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CONCEPTUAL DESIGN OF INHERENTLY SAFE FAST REACTOR WITH REACTOR CONTROL SYSTEM

Yoshiro Asahi
Institute of Science and Technology for Society, Japan

ABSTRACT

ISFR is a boiling heavy water fast reactor, which is of process inherent ultimate safety (PIUS) type. Unlike PIUS, however, the primary system of ISFR does not contain boron. ISFR may breed fuel in the core. The fuel contains minor actinides. It is shown that safety and control problems resulting from a positive void coefficient may be resolved by modifying the PIUS concept.

1. **Introduction**

In this work, applying the process inherent ultimate safety (PIUS) [1, 2] concept, we will propose Inherently Safe Fast Reactor (ISFR) (Figs. 1 and 2) [3], which is a boiling heavy water reactor with a positive void coefficient γ_α (>0). Originally, the PIUS concept was intended for applications to pressurized water reactors (PWRs) [1, 4] which have a negative void coefficient γ_α (<0). In this work, it will be shown that the application of the PIUS concept to ISFR is possible, provided that (1) the time constant of void feedback τ_α is sufficiently large, (2) initially closed two-way check valves (TCVs) to be used as passive switches are placed at the lower honeycombs, and (3) the secondary system has the passive safety shutdown system (PSSS, 95 m^3) (Fig. 2) [6], which is an application of the PIUS concept. As a result of $\gamma_\alpha > 0$, unlike the original PIUS, ISFR can do without boron in the primary system. Due to these differences from the PIUS concept, the shutdown mechanism of ISFR will be referred to as the ISFR shutdown mechanism. Owing to γ_α >0, ISFR is unstable by itself. Appropriately designing a reactor control system, we will show that ISFR can be sufficiently stabilized. For long term cooling, refer to Ref. 4. In the discussions in this work, the THYDE-NEU code [5] will play an important role in representing ISFR.

