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REACTIVITY WORTH OF LIQUID POISON JETS IN THE MODERATOR

KAMALA BALAKRISHNAN, UMASANKARI KANNAN and ANIL KAKODKAR
Reactor Engineering Division, Bhabha Atomic Research Centre, Bombay 400085, India

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Abstract—The safety requirement of two shutdown systems functioning on diverse principles has led to the introduction of a secondary shutdown system which functions by injecting liquid neutron poison jets at high pressure into the bulk moderator. The poison enters the moderator in the form of high-speed jets, in which the cross-section increases and the poison concentration falls as the jet develops. A formalism has been developed for estimating the reactivity worth of these jets. This formalism is different from currently used formalisms, in which the conical jet is approximated by equivalent cylinders whose radius changes from cell to cell. In the formalism presented in this paper, both the cross-section of the jet and the concentration of the poison are taken to be continuously varying from the origin of the jet to the end of the jet where it starts diffusing into the moderator. The formalism has been used to calculate the reactivity worth of the secondary shutdown system of the 500 MW(e) PHWR, making use of jet growth data that have been made available from experiments performed in our laboratory.

1. INTRODUCTION

Pressurized heavy water reactors (PHWRs) of advanced design are expected to have two independent fast-acting shutdown mechanisms in order to cater to the present-day safety requirement of defence in depth. The 500 MW(e) Indian PHWR is one such reactor which is being designed to have two independent shutdown systems functioning on diverse principles. The first of these is called the primary shutdown system (SDS-1), and consists of 28 mechanical shutoff rods which provide a shutdown worth of approx. 55 mk when two of the maximum worth rods of the set fail to actuate.

The second system, which is referred to as the secondary shutdown system (SDS-2), is based on totally different principles. It functions by injecting a concentrated solution of gadolinium nitrate directly into the moderator. The injection system within the moderator consists of tubes with holes drilled into them. When poison solution at high pressure is pumped through these tubes, the poison enters the bulk moderator in the form of high-speed liquid jets.

When it comes to estimation of the reactivity worth of the shutdown system, a system of the kind described above is different from those that were the norm until a few years ago, viz. the black control rod, black control plates, poison curtains and the grey control rod. The reactor physics formalisms used in those cases are not directly applicable here, at least not without substantial modifications. What we have here are conical jets (in the case where the holes through which the poison jet is injected are circular) or wedge-shaped jets (in the case where the holes are in the form of elongated slits), in which the concentration of the poison is continuously varying, starting from very high concentrations at the small end of the jet and steadily falling off to relatively much lower values as the jet proceeds.

The commonly used method for modelling these jets is to approximate them by equivalent cylinders of increasing radius as the jet proceeds. In any cell, the radius is taken as constant.

We have developed a formalism in which the continuously increasing cross-section of the jet is taken more exactly. Details of this formalism and calculated values of the reactivity worths are presented in this paper.

2. THE REACTOR CORE

The 500 MW(e) PHWR consists of 392 fuel channels arranged along a square lattice of 28.575 cm pitch. The fuel bundles are 37 rod clusters of natural uranium oxide. The coolant is pressurized heavy water, while the moderator is unpressurized heavy water at low temperature. The calandria is a horizontal cylinder. The fuel channels are parallel to the axis of the calandria and, as such, are also horizontal. All reactivity devices are arranged perpendicular to the fuel channels. These include 28 shutdown rods belonging to SDS-1, which are normally outside the core, 21 adjuster rods, 14 zonal control units and 4 control rods. The locations of all these devices within the reactor core are shown in Fig. 1. Of these, the adjuster rods, zonal control units and control rods can be expected to be present in the core during normal operation. Thus, the worth of SDS-2 in the presence of these devices is also important.

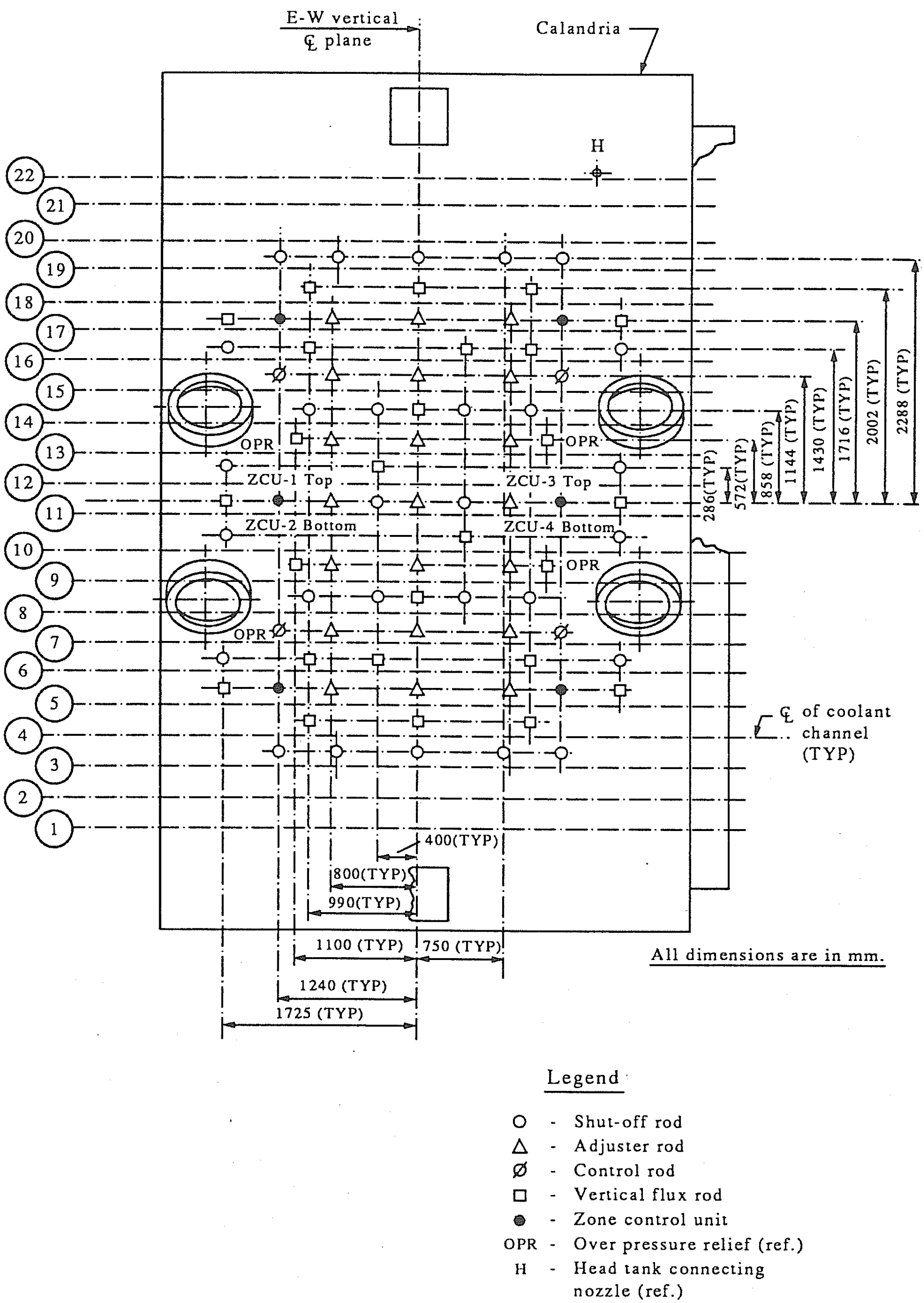

Fig. 1. Reactivity control devices: location of vertical devices.

