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Institut für Reaktorentwicklung

Models, Methods and Digital Computer Programs for Analyses in Reactor Dynamics with Emphasis on Fast Breeder Reactors and Compressible Single-Phase Coolants

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K. Hornyik

Gesellschaft für Kernforschung m.b.H., Karlsruhe

[*)] Work performed within the association in the field of fast reactors between the European Atomic Energy Community and Gesellschaft für Kernforschung m.b.H., Karlsruhe.

Preface

Obsoleteness is a common and often inherent feature found with digital computer codes. In spite of it a threefold purpose is seen in compiling a report such as this. One of its objectives is to serve as a manual for direct application of the codes described to the class of reactors and problems for which they were indended (see title). Secondly, a description of the model employed is to give sufficient information for potential applications and extensions to a range of cases wider than originally foreseen. Finally, some methods and techniques are presented which were developed during the course of this work and which are believed to have general significance in the field of reactor dynamics analysis.

The model and program described herein evolved from the FORE-code /‾1,2_7. Therefore nearly all the model features of that code are incorporated as constituents of the basic model presented here. Abandoned parts are those which appeared either too restrictive (incompressible coolant) or overly simplifying (treatment of parallel channels). Many new features have been added; the most prominent ones concern the hydraulics model now able to cover any compressible single-phase coolant flowing through the reactor in two sections connected in series. Each of these sections itself may consist of an arbitrary number of different flow channels connected in parallel.

In this place the helpful assistance and advise is to be acknowledged of all those people who contributed to the completion of this work at various stages. The author is obliged especially to Ing. D. Janssen for valuable help with digital programming.

Karlsruhe, December 1968

Table of Contents

I. Introduction

Work reported here started as a part of the steam cooled fast breeder reactor project pursued by the GfK. Its early goal was to make available a tool for the analysis of the dynamic behavior of the type of reactors being considered at that time. Although a rather detailed analog model already existed /‾3_7 it was found necessary to complement it with a digital code. Arguments concerning the choice of computational means are as numerous as they are inconclusive. Extensive experience gained during this work from comparisons with analog calculations have led to the conclusion that neither system is pre-eminently suited for the whole range of problems posed in reactor dynamics. It appears that reactor stability and control as well as systems circuit analysis are mainly a domain of analog studies whereas reactor accident analysis and certain aspects of reactor stability are suitably studied by using digital techniques. Storage capacity and computing speed of second generation machinery (IBM 7074/7094) together with considerations of numerical stability restricts the study of dynamics models to roughly the same amount of detail as can be accommodated by models designed for large analog computers (76 integrators, 34 multipliers, 360 pots) where number of components is the only restriction. Only third generation digital computers (IBM 360) give a lead to digital methods with respect to handling complex nonlinear problems encountered in accident analysis. However, the ease of making adjustments to the model which is afforded by the analog computer cannot be matched on digital machines, a situation which has remained essentially unaffected by the advent of even the latest digital equipment.

The model which has been adopted here is characterized by the following prominent features:

a) The model covers only components of the reactor proper, such as: core, blankets, bypasses within the pressure vessel, orifices, plenum chambers, etc. An external reactivity disturbance as well as one out of a choice of three boundary conditions for the coolant at reactor entry and exit must be given as functions of time ("driving functions").+)

+) A digital model describing the dynamic behavior of all circuit components external to the reactor is being developed by the IRB (Institute for Reactor Components) at the GfK. Both programs are designed to be integrated into a single code giving a complete description of the entire reactor system.

b) The reactor is assumed to remain intact at all times. The only changes in reactor geometry are those associated with certain feedback mechanisms. They are assumed to have negligible effects on the thermo-hydraulic characteristics of the reactor.

c) Fuel elements are assumed to have the shape of solid cylinders (pins) surrounded by annular cladding and cooled uniformly over the perimeter. Fuel melting can be handled in good approximation. The coefficient of heat transfer through the fuel cladding-gap is assumed to be invariant. Coolant flow within the fictitious annular channel is assumed to be entirely in the turbulent regime. Any structural components inside the core and the blankets are accounted for by introducing equivalent structure along the flow channel.

