A COMPARATIVE STUDY OF KINETICS OF NUCLEAR REACTORS

by

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The paper deals with the study of reactivity initiated transients to investigate major differences in the kinetics behavior of various reactor systems under different operating conditions. The article also states guidelines to determine the safety limits on reactivity insertion rates. Three systems, light water reactors (pressurized water reactors), heavy water reactors (pressurized heavy water reactors), and fast breeder reactors are considered for the sake of analysis. The upper safe limits for reactivity insertion rate in these reactor systems are determined. The analyses of transients are performed by a point kinetics computer code, PKOK. A simple but accurate method for accounting total reactivity feedback in kinetics calculations is suggested and used. Parameters governing the kinetics behavior of the core are studied under different core states. A few guidelines are discussed to project the possible kinetics trends in the next generation reactors.

Key words: reactor kinetics, reactivity feedback, reactivity insertion rates, reactor safety, reactivity initiated transients

INTRODUCTION

The discovery of fission of nuclei with large mass number and consequently large energy release opened the gate for large energy resource for the mankind. Subsequently to the demonstration of achieving sustained fission chain reaction in Chicago pile in 1942, different reactor concepts, to convert nuclear energy into electricity, evolved. Countries with an enrichment facility, by and large, opted for light water reactors (LWR) and those without this facility opted for natural uranium based reactors (CANDU/pressurized heavy water reactors). Later, based on the choice of different moderators and coolants, other systems such as gas cooled reactors, graphite moderated reactors, *etc*. were developed. However, considering economics, safety, and technical feasibility, three concepts have emerged as the dominant concepts of these reactors; *i. e*, LWR (PWR and BWR), PHWR/CANDU, and fast breeder reactors (FBR). Some of the basic differences in core physics design make them different in terms of kinetic their behavior. This paper highlights the differences in the kinetics behavior of these three systems under various core states. This comparative study can also provide a better insight in judging the kinetics behavior of alternate reactor core concepts that may come up in future. The study is restricted to small reactivity addition rates that are important from operation view point. Analysis is extended to investigate the upper safe limit of reactivity insertion rate in these reactors based on safety criteria.

In the next section, the methodology of the kinetics calculations is explained. In the section on comparative kinetics study, factors affecting the kinetics are discussed in detail, and, based on that, the comparative kinetics behavior of different type of reactors is discussed. Limits of safe reactivity insertion rates have been investigated using operational and design safety criteria in the section on safe reactivity insertion. Possible kinetic trends of the next generation reactors are discussed in the section on advanced reactor systems, and results are summarized in the last section.

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METHODOLOGY

The reactor power behavior under transient conditions is studied through a numerical solution of the conventional point kinetics equations. The point kinetics equations for six delayed groups are

$$\frac{\mathrm{d}P(t)}{\mathrm{d}t} = \frac{\rho(t) - \beta}{\Lambda} P(t) + \sum_{i=1}^{6} \lambda_\mathrm{i} C_\mathrm{i} + S(t) \quad (1)$$

$$\frac{\mathrm{d}C_\mathrm{i}(t)}{\mathrm{d}t} = \frac{\beta_\mathrm{i}}{\Lambda} P(t) - \lambda_\mathrm{i} C_\mathrm{i}(t) \quad i = 1, 2, \ldots 6 \quad (2)$$

The appropriate initial conditions that apply to eqs. (1) and (2) are based on the assumption that transient is initiated from a steady-state, *i. e.*,

$$\frac{\mathrm{d}P}{\mathrm{d}t} = 0 \quad \text{and} \quad \frac{\mathrm{d}C_i}{\mathrm{d}t} = 0$$

This gives,

$$P(0) = P_0, \quad C_\mathrm{i}(0) = \frac{\beta_i}{\lambda_\mathrm{i}\Lambda} P_0$$

Equations (1) and (2) are a system of coupled ordinary differential equations. These equations are stiff and pose severe problems in numerical solution. Numerical scheme demands a very fine grid in time domain. Significant research has been done to address the problem of stiffness in the field of reactor kinetics. In this study, a modified Runge-Kutta method, devised and implemented by Sanchez [1] has been used [2] to derive the solution of the set of differential equations. This method constitutes an easy to implement algorithm that provides results with sufficient accuracy for most applications. The main advantage of this method is that it allows systematic time step size control and the estimation of the truncation error is possible at each time step. The verification of the kinetics code, PKOK, has been carried out against the sample problems discussed in ref. [1]. The time dependent reactivity has been estimated by taking into account the combined effect of external reactivity and feedback reactivity. That is

$$\rho(t) = \rho_\mathrm{ex}(t) + \rho_\mathrm{fb}(t)$$

In this analysis, the feedback reactivity has been calculated through the use of the dynamic power coefficient of reactivity and feedback reactivity time constant. If α is the power coefficient of reactivity (in pcm/MW_t) and ΔP is the incremental change in power (in MW_t), and τ is the feedback time constant, then the feedback reactivity, ρ_fb (in pcm), can be calculated as

$$\rho_\mathrm{fb}(t) = \int_0^t k_\mathrm{p}(t - \lambda) \Delta P(\lambda)\,\mathrm{d}\lambda$$

where $k_\mathrm{p}(t) = (\alpha/\tau)\mathrm{e}^{-t/\tau}$, is the impulse response function of the reactor, $\Delta P(\lambda) = P(\lambda) - P(0)$, $P(\lambda)$ is the power at anytime λ, and $P(0)$ is the power at the time $t = 0$. The typical values of time constants for fast and thermal reactors are given in ref. [3]. As mentioned above, the kinetics of three systems, PHWR, PWR, and FBR, are studied, and the core physics design details of these systems in the context of kinetics parameters are briefed in the following for the sake of completeness.