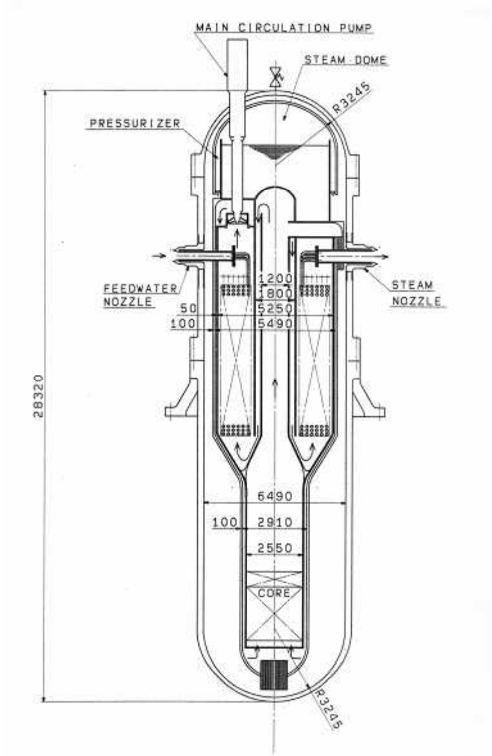


Fig. 1 Cross-section of ISF

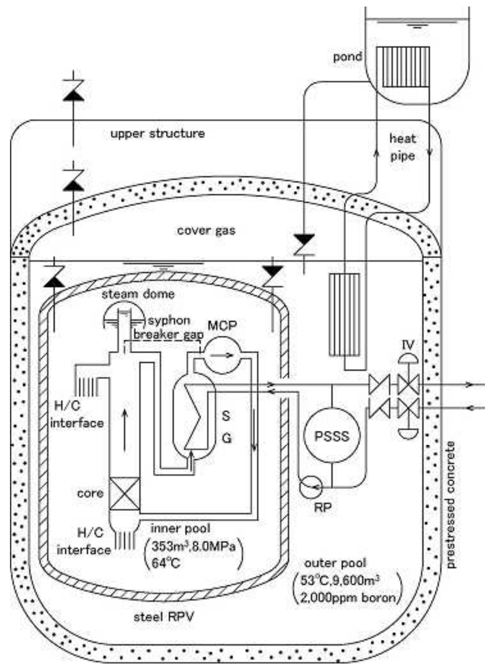


Fig.2 Schematic of ISFR

2. **Overview of ISFR**

ISFR (533 MW_{th}) is loaded with mixed oxide (MOX) fuel. ISFR is an integrated reactor (Figs. 1 and 2) such that the circulating primary system (CPS) is submerged in the inner pool within the RPV (28.3 m in height, 6.49m in diameter, 0.3 m in thickness). The RPV is, in turn, submerged in the outer pool contained in the reactor containment vessel (RCV) (Fig. 2). The helical coil SG consists of 2,000 tubes (27mm x 27mm, 22.2 mm in outer diameter, 16.0 mm in inner diameter, 80 m in length). The TCVs are placed at the lower honeycomb below the reactor as well as the PSSS tank. The former and latter are referred to as the PTCVs and STCVs, respectively. The TCVs are separated into two kinds, namely, the one half allowing upward flows and the other allowing downward flows.

In a PIUS type reactor, the following conceptual relationship at a steady state must be satisfied

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

where

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

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

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

Note that Eqs. (1) and (2) must hold during a constant power operation as well as power level shifts. Strictly speaking, during a constant operation of ISFR, they do not exactly hold, since a small oscillation is superposed (refer to section 6).

The regulating pump (RP) (Fig. 2) is placed to obtain pressure balance of the PSSS configuration. The fuel rods are almost equivalent to those of PWRs, while the lattice is rather tight (volume ratio＝0.643). Each fuel assembly of ISFR has neither a channel box nor an assembly bypass region. 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]. ISFR fuel contains minor actinides (MAs), which help reduce k_{eff}^{max} in a reactor life. This is preferable, since ISFR has neither a chemical shim nor control rods. In this work, we rather arbitrarily let the primary pressure be 80 bars. Given a primary pressure, the breeding ratio depends on subcooling ΔT_{sub} at the reactor inlet. In this work, ΔT_{sub} at the reactor inlet is 5.4 ^{O}C, while subcooling at the main coolant pump (MCP) inlet is 29.0 m in head. Let h_{PR} and $h_{SG\text{-}PSSS}$ be average specific enthalpies of the primary system and the SG-PSSS, respectively. Then, h_{PR} and $h_{SG\text{-}PSSS}$ are calculated to be 629.9 kJ/kg and 551.8 kJ/kg, whose saturation pressures are 4.7 bars and 2.85 bars, respectively. ISFR does not have assembly bypass flows, but has the reactor bypass flow, which flows 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 can breed within the reactor. The TCVs are closed during a steady state and will be made use of as passive switches.

Owing to $\gamma_\alpha > 0$, it is required that its time constant τ_α is sufficiently large so that ISFR can be sufficiently stable. If we wish to make τ_α large, we should make, for example, h_{gap} small. Gap conductance h_{gap} can be expressed approximately as $\kappa_{gap} / (\Delta r)_{gap}$, where κ_{gap} is inversely proportional to $(M_{gap})^{1/2}$. Hence, Ar is used as the gap gas. In this work, we assume h_{gap} = 1. kW/($m^2 \cdot {}^oC$), which is smaller than that of existing LWRs, namely, about 5. kW/ ($m^2 \cdot {}^oC$) . Note that, for h_{gap} = 1. kW/ ($m^2 \cdot {}^oC$) and peaking factor = 2.2 in the core, the peak fuel temperature of ISFR turns out to be almost the same as in LWRs, since the linear heat rate in the core is rather small (~ 8.35 kW/m).

3. **Neutronics and Positive Void Feedback**

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

Preliminary 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 of UO_2 fuel in PWRs (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 the 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 takes place and hence burnable poisons should be used.