d) The hydraulic model permits rather accurate treatment of any single phase coolant (liquid or gaseous) for which the standard relations of state variables can be supplied. Pressure disturbances are assumed to propagate with infinite velocity throughout the coolant (extended version of the integral momentum model [4]). A rather general formulation of the relation for the heat transfer between channel walls and coolant permits a wide range of applications. Coolant pressure drops in orifices and in the coolant channels are treated in the customary way and allow for integral treatment of turbulence promoters. An arbitrary number of different parallel flow channels individually orificed may be specified in both of the two main sections (radial blanket, core and axial blankets) which in turn are connected in series via an intermediary plenum chamber. Complete mixing and zero residence time are assumed for all of the three plenum chambers. Flow channels in the first section (radial blanket) may be treated as bypasses.

e) A special feature of the model is its ability to handle transient problems where flow stagnation or reversal occurs.

f) The time dependent behavior of the neutron density in the reactor core and blankets is described by the well known point reactor kinetics model. In order for this model to be consistent with the models for thermohydraulics and feedback it is consequent to assume time invariant functions for the spatial distribution of the thermal power density as well as for the reactivity importance throughout the reactor. The implications of these assumptions shall not be discussed in this report. Simplicity of this model was the guiding aspect in making this choice.

g) A versatile and comprehensive feedback model is incorporated which accounts for the Doppler effect, for various causes of density changes due to thermal expansion of components and for changes in the overall core geometry due to thermal expansion of certain components.

h) The reactor is assumed to be at an initial state of delayed criticality operating on a prescribed power level. The entire feedback of reactivity is thought to be balanced by external reactivity adjustments. (The relative value of this reactivity at different initial states can be used as a measure of the aperiodic stability of the reactor /‾5_7.) Furthermore, the thermohydraulic variables of the reactor also are assumed to be in a state of equilibrium at this power level. This equilibrium solution is obtained in a separate calculation but it is consistent with the set of equations describing the transient behavior.

i) The transient solution is obtained by integration of the pertinent system of differential equations in discrete steps using explicit first order backward difference formuli. The size of these steps may be determined from considerations of numerical stability and accuracy internal to the program.

In addition to these main features and functions of the basic model there are some contingent areas which have been given special attention as they are of considerable importance for many problem cases of a general class. Three of these are listed below.

j) The relations between state variables for superheated steam cannot be reduced to simple analytical formulations. Rather complex expressions on one hand and extensive tables on the other do not satisfy the need for compact and fast algorithms such as required by dynamics calculations in conjunction with multi-node models. Therefore, a set of polynomial expansions was generated by means of least squares fitting to the relations which are concerned and which were supplied accurately but inefficiently by other subprograms /‾6_7. Since excessive accuracy is not required here these expansions have proved to be of all important convenience and this technique is recommended for all coolants where simple relations for the state variables do not exist in the range of interest.

k) Since many applications of this model relate to reactor accidents (excursions)-analyses a rather versatile model for SCRAM functions (external reactivity vs. time, for emergency shut down) was worked out in several options to be described in this report.

1) The computer program based on this model (subroutine REXION) is designed to be integrated with another program describing the dynamic behaviour of the system external to the reactor. However, there are instances where such a program does not exist and/or may not be required. Examples for such cases are:

   - stability and dynamics studies of the reactor alone
   - analyses of rapid excursions with little feedback from the reactor on the coolant circuit behavior.

   To facilitate such studies the program is provided with a control section (main program REX) which admits applications independent of any other program. Of course, in such cases time dependent boundary conditions for the coolant at reactor inlet and outlet must be supplied as input information to the control section.

Subsequently the model will be described in greater detail. Then a concise description of the computer program will be given complete with instructions for input preparation and output listings. The pertinent system of equations is compounded in APPENDIX A. Further appendices are dedicated to the treatment of several special topics regarding models, methods and codes. An annotated sample problem is included for illustration in the last appendix.

