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Reaktorsicherheit (GRS) mbH

GRS-Bericht

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A Digital Code for Real-Time Calculation of the Transient Behaviour of Nodal and Global Core and Plant Parameters of BWR Nuclear Power Plants

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Abstract

A program description of the code GARLIC-B is given. The code is based on a nonlinear transient model for BWR nuclear power plants which consist of a 3D-core, a top plenum, steam removal and feed water systems and a downcomer with main coolant recirculation pumps. The core is subdivided into a number of superboxes and flow channels with different coolant mass flow rates. Subcooled boiling within these channels has an important reactivity feed back effect and has to be taken also into account. The code computes the local and global core and plant transient situation as dependent on both the inherent core dynamics and external control actions, i.e., disturbances such as motions of control rod banks, changes of mass flow rates of coolant, feed water and steam outlet. The case of a pressure-controlled reactor operation is also considered.

The code is aimed to be used on an on-site process computer in parallel to the actual reactor process (or even in predictive mode). Thus, special measures had to be taken into account in order to increase the computational speed and reduce the necessary computer storage. This could be achieved by

- separating the neutron and power kinetics from the xenon-iodine dynamics,
- treating the neutron kinetics and most of the thermohydrodynamics in a pseudostationary way,
- developing a special coupling coefficient concept to describe the neutron diffusion.

The coupling coefficients are calculated from a basic neutron kinetics code, combining coarse mesh elements into superboxes, taking advantage of the symmetry properties of the core and applying a sparse matrix technique for solving the resulting algebraic power equation system.

The program structure, the arrangement of the input data and the form of the output are described in considerable detail.

Kurzfassung

Der vorliegende Bericht enthält die Programmbeschreibung des Codes GARLIC-B. Das Programm basiert auf einem nichtlinearen Transientenmodell für SWR-Kernenergieanlagen, die sich zusammensetzen aus einem dreidimensionalen Kern, einem Oberen Plenum, einem Frischdampf- und einem Speisewassersystem sowie einem Fallraum mit Kühlmittelumwälzpumpen. Der Kern ist unterteilt in eine Anzahl von Superboxen sowie eine Anzahl von Parallelkanälen, in denen das Kühlmittel mit unterschiedlicher Geschwindigkeit nach oben strömt (unterkühltes Sieden muß in Betracht gezogen werden). Das Programm berechnet das transiente Verhalten der lokalen und globalen Kern- und Anlagenparameter in Abhängigkeit sowohl von der inhärenten Kerndynamik als auch von Eingriffen von außen, wie z.B. Bewegungen der Regelstabbänke sowie Störungen in den Massenströmen der Hauptkühlmittelpumpe, des Speisewassers und der Dampfentnahme. Ein druckgeregelter Reaktorbetrieb kann ebenfalls simuliert werden.

Das Programm wurde so konzipiert, daß es auf einer im Reaktorgebäude befindlichen Prozeßrechneranlage ablauffähig ist, wobei der tatsächliche Prozeßverlauf im Reaktor entweder parallel oder sogar in prädiktiver Weise nachgerechnet werden soll. Die dadurch bedingten speziellen Anforderungen an das Verfahren, vor allem bezüglich schnellerer Rechenzeiten und Einsparungsmöglichkeiten im Speicherplatzbedarf, konnten erreicht werden durch

- Separation der Neutronen- bzw. Leistungskinetik von der Xenon-Jod-Dynamik,
- pseudostationäre Behandlung der Neutronenkinetik und Thermo- und Hydrodynamik,
- Einsatz eines Kopplungskoeffizientenkonzepts für die Darstellung der Neutronendiffusion.

Die Kopplungskoeffizienten aus Startrechnungen werden mit einem Basis-Neutronenkinetik-Code bestimmt durch Zusammenfassen

von Grobgitterboxen des Kerns in Superboxen. Dabei können gleichzeitig die Vorteile der Symmetrieeigenschaften des Reaktorkerns nutzbar gemacht und die resultierenden algebraischen Leistungsdichtegleichungen mit Hilfe einer Sparse-Matrix-Technik gelöst werden.

Der Programmaufbau, die Anordnung der Eingabedaten (eingelesen sowohl über ein Kartendeck als auch über Magnetbänder) sowie die Form der zu erwartenden Ausgabetabellen und -bilder werden ausführlich beschrieben.

CONTENTS

1. INTRODUCTION

Theoretical models and codes which can simulate the transient behaviours of the local and global core and plant parameters of nuclear power plants with reasonable computation speed and memory capacity are of interest because of their potential use in off-line simulations of the core and plant dynamics and on-line real-time applications for reactor core surveillance, state prediction and control.

Such an attempt has been made by "Gesellschaft für Reaktorsicherheit (GRS) at Garching, F.R.G." to develop a theoretical model and the corresponding code GARLIC (Ho, Lu 82; Ho, Lu 8o; Ho, Lu 81) for simulation of PWR power plant dynamics. Later, the code which is presented in this report, based on a theoretical model as described in refs. (Er 82; Ho et al. 81) was initiated (at the beginning of 1980) with the support of the Alexander von Humboldt Foundation (Bonn) for the purpose of developing an analogous model and a computer code for the BWR nuclear power plants. The plant, which is considered in this study and depicted in figure 1, consists of a core, a top plenum, steam removal and feed water systems and main coolant circulation pumps. Starting from this physical configuration, a nonlinear mathematical model has been developed assuming a 3D-core, parallel flow and subcooled boiling (Er 82; Ho et al. 81). The computer code GARLIC-B is based on this mathematical model and aims to simulate in real-time the transient behaviours of nodal core and global plant parameters of BWR nuclear power plants in response to external disturbance and control inputs.

2. BASIC FEATURES OF THE THEORETICAL MODEL

Since the BWR model which is used in GARLIC-B was developed in parallel to, but later than the PWR model of GARLIC (Ho, Lu 82; Ho, Lu 80; Ho, Lu 81), the past experience accumulated from development of GARLIC could be used directly in constructing the model for GARLIC-B.

Therefore, the assumptions dealing with the neutron kinetics and some concerning the thermo-hydrodynamics (e.g., those related to the calculation of fuel temperature distribution) are the same as in GARLIC. For the present BWR model obviously a number of new assumptions has been made. Different methods have been developed to describe most of the thermo-hydrodynamic parameters and to calculate the transient behaviour of the total plant.

The main features of the BWR model which is the basis of the code GARLIC-B are summarized below:

- The model describes the transient behaviour of the characteristic core and also the global plant parameters.

- The neutron kinetics, most of the thermo- and hydrodynamic calculations and xenon-iodine dynamics are decoupled from each other, calculated separately, and then combined into a total system by a recursive procedure.

- The application of the code is restricted to the normal operational transients, i.e., to not-too-fast varying perturbation signals. Thus, the neutron kinetics and most of the thermo- and hydrodynamics are treated as pseudostationary.

- Usually, the neutron current density, the flux and thus also the power density distribution in a large core have to be calculated by codes which solve the neutron kinetic diffusion equations in a direct and thus very time-consuming way (e.g., QUABOX/CUBBOX (La et al. 77a; La et al. 77b; La et al. 78), ABCBOX (Fi 78), IQSBOX (Fi et al. 77; Fi, Ra 79), dividing the total core into a fairly large number of basic (coarse mesh) volume elements. Expressing now the neutron interactions between neighbouring elements by means of appropriately defined (spatial) coupling coefficients means that the very time-consuming set of partial differential equations can be replaced by an algebraic equation system. Neutron flux, power, xenon and cross-section values

from calculations with the above mentioned kinetic codes (at a working time point t_w) will then be taken as a basis for the code CARLIC-B to evaluate these coefficients.