After mathematical manipulations, we can obtain

$$\gamma_p = \alpha \gamma_\rho (d\rho_g/dp) \quad , \qquad (3)$$

and

$$\gamma_\alpha = -\gamma_\rho (\rho_\ell - \rho_g) \quad . \qquad (4)$$

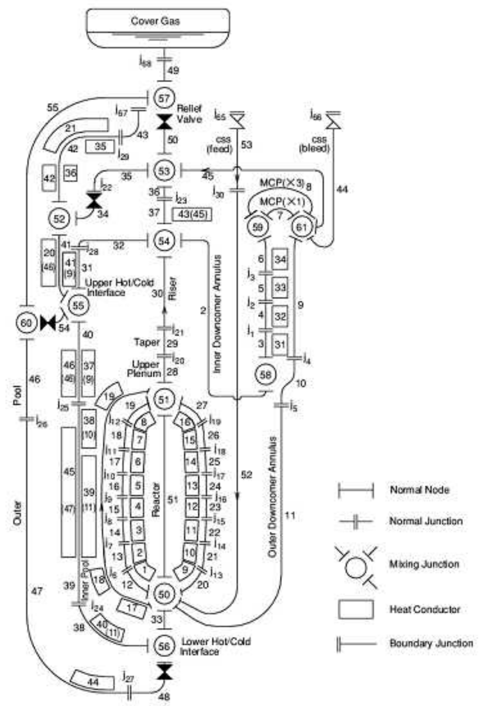
Looking over Eqs. (3) and (4), note that, the sign of γ_p or γ_α depends on the sign of γ_ρ. The density coefficient γ_ρ = -13.9 \$/($\Delta\rho/\rho$) shown in Table 2 was obtained for (E_{PU} , E_{MA}) = (0.141, 0.013) corresponding to α = 0.40 in Table 1. Throughout dynamics calculations in this work, this value for γ_ρ will be used. Due to γ_ρ <0 (Table 2), Eq. (4) gives γ_α > 0, while Eq. (3) gives γ_p<0. Owing to γ_p<0, ISFR can use an indirect cycle.

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(ρ)	linearly decreasing
loss of on-site power	n = 0.05
τ_{MCP}	10. s for coast down 100. s for reactor control
τ_{TCV}	0.1 s

4. **THYDE-NEU Representation of ISFR**

The primary system and the SG-PSSS are nodalized as shown in Figs. 3 and 4, respectively. Prior to transient calculations with THYDE-NEU, we perform adjustment calculations [5] to obtain an initial steady state of ISFR, which satisfy, for example, Eqs. (1) and (2). Among the adjustments is to multiply a spatially uniform factor to the SG heat transfer area. The factor turned out to be 1.108.



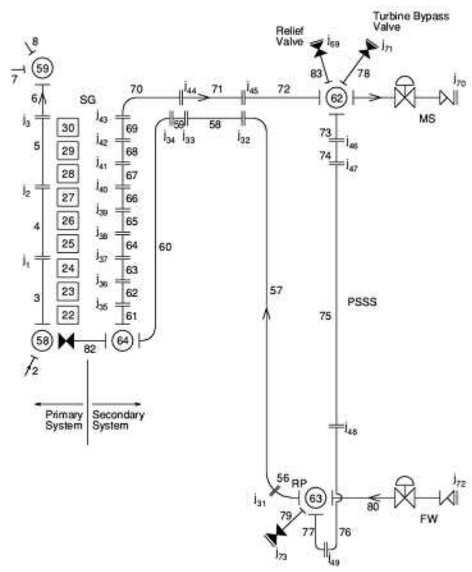


Fig.3 Noding of ISFR
(Primary System and Outer Pool)

Fig. 4 Noding of ISFR
(SG Secondary System and PSSS)

5. **TCVs as Passive Switches**

Since a check valve has a form of a passive switch, we will make use of the TCVs as passive switches for the pumps, the steam dome heater and the reactor control system so that a reactor shutdown can take place soon enough to suppress the positive void feedback. Since the TCVs are check valves, they are to open if

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

ISFR can not help but exhibit a small superposed oscillation (refer to section 6). Let $(\Delta p)_{TCV}^{MAX}$ be the maximum of $|(\Delta p)_{TCV}|$ during a constant power operation. Then, $(\Delta p)_{TCV}^{OPN}$ should be sufficiently larger than $(\Delta p)_{TCV}^{MAX}$ so that the TCVs can remain closed. Note that they must also remain closed during a power level shift. In this work, $(\Delta p)_{TCV}^{OPN}$ will be assumed to be 2.0 kPa for both PTCVs and STCVs. As $(\Delta p)_{TCV}^{OPN}$ decreases, safety increases, whereas difficulties in startup and operation increase.