II. Thermo-Hydraulic Model

II.1 General Lay-Out

The most general configurations that can be treated are sketched in Fig. 1. The coolant passes the reactor in two sections which are connected in series. These sections are separated by the intermediary plenum chamber and terminated by the entry and exit plenum chamber, respectively. The spatial arrangement of plenum chambers and flow sections is arbitrary and may be of a kind as shown in Fig. 1. With respect to the sketch on the left it must be remarked that the length of both flow sections is assumed to be equal. Order and nomenclature of these components are associated with the initial direction of coolant flow which is from the entry to the exit plenum chamber as depicted in Fig. 1.

The plenum chambers are characterized by complete and instant mixing of all entering coolant streams, zero residence time and zero pressure drop of the coolant.

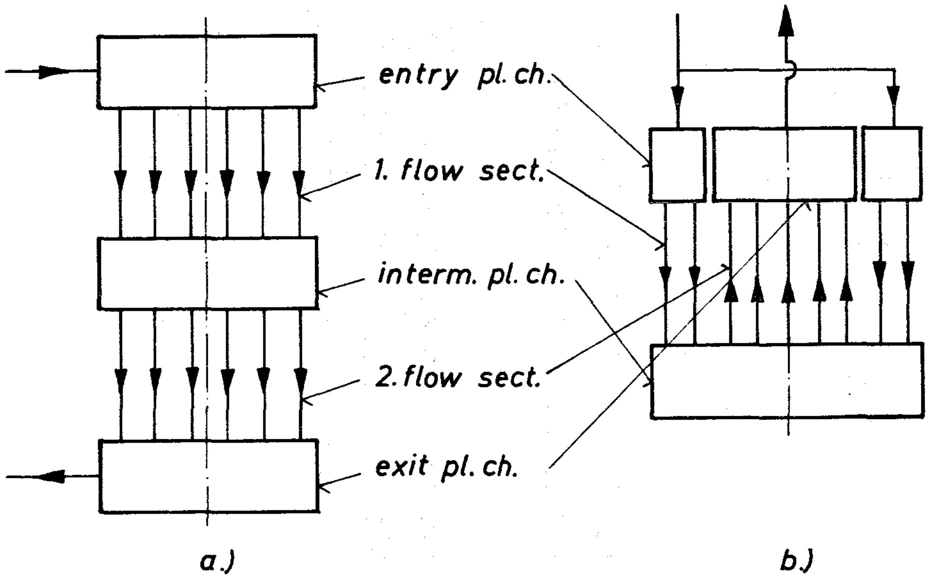


Fig. 1 Two Possible Configurations of Main Components

The first flow section is thought to represent the radial blanket. Its thermo-hydraulics are treated in a manner more crude than the one adopted for treating the second section. It does not contribute to the feedback of reactivity. It may be skipped entirely in the calculation. The coolant passes this first section through a number of parallel channels. Channels with identical parameters are called a radial zone and are represented in the calculation by only one such channel. The number of radial zones is arbitrary [+)]. Either one out of two different types of channels may be specified for any radial zone of the first section. The first type is to represent a typical radial breeder pin-channel-structure-combination consisting of a cylindrical pin with a uniform heat source, an equivalent annular flow channel which may be orificed at the entry, and an equivalent structural component (see Fig. 2). Neither axial subdivisions of the pin-channel-structure-unit nor annular subdivisions of the pin are provided since a rough model appears to be adequate in this place. The second type of channel is to represent a bypass and consists of two concentric tubes with coolant flowing in between. The inner tube may have an uniformly distributed heat source. Both tubes are assumed to be thermally insulated on their dry surfaces and may be orificed at the entrance. In particular, such a bypass may represent a single annular flow path outside the perimeter of the radial blanket.