PHWR: The Indian PHWR (pressurized heavy water reactor) is a tube type reactor using heavy water as both coolant and moderator [4]. Use of high quality heavy water allows natural uranium (in oxide form) to be used as fuel. Because of very high moderation ratio and small moderating power, the thermalization time is quite large in heavy water systems. This feature enlarges the prompt neutron lifetime by a factor of 25 compared to conventional LWR. The coolant is physically separated from the moderator by being contained inside the pressure tube where it is maintained at high temperature (~280 °C) and pressure (~95 bar). The moderator heavy water is at relatively low temperature (~60 °C) and is unpressurised. The circuits of coolant and moderator are separated, the system is overmoderated, this results in positive void coefficient. In an equilibrium core, 40% of the fission energy comes from plutonium; therefore the equilibrium core delayed neutron fraction value of PHWR is relatively small and the magnitude of Doppler coefficient is also smaller. Thus the overall reactivity feedback effect is poor in case of PHWR. A large uranium oxide mass associated with PHWR results in large feedback delay compared to light water systems.

For the sake of analysis, a standard 540 MW_e (1730 MW_t) Indian PHWR equilibrium core is considered and analyzed. Typical data used in the analysis are: reactor power: 1730 MW_t (for 540 MW_e core), 768 MW_t (for 220 MW_e core), power coefficient: –0.11 pcm/MW_t (for 540 MW_e core), –0.44 pcm/MW_t (for 220 MW_e core), time constant: 5 s for 540 MW_e core, 3 s for 220 MW_e core, delayed neutron fraction – 0.00532, neutron lifetime – $0.8 \cdot 10^{-3}$ s, effective neutron lifetime – $63 \cdot 10^{-3}$ s, and average core power density: 8.5 kW/l.

The effective neutron life time (l_eff), which is used to understand the kinetics behavior in gross, is given by

$$l_\mathrm{eff} = (1 - \beta_\mathrm{eff}) \cdot \text{prompt neutron life time} + \beta_\mathrm{eff} \cdot \text{delayed neutron life time}$$

PWR: A standard VVER of 1000 MW_e capacity, being constructed in India [5] is taken as representative of pressurized water reactors. VVER reactors belong to the class of PWR with triangular lattices fuel pins. They use slightly enriched (3-4%) uranium (oxide form) fuel with pressurized water (~157 bar) as the coolant and moderator. High moderating power of light water and small fuel pin pitch makes neutron lifetime small in case of PWR compared to PHWR. Relatively large Doppler feedback effect (due to harder neutron spectrum compared to PHWR) and negative void coefficient also result in a reasonably strong negative power coefficient. A small uranium oxide mass also results in small feedback delay compared to

PHWR. Following data for equilibrium core are used for the kinetics analysis: reactor power: 3000 MW_t (1000 MW_e), power coefficient: –0.4 pcm/MW_t, delayed neutron fraction – 0.0064, neutron lifetime – – 30 $^{-3}$ s, effective neutron lifetime – 69 $^{-3}$ s, time constant – 3 s, average core power density – 107 kW/l.

FBR: Fast breeder reactors are designed to operate in the fast neutron spectrum and therefore practically do not have the moderator. A typical 500 MW_e Prototype Fast Breeder Reactor (PFBR) being constructed in Kalpakkam, India, is considered for the sake of analysis [6]. It has 20-30% enriched mix oxide (uranium oxide and plutonium oxide) fuel and liquid sodium as the coolant. The power coefficient in FBR is mainly due to Doppler coefficient as the coolant reactivity feedback effect is poor. Following data are used for the kinetics analysis: reactor power: 1250 MW_t (500 MW_e), power coefficient: –0.7 pcm/MW_t, delayed neutron fraction – 0.0034, neutron lifetime – 0.39 $^{-6}$ s, effective neutron lifetime – $0.28 \cdot 10^{-3}$ s, time constant – 1.5 s, average core power density – 350 kW/l.

COMPARATIVE KINETICS STUDY

The reactor parameters that influence the kinetic behavior are delayed neutron fraction, prompt neutron life time, neutron source strength, feedback reactivity and its time constant, and the operational state of the reactor. These governing parameters have different weight in different operating states of the reactor. Governance of different kinetics parameters under different phases is discussed in this section and then used to compare the behavior of different reactor systems. A case study is done for a typical 540 MW_e PHWR core and then other systems are compared.

