CONCEPTUAL CORE DESIGN OF PASSIVELY SAFE SMALL REACTOR FOR DISTRIBUTED ENERGY SYSTEM, PSRD-100

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ABSTRACT

The Japan Atomic Energy Research Institute has been conducting a conceptual design of a passively safe small reactor for distributed energy system, PSRD-100. The PSRD-100 is an integral type light water reactor with a thermal output of 100 MW aimed at use of supplying district heat, electricity to small grids, and so on. The PSRD-100 has been designed on the basis of a basic design of the advanced marine reactor MRX and it adopts the natural circulation core cooling and the self-pressurization pressure control in the primary system. To simplify the system, the PSRD-100 is designed to operate without the volume control system and the purification system for a long time operation. From the neutronic and reactor physics analyses of the core, a long life time core operation of about 10 years without refueling or fuel shuffling was confirmed on the condition of using the low enrichment using the low enriched UO_2 fuel rods and the reactor load factor of 50 %, after parameter surveying on pin pitch, fuel enrichment, fuel rod arrangement in assembly, etc. The reactor physics analyses also indicated that the reactor control systems have enough safety margins for the state of clod shutdown of the reactor, although that is the most severe condition for the safety analyses for the PSRD-100 core.

1. INTRODUCTION

The nuclear energy is one of promising distributed energy sources which can stably supply the energy for long period of time without refueling and also has advantages comparing with other energy sources from a viewpoint of energy security and of contribution to cure the global warming. Enhancement of safety, reliability, and economic competitiveness are required for the nuclear plant as the energy sources of the distributed energy system. The U.S. Department of Energy, DOE, surveyed the feasibility of deployment of small power plants as a potential option in providing electric power to remote areas that are deficient in transmission and distribution infrastructures [1]. The thermal outputs of reactor plants required fell in a range of 60 to 200 MWt for most of the case. To realize deployment of such distributed energy systems in near feature, reactor plants should not have many key technologies to be developed because newly developed technologies always require a long period of time to prove its safety or reliability. In the other hand, it can be said that marine reactors are appropriate for the distributed energy systems because they have extensive operating experiences and most of key technologies to be used for the marine reactors are proven ones. The distributed energy systems are expected to follow various change of energy demand. Therefore, the marine reactors designed to follow severe load change are also suitable for such energy systems. To utilize the proven technologies of the marine reactors for the distributed energy systems, optimization and trade-off of the design to meet the demand of customers for the energy systems are required because it is not necessary to impose severe design conditions such as a marine weather and a load change which are peculiar to marine reactors.

The Japan Atomic Energy Research Institute (JAERI) conducted design study of advanced marine reactors on the base of experiences obtained from N.S. Mutsu, and an advanced marine reactor for large ship, MRX [2], and a very small reactor for scientific observation in deep sea, DRX [3]. JAERI has proposed a concept of PSRD (**P**assively Safe **S**mall **R**eactor for **D**istributed Energy System) that can be used as the distributed energy source [4]. In the present study, the discussions focus on the core design of the PSRD-100 whose thermal output is 100 MWt as a standard model.

In Sec. 2, a concept of the PSRD-100 related to neutronic design is described. In Sec. 3, core design policy and results of neutronic design are discussed. Results of assessment of netronic safety of the PSRD-100 core are discussed in Sec. 4. Conclusions are given in Sec. 5.

2. CONCEPT OF PSRD-100

Basic concept of the PSRD-100 adopts an established concept for the advanced marine reactor MRX. The PSRD-100 is an integral type pressurized light water reactor that all the equipment which constitutes the primary system such as a reactor core, steam generators, and control rod drive mechanisms (CRDMs) are installed inside the reactor vessel. The primary circuit adopts the natural circulation core cooling and self-pressurized pressure control and does not have any primary circuit pumps and pressurizers. JAERI has proposed a concept of the PSRD-100 for heat supply and electricity generation whose thermal power is 100 MWt as standard model of the PSRD. Schematic view of the PSRD-100 is shown in Figure 1 and major specifications of the PSRD-100 are summarized in Table I. Design of the PSRD-100 also adopts well established technologies of light water reactors proved from long operating experiences.

Adoption of a passive emergency decay heat removal system and the natural circulation method for the primary system and reduction of number of pipes which penetrate a pressure boundary make possible to achieve enhancement of safety. An occurrence probability of the loss of coolant accident is able to minimize because the PSRD-100 has no large radius pipes in the system. The loss of flow accident can also be eliminated by adoption of the natural circulation core cooling in the primary system. Adoption of an in-vessel type CRDM developed by JAERI [5] makes possible to eliminate the control rod ejection accident.