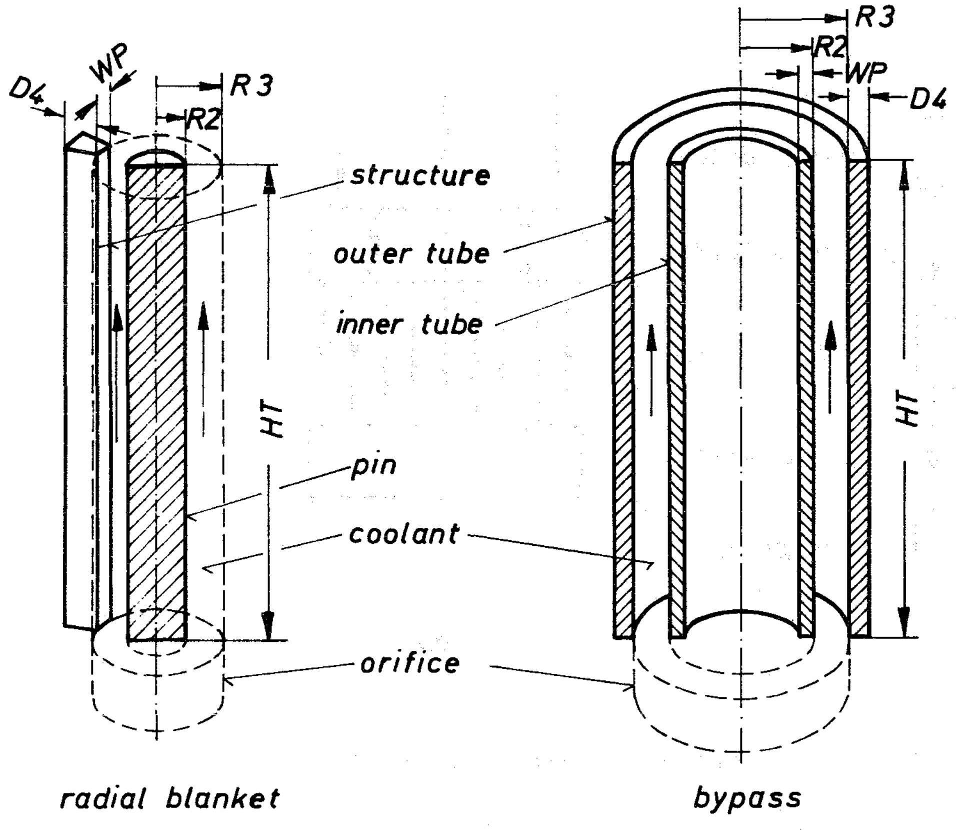


Fig. 2 Channel Types of First Section

[+)] Here, as well as in all subsequent instances arbitrary numbers of components and zones are restricted only by DIMENSIONS specified in the corresponding programs. In the present version these are chosen to accomodate most cases of practical interest and may be extended whenever necessary.

The second flow section is in many ways similar to the first one. It is to represent the core and the axial blankets of the reactor. Only one type of channel can be specified. Again, anyone such channel stands for a whole (radial-) zone of identical channels. The number of zones differing in geometry and/or thermo-hydraulic parameters is arbitrary. A channel consists of a cylindrical pin surrounded by an equivalent annular stream of coolant and an equivalent structural component. Flow may be orificed at the entrance. In axial direction (= direction of flow) the pin-channel-structure-unit is divided into the core section and one axial blanket section at both ends. Either one or both of these axial blanket sections may be omitted. The core section alone may be subdivided further into an arbitrary number of sections of equal height. In the core section the pin is composed of a cylindrical fuel body surrounded by annular cladding. For adequate description of the temperature distribution the fuel cylinder is subdivided by fictitious interfaces into an arbitrary number of concentric annuli of equal volume except for the outermost annulus and the center cylinder having half this volume.

