ADVANCED 4S (SUPER SAFE, SMALL AND SIMPLE) LMR

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Abstract

This paper describes a new nuclear power system which can be used for a greater variety of applications. The 4S liquid metal reactor has high inherent safety and passive safety characteristics. It is also easy to operate, maintain and inspect, faster to construct, more flexible in location, requires less initial investment, and is better suited to electrical grid management. The reactor offers a new route through which to expand the use of safe nuclear technology in the world.

1. INTRODUCTION

In the 21st century, we will be confronted with how to solve some very serious problems which have not been faced by mankind in the past. That is the so called trilemma problems energy security, environmental protection and socio-economic development which compete against each other.

Nuclear power appears to have the potential to help to solve these problems. However, to make it a reality, it is necessary to improve nuclear power technology to make it more applicable to a greater variety of utilizations and locations.

To achieve this target, the following key items are essential.

a) Enhancing the efficiency of nuclear power utilization
b) Increasing the flexibility of nuclear power siting
c) Assurance and improvement of safety and reliability
d) Improving the economics
e) Promoting public acceptance of nuclear power
f) Nuclear power utilization in developing countries
g) Improving the fuel cycle and waste management
h) Providing the high proliferation resistance

2. BASIC CONCEPT

Based on the requirements, one of the most promising nuclear reactor designs is a small or medium size modular type nuclear reactor with high inherent safety and passive characteristics. It is preferable that the following features are taken into considerations; greater simplicity, easy to maintain, inspect and operate, less influence of human factors, high reliability, improved availability and capacity, design standardization, easier to construct, quicker to construct, more flexibility in siting, lower initial investment and better adaptability to electrical grid management.

All these features of nuclear power plants make it very attractive for developing countries to introduce nuclear power and for industrialized countries to expand nuclear power usage. In addition, the need to improve the fuel cycle, waste management and nuclear proliferation resistance, requires special design characteristics and fuel management provisions.

Our design efforts to satisfy these conditions have resulted in the development of the Super Safe, Small and Simple (4S) fast reactor with an electric power output of 50 MWe.[1),2),3),4),5)] There are several advantages of the 4S reactor:

a) The 4S will play an important role in accelerating nuclear power utilization throughout the world, because the reactor provides an effective power supply on isolated locations, and medium or large power stations are also feasible by the core or reactor module configuration.

b) Regarding site selection, the 4S has some favorable characteristics. First, the required site boundary is 20m based on the source term evaluation and thus the 4S plant satisfies the required area by it's construction area. Second, the small reactor vessel has a high seismic resistance. The 4S can be constructed to withstand any earthquake condition without changing the main design. Third, as the reactor is embedded, external accidents such as falling aircraft do not pose serious safety problems.

c) Higher safety can be achieved by designing all reactivity feedback coefficients including coolant void reactivity to be negative and by controlling neutron leakage from the core by an annular reflector. The potential for super prompt criticality, particularly during start up, is completely excluded by using metallic fuel. A fully passive heat removal system is employed in the 4S so that the auxiliary support system for the safety system can be eliminated, thus improving the reliability of the safety system.

d) The 4S is made more economical by simplifying the entire plant design. In the reactor assembly, control rod drive mechanisms, a rotating plug for refueling and a refueling machine are not necessary. All auxiliary systems in the nuclear building are eliminated by removing heat by natural air circulation. No complex control system is required. These simplicities greatly reduce the cost of the 4S plant.

e) In order to allay public fears, "a sense of security" is essential, which means that a clearly safe concept, proven or easily demonstrable technology and small system technology are preferable. The safety of the 4S can easily be demonstrated in a full scale test because of its small size. As the 4S is a modular type reactor, the full advantages of modular reactors are directly applicable. We believe that a simple system like the 4S will be readily understood and accepted by the public.

f) In order to introduce nuclear power plants to developing countries, the plant should be easy to operate and require less maintenance. These are both features of the 4S plant. Completely automatic operation is possible because any malfunctions during start up and power generating operation do not cause severe reactivity insertion. There are no rotating parts which require frequent maintenance. The coolant can be driven by electromagnetic pumps. Because the safety systems are passive, no active tests are required. These factors greatly reduce the number of operators required. In addition, the refueling interval is ten years, and this also reduces the fuel exchange workload on operators. Other requirements for reactors in developing countries are related to environmental problems. Reactors need to address the problems faced by such countries in the future, which include rapid population growth, carbon dioxide production and desertification.

g) Improving the fuel cycle and waste management is most important for future nuclear systems. A fast reactor technology using a metallic fuel cycle appears to be a most promising approach.[6] The technology is valuable because it has the potential to simplify reprocessing, fuel fabrication process and nuclear waste disposal, and it includes actinide recycling which is important from the viewpoint of resource utilization. It also reduces the fuel cycle cost dramatically.

h) In order to keep strict control over the plutonium used, the 4S incorporates a new concept by using metallic fuel which significantly helps to achieve the non-proliferation goal; a large amount of fuel can be confined for a long time in the reactor vessel without refueling. During the initial start up, the reactor is sealed in the presence of IAEA (International Atomic Energy Agency) authorities and the IAEA maintain long-term control over operations to ensure non-proliferation.

The 4S reactor assembly and plant design are shown in Fig. 1 and Fig. 2, respectively. The diameter of the reactor vessel is 2.5 m and the area of the nuclear building is 26m x 16m, thus requiring only a small ground space.

