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Conceptual Design of 1,000 MWth Inherently Safe Fast Reactor (ISFR)

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Abstract. ISFR is a boiling heavy water fast reactor of process inherent ultimate safety (PIUS) type with a positive void coefficient. Fuel breeding may occur in the core. Unlike PIUS, however, the primary system does not contain boron. In accidents, ISFR shutdowns passively occur, because, due to the positive void coefficient, a negative reactivity will be induced by ingress of cold pool water into the circulating primary system (CPS). Since ISFR has not only the positive void coefficient, but also voids in the reactor already at the steady state, the PIUS concept must be modified so that safety and stability can be ensured. To this end, (1) a mixture of He and Ar is used as the gap gas so that the time constant τ_α of the positive void feedback process can be sufficiently large, (2) initially-closed two-way check valves (TCVs) to be used as passive switches are installed at the lower honeycombs, and (3) a reactor control system is designed. As a result, ISFR can be stabilized enough to perform not only constant power operations, but also power level shifts. Items (1) and (2) also help ensure safety of ISFR, because item (1) slows down the positive feedback, while item (2) speeds up an actuation of the ISFR shutdown mechanism. In long term cooling after reactor shutdowns, heat pipes effectively transfer decay heat to the atmosphere. Much work is still needed to prove feasibility of ISFR.

1. Introduction

1.1 General

At the beginning of the eighties, the PIUS concept [1, 2] was proposed. But, by that time, the light water reactor (LWR) technology had been almost established and hence it was difficult for a new LWR concept such as PIUS to be accepted as commercial reactors. On the other hand, fast breeder reactors (FBRs) are now under development so that it is not too late to apply the concept to them. Hence, in this work, applying the PIUS concept with modificationbs, ISFR [3] will be proposed. ISFR is a boiling heavy water fast breeder reactor. The cross-section of ISFR is shown in Fig. 1, while its schematic with the passive engineered safety features is shown in Fig. 2.

1.2 Inherent Safety

In conjunction with the design of the PIUS reactor, the notion of inherent safety was proposed. In discussions of inherent safety, there are two key words, namely, fuel integrity and passive safety. They are related to each other in the following manner. First of all, in inherently safe reactors, the safety criterion is maintenance of fuel integrity, while, for example, in the present licensing of LWRs, the safety criterion is maintenance of coolable fuel geometry and hence a loss of fuel integrity is not prohibited. Inherently safe reactors are designed to ensure fuel integrity by means of passive means as much as possible. Suppose that an accident happens in a reactor equipped with passive safety means. Generally speaking, if the accident is to be safely terminated with maintaining fuel integrity, passive means alone do not suffice, but active means are required finally to intervene at a certain time t_W after the accident occurrence. Then, the maximum of t_W is called the walk-away (or grace) period of the accident. The larger t_W, the smaller a possibility of a failure of the active interventions. Because, as t_W increases, not only the decay heat, but also stored energy in the system decrease. The walk-away period of the reactor can be defined as the minimum of all t_W's. A walk-away period of a reactor is a measure of its inherent safety. The walk-away period of PIUS is claimed to be 7 days. It would be interesting to imagine what would have become of the design of existing LWRs, if there were the notion of inherent safety at the very beginning of their development.

Being of PIUS type, ISFR does not have control rods and hence does not have a possibility of large reactivity-initiated accidents. Moreover, since ISFR is an integrated reactor, a large break loss-of-coolant accident need not be hypothesized. The fact is one of the main reasons why, without control rods, ISFR can have a positive void coefficient. In this work, in order to exemplify passive safety of ISFR, calculated results of a steam generator tube rupture (SGTR) and a main coolant pump (MCP) trip will be presented. The latter will be calculated to show long term cooling of ISFR. Note that any reactor needs to have at least one negative reactivity coefficient. It is the Doppler coefficient γ_D that ISFR has as a negative coefficient. If it were not for the negative Doppler coefficient γ_D, ISFR would not be feasible.