- A further simplification of the theoretical formulation can be achieved if the two-group neutron kinetic representation is reduced to a "1 $^1/_2$-group" formalism by replacing the neutron flux terms by power density expressions and introducing corresponding modified coupling coefficients.

- Since the above considerations are only valid for nodes whose lenghts do not exceed a certain limit (determined by the neutron migration length of about 8 - 10 cm) and on the other hand the theoretical model should be restricted to a minimum number of nodes, special measures have to be taken to be able to combine a cluster of coarse mesh elements into a "superbox" without losing too much on exactness. This can be achieved by homogenizing (by means of adequate averaging procedures) the corresponding core parameters over these superboxes and calculating the new coupling coefficients according to a rebalancing method as proposed by Siewers (Si 76). These coupling coefficients can be expected to stay almost constant throughout different transient conditions.

- According to the symmetry properties of the total core, the calculations can be restricted to only a half, a quarter or an eighth (rectangular or jagged) core, respectively. (The special case of a quarter core with rotational symmetrical control rod arrangement is also considered.) Either a regular (with each superbox having only one neighbour in one direction) or a non-regular node pattern can be chosen for the calculations, each of them offering certain benefits to the problem to be solved. Only nodes within the fuel region will be considered. The influence of a reflector on the neighbouring core nodes will be taken into account by adequately corrected coupling coefficients.

- As a benefit of the coupling coefficient concept, the pseudostationary treatment of the process and the $1^1/_2$-group formalism of the neutron kinetics, it turns out that the power density values can be found from a set of algebraic equations. Additionally, because of the structure of the matrix, the solution procedure can make use of sparse matrix techniques (AE 80) which help to save a further large amount of computer time and capacity.

- In the case of a BWR core the hydrodynamic influence between superboxes is restricted to the axial direction. It therefore seemed reasonable for the matrix representation to count the nodes (superboxes) at first in the z-, then x- and y-direction.

- In general, nonlinear equations were used as a basis for the transient calculations of the neutron kinetics, xenon-iodine densities as well as thermo-hydraulic parameters.

- Because of the pseudostationary assumption, the spatial changes in the coolant flow rate along any channel can be neglected, i.e., the local coolant flow rate is equal to its entrance value. To determine the flow distribution at the core inlet, the total pressure drops are calculated along all channels for an initial flow distribution which is then modified recursively until the pressure drops over the whole length of all channels are equal to each other and the sum of the flows through the channels are equal to the total core flow.

- Since the coolant density changes which arise from void fraction variations affect the core power very strongly in a BWR, nodal steam quality values are determined by taking into account also subcooled boiling effects within a channel. The point of net vapor generation is found by using the Saha and Zuber correlation (Sa, Zu 74). In adaptation of this correlation to the superbox model, some extra precautions had to be taken. Steam quality calculations are

repeated at each time step during transient calculations. The flashing and condensation effects resulting from system pressure changes are included in the equations.

- Nodal void fraction values are calculated from the nodal steam qualities and the system pressure by using the Bankoff (Ba 60) two-phase correlation.

- Coolant temperature distribution is determined by distinguishing between non-boiling, subcooled boiling and bulk boiling regions.

- For fuel temperature calculations temperature dependent heat conduction coefficients are assumed. At present, only two separate overall heat transfer coefficients are used, one for the one-phase and one for the two-phase flow region.

- System pressure, water level and water volume within the top plenum are calculated by assuming uniform two-phase mixture within the top plenum and using non-stationary equations. Flashing and condensation effects are taken into account.

- The system may be disturbed by motions of control rod banks and/or changes in coolant mass flow rate, feed water mass flow rate, feed water temperature and outlet steam mass flow rate. In addition, in order to describe a pressure controlled reactor, the system pressure may be free or forced to follow a given function in time while keeping the water level in the plenum constant.

3. THE COMPUTER CODE GARLIC-B

Based on the model, the digital code GARLIC-B (Garching Real-Time Core and plant Model for BWR) was established. It is written in FORTRAN IV (H-Extended) language and tested on AMDAHL 470/VI type of computer.

The basic features of the code GARLIC-B are as follows:

- In order to save memory space, variable dimensioning of the arrays is adopted and all arrays are stored into a pool vector USE whose partition is changed during different steps of the program execution.

- Subroutines which deal with the node pattern and perform the neutronic calculations (printing of node pattern, coupling coefficient calculations, homogenization and rebalancing procedures) could be taken from the code GARLIC (Ho et al. 82) with no or only slight changes.

- The variations in parameters during on time step are calculated by iteration. Because of the interdependency of the parallel flow and steam void fraction multiple iteration loops had to be used.

- Stability of recursions are provided by two different types of iteration formula (see also Appendix 2),

  i) a linear, weighted recursion formula which updates a parameter by taking a weighted average of its starting value (at the beginning of an iteration cycle) and its new value (calculated at the end of the same iteration cycle),

  ii) a formula which updates a parameter value by considering its values during the last two iteration cycles such that the initial value at the beginning of an interation cycle will be the same as the newly calculated value of the end of that cycle.

  The weighting coefficients and the criteria to select one or the other of the formulae are specified externally by input parameters. (For more details see sec. 3.2 and Appendix 2.)

- As a consequence of multiple iteration loops, the computation time per time step may be relatively long. Hence, the

number of time steps during the solution are reduced by increasing the time step size whenever possible, especially when no external perturbances occur and only xenon-iodine dynamics dominate the transient behaviour. Sizes of the time steps are regulated externally by input parameters.

- Water and steam properties at the working point are given as inputs and updated during transient runs by using linear interpolation.

3.1 Program Structure

The connection between the basic code QUABOX/CUBBOX and GARLIC-B is established by the support program QORGA which reads the data from the basic model QUABOX/CUBBOX, organizes it in a GARLIC-B standard form and stores it on disk so that the data are read directly by GARLIC-B. (A similar support program AORGA will soon be available for use with ABCBOX.)

The structure of the code GARLIC-B is seen in figures 2 and 3 in the form of a block diagram. A short description of the important subroutines is given below. (The subsequent letters, mostly YUC, of the subroutine names have no significance to other users.)

CIN: Reading, printing, checking and interpretation of the card input data

The subroutines used by CIN:

INC:
Reading of card input data

RNP, DNP:
Analysis of the alphanumeric input data which specify the node pattern

NGC, EDI:
Establishment of neighbour relations

ADR:

Variable storage definition (vector USE), adress calculation

CI1, CI2:

Auxiliary routines

AD1 (entry to ADR):
Print out of information about the used and available computer storage

ADP: Print out of the partition of vector USE (if LPUSE = 1)

PHI: Initiation for the entries PH1, PH2, ...