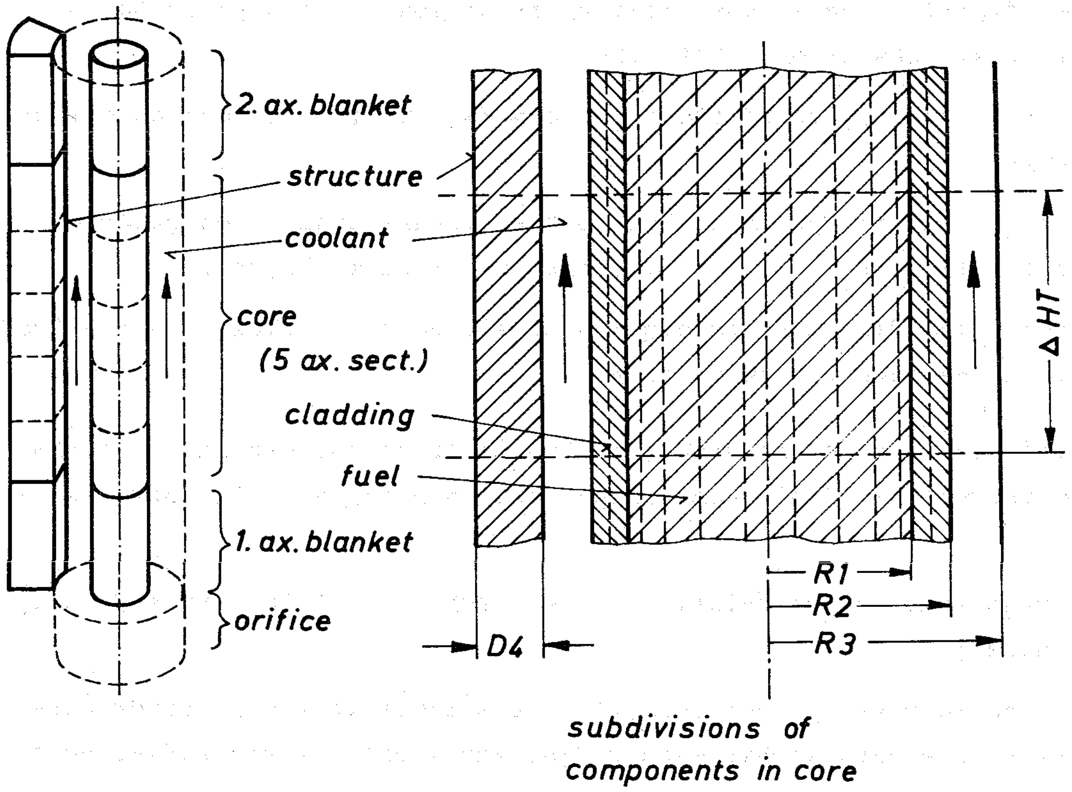


Fig. 3 Pin-Channel-Structure-Unit of the Second Section

II.2 Heat Source Distribution

The reactor power determined by neutron kinetics in conjunction with external reactivity as well as feedback is released as thermal energy in various components of the reactor. The spatial distribution functions are assumed to be time invariant and are prescribed. Thus, a fixed fraction of the total power is released within the pins of each radial blanket zone and the walls of the inner tubes of each bypass zone. These fractions PB together with the dimensions of the components involved and in conjunction with the assumption of uniform heat source distribution determine the volumetric heat source strength required for the calculation of temperatures in the first flow section.

In the second flow section fixed fractions PBE and PBA of the total power are assumed to be released within the first and the second axial blanket, respectively. Distribution over radial zones and components of the axial blankets conform with those of the core. The remaining power (= total - (radial bl. zones + bypass zones) - 1.ax. bl - 2.ax. bl) is distributed over the core in the following way (see also Fig. 4):

a) The axial distribution is specified by fractions corresponding to individual axial subsections. Note that:

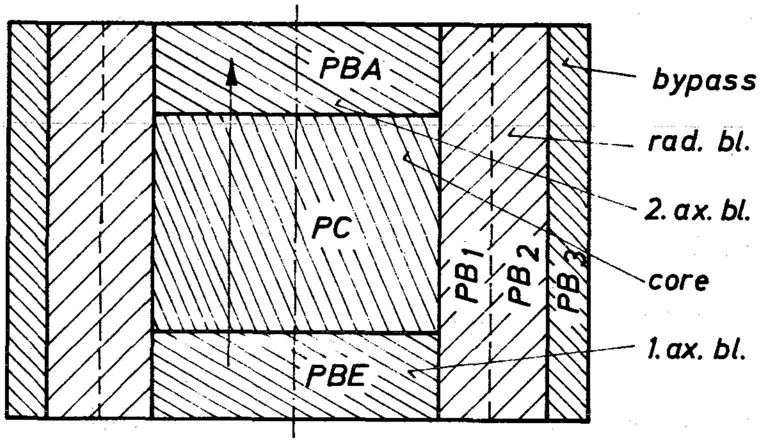
   - these fractions may be relative since normalization is carried out by the program;
   - these fractions are proportional to the average linear rod power of each subsection as these subdivisions are of equal height;
   - the same axial distribution applies to all parallel flow channels (rad. zones) in the second flow section.