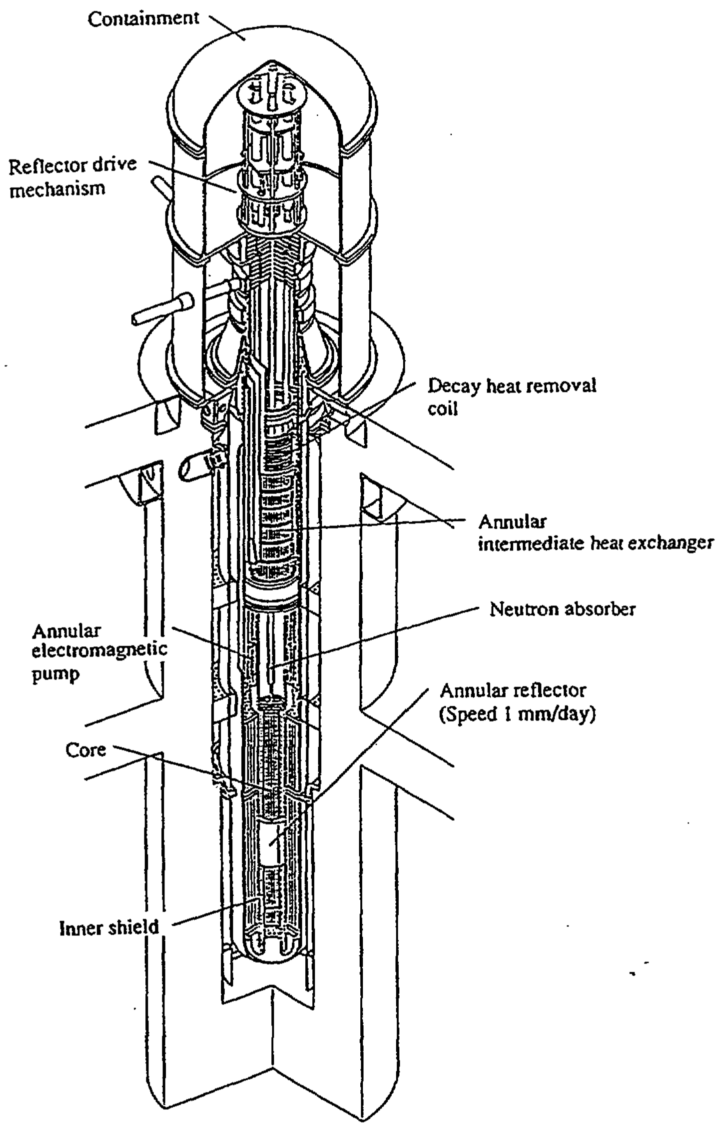


Fig. 1 4S Reactor Assembly

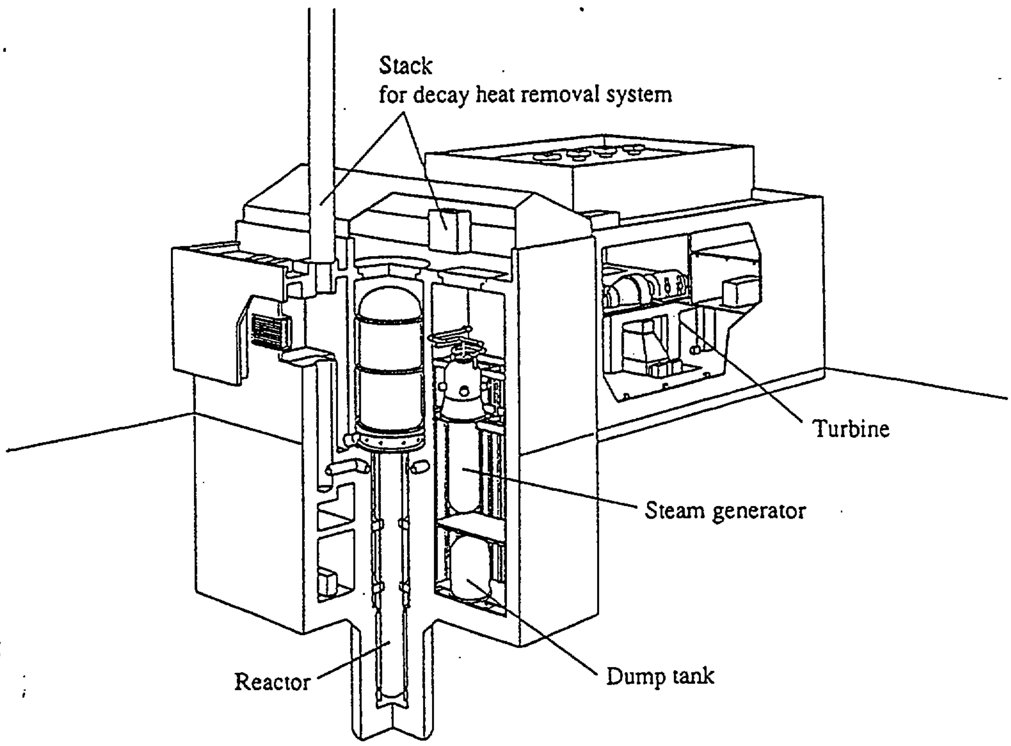


Fig. 2 4S Plant Concept

3. CORE AND REACTOR SYSTEM

3.1. Core and Reactivity Control System

The 4S employs a reactivity control system with an annular reflector in place of the control rods and driving mechanisms which traditionally require frequent maintenance service. Reactivity is controlled only by the vertical movement of the annular reflector during plant startup, shutdown and power generation, thus eliminating the necessity for complicated control rod operations. Although this reactivity control method using a reflector has been studied in some projects[7),8)], using this method for the core burn-up phase is a new approach.

The reflector is installed inside the reactor vessel and the heat generated in the reflector is cooled by sodium. The equivalent core diameter is 0.8m which satisfy negative void reactivity requirements. The reflector length is 1.5m and the reflector gradually moves up to control the reactivity leading to burn-up. The axial power distribution changes as shown in Fig. 3 according to the reflector position.

The structure of the reflector is shown in Fig. 4. The upper part of reflector must be made of a material with a lower reflection effect than the coolant itself in order to increase its ability to control neutron leakage. The reflector therefore has a gas cavity which can increase 3% Δk of the reflector reactivity compared to a reflector without a cavity.

Table 1 lists the major specifications of the core and fuel. The cross section is shown in Fig. 5. The core has an active length of 4m.

The fuel inventory balance is shown in Table 2. The amount of $Pu^{fissile}$ is 1.3tons at start up of the 4S core and 1.2tons remain after ten years of operation. In this sense, the 4S core could be called a plutonium burning storage core.

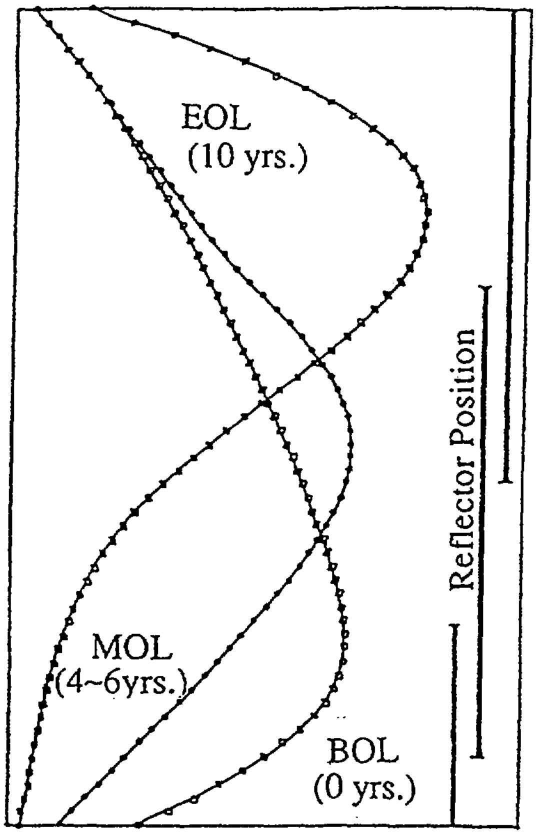


Fig. 3 Axial Power Distribution as a Function of Reflector Position

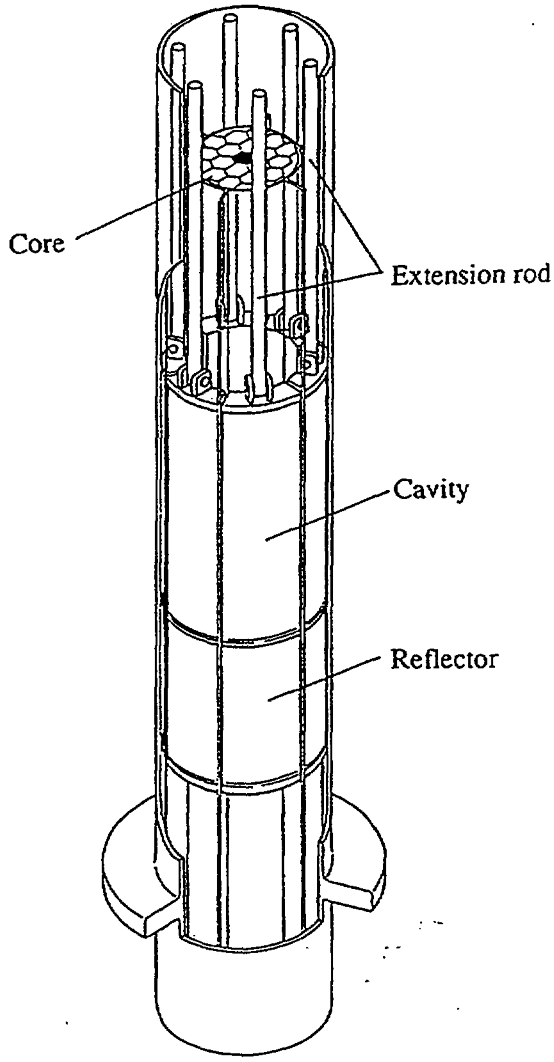


Fig. 4 Structure of Reflector

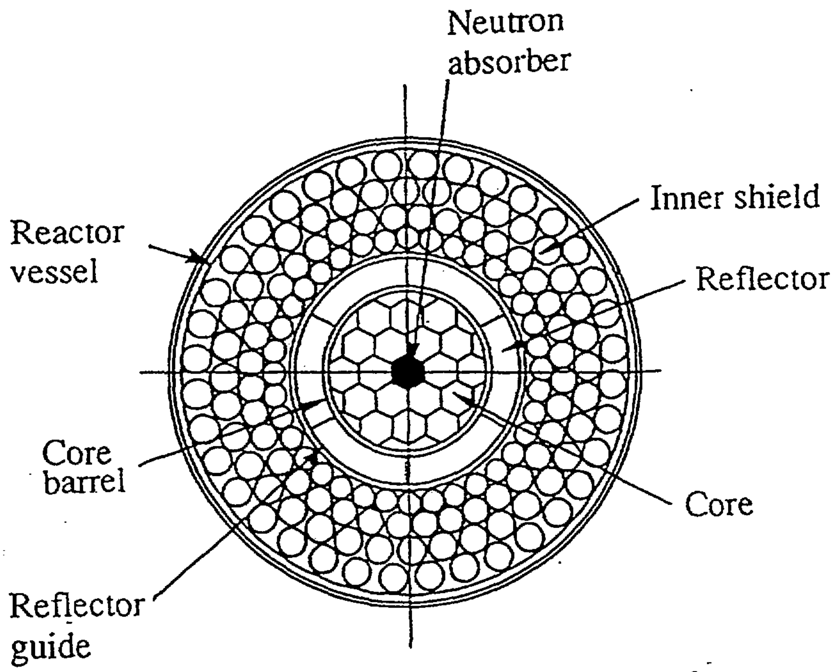


Fig. 5 Cross Section of Core and Reactor Vessel

Table 1 Major Core Design Parameters

FUEL COMPOSITION (Metallic Fuel)	U·Pu·Zr or U·Zr
CONVERSION RATIO	0.7
VOID REACTIVITY	–2.5$ (Diffusion Model) –1.0$ (Transport Model)
REFUELING INTERVAL	10 years
Pu^{fiss} INVENTORY	1.3 ton
No. of SUBASSEMBLIES	18
No. of PINS/S/A	217
PIN DIAMETER	1 cm
PIN LENGTH	610 cm