MIN: Read, check and homogenization of input data given by disk from the support program QORGA (or AORGA) (Logical unit ITAP = 2)

The subroutines used by MIN:

QCI (with the QC1, QC2, QC3, QC4):
Print-out of characteristic QUABOX/CUBBOX data (if LPBMOD is properly spe cified; see Appendix 1)

AVI (with entry AVG):
Homogenization of input values

HMJ (with entries HJX, HJY, HJZ):
Homogenization of neutron current densities

PNP: Print out of node pattern in the x-y plane

PNZ: Print out of node pattern along the z-axis

PCU: Print out of homogenized neutron current densities (if LPHOM $\neq$ 0 or -1)

CPF: Computation of the nondiagonal spatial coupling coefficients using geometrical data and diffusion constants (Fick's formula) and of the diagonal ones by using the

neutron fluxes and cross sections from the basic code and by satisfying then the diffusion equations (see also definition of LCOUPL in Appendix 1, p. A1-1)

The subroutines used by CPF:

SUR:
Computation of the surface areas between neighbouring nodes

CPL: Computation of the diagonal and nondiagonal coupling coefficients by using the neutron fluxes and currents from the basic model (see also definition of LCOUPL in Appendix 1, p. A1-1)

CCP: Computation of the rebalanced coupling coefficients

CCO: Computation of the unhomogenized nondiagonal coupling coefficients

CCD: Computation of the unhomogenized diagonal coupling coefficients

COG: Computation of the unhomogenized nondiagonal and diagonal coupling coefficients in the $1^1/_2$-group representation

CPO: Print out of unhomogenized diagonal coupling coefficients

COM: Storage of nondiagonal coupling coefficients in a matrix

CHB: Homogenization of coupling coefficients

PCP: Print out of the rebalanced nondiagonal coupling coefficients (if LPHOM > 0 or -2)

PH4: Print out of the homogenized core parameters (if LPHOM $\neq$ 0)

AXW (AXWREB, AXWNOD): Execution of validity tests by comparing the data from basic model and the data computed by GARLIC-B. Print out of the test results
(AXWREB: Rebalanced Version)
(AXWNOD: Nodal Version)

The subroutines used by AXW:

PHØ, PH0, PH1, PH2, PH3, PH5:

Print out of validity tests and diagonal coupling coefficients (if LPHOM $\neq$ 0 or -1)

WKP: Calculations of important parameters (power densities, thermo- and hydrodynamic values, xenoniodine densities) at the working point t_ω and of the vectors and matrices needed for the transient power density and xenon-iodine computations

The subroutines used by WKP:

PHB, PHC:

Print out of control rod correction factor

DXI:

Computation of data for xenon-iodine behaviour and the xenon and iodine density distributions at the working point

THW:

Calculations of the thermo- and hydrodynamic nodal and global core parameters at the working point (mass flow, coolant water temperature, fuel rod temperature, steam quality, void fraction distributions)

The subroutines used by THW:

SUB:

Computation of coolant mass flow rate, steam quality and void fraction distributions within the core (uses the subroutines RTN, GAM and XKS)

CFT:

Computation of coolant and fuel rod temperature distributions at the working point (uses the subroutine PRNODE)

NRM:

Definition of the normalization constants

PH7:

Print out of nodal and mean power, xenon-iodine densities, thermo- and hydrodynamic core parameters

PMA:

Print out of the power state matrix FPWW (if LPMATR = 1)

S12N:

Computations dealing with the power feedback from the fuel rod temperature

LAMNJ:

Computations dealing with the power feedback from the coolant water temperature

WNJ:

Computations dealing with the power feedback from the void fraction

PH8, PHA:

Print out of the perturbation vectors which are needed for the transient power density calculations

MA28A:

Inversion of the power state matrix using sparse matrix technique (if LFULLM = 0) (AE 80)

DOT:

Tape output of the parameter values, state and coefficient matrices at the working point (if LTAPMC $\neq$ 0) (at present, not available)

TRS: Transient calculations

The subroutines uses by TRS:

MINV:

Full power state matrix inversion (if LFULLM $\neq$ 0)

PMA:

Print out of inverse power state matrix (if LPMATR = 1 and LFULLM $\neq$ 0)

ASS (with entry AS1):

Saves the results of the transient calculations for printing

ASP (with entry AP1):

Saves the results of the transient calculations for plotting

PTB:

Computations of the cnages of the system perturbing parameters (control rod motion; mass flow rates of coolant, feed water and outlet steam; feed water temperature) during a time step

The subroutines by PTB:

PLG:

General computation of the value, at any time point t, of a polygon function of time from its basic points

UNR (with netry UN1):

Computation of the nodal influence of a control rod bank movement

PH9:

Print out of the results from UNR within the time interval between TTEST1 and TTEST2 (if LPMATR > 0)

DEL:

Calculation of the variations of the core and plant parameters during one time step

The subroutines used by DEL:

MA28C:

Solution of the power equation when sparse matrix technique is used (LFULLM = 0) (AE 80)

BOTRSU:

Calculations of bubble detachment points

STTRSU, STTRCP:

Calculation of the steam quality and void fraction distributions

GAM2, XKS2:

Auxiliary subroutines for the calculation of pressure drops along channels

TRT:

Calculation of transient coolant water and fuel rod temperature distributions (uses the subroutine PRNDTR for nodal pressure)

OUL:

Print out of the transient parameters in blocks of maximum 50 according to the input options (uses the subroutine TIM which gives time in hour-minute-second format)

OUP, DES:

Plotting of the transient parameters according to the output options

3.2 Input Data

Two types of input data are required by the code:

i) Input data by card deck

ii) Input data which are calculated by a basic model (QUABOX/CUBBOX, or ABCBOX), organized by the support program (QORGA or AORGA), and submitted to GARLIC-B by the logical unit ITAP = 2.

3.2.1 Input Data by Card Deck

Card input data include the basic data to select the program options and to specify the values of model and the program parameters. The arrangement of the data is shown in table 1.

All cards, except the identification card and the cards which specify the node pattern, have seven data fields each with ten characters. All numerical input data (integers included) are real and have the format ±x.xxxx±xx.

More detailed information about the card data is given below:

I) First card is the title card and may contain any alphanumeric data.

II) In the next three cards, program control parameters are given. Their meanings are explained in Appendix 1.

III) The following two cards specify the parameters which are needed by the recursions. The different iteration formulae and the related parameters are described in Appendix 2.

IV) IMAX, KMAX and MMAX are respectively the number of volume elements in the x-, y- and z-directions of the basic model (volume elements which lie in the reflector zone are included). NRM is the total number[1]) of controller groups (soluble poisoning is included always as a controller group)[2]). NRR is the maximum number of rods in the control rod groups. NTRS is the maximum number of transients which are to be printed, including the perturbation signals and time. NPLOTM is the total number of curves to be plotted.

V) KMAX cards with alphanumeric characters are used to describe the node pattern in the x-y plane of the full, half, quarter or one-eighth core, whichever is appropriate. Nodes may have more (or less) than six neighbours (unregular node partition), but have to be rectangular cross sectioned (not necessarily square), except in the rebalancing option, where nodes are allowed to have jagged boundaries with the reflector zone. A coherent group of equal characters (i.e., not being separated from each other except by a blank) designates a node (superbox) whose characteristic parameters will be obtained during the GARLIC-B calculations from the volume elements by a homogenization procedure.

Another card containing MMAX alphanumeric characters gives the partition along the z-axis starting from the lowest layer.

The way in which the half, quarter or eighth core is contained in GARLIC-B is characterized by the input parameters LPARTC where 1/LPARTC represents the fraction

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1) At present, $NRM_{max} = 20$.

2) Although soluble poisoning is not used in BWR power plants, it is included as a historical consequence into the programs (some programs are taken from GARLIC which use boron poisoning).

of the reactor core computed by GARLIC-B. For describing rotational symmetry negative values are used for LPARTC (e.g. LPARTC = -4 means GARLIC-B computation with $^1/_4$-core rotational symmetry).

The node pattern for an eighth core has to be given in the first quadrant so that the X-axis represents a symmetry axis, for a quarter core in the first quadrant and for a half core in the first two quadrants. (Note: In the node pattern representation for an eighth core the alphanumeric signs for the diagonal boxes don't represent of course full rectangular boxes as usual but only half of them).