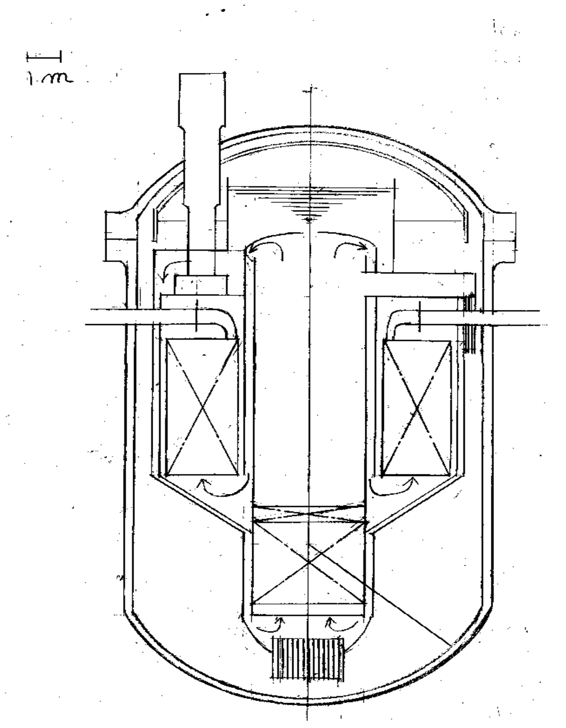

Fig. 1 Cross-section of ISFR

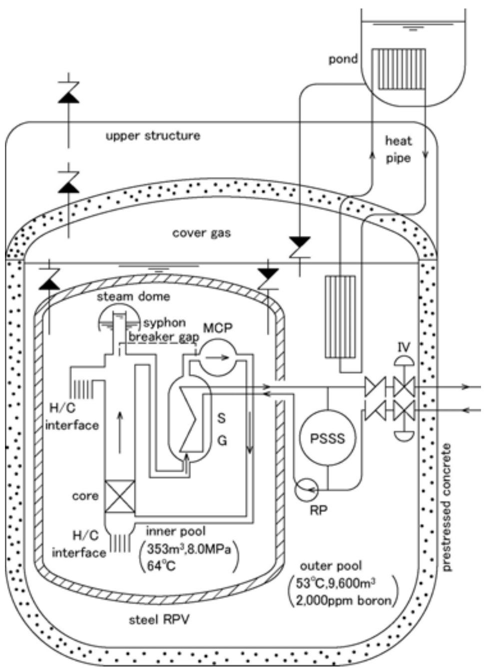

Fig.2 Schematic of ISFR

1.3 Problems Resulting from Positive Void Coefficient

The PIUS concept is characterized by a circulating hot loop submerged in a cold borated pool. The loop and the pool are thermal-hydraulically connected to each other through upper and lower honeycombs, where a hot/cold (H/C) interface is present. Originally, the PIUS concept was intended for applications to pressurized water reactors (PWRs) [1, 4] with a negative void coefficient $\gamma_\alpha < 0$.

But, ISFR is a boiling heavy water reactor with a positive void coefficient $\gamma_\alpha > 0$, which is expected to bring about difficulties regarding safety and stability. For example, owing to $\gamma_\alpha > 0$, ISFR is unstable by itself. In this work, it will be shown that those problems resulting from $\gamma_\alpha > 0$ can be resolved, provided that (1) the time constant of void feedback τ_α is sufficiently large, (2) initially closed TCVs to be used as passive switches are placed at the lower honeycombs, (3) a reactor control system is suitably designed and added and (4) the passive safety shutdown system (PSSS) [5] is installed in the secondary system (Fig. 2). The PSSS is another application of the PIUS concept. The regulating pump (RP) is installed to obtain pressure balance. Items (1), (2) and (4) help ensure safety, while items (1), (2) and (3) are combined to enhance stability. With regard to passive shutdown methods, PIUS and ISFR are different as follows. Although a passive shutdown of both PIUS and ISFR may rely on ingress of cold pool water into the CPS, cold pool water needs to be borated for PIUS, but not for ISFR. Therefore, in order to differentiate the two methods, the shutdown mechanism of ISFR will be referred to as the ISFR shutdown mechanism.

1.4 Representation of ISFR with THYDE-NEU Code

Throughout the discussions in this work, the THYDE-NEU code [6] will play an important role. In this work, 82 nodes, 73 junctions and 46 heat conductors will be used to represent the primary and SG-PSSS systems of ISFR. One of the most important features of THYDE-NEU is that it is capable of performing a null transient for stable systems. A system transient code with this capability can be applied to unstable systems in such a way as to examine if stabilization by controls is effective or not. In this work, this is exactly what will be done with THYDE-NEU when designing a reactor control system for ISFR. A typical set of homologous curves is assumed for the pumps.

2. **Features of ISFR**

2.1 Overview

ISFR (1,000 MW_{th}) is loaded with mixed oxide (MOX) fuel. The reactor pressure vessel (RPV) (steel, 17.0 m in height, 10.1 m in diameter, 0.3 m in thickness) contains the CPS, the helical coil steam generator (SG) and the inner pool (IP). Hence, ISFR is an integrated reactor. Note that the RPV contains the IP, which submerges both the CPS and the SG. The RPV is, in turn, submerged in the outer pool (OP) contained in the prestressed concrete reactor containment vessel (RCV) (Fig. 2). Also the PSSS (318.7 m^3) (Fig. 2) is submerged in the OP. In Fig. 2, ISFR is shown as a loop type, but, in actuality, it is of annulus type. At present, as shown in Fig.2, the PSSS is an independent tank separated from the RPV, but, in the future, it is conceivable to let it be an annulus surrounding the RPV. The SG consists of 2,000 tubes (27mm x 27mm, 22.2 mm in outer diameter, 16.0 mm in inner diameter, 90 m in length). The siphon breaker gap breaks thermal-hydraulically the siphon structure in the CPS, when the water level in the RPV decreases below the gap. The thermal conductivity and the thickness of the insulator at the outer surface of the CPS shell are assumed to be 1.25604 x 10^{-3} kW/(m^{O}C) and 5 cm, respectively. Passive isolation valves are placed in the main steam (MS) and feed water (FW) lines and passively close, when a loss of the on-site power takes place in accidents. Relief valves are installed in the MS line and at the top of the RPV (Fig. 2).

Each fuel assembly of ISFR has neither a channel box nor an assembly bypass region. But, ISFR has the reactor bypass flow, which flows upwards through the outside of the blanket. Both core and blanket flow rates should be small enough to give sufficiently large α at the reactor exit so that fuel breeding can take place within the reactor. On the other hand, the reactor bypass flow should be sufficiently large so that subcooling at the MCP inlet can be sufficiently large.

In this work, we rather arbitrarily let the primary pressure be 80 bars. Given a primary pressure, as subcooling ΔT_{sub} at the reactor inlet decreases, the breeding ratio increases. In this work, ΔT_{sub} at the reactor inlet is 5.4 ^{O}C, while subcooling at the MCP inlet is 29.0 m in head. The number of MCPs is four. Let h_{PR} and $h_{SG\text{-}PSSS}$ be average specific enthalpies of the primary system and the SG-PSSS system, respectively. Then, h_{PR} and $h_{SG\text{-}PSSS}$ are calculated to be 617.3 kJ/kg and 394.9 kJ/kg, whose saturation pressures are 0.479 MPa bars and 0.090 MPa, respectively. These low values imply inherent safety of ISFR.

Owing to the positive void coefficient, ISFR is unstable by itself. Therefore, in addition to stabilization by controls, a modification of the PIUS concep with TCVs is needed. TCVs are separated into two kinds, namely, the one half allowing upward flows and the other half allowing downward flows. Being initially closed check valves, it may be used to switch power sources off in accidents. TCVs are placed at both primary and secondary lower honeycombs to be referred to as the PTCVs and the STCVs, respectively.

