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**LARGE-SIGNAL, DYNAMIC SIMULATION OF THE
SLOWPOKE-3 NUCLEAR HEATING REACTOR**

**Simulation dynamique, à grand signal,
du SLOWPOKE-3, réacteur nucléaire thermogène**

C.M. TSENG and R.M. LEPP

Paper presented at the 1983 Summer Computer Simulation Conference,
Vancouver, 1983 July 11-13

Chalk River Nuclear Laboratories

Laboratoires nucléaires de Chalk River

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Simulation dynamique, à grand signal,
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Résumé

Un réacteur nucléaire de 2 Mwt, appelé SLOWPOKE-3*, est en voie de développement aux Laboratoires nucléaires de Chalk River (LNCR). Ce réacteur refroidi par circulation naturelle est destiné à produire de l'eau chaude pour le chauffage urbain et il pourrait engendrer de l'électricité dans les régions éloignées où le coût des autres formes d'énergie est élevé.

Une simulation dynamique, à grand signal, de ce réacteur, sans contrôle en boucle fermée, a été développée et mise en oeuvre sur un ordinateur hybride en ayant recours aux équations fondamentales de conservation de masse, d'énergie et de moment. La circulation naturelle, par écoulement en tube de descente dans la piscine du réacteur, a été simulée au moyen d'un filtre spécial pouvant modéliser diverses conditions d'écoulement. On a ensuite utilisé la simulation pour étudier la réaction transitoire, à long et à moyen terme, de SLOWPOKE-3 aux grandes perturbations comme une perte de dissipation thermique, un dérèglement, des variations quotidiennes de charge et un refroidissement excessif du caloporteur.

Les résultats de la simulation montrent qu'aucune de ces perturbations n'entraîne de phénomènes transitoires dangereux.

* SLOWPOKE = Safe-Low-Power Critical Experiment

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LARGE-SIGNAL, DYNAMIC SIMULATION OF THE SLOWPOKE-3
NUCLEAR HEATING REACTOR

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ABSTRACT

A 2 MWt nuclear reactor, called SLOWPOKE-3*, is being developed at the Chalk River Nuclear Laboratories (CRNL). This reactor, which is cooled by natural circulation, is designed to produce hot water for commercial space heating and perhaps generate some electricity in remote locations where the costs of alternate forms of energy are high.

A large-signal, dynamic simulation of this reactor, without closed-loop control, was developed and implemented on a hybrid computer, using the basic equations of conservation of mass, energy and momentum. The natural circulation of downcomer flow in the pool was simulated using a special filter, capable of modelling various flow conditions. The simulation was then used to study the intermediate and long-term transient response of SLOWPOKE-3 to large disturbances, such as loss of heat sink, loss of regulation, daily load following, and overcooling of the reactor coolant.

Results of the simulation show that none of these disturbances produce hazardous transients.

NOMENCLATURE

| <u>Symbol</u> | <u>Description</u> | <u>Units</u> |
|---------------|--|--|
| A_s | surface area | m^2 |
| C | delayed neutron density | $n \cdot m^{-3}$ |
| c_p | specific heat capacity | $J \cdot K^{-1} \cdot kg^{-1}$ |
| g | acceleration due to gravity (9.80665) | $m \cdot s^{-2}$ |
| H | heat transfer coefficient | $J \cdot m^{-2} \cdot s^{-1} \cdot K^{-1}$ |
| I | iodine density | $n \cdot m^{-2}$ |
| β | reactivity | |
| l | neutron lifetime | s |
| β^* | neutron generation time (i.e. l/k_{∞}) | s |
| L | length | m |
| L_m | depth of mixing region | m |
| M | mass | kg |