Some examples of node pattern specification are presented below:

a) Full core:

Basic core (IMAX = 18, KMAX = 8, MMAX = 10) homogenized to an irregular GARLIC-B core:

x-y plane:

```
    RRRRRRRRR
  RRRRRRRRRRRR
RRRAAKKKKKKKFFRRR
RRRAA11112222FFRRR
RRR***BBB2222LLRRR
RRRAAFFFFFFFF33RRR
  RRRRRRRRRRRRR
    RRRRRRRRR
```

or

```
      R         R
    RRRR          R
R   A K   K   KF RRR
R   A 1   2    F R R
R R* *B B2 22L RRR
R   A F       3 R R
  R             R
    R R RRR   R
```

z-axis:
RRAABBCDRR
LPARTC = 1

b) Quarter core:

Basic quarter core (IMAX = 6, KMAX = 6, MMAX = 10) homogenized to a regular GARLIC-B quarter core:

x-y plane:

right presentation

```
RRRRRR
AABBCR
DDEEFR
AAHHIR
AAHHIR
```

wrong presentation

```
RRRRRR
AABBCR
DDEEFR
AADDIR
AADDIR
```

z-axis:
RAABBCCDDR

With a fully symmetric core structure band control rod arrangement:

LPARTC = 4

With a rotational symmetric core structure and control rod arrangement:

LPARTC = -4

c) One-eighth core:

One-eighth core GARLIC-B computation from quarter core basic model data (IMAX = 11, KMAX = 11, MMAX = 22).

x-y plane:

```
          RRR
         PYRR
       EQNRRRR
      DGKLMMRR
     ABCHIJJRR
    AABCHIJJRR
   AAABCHIJJRR
```

z-axis:
RRAABBCCCDDDDEEEFFGGRR
LPARTC = 8

A more detailed description of the node pattern input procedure is given in subroutine RNP.

VI) After the node pattern description, the cards which contain the operational values, geometry and structural properties of the power plant at the working point follow. When choosing the parameter values one has to take into account that the total BWR plant is assumed to consist of a full, half, quartern or one-eighth core, and only a single steam outlet and a single feed water inlet port. More detailed description of these data are given in table 2.

VII) The system perturbation signals are given in absolute values, and can be the core mass flow (G_E), a movement of one or more control rod banks (u_r, r=1,..., NRM-1), outlet steam flow (G_{ST}), feed water flow (G_{FW}), and feed water temperature (T_{FW}). In addition, in order to simulate a pressure controlled reactor, the system pressure may be free or forced to follow a given function in time while keeping the water level in the top plenum constant.

The perturbation signals are represented by polygons in time which are defined by the number of their basic points and the functional values at these basic points. The number of basic points are entered into the program by specifying the parameters $N_{UR}(r)$; (R = 1,...,NRM-1) N_{GE}, N_{GST}, N_{GFW}, N_{TEW}, N_P (N_P is specified when the system pressure is controlled). Then, for each perturbation a pair of data sets is given. The first set (T?) has the instants of time at which the basic points of the polygon are placed; the second set (P?) has the corresponding functional values at these points.

VIII) The last set of cards specifies the options which govern the transient output. A number of global as well as nodal[1]) and channel[1]) parameters may be printed by setting the corresponding number $N_{A?} \neq 0$[2]). In the case of nodal or channel parameters the corresponding value of $N_{A?}$ is set to the node or channel number. Similarly, specifying $N_{F?} \neq 0$[2]) means that the results will be represented by a plot on the frame of number $N_{F?}$. Maximum ten frames, each with up to ten curves are allowed.

3.2.2 Input Data from Logical Unit ITAP (= 2)

The neutronic data and the power distribution at the working point are supplied to GARLIC-B by an accurate basic code such as QUABOX/CUBBOX (La et al. 77a; La et al. 77b; La et al. 78), ABCBOX (Fi 78), etc. (At present, raw data is obtained from static calculations with QUABOX/CUBBOX. Use of ABCBOX is not available yet.) The raw output data from the basic program is available on magnetic tape. A support program (QORGA) reads the raw data from tape and reorganizes the necessary input data for GARLIC-B in a standard form.

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1) Limited to five nodes or channels for each type of variable.
2) Mnemonic code for the following letters is given in table 3.

3.3 Output

Output from GARLIC-B is in three ways:

3.3.1 Printed Output Data

The printed data consist of the following main parts:

a) list of input data from card deck

b) information over the used and available computer storage and the partition of the vector USE (if LPUSE = 1)

c) list of input data from tape (regulated by LPBMOD as explained in Appendix 1)
   - characteristic parameters of the basic model
   - length of basic elements
   - volume of basic elements
   - initial cross section reference table
   - cross section disposition
   - rod bank configuration in x-y plane
   - cross section change due to rod bank insertion
   - fast and thermal neutron current densities in positive x-, y- and z-direction
   - fast and slow neutron fluxes
   - neutron group constants (diffusion constants, absorption and fission cross sections for fast and slow neutrons, slowing down cross sections)
   - power, xenon and iodine densities

d) core node pattern in the x-y plane before and after homogenization (layer NCZ = 1)

e) node layer partition along z-axis and control rod insertions (pictorial)

f) values after homogenization (regulated by LPHOM as explained in Appendix 1)

- fast and slow neutron currents (not densities)
- non-diagonal fast and slow coupling coefficients
- diagonal coupling coefficients
- validity test of the basic diffusion equations

g) data about the core geometry

h) characteristic core and plant data at the working point:

- information about the parallel flow computations, mass flow rate and velocity distributions, locations of bubble detachment points, etc.
- mean core and plant parameters
- nodal values of core parameters

i) normalization values

j) dump of the state matrix and the perturbation vectors needed for the transient calculations (if LPMATR = 1)

k) different test data within the time interval $t_{TEST1} \leqq t \leqq t_{TEST2}$, if $t_{TEST1} < t_{TEST2}$

l) transient behaviour of the perturbation and interesting plant signals (time t in h; min; sec) according to the chosen output options

m) information to monitor the convergence rates during transient calculations, warning and error messages

3.3.2 Plotting of the Curves

If the corresponding option values in the input card deck are chosen appropriately, transient results can be presented as plots. The corresponding perturbation signals will also be

plotted. The scalings of the ordinate and the abscissa of the curves are done automatically.

3.3.3 Output Data on Logical Unit IOUT[1])

If LTAPMC = 1, important data from the GARLIC-B calculations are stored on the logical unit IOUT = 3 (e.g., a magnetic tape). This data can be used for the core and plant control purposes.

4. FINAL REMARKS

Currently, extensive tests of the model and the corresponding code GARLIC-B are being carried out. Although the tests are not completed yet, the results seem to be promising. Test runs show that the program calculates the transient behaviours of the core and plant parameters in response to external perturbances with a reasonable computation speed. Computation times, especially of the pressure controlled runs, are sufficiently short so that the code may be used for real time calculations and direct digital control applications.

Accuracy of the results must yet be tested. For this purpose comparative studies with results from the accurate basic models must be carried out. Finally, post calculations of the transients that are measured at an actual BWR power plant must be performed and the results must be compared to the measured data. These tests, however, will require close collaboration with the nuclear power plant vendors and utility companies, since the data for these tests seem to be quite scarce and the existing data are not open to public.

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[1]) This output is not available from the program yet.