Table 2 Fuel Inventory Balance

	BOL (kg)	EOL (kg)	BOL-EOL (kg)	FISSION CAPTURE DECAY (kg)	FISSION (kg)	CONTRIBUTION TO TOTAL FISSION (%)	CAPTURE (kg)	DECAY (kg)	REMARKS
U^{235}	23.9	17.4	6.5	6.5	5.2	1.1	1.3		neutron capture
U^{236}	0	1.3	–1.3						
U^{238}	7946.0	7621.2	324.8	324.8	65.0	14.3	259.8 (a)		neutron capture
U^{TOTAL}	7969.9	7639.9	330.0	331.3	70.2	(15.4)			
Pu^{239}	1272.9	1143.6	129.3	389.1 (*1)	326.8	71.8	62.3		neutron capture
Pu^{240}	520.7	510.6	10.1	72.4	38.9	8.6	33.5 (b)		neutron capture
Pu^{241}	38.9	37.8	1.1	34.6	14.0	3.1	2.3	18.3	neutron capture & decay
Pu^{242}	96.4	88.7	7.7	10.0	5.0	1.1	5.0		neutron capture
$Pu^{fissile}_{Total}$	1311.8	1181.4	130.4	423.7 (c)	340.8	(74.9)			
Pu^{Total}	1928.9	1780.7	148.2	506.1	384.7	(84.6)			
Total Heavy Metal	9898.8	9420.6	478.2		454.9	100			

(*1) 129.3+259.8

Breding Ratio= $\frac{(a)+(b)}{(c)}$ =0.69

3.2. Reactor Assembly

The major specifications of the reactor are shown in Table 3. The primary coolant flow path is shown in Fig. 6. The coolant flows out of the core, rises in the hot pool and

Table 3 Major Reactor Design Parameters

THERMAL POWER	125 MWth
REACTOR OUTLET TEMP. INLET TEMP.	510°C 355°C
REACTIVITY CONTROL	ANNULAR REFLECTOR
PRINARY PUMP	TWO ANNULAR SINGLE STATOR EMPs JOINED IN SERIES
INTERMEDIATE HEAT EXCHANGER	ANNULAR STRAIGHT TUBE TYPE
VESSEL DIAMETER	2.5 m
VESSEL THICKNESS	25 mm
VESSEL MATERIAL	SUS 304
CORE INTERNAL MATERIAL	Mod9Cr·1Mo

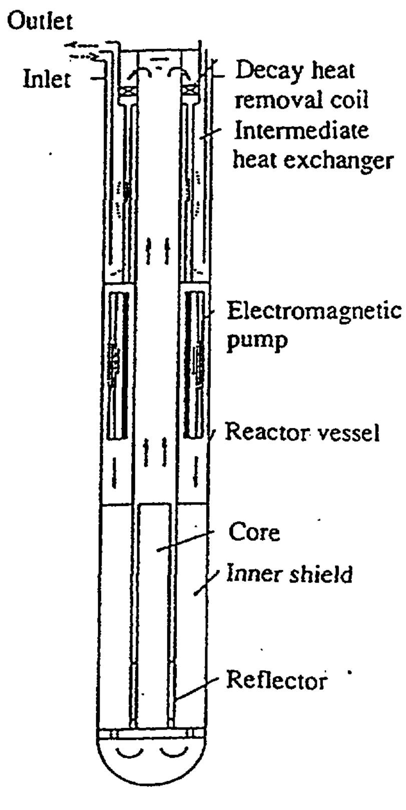


Fig. 6 Primary Coolant Flow Path

descends in the intermediate heat exchanger through which the heat is transferred to the secondary system. It is pressurized by a primary electromagnetic pump at the bottom of the intermediate heat exchanger and flows down in the annular space. Then, the coolant turns up at the bottom of the reactor vessel and enters the core.

The intermediate heat exchanger (IHX) and the electromagnetic pump (EMP) have an annular shape and an annular short vertical redan is installed to form an annular flow path. A space is provided outside the core barrel, in which the reflector moves vertically. An upward flow path for the coolant is formed in this space to remove the heat generated in the reflector body.

The primary pump is composed of two annular single stator EMPs joined in series. The feasibility of this type of sodium-immersed, self-cooled EMP has already been established by a small model.[9)]

The reflector driving mechanism consists of a hydraulic system which operates at start up and shutdown and a ball screw that is connected to a motor which is operating during normal operation. The mechanism has six driving systems corresponding to the number of reflector segments.

The reflector is moved upward by the hydraulic pump during start up. During power operation, the reflector is held by the hydraulic system and gradually moves up for burn-up compensation at a constant speed of 1mm/day without any speed control system. To attain this very slow speed, a reduction mechanism composed of paradox planetary gears is installed. The technical reliability of the gears has been demonstrated elsewhere. However, a spare set of gears is installed in the 4S in case of trouble. To shut down the reflector, the scram valve is opened in the hydraulic circuit. When the reflector lowers 1m, the core reaches the subcritical cold shutdown state. The length of the downward movement of the reflector is determined by the capacity of the hydraulic cylinder. It cannot move otherwise.

A natural air cooling system is employed to cool the reactor cavity. While its main purpose is to remove heat from the reactor during normal operation, it also functions to remove decay heat.

4. INHERENT AND PASSIVE SAFETY

4.1. Inherent core safety

4.1.1. Negative void reactivity

One of the attractive features of the fast reactor is its hard neutron spectrum. To expand this feature, a metallic fuel core is employed in the 4S. However, it is more difficult to reduce void reactivity for a core with a harder spectrum. It is very important to design the void reactivity to be negative in order to prevent a severe nuclear accident in the event of sudden loss of coolant, sudden loss of coolant flow or a large gas bubble entrainment in the core.

There are two generic approaches to reducing void reactivity. Reducing the core height is one popular approach, and a core with a small diameter is another effective method. In the 4S, making the core diameter small is the preferred approach because this reduces the vessel diameter and enhances the value of the reflector reactivity. By reducing the core diameter, neutron leakage is enhanced in the radial direction so that negative void reactivity is maintained during the entire core life time. The void reactivity depends on the diameter and fuel volume fraction as shown in Fig. 7.

For the selected core, the void reactivity of the total core is -1$ at the end of life based on the transport calculation. Other temperature feedback coefficients are all negative as shown in Table 4.

