Ann. Nucl. Energy, Vol. 21, No. 1, pp. 1–9, 1994
Printed in Great Britain.

0306-4549/94 $6.00+0.00

OPTIMIZATION OF THE INITIAL FUEL LOADING OF THE INDIAN PHWR WITH THORIUM BUNDLES FOR ACHIEVING FULL POWER

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(Received 9 June 1993)

Abstract—When attempting initial power flattening with thorium bundles, the placement of the bundles should take into account not only the need for power flattening, but also the fact that sharp flux depressions caused by the presence of thorium can alter the reactivity worth of shutdown systems. Since the safety assessment of the reactor is made under the assumption of certain shutdown worths, it is important that these worths are not disturbed by the fuel loading. We describe here a method by which this problem is tackled. The thorium loading that was worked out using this method was found to satisfy all the desired criteria of full power, and no loss of worth of the two independent shutdown sysems. This loading has been used in the Indian PHWR at Kakrapar, the KAPS-1, which went critical on 3 September 1992.

1. INTRODUCTION

The Indian Pressurized Heavy Water Reactor (PHWR) is a tube-type reactor fuelled with natural uranium, and using heavy water as both coolant and moderator. The coolant is physically separated from the moderator by being contained inside the pressure tube where it is maintained at high temperature (~270°C) and pressure. The moderator heavy water is at a relatively low temperature (~55°C) and unpressurized.

The reactor core consists of 306 pressure tubes arranged along a square lattice of 22.86 cm pitch. The fuel pins and the coolant are contained within these pressure tubes. The direction of coolant flow in adjacent channels is in opposite directions. The fuel is in the form of a string of 12 bundles, each bundle is a 19-rod cluster of 49.5 cm length. Of the 12 bundles, 10 are in the active portion of the core, the remaining 2, 1 on each end, are outside the core.

Refuelling is done on-power by simply pushing out 8 bundles from a channel on one end, while 8 fresh bundles are inserted from the other end. The direction of the bundle movement is the same as that of the coolant flow, so that alternate channels are fuelled in opposite directions. This helps in maintaining overall axial symmetry.

Table 1 gives a general description of some of the important physical parameters of the core of the Indian PHWR.

2. REACTIVITY DEVICES

The core contains various reactivity devices. These are:

(a) The SDS-1: the primary shutdown system. This system consists of 14 mechanical shutoff rods whose absorber element is a hollow cadmium cylinder sandwiched in stainless steel (M1, M2, ..., M14).

Table 1. Description of the PHWR reactor core

No. of fuel channels	306
Lattice pitch	22.86
Calandria inner radius (cm)	299.8
Calandria length (cm)	500.0
No. of bundles per channel inside the active portion of the core	10
Extrapolated core radius (cm)	303.3
Extrapolated core length (cm)	508.5
No. of absorber rods (for xenon override)	4
No. of regulating rods (for reactor regulation)	2
No. of shim rods (to provide backup for regulation)	2
No. of mechanical shutoff rods (SDS-1)	14
No. of liquid poison tubes (SDS-2) shut down system)	12
Total thermal power to coolant (MWth)	756
Maximum channel power (MW)	3.2
Maxiumum bundle power (MW)	440
Maximum coolant outlet temperature (°C)	299
Reactivity worth of SDS-1 (mk)	31.9
Reactivity worth of SDS-2 (mk)	32.1
Coolant inlet temperature (°C)	249
Average fuel temperature (°C)	625
Average coolant temperature (°C)	271

(b) The SDS-2: the secondary shutdown system. This system consists of 12 zircaloy tubes running vertically inside the core. A solution of lithium pentaborate is injected into these tubes for fast shutdown. These are generally referred to as liquid poison tubes (L1, L2, . . . , L12).

(c) The adjustor rods: these are provided for xenon override. They are 4 in number and, in their nominal position, they are fully inserted into the core. They are normally referred to as ARs (A1, A2, A3, A4).

(d) The regulating rods: their function is to provide fine control for reactivity regulation. There are 2 of these, and their nominal position is at an insertion of 80% into the core. They are referred to as RRs (R1, R2).

(e) The shim rods: they serve as backup for the RRs. They are 2 in number, and their nominal position is outside the core. They are referred to as SRs (S1, S2).

3. POWER DISTRIBUTION

Once the reactor has attained conditions of equilibrium fuelling, the core is treated as consisting of two radial regions for the purpose of fuelling. The fuel in the inner region is discharged at a higher burnup than that in the outer region. Thus, the average burnup in the inner region is higher than that in the outer region, and therefore its reactivity is lower. This leads to a power flattening in the inner region so that more power can be extracted from the core than if the burnup had been uniform throughout. The rated power of the reactor, or the nominal power as it is called, is calculated using this power distribution.

At the beginning of core life, when the entire core is loaded with fresh fuel, the power distribution is highly peaked in the centre, and it will not be possible to get the full rated power from the core unless some other way of achieving power flattening were followed. The normal practice in CANDU-type reactors is to flatten the power distribution by loading some depleted uranium bundles in the central region of the core. This was also the practice followed in the Indian reactors RAPS, MAPS and NAPS.