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FIGURES

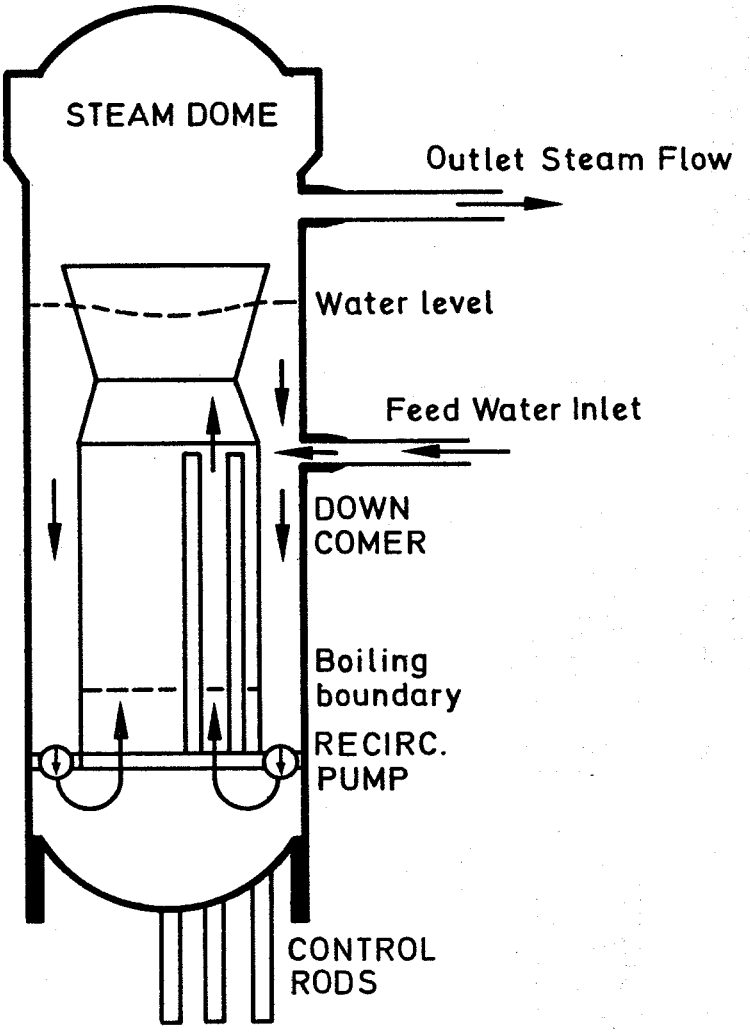

Figure 1:
Schematic Diagram of a BWR

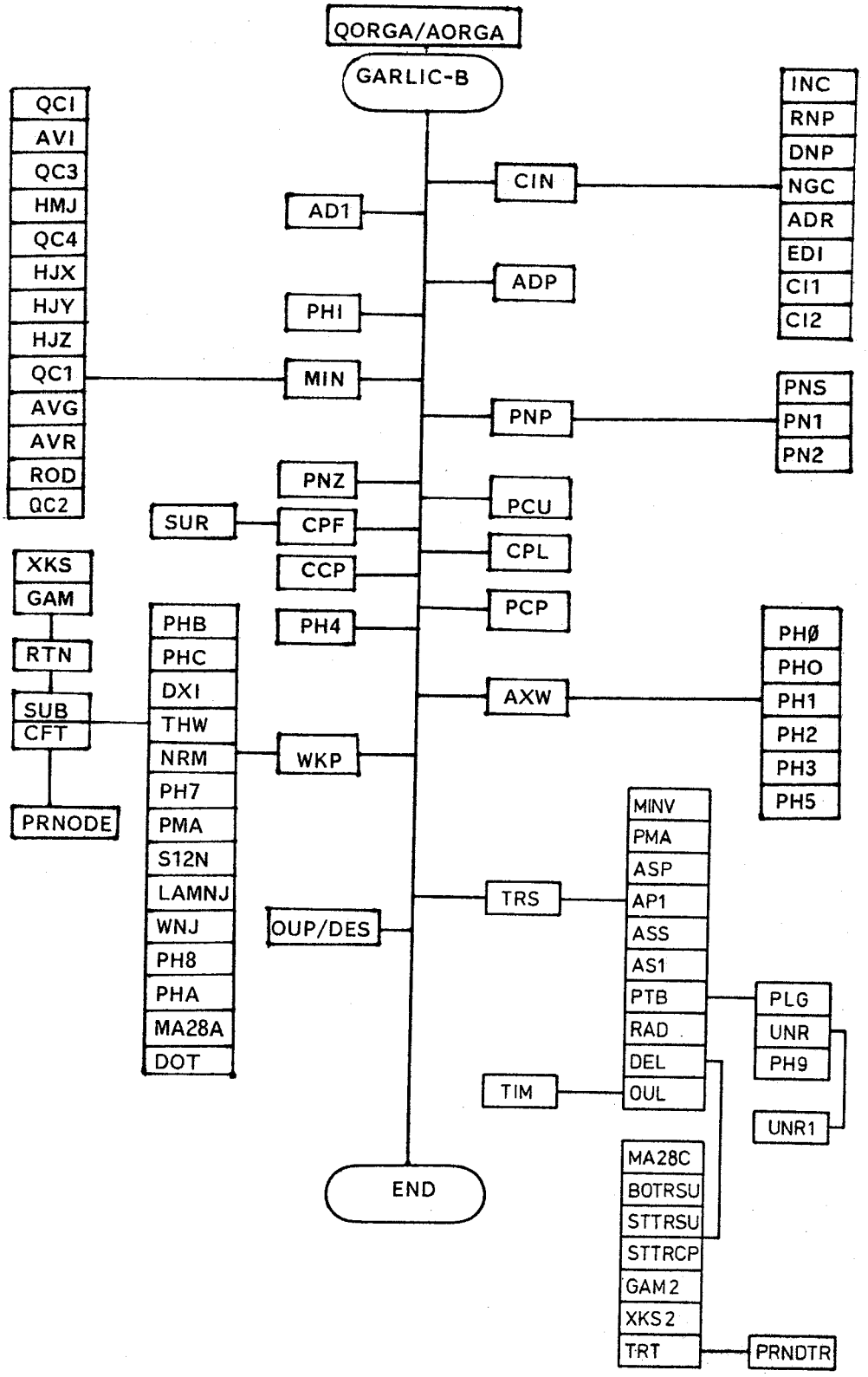

Figure 2:

Block Diagram of GARLIC-B (no rebalancing)