From a view point of economics, drastic simplification of reactor systems and modularization of a plant make possible significant reduction of capital cost of the reactor plant. The reactor auxiliary system can be drastically simplified because the PSRD-100 does not utilize the soluble boron for the reactivity control and it is not necessary to control water quality of the primary system during normal operation. Operation and maintenance cost can be reduced by achievement of long life core and reduction of personal requirements with highly automatic and remote operation. These features of the PSRD-100, namely, no use of the soluble boron and aiming at long core life, are of importance for the present neutronic design.

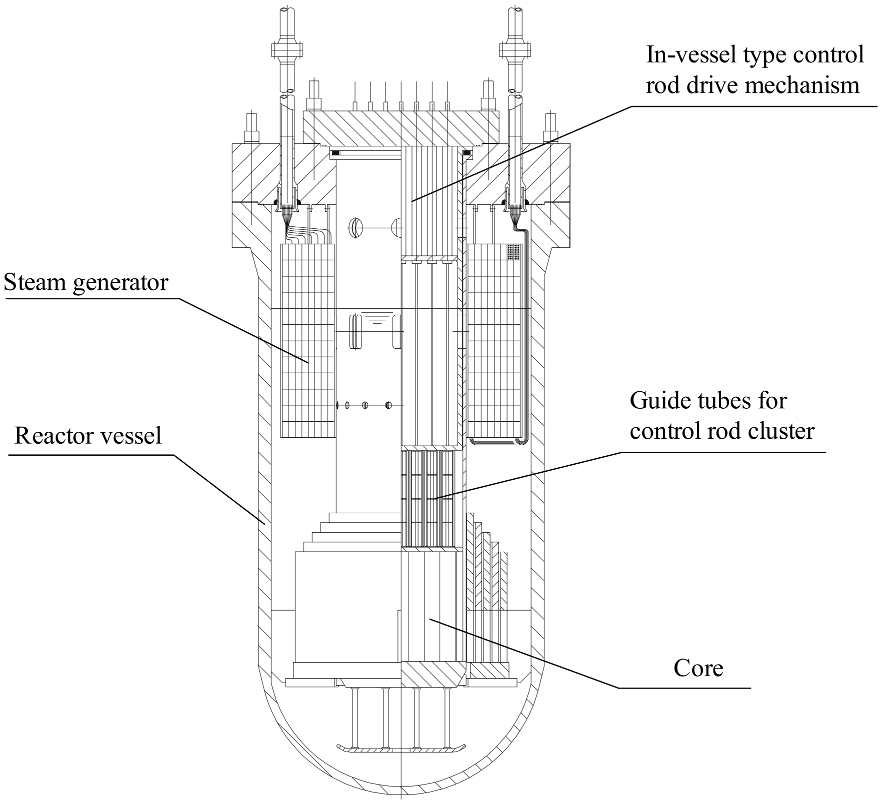


Figure 1. Conceptual drawing of the PSRD-100.

3. NUETRONIC DESIGN OF PSRD-100 CORE

3.1 NUETRONIC CORE DESIGN POLICY

One of design goals for the PSRD-100 core is to achieve long core life without refueling or shuffling for enhancement of economic competitiveness. In the present study, we aimed to operate the PSRD-100 continuously for 10 years without refueling or shuffling considering 50 % of load factor of the core which was determined from survey of energy demand for the distributed energy systems. A design condition for the reactivity at the end of the core life (EOL) is to keep enough residual reactivity (≥ 2 %) for overriding Xe poisoning to be capable of immediate re-startup of the reactor after unexpected or unscheduled shutdown. The chemical volume control system would not be utilized during normal operation of the reactor to simplify the system drastically from a view point of enhancement of safety and economics. To meet this requirement, the soluble boron for the reactivity control would not be used for the PSRD-100. Therefore the moderator temperature coefficients of reactivity can always be maintained negative values for any temperature conditions of the core. Contrary to this advantage, this means that the PSRD-100 must have another means of reactor shutdown system instead of use of the soluble boron for reactor shutdown. As shown in Table I, the average linear power density is lowered to

7.3 kw/m compared to ordinary reactors which adopt the forced circulation core cooling from a view point of thermal hydraulics design. Basic policy for design of the PSRD-100 is based on proven technologies of light water reactors. Therefore the zircaloy-4 cladding UO_2 fuel is used for the PSRD-100 core and the specification of fuel rods used for the PSRD-100 is same as that used for the 17×17 type assembly of current PWRs. Low enriched UO_2 whose ^{235}U enrichment is less than 5 % would be used for the PSRD-100 core since the PSRD-100 should be designed in a framework of the currently effective regulations.