In India, however, there is an incentive for replacing the depleted uranium by thorium bundles because the ^{233}U generated in these bundles can be used to initiate thorium cycle studies, even if in a small way. Moreover, the number of thorium bundles to be fabricated will also be much smaller than that required in the case of depleted uranium.

The other side of the thorium picture is that thorium, being a much stronger absorber than depleted uranium, causes stronger flux depressions in its vicinity. Thus, there is a likelihood of the worth of the reactivity devices being affected.

4. EVALUATING THE CORE LOAD PATTERNS

Study of the power distribution and reactivity worths in any given core loading pattern is carried out using the computer code DIMENTRI (Balakrishnan and Srinivasan, 1966), which solves the two-group diffusion theory equations using a finite-difference method. The lattice parameters used in the DIMENTRI calculations are obtained from a cell calculational code RHEA (Singh *et al.*, 1980), in which cell calculations are done in five-group integral transport theory and then the lattice parameters are collapsed into two groups.

DIMENTRI is used for the core loading calculations and each fuel bundle is represented by one mesh. The reactivity devices are represented by smearing over one or two bundles depending upon the location of the device *vis-à-vis* the centre of the nearest bundle.

5. INITIAL FUEL LOADING IN THE ABSENCE OF SHUTDOWN SYSTEMS

In the earlier PHWRs built in India (RAPS and MAPS), shutdown was achieved by dumping the moderator. Thus, shutdown was not dependent on reactivity devices entering the core and no constraint was imposed on the core loading pattern due to the presence and position of reactivity devices. In this case, the choice of core loading with thorium bundles in order to achieve power flattening was relatively easy. A straightforward way of placing thorium bundles in a small zone at the centre of the core gave adequate results. Such a loading is shown in Fig. 1 (this is referred to as Loading-I). This loading can give 95.1% power from the first day, and can be generally considered adequate in a PHWR that uses moderator dumping for reactor shutdown.

6. PHWR WITH IN-CORE SHUTDOWN SYSTEMS

In the present design of the Indian PHWR, the shutdown systems are in-core devices as described in Art. 2. The positions of SDS-1 and SDS-2 are indicated in Fig. 2, which is a view of the reactor from the top. Computations have shown that, with the thorium loading of Fig. 1, the reactivity worth of SDS-1 increases by 22.3%, while the worth of the SDS-2 decreases by 38.3%. This decrease of over 40% in the

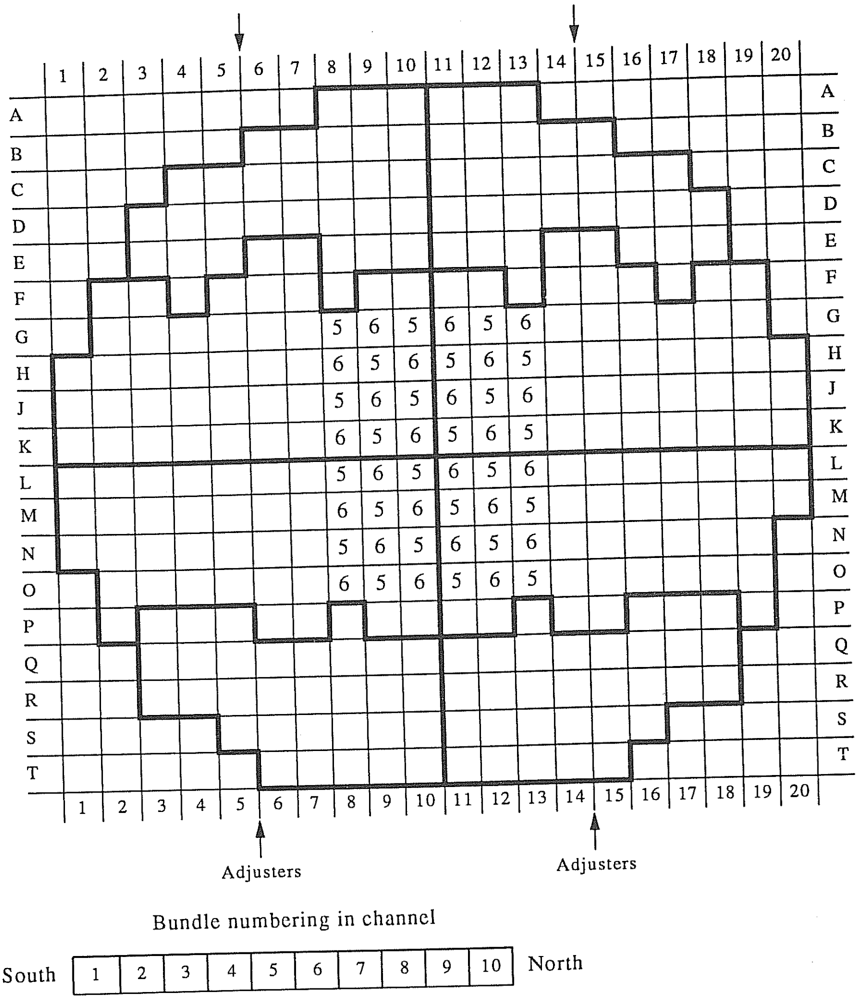

Fig. 1. Thorium Loading-I. There are 48 thorium bundles; the axial positions of the bundles in the channel are indicated by Arabic numerals. The remaining 3012 bundles are natural uranium.

worth of the SDS-2, which is a safety system, is clearly unacceptable.