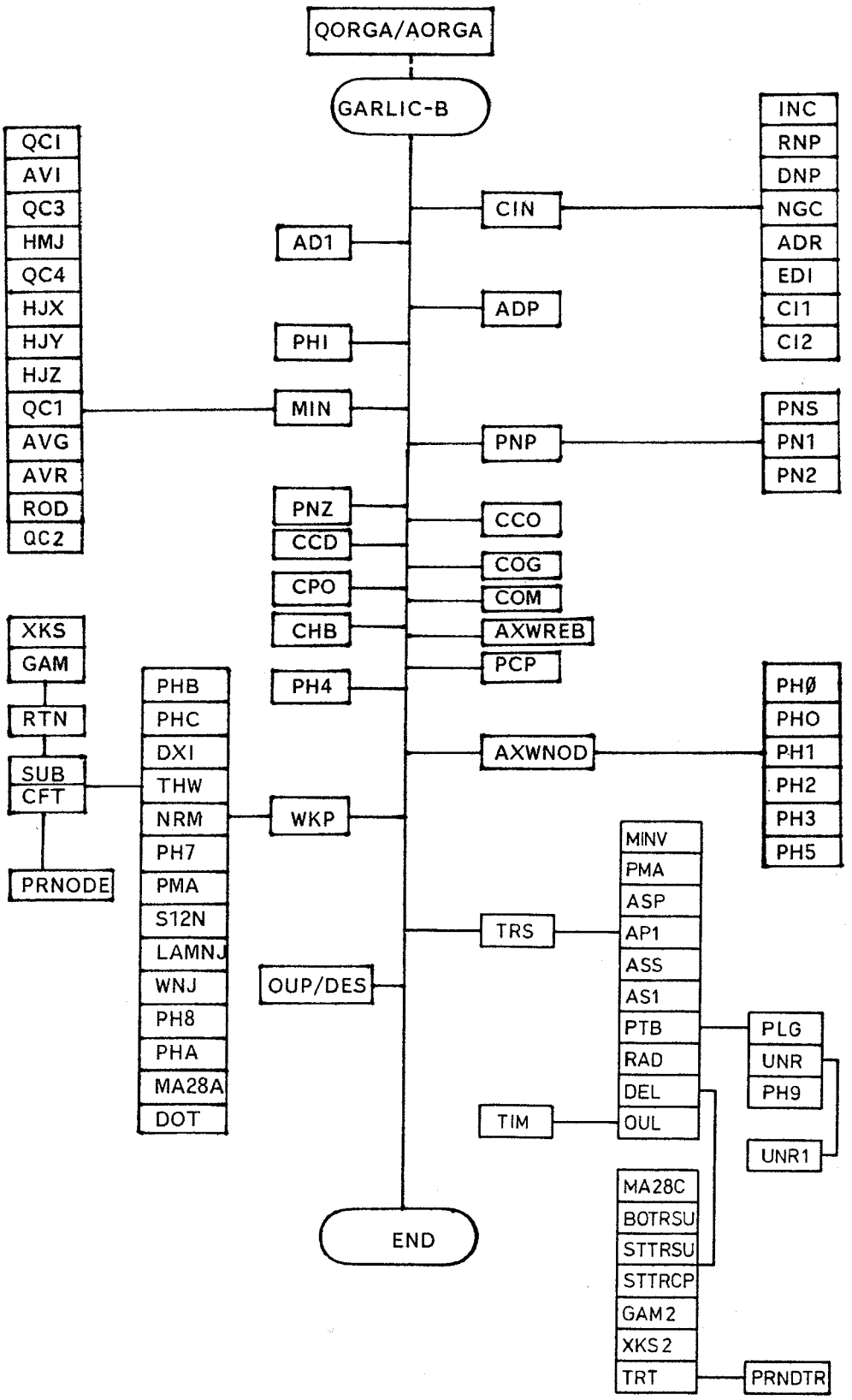

Figure 3:
Block Diagram of GARLIC-B (with rebalancing)

TABLES

Table 1 (1):

Arrangement of Card Input Data for GARLIC-B

IDENTIFICATION CARD (Any combination of alphanumeric characters)

PROGRAM CONTROL PARAMETERS:

LCNTR	LFULLM	LREBAL	LTAPMC	LSTORE	LRESTA	LCOUPL
LPBMOD	LPHOM	LPMATR	LPUSE	LPCORP	LNOHOM	LNORM
NONLIN	IWLDY	ITSITR	IWVWLC	LTUNE		
ITRMA2	ITERMA	WEIG1	WEIG2	TRECUR	ENDITG	TRECU2
IPRITR	TRECST					
IMAX	KMAX	MMAX	NRM	NRR	NTRS	NPLOTM

NODE PATTERN SPECIFICATIONS:

(KMAX cards containing IMAX alphanumeric characters)
(One card containing MMAX alphanumeric characters)
LPARTC

OPERATIONAL VALUES:

TW	TEND	DT	TTEST1	TTEST2	DTTEST	
TSTORE	TRESTA	TSWITC	TSWIT2	TSWIT3	DTXEN	QGENW
QW	GEW	PW	GFWW	ZWLW	VWTW	BORNRM
RA	EVF	VT	XLMNFR	XLMBFR	DHK	
ALF1P	ALF2P	CLAMT	XLAMFC	EFGAM		
RHOPW	RHOPDW	HPW	HDPW	RHOWEW	HFWW	
RHOPP	RHODPP	HPP	HDPP	HWT	TSW	TSP
GAMX	GAMI	SLAX	SLAI	EEFF	VNY	
WKF	ARATIO	HWP	SIDEFA	RHOWP	DRWDT	DRWDA
TMPWRF	TMPFRF					
RK(1)	RK(2)	...	...	...	...	...
...	...	...	RK(NXY)[1])			
URW(1)	URW(2)	URW(3)	URW(4)	URW(5)	URW(6)	URW(7)
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	URW(NRM)				

[1]) NXY is the number of coolant channels

Table 1 (2):

Arrangement of Card Input Data for GARLIC-B

DEPENDENCE OF MACROSCOPIC CROSS SECTIONS ON DIFFERENT PARAMETERS

ε^{FR}_{3a1} ↔	ε^{FR}_{3a2} ↔	ε^{FR}_{3f1} ↔	ε^{FR}_{3f2} ↔	$\varepsilon^{FR}_{3,1-2}$
Σ^{M}_{a1}	Σ^{M}_{a2}	Σ^{M}_{f1}	Σ^{M}_{f2}	Σ^{M}_{1-2}
ε^{CR}_{1a1}	ε^{CR}_{1a2}	ε^{CR}_{1f1}	ε^{CR}_{1f2}	$\varepsilon^{CR}_{1,1-2}$
Σ^{X}_{a1}	Σ^{X}_{a2}	Σ^{X}_{f1}	Σ^{X}_{f2}	Σ^{X}_{1-2}
Σ^{B}_{a1}	Σ^{B}_{a2}	Σ^{B}_{f1}	Σ^{B}_{f2}	Σ^{B}_{1-2}
ε^{CR}_{2a1}	ε^{CR}_{2a2}	ε^{CR}_{2f1}	ε^{CR}_{2f2}	$\varepsilon^{CR}_{2,1-2}$
$\Delta\Sigma_{a1,1}$	$\Delta\Sigma_{a2,1}$	$\Delta\Sigma_{f1,1}$	$\Delta\Sigma_{f2,1}$	$\Delta\Sigma_{1-2,1}$
⋮	⋮	⋮	⋮	⋮
$\Delta\Sigma_{a1,(NRM-1)}$	$\Delta\Sigma_{a2,NRM-1}$	$\Delta\Sigma_{f1,NRM-1}$	$\Delta\Sigma_{f2,NRM-1}$	$\Delta\Sigma_{1-2,NRM-1}$

OUTSIDE PERTURBATION (in seconds and not-normalized values)

NUR(1)	...	...	...	...	...	...	
...	...	...	NUR(NRM)				
NGE	NGST	NGFW	NTFW	NZWL	NP		
TNUR(1,1)	...	...	...	...	...	...	
PNUR(1,1)	...	...	...	...	...	...	if NUR(1)>0
...	...	TNUR(NUR(1),1)					
...	...	PNUR(NUR(1),1)					
...	...	...	...	...	...	...	
...	...	...	...	...	...	...	
...	...	...	...	...	...	...	
...	...	...	...	...	...	...	
TNUR(1,NRM)		...	...	...	...	...	
PNUR(1,NRM)		...	...	...	...	...	if NUR(NRM)>0
...	...	...	TNUR(NUR(NRM),NRM)				
...	...	...	PNUR(NUR(NRM),NRM)				

Table 1 (3):

Arrangement of Card Input Data for GARLIC-B

TGE(1)	...	...	...	...	...	...	
PGE(1)	...	...	...	...	...	...	if NGE>0
...	...	TGE(NGE)					
...	...	PGE(NGE)					
...	...	...	...	...	...	...	
...	...	...	...	...	...	...	
...	...	...	...	...	...	...	
...	...	...	...	...	...	...	
TP(1)	...	...	...	...	...	...	
PP(1)	...	...	...	...	...	...	if NP>0
...	...	TP(NP)					
...	...	PP(NP)					