2.2 Fundamental Relationship

Prior to transient calculations, adjustment calculations [6] are performed with THYDE-NEU to obtain an initial steady state, which satisfies all the system equations with time derivatives being vanishing. With an initial state thus obtained, THYDE-NEU can generate a null transient, if the system is stable. Such considerations are required from the view point of well-posedness of transient problems. Among the THYDE-NEU equations describing an initial state of ISFR is

$$\Delta\rho g H = K G_r^{\,2} / (2\rho_r) \qquad (1)$$

where

$$\Delta\rho = \rho_{IP} - \rho_{riser} \quad .$$

In actuality, in THYDE-NEU representation of ISFR, Eq. (1) takes on a more elaborate form, but, throughout this work, Eq. (1) will be referred to as symbolically characterizing a steady state of ISFR. Let $(\Delta p)_{TCV}$ mean the pressure difference across the TCVs. At a steady state, the TCVs are closed without a pressure difference and hence we have

$$(\Delta p)_{TCV} = 0 \quad , \qquad (2)$$

which is more general than Eq. (1) in that it applies to both the primary and secondary PIUS configurations. Among the adjustment calculations is to satisfy Eq. (1) by varying form loss coefficient K. The adjustment corresponds to designing the number of grids or the opening of the reactor inlet valves. For the secondary PIUS configuration, another adjustment is made to satisfy Eq. (2) by varying the head of the RP (Fig. 2).

Note that Eqs. (1) and (2) are required to hold during power level shifts as well as constant power operations. In these normal operations, however, strictly speaking, Eqs. (1) and (2) do not exactly hold, because small oscillations resulting from stabilization by controls are superposed (refer to Figs. 3, 4 and 6).

2.3 Fuel

The fuel rods are almost equivalent to those of PWRs, while the lattice is rather tight (volume ratio＝0.643). The average linear heat rate in the core is 9.22 kW/m, which is about a half of that of PWRs, whereas the power density in the core is 69 kW/l, which is almost equal to that of PWRs and about two times as large as that of existing BWRs. With h_{gap}=1. kW/ $(m^2 \cdot {}^{O}C)$ which is rather small for the dynamical reasons (refer to the discussion below regarding h_{gap}), the peak fuel center temperature is calculated to be 1,202 ^{O}C assuming that the peaking factor for the core is 1.71.

ISFR fuel contains minor actinides (MAs). Note that MAs such as ^{241}Am and ^{237}Np are not only fertile materials, but also burnable poisons and hence, given a Pu enrichment, MAs such as ^{241}Am and ^{237}Np help decrease k_{eff}^{max} in a reactor life. This effect is preferable, since ISFR has neither a chemical shim nor control rods.

2.4 Heavy Water as Primary Coolant

Heavy water is used as the coolant in the primary system of ISFR, since (1) heavy water has a smaller slowing down power $\xi\Sigma_S$ than light water and (2) in heavy water, we can have photo-delayed neutrons [7, 8]. Note that $\xi\Sigma_s$ is 1.35 and 0.176 for H_2O and D_2O, respectively. The contribution of photo-delayed neutrons is expected to be $\beta \approx 0.0011$ for ^{235}U fuel cooled by heavy water, for example. Note that since β can be regarded as a measure for the margin to prompt criticality, it is desired to be as large as possible.

2.5 Gap Conductance

Owing to $\gamma_\alpha > 0$, it is required that time constant τ_α is sufficiently large so that transients of ISFR can be sufficiently mild. In fact, it has been noticed with THYDE-NEU calculations that, as τ_α becomes larger, the safety and stability problems become easier to solve. One method to increase τ_α is to reduce h_{gap} for the following reason. Note that h_{gap} can be expressed approximately as $\kappa_{gap} / (\Delta r)_{gap}$, where κ_{gap} is inversely proportional to $(M_{gap})^{1/2}$, and hence h_{gap} decreases, as M_{gap} increases. Therefore, in this work, the gap gas is assumed to be a mixture of Ar and He with mole fractions 0.43 and 0.53, respectively. Then, we have $h_{gap} \sim 1.$ kW/($m^2 \cdot {}^{O}C$) , which is about one fifth of that of existing light water reactors.

3. **Neutronics and Positive Void Feedback**

3.1 Cell Calculations

Cell calculations were performed with the SRAC code [9]. The MOX fuel is assumed to be composed of Pu, MAs and depleted uranium (DU). MAs were assumed to have been cooled three years after a burnup of 33 GWD/t in PWRs (UO_2 fuel, 3,410 MWth). Parameter surveys were performed for α = 0.0, 0.4 and 0.8 to find a pair of E_{PU} and E_{MA} that give k_{eff} sufficiently close to unity at 30 GWD/t. Note that $E_{PU} + E_{MA} + E_{DU} = 1.0$. The result is shown in Table 1, where Δk_{eff} stands for a change of k_{eff} in a burnup of 30 GWD/t. As shown in Table 1, in the upper core region, fuel breeding takes place, whereas, in the lower subcooled region, fuel consumption occurs and hence fuel should have a sufficiently large Pu enrichment with burnable poison.