3.2 DETERMINATION OF CORE PARAMETERS

Major parameters of the PSRD-100 determined from the above mentioned design policy are summarized in Table I. Difference of parameters between a heat supply reactor and a power generation reactor exists in operating pressures and temperatures of the primary system. A cross sectional view of the PSRD-100 core is shown in Figure 2. Equivalent diameter is 162 cm and effective core height is 140 cm. Dimension of the core was determined from the thermal output, average linear power density, and pin pitch so that the reactor core can be installed inside the core barrel whose outer diameter is 200 cm. Space between the core barrel and outside the fuel assembly is filled with zirlaoy-4 reflectors. The reactor core consists of 37 fuel assemblies and control rods as the reactor shutdown system would be installed to all assemblies to maintain enough shutdown margin. The reactor shutdown system is divided into two systems: reactivity control and shutdown system with 16 control rod clusters, and backup shutdown system with 21 control rod clusters. All control rods for backup shutdown system are withdrawn during normal operation.

Table I. Major parameters of the PSRD-100.

	Heat supply reactor	Power generation reactor
Reactor power		
Thermal power	100 MWt	100 MWt
Average linear power density	7.3 kW/m	7.3 kW/m
The primary system		
Pressure	3 MPa	8.3 MPa
Temperature	225.5 °C	290 °C
Dimension of core		
Equivalent diameter	162 cm	162 cm
Effective height	140 cm	140 cm
Fuel		
No. of fuel assembly	37	37
Outer diameter	9.5 mm	9.5 mm
Pitch	13.9 mm	13.9 mm
Enrichment	4.7 wt%	4.9 wt%
Fuel inventory	6.7 t	6.7 t
Burnable poison	6 wt% of Gd_2O_3	6 wt% of Gd_2O_3
Core life	10 years	9.8 years
Average burn-up	29 GWd/t	28 GWd/t
Control Rod		
No. of CRDM	37	37
No. of control rod	16 (per CRDM)	16 (per CRDM)
Absorber	B_4C	B_4C

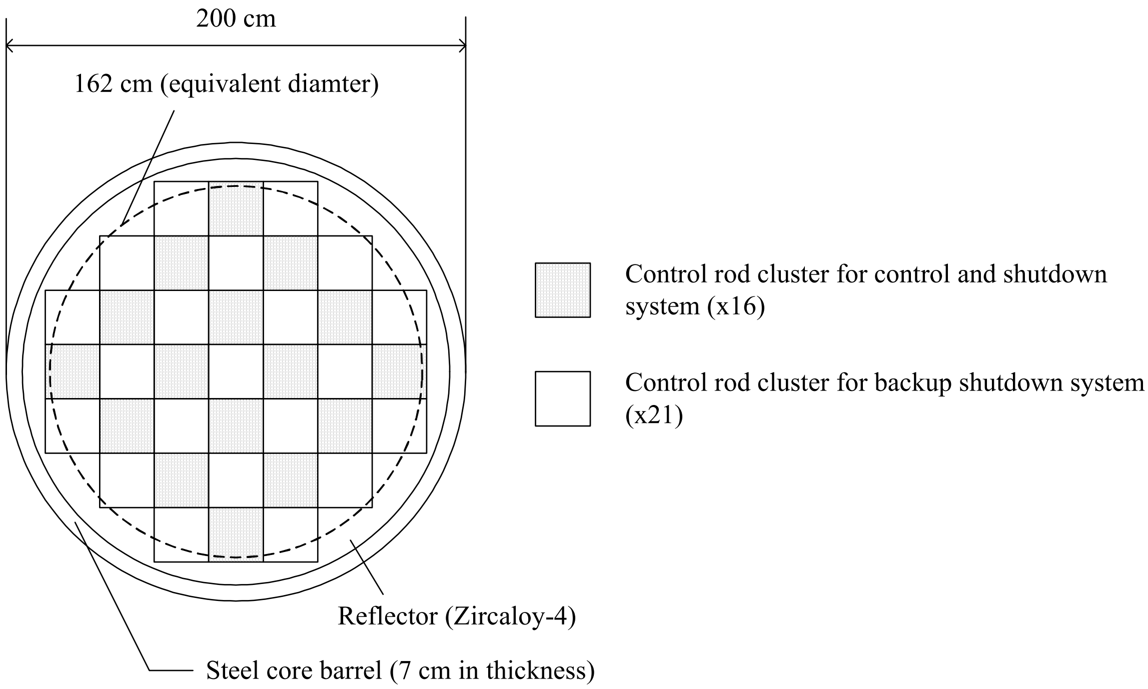


Figure 2. Cross sectional view of the PSRD-100 core.