b) The radial distribution is specified by fractions corresponding to the relative thermal power of each channel representing a radial zone. Note that:

   - these fractions may be relative since normalization is carried out by the program;
   - these fractions are proportional to the volumetric radial power distribution (averaged within each radial zone) only if the radial core zones have equal geometry;
   - the radial distribution specified by these fractions applies to all axial core sections and to the axial blankets.

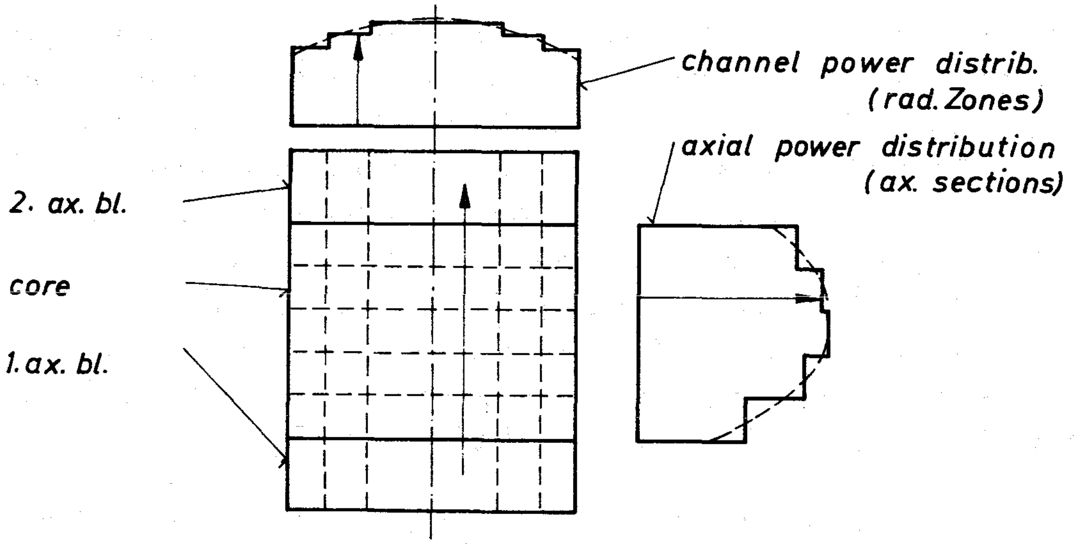
c) The power distribution over the core components is specified by fractions giving the relative volumetric thermal power density in each component (fuel, clad, coolant, structure). Note that:

- these fractions may be relative since normalization is carried out by the program;
- uniform power distribution is assumed in each of the four components;
- these fractions apply to all radial zones and axial sections of the core;
- in both, the radial and the axial blanket all power is assumedly released in the pins only.

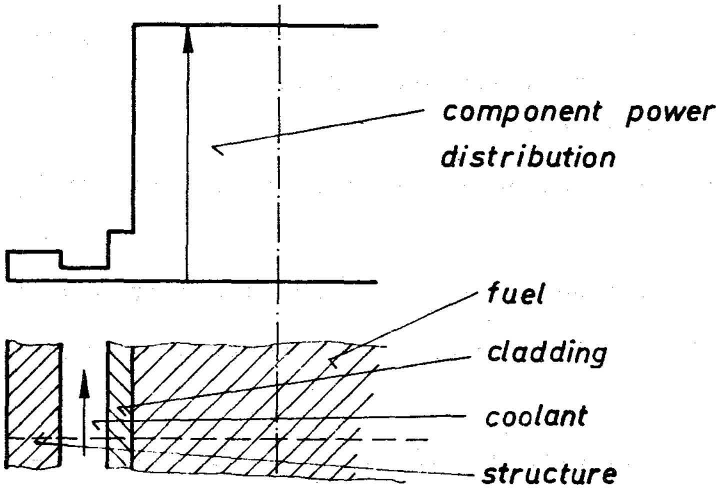


$$PC + PBE + PBA + \sum_i PB_i = 1$$

a) Power Distribution: Core-Blankets-Bypasses



b) Radial and Axial Power Distribution in Core (and Axial Blankets)



c) Power Distribution in Core-Components

Fig. 4 Power Distribution

II.3 Heat Flow and Temperatures

For the calculation of the temperatures in the fuel pin the customary assumptions of