Table 1. E_{PU} and E_{MA} to give keff ~ 1.0 at Burnup = 30 GWD/t

α	0.0	0.4	0.8
E_{PU}	0.164	0.141	0.127
E_{MA}	0.014	0.013	0.012
Δk_{eff}	-0.055	-0.027	0.008
Breeding ratio	0.912	1.060	1.185

3.2 Reactivity Feedback Coefficients

Let us represent pressure and void coefficients of a boiling water reactor in terms of density coefficient $\gamma_\rho = (d\Gamma_\rho/d\rho)$, where Γ_ρ is density reactivity. Note that Γ_ρ is a function of ρ for water reactors. For the time being, we neglect subscript "r" of ρ_r. In general, a coolant state can be determined by two variables. As the two variables, let us choose p and α, since ISFR is a boiling reactor. Then, we can discuss coolant feedback effects of a boiling reactor in terms of void coefficient γ_α and pressure coefficient γ_p . Coolant density ρ can be expressed such that

$$\rho = (1-\alpha)\,\rho_\ell + \alpha\rho_g \quad . \tag{3}$$

Then, we have

$$(\partial\rho/\partial\alpha)_p = -\rho_\ell + \rho_g \tag{4}$$

and

$$(\partial\rho/\partial p)_\alpha = (1-\alpha)\ d\rho_\ell/dp + \alpha d\rho_g/dp \sim \alpha d\rho_g/dp \quad . \tag{5}$$

Making use of Eqs. (4) and (5), we will express reactivity coefficients as follows. With the help of Eq. (5), we obtain

$$\gamma_p = (\partial\Gamma_\rho/\partial p)_\alpha = \gamma_\rho(\partial\rho/\partial p)_\alpha = \alpha\gamma_\rho(d\rho_g/dp) \ . \tag{6}$$

Similarly, with the help of Eq. (4), we obtain

$$\gamma_\alpha = (\partial\Gamma_\rho/\partial\alpha)_p = -\gamma_\rho(\rho_\ell - \rho_g) \quad . \tag{7}$$

Looking over Eqs. (6) and (7), note that, the sign of γ_p or γ_α is governed by the sign of γ_ρ. Note that for subcooled water, instead of Eq. (6), we have $\gamma_p = (\partial\Gamma_\rho/\partial p)_h = \gamma_\rho(\partial\rho/\partial p)_h$, which is very small.

Table 2 shows the main dynamics parameters to be used in this work. Among them, the density coefficient $\gamma_\rho = -13.9$ \$/($\Delta\rho/\rho$) was obtained for (E_{PU} , E_{MA}) = (0.141, 0.013) corresponding to α = 0.40 in Table 1. Due to $\gamma_\rho < 0$, Eqs. (6) and (7) give $\gamma_p < 0$ and $\gamma_\alpha > 0$, respectively.

Table 2. Main Dynamics Parameters of ISFR

delayed neutron fraction	0.003156 (15 groups)
γ_D	-0.00697 \$/^{O}C
γ_ρ	-13.9 \$/($\Delta\rho/\rho$)
$k_{eff} = f(\rho)$	linearly decreasing
loss of on-site power	q = 0.05
τ_{MCP}	10. s for coast down 100. s for reactor control
τ_{TCV}	0.1 s

Generally speaking, from an economical point of view, a size of an SG is desired to be as small as possible, especially so for an integrated reactors such as ISFR. If γ_α is negative, γ_p is positive and hence the volume of an SG needs to be large enough to have a sufficiently large time constant for the positive pressure feedback. But, for ISFR, due to $\gamma_\alpha > 0$, γ_p is negative and hence ISFR can make use of an indirect cycle with a sufficiently small SG.

4. **TCVs as Passive Switches**

Since a check valve has a form of a switch, the TCVs can be made use of as passive switches of power sources to the pumps, the steam dome heater, and the reactor control system. Note that, in accidents initiated in the primary system, the PTCVs first open and then the STCVs open, while, in accidents initiated in the secondary system, the STCVs first open and then the PTCVs open.

The role that the TCVs play in a primary accident can be explained as follows. Due to the accident, the entire system will be disturbed and hence, for example, Eq. (1) will break down to open the PTCVs. When the PTCVs open, cold IP water passively enters the CPS through the upper or lower honeycomb to decrease the void fraction within the reactor. Since ISFR has a positive void coefficient, a negative reactivity will be introduced to passively shutdown the reactor, although the reactor power first may rise due to $\gamma_\alpha > 0$. Since the opening of the PTCVs brings about a loss of power source, the MCPs start to coast down and hence a natural circulation tends to be established along the path : the lower honeycomb => the reactor => the riser => the upper honeycomb => the IP => (back to the lower honeycomb). In the secondary system, owing to the disturbances,which has been amplified by the pump coastdowns, the STCVs will also passively open to introduce PSSS water into the SG secondary flow. Note that the PSSS acts as a heat sink to damp the disturbances brought about by the accident. Finally, a loss of on-site power takes place and hence the isolation valves in the MS and FW lines passively close to bring about an SG-PSSS isolation. As a result, a secondary natural circulation will be established with the flow path : the lower honeycomb => the SG secondary system => the upper honeycomb => the PSSS tank => (back to the lower honeycomb). For accidents initiated in the secondary system (refer to section 7), similar scenarios are expected to apply except initial transients.

Since the TCVs are check valves, they are to open if

$$|(\Delta p)_{TCV}| > (\Delta p)_{TCV}^{OPN} \quad . \qquad (8)$$

It will be shown in the next section that, during normal operations, owing to stabilization by the reactor controls, $(\Delta p)_{TCV}$ can not help but exhibit small oscillations (Figs. 3, 4 and 6). Let $(\Delta p)_{TCV}^{MAX}$ be the maximum of $|(\Delta p)_{TCV}|$ during normal operations. Then, $(\Delta p)_{TCV}^{MAX}$ must be sufficiently smaller than $(\Delta p)_{TCV}^{OPN}$ so that the TCVs can remain closed. In this work, $(\Delta p)_{TCV}^{OPN}$ will be assumed to be 2.0 kPa for both PTCVs and STCVs.

Note that as long as the system is in transients, openings and closings of the TCVs alternately occur with a finite value of time constant and hence the TCVs remain partially open. Therefore, the TCVs can be regarded as passive irresettable switches to cut the power sources off.