3. DESCRIPTION OF THE SECONDARY SHUTDOWN SYSTEM (SDS-2)

SDS-2 has been visualized as consisting of 6 horizontal poison injection tubes with holes drilled into them, so that when the system is triggered it injects a concentrated solution of gadolinium nitrate directly into the moderator. These tubes are in a direction perpendicular to the pressure tubes. The 6 tubes are along the intersection of 2 horizontal planes and 3 vertical planes. The horizontal planes are symmetrically placed above and below the central plane of the horizontal cylinder which forms the calandria. The 3 vertical planes are perpendicular to the axis of the calandria, one being at the axial mid-plane and the other two placed symmetrically on either side (Fig. 2a). The holes meant for the ejection of the poison from the tubes into the moderator are placed in clumps of 16 holes each. These clumps are so positioned that they fall mid-way between those points on the tube that will be facing calandria tubes. The 16 holes are further divided into 4 sets of 4 holes each. Each set of 4 holes lies in a plane perpendicular to the axis of the poison tube. The planes of the 4 sets are at a distance of 3 cm one from the next. In any set, the holes are at an angular separation of 90° and alternate sets of holes are turned by 45° (see Fig. 2b). This is intended to give a more uniform distribution of the poison within the calandria.

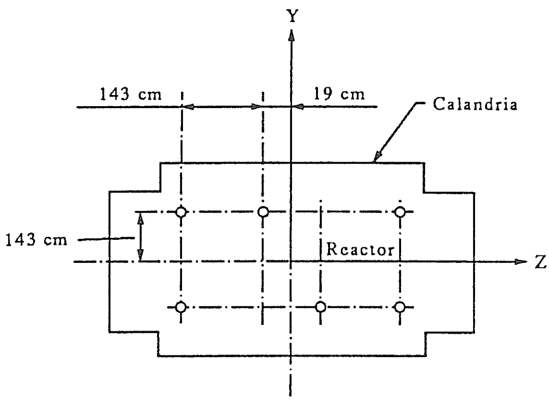

Fig. 2a. Location of poison tubes in the calandria.

The jet growth will depend on the size of the hole and the pressure with which the liquid is injected into the moderator. The negative reactivity introduced by the jets will depend upon the total volume occupied by the poison jets, and also on the poison distribution within the jet volume. The poison concentration in the jet volume will be a continuously varying function,

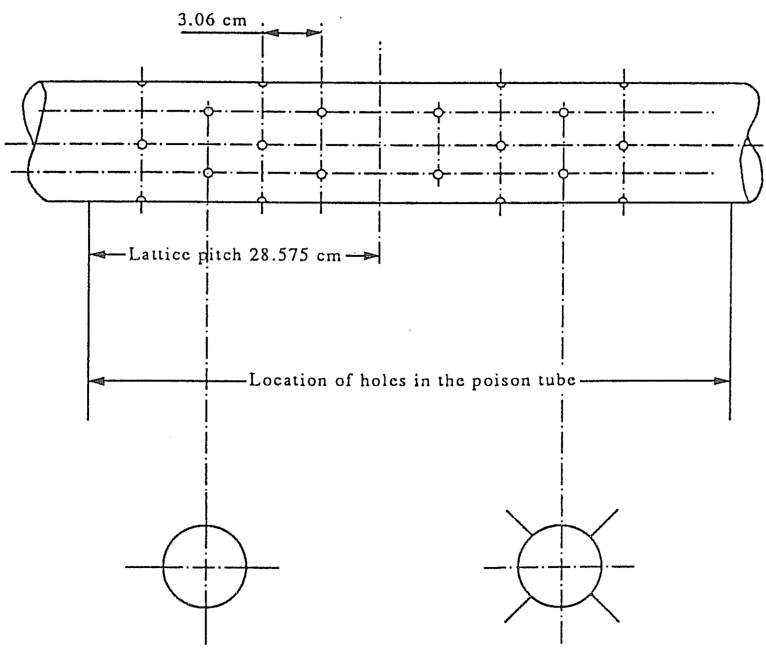

Fig. 2b. Jets from alternate sets of holes.

starting from a very high value at the point where it leaves the poison tube to much lower values at the point where the jet is fully developed. The exact functional dependence can be expected to depend upon the injection pressure and the hole size. A series of experiments was carried out to study the progression of such submerged jets. Parameters like the shape of the jet, the rate of jet development as a function of time, the discharge rate of the liquid poison etc. were measured. Full details of the experiments and measurements are given in Nawathe *et al.* (1991). The results were compiled as jet progression curves for different injection pressures and nozzle dimensions.

4. METHOD OF CALCULATION

The jets issuing from the poison tubes are all functionally similar. By the complexity of the design of the system, each jet is at a different orientation and position. Since the basis of any reactor physics calculation is the reactor lattice cell, one has to compute how the jets perturb the lattice cell. The reactor is an ensemble of such representative cells. The poison, being distributed globally, could perturb any of these cells. In order to calculate the effect of the poison jet in any given cell, one has to know the orientation of the poison jet with respect to the cell. The extra absorption would then depend upon the volume of poison in that cell and its distribution within a cell. Since the volume of poison in a cell and its distribution are both functions of the distance of the cell from the poison tube, we assume that the contribution to the extra absorption ($\Delta\Sigma_a$) from any jet is a function of the distance of the cell from the origin of the jet.

We now develop a formalism to calculate the reactivity worth of these jets. This is done in three stages:

(i) Treatment of one single jet in the moderator and calculation of the flux distribution over the jet and surrounding unpoisoned moderator.
(ii) Calculation of the contribution to the absorption of any reactor lattice cell using this flux distribution and the jet distribution in the reactor.
(iii) Calculation of the net absorption by adding the contributions due to all such poisoned cells and hence calculation of the reactivity worth.

4.1. Treatment of the jets

The jet is represented in a two-region domain. Poison with surrounding moderator is assumed for the calculations. The jet growth studies are made for two different types of geometries: slits and holes. The jet development for the two geometries will be different: in the case of slits, the jet formation will be trapezoid in nature; whereas in the case of holes, it will be conical. The jet spread is calculated from experimental observations. In both these geometries, the cross-sectional area will be conical ignoring the width of the slit. So two independent formalisms are developed to treat the jets issuing from the holes and slits.

4.1.1. Formalism developed for the slits. The jet formation depends upon the injection pressure and the dimensions of the slit. In our calculations we assume that the jet spreads only along the width of the slit and not along the length. The extent of the jet depends on the injection pressure. The jet being in the form of a trapezoid, we decide to take the longitudinal cross-section and calculate the flux distribution. The extra absorption is calculated by using proper area weightages for the three-dimensional calculations.

The flux distribution over this two-region problem is calculated by simulating the jet in a moderating medium. The poison is confined to a sector made by the half-angle of the cone, as shown in Fig. 3a. The variation in concentration along the jet is taken explicitly. It is assumed that the neutrons are well-thermalized and so one-group calculations are performed.

The flux distribution is calculated in a plane per-

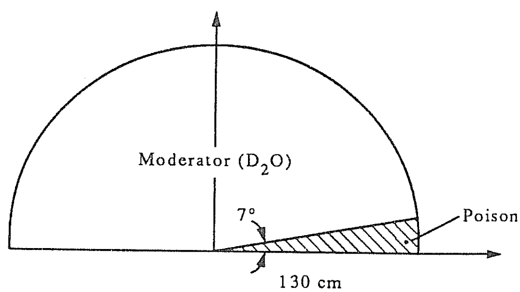

Fig. 3a.