OPTIONS GOVERNING THE TRANSIENT OUTPUT:

NAPM	NAXM	NAIM	NATFM	NATWM	NAQ	NAQGEN
NFPM	NFXM	NFIM	NFTFM	NFTWM	NFQ	NFQGEN
NATE	NAGE	NAZWL	NAXMT	NAP	NAZBM	NAALT
NFTE	NFGE	NFZWL	NFXMT	NFP	NFZBM	NFALT
NASTFL	NAVWT	NAKCOR	NAKCDI			
NFSTFL	NFVWT	NFKCOR	NFKCDI			

Table 1 (4):

Arrangement of Card Input Data for GARLIC-B

NAPN(1)	NAPN(2)	NAPN(3)	NAPN(4)	NAPN(5)
NFPN(1)	...	...	...	NFPN(5)
NAXN(1)	...	...	...	NAXN(5)
NFXN(1)	...	...	...	NFXN(5)
NAIN(1)	...	...	...	NAIN(5)
NFIN(1)	...	...	...	NFIN(5)
NATFN(1)	...	...	...	NATFN(5)
NFTFN(1)	...	...	...	NFTFN(5)
NATWN(1)	...	...	...	NATWN(5)
NFTWN(1)	...	...	...	NFTWN(5)
NAXSN(1)	...	...	...	NAXSN(5)
NFXSN(1)	...	...	...	NFXSN(5)
NAALN(1)	...	...	...	NAALN(5)
NFALN(1)	...	...	...	NFALN(5)
NAZBK(1)	...	...	...	NAZBK(5)
NFZBK(1)	...	...	...	NFZBK(5)
NAGEK(1)	...	...	...	NAGEK(5)
NFGEK(1)	...	...	...	NFGEK(5)

END OF CARD DECK

Table 2 (1):

Parameters which Specify the Operational Values at the Working Point[1]) (see Table 1 for arrangement of the data)

Parameter	Description	Units
TW	Time at the working point	s
TEND	Time at the end of transient calculations	s
DT	Time step length at the beginning of transient calculations and during perturbations	s
TTEST1	Time at start of test print-out	s
TTEST2	Time at end of test print-out (if TTEST2 ≦ TTEST1: no test print-out)	s
DTTEST	Interval of test print-out	s
TSTORE	Time of data storage (This parameter ist not used at present. It is reserved for the restart version)	s
TRESTA	Restart time (This parameter is not used at present. It is reserved for the restart version)	s
TSWITC	First switching time from time step length of DT to DTXEN	s
TSWIT2	First switching time from time step length of DTXEN to DT	s
TSWIT3	Second switching time from time step length of DT to DTXEN	s
DTXEN	Time step length if no perturbances are present and only Xe-I dynamics are dominant	
QGENW	Generator power	W
QW	Thermal reactor power	W
GEW	Rate of total coolant flow through core	kg/s
PW	System pressure	J/cm^3
GFWW	Rate of feed water flow	kg/s
ZWLW	Height of water level in top plenum (measured from the core outlet)	cm
VWTW	Water volume in top plenum	cm^3
BORNRM	Concentration of soluble boron acid poisoning (not used)	ppm
RA	Fuel rod radius	cm
EVF	Fuel volume fraction within the core (V_F/V_{total})	-

1) When choosing the parameter values one has to take into account that total BWR plant has been assumed to consist of a full, half, quarter or one-eighth core and only one single steam outlet and only one single feed water inlet port.

Table 2 (2):

Parameters which Specify the Operational Values at the Working Point

Parameter	Description	Units
VT	Top plenum volume	cm^3
XLMNFR	One-phase friction factor (in non-boiling regions of channels)	-
XLMBFR	Two-phase friction factor (in boiling regions of channels)	-
DHK	Hydraulic diameter of flow channels	cm
ALF1P	Overall heat transfer coefficient in 1-phase flow region	W/cm^2-C
ALF2P	Overall heat transfer coefficient in 2-phase flow region	W/cm^2-C
CLAMT	C_λ^T in eq. $\lambda_F = \lambda_{FC}/[1+C_\lambda^T T_F(r)]$ where λ_F: heat conduction coefficient in fuel	1/C
XLAMFC	λ_{FC} T_F: radial fuel temperature	W/cm-C
EFGAM	Fraction of power that is emitted by γ radiation	-
RHOPW	Liquid water density at saturation state	kg/cm^3
RHODPW	Steam density at saturation state	kg/cm^3
HPW	Specific enthalpy of water at saturation state	J/kg
HDPW	Specific enthalpy of steam at saturation state	J/kg
RHOWEW	Density of coolant water at core entrance	kg/cm^3
HFWW	Specific enthalpy of feed water	J/kg
RHOPP	Derivative of liquid water density (at saturation state) with respect to pressure	kg/J
RHODPP	Derivative of density of steam (at saturation state) with respect to pressure	kg/J
HPP	Derivative of liquid water enthalpy (at saturation state) with respect to pressure	cm^3/kg
HDPP	Derivative of steam enthalpy (at saturation state) with respect to pressure	cm^3/kg
HWT	Specific heat capacity of water at constant pressure	J/kg-C
TSW	Saturation temperature	C
TSP	Derivative of saturation temperature with respect to pressure	$C\text{-}cm^3/J$

Table 2 (3):

Parameters which Specify the Operational Values at the Working Point

Parameter	Description	Units
GAMX	Xenon fission yield	Xe/Fiss.
GAMI	Iodine fission yield	I/Fiss.
SLAX	Xenon decay constant	s^{-1}
SLAI	Iodine decay constant	s^{-1}
EEFF	Energy conversion factor	J/Fiss.
VNY	Number of neutrons (fast and slow) per fission	N/Fiss.
WKF	Thermal conductivity of liquid water	W/cm-C
ARATIO	Ratio of net flow area to total area in a channel	-
HWP	Derivative of liquid water specific enthalpy with respect to pressure	cm^3/kg
SIDEFA	Nodal side area factor (= total fuel rod periphery/ total net flow area)	cm-1
RHOWP	Derivative of liquid water density with respect to pressure	kg/J
DRWDT	Derivative of liquid water density with respect to temperature	kg/cm^3-C
DRWDA	Derivative of (two-phase) water density with respect to void fraction	kg/cm^3
TMPWRF	Water reference temperature (T_{CR}) corresponding to the constants $\varepsilon^{CR}_{1?i}$ and $\varepsilon^{CR}_{2?i}$ Note: $\Sigma_{ain}(T_{Cn}) = \Sigma^{CR}_{ai} + \varepsilon^{CR}_{1ai}[\rho_W(T_{Cn}) - \rho_W(T_{CR})] + \varepsilon^{CR}_{2ai}[\rho_W(T_{Cn}) - \rho_W(T_{CR})]^2$ $(i=1,2;n=1,\ldots,N)$	C
TMPFRF	Fuel rod reference temperature (T_{FR}) corresponding to $\varepsilon^{FR}_{3?i}$ Note: $\varepsilon^{FR}_{3?i} = \gamma^{FR}_{?i}\,\Sigma^{FR}_{?i}$ and $\Sigma_{ain}(T_{Fn}) = \Sigma^{FR}_{ai}\,[1 + \gamma^{FR}_{ai}\,(\sqrt{T_{Fn}} - \sqrt{T_{FR}})]$ $(i=1,2;n=1,\ldots,N)$	C
RK(IC)	Hydraulic resistance at channel inlet throttling (pressure drop across the resistance is $\Delta p = r_k G_k^2$)	$cm^{-1}kg^{-1}$
URW(NR)	Insertion depth of control rods (NR=1,..NRM-1)	cm
URW(NRM)	Concentration of soluble boron acid poisoning	ppm