- uniform heat release within the entire fuel pin volume of any axial section and
- no heat conduction in axial direction of the fuel pin

are made. The cylindrical fuel body is subdivided by fictitious interfaces such as described before. The temperature distribution in each axial section of any such annulus is represented by a single temperature and heat transfer as well as heat storage is computed in terms of this temperature ("nodal model", "lumped model"). Under steady state conditions this temperature is equal to the volume average temperature of the annular cell; for the central cylinder it is the central (maximum) temperature and for the outermost annulus it is the fuel surface temperature. If the thermal conductivity of the fuel is a function of temperature these statements are no longer accurate since the program evaluates the conductivity for each annulus at the temperature of the adjacent outer annulus.

In addition to the thermal conductivity the specific heat of the fuel also may be a prescribed function of the fuel temperature.

Fuel melting is treated in an approximate form: if the representative temperature of any fuel node reaches the melting point upon rising, it is kept constant until the net influx of heat into the volume equals the latent heat of fusion.

Recrystallization is treated in a similar manner upon a temperature drop through the temperature of recrystallization. Both, the temperature as well as the heat of fusion and recrystallization are taken to be equal. The program also admits the case that a part or all of the cells (nodes) in the fuel are molten at the initial equilibrium.

The nodal model which was selected here is one out of many possible choices. It is distinguished by yielding a correct steady state solution when the nodal temperatures are identified with the volumetric averages. This is significant especially with respect to calculating the reactivity feedback associated with the Doppler effect in the fuel. Regarding the transient solution one only can state that heat is conserved in the system of equations and that an increasing number of subdivisions will make the solution converge asymptotically to the correct solution. The results of a special study carried out for this purpose are described in APPENDIX B. and may serve as an aid in the selection of an adequate number of annular subdivisions for any particular case as a function of fuel parameters and accuracy requirements.

Heat transfer through the gap between fuel and cladding is assumed to be a function of the difference between the interface temperatures of fuel and clad only. The coefficient of heat transfer through the gap thus is a prescribed constant. More sophisticated models relating to this part may be introduced as they become available.

The annular cladding is treated as a thin slab and is subdivided by a fictitious interface into two annuli (slabs) of equal thickness. The nodal temperatures associated with these two annuli coincide with the temperatures at the inner and outer surface at steady state. In contrast to the fuel, the material parameters of the cladding are taken to be invariant. A heat source may be specified for the cladding and is assumed to be distributed evenly over the volume of each axial section.

In order to account for the effects brought about by the presence of structural components in core and blanket it is assumed that each channel also comprises a rectangular body of structural material extending over its full length (core + ax. blankets). This body is to be equivalent to the actual structure with respect to thermo-hydraulic characteristics. Three faces of the prismatic body are assumed to be thermally insulated, the remaining face is in contact with the stream of coolant and permits exchange of heat. Only in the core region heat sources may be specified for the structure, which then are distributed uniformly over the entire volume of an axial section (the axial distribution being the same as in fuel, cladding, and coolant). The nodal temperature representative for the actual temperature distribution of each axial section coincides with the volume average temperature at steady state conditions.