The objective of the work presented in this paper was to develop an optimization technique that can be used to determine a loading of thorium bundles which avoids this kind of loss in the worth of the SDS-2.

7. THE OPTIMIZATION PROBLEM

The problem is formulated by identifying the following entities:

(a) The objectives of the optimization problem have to be chosen. In the case of the problem herein, these are:

- (i) The power produced by the maximum rated bundle in the reactor should be minimized.
- (ii) The power produced in the maximum rated channel in the reactor should be minimized.
- (iii) The value of the coolant outlet temperature in the hottest channel should be minimized.
- (iv) The reactivity worth of SDS-1 should be maximized.
- (v) The reactivity worth of SDS-2 should be maximized.

(b) The next step is to choose the decision variables. Obviously, since our objective is to find a core loading that satisfies the conditions enumerated in (a) above, and since there are 3060 bundle

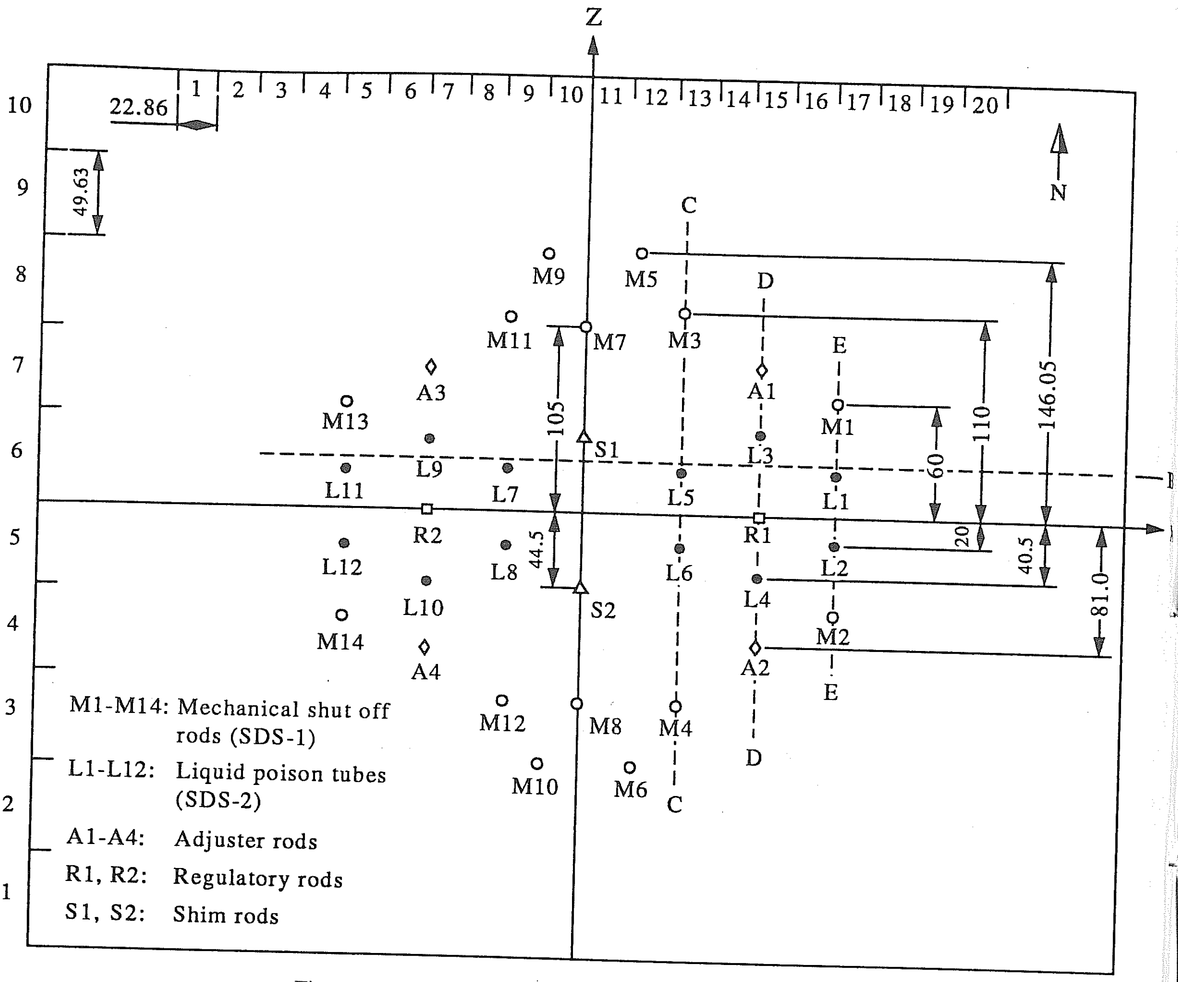

Fig. 2. Location of the reactivity devices in the PHWR.