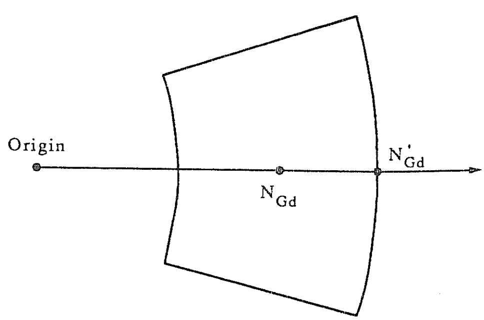

Fig. 3b. *R*–*θ* mesh.

pendicular to the axis of the poison tube. The calculations are made in R–θ geometry so that the jet is represented exactly. The flux is assumed to be constant over any R–θ mesh (Fig. 3b). The problem has symmetry about the $\theta = 0$ axis. The reflective boundary condition is used at $\theta = 0$. The white boundary condition is used elsewhere. The extent of the jet is the maximum penetration depth achievable for that injection pressure. The poison concentration is assumed to be uniform over the whole mesh and equal to that at the end of the mesh. This being done so that we are conservative in our estimation of the reactivity worth. If we calculate an average poison concentration over the mesh it would amount to a homogenous mixture over the entire mesh and thereby lead to an over-estimate, i.e.

$$N_{\mathrm{Gd}} = N'_{\mathrm{Gd}} \tag{1}$$

and

$$C(r) = \frac{C_0(r)}{r^a} \quad \text{(Section 4.2).} \tag{2}$$

The mesh sizes is suitably chosen so that the poison concentration does not vary more than 10% over the mesh. A parametric analysis is done to find the optimum mesh size.

The flux distribution over this moderator–poison region is calculated using a two-dimensional transport theory (Section 4.3). A typical flux distribution for a poison jet sitting in a predominantly moderating medium is shown later in Fig. 7. This distribution is then used to calculate the extra absorption in a reactor lattice cell.

4.1.2. Formalism developed for the holes. The jet formation in the case of holes is conical. The jet development depends on the injection pressure and hole dimension. The contribution to absorption in any cell would depend on its distance from the poison tube. For the holes case, the jet is treated in a plane perpendicular to the axis of the jet.

The flux distribution over this moderator–poison domain is calculated in one-dimensional cylindrical geometry; the domain being a central poison region of uniform concentration surrounded by an annular moderator region, as shown in Fig. 4a. The poison is confined to the cross-sectional area formed by the angle of the cone. The extent of the moderator is decided by the number of cells sharing a jet. An equivalent circular radius is calculated as shown (Fig. 4a).

The flux is assumed to be constant over any r-mesh (Fig. 4b). The reflective boundary condition is used on the top and bottom and the white boundary condition is used on the R boundary in order to estimate the neutron losses. The poison concentration will be $C(x) = C_0(x)/x^a$, where x is the distance from the poison tube.

The flux distribution is calculated in a plane perpendicular to the axis of the jet. A series of such calculations at various planes situated at different distances from the origin of the jet is performed throughout the length of the poison jet, as shown in Fig. 4c. The contribution to the absorption at any distance from the poison tube is calculated by integrating the flux over the reactor lattice cell (Section 4.4).

4.2. Calculation of the poison concentration along the jet

The poison concentration changes along the length of the jet as it advances into the moderator. This variation depends on the injection pressure and hole dimensions. Some experiments are performed to study the variation of the poison concentration as a function of the length of the jet. The discharge rate is calculated from the volume of the poison discharged. The discharge rates for different injection pressures and penetration depths are shown in Table 1. The volume of the poison cone can be calculated mathematically. A least-square fit is then done on these experimental discharge rates using the calculated volumes of the poison jets.

The volume of the cone at any distance from the origin of the jet, from geometrical considerations (Fig. 4d), is given by

$$V(r) = \int_0^r \pi r^2 \tan^2\theta \, \mathrm{d}r. \tag{3}$$

The volume of the poison in the jet is then given by

$$D(r) = \int_0^r C(r)\pi r^2 \tan^2\theta \, \mathrm{d}r. \tag{4}$$

This volume of the poison is equal to the discharge rate obtained from the experiments. A least-square fit is done on these volumes of the poison, as obtained from the experiments, with the calculated volumes of the poison. The fitting curve is plotted in Fig. 5.

The formula for the decrease in concentration used in this fitting is assumed to be $C(r) = A/r^k$. The value of k for which the deviation was a minimum is then estimated. This exercise is then carried out for all the different experiments and the value of k found to vary between 1.0 and 1.2, as shown in Table 2. In order to be conservative in our estimate of the reactivity worth we decide to take 1.25 as the value of k. The constant A is then determined in the limit of $r = 0$, where the concentration would be that in the discharge tank. So

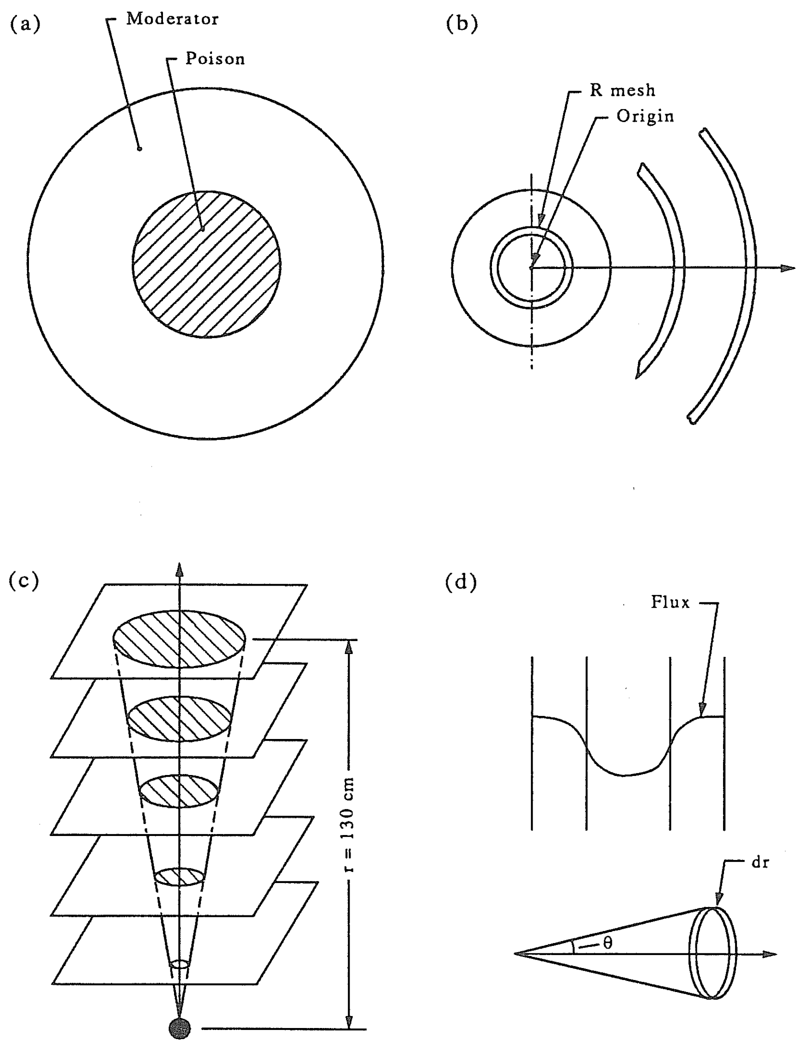

Fig. 4a–d.

the concentration of the poison at any point along the axis of the jet is given by

$$C(r) = \frac{C_0}{r^k}, \tag{5}$$

where C_0 is the initial concentration or the concentration in the poison tank and r is any point on the axis of the poison jet.