Table 3:

Mnemonic Code for Transient Output Options

PM	: Mean power density
XM	: Mean xenon density
IM	: Mean iodine density
TFM	: Mean fuel rod temperature
TWM	: Mean coolant water temperature
Q	: Thermal power
QGEN	: Generator power
TE	: Coolant temperature at core inlet
GE	: Total coolant mass flow rate
ZWL	: Water level in top plenum
XMT	: Mean steam quality in top plenum
P	: System pressure
ZBM	: Mean distance of boiling boundary to core entrance
ALT	: Mean void fraction in top plenum
STFL	: Rate of steam flow from core into top plenum
VWT	: Water volume in top plenum
KCOR	: K_{core}
KCDI	: $1-K_{core}$
PN	: Nodal power density
XN	: Nodal xenon density
IN	: Nodal iodine density
TFN	: Nodal fuel rod temperature
TWN	: Nodal coolant temperature
XSN	: Nodal steam quality
ALN	: Nodal void fraction
ZBK	: Channel boiling boundary location
GEK	: Channel coolant flow rate

APPENDIX 1

Description of the Option Parameters for GARLIC-B

Option LCNTR

LCNTR = 0 No control

LCNTR = 1 Pressure control

Option LFULLM

LFULLM = 0 Sparse matrix technique is used for power matrix inversion

LFULLM = 1 Full matrix is used in power matrix inversion

Option LREBAL

LREBAL = 0 Special rebalancing procedure omitted in coupling coefficient calculations

LREBAL = 1 Rebalancing is used in calculation of coupling coefficients

Option LTAPMC

At present this option is not used. It is reserved for control applications.

Options LSTORE and LRESTA

At present these options are not used. They are reserved for a restart version.

Option LCOUPL

LCOUPL = 0 Coupling coefficients are calculated using subroutine CPF

LCOUPL > 0 Normally, coupling coefficients are calculated by using subroutine CPL. However, subroutine CPF is used if (FLUX(NC)-FLUX(N))/FLUX(N)<LIMIT, where LIMIT = I/LCOUPL. (NC is the neighbouring node of node N)

Option LPBMOD

Option LPBMOD regulates print out of basic model data.

LPBMOD = 0 No print out of basic model data

LPBMOD = -1 No print out of basic model data when LREBAL = 0. Full print out of 1 $^1/_2$ group homogenized coupling coefficients and validity test data when LREBAL = 1

LPBMOD = -2 Maximum output from basic model

LPBMOD = IJK Output as in -2 except that only data related to coarse mesh layers I, J, K, (MMAX+1-I), (MMAX+1-J) and (MMAX+1-K) are printed

Option LPHOM

Option LPHOM regulates print out of the resulting parameters after homogenization and the data from validity tests.

LPHOM = 0 No print out and no validity tests performed

LPHOM = -1 Only homogenized core parameters printed (no validity tests)

LPHOM = -2 Maximum output of homogenized data and validity tests

LPHOM = -3 Homogenized core parameters and group constants printed only

LPHOM = IJK Output as for -2, but only for superbox layers I, J, K, (NCMZ+1-I), (NCMZ+1-J) and (NCMZ+1-K) where NCMZ is the total number of layers

LPHOM also regulates print out of control rod correction factor:

LPHOM = 0 No print out

LPHOM = 1 Print out of control rod correction factors

(Note: When LPHOM > 0 or -2 then LPHOM is set to 1; when LPHOM = -3, then LPHOM is set to 0 before the working point calculations)

Option LPMATR

Option LPMATR regulates print out of power state matrix FPWW and its inverse, information on control rod homogenization, and matrices used by sparse matrix technique.

LPMATR = 0 No print out

LPMATR = 1 Maximum print out (no information about control rod homogenization)

LPMATR = 2 Print out of only the first one hundred and last ten elements of the matrices that are used by sparse matrix procedure (test from WKP)

LPMATR < 0 Print out of information on control rod homogenization only

Option LPUSE

LPUSE = 0 No print out

LPUSE = 1 Print out of partition in pool vector USE, which is used for variable programming, during various steps of GARLIC-B

Option LPCORP

Option LPCORP is not used at the present time. It is reserved to store at each time step important nodal core parameters resulting from the transient calculations (e.g., for display purposes).

Option LNOHOM

This option is not used at the present time. It is reserved for possible future tests.

Option LNORM

LNORM = 0 Transient results are printed without normalization

LNORM = 1 Transient results are first normalized by their respective normalization values (mean or nodal values at the working point) and then printed

Option NONLIN

NONLIN = 0 Nonlinear terms in right hand side of the power equation are omitted

NONLIN ≠ 0 Nonlinear terms in right handside of the power equation are included

Option IWLDY

IWLDY = 0 Pseudostationary equations are used in water level calculations

IWLDY = 1 Non-stationary equations are used in water level calculations

Option ITSITR

ITSITR = 0 No detailed convergence information from subroutine DEL

ITSITR ≠ 0 More detailed convergence information is printed out from subroutine DEL at the iteration cycles greater than 45 as well as at the 30th and 40th cycles

Option IWVWLC

This option is to be non zero only if LCNTR = 1

IWVWLC = 1 Pressure control at constant water volume

IWVWLC = 2 Pressure control at constant water level

Option LTUNE

An option to tune the GARLIC-B neutronic part to QUABOX/CUBBOX neutronic part. When LTUNE = 0, no tuning is done (see ref. (Ho, Lu 82) for further details).

APPENDIX 2

Recursion Formulae and Parameters

Two different type of recursion formula are used in the code.

i) A linear, weighted recursion formula which updates a parameter by taking the weighted average of its starting value (at the beginning of the last iteration cycle) and its new value (calculated at the end of the last iteration cycle) according to the formula

$$P_{b,n} = \text{WEIGHT} \cdot P_{b,n-1} + (1-\text{WEIGHT})P_{e,n-1}$$
$$(0 \leq \text{WEIGHT} \leq 1)$$

Here, P indicates a general parameter (nodal power density, void fraction, etc.). The first subscripts refer to the value of the parameter either at the beginning (subscript b) or the end (subscript e) of an iteration cycle. Second subscript designates the iteration cycle.

ii) A formula which updates a parameter value by considering its values during the last two iteration cycle such that the initial value at the beginning of an iteration cycle will be the same as the newly calculated value at the end of that cycle. This formula is expressed as

$$P_{b,n} = (-SP_{b,n-1} + P_{e,n-1})/(1-S)$$

with

$$S = \frac{P_{e,n-1}-P_{e,n-2}}{P_{b,n-1}-P_{b,n-2}}$$

The recursion parameters that are specified as program inputs are listed below:

ITRMA2: Maximum allowable iteration cycles during transient calculations

ITERMA: Maximum allowable iteration cycles during working point calculations

WEIG1: Value of WEIGHT in recursion formula type I for transient calculations of parameters other than xenon

WEIG2: Value of WEIGHT in recursion formula type I for transient xenon calculations

TRECUR: When the differences in values of parameters (except system pressure) between the beginning and end of an iteration cycle are less than TRECUR, formula type I will be used instead of formula type II since the latter is singular exactly at the solution

TRECU2: Same as TRECUR, but used for the system pressure calculations

ENDITG: When differences in values of parameters between the beginning and end of an iteration cycle are less than ENDITG, the solution is reached and iteration is terminated