positions in the core, each one with the possibility of being loaded with either a uranium bundle or a thorium bundle, one can conclude that there are 3060 decision variables having binary values of, say, 1 or 0. This, however, is not a very conducive situation for the application of optimization techniques, which are more easily applied when the decision variables are capable of taking up continuous values. It was therefore decided to choose as decision variables the distances of each thorium bundle from the various rods of SDS-1 and SDS-2, as also their distance from the reactor centre and the reactor boundary. Since there are 14 rods in SDS-1, 12 tubes of SDS-2, and of course the reactor centre and periphery, this makes 28 decision variables per thorium bundle. In addition, the number of thorium bundles was also treated as a decision variable. Since we expect the number of thorium bundles required to be approx. 30–40, this again gives the total number of decision variables to be around 1000. This problem can be tackled by declaring combinations of decision variables to be 1 decision variable. Thus, the 14 decision variables representing the distance of a thorium bundle could be combined into 1 variable by choosing the average distance from the 14 rods as 1 variable. Various combinations, with different weightages, have been tried, to reduce the number of decision variables. Finally, we have decided upon the following variables:

x_1: Number of thorium bundles.
x_2: Arithmetic average of the distances between all the thorium bundles and the rods of SDS-1, i.e. the average of $14 * x_1$ quantities.
x_3: Arithmetic average of the distances between all the thorium bundles and the tubes of SDS-2, i.e. the average of $12 * x_1$ quantities.
x_4: Arithmetic average of the distances of all the thorium bundles from the reactor centre, i.e. the average of x_1 quantities.
x_5: Arithmetic average of the distances of all the thorium bundles from the reactor periphery, i.e. the average of x_1 quantities. The distance considered here is the shortest distance to the reactor boundary.

(c) *Constraints.* Finally, some constraints are also imposed on the problem:

(i) The total power need not exceed 100%.
(ii) The maximum bundle power should not be more than 440 kW.
(iii) The maximum channel power should not exceed 3.08 MW.
(iv) The maximum coolant outlet temperature should not be more than 299°C.
(v) The decrease in worth of SDS-1 should not be more than 5%.
(vi) The decrease in worth of SDS-2 should not be more than 5%.
(vii) The total reactivity load of the thorium bundles should not exceed 20 mk.

8. THE OBJECTIVE FUNCTION

The next task is to set up the objective function that is to be minimized in this optimization problem. This has been chosen as

$$\mathrm{OF} = (W_b B)^2 + (W_c C)^2 + (W_t T)^2 + (W_1 S_1)^2 + (W_2 S_2)^2,$$

where

B = maximum bundle power in the core at 100% total power,
C = maximum channel power in the core at 100% total power,
T = maximum coolant channel outlet temperature in the core at 100% total power,
S_1 = decrease in worth of SDS-1 from its nominal value

and

S_2 = decrease in worth of SDS-2 from its nominal value.

The value of S_1 and S_2 is always taken as positive or zero. If it turns out to be negative, it is set equal to zero. Effectively, this means that if the worth of any of the SDS is higher than the nominal value, no credit is given for that. This is because we are interested only in making sure that the SDS worths do not decrease. While an increased SDS worth is definitely an advantage, we cannot define the objective function in such a manner that a loss is worth of one system can be compensated by a gain in worth of the other system.

The W are certain weight factors. These are needed to take care of the fact that different quantities are expressed in different units. This also permits us to attach different levels of importance to different quantities.

9. THE SOLUTION OF THE PROBLEM

In order to minimize the objective function, we define a figure-of-merit for each loading. To start with, we take the 5-dimensional vector which is a function of the five decision variables x_1, x_2, x_3, x_4 and x_5. This vector can be written as

$$[Y] = \begin{vmatrix} W_b B(x_1, x_2, x_3, x_4, x_5) \\ W_c C(x_1, x_2, x_3, x_4, x_5) \\ W_t T(x_1, x_2, x_3, x_4, x_5) \\ W_1 S_1(x_1, x_2, x_3, x_4, x_5) \\ W_2 S_2(x_1, x_2, x_3, x_4, x_5) \end{vmatrix}.$$