Nomenclature (cont'd)

| <u>Symbol</u> | <u>Description</u> | <u>Units</u> |
|---------------|--|-------------------------------|
| n | neutron density | $n \cdot m^{-3}$ |
| ΔP | pressure drop | Pa |
| q | rate of change of temperature | $K \cdot s^{-1}$ |
| Q | total heat flow | $J \cdot s^{-1}$ |
| t | time | s |
| T | temperature | $^{\circ}C$ |
| u | velocity | $m \cdot s^{-1}$ |
| V | total volume | m^3 |
| W | mass flow | $kg \cdot s^{-1}$ |
| X | xenon density | $n \cdot m^{-2}$ |
| Y | dependent variable | |
| z | spatial distance | m |
| β | fission yield of delayed neutrons | |
| γ | fission yield | |
| Δ | small perturbation or deviation from the reference condition | |
| λ | decay constant | s^{-1} |
| ρ | density | $kg \cdot m^{-3}$ |
| σ_x | absorption cross section of xenon-135 | $m^2 \cdot n^{-1}$ |
| ϕ | neutron flux | $n \cdot m^{-2} \cdot s^{-1}$ |
| ϕ' | fission power per unit volume of the fuel | $J \cdot m^{-3} \cdot s^{-1}$ |

Subscripts

| | |
|-----|-----------------|
| d | downcomer |
| D | reactor coolant |
| e | heat exchanger |
| F | fuel |

*Safe-Low-Power Critical Experiment

Subscripts (cont'd)

| | |
|---|----------------------------------|
| I | iodine |
| s | water above heat exchangers |
| R | reactor channel |
| u | riser |
| X | Xenon |
| o | steady-state value |
| 1 | primary side of heat exchanger |
| 2 | secondary side of heat exchanger |
| i | inlet |

Superscripts

() average of ()

INTRODUCTION

A 2 Mwt nuclear reactor, known as SLOWPOKE-3, is being developed at the Chalk River Nuclear Laboratories [1] for commercial space heating and electricity generation. This pool-type reactor, shown in Figure 1, is being designed for unattended operation at atmospheric pressure and coolant temperatures below 100°C. The reactor core, located near the bottom of an 8-m deep pool of water, consists of about 200 slightly enriched uranium oxide fuel elements. Heat generated in the core is removed by the natural circulation of water in the pool and transferred to the buildings being heated through primary and secondary loops in which plate-type heat exchangers are used.

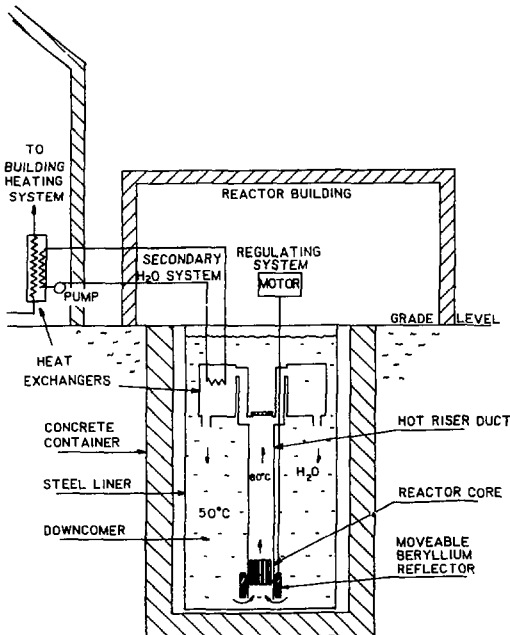


FIGURE 1 2 MW SLOWPOKE-3 HEATING REACTOR

Natural circulation is set up because the heat added by the reactor decreases the density of the fluid in the riser duct relative to the fluid in the adjacent pool (downcomer). Automatic regulation of reactor power is carried out using a motor-driven beryllium reflector surrounding the core.

This paper describes the large-signal, dynamic simulation of SLOWPOKE-3, developed to investigate the intermediate and long-term behavior of the system, i.e. over 1 minute to several days, in response to large external perturbations, such as the loss of heat sink, loss of regulation, daily load following, and overcooling of the primary coolant. The large-signal simulation is based on a small-signal simulation developed earlier [2]. The major change is that high-order, non-linear terms previously discarded during the linearization process are retained.

EQUATIONS

For simulation purposes, the reactor system was divided into the 10 subsystems shown in Figure 2, and equations were developed for each.