In accidents, the PTCVs and the STCVs help each other speed up an actuation of the ISFR shutdown mechanism in the folowing manner. Suppose that an accident occurs in the secondary system. If the STCVs were not used as switches, then an actuation of the ISFR shutdown mechanism would be delayed, because an opening of the PTCVs satifying Condtion (8) would be delayed.

5. Stabilization by Controls

5.1 Design of Reactor Control System

Let $q_C(t)$ be the target for q(t) to be specified beforehand by the ISFR operator. For example, $q_C(t)$ should be unity for a constant power operation. Test calculations with THYDE-NEU indicated that stabilization by $h_{gap} \sim 1.$ kW/(m^2・^{O}C) along with the TCVs is not sufficient for ISFR even to follow $q_C(t)$ =1. Hence, it was decided to design a reactor control system. First, an MCP speed control was tested. Then, stability was considerably improved, but, as time passed by, the PTCVs eventually opened, because $|(\Delta p)_{TCV}|$ of the superposed oscillation tended to gradually increase and finally exceeded 2.0 kPa. Next, it was tested to control (1) the RP speed to satisfy $(\Delta p)_{STCV} = 0$, (2) the steam dome heater and the reactor inlet valves to satisfy $(\Delta p)_{PTCV} = 0$ and (3) the FW flow rate to decrease with q. In order to use the steam dome heater for reactor control, there must be initial bubbles in the steam dome and hence the spray flow rate must be sufficiently small, whereas the heat input must be sufficiently large. With these controls helping each other, finally, ISFR was sufficiently stabilized. Each control was represented by a first delay operator LAG. Among them, the MCP speed control (Table 3) plays a main role. It was designed in view of the fact that, as MCP speed ω increases, relative reactor power q decreases, because as ω increases, the discharge pressure of the MCPs increases and hence void fraction α in the reactor decreases. From the viewpoint of safety, the time constants of the LAGs should be sufficiently large, i.e., 80s～100 s so that the reactor control system can not jeopardize a rapid actuation of the ISFR shutdown mechanism.

Table 3 MCP Speed Control of ISFR : $dy/dt = (y_c-y)/\tau$

y	objective	y_c	τ
MCP speed ω (relative value)	$q = q_C$	= 0.9 for $(q-q_c)<0$ = 1.1 for $(q-q_c)>0$	100s

5.2 Calculated Power Level Shift

Stabilization by the reactor control system designed above is not capable enough to cope with rapid transients such as sudden loss-of-loads. Therefore, in a reactor power shift, it was assumed that $q_C(t)$ quasi-statically decreases periodically with a sufficiently slow ramp followed by a constant (Fig. 3). Then, THYDE-NEU predicts that, with the help of the reactor control system designed above, $q(t)$ can follow $q_C(t)$ with the small oscillation being superposed (Fig. 3). Figure 4 shows total reactivity, while Fig. 5 shows the steam dome pressure, which slowly decreases. Figure 6 shows the pressure difference across the PTCVs, which keeps unsatisfying Condition (8) as required, in agreement with the fact that ISFR is calculated to keep operating without a shutdown.

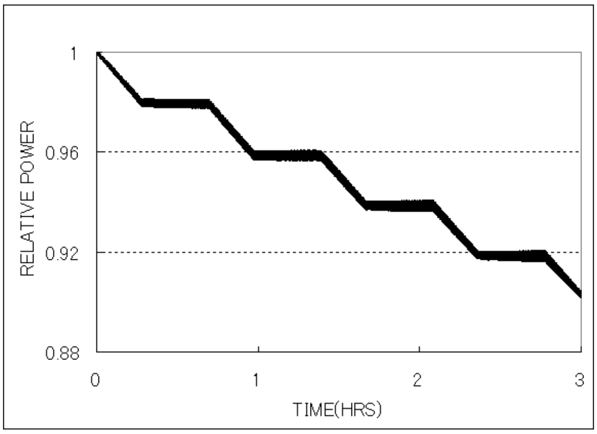

Fig. 3 Reactor Power (Power level Shift)

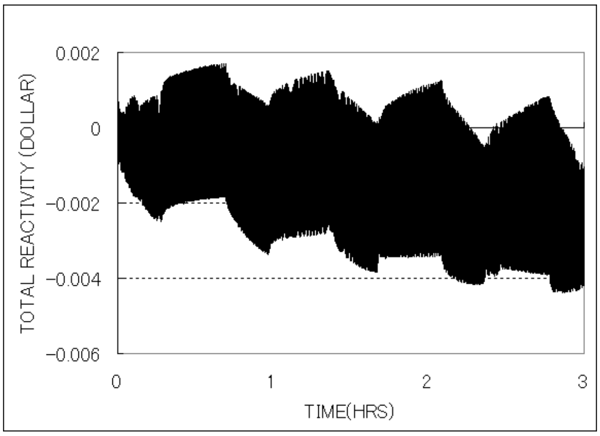

Fig. 4 Total Reactivity (Power level Shift)

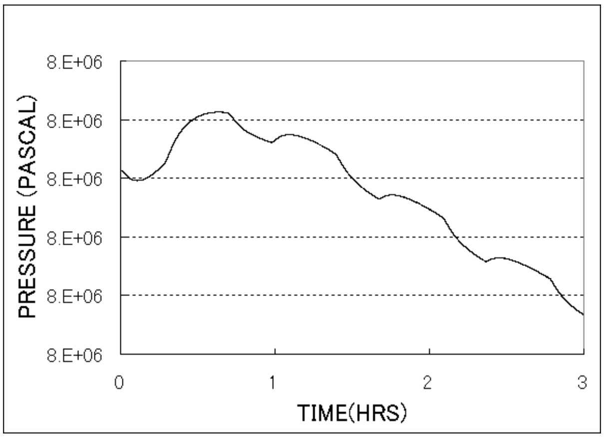

Fig. 5 Steam Dome Pressure (Power Level shift)