Although design of fuel assemblies for the PSRD-100 is based on that of the 17×17 type assembly of current PWRs, arrangement of fuel rods and thimbles were slightly changed from original configuration as shown in Figure 3. Thimbles arranged near center of the current 17×17 type assembly were moved to outer zone of the assembly to reduce flow resistance in upper part of the core barrel because the control rods are used for all assemblies and much space is occupied by CRDMs compared with ordinary 17×17 type assembly. Fuel rods doped with 6 wt% Gd_2O_3 are used to suppress the excessive reactivity in the beginning of core life (BOL). Since the PSRD-100 core has relatively large excessive reactivity compared to ordinary light water reactors to achieve long core life, number of Gd_2O_3 doped fuel rods was increased to 28 while 24 burnable poison rods are arranged in the conventional 17×17 type assembly. For the PSRD-100 core for electricity generation, a fuel rod in the center of the assembly was replaced with a burnable poison rod to increase ability of suppressing the reactivity at the BOL.

Aiming at efficient burn-up of fuel and higher moderation, a wider pin pitch of 13.9 mm was adopted in the PSRD-100 design while the pin pitch of the ordinary 17×17 type assemblies is 12.6 mm. This modification results in long core life because the reactivity of the core is possible to be larger than that of ordinary light water reactors due to higher moderation. The zircaloy-4 cladding UO_2 pellets whose outer diameter is 9.5 mm are used for the fuel rods as same as the ordinary PWRs. Absorbers made of B_4C with 90% enriched ^{10}B are used for the control rods of the PSRD-100. Outer diameter of pellets of the control rod element is 9.9 mm and is thicker than that of used in ordinary PWR assemblies to increase shutdown margin of the PSRD-100 core. Enrichment of ^{235}U was adjusted so as to be maintained required 2 % of the excessive reactivity for immediate re-startup operation at EOL.

To determine core parameters of the PSRD-100 general purpose neutronic code system SRAC95 developed by JAERI [6] was utilized; the ASMBURN module was used for assembly calculation and the COREBN module was used for burn-up calculation. The SRAC95 was also used for neutronic