4.3. *Transport theory model for the jets*

The flux distribution over a moderator–poison region is obtained using a two-dimensional transport theory code. The code used for this purpose is CALC (Kapil and Balaraman, 1975), which solves the Boltzmann transport equation using the DS_n formalism to obtain the angular fluxes as a function of space and direction.

The transport equation can be written as

$$\mathbf{\Omega} \cdot \operatorname{grad} \phi_g(\mathbf{r}, \mathbf{\Omega}) + \Sigma_t^g(\mathbf{r})\phi_g(\mathbf{r}, \mathbf{\Omega})$$

$$= +\sum_{g'} \int_{\Omega'} \Sigma^{g' \to g}(\mathbf{r}, \mathbf{\Omega}' \to \mathbf{\Omega})\phi_{g'}(\mathbf{r}, \mathbf{\Omega}')\, \mathrm{d}\Omega' + S_g(\mathbf{r}, \mathbf{\Omega})$$

$$+ \frac{\chi_g}{4\pi} \sum_{g'} \int_{\Omega'}^{g} \nu\Sigma_f^{g'}(\mathbf{r})\phi_{g'}(\mathbf{r}, \mathbf{\Omega}')\, \mathrm{d}\Omega'. \tag{6}$$

Table 1. Volume of poison discharged vs jet length: experimental data

		Injection Pressures			
10 kg/cm^2		15 kg/cm^2		20 kg/cm^2	
Jet length (cm)	Volume of poison discharged (cm^3)	Jet length (cm)	Volume of poison discharged (cm^3)	Jet length (cm)	Volume of poison discharged (cm^3)
		Hole size = 3.2 mm			
20.0	6.913	40.0	24.478	40.0	22.22
30.0	13.826	50.0	36.716	60.0	44.44
40.0	24.195	60.0	48.955	70.0	57.772
60.0	43.39	70.0	65.274	80.0	75.548
70.0	62.216	80.0	85.672	100.0	124.432
80.0	79.498	90.0	110.15		
		Hole size = 4.0 mm			
40.0	24.888			40.0	22.121
60.0	49.776			60.0	49.774
70.0	66.368			70.0	66.365
80.0	87.108			80.0	82.956
90.0	111.996			100.0	127.199

This is the neutron balance equation. The angular variable $\bar{\mu}$ is expressed as

$$\phi(\mathbf{r}, \boldsymbol{\Omega})\, \mathrm{d}\boldsymbol{\Omega} = \phi(r, \bar{\mu})\, \mathrm{d}\bar{\mu}, \tag{7}$$

where $\bar{\mu} = \cos\theta$; θ is the angle between the direction of motion of the neutron and the radius vector.

The flux in the transport equation is a function of position, time, direction of flow and the neutron speed. The transport equation is solved by first discretizing the energy variable. In the DS_n method the other variables, i.e. position and angle, are also discretized.

The integro-differential form of the transport equation includes terms depending on the scalar flux, which is obtained by integration of the angular fluxes over the direction variable. This is done numerically.

The method of solution used here is the discrete ordinates method. The angular variable $\bar{\mu}$ is divided into discrete directions. The scalar flux is then obtained by a suitable weighted sum of fluxes along these directions. A mesh in the $(r, \bar{\mu})$ domain is defined as shown in Fig. 6. The order of quadrature used is S_8, which means the angular variable has been divided into 8 discrete directions. Here, the discrete form of the transport equation is derived as a conservation equation over a cell, which in the limit of small steps in variables is shown to reduce to the Boltzmann transport equation.

The transport equation in the finite-difference form in the DS_n formalism can be written as

$$\begin{aligned} & w_m \mu_m (A_{i+1,j+1/2} N_{i+1,j+1/2,m} - A_{i,j+1/2} N_{i,j+1/2,m}) \\ & \quad + (\alpha_{m+1/2} N_{i+1/2,j+1/2,m+1/2} - \alpha_{m-1/2} N_{i+1/2,j+1/2,m-1/2}) \\ & \quad + w_m \eta_m (B_{i+1/2,j+1} N_{i+1/2,j+1,m} - B_{i+1/2,j} N_{i+1/2,j,m}) \\ & \quad + \Sigma_{\mathrm{tr}} w_m N_{i+1/2,j+1/2,m} V_{i+1/2,j+1/2} \\ & = w_m V_{i+1/2,j+1/2} S_{i+1/2,j+1/2,m}, \end{aligned} \tag{8}$$

where w are the directional weights and μ and η are the direction cosines; A and B are the areas of the (i, j) mesh perpendicular to the i- and j-directions; V is the volume element and S is the source. These equations are solved using a diamond differencing scheme, in which, the cell-average angular flux is the arithmetic mean of the angular fluxes at the opposite boundaries of the cell in the space and angle-phase space. A typical flux distribution calculated using this formalism is shown in Fig. 7.

4.4. Calculation of $\Delta\Sigma_a$ in the cell

The two-dimensional fluxes over the poison jet and the surrounding unpoisoned moderator obtained from the transport theory modelling are used to calculate the extra absorption in a given cell. The representative cell with its fuel, clad, coolant and moderator is already homogenized with space- and energy-dependent fluxes. We now assume that this homogenized cell is perturbed by the presence of the poison jets, as shown in Fig. 8. The two-dimensional flux distribution along the jet and in the surroundings, with proper accounting for the orientation of the jet within the cell, is taken explicitly and used to

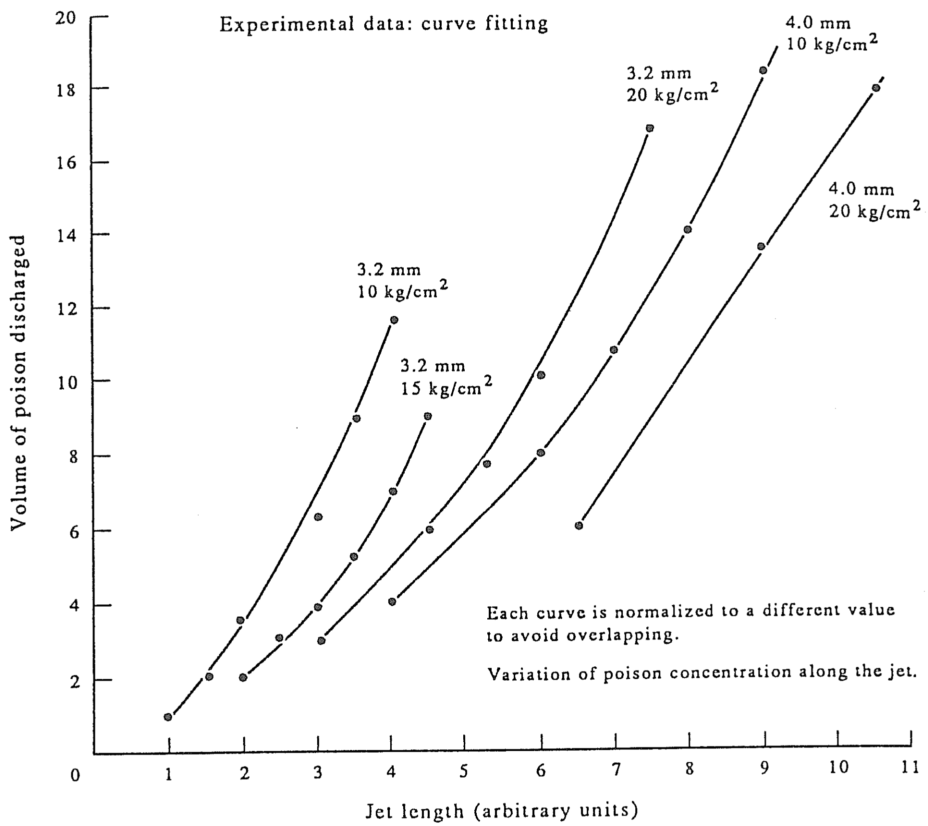

Fig. 5.

integrate for $\Delta\Sigma_a$ over the cell. The manner in which this integration is done over the jet is described below.