Kinetics in subcritical phase

To investigate the effect of kinetics parameters on the kinetics behavior of the reactors in subcritical state, a kinetics study is carried out by fixing the neutron source strength. Transient is initiated at 10 $ (53.2 mk) subcriticality and it is assumed that the reactor is initially in steady-state at the neutron source. Power is assumed to be 1 W at the beginning of the transient. A reactivity initiated transient of 2 cents/s (10.64 pcm/s) reactivity addition is considered for analysis. Criticality is achieved in 500 s. The effect of delayed neutron fraction on kinetics is shown in fig. 1. In the deep subcritical state (say 3-10 $), kinetics is governed by the source strength. In the present analysis, a fixed neutron source which obviously linearizes the kinetics behavior is considered. The exponential behavior of kinetics is expected near to criticality only, which is clearly shown in fig. 1. Figure 1 also shows that the kinetic behavior of the reactor is weakly dependent on prompt neutron life-

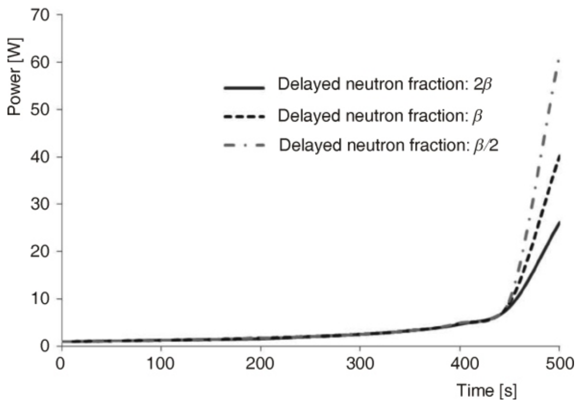

Figure 1. Effect of delayed neutron fraction in subcritical phase of kinetics

time. The dependence is governed mainly by the net effective neutron lifetime which is dominated by delayed neutron lifetime. However close to criticality, a higher delayed neutron fraction slows down the kinetics which ultimately affects the reactor power and period at criticality. The power at criticality is proportional to the neutron source strength. Higher the reactivity addition rate, lower is the power at criticality and lower will be the reactor period. However, the power and period at criticality can be controlled by approaching the criticality in steps.

Kinetics at low power

At low power operation, reactivity feedbacks are absent. A case study is done with the reactivity insertion rate of 20 pcm/s (4 Cents/s) to assess the effect of delayed neutron fraction and neutron lifetime. The results are shown in figs. 2 and 3. It can be seen that the prompt neutron lifetime does not affect the kinetics in the initial small super criticality, but starts affecting it as the super criticality increases. The delayed neutron fraction affects the kinetic behavior of a system signif-

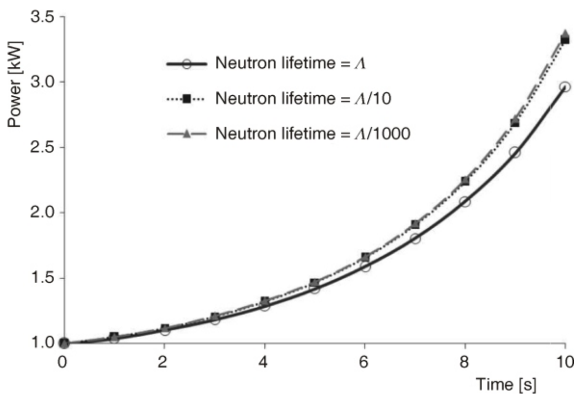

Figure 2. Effect of neutron lifetime at low power

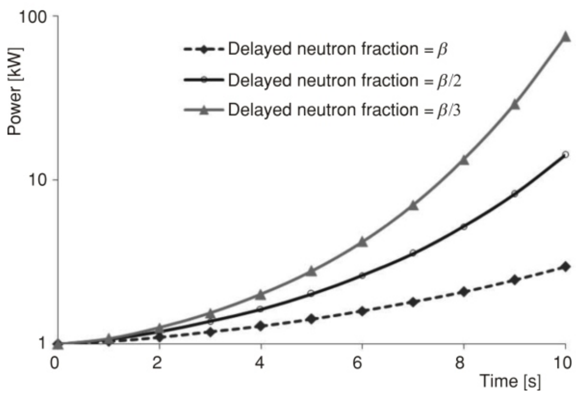

Figure 3. Effect of delayed neutron fraction at low power

icantly. Smaller the delayed neutron fraction, faster the kinetics (rate of power rise) is.

A reactivity initiated transient (RIT) with 3 Cents/s of reactivity insertion is studied to compare the kinetics of different core systems, and the results are reported in figs. 4 and 5. Figure 4 clearly shows that when there is no feedback effect (at low power operation), large neutron lifetime in case of PHWRs makes the kinetics slow, and kinetics is faster in PWR and FBR because of smaller effective neutron lifetime. It is noticed that the kinetics of FBR is slower than VVER. It is mainly due to the fact that the reduction in neutron lifetime does not make difference as the delayed neutron effect is dominant (see fig. 2). Further, 3 Cents/s for FBR is 10 pcm/s, whereas it is 20 pcm/s for VVER. Therefore, the rise in supercriticality is slower for FBR and hence slower the kinetics. The effect of neutron lifetime and delayed neutron fraction can be explicitly understood from the case study of reactivity initiated transient with 20 pcm/s for the both cores. This is shown in fig. 5, which shows that kinetics of a fast reactor is faster than the kinetics of VVER.