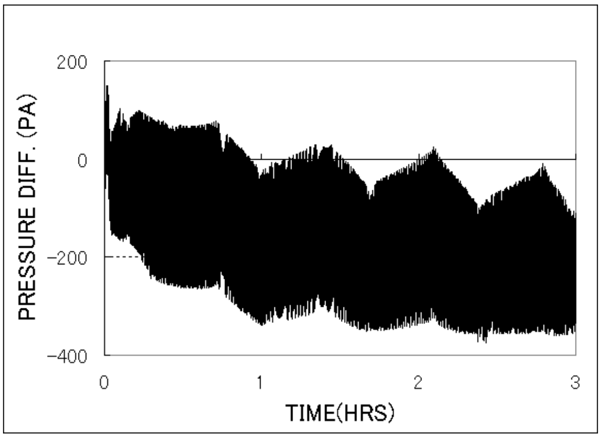

Fig. 6 Pressure Difference across PTCV (Power level Shift)

6. SGTR Analysis

In the following, a scenario of an SGTR calculated with THYDE-NEU for a double-ended rupture of 50 SG tubes is presented. Soon after an occurrence of the SGTR, the break flow rate rapidly increases, while the reactor power rises (Fig. 7) due to $\gamma_\alpha > 0$. At 0.096 s, $|(\Delta p)_{STCV}|$ reaches $(\Delta p)_{TCV}^{OPN} = 2.0$ kPa and hence the STCVs open not only to induce an upward flow (Fig. 8) through the PSSS, but also to trip all the pumps and the heaters as well as the reactor control system. As a result, the PTCVs also open at 0.372 s and hence the cold IP water enters the CPS. Consequently, an induced negative reactivity overrides the positive void feedback and hence the reactor power turns around at 1.15 s and decreases finally to the decay heat level (Fig. 7). As the break flow persists, the secondary pressure increases. When it becomes 6.6 MPa at 4.72 s, the secondary relief valves open (Fig. 9) and hence simultaneously the cover gas pressure in the RCV (Fig. 2) starts to increases (Fig. 10). At 32.8 s, since the relief flow stops, so does the increasing trend of the cover gas pressure. At 58.69 s, a loss of on-site power occurs to isolate the SG-PSSS system and hence a natural circulation tends to be established in the SG-PSSS system (Fig. 8). Note that, without the PSSS, the system responses would be entirely different, since the PSSS helps mitigate the impacts of the accident.

Except initiating events, the calculated scenario is expected to apply to any other accident. That is, it is expected that, in accidents, (1) ISFR passively shuts down to the decay heat level with an SG-PSSS isolation and (2) natural circulations will be established in both the primary and SG-PSSS systems, whose pressures tend to decrease first to saturation pressures of h_{PR} and $h_{SG\text{-}PSSS}$ i.e., 4.75 and 2.85 bars, respectively. Long term system behaviors to be discussed next are expected also to apply to all conceivable accidents, regardless of initiating events.

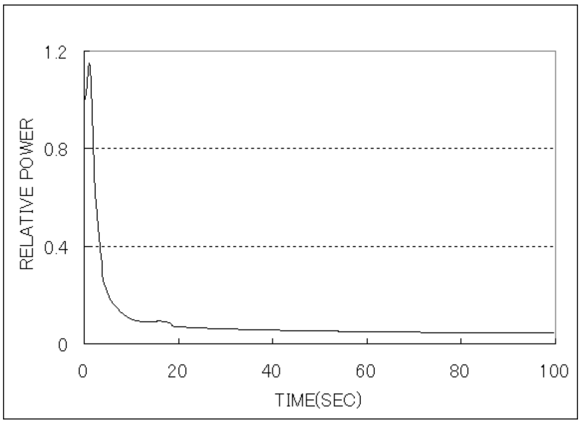

Fig. 7 Reactor Power (SGTR)

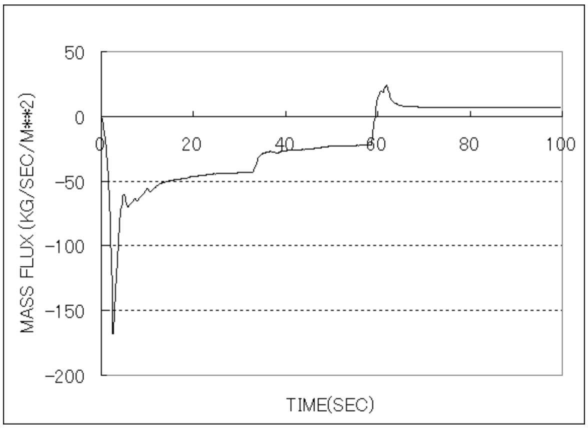

Fig. 8 Mass Flux of PSSS (SGTR)

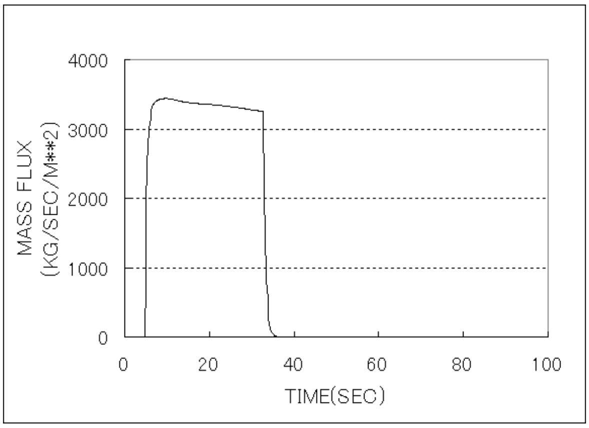

Fig. 9 Secondary Relief Flow (SGTR)