6. **Design of Reactor Control System and Power Level Shift**

Let $n_C(t)$ be the target for n(t). For example, $n_C(t)$ should be unity for a constant power operation. Test calculations with THYDE-NEU indicated that h_{gap} ~ 1. kW/($m^2 \cdot {}^OC$) and TCVs do not stabilize ISFR enough to follow $n_C(t)$ =1, for example. Hence, it was felt necessary to further stabilize the system by designing controls for the MCPs, the RP, the steam dome heater, the FW and the core inlet valves. Each of them was represented by a first delay operator. It was found that the resultant controls help each other stabilize ISFR. The MCP speed control playing a main role alone does not suffice, but the other controls also are needed to make $(\Delta p)_{TCV}$ vanish, for example.

Among them, the MCP speed control will be done as follows. Note that as MCP speed ω increases, relative reactor power n decreases, because as ω increases, the discharge pressure of the MCPs increases and hence void ratio α in the reactor decreases. In view of this fact, we can decide the logic as shown in Table 3.

Table 3 MCP Control of ISFR

$$dy/dt = (y_c - y)/\tau$$

y	objective	y_c	τ
MCP speed ω (relative value)	$n = n_C$	= 0.9 for $(n - n_c) < 0$ = 1.1 for $(n - n_c) > 0$	100s

In the following, with the help of the reactor control system thus designed, ISFR can shift its power, provided that n_C (t) is suitably given. During a power shift of ISFR, $|(\Delta p)_{TCV}|$ should be kept less than $(\Delta p)_{TCV}^{OPN}$ = 2 kPa so that not only an ISFR shutdown can be avoided, but also the ISFR shutdown mechanism can be ready to come into effect, whenever an accident should happen. Therefore, during power level shifts, $n_C(t)$ must change quasi-statically so that Eq. (1) and Eq. (2) can practically hold. It was found, as shown in Figures 5 and 6, that if $n_C(t)$ changes sufficiently slowly, reactor power n(t) can follow it with the small oscillation being superposed.

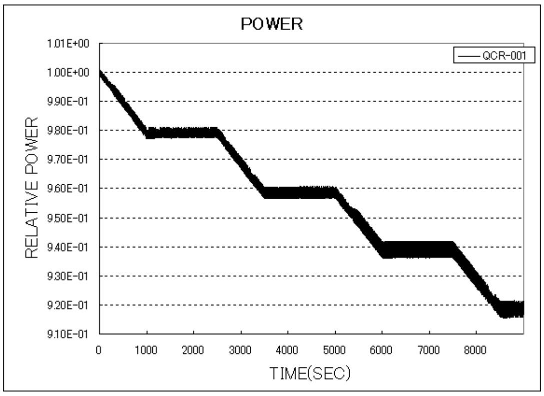


Fig. 5 Reactor Power (Power level Shift)

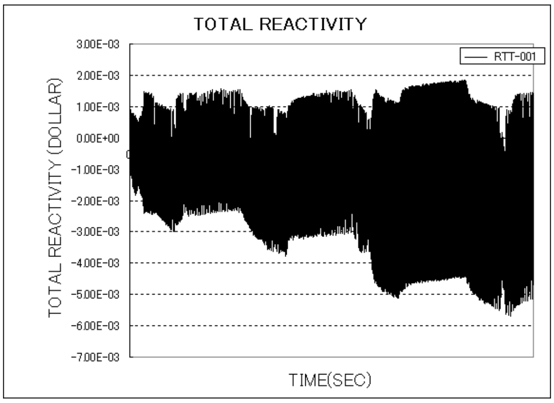


Fig. 6 Total Reactivity (Power level Shift)

7. **SGTR Analysis**

In the following, we will present the scenario of an SGTR calculated with THYDE-NEU for a double-ended rupture of 50 SG tubes. Soon after the occurrence of the SGTR, the break flow rate rapidly increases, while the reactor power rises (Fig. 7) due to the positive void feedback. At 0.07 s the STCVs open not only to induce an upward flow through the PSSS, but also to trip all the pumps as well as the reactor controls. Then, the PTCVs also open at 1.236 s and hence the cold inner pool water enters the CPS. Thus, the reactor power decreases to the decay heat level (Fig. 7). At 66.4 s, a loss of on-site power occurs to isolate the SG-PSSS and hence the natural circulation tends to be established in the SG-PSSS (Fig. 8).