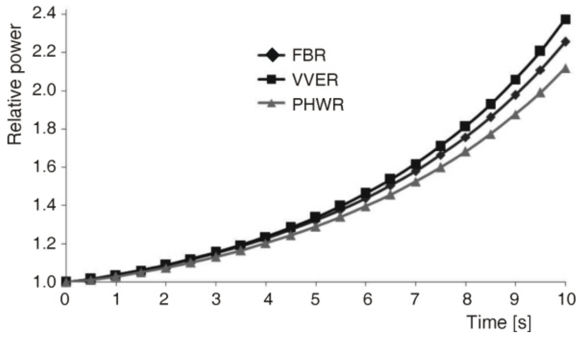

Figure 4. Comparative kinetics behavior (low power)

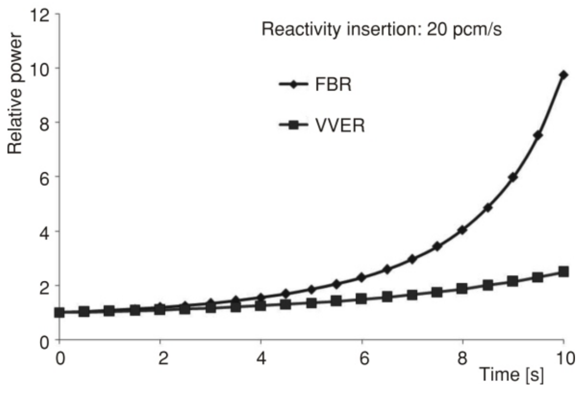

Figure 5. VVER *vs*. FBR (low power)

Kinetics at high power

At high power operation, reactivity feedbacks are effective; therefore, the relative importance of delayed neutron fraction and neutron lifetime is poor. A case study is carried out with the reactivity insertion rate of 20 pcm/s (4 Cents/s) to assess the effect of different parameters at high power. The results are shown in figs. 6, 7, 8, and 9. Figure 6 shows that at high power the effect of neutron lifetime is very small. Figure 7 shows that delayed neutron fraction affects the kinetics but the effect is not as strong as seen in case of low power (fig. 3). The kinetics governance of feedback parameters at high power operation can be understood from figs. 8 and 9. A strong negative power coefficient slows down the kinetics. Reactor cores which have

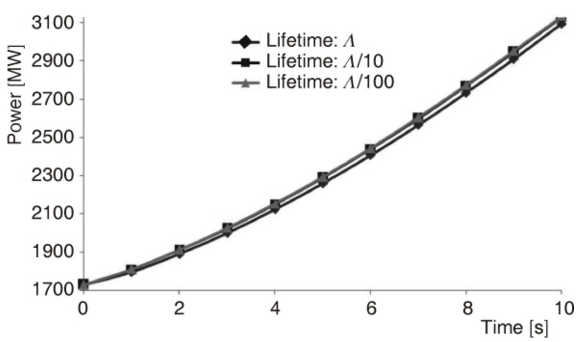

Figure 6. Effect of neutron lifetime (Λ) at high power

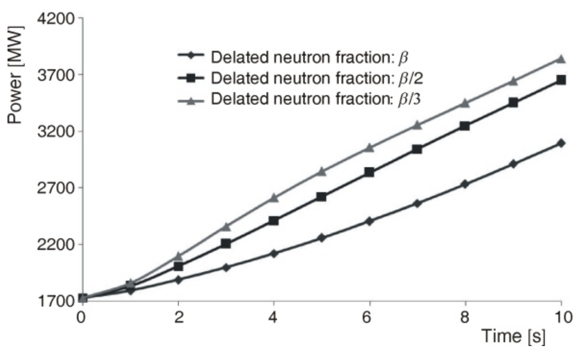

Figure 7. Effect of delayed neutron fraction (β) at high power

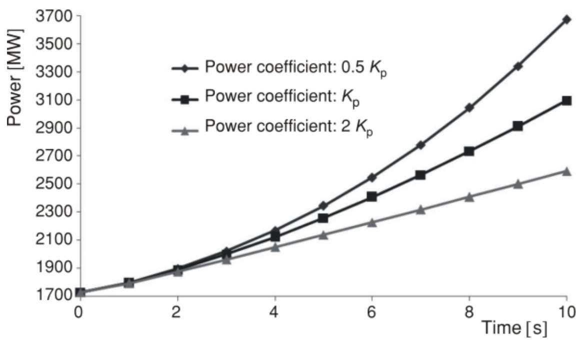

Figure 8. Effect of power coefficient (K_p)

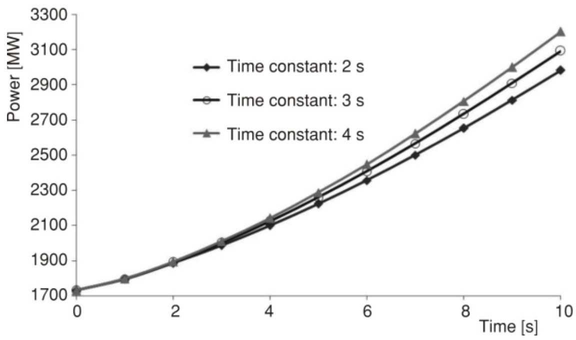

Figure 9. Effect of time constant (τ)

small thermal inertia (like FBR) have smaller delay in the reactivity feedback and therefore have relatively slower kinetics at high power operation. Table 1(a) and 1(b) show the quantitative effect of feedback parameters. The tables give the time in which 110% and 115% power is achieved. Table 1(a) shows that a 100% rise in power coefficient increases the overshoot time by 15% for power rise from 110% to 115%. Similarly, a 40% rise in time constant decreases the overshoot time by 2% for the power rise from 110% to 115%.