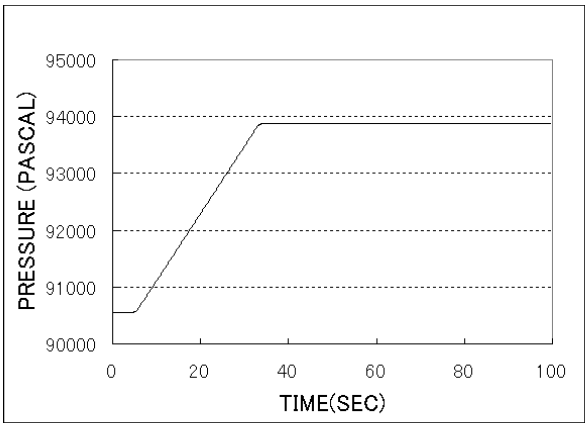

Fig. 10 Cover Gas Pressure (SGTR)

7. **Long Term Cooling after Reactor Shutdown**

In an accident, after the reactor shutdown is completed with an SG-PSSS isolation, the heat pipes (Fig. 2) [4] come into effect to slowly transfer the decay heat from the primary system to the OP and finally to the atmosphere which is the ultimate heat sink. In order to confirm the effect of heat pipes, an MCP trip was calculated with THYDE-NEU until 72.2 hours. The long term system behaviors are quasi-static so that the primary and secondary systems keep being almost at thermal equilibrium with each other, each having the respective natural circulation.

Hence, for example, the primary and secondary pressures behave almost in the same manner, although initially they tend to decrease to their respective saturation pressures, namely, 4.75 and 2.85 bars. The primary pressure is shown in Fig. 11. The outer pool temperature reaches its maximum 63 ^{O}C at 35 hours and then gradually decreases (Fig. 12). Except during initial transients, voids are never generated in the reactor. The fact can be confirmed by looking over the behavior of mass quality at the hot channel exit shown in Fig. 13, which is enlarged in the neighborhood of quality=0. First, it decreases from the initial value 0.801 down to -0.399 at 95.5 s owing to the ingress of cold IP water into the CPS. Then, during the reactor shutdown, it remains negative and hence total reactivity also remains negative (Fig. 14).