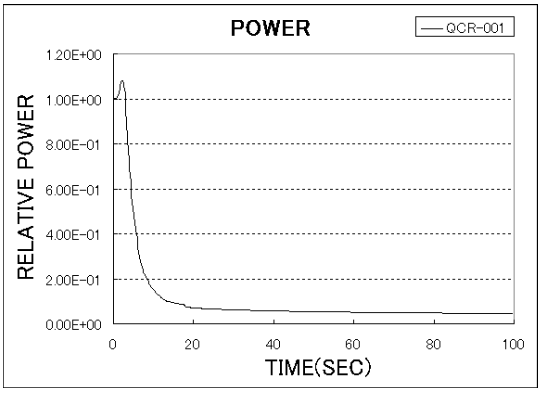


Fig. 7 Reactor Power (SGTR)

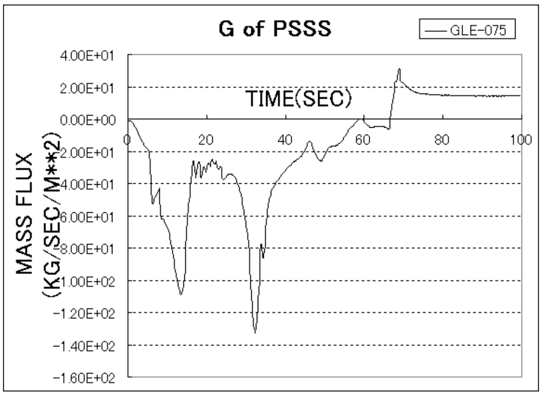


Fig. 8 Mass Flux of PSSS (SGTR)

8. **Conclusions**

The specifications of ISFR were (a) a positive void coefficient, (b) the ISFR shutdown mechanism, (c) fuel breeding in the core, (d) no boron in the primary system, (e) a sufficiently small h_{gap} and (f) the indirect cycle. Item (a) had big influences on all the other items such that items (c), (d) and (f) were advantages resulting from item (a), while items (b) and (e) were implemented to overcome safety and stability problems resulting from item (a). In this work, it was able to do without satisfying the usual condition of a negative void coefficient, which has been one of the biggest constraints in neutronics design.

It was shown that the reactor control system designed in this work enables ISFR to perform not only a constant power operation, but also power level shifts as well as burnup compensation of k_{eff}. The control system designed in this work consist of a set of first delay operators. It could be refined by an application of modern control theory.

In this work, the double-ended rupture of 50 SG tubes was analyzed up to 100 s. The reactor first increased due to the positive void feedback, but then decreased due to 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. It was expected that the heat pipes would come into effect in the long run.

It is possible to reduce the height of the RPV for the following reasons. Given a vessel material, the maximum allowable diameter of the vessel is inversely proportional to the pressure. At present, ISFR uses the RPV of IRIS [4] whose primary pressure is 150 bars and hence the diameter of the RPV can be about twice as large. As a result, the height of SG can be smaller. The other reason results from Eq. (1). Unlike IRIS, the riser coolant is two-phase and hence ρ_{riser} is significantly smaller. Thus, for the fixed right hand side, with a large $\Delta\rho$, Eq. (1) gives a significantly smaller H. Note that the reactor power can be larger with an increased diameter of the RPV.

Conventional components seem to suffice for development of ISFR, except (1) the TCVs and (2) the thermal insulator at the outer wall of the vessel between the CPS and the inner pool. We need to perform further investigations in order to prove that ISFR is inherently safe with a sufficiently large walk-away period.

Appendix A References

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Appendix B 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}	ffective neutron multiplication factor
K	Form loss coefficient
M	Atomic mass
n	Relative reactor power
$n_C(t)$	Reference relative reactor power
p	Pressure (Pa)
$(\Delta r)_{gap}$	Gap width (m)
α	Void fraction
$(\Delta p)_{TCV}$	Pressure difference across the two-way check valves (Pa)

ΔT_{sub}	Subcooling	(^{O}C)
κ	Thermal conductivity	(kJ/(m s ^{O}C))
γ_{α}	Void reactivity coefficient	($ $(\Delta\alpha/\alpha)^{-1}$)
γ_{D}	Doppler reactivity coefficient	($ $(^{O}C)^{-1}$)
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 feedwater.
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.
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.