The objective function that we are seeking to minimize can now be written in the form

$$\mathrm{OF} = [Y^t][Y].$$

Next, we set up the Jacobian matrix of the objective function,

$$J = \begin{vmatrix} W_b \dfrac{\partial B}{\partial x_1} & W_b \dfrac{\partial B}{\partial x_2} & \cdots & W_b \dfrac{\partial B}{\partial x_5} \\ W_c \dfrac{\partial C}{\partial x_1} & W_c \dfrac{\partial C}{\partial x_2} & \cdots & W_c \dfrac{\partial C}{\partial x_5} \\ W_t \dfrac{\partial T}{\partial x_1} & W_t \dfrac{\partial T}{\partial x_2} & \cdots & W_t \dfrac{\partial T}{\partial x_5} \\ W_1 \dfrac{\partial S_1}{\partial x_1} & W_1 \dfrac{\partial S_1}{\partial x_2} & \cdots & W_1 \dfrac{\partial S_1}{\partial x_5} \\ W_2 \dfrac{\partial S_2}{\partial x_1} & W_2 \dfrac{\partial S_2}{\partial x_2} & \cdots & W_2 \dfrac{\partial S_2}{\partial x_5} \end{vmatrix}, \quad (1)$$

and its transpose J^t,

$$J^t = \begin{vmatrix} W_b \frac{\partial B}{\partial x_1} & W_c \frac{\partial C}{\partial x_1} & \cdots & W_2 \frac{\partial S_2}{\partial x_1} \\ W_b \frac{\partial B}{\partial x_2} & W_c \frac{\partial C}{\partial x_2} & \cdots & W_2 \frac{\partial S_2}{\partial x_2} \\ W_b \frac{\partial B}{\partial x_3} & W_c \frac{\partial C}{\partial x_3} & \cdots & W_2 \frac{\partial S_2}{\partial x_3} \\ W_b \frac{\partial B}{\partial x_4} & W_c \frac{\partial C}{\partial x_4} & \cdots & W_2 \frac{\partial S_2}{\partial x_4} \\ W_b \frac{\partial B}{\partial x_5} & W_c \frac{\partial C}{\partial x_5} & \cdots & W_2 \frac{\partial S_2}{\partial x_5} \end{vmatrix}. \quad (2)$$

The Gauss method, which we have used in our optimization study here, makes use of the recurrence equation:

$$[J^t J][\Delta \mathbf{X}] = -J^t[Y], \quad (3)$$

where [X] is the vector of the five decision variables

$$[\mathbf{X}] = \begin{vmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{vmatrix}. \quad (4)$$

Combining equations (3) and (4), we get

$$\begin{vmatrix} \sum_{i=1}^{5} J^t_{1i}J_{i1} & \sum_{i=1}^{5} J^t_{1i}J_{i2} & \sum_{i=1}^{5} J^t_{1i}J_{i3} & \sum_{i=1}^{5} J^t_{1i}J_{i4} & \sum_{i=1}^{5} J^t_{1i}J_{i5} \\ \sum_{i=1}^{5} J^t_{2i}J_{i1} & \sum_{i=1}^{5} J^t_{2i}J_{i2} & \sum_{i=1}^{5} J^t_{2i}J_{i3} & \sum_{i=1}^{5} J^t_{2i}J_{i4} & \sum_{i=1}^{5} J^t_{2i}J_{i5} \\ \sum_{i=1}^{5} J^t_{3i}J_{i1} & \sum_{i=1}^{5} J^t_{3i}J_{i2} & \sum_{i=1}^{5} J^t_{3i}J_{i3} & \sum_{i=1}^{5} J^t_{3i}J_{i4} & \sum_{i=1}^{5} J^t_{3i}J_{i5} \\ \sum_{i=1}^{5} J^t_{4i}J_{i1} & \sum_{i=1}^{5} J^t_{4i}J_{i2} & \sum_{i=1}^{5} J^t_{4i}J_{i3} & \sum_{i=1}^{5} J^t_{4i}J_{i4} & \sum_{i=1}^{5} J^t_{4i}J_{i5} \\ \sum_{i=1}^{5} J^t_{5i}J_{i1} & \sum_{i=1}^{5} J^t_{5i}J_{i2} & \sum_{i=1}^{5} J^t_{5i}J_{i3} & \sum_{i=1}^{5} J^t_{5i}J_{i4} & \sum_{i=1}^{5} J^t_{5i}J_{i5} \end{vmatrix} \cdot \begin{vmatrix} \Delta x_1 \\ \Delta x_2 \\ \Delta x_3 \\ \Delta x_4 \\ \Delta x_5 \end{vmatrix} = - \begin{vmatrix} \sum_{i=1}^{5} J^t_{1i}Y_i \\ \sum_{i=1}^{5} J^t_{2i}Y_i \\ \sum_{i=1}^{5} J^t_{3i}Y_i \\ \sum_{i=1}^{5} J^t_{4i}Y_i \\ \sum_{i=1}^{5} J^t_{5i}Y_i \end{vmatrix}, \quad (5)$$

which can then be written as

$$\sum_{j=1}^{5} \sum_{i=1}^{5} J^t_{1i}J_{ij}\Delta x_j = -\sum_{i=1}^{5} J^t_{1i}Y_i,$$

$$\sum_{j=1}^{5} \sum_{i=1}^{5} J^t_{2i}J_{ij}\Delta x_j = -\sum_{i=1}^{5} J^t_{2i}Y_i,$$

$$\sum_{j=1}^{5} \sum_{i=1}^{5} J^t_{3i}J_{ij}\Delta x_j = -\sum_{i=1}^{5} J^t_{3i}Y_i,$$

$$\sum_{j=1}^{5} \sum_{i=1}^{5} J^t_{4i}J_{ij}\Delta x_j = -\sum_{i=1}^{5} J^t_{4i}Y_i$$

and

$$\sum_{j=1}^{5} \sum_{i=1}^{5} J^t_{5i}J_{ij}\Delta x_j = -\sum_{i=1}^{5} J^t_{5i}Y_i.$$