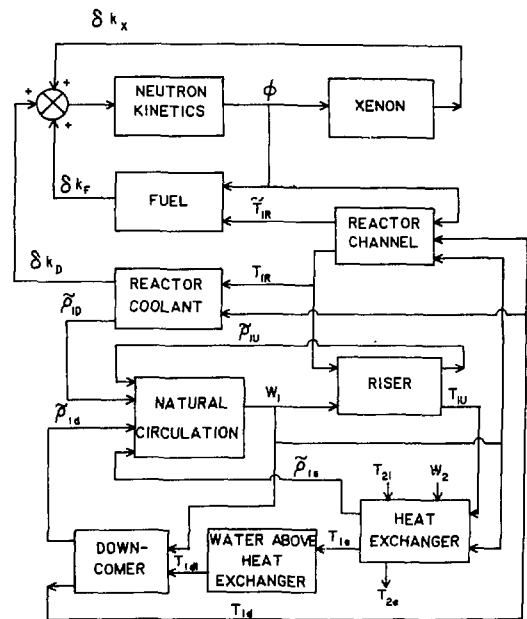


FIGURE 2 BLOCK DIAGRAM OF THE SLOWPOKE-3 SIMULATION

The assumptions used in deriving these equations include;

- Subsystems with a time constant of 5 s or less are treated as instantaneous.
- The reactor core is represented by a point kinetics model with one group of delayed neutrons.

- Heat transfer between the riser and downcomer is neglected.
- The fluid in the riser is single-phase flow only.
- No controller is used in the primary circuit.
- One-dimensional flow is assumed throughout the circuit.

As well, the heat loss from coolant to the surroundings is neglected, but could be easily added if desired.

Neutron Kinetics

The dynamics of the nuclear fission process are governed by the excess reactivity in the core as well as the decay of delayed neutrons. Assuming one delayed neutron group, the neutron kinetics equations are [3]

$$\frac{1}{\beta^*} (\lambda - \beta) n + \lambda C = 0 \quad (1)$$

$$\frac{dC}{dt} = \frac{\beta}{\beta^*} n - \lambda C \quad (2)$$

Fuel

Heat generated in the fuel by nuclear fission is transferred to the coolant. This fuel-to-coolant heat flow is expressed as

$$Q = HA_{SF} (T_F - \tilde{T}_R) \quad (3)$$

and the fuel temperature is given by

$$c_{pF} \rho_F V_F \frac{dT_F}{dt} = \phi' V_F - Q \quad (4)$$

Reactor Channel

The coolant flows through the reactor in less than 2 s. Therefore, the dynamics of the reactor channel are considered instantaneous and the energy equation for single-phase flow is

$$T_R = T_d + \frac{Q}{c_{pR} w_1} \quad (5)$$

This equation is valid for the entire operating range of the simulation which permits subcooled-nucleate but not bulk boiling in the reactor core.

Xenon

The major fission product in a thermal reactor is xenon. It is created directly as a by-product of fission and by the decay of iodine, another by-product of fission.

The kinetics of this process are expressed as [3],

$$\frac{dX}{dt} = \gamma_X \phi + \lambda_I I - \lambda_X X - \alpha_X X \phi \quad (6)$$

$$\frac{dI}{dt} = \gamma_I \phi - \lambda_I I \quad (7)$$

Circulation Flow

Flow through the reactor is by natural circulation, thus eliminating the need for pumps.

Three relationships are used to determine the circulation mass flow,

$$W_1 = w_1 (\Delta P) \quad (8)$$

$$\Delta P = g(L_R \bar{\rho}_R + L_U \bar{\rho}_U - L_{1e} \bar{\rho}_{1e} - L_d \bar{\rho}_d) \quad (9)$$

$$\bar{\rho} = \bar{\rho}(T) \quad (10)$$

The relationship between coolant flow and pressure drop (equation (8)) was obtained from a detailed thermal-hydraulics simulation [4]. This relationship, implemented as a table lookup in our simulation, is valid for a reactor power range of 0.04 to 4 MWt and an inlet coolant temperature in the range 10°C to 100°C. Relationship (10) is obtained from steam tables [5].