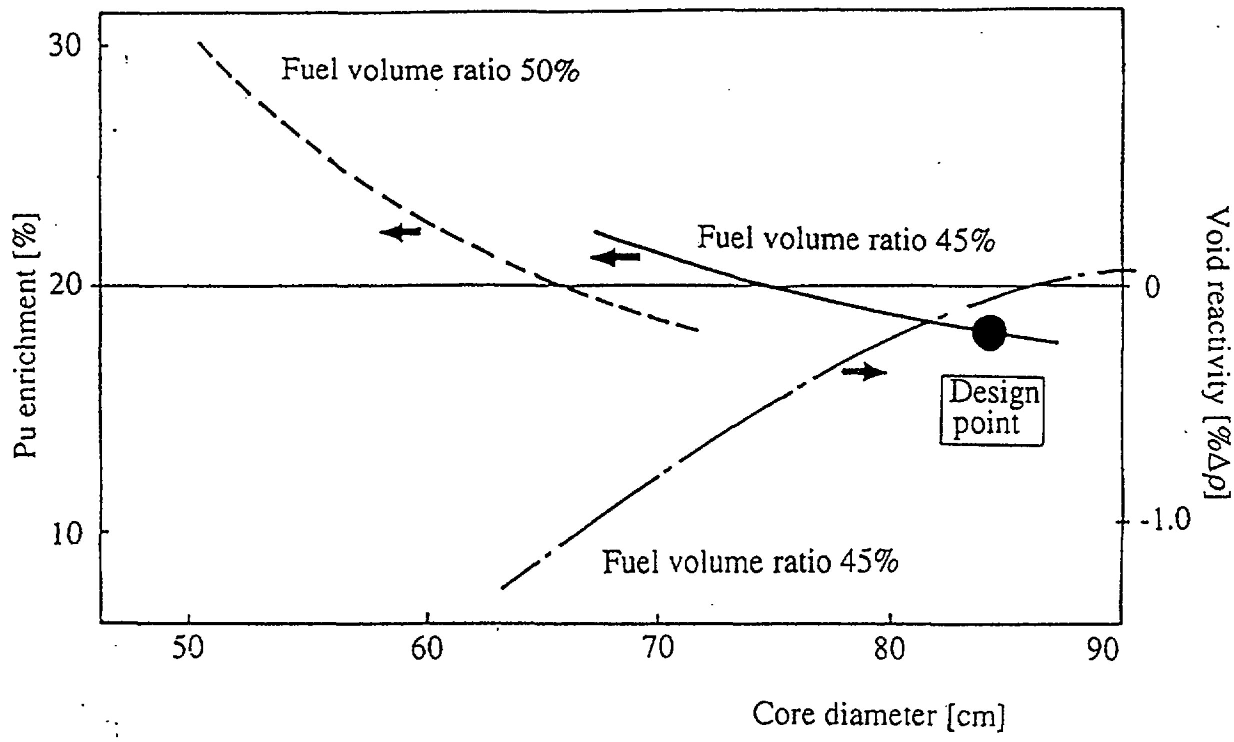


Fig. 7 Design Point for Ten Year Core with Negative Void Reactivity

Table 4 Feedback Temperature Coefficients

	BOL (BARE) (0 YRS.)	BOL (REFLECTOR) (0 YRS.)	MOL (4~6 yrs.)	EOL (10 yrs.)
FUEL $\left(\frac{K/KK'}{°C}\right)$	-8.87×10^{-6}	-8.23×10^{-6}	-7.37×10^{-6}	-7.29×10^{-6}
STRUCTURE $\left(\frac{K/KK'}{°C}\right)$	-1.62×10^{-6}	-1.30×10^{-6}	-0.42×10^{-6}	-0.50×10^{-6}
COOLANT $\left(\frac{K/KK'}{°C}\right)$	-6.03×10^{-6}	-5.22×10^{-6}	-2.87×10^{-6}	-3.23×10^{-6}
CORE SUPPORT $\left(\frac{K/KK'}{°C}\right)$	-8.34×10^{-6}	-7.87×10^{-6}	-6.84×10^{-6}	-6.70×10^{-6}
DOPPLER $\left(T\frac{dk}{dT}\right)$	-1.83×10^{-3}	-2.22×10^{-3}	-2.79×10^{-3}	-2.80×10^{-3}

4.1.2. Preventing potential super prompt criticality.

It is essential for the safety of the reactor to exclude the possibility of super prompt critical state at all times. This requires that the inserted reactivity at potential events should be below 1$ under conservative conditions, neglecting reactivity feedback coefficients.

The largest reactivity change occurs during plant start up. The reactivity decrease from criticality at zero power under cold temperature conditions to full power is generally above 1$. The worst case is reactivity insertion under cold temperature conditions.

At plant start up in the 4S, the system temperature is raised to 350°C by heat input from the electromagnetic pump before raising the reflector. This procedure greatly reduces the reactivity temperature swing. The reactivity to be inserted to increase the power is about 86¢, which causes the following reactivity effects; thermal expansion of the fuel, structure, coolant, core support grid and doppler reactivity. Because metallic fuel is employed in the 4S, the reactivity is small compared with the 150¢ for MOX (Mixed Oxide) fuel, mainly due to its small Doppler coefficient.

The basic dynamic characteristics of the core under various reactivity insertion conditions are shown in Fig. 8. The power transient reflects the super prompt critical condition when a large reactivity insertion occurs. On the other hand, the power transient is small for the 4S during potential reactivity insertion at the plant start up phase.

4.1.3. Neutron leakage control by reflector.

In the 4S core, all reactivity change is controlled by the reflector. This neutron leakage control system has a decisive advantage compared with control rod system from the safety point of view.

The active length of the core is 4m, which is surrounded by a 1.5m long reflector. The reflector is separated into six azimuthal parts, each of which can move from the bottom to the top of the core along with the core burn-up. If an uncontrolled lift of each part of the reflector occurs, the core criticality cannot be sustained. The new geometry of the reflected region causes negative reactivity insertion because of the enhanced neutron leakage.

Figure 9 shows that lifting up parts of the reflector gives strong negative reactivity except lifting up all of the reflector. Although the figure shows negative insertion, a small positive insertion up to ten cents may be possible if each segment of the reflector moves up a small distance from the original position. The maximum is -4$ when three parts are lifted up. This geometry gives the minimum criticality which maximizes neutron leakage.

Thus, the inherent core safety against partial movement of the reactivity control system is assured for the 4S core.

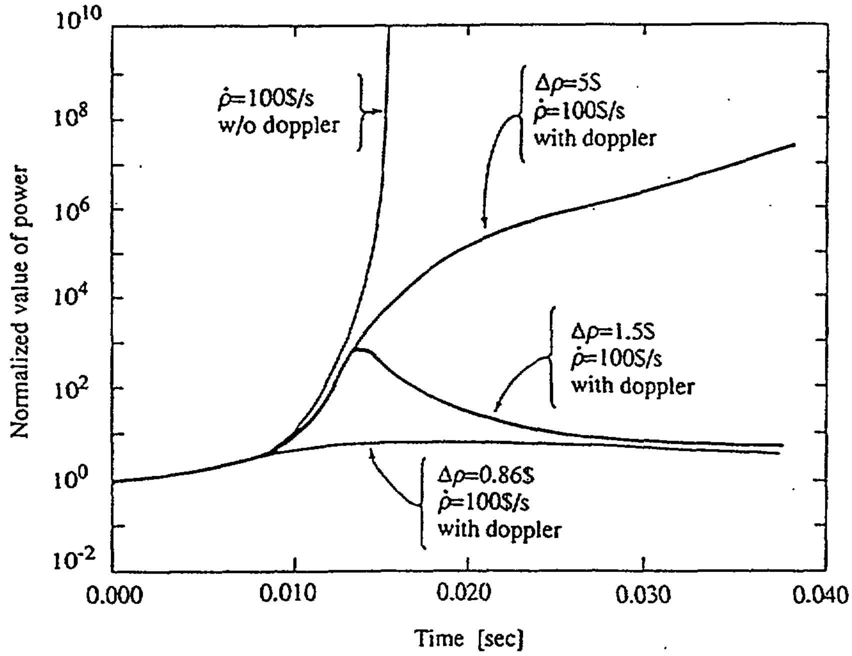


Fig. 8 Reactor Power Transients for Various Reactivity Insertion with ρ =100$/s

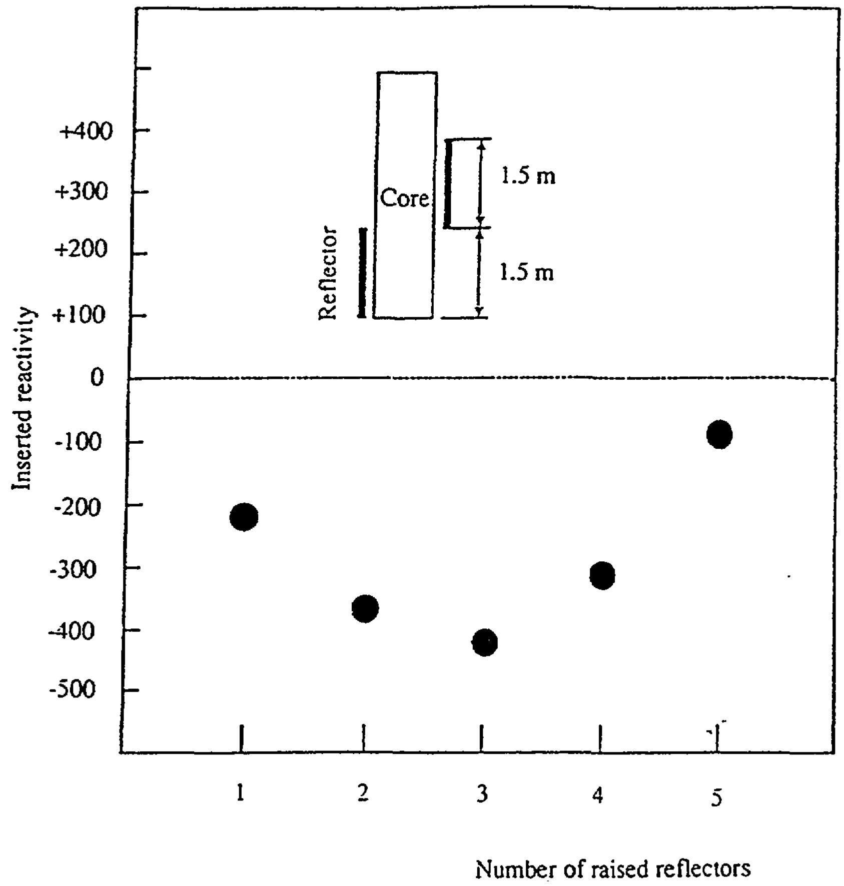


Fig. 9 Reactivity Insertion when Lifting Partial Segments of Reflector up to 1.5m

4.2. Passive Safety for Unlikely Events

4.2.1. Loss of all station power without scram.

In the 4S, following the loss of off-site power, the primary loop shifts to natural circulation. The pump in the secondary loop of the decay heat removal system does not work assuming the loss of emergency power following loss of off-site power. Under such conditions, the secondary coolant operates in natural circulation mode and natural air-cooling operates in the air cooler. Thus, a passive heat removal circuit is established.