This is a system of five simultaneous equations in Δx_1, Δx_2, Δx_3, Δx_4 and Δx_5. Solving it, we get the values of Δx_1 etc. and the next iterate for the decision variables becomes

$$x_1^{(n+1)} = x_1^{(n)} + \Delta x_1,$$

$$x_2^{(n+1)} = x_2^{(n)} + \Delta x_2,$$

$$x_3^{(n+1)} = x_3^{(n)} + \Delta x_3,$$

$$x_4^{(n+1)} = x_4^{(n)} + \Delta x_4,$$

and

$$x_5^{(n+1)} = x_5^{(n)} + \Delta x_5.$$

To start the solution, we take one set of values of the decision variables, $x_1(0)$, $x_2(0)$, $x_3(0)$, $x_4(0)$ and $x_5(0)$, carry out the core calculations and evaluate the objective function

$$(W_b B)^2 + (W_c C)^2 + (W_t T)^2 + (W_1 S_1)^2 + (W_2 S_2)^2.$$

Now make an arbitrary change in the decision variables, and choose $x_1(1)$, $x_2(1)$, $x_3(1)$, $x_4(1)$ and $x_5(1)$. All calculations are repeated for this set and the new value of the objective function OF(1) as well as the partial derivatives

$$\frac{\Delta B}{\Delta x_1}, \frac{\Delta B}{\Delta x_2}, \ldots, \frac{\Delta C}{\Delta x_1}, \ldots, \frac{\Delta T}{\Delta x_1}, \ldots,$$

are obtained. Equations (1)–(3) can be solved to give Δx_1, Δx_2, Δx_3, Δx_4 and Δx_5, and equation (5) used to get the new set of decision variables $x_1(2)$, $x_2(2)$, $x_3(2)$, $x_4(2)$ and $x_5(2)$. With each successive iteration, the difference between successive values of OF steadily decreases. The process is continued until convergence is achieved.

The success of the method depends upon the choice of decision variables, and the weight factors used in the objective function. Also, the translation of each new iterate of decision variables into a corresponding core configuration involves a fair bit of judgement. The choice of 5 variables appears to work reasonably well in this case.

10. RESULTS

Lattice parameters for both uranium and thorium cells were generated. Cell parameters modified for the presence of reactivity devices were also calculated at the outset for both uranium and thorium cells. The DIMEN3 calculations for the power distribution and for the worth of SDS-1 and SDS-2 were done at every iteration, which makes three whole core calculations for each iteration.

As far as the weighting factors are concerned, the results presented in this paper were obtained giving greater weightage to S_1 and S_2. The studies were made assuming all reactivity devices to be in the nominal configuration, i.e. all the mechanical shutoff rods M1, M2, . . . , M14 are outside the core, all the liquid poison tubes L1, L2, . . . , L12 are drained of the poison solution, the adjustor rods A1, A2, A3, A4 are fully inserted, the regulating rods R1, R2 are inserted to a depth of 80% and the shim rods S1, S2 are fully outside the core.

The application of the optimization method gives the loading shown in Fig. 3 (referred to as Loading-II).

