanger of the Power Circuit	
Type	Once through type Double wall tube helical coil
Number	1
Mode of operation	Secondary coolant outside of the tubes
Total tube surface area (indicate – inside or outside)	215 m^2
Number of heat exchanger tubes	42
Tube outside diameter	31.8 mm
Tube material	Modified 9Cr-1Mo
Transport weight	-
Intermediate Heat Exchanger	
Type	Shell-and-tube type
Number	1
Mode of operation	Secondary coolant inside tubes
Total tube surface area (indicate – inside or outside)	-
Number of heat exchanger tubes	1074
Tube outside diameter	21.7 mm
Tube material	-
Transport weight	-
Primary Circulation System	
Circulation Type	Forced
Pump type	Single stator type Linear annular induction pump
Number of Pumps	2
Pump speed or Other characteristic	-
Head at rated conditions	10 m
Flow at rated conditions	10.6 m^3/s
Intermediate Circulation System	
Circulation Type	Forced
Pump type	Annular linear induction EM pump
Number of Pumps	1
Pump speed or Other characteristic	-
Head at rated conditions	25 m
Flow at rated conditions	9.3 m^3/s
Circulation System of the Power Circuit	
Circulation Type	Forced
Pump type	Turbo type
Number of Pumps	2
Pump speed or Other characteristic	-
Head at rated conditions	-

Flow at rated conditions	-
Pressurizer, if applicable	
Type	n/a
Total volume	n/a
Working medium volume: full power/zero power	n/a
Active devices used	n/a
Primary Containment	
Type	Guard vessel / Top dome
Overall form (spherical/cylindrical)	Cylindrical / Spherical
Dimensions (diameter)	3.65 / 8.0 m
Design pressure/temperature	-
Design leakage rate	-
Secondary Containment, if applicable	
Type	n/a
Overall form (spherical/cylindrical)	n/a
Dimensions (diameter/height)	n/a
Design pressure/temperature	n/a
Design leakage rate	n/a
Equipment and Systems located in the space between the primary and the secondary containment	n/a
Residual Heat Removal Systems	
Active/passive systems	RVACS – passive IRACS – passive, forced
Safety Injection systems, if applicable	
Active/passive systems	-
Turbines	
Type of turbines	Single-casing type
Number of turbines	1
Number of turbine sections per unit (e.g. HP/MP/LP)	1
Turbine speed	3600 rpm
HP turbine inlet pressure/temperature	10 MPa / 450 ℃
Generators	
Type	-
Number	1
Rated power	11 MVA
Active power	10 MW
Voltage	-
Frequency	60 Hz
Total generator mass including exciter	-
Condensers	
Type	Surface type
Condenser pressure	8 kPa
Compressors, if applicable	
Type	-
Pressure before and after the compressor	-

Plant Configuration and Layout	
Plant configuration options	See Section 9
Surface area of the plant site	-
Elevation or underground embedding of the nuclear island	Underground embedded
Core catcher	n/a
Protection against aircraft crash	Underground embedded
Protection against flooding	-
For barge-mounted plant options only: Features for protection against tsunamis, collision with other ships, etc.	n/a