In the safety analysis, all active shutdown systems are assumed to fail, and negative feedback coefficients are taken into consideration for the analysis. Figure 10 shows the analysis results. The primary natural circulation flow rate is about 10% of the rated flow due to the large distance between the core and decay heat removal coil. The reactor power is decreased by the negative feedback coefficients and the transient peak temperature of the cladding is 810°C, dropping to 510°C after 150 seconds. No cladding damage is expected during the accident.

4.2.2. Loss of decay heat removal function.

In the 4S, the decay heat is removed by two systems consisting of the decay heat removal coil installed in the reactor (PRACS) and the natural air ventilation from outside the guard vessel (RVACS). The analysis considers the destruction of PRACS and the RVACS cooling stack by a large falling aircraft. In addition to this extreme severe condition, 50% of the cross sectional area of the RVACS stack is assumed to be blocked.

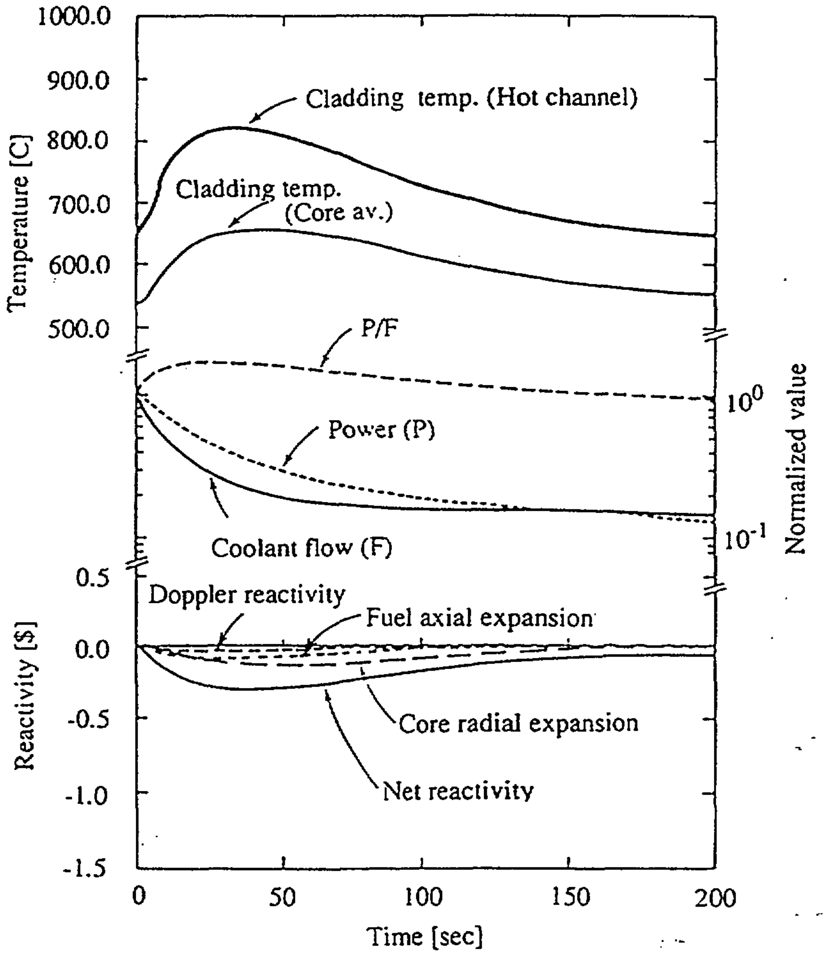


Fig. 10 Core Response for Loss of all Station Power without Scram

Figure 11 shows the analysis results of the primary coolant temperature. The coolant temperature gradually rises and peaks at 700°C after 35hrs. The structural integrity is a major concern in this type of accident. However, a creep damage during the accident is less than 0.1 as the usage factor, and so the structural integrity is maintained.

4.2.3. Sodium-water reaction in steam generator.

The breakage of all heat transfer tubes in the steam generator was assumed, and protective actions like water steam dumping were neglected to find the passive safety features against this type of accident.

The water leak rate increases as the tubes break, but is limited by the feedwater pump capacity. After the water leak rate reaches the peak value, the main steam pressure decreases because the turbine trips due to the reduction of the main steam flow rate, and the feed water pump trips due to the reduction of its rotational frequency. Due to these quasi-passive features, the water leak rate decreases and adverse consequences can be avoided by providing two pressure relief pipings with rupture disks at the bottom of the steam generator which operate at a pressure of 11 kg/cm^2.

Figure 12 shows the pressure transients. The three lines show (1) water, steam side pressure, (2) pressure without relief piping and (3) pressure in IHX with two relief pipings. The pressure of IHX in line (3) is found to be within the allowable pressure of 9 kg/cm^2.

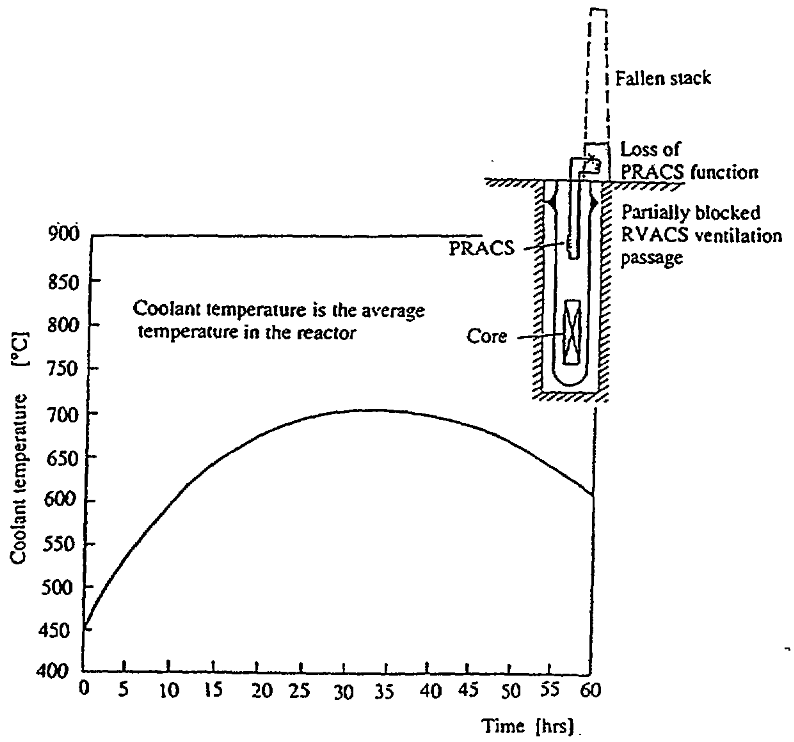


Fig. 11 Primary Coolant Temperature Response upon Loss of Decay Heat Removal System

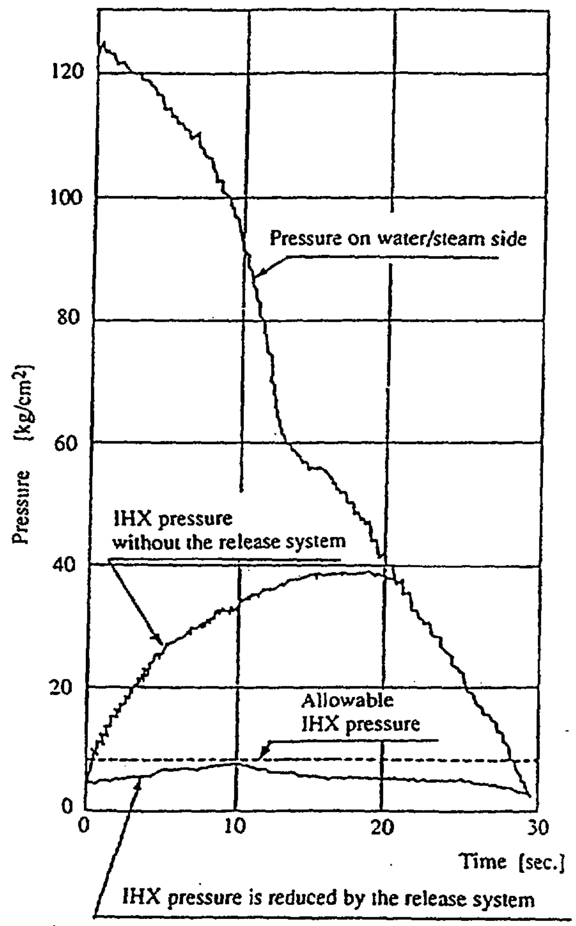


Fig. 12 Pressure Transients upon Total Tube Breaks in Steam Generator

5. OPERATION

One of the excellent features of the 4S is that it is simple to operate. There are no feedback control systems and no human intervention is required. All reactivity control is performed by the automatic movement of the reflector as shown in Fig. 13.