The homogenized cell is divided into thin strips of 1 mm thickness. Considering any strip shown in Fig. 8c, the extra absorption due to the presence of poison in that strip is evaluated over that strip by integrating over space. This integration is carried throughout the entire length of the jet. The $\Delta\Sigma_a$ is calculated by flux averaging. Any strip over the perturbed cell will have a poison region and a surrounding unpoisoned region.

Table 2. Least-square fitting for the factor *k*

Hole size (mm)	Pressure (kg/cm^2)	*k*
3.2	10.0	1.17401
	15.0	1.1557
	20.0	1.23875
4.0	10.0	1.08572
	20.0	1.17401

The space-wise flux distribution obtained from the earlier transport theory calculations is integrated over the strip. This integration is carried throughout the length of the strip and the $\Delta\Sigma_a$ is calculated as a function of the distance from the origin of the jet. We now get a parametric curve for the extra absorption over a cell due to the presence of poison as a function of the distance from the origin of the jet (Fig. 9).

The extra absorption over any strip in Fig. 8c is given by

$$\Delta\Sigma_a = \frac{\int_{x_1}^{x_2}\int_{y_1}^{y_2} \Sigma_a(x, y)\phi(x, y)\,dx\,dy}{\int_{x_1}^{x_2}\int_{y_1}^{y_2} \phi(x, y)\,dx\,dy}. \tag{9}$$

This is a function of the distance of the strip along the jet from the poison tube. In order to calculate the $\Delta\Sigma_a$ in a three-dimensional reactor lattice cell, proper volume weightages are given to the other dimensions.

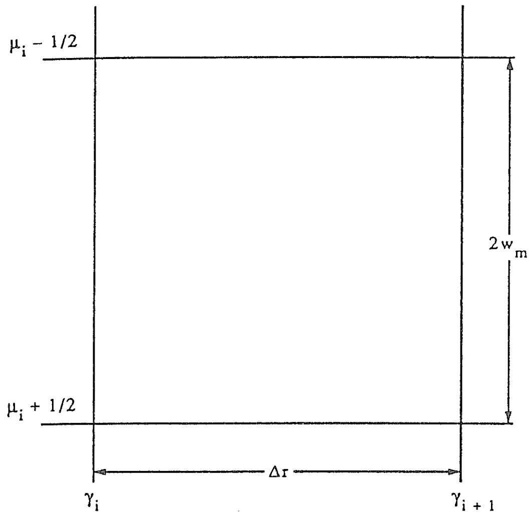

Fig. 6. (r, μ) mesh.

The total contribution due to any jet of any length is then read directly from this graph.

A program, ODEON, which does all this has been written and forms part of the KONICA code system.

4.5. *Identification of poisoned cells*

The individual cells perturbed by the poison are identified using the jet distribution and the jet propagation profile obtained from the experiments. Given a particular jet distribution consisting of the total number of jets issued, their penetration depths and their orientations with respect to the poison tube, the cells encountered by the poison jets are determined.

The whole-core calculation is done in cartesian geometry, where the finite reactor is divided into a number of meshes. One mesh corresponds to one fuel bundle. A coordinate system is laid down upon the reactor core, so that the Z-axis is along the axis of the horizontal cylindrical reactor vessel and the Y-axis is in the vertical direction. The positions of the poison tubes are marked out with respect to this coordinate system. The course of the poison jets is then mapped over the reactor cell grid and the individual cells affected by the poison are identified. A code, ALPHA, has been written which identifies each poisoned cell and its location, given any jet distribution.

A cell could be perturbed by any number of jets and the length of a jet inside a cell could be different depending upon its orientation. The total extra absorption of that cell is taken as the sum of the contributions due to all these jets as if they were present individually. These absorptions are calculated for all such poisoned cells using the code LIBRA. This code compiles the absorptions due to all the poisoned cells in the reactor and prepares an extra absorption table for any given configuration during the operation of SDS-2.

4.6. *Global reactivity calculations*

Having obtained the $\Delta\Sigma_a$ as a function of space in the reactor, the reactivity worth of SDS-2 is determined from the whole-core calculation. This basically involves the three-dimensional core simulation of the 500 MW(e) PHWR core in cartesian geometry and the calculation of k_{eff}. The whole-core calculation is done using a two-group diffusion theory code. The coupled two-group diffusion equations can be written as

$$D_1\nabla^2\phi_1 - \Sigma_{a1}\phi_1 - \Sigma_{r1}\phi_1 + \frac{\chi_1}{k_{eff}}\sum_j(\nu\Sigma_{fj})\phi_j = 0 \qquad (10)$$

and

$$D_2\nabla^2\phi_2 - \Sigma_{a2}\phi_2 - \Sigma_{r2}\phi_2 + \Sigma_{r1}\phi_1 + \frac{\chi_2}{k_{eff}}\sum_j(\nu\Sigma_{fj})\phi_j = 0, \qquad (11)$$

where the symbols have their usual meaning. The poisoned cells have also been identified. These diffusion equations are solved over the finite reactor and the flux distribution and k_{eff} calculated using finite-difference methods. The reactivity is then given by

$$\rho = \frac{k_1 - k_2}{k_1 k_2}, \qquad (12)$$

where k_2 is the k_{eff} without SDS-2 operating and k_1 is that with SDS-2 operating.

A code system has been developed for calculation of the reactivity worth of SDS-2. A detailed flow-chart of the calculational scheme is shown in Fig. 10. The entire reactivity calculation is done by the code system KONICA, this entails the treatment of a single jet with its surrounding unpoisoned moderator, the $\Delta\Sigma_a$ calculation as a function of the distance of the jet from the poison tube, the calculation of the total contribution to the absorption in a cell and, finally, the reactivity worth calculation of each of these involving inputs of different kinds as illustrated.

4.7. *Other spatial effects*

The jet distribution in the actual reactor will be disturbed by the presence of the calandria tubes and