Heat Exchanger

The energy conservation equations for the heat exchangers in the reactor pool are [6]

$$\frac{\partial T_1}{\partial t} + u_1 \frac{\partial T_1}{\partial z} = -q \quad (11)$$

and

$$\frac{\partial T_2}{\partial t} + u_2 \frac{\partial T_2}{\partial z} = q \quad (12)$$

where

$$q = \frac{HA_{SF} u_1}{c_{p1} w_1 L_{1e}} (\tilde{T}_2 - \tilde{T}_1) \quad (13)$$

and

$$\tilde{T}_1 = \frac{1}{L_{1e}} \int_0^{L_{1e}} T_1(z) dz \quad (14)$$

$$\tilde{T}_2 = \frac{1}{L_{2e}} \int_0^{L_{2e}} T_2(z) dz \quad (15)$$

Spatial integration of equations (11) and (12) over the length of the heat exchanger gives

$$\frac{d}{dt} \tilde{T}_1 + \frac{u_1}{L_{1e}} (T_u - T_{1e}) = -q \quad (16)$$

and

$$\frac{d}{dt} \tilde{T}_2 + \frac{u_2}{L_{2e}} (T_{2d} - T_{2e}) = q \quad (17)$$

Downcomer

The dynamic behavior of the downcomer will be different depending on whether there is an increase or a decrease in the temperature of the water entering the downcomer from the heat exchanger. When the water entering is warmer (lower density) than the water already in the downcomer, no mixing occurs. Instead, the warmer water moves as a stratified layer towards the reactor core inlet. This is described by the equation for a transport delay,

$$\frac{\partial T_d}{\partial t} + u_1 \frac{\partial T_d}{\partial z} = 0 \quad (18)$$

When the incoming water is cooler than that already in the downcomer, immediate fluid mixing is assumed. The depth of the mixing region, L_m , is determined theoretically by

$$\frac{1}{L_m} \int_0^{L_m} T_d(z) dz = \bar{T}_d(L_m) \quad (19)$$

where

$$T_d(L_m) \leq \bar{T}_d(L_m) \quad (20)$$

The mixing process which is considered instantaneous and thorough is described by the equation

$$\frac{d\bar{T}_d}{dt} = \frac{W_1}{M_d} (\bar{T}_d - T_{di}) \quad (21)$$

Riser

Riser dynamics are similar to those of the downcomer except that the flow through the riser is a factor of ~20 faster.

Core Reactivity

The core reactivity is a function of three parameters, beryllium reflector position, fuel temperature, and reactor coolant density. In this simulation the contribution of reflector position to core reactivity is neglected since no controller is used, and hence it is assumed that the reflector does not move.

Changes in fuel temperature have a negative effect on core reactivity and are expressed as the linear function

$$\Delta k_F = \left(\frac{\partial k}{\partial T_F} \right) \Delta T_F \quad (22)$$

where

$$\frac{\partial k}{\partial T_F} \text{ is a constant}$$

As reactor power increases the coolant density decreases, causing a decrease in core reactivity and hence stabilizing the neutron flux. The relationship between core reactivity and coolant density is a complicated non-linear function, since it includes the effects of neutron flux distribution in the core, subcooled boiling in the channel, inlet coolant temperature, and mass flow. In this simulation we use a reactivity relationship based on experimental data and tabulated as a function of two variables, reactor inlet and outlet coolant temperatures [4]. The average coolant density in the core is calculated using a similar function [4].

Water Above Heat Exchangers

The pool of water above the heat exchangers (see Figure 1) can be considered as a mixing tank whose temperature will increase if the coolant temperature discharged from the heat exchanger increases, but remains constant if the coolant temperature decreases. Therefore

$$\frac{d}{dt} T_s = \frac{W_1}{M_s} (T_{1e} - T_s) \quad \text{for } T_{1e} > T_s \quad (23)$$

$$\frac{d}{dt} T_s = 0 \quad \text{for } T_{1e} \leq T_s \quad (24)$$

DYNAMIC SIMULATION

For implementation, the equations are first converted into their deviation form by replacing the dependent variables with the equation

$$Y = Y_0 + \Delta Y \quad (25)$$

where

$$Y_0 = \text{steady-state value}$$

$$\Delta Y = \text{deviation from steady state}$$

and setting Y_0 near the centre of the simulation range. This is done to obtain higher resolution in analog simulation. For our simulation, the resulting equations corresponding to the reactor operating at 2 MWt. The steady-state values are obtained by solving the original equations with the time derivative terms set to zero. The high-order, non-linear terms are retained in the resulting equations.