The plant starts up by heat entering from the primary pump and the system temperature rises to 350°C from the cold shutdown state. Under this condition, all parts of the system, including the recirculation line in the water system, are uniformly heated. Then, a neutron absorber at the center of the core is withdrawn. At temperatures below 350°C, the neutron absorber cannot be withdrawn by the self-connected mechanism using the thermal expansion difference between the stainless steel and Cr-Mo steel (Fig. 14). After withdrawal of the neutron absorber, the reflector is lifted up by the hydraulic system to reach critical condition at 350°C. A fuzzy control system is employed for this approach and a fully automatic operation circuit is provided because no malfunction causes severe reactivity insertion as described previously.

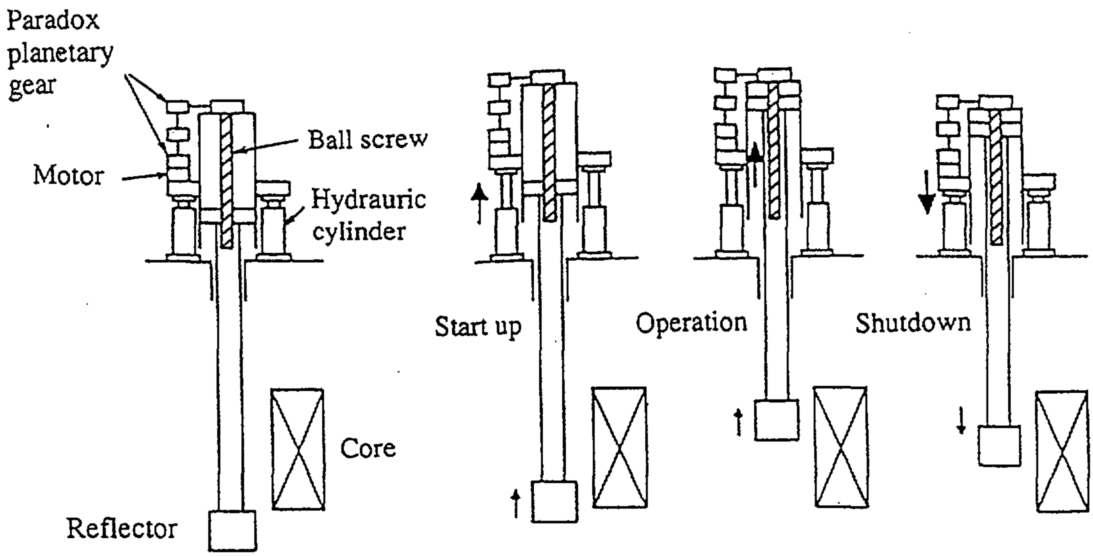


Fig. 13 Reflector Drive Mechanism and Reflector Position During Plant Operation

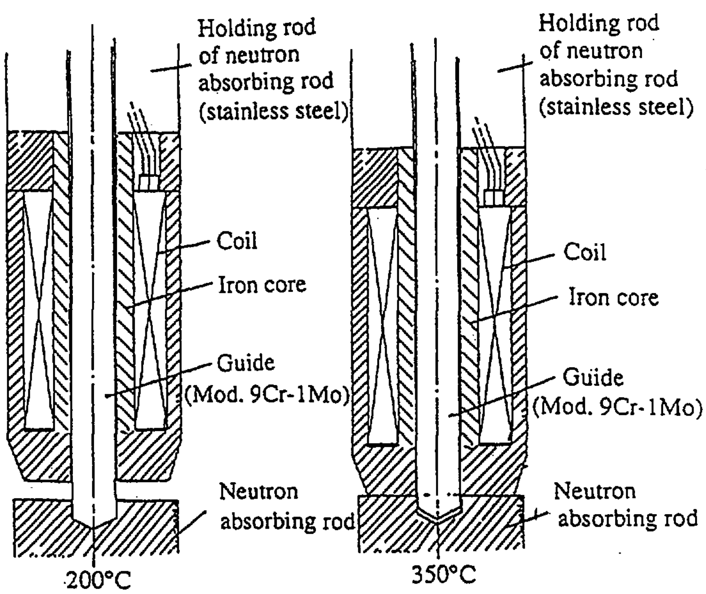


Fig. 14 Self-connected Mechanism

To increase the power to 20% of the rated power to start the turbine generator system, the reflector is periodically lifted up at a speed of 1mm per 15 minutes in automatic mode. Periodic operation is needed to stabilize the system heat balance. At the same time, the pressure of the water steam separation tank is decreased to generate steam and to reduce the re-circulation flow. After this, the power is increased to full power by lifting up the reflectors and increasing the feed water flow.

Regular power operation is attained by moving the reflector upward at a constant speed of 1mm/day to compensate for the reactivity decrease due to the burn-up of the core. Since no feedback system or control system are used, the reflector speed remains constant and the electric output is adjusted by varying the feed water flow rate to control the core inlet temperature. The controllable range of the power level by the water flow is ±10% at the rated power, which is limited by the steam generator heat balance. Beyond this range, a back-up control mechanism to adjust the reflector position is installed in the driving mechanism.

To follow the load, the core inlet temperature is changed by controlling the water flow so that the generator output coincides with the load-following control, thus causing the reactor output to follow.

Figure 15 shows the changes in system parameters as a function of time in the event of a sudden 20% loss of power. It takes 10 minutes for the reactor to shift to the new plant conditions corresponding to the load since each system or component has a time lag due to thermal inertia. No movement of the reflector is required.

As mentioned above, elimination of all feedback control systems from the reactor and secondary heat transport systems makes the 4S plant control system very simple and economic.

6. MULTIPLE USES OF THE 4S

6.1. Sea Water Desalination

A design study has investigated using the 4S to supply drinking water and other service water in regions where serious water shortages are forecast to occur in the next century.[10] The study has been extended to create green belts in desert areas in order to stop further desertification and to create more greenery to absorb CO_2.

6.1.1. Use to supply drinking water.

The concept of a nuclear seawater desalination plant is shown in Fig.16. The sea water desalination plant is planned based on a two stage reverse osmosis system with a capacity of 240000m^3/day x 7 lines by using a single 4S plant. The plant can be constructed on a site of about 210m x 140m.

Since the island system is employed, an auxiliary power facility of 5000kW is required to startup the 4S and a gas turbine plant is constructed for this purpose. The electric power consumption of the reverse osmosis system is about 5kWh/m^3. Assuming 1kWh/m^3 is required to pump the water produced, about 6 kWh/m^3 in total is required to operate the sea water desalination plant. Since the house load of the nuclear plant is 4100kW, a total power of 46MWe is required for the plant.

The nuclear power plant used is the 4S plant shown in Fig. 2. Refueling is not required for ten years, thus greatly reducing the refueling workload. The plant operation of the 4S, including full automatic start up without any control system, eliminates safety problems. These are attractive features, particularly for developing countries.