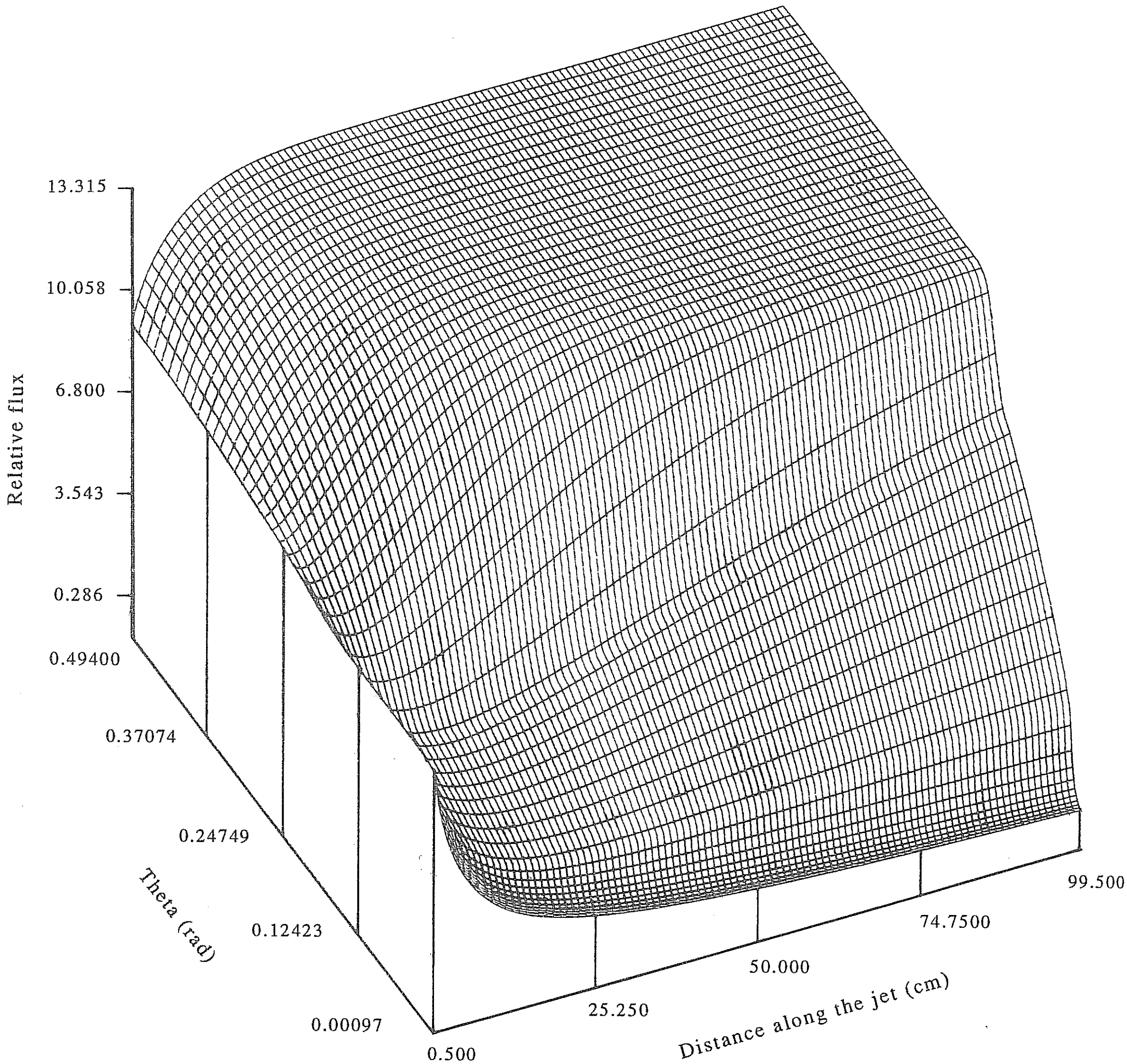

Fig. 7. Flux distribution over an R–θ domain in a plane perpendicular to the poison tube.

other in-core structures. Also, jets issuing from neighbouring holes could interact with one another depending on the jet spread. These interactions should be properly accounted for. We now present our approach to these reactor-specific situations where the jets are disturbed.

4.7.1. Interaction between neighbouring jets. There are 4 sets of holes between 2 pitches. Each set is separated by about 3.0 cm. Jets issuing from these holes will interact with one another and the contribution to the absorption in the cell will be altered. The approach is to calculate an effective $\Delta\Sigma_a$ by calculating an interaction factor for the interacting jets in any cell. Consider a cell with interacting jets, as shown in Fig. 11a. A one-dimensional transport theory calculation is done and the flux distribution over the cell, with a central poison region of uniform concentration which is the cross-section of the poison cone, is calculated. The interaction factor is calculated using this flux distribution and by assuming maximum interaction where the poison concentration would be double. This is done throughout the length of the jet at various distances from the origin of the jet where the poison concentration also varies.

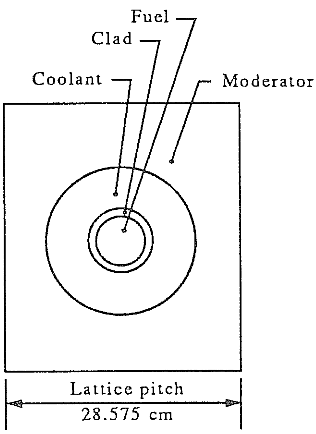

Fig. 8a. Reactor lattice cell.

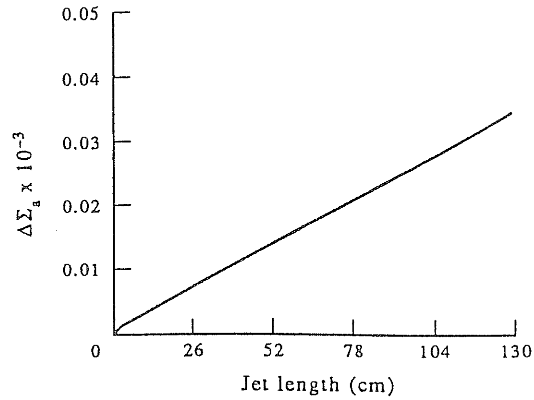

Fig. 9. Contribution to Σ_a (thermal) of the cell.

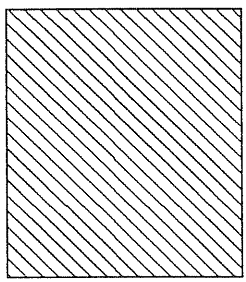

Fig. 8b. Homogenized reactor lattice cell.

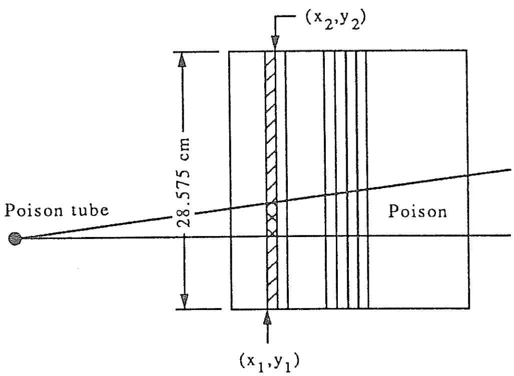

Fig. 8c. Poisoned lattice cell.

4.7.2. Terminated or hampered jets. The effects of jets hitting the calandria tubes is also accounted for. The poison tubes are perpendicular to the calandria tubes. The poison jets coming out of the poison tubes are at different orientations. Some of these jets could hit the calandria tubes (Fig. 11b). Once they hit the calandria tubes they no longer remain conical. These hampered jets then have to be treated differently. After they hit the calandria tubes, they are considered to be cylindrical in shape. The concentration of the poison would also remain constant. The course of the jet is the same up to the point where they hit the calandria tubes, after which the $\Delta\Sigma_a$ would be the same because of the nature of the geometry. There would be some spread in the jet, but we have ignored this spread in order to be conservative in estimation of the worths of the poison jets.

5. METHOD OF ANALYSIS

The reactivity worth which the system will have in the actual reactor is indicative of its adequacy. To this end, it is important to compute the worth and also to make a complete safety analysis of various accident scenarios in the reactor on the assumption that SDS-1 has failed and the integrity of the reactor is dependent on the efficacy of SDS-2. It is also necessary to evaluate the worth of the system under various core configurations and in the presence of other reactivity devices in the core.