Among the three systems considered, *i. e.*, PHWR, VVER, and FBR, FBR has strong negative feedback characteristics; hence, it shows a slower kinetics (fig. 10). In this analysis, large sized LWR (VVER) is considered, hence one can note an interesting observation that the high power kinetics of VVER-1000 is faster than FBR 500. Had two systems been of identical capacity (say 500 MW_e), the results

Table 1(a). Effect of power coefficient on power overshoots

Power level [%]	Time [s] at wich power level is achieved for different power coefficients K_p		
	0.5 K_p	K_p	2 K_p
100	0.0	0.0	0.0
110	2.01	2.06	2.17
115	2.70	2.79	3.01

Table 1(b). Effect of feedback delay constant on power overshoots

Power level [%]	Time [s] at wich power level is achieved for different time constants τ		
	$\tau = 3$	$\tau = 5$	$\tau = 7$
100	0.0	0.0	0.0
110	2.12	2.06	2.04
115	2.90	2.80	2.75

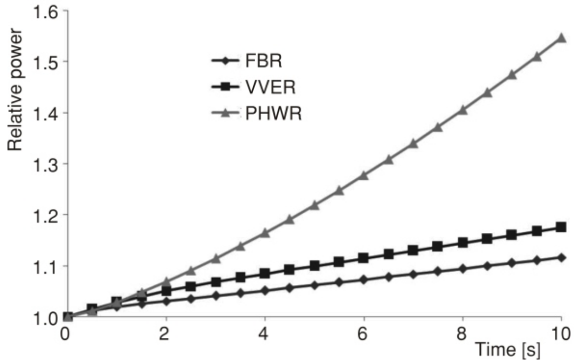

Figure 10. Comparative kinetics behavior (high power, 3 Cents/s)

would have been different because a small PWR/VVER (of about 500-600 MW_e capacity) could have power coefficient as high as –1 pcm/MW_t as power defect (which is the reactivity load incurred in raising the power of a critical reactor from hot zero power state to full power) is maintained constant in such core designs.

Feedback effect is poor in case of PHWR and the power coefficient of PHWR is small due to highly soft neutron spectrum and large seized core and it comes down with burnup due to plutonium buildup. Feedback delay is also large due to the enormous thermal mass (about 60 kg/MW_t, small core power density).

At high power, small core shows slower kinetic behavior compared to larger cores (fig. 11). This is due to small time constant and larger negative power coefficient, *e. g.*, PHWR-540 is about 3 times more bulky than PHWR-220; therefore, it will obviously have large thermal inertia and large feedback delay thereof. Thus a large feedback constant and small power coefficient (due to the large size, as explained above) will result in faster kinetics of large cores.

Reactor SCRAM and shut down

The low feedback characteristic is advantageous during SCRAM. Due to poor feedback, PHWRs respond quickly to the SCRAM reactivity as shown in fig. 12. Therefore, for slow SCRAM operations (*e. g.* slow boron

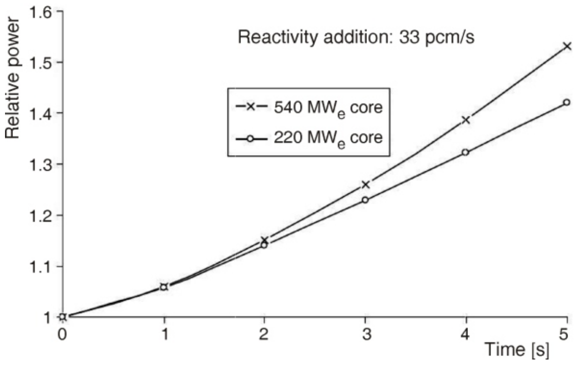

Figure 11. Core size effect (high power)

injection), PHWRs will attain safe shutdown state more rapidly without excess feedback resistance. However, in reactor protection systems, this feature will not be effective as shut down system worth of reactor protection systems is much larger (about 50 mk) than the total power defect (it is about 10 mk in LWR, 2-6 mk in PHWR) in any core design. This can be understood from fig. 13, where large SCRAM reactivity brings down the power to 10% level within a second.