For example, the neutron kinetics equations are rewritten as

$$\Delta n = \frac{\rho}{\beta} \Delta k + \frac{1}{\beta} \Delta n \cdot \Delta k + \frac{\rho^*}{\beta} \lambda \Delta C \quad (26)$$

$$\frac{d}{dt} \Delta C = \frac{\beta}{\lambda} \Delta n - \lambda \Delta C \quad (27)$$

and

$$\Delta k = \Delta k_x + \Delta k_F + \Delta k_D (\Delta T_R, \Delta T_d) \quad (28)$$

where Δk_D is a non-linear function of ΔT_d and ΔT_R .

These equations were implemented on the hybrid computer of the Dynamic Analysis Facility at the Chalk River Nuclear Laboratories. Non-linear functions that do not contain time delays, such as the core reactivity as a function of void fraction and reactor power, were programmed on the hybrid computer using a piecewise-linearization package [7]. Other non-linear functions that contain time delays were implemented using a special digital filter.

An example of the latter is RUNAV3, a filter developed to simulate the downcomer flow in the pool. Natural circulation in the downcomer changes from mixed to stratified flow, or a combination of both, depending on whether the inlet water temperature is increasing or decreasing. To simulate this, the downcomer is first divided into a number of small elements. The number of elements is a function of the

sampling period used and the transit time of the fluid in the downcomer. At each sampling interrupt, the program compares the new sample of inlet temperature with the previous value at that element to determine the local flow condition; stratified or mixed.

For instance, if the downcomer temperature profile at $t=t_0$ is monotonically decreasing as shown in Figure 3(a), stratified flow is assumed. If at $t=t_1$, the temperature of the inlet fluid drops as shown in Figure 3(b), the fluid in elements 1, 2, and 3 will mix by natural convection and assume an average mixture temperature, as shown in Figure 3(c). This mixing process, which starts at the top and progresses towards the bottom, stops when the resulting mixture temperature is greater than or equal to the temperature of the fluid in the next element. If the mixing process stops before reaching the bottom, Figure 3(c), the lower elements remain undisturbed, and the program resumes with stratified flow, using the new temperature profile. If at $t=t_2$ the inlet fluid temperature increases as shown in Figure 3(d), no mixing occurs, as was the case in Figure 3(a).

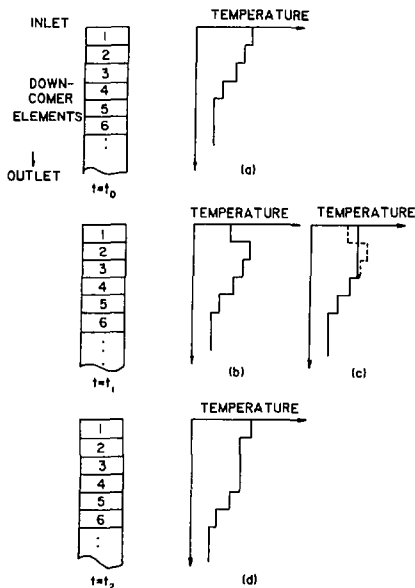


FIGURE 3 DOWNCOMER SIMULATION

SIMULATION RESULTS

Once the simulation was implemented and verified, it was used to determine the reactor response to the 4 system upsets of concern. One of these is the sudden loss of heat removal by the secondary side, i.e. a loss of heat sink.

Loss of Heat Sink

A loss of heat sink is simulated by setting the system to full power equilibrium and then instantaneously reducing the secondary mass flow, W_2 , from 100% to 0%. The time responses of the various system parameters in the absence of a controller are given in Figure 4.