The jet growths at each pitch as a function of time, the injection pressure, the volume of the poison, the jet spread etc. have been studied in detail elsewhere (Nawathe *et al.*, 1991). The penetration depth at each pitch depends upon the hydrodynamics of the system. It is the negative reactivity insertion during the first second that is of greater importance to the safety function of SDS-2. The reactivity worth of SDS-2 is calculated as a function of time for different injection pressures and nozzle dimensions. These calculations are not continued beyond 1 s at this stage. Also, the

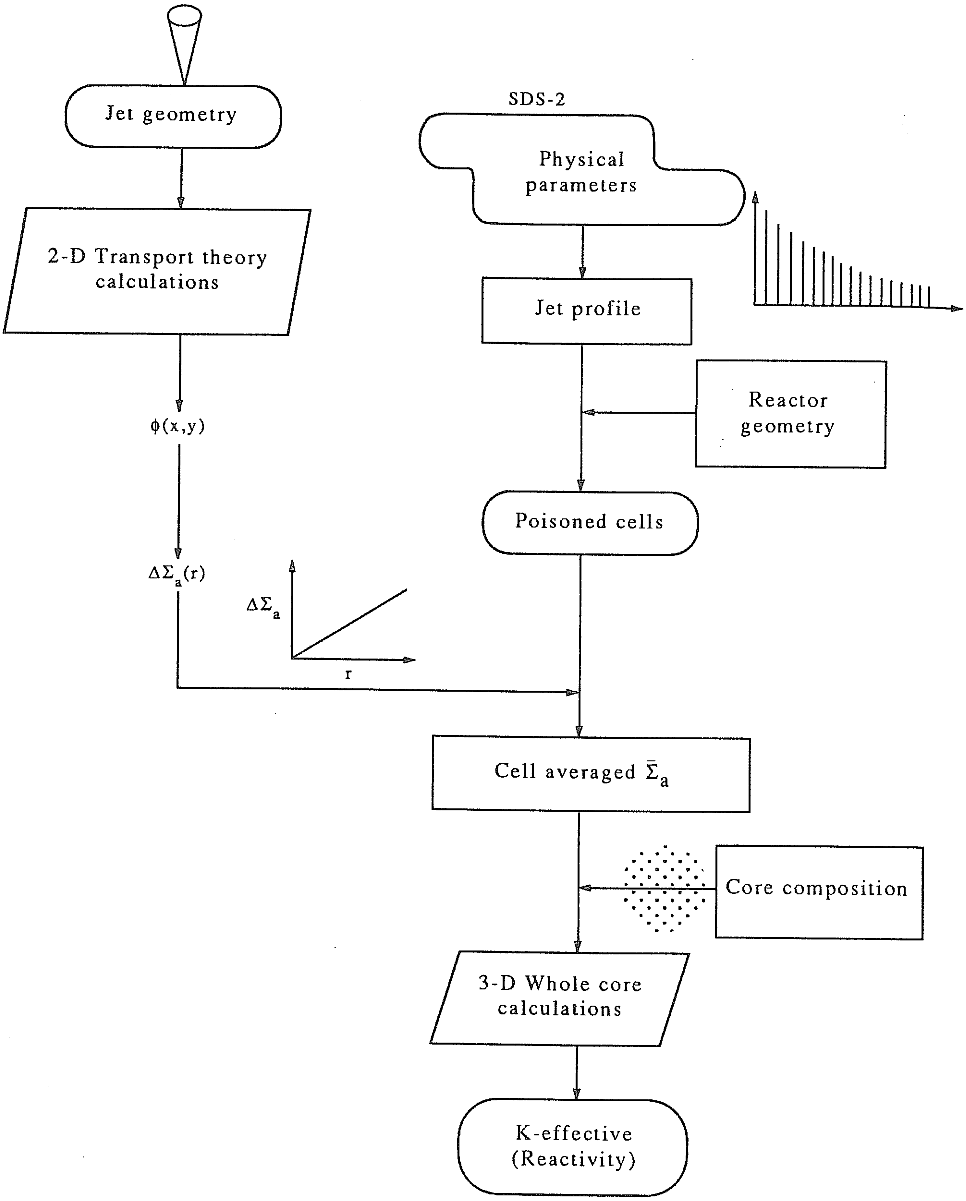

Fig. 10. Simplified flow-chart of the computer code KONICA for calculation of the reactivity worth of SDS-2.

worths have been evaluated in the presence of other reactivity devices, such as adjusters and zonal control units (ZCU).

The following calculations have been done:

I. Reactivity worth as a function of time for a fresh core with all natural uranium loading. No xenon and no reactivity devices.
 (i) Injection pressure = 40 kg/cm^2; hole sizes = 3.2 and 4.0 mm.
 (ii) Injection pressure = 60 kg/cm^2; hole sizes = 3.2 and 4.0 mm.
 (iii) Injection pressure = 80 kg/cm^2; hole sizes = 3.2 and 4.0 mm.

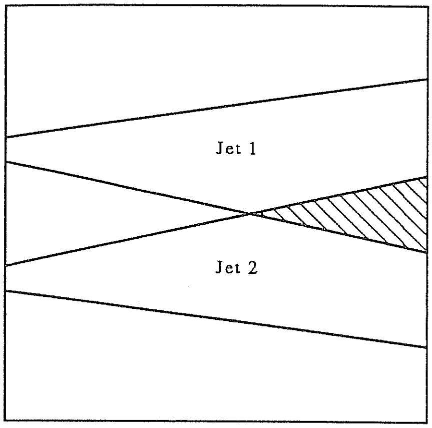

Fig. 11a.

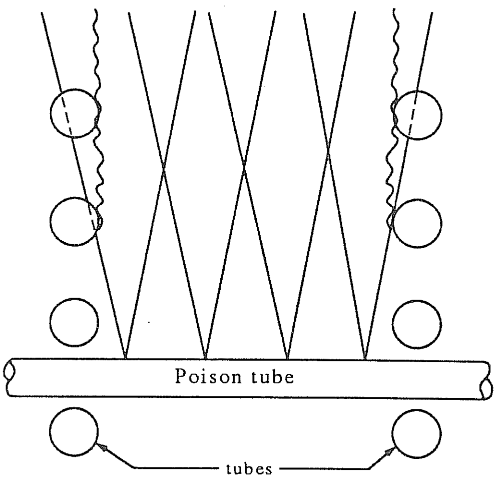

Fig. 11b.

II. Reactivity worth of SDS-2 in the presence of other reactivity devices and various core loadings. The jet growth considered was that of fully formed jets (i.e. at 1 s) for an injection pressure of 80 kg/cm^2.
  (a) Fresh core; all natural uranium loading; no xenon.
    (i) No reactivity devices.
    (ii) Adjusters present.
    (iii) ZCU present.
    (iv) Both adjusters and ZCU present.
  (b) Equilibrium core; 8350 MWd/te/6450 MWd/te.
    (i) No reactivity devices.
    (ii) Adjusters present.
    (iii) ZCU present.
    (iv) Both adjusters and ZCU present.

6. RESULTS

At present, only phase I of the experiments (Nawathe *et al.*, 1991) has been completed. The complete evaluation of the system will be done after the phase II experiments using the full-scale mockup have been carried out. However, the worth evaluation for the system based on the phase I experiments has been made. This paper presents the calculations based on the phase I experiments on jet growth studies.

The reactivity worth of SDS-2 calculated based on the above scheme is tabulated in Tables 3 and 4. The jet growths obtained from the experiments have been analysed. A full-scale mockup experiment is planned for the future when these calculations will be repeated.

6.1. Zero time

The time $t = 0$ corresponds to the moment of valve opening. The poison released from the tank would take some finite time to reach the first set of holes.