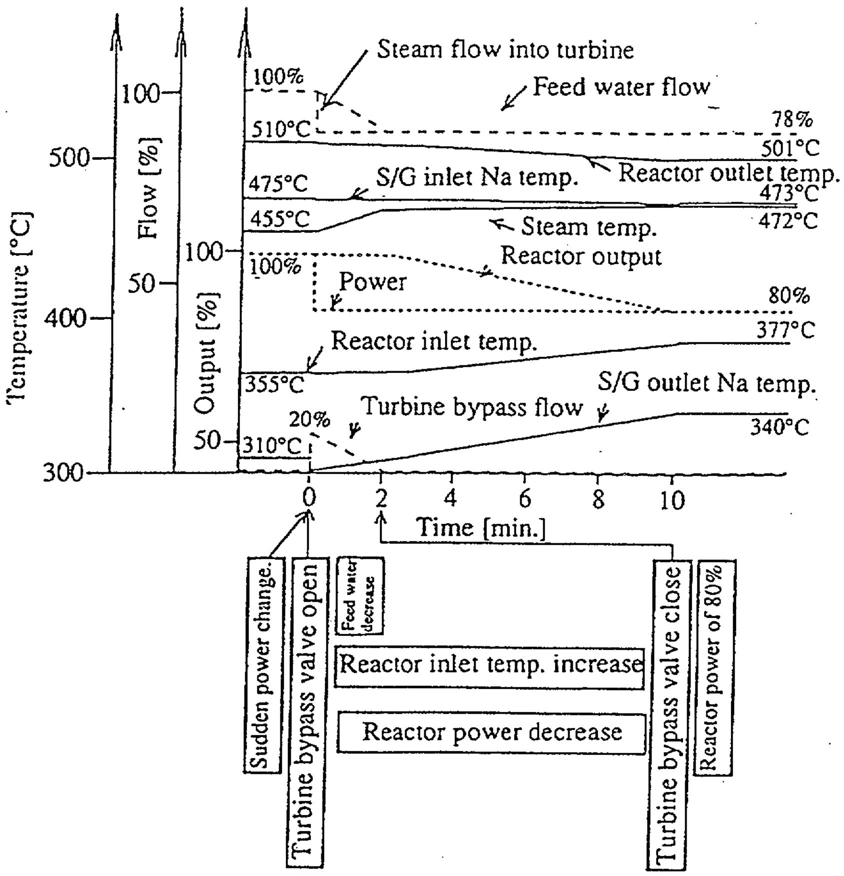


Fig. 15 System Parameters as a Function of Time for a Sudden 20% Loss of Power

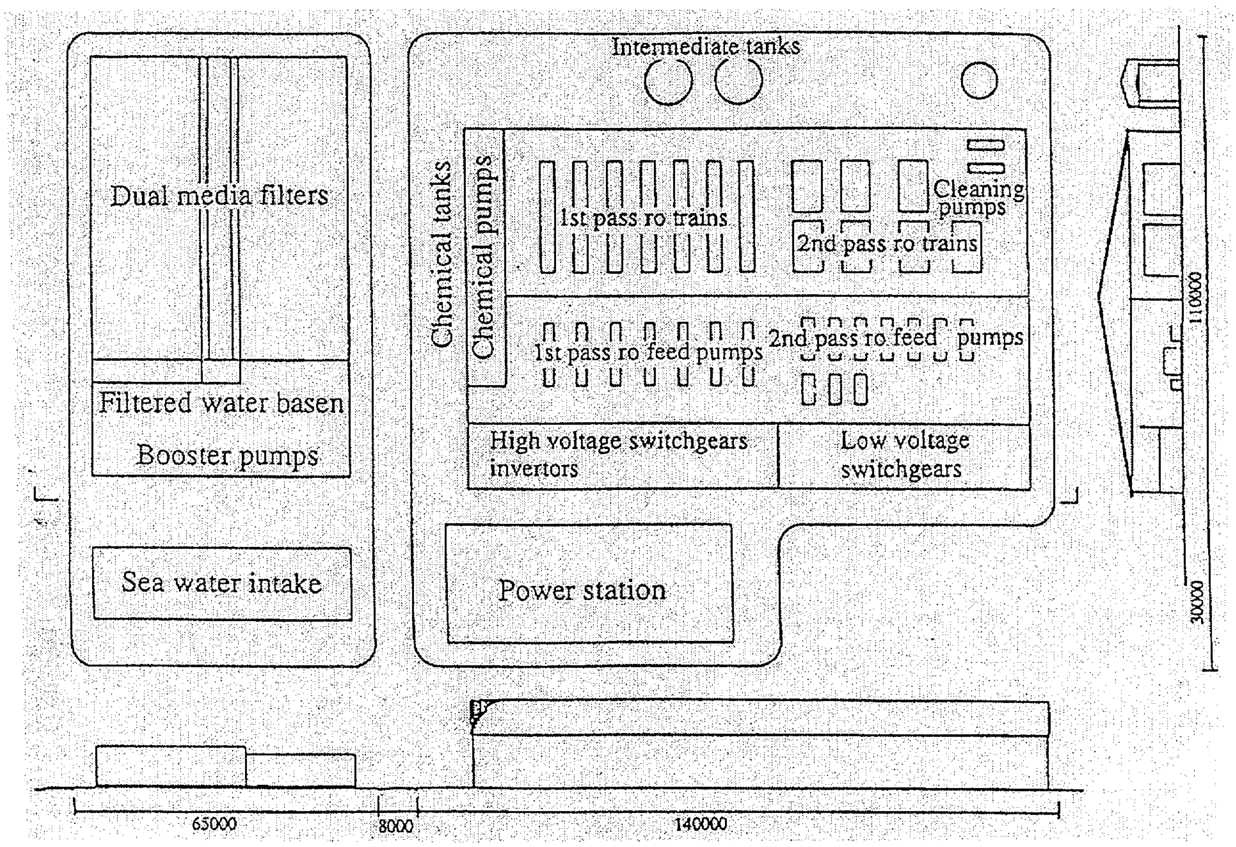


Fig. 16 Plan View of Nuclear Desalination Plant with Water Production Capacity of 24000 $m^3/d \times 7$ Lines

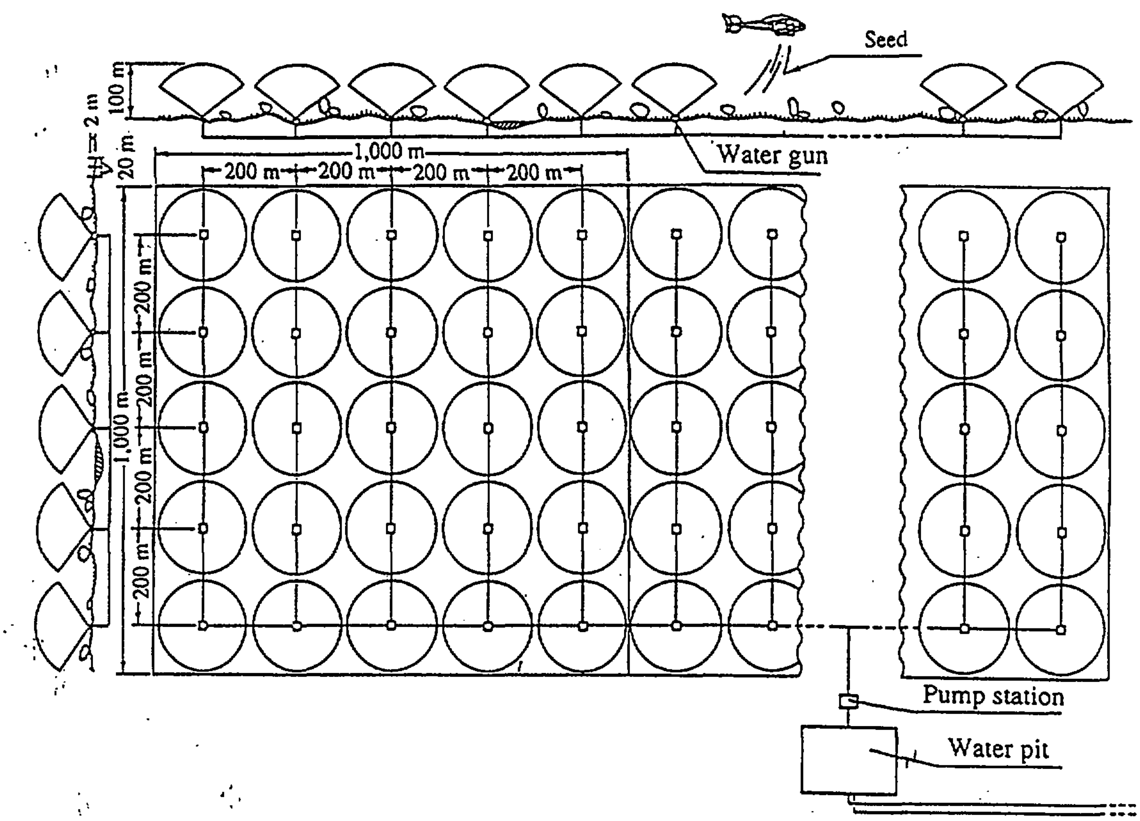


Fig. 17 Schematic of Water Supply Units

6.1.2. Creating green belts in desertification areas.

Six million hectares are devastated annually in the world by a process known as "desertification". To control desertification, we need to create grasslands or green belts at the leading edge of the desert area. A dual-purpose plant for electric power and water production is significant in this case because the desalination power plant can also supply surplus power to the desert areas. This helps to preserve forests when energy requirements in such areas are met by wood fuel, preventing desertification in a double sense.[1)]

The sea water is desalinated by two 4S units with a combined power of 100MWe, of which 10MWe is supplied to neighbouring towns for electricity and 10MWe for power for spraying water. If the remaining 80MWe are used for desalination, water can be desalinated at a rate of about 30 x $10^4 m^3$/day.