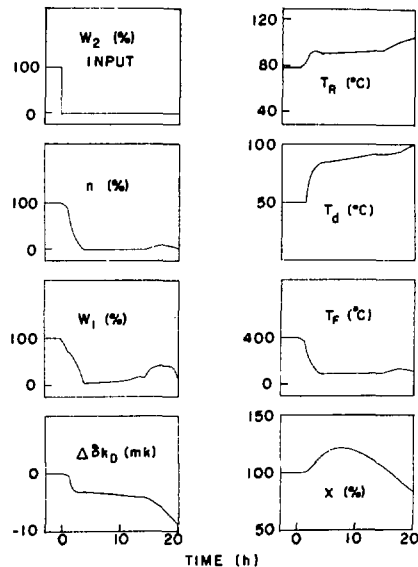


FIGURE 4 RESPONSE OF THE SLOWPOKE-3 SIMULATION TO A LOSS-OF-HEAT-SINK PERTURBATION

The results show that the neutron flux, core reactivity and fuel temperature all behave in a desirable way as they decrease in response to the flow reduction. This is caused by the increase in coolant temperature out of the heat exchanger, producing a decrease in the recirculation flow and an increase in reactor outlet temperature. Because of the negative reactivity feedback in the core, this leads to a gradual reduction in core reactivity and reactor power. The reactor reaches zero power approximately 4 h after the loss-of-heat-sink perturbation. Meanwhile the density of xenon poison continues climbing, reaching approximately 120% of its full-power value in approximately 8 h. Then because of its decay constant of ~ 9 h, it begins decreasing, causing the core reactivity to increase and reach criticality in approximately 13 h. The resultant power excursion reaches a maximum value of 10% of full power before the reactor again shuts down. It is therefore concluded that the loss-of-heat sink is not a transient of concern.

Loss of Regulation

The worst loss-of-regulation incident would occur if the beryllium reflector were to move at its full design speed over its allowable travel. Simulation results for this accident showed that the reactor power increases to about 170% of its rated power of 2 MWt before decreasing to a steady value of 125% of rated power. Since the reactor fuel can withstand these power levels without damage, this system upset is not of concern.

Load Following

Since the heating demand for buildings varies with outside temperature, the load-following capabilities of the SLOWPOKE-3 reactor were investigated. A

daily load-following demand was simulated by setting the simulation to full power and perturbing the secondary circuit with a 24 h sinusoidal heat load. The results show that the reactor system can adjust itself automatically to meet the variation of the load demand without a controller. For example, in response to a 70 to 130% load variation, the neutron flux varies from approximately 70% to 130%, the primary mass flow from 86% to 108%, and reactor outlet temperature from 72°C to 81°C. These are all within the safe operational range of the reactor.

Overcooling of Primary Coolant

This upset condition could be caused by a sudden large increase in load demand from the secondary circuit. To investigate the consequence of this upset condition, the simulation was set to full power and the secondary circuit was perturbed with a step increase in heat demand.

The results show that upon the input disturbance the downcomer temperature decreases and circulation mass flow increases. In response to a step increase of 50% in heat load, the mean fuel temperature and neutron flux reach maxima of approximately 560°C and approximately 155% of full power, respectively, in approximately 6 h and then decrease gradually thereafter. No hazardous transient developed as a result of the overcooling of the primary coolant. However, it should be noted that this conclusion applies over the range of validity of the simulation and may not necessarily be an accurate reflection of fast, short-term transients. In particular, thorough mixing of the coolant in the downcomer was assumed so that changes in core inlet temperature and associated reactivity were gradual. A sudden drop in core inlet temperature could result in a correspondingly fast power excursion.

SUMMARY AND CONCLUSIONS

A large-signal, dynamic simulation of the SLOWPOKE-3 reactor was developed. Basic equations of mass, energy and momentum were used to describe the physical phenomena in the subsystems that make up the reactor system. The equations were rewritten in the form of deviations from steady-state, for implementation on a hybrid computer. Non-linear terms were retained, but subsystems with time constants of 5 s or less were treated as instantaneous. This is in line with the purpose of the simulation which was to examine system response to slow upsets such as loss of heat sink.

Non-linear functions that do not contain time delays were implemented using an analog, piecewise-linearization method. Other non-linear functions that contain time delays were implemented using a digital program. An example of the latter was the downcomer simulation. The downcomer model was implemented to represent either stratified or mixed flow depending on the sign of the temperature derivative at the inlet.

After implementation and validation, the simulation was used to study the intermediate and long-term transient response to large external input disturbances. The simulation results show that the reactor automatically shuts itself down in response to a loss of heat sink even in the absence of a controller. However, the coolant temperature in the pool, as indicated by downcomer temperature, will increase gradually and begin to boil if no heat is lost to the surroundings.

The system response to the loss-of-regulation perturbation is a slow transient that eventually reaches a new steady-state power that the reactor can tolerate. Daily load following is also acceptable as the reactor is able to automatically adjust itself to meet the demand, without closed-loop control. The simulation results also indicate that no hazardous transient develops as a result of overcooling of the primary coolant, provided that the coolant mixes thoroughly in the downcomer before reaching the reactor core.

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