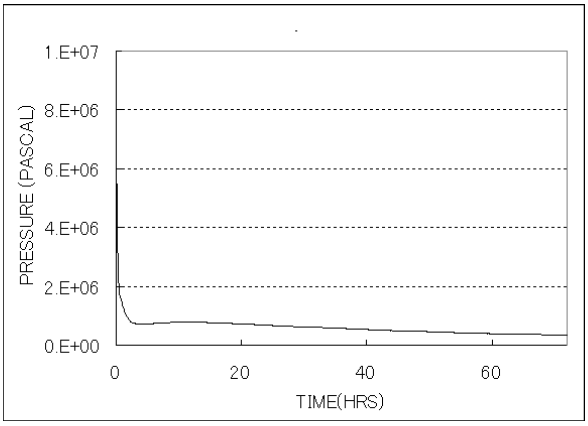

Fig. 11 Primary Pressure in MCP Trip

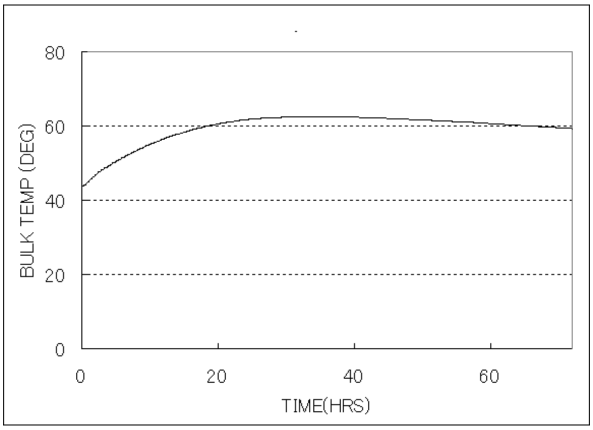

Fig. 12 Outer Pool Temperature in MCP Trip

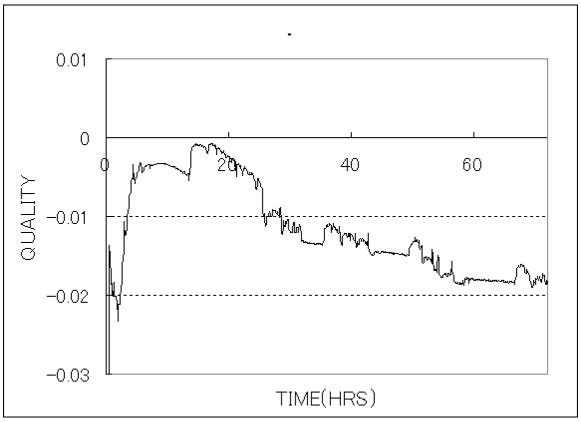

Fig.13 Hot Channel Exit Quality in MCP Trip

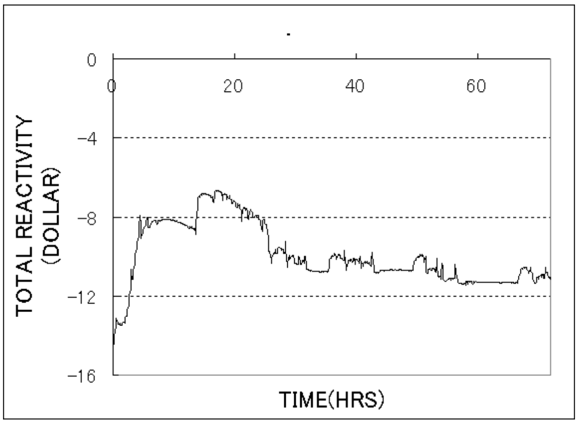

Fig. 14 Total Reactivity in MCP Trip

8. **Conclusions**

The specifications of ISFR were (a) a boiling heavy water reactor with a positive void coefficient, (b) the ISFR shutdown mechanism, (c) fuel breeding in the core, (d) no boron in the primary system, (e) the indirect cycle, (f) the small h_{gap} and (g) the tight lattice. They are related to each other in the following manner. Items (b), (c), (d) and (e) were materialized by item (a), while item (f) made the time constant of the positive void feedback large and hence helped overcome safety and stability problems resulting from item (a). Heavy water used as the moderator and item (g) help each other to harden the neutron spectrum to materialize item (c). Item (e) is preferable from the viewpoint of defense-in-depth regarding safety, because an SG not only acts as a pressure boundary, but also keeps the balance of plant from being contaminated by radioactivity. In spite of item (f), the power density was able to be as large as that of existing PWRs thanks to item (g). Item (d) brings about the following dynamical advantages. Firstly, we need not worry about boron dilution accidents or an increase of γ_α which might occur for a large boron concentration. Secondly, reactor control will be made easier, because, especially for power level shifts, if boron were contained in the IP, it would enter the CPS and hence the reactor control logic might become complicated.

Owing to the positive void coefficient, ISFR is unstable by itself and hence the system was stabilized by means of item (f), the installation of the TCVs and the design of the reactor control system. As a result, it was confirmed that ISFR can perform not only constant power operations, but also power level shifts. During the normal operations, the system responses could not help but exhibit the small superposed oscillations due to the MCP speed control. But, it was confirmed that they are small enough for the TCVs to remain closed. It should be reminded that the system stabilization is not capable enough to cope with rapid transients such as sudden large loss-of-loads. Note also that the reactor control system enables ISFR to automatically cope with burnup compensation of k_{eff}. The fact is another reason why ISFR can do without both control rods and boron in the primary system. It is rather important to note that, in this work, it was shown possible for ISFR to need not satisfy the usual condition of a negative void coefficient, which has been one of the most stringent constraints in neutronics design of water reactors.

In this work, the double-ended rupture of 50 SG tubes was calculated up to 100 s. The reactor power first increased owing to the positive void feedback, but soon turned around and then decreased to the decay heat level with the help of the ISFR shutdown mechanism. In spite of the tight lattice, a departure from nucleate boiling did not take place and hence the fuel temperatures decreased very smoothly to values corresponding to the decay heat.

It is conceivable that if $\gamma_\alpha > 0$ were excessively large, the ISFR shutdown mechanism could not override a positive reactivity feedback. Thus, it is required to obtain the largest possible void coefficient and to confirm that even for the maximum value of γ_α, the ISFR shutdown mechanism can override the positive feedback. Note that the value of γ_α used in this work was considerably large.

In the long term cooling after reactor shutdowns, the heat pipes were found very effective with the help of the small values of h_{PR} and $h_{SG\text{-}PSSS}$. Except initiating events, the accident scenario calculated with THYDE-NEU is expected apply to any other accident conceivable for ISFR. Hence, ISFR is considered to have a very long walk-away period.

Among components to be developed for ISFR are (1) TCVs, (2) MCPs with a sufficiently small net positive suction head and (3) insulator to be placed at the outer surface of the CPS.

As a result of this work, several interesting items to be further investigated were found. Among them are (1) smaller values of volume ratio V_m/V_f, (2) using sodium as the primary coolant and (3) examining if the amount of MAs in ISFRs tends to be saturated or not, when MAs are recycled with fuel reprocessing. The possibility of item (2) stems from the fact that ISFR can do without boron in the primary system.

Appendix A Nomenclature

E	Enrichment or weight fraction
g	Gravitational acceleration (= 9.80 m/s^2)
G	Mass flux (kg m^{-2} s^{-1})
h	Specific enthalpy (kJ/kg)
h_{gap}	Gap conductance (kJ/(m^2 s ^{O}C)
H	Height of the upper hot/cold interface in reference to the lower hot/cold interface (m)
k_{eff}	Effective neutron multiplication factor
K	Form loss coefficient
M	Atomic mass
q	Relative reactor power
$q_C(t)$	Reference relative reactor power
p	Pressure (Pa)
t_W	Walk-away period (days)
V_m/V_f	Volume ratio in neutronics
$(\Delta r)_{gap}$	Gap width (m)
α	Void fraction
κ	Thermal conductivity (kJ/(m s ^{O}C))

$(\Delta p)_{TCV}$ Pressure difference across the two-way check valves (Pa)
ΔT_{sub} Subcooling (^{O}C)
Γ Reactivity ($)
γ_α Void reactivity coefficient ($ $(\Delta\alpha/\alpha)^{-1}$)
γ_D Doppler reactivity coefficient ($ $(^{O}C)^{-1}$)
γ_p Pressure reactivity coefficient ($ $(\Delta p/p)^{-1}$)
γ_ρ Density reactivity coefficient ($ $(\Delta\rho/\rho)^{-1}$)
$\xi\Sigma_S$ Slowing down power (1/cm)
ρ Coolant density (kg m^{-3})
τ Time constant (s)
ω Relative MCP speed

Sub- and super-script

core Refers to the core.
D Refers to the Doppler effect.
DU Refers to depleted uranium.
FW Refers to the feed water.
gap Refers to the fuel gap.
g Refers to a saturated gas.
IP Refers to the inner pool.
ℓ Refers to a saturated liquid.
max Refers to a maximum.
MA Refers to minor actinides.
O Refers to an initial or steady state.
OP Refers to the outer pool.
OPN Refers to a condition to open a valve.
p Refers to pressure.
PR Refers to the primary system.
PTCV Refers to the primary two-way check valves.
Pu Refers to plutonium.
r Refers to the reactor.
riser Refers to the riser.
SG-PSSS Refers to the SG-PSSS system
STCV Refers to the secondary two-way check valves.
sub Refers to subcooling.
α Refers to void.
ρ Refers to coolant density.

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