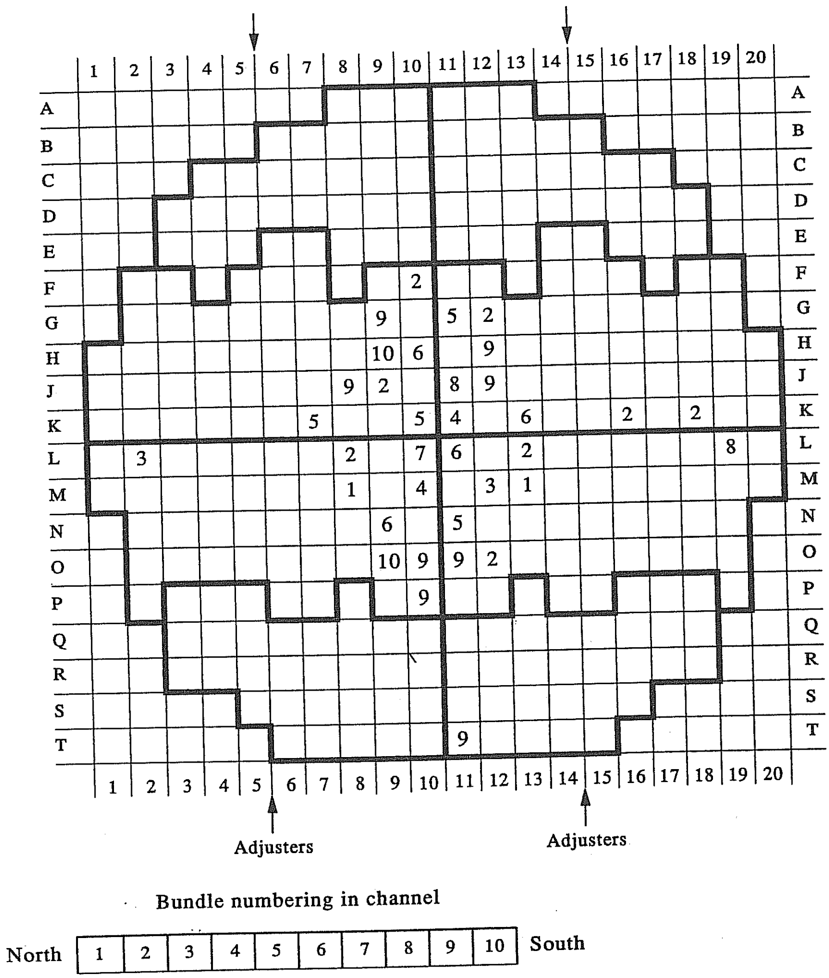

Fig. 3. Thorium Loading-II. There are 35 thorium bundles; the axial positions of the bundles are indicated by Arabic numerals. The remaining 3025 bundles are natural uranium.

Table 2. Comparison of the performance characteristics of the two thorium loadings

	Loading-I	Loading-II
No. of thorium bundles	48	35
Maximum channel power (MW)	3.02	3.01
Maximum bundle power (kW)	440	440
Maximum coolant outlet temperature (°C)	297.6	298.2
Total reactor power (MWth)	713	716
Power as fraction of nominal value	0.951	0.955
Reactivity load of the thorium bundles (mk)	16.8	13.6
Change in worth of SDS-1 (mk)	+7.11	+1.06
Change in worth of SDS-2 (mk)	−12.3	+1.01

As we can see, there are 35 bundles in this loading. They are spread over the core, unlike in Loading-I where they are all clustered around the centre. The first loading with which we initiated the calculations was Loading-I. It is also seen that in Loading-II, the thorium bundles are placed far from the shutoff rods and poison tubes.

Table 2 gives a comparison of the performance characteristics of the two loadings, Loading-I shows a loss of 12.3 mk in the reactivity worth of SDS-2. Since the system worth is 32.1 mk to begin with, this is not an affordable loss, Loading-II, which is the loading obtained using the optimization procedure described here, does not show any decrease in the worth of either SDS-1 or SDS-2. Other performance characteristics, like total power, maximum coolant outlet temperature and maximum channel power, are roughly the same. Loading-II also uses a smaller number of thorium bundles with a lower combined reactivity load. This, though, is not a particularly important point.

11. DISCUSSION

It is interesting to see how the placement of thorium bundles in the two loadings affects the flux shapes in the reactor, leading to the performance characteristics that are actually observed. Figures 4–7 show the spatial variation of the thermal flux in the reactor.

Figure 4 shows a plot of the thermal flux in the reactor along a horizontal line which passes close to the liquid poison tubes of SDS-2. This line is indicated by BB in Fig. 2. The flux has been normalized to a value of 100 in the maximum flux location in the reactor. The positions of the poison tubes are indicated in the figure, and we can clearly see how the flux in Loading-I dips all over the central part of the reactor, while that of Loading-II dips only in the very middle and stays at relatively high values near the

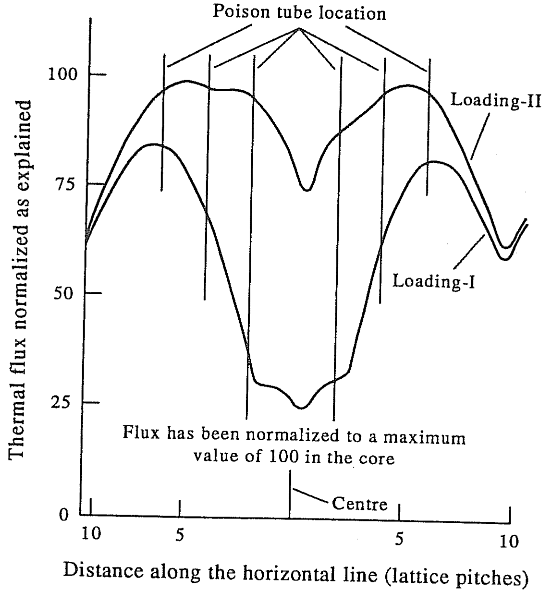

Fig. 4. Thermal flux in the PHWR core with thorium loading: along a horizontal line perpendicular to the axis and passing close to the poison tube locations (BB in Fig. 2).