Assuming that 1000-2000mm/year of sprayed water is required to grasslands, taking evaporation in the desert into consideration, a green belt 1km wide and 100km long can be created. By locating 100m class spray guns at intervals of 200m, the plan requires 2500 guns to be installed to create a green belt 100km long and 1km wide shown in Fig. 17.

6.1.3. Renewal of the earth.

According to documents from the Intergovernmental Panel on Climatic Change, the greenhouse effect is likely to have a far more serious impact than expected. In the worst case, the carbon dioxide produced by developing countries, whose total population is expected to reach seven billion by the year 2030, could exceed 13 billion tons per year.

If it were possible to transform approximately 28 million km^2 of desertified area to at least grassland condition, this could create a carbon dioxide absorbing capacity of 14 billion tons/year, since grassland fixes absorbed carbon dioxide in the form of leaves, and stems at the rate of $500g/m^2$. Thus, the vegetation recreated in desertified areas would be sufficient to absorb and fix the carbon dioxide produced in 2030. However, the power required to create such an immense area of grassland by sea water or underground water desalination is too large and is not realistic. A realistic approach may be 1) suppression of CO_2 release, 2) balanced population growth, and 3) full use of dual-purpose nuclear power plants for electric power and water production. The nuclear plant, in this case, should be safe, and easy to operate like the 4S.

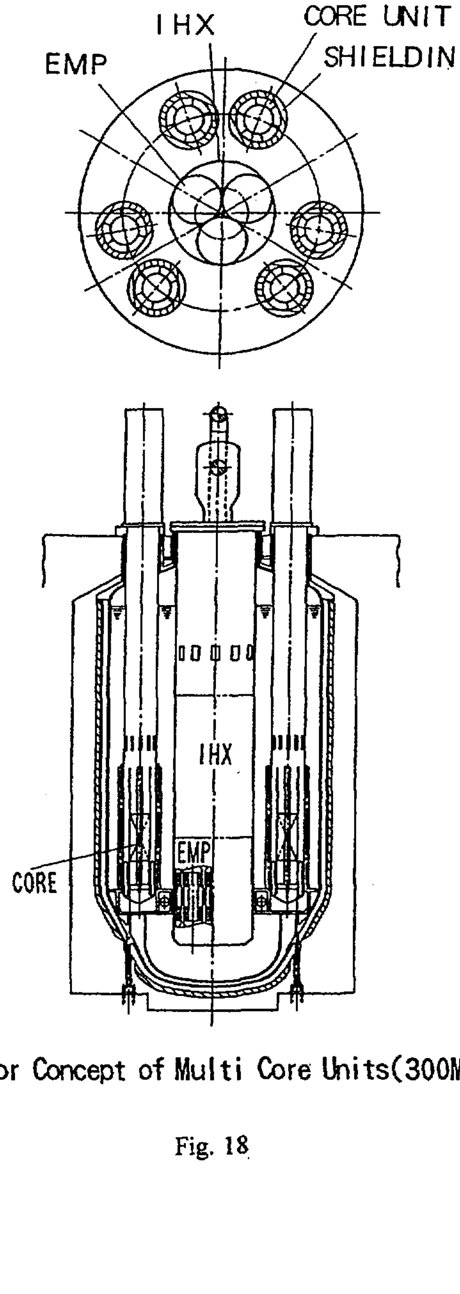
6.2. Integral concept

To minimize the time and cost for development, a modular core assembly system is preferable so that the reactor electric output can be expanded only by adding 50MWe core units in the reactor vessel. This requires the development of a single 50MWe core unit. Once developed, the reactor output can be increased without further R&D effort.

6.2.1. Modular Core Assembly Concept.

By arranging six nuclear de-coupled core units within the reactor vessel, the economy of scale increases while maintaining the safety of the 4S. The electric output is 300MWe, with six 50MWe cores to eliminate the need for refueling for ten years.

The longitudinal cross section of the reactor is shown in Fig. 18. The diameter of the reactor vessel is approximately 9m using three electromagnetic pumps combined with an intermediate heat exchanger.



Reactor Concept of Multi Core Units(300MWe)

Fig. 18

6.2.2. Modular Reactor Assembly Concept.

Figure 19 shows the nuclear power plant with fuel cycle facility. The total electrical output is 1000MWe with 10 reactor assemblies of two 4S units and one turbine system. The capacity of the fuel cycle facility is 20ton/year and is able to reprocess the spent fuel from 4S for ten years.

The spent fuel discharged from the reactor after ten years of operation will be treated by IFR type reprocessing as advocated by ANL[6] so that it can be re-used as reactor fuel, while the long half-life wastes will be confined within the fuel cycle.

Thus, we could establish a self-supporting system in which plutonium is safely contained for a long time until more energy is needed, while covering the management cost with by revenues from power generation.

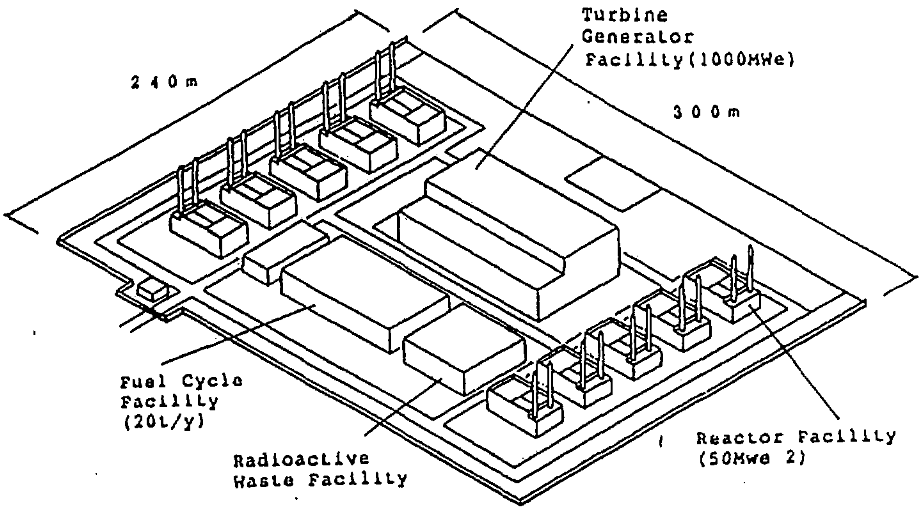


Fig. 19 Nuclear Power Plant Concept with 4S-Units

7. FURTHER R&D ITEMS

Although most of the technologies used in the 4S are already proven or under development, further R&D work is required for some key technologies. These are criticality experiments of the metallic core with reflector, higher reliability of the reflector driving mechanism and fuel performance of a long fuel slug.

A full scale critical experiment is important to evaluate the calculated results such as reactivity coefficients and critical conditions. As neutron leakage is enhanced in the 4S core, the conventional calculation method is not sufficient to accurately predict the core characteristics. A critical experiment is thus the most urgent R&D item.

All reactivity during plant operation is controlled just by moving the reflector without feedback control systems. Thus, a fine movements of the reflector are required. The technologies proposed for this purpose are all new to the nuclear industry, but are tried and tested in other fields. Reliability experiments are needed.

The feasibility of keeping a long metallic fuel slug in the core for ten years needs to be carefully examined. The preliminary assessment of creep deformation after ten years operation by the metallic fuel performance code shows about 5 % deformation and is within the allowable value. However, the performance of longer fuel slugs must be demonstrated.

8. CONCLUSIONS

Efforts to develop nuclear power reactors have been focused on the enhancement of safety and reliability by using active safety systems with redundancy and diversity while improving economy through scale factor. Although the goals have been fairly achieved, traditional power reactors can be used only under the prerequisites and are thus usable for a limited area of application.

Efforts have focused in recent years on developing small and medium sized power reactors with inherent, passive safety characteristics. Successful development of such reactors will lead to a wider range of application of nuclear power.

The 4S is a new concept of fast reactor designed to meet the goals of nuclear power and offers many attractive advantages. Commercial operation of the 4S is expected to solve a number of problems that humans will encounter in the 21st century.

Finally, the author would like to emphasize the need for worldwide cooperation on the development of the 4S reactor.

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