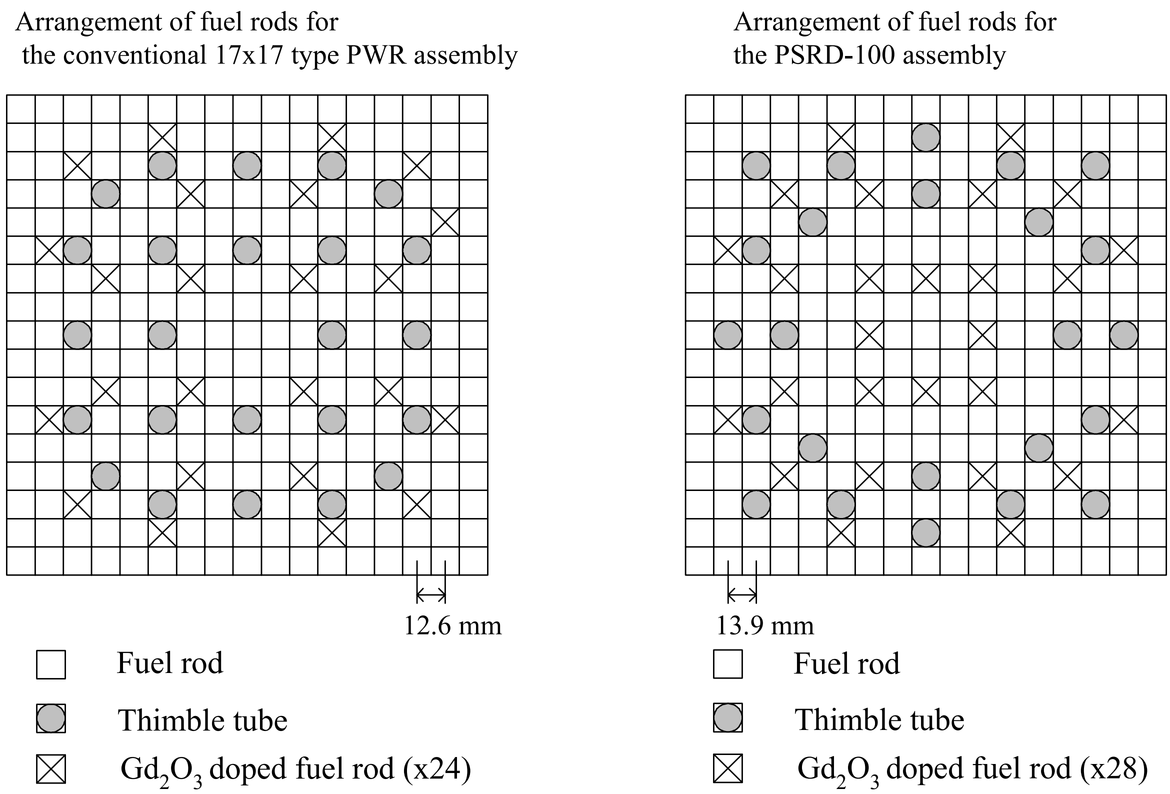


Figure 3. Arrangement of fuel rods in assembly.

analyses to assess the shutdown margin of the PSRD-100 core described in Sec. 4.

3.3 BURN-UP CHARACTERISTICS

Burn-up characteristics of the PSRD-100 core is shown in Figure 4 for a condition of continuous full power operation. The present analyses indicate that it is possible to continuously operate the PSRD-100 for heat supply for 5.0 years with full power using 4.7 % enriched fuel. The core life of the PSRD-100 for heat supply is 10 years considering 50 % of load factor of the core. For the PSRD-100 for electricity generation, continuous full power operation for 4.9 years is achieved using 4.9 % enriched fuel and core life considered 50 % load factor is 9.8 years. It can be said the present core design accomplished a design goal to achieve approximately 10 years core life considering 50 % load factor which had determined from energy demand of the distributed energy systems for both of the heat supply reactor and power generation reactor. Although flat change of the excessive reactivity throughout core life is desirable, rapid increase of excessive reactivity after fading reactivity suppressing effect of Gd_2O_3 was found as shown in Figure 4. Therefore it is necessary to optimize core parameters to reduce change of reactivity during burn-up period.

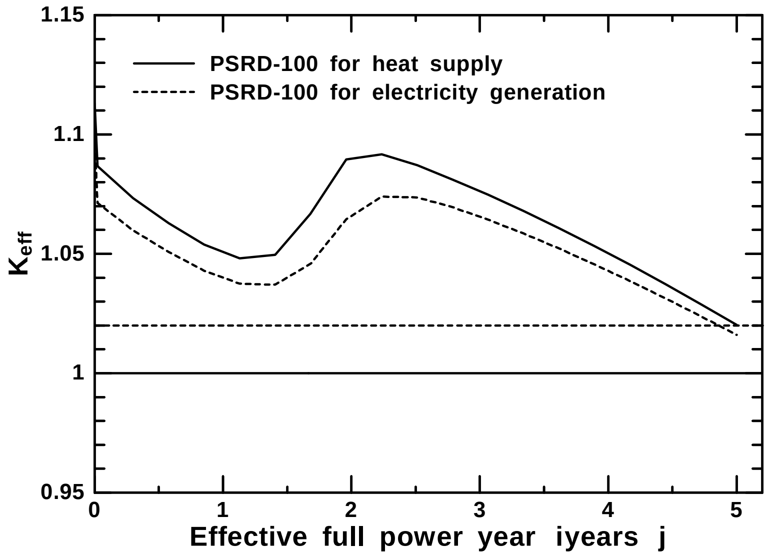
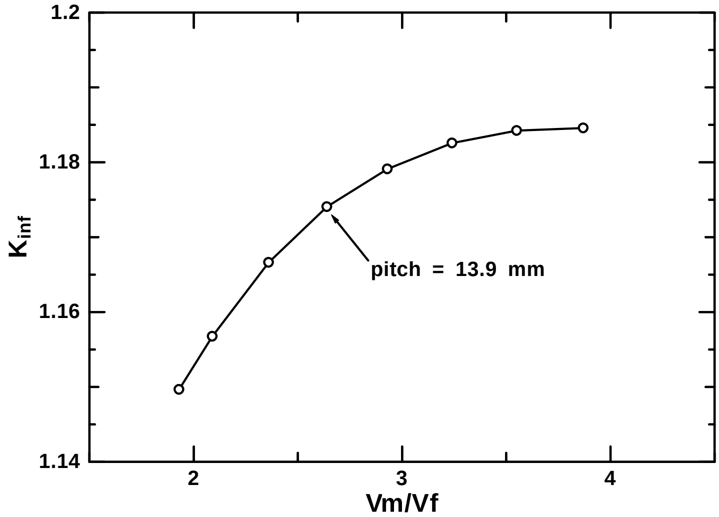