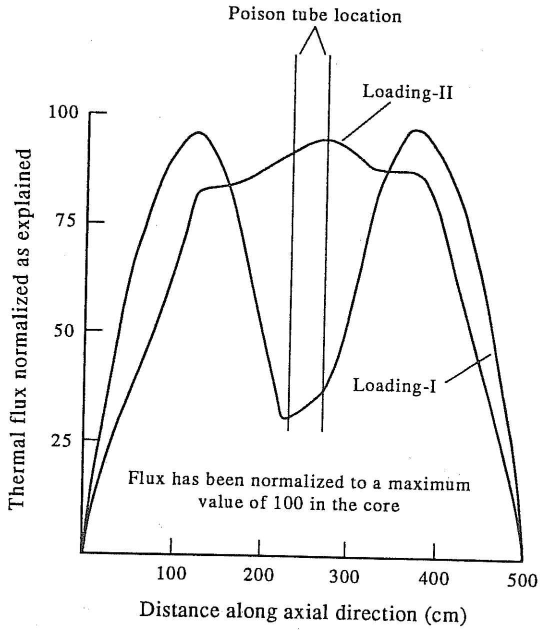

Fig. 5. Thermal flux in the PHWR core with thorium loading: along a line parallel to the axis and passing through the inner poison tube locations L5–L6 (CC in Fig. 2).

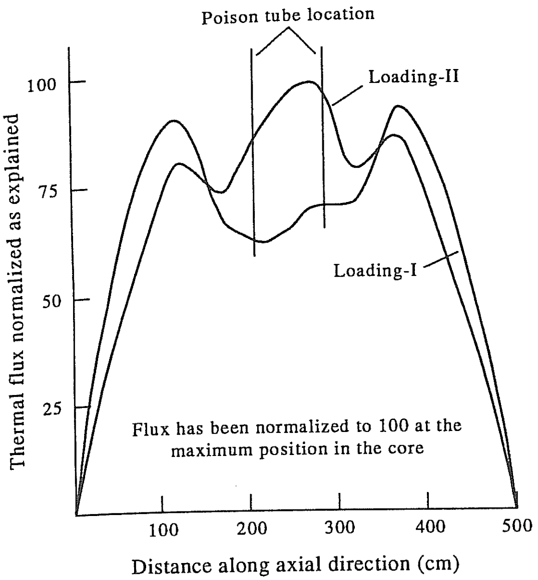

Fig. 6. Thermal flux in the PHWR core with thorium loading: along a line parallel to the axis and passing through the intermediate poison tube locations L3–L4 (DD in Fig. 2).

poison tube locations. This is a direct consequence of the selection of x_3 as one of the decision variables in the problem, which ensures that, on average, the thorium bundles cannot be placed very close to poison tube locations.

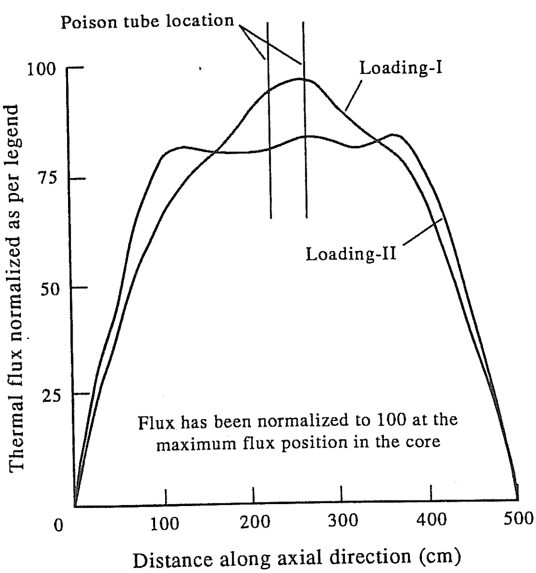

Fig. 7. Thermal flux in the PHWR core with thorium loading: along a line parallel to the axis and passing through the outer poison tube locations L1–L2 (EE in Fig. 2).

Figures 5–7 show the thermal fluxes along three lines parallel to the axis of the cylindrical core. Figure 5 is along a line passing through the two innermost poison tubes, i.e. line CC of Fig. 2. The flattening caused by the optimized loading is clearly visible against the deep flux depressions created by the lumped loading.

Figures 6 and 7 show fluxes along the outer poison tubes, lines DD and EE in Fig. 2. The same effect of high flux at the poison tube locations can be seen in these plots as well.

12. CONCLUSION

It can be concluded that this optimization method works fairly well. It is not possible to prove that this is the best solution. In fact, better solutions might exist. What is very clear, however, is that a placement of thorium bundles of the kind shown in Fig. 3 cannot be thought up without the use of some form of methodical approach, and the method given here, works well. On making slight changes in the loading it was found that there was a slight degradation in the performance characteristic. When changes were greater, the degradation was more. This of course, was only to be expected, since the essence of the method is to calculate the changes in the figure-of-merit as a result of changes in the decision variables, and then to make corresponding changes in the decision variables. At the very least, the method was bound to lead to a local minimum.

The configuration of Loading-II has been loaded into the initial core of Unit-1 of Kakrapar Atomic Power Station, which attained criticality on 3 September 1992. Startup experiments showed that measured shutdown worths were close to the estimated values. In fact, it is fairly certain that without using this method, it would have been difficult to find an initial core configuration which uses thorium bundles for power flattening without adversely affecting the reactivity worth of the shutdown systems.

Acknowledgement—The authors wish to express their gratitude to Dr P. K. Iyengar, erstwhile Chairman of the Indian Atomic Energy Commission, for his encouragement during the progress of this work.

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