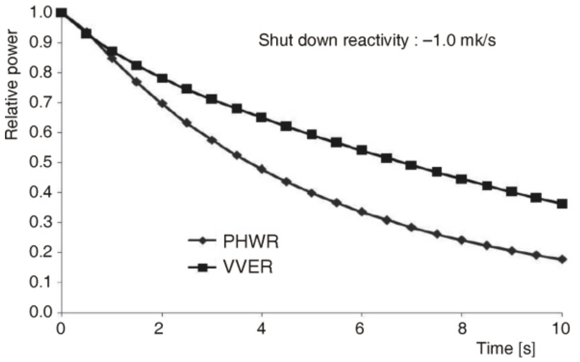

Figure 12. Reactor scram behavior (slow SCRAM)

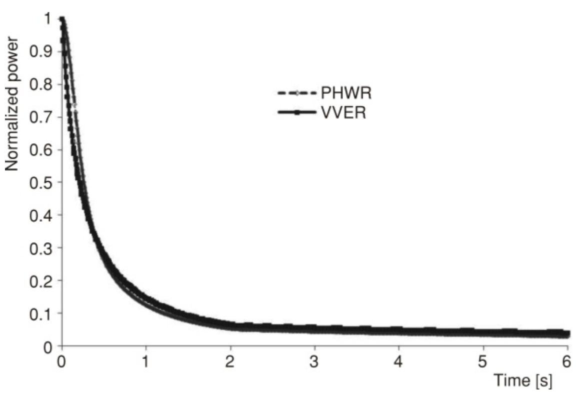

Figure 13. Reactor scram (quick SCRAM)

SAFE REACTIVITY INSERTION RATES

Criteria

Reactivity addition rate in a nuclear reactor is fixed based on the following considerations.

– The safety implications of continuous uncontrolled withdrawal (reactivity initiated transient) of an absorber rod/addition of positive reactivity, particularly during the startup of the reactor (consideration of startup accident). Here the startup is taken as achieving criticality and full power operation.
– Operational consideration like the start-up time and reactor period while raising the power of the reactor.

As the reactor start-up time is to be minimized, the rate of reactivity addition is close to the upper safe limit, which is evaluated using the following criteria [7].

– For ensuring the safety for accidents initiated during start-up, the power at criticality should be sufficiently high to permit accurate period measurements and the period at criticality should be more than an assigned value (the criteria of limit on power and period at criticality). About 100 counts per second are considered to be good for period measurements. A reactor period of 10 to 20 s or more (more than the period trip level: the reactor would trip on low period after crossing criticality) at criticality is also considered good for gradual attainment of criticality.
– Reactor should not attain prompt criticality (the criteria of limit on prompt criticality).
– While raising power, the period should not fall below a threshold within a few seconds so that unnecessary trip can be prevented.
– The rate of power rise should be slow enough, so that the reactor SCRAM is ensured before any of the design safety limit is crossed (the criteria on power rise/overshoots).

Considering the above criteria, a detailed study to investigate the upper safe limit of reactivity insertion in PHWR is discussed here and the results of the analysis of other cores like PWR and FBR are listed.

In the subcritical phase, the rates of reactivity insertion are governed by the power and period attained at criticality. The insertion rate should be limited to avoid short reactor period at criticality and have sufficiently high power to have better count rate for the power and period measurement. A transient, initiated at 10 $ subcriticality is considered. The reactor is assumed in the steady-state on neutron source. The initial power is taken as 1 W. The results in terms of power and period at criticality for different reactivity addition rates are given in tab. 2. A regulatory limit of 2 to 4 counts per second (CPS) is maintained before

Table 2. Period and power at criticality

Reactivity addition rates [pcm/s]	Period at criticality [s]	Power at criticality [W]
5	28.77	52.9
10	18.21	40.98
20	11.35	32.24
30	8.54	28.22
33	7.99	27.37
40	6.97	25.76
45	6.40	24.83
50	5.93	24.04

the reactor start-up. Thus, if 10 s be the trip period level and 100 CPS (50 to 25 times power), then 20 pcm/s will be the upper safe limit of reactivity addition rate for transients initiated in subcritical phase.

At low power, reactor kinetics is mainly governed by effective neutron lifetime. For the equilibrium PHWR core, effective neutron lifetime is 63 10^{-3} s. The results (the variation of power and period) for reactivity initiated transient at low power operation for different reactivity addition rates are given in figs. 14 and 15. The results show that the period of 10 s is achieved within a few seconds (less than 5 s) of initiation of the power rise for reactivity addition rates more than 20 pcm/s. This means that, for larger reactivity addition rates, the trip period level (say 10 s) is achieved in less than 5 s. Such situation may lead to inadvertent reactor trip and abort the power raising operations if the operator is not very attentive. From this consideration, it is necessary that reactivity addition rates be restricted to about 20 pcm/s.

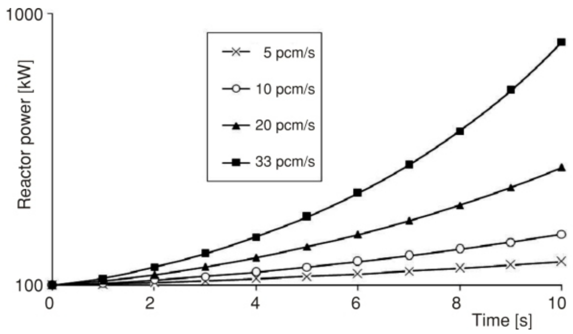

Figure 14. Power *vs.* time (low power)

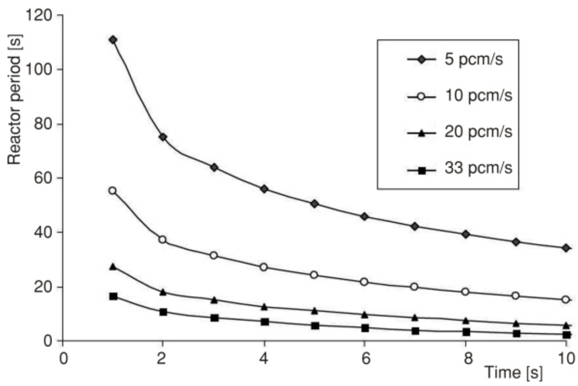

Figure 15. Reactor period *vs.* time (low power)