Figure 4. Burn-up characteristics of the PSRD-100 core.



4. NEUTRONIC SAFETY OF PSRD-100

Figure 5. k_{inf} of the PSRD-100 assembly as a function of V_m/V_f.

4.1 MODERATOR TEMPERATURE COEFFICIENTS

The PSRD-100 core has advantage from a view point of neutronic safety that the moderator temperature coefficients of reactivity can be kept negative values at any temperature conditions of the moderator from normal operation to the state of cold shutdown because the soluble boron would not be used for reactivity control. Figure 5 illustrates change of the infinite multiplication factor k_{inf} as a function of the volume ratio of moderator to fuel (V_m/V_f). In the present design, the pin pitch was chosen so that the reactivity always decreases when the V_m/V_f value decrease due to increase of the moderator temperature. This result assures that the moderator temperature coefficients of reactivity are always negative values for the PSRD-100 core.

4.2 INDEPENDENCY AND DIVERSITY OF REACTOR SHUTDOWN SYSTEM

Design guidelines for the safety examination of the Nuclear Safety Commission of Japan requires that two independent reactor shutdown systems must be installed to a reactor. As shown in Figure 2, 37 control rod clusters were apportioned to two shutdown systems: the control and shutdown system has 16 clusters and the backup shutdown system has 21 clusters. It can be said that the PSRD-100 core has two dependent reactor shutdown systems. In addition to independency of the reactor shutdown system, diversity of the reactor shutdown system is realized by adoption of two different methods to release control rods from the clusters; control rods for control and shutdown systems are released from the clusters by opening control rod latching mechanically, while control rods for backup shutdown system are released from the clusters by opening latching by de-energizing the magnet coil.

4.3 SHUTDOWN MARGIN OF PSRD-100 CORE

As described in the previous section, two independent reactor shutdown systems with use of control rods are installed in the PSRD-100 core. Design guidelines for the safety examination of the Nuclear Safety Commission of Japan also requires that either of the shutdown systems have to possess capability to keep non-criticality by the single system at the state of cold shutdown. The effective multiplication factors were calculated at room temperature, 30 °C, for a condition that all control rods in one of shutdown systems are fully withdrawn and all control rods in another shutdown system are fully inserted. This condition is the most sever case for assessment of neutronic safety of the PSRD-100 core. Estimated shutdown margins, which were subtracted 10% of safety margin, are summarized in Table II. The analyses were carried out at BOL where the excessive reactivity is the largest during burn-up. The present result indicated that both reactor shutdown systems are possible to maintain non-criticality by the single system and have enough shutdown margins greater than 1 %.

Table II. Shutdown margin of the PSRD-100 core for the cold shutdown condition.

	Shutdown margin (%Δk/k)	
	Heat supply reactor	Power generation reactor
Control and shutdown system	1.8	1.2
Backup shutdown system	2.4	1.8

5. CONCLUSIONS

In this study, neutronic design of the PSRD-100 core to be used for the distributed energy source has been carried out. Although present neutronic design is on basis of the current 17×17 type PWR assembles, arrangement of the fuel pins, pin pitch and enrichment of ^{235}U were modified to achieve long core life. The present core design accomplished the design goal to achieve long core life, about 10 years considering load factor without refueling or fuel shuffling by using low enriched UO_2 fuel rods. The present nuetronic safety assessment indicates that the reactor control systems have enough safety margins for the state of clod shutdown that is the most severe condition for the safety analyses for the PSRD-100 core. The PSRD-100 core needs more optimization study regarding core parameters taking into account thermal hydraulics and structural requirements. As for the reactor physics issues, reduction of reactivity change throughout core life is required.

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