Table 3. Reactivity worth as a function of time and injection pressure

	4.0 mm		3.2 mm	
Pressure (kg/cm^2)	Time (s)	Reactivity worth (mk)	Time (s)	Reactivity worth (mk)
	0.4	0.096	0.4	0.0791
	0.5	3.21	0.5	2.989
40.0	0.6	9.626	0.6	9.429
	0.9	30.96	0.9	31.256
	1.0	38.65	1.0	39.24
	0.4	2.75	0.4	2.538
	0.5	10.605	0.5	10.318
60.0	0.6	19.57	0.6	19.581
	0.9	47.568	0.8	37.648
	1.0	57.80	1.0	58.767
	0.3	0.422	0.3	0.343
	0.4	7.272	0.4	7.032
	0.5	17.68	0.5	17.46
80.0	0.6	27.44	0.6	27.684
	0.8	50.01	0.8	50.986
	0.9	61.63	0.9	62.74
	1.0	73.418	1.0	75.425

Table 4. Reactivity worth of SDS-2 for various loadings (injection pressure = 80 kg/cm^2; time after the moment of valve opening = 1 s)

	Reactivity Worths (mk)			
	Fresh core		Equilibrium core	
Reactivity device	3.2 mm	4.0 mm	3.2 mm	4.0 mm
No device	70.73	69.121	69.95	68.805
Adjusters in	64.768	63.917	60.788	60.17
ZCU present	70.416	68.915	69.423	68.338
Adjusters+ZCU	61.45	60.852	57.165	56.77

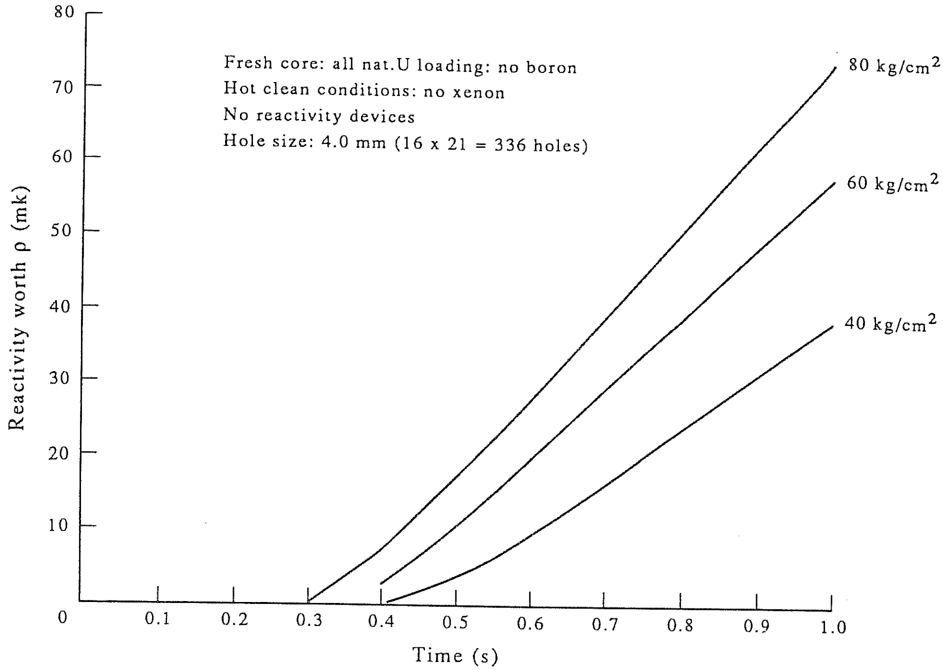

Fig. 12. Reactivity worth vs time for 4.0 mm holes for SDS-2 of a 500 MW(e) reactor.

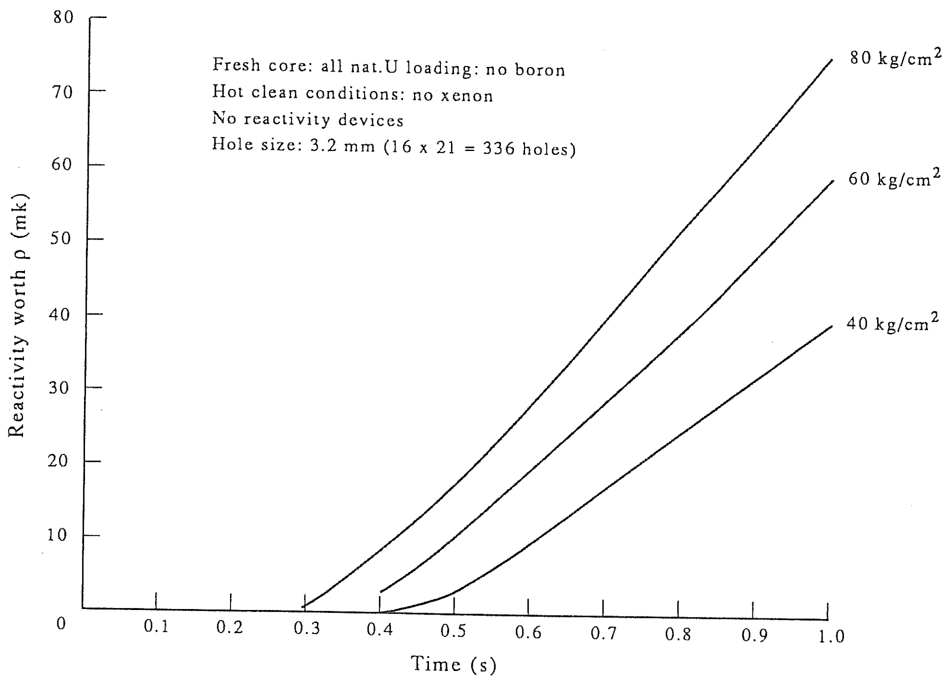

Fig. 13. Reactivity worth vs time for 3.2 mm holes, for SDS-2 of a 500 MW(e) reactor.

But other delay times, like sensing if SDS-1 has not operated and the electrical circuit delays, have not been accounted for. In actual safety analyses, these delays have to be added before the zero time as defined here.

6.2. Reactivity worth calculations

A preliminary calculation for the design of 16 holes between 2 pitches, i.e. 336 holes in all with no reactivity devices, was done for a fresh core and with all natural uranium loading; the results are tabulated in Table 3. For a hole size of 4.0 mm the worths calculated are 38.65 mk for an injection pressure of 40 kg/cm^2, 57.80 mk for 60 kg/cm^2 and 73.42 mk for a pressure of 80 kg/cm^2. For a hole size of 3.2 mm the calculated worths are 39.24, 58.76 and 75.42 mk, respectively, for the three pressures. The negative reactivity as a function of time and injection pressures is plotted in Figs 12 and 13.

The worths in the presence of reactivity devices in both the fresh fuel loading and equilibrium fuel loading are tabulated in Table 4, where the case of fully formed jets and an injection pressure of 80 kg/cm^2 is considered. The worth of SDS-2 in the presence of both adjusters and ZCU for the equilibrium loading was found to be 56.77 mk.

7. CONCLUSIONS

Although the final confirmation will have to come from the full-scale mockup experiment which is being planned, it is fairly clear that the liquid poison injection system that has been designed and described above will be found reasonably adequate in providing fast shutdown capability for the PHWR. The size of the holes does not appear to have a great effect on the reactivity worths that are possible with this system. On the other hand, the worth seems to be very sensitive to the injection pressure. It is however possible, that the hole size could make a difference for sizes very different from those considered here. The smaller holes give larger worths due to the fact, that for the same pressure, the jet travels longer distances. For comparatively large holes, the worth could reduce quite drastically because all the poison might be discharged from the first few holes, thus defeating the objective of rapidly disseminating the poison throughout the moderator body, which is the basic aim of the poison injection system. For very small holes, it is possible that the 7° divergence of the jet may not materialize; also, the discharge rate may be so slow that it may take a long time to achieve the full worth.

One other conclusion drawn from these experiments is that adequate worths are as possible with holes as with slits.

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