At the full power, reactivity feedbacks are effective. Therefore, the kinetic behavior of the reactor at the full power is slower; hence, larger permissible reactivity addition rates would be acceptable. For 540 MW_e core, the power coefficient of reactivity is –0.11 pcm/MW_t, whereas this is –0.443 pcm/MW_t for 220 MW_e core. Due to this, different kinetic behavior is expected at high power. The results of power rise for different reactivity addition rates at full power are shown in fig. 16 (540 MW_e core). At high power, reactivity addition rates are also restricted by the rate of power rise, *i. e.*, over shoot of power at "trip power level" during the delay time of reactor trip actuation and shut down rods becoming fully effective. In this study, the upper limit for this delay is taken as 0.5 s. It is also assumed that the total uncertainty in power measurements, trip setting and noise level is 3%. Therefore, the power overshoot reached in 0.5 s after the trip power level (110% of full power), should be less than 3%. In tab. 3, the results are given for the time at which 110% power is reached for different reactivity insertion rates. Along with this, power levels achieved in the next 0.25-0.5 s are also tabulated. It can be seen that with the reactivity insertion rate of 20 pcm/s, the overshoot of power above 110% power level remains within 3% with the delay time of 0.5 s in making the shutdown fully effective. However, for higher reactivity addition rates, the power overshoot is more than 3% in 0.5 s delay time. If the said delay time is smaller than 0.5 s (say 0.25 s), higher reactivity addition rates would be acceptable. To be on the conservative side, reactivity addition rates for transients at higher power should be limited to 20 pcm/s.

Safety limits for other systems

The reactivity insertion limits in the above section have been derived for PHWR. It is well known that the

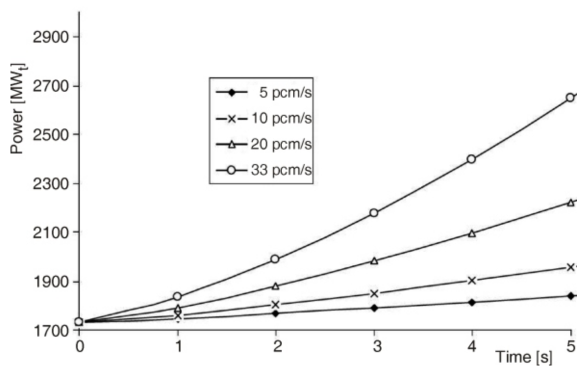

Figure 16. Power *vs.* time (full power)

Table 3. Power overshoots in 0.5 s for rod withdrawal at full power

Reactivity insertion rates [pcm/s]	Time [s]	Power [MW]	Relative power	Power rise [%]
10	0.00	1730	1.000	0.00
	4.05	1903	1.100	10.0
	4.30	1916	1.107	10.7
	4.55	1930	1.115	11.5
20	0.00	1730	1.000	0.00
	2.23	1903	1.100	10.0
	2.48	1928	1.114	11.4
	2.73	1954	1.129	12.9
25	0.00	1730	1.000	0.0
	1.85	1903	1.100	10.0
	2.10	1933	1.117	11.7
	2.35	1966	1.136	13.6
33	0.00	1730	1.000	0.0
	1.47	1903	1.100	10.0
	1.72	1943	1.123	12.3
	1.97	1984	1.146	14.6

physics design characteristics of PHWR, PWR and FBR are quite different, *e. g.*, neutron lifetime is about 80 millisecond in case of PHWR whereas it is 30 microsecond in case of PWR. Therefore, a distinct kinetics behavior is expected. The factors governing the kinetics have already been discussed in the section III. The details of data related to kinetics parameters for variety of reactors are also given in section II. The limits of reactivity insertion rates for other reactor cores based on the above discussed criteria are given in tab. 4. At high power operation, smaller periods are not achieved even at reactivity insertion rates as high as 8-10 cents/s in case of VVER and FBR due to strong negative feedback. In this situation, reactivity insertion is limited mainly due to the limits posed by power overshoots.

Table 4. Permissible reactivity addition rates [Cents/s]

Core	Low power	High power
PHWR	3.8	3.8
VVER	3.1	7.8
FBR	2.9	14

KINETICS TREND OF ADVANCED REACTOR SYSTEMS

In the new era of nuclear industry, new generation of nuclear reactors are currently being developed in several countries [8]. The first (3rd generation) advanced reactors have been operating in Japan since 1996. Late 3rd generation designs are now being built. The major objectives of advanced reactor designs are:

– a standardized design for each type to expedite licensing, reduce capital cost, and reduce construction time,
– a simpler and more rugged design, making them easier to operate and less vulnerable to operational disturbances,
– higher availability and longer operating life,
– reduced possibility of core melt accidents,
– minimal effect on the environment,
– higher burn-up to reduce fuel use and the amount of waste, and
– burnable absorbers ("poisons") to extend fuel life.

To achieve these goals, several newer concepts *e. g.*, AP1000, EPR, and ACR *etc*. have come into vogue.

Based on the conducted study, one can easily extrapolate the kinetics trend of these new systems. A few guidelines are discussed to project the kinetics trend of these new systems.

Advanced PWR

Almost all advanced PWR (AP1000, EPR, APR-1400, and VVER-1200) have the similar core physics design features with minor changes involved in the position and arrangement of burnable absorbers to maximize the burnup. Material combination like slightly enriched (2-4%) uranium oxide as the fuel, and pressurized borated water as the coolant are like in previous PWR. Average core power density (about 100 kW/l) has also remained unchanged. Thus it can be said that the neutron lifetime and delayed neutron fraction of these systems will be closer to the existing systems. Reactor size is scaled up in all the new systems. This feature will decrease the feedback reactivity effects (due to increase in reactor time constant and decrease in power coefficient) and therefore kinetics of these advanced PWR will be slightly faster at high power compared to existing PWR. The upper limit of reactivity insertion rate will be slightly lower in advanced PWR.

Advanced PHWR

The presence of slightly positive void coefficient in the present age heavy water reactors has always been a matter of safety concern across the globe. Therefore new heavy water moderated cores are designed (ACR, AHWR) to have a non-positive void coefficient. This feature has changed overall core physics design drastically. Average fuel enrichment has increased up from 0.7% to 2%. Core power density has also risen up. Heavy water requirement has gone down significantly. Thus there will be changes in the kinetics governing parameters. Under-moderated neutron spectrum feature will decrease neutron lifetime. High fuel enrichment will give relatively large magnitude of negative Doppler coefficient. Negative void coefficient will also assist to increase the magnitude of overall negative power coefficient. Thus kinetics of these systems will be slower at full power operation compared to the existing systems.

CONCLUDING REMARKS

The study explained the kinetics behavior of different reactor concepts. The importance of kinetics parameters in different states of a system is identified. Kinetics study has also been used to assess the maximum permissible reactivity addition rates in power reactors. The study is extrapolated to predict the possible kinetics trends in future reactor systems. Based on the study, the following concluding remarks can be stated.

A simplified methodology for rapid kinetics analysis using dynamics power coefficient has been used. This method of accounting reactivity feedback through power coefficient and reactor feedback time constant is simple but accurate enough as it accounts for the total reactivity feedback (through power coefficient) and time delayed involved in making feedback effective (via feedback time constant and time integral).

Comparative kinetics study reemphasizes the varying influence of different core design parameters in different operational states and transients. This study can be useful in handling the operational transients in nuclear power plants.

A comprehensive methodology has been suggested to evaluate maximum permissible reactivity insertion rate considering the regulatory requirements and operational conveniences.

Considering the proposed changes in the core design of advanced reactors and insight gained from this study, it can be concluded that the next generation heavy water reactors (*e. g.* ACR) will show considerably slower kinetics at higher power compared to present PWHRs. However, the next generation PWRs (like EPRs) will not be very different in terms of kinetics behavior compared to the existing PWR systems.

NOMENCLATURE

C_i – a constant proportional to the i_{th} group delayed neutron precursor concentration
Cent – unit of reactivity in terms of delayed neutron fraction (1 Cent = 0.01 $)
kW/l – unit of core power density expressed in kilo watts per litre
l_{eff} – effective neutron life time
MW_t – reactor thermal power in mega watts
MW_e – reactor electrical power in mega watts
mk – unit of reactivity (10^{-3} k/k), k being reactor multiplication factor
P – reactor power
pcm – unit of reactivity (10^{-5} k/k)
$S(t)$ – time dependent neutron source function
$ – unit of reactivity in terms of delayed neutron fraction (1 $ = β)

Greek letters

α – power coefficient of reactivity
β – total delayed fraction
β_i – i^{th} group delayed neutron fraction
Λ – neutron generation time
λ_i – i^{th} group decay constant
$\rho(t)$ – time dependent reactivity function
ρ_{ex} – external reactivity
ρ_{fb} – feedback reactivity

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УПОРЕДНО ПРОУЧАВАЊЕ КИНЕТИКЕ НУКЛЕАРНИХ РЕАКТОРА

У раду се проучавају прелазна стања изазвана променом реактивности са намером да се испитају знатнија неслагања кинетика различитих реакторских система у различитим радним условима. Такође, у чланку се утврђује смернице за успостављање сигурносних граница брзине унете реактивности. Ради анализе разматрана су три система: лаководни реактори (реактори са водом под притиском), тешководни реактори (реактори са тешком водом под притиском) и брзи оплодни реактори. У овим реакторским системима утврђене су горње сигурносне границе брзине унете реактивности. Анализе транзијентних стања обављене су ПКОК рачунарским програмом за тачкасту кинетику. За урачунавање укупне повратне спреге реактивности у кинетичким прорачунима изабрана је и употребљена једна једноставна и тачна метода. Параметри који регулишу кинетичко понашање језгра проучавани су за различита стања језгра. У циљу предвиђања кинетичког понашања реактора следеће генерације, размотрени су неки могући правци развоја.

Кључне речи: реакторска кинетика, повратна спрега реактивности, брзина уношења реактивности, реакторска сигурност, прелазна стања иницирана реактивношћу