Heat transfer between the coolant and either the cladding or the equivalent structure is computed following a slightly generalized form of the Nusselt equation as proposed by Sutherland [7]. It is based on the assumption of a coolant wholly in the turbulent flow regime+)

$$\mathrm{Nu}^{*} = \mathrm{CH} \cdot \mathrm{Re}^{\mathrm{AL1}} \cdot \mathrm{Pr}^{\mathrm{AL2}} \cdot \left(\frac{\mathrm{T3} + 273.16}{\mathrm{TW} + 273.16}\right)^{\mathrm{AL3}} \qquad (1)$$

$$\mathrm{Nu}^{*} = \frac{(\mathrm{H3} - \mathrm{AL4}) \cdot \mathrm{DH}}{\mathrm{FLAM}} \qquad (2)$$

$$\mathrm{Re} = \frac{\mathrm{N} \cdot \mathrm{DH}}{\mathrm{ETA}} \qquad (3)$$

$$\mathrm{Pr} = \frac{\mathrm{CP3} \cdot \mathrm{ETA}}{\mathrm{FLAM}} \qquad (4)$$

CH, AL1, AL2, AL3, AL4 ... prescribed parameters

Solving equation (1) for the film coefficient H3 we get

$$\mathrm{H3} = \mathrm{AL4} + \frac{\mathrm{CH}}{\mathrm{DH}^{(1-\mathrm{AL1})}} \cdot (\mathrm{N})^{\mathrm{AL1}} \cdot \left(\frac{\mathrm{FLAM}^{(1-\mathrm{AL2})} \cdot \mathrm{CP3}^{\mathrm{AL2}}}{\mathrm{ETA}^{(\mathrm{AL1}-\mathrm{AL2})}}\right) \cdot \left(\frac{\mathrm{T3} + 273.16}{\mathrm{TW} + 273.16}\right)^{\mathrm{AL3}} \qquad (5)$$

The additional constant AL4 is introduced in equation (2) for convenience of specifying an invariant film coefficient H3 = AL4 while at the same time setting AL1 = AL2 = AL3 = 0.

+) see APPENDIX A for nomenclature

All of the intensive parameters in equation (5) refer to the coolant with exception of the wall temperature TW. These parameters are evaluated at the midpoint of each axial section.The state variables of the coolant are taken to vary linearily over the length of each section. The occurrence of TW in equation (5) necessitates an iterative procedure for determination of TW at the initial equilibrium. This is described in APPENDIX D.

The energy balance of the coolant is computed in terms of its enthalpy. Contributions of kinetic and potential energy are neglected. The coolant pressure is obtained from hydraulics calculations described in the next chapter. These two state variables are sufficient for obtaining all of the remaining coolant properties required in equation (5) by way of state relationships(i.e. temperature, specific heat, specific volume, viscosity and thermal conductivity). For the energy balance in the transient case it is assumed that heat storage in the coolant of each axial section is associated with the value of the *exit* enthalpy. This particular choice of a nodal model is not quite as accurate as the one employing the enthalpy *averaged* along the channel length of each individual section. However, the error in the transient may be kept small by increasing the number of axial sections. On the other hand, this nodal representation is particularily suited for handling the case of flow reversal during a transient, which is a major objective of this work. For further details concerning the treatment of flow stagnation and reversal see APPENDIX E.

Much of what is said above also applies to the calculation of temperatures in the radial and axial blankets as well as in the bypass(es). However, there the calculation is simplified by prescribing invariants for all material properties as well as for the film coefficient of heat transfer to the coolant and by lumping the pin temperature distribution of each section into one node. In the case of the blanket pin the nodal temperature coincides with the maximum temperature on the center axis for steady state conditions, when the coefficient of heat transfer is specified so as to include also heat transfer through cladding gap and breeder pin, which are not accounted for separately +). For the nodes associated with equivalent structure and/or bypass walls the nodal temperatures agree with the

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+) For the case indicated above the coefficient of heat transfer can be obtained from:

1./HFS = R1/R2·(R1/C4·C01)+1./HGP+(R2-R1)/C02+R1/(R2·H23))

if the blanket pin is of a design similar to the fuel pin.

volume averaged temperatures under the same conditions as before. It is recalled that the model does not provide axial subdivisions for any of the blankets and/or bypasses. Fig. 5 sketches the nodal representation of the reactor, on which the thermo-hydraulic model is based.

In solving the ordinary differential equations resulting for this nodal model (see APPENDIX A) a single explicit backward difference scheme is applied. It is known that in this case the step size for integration over time must comply with certain criteria in order to ensure numerical stability of this method. Since these criteria are prohibitively complex in the underlying case approximate criteria were developed, which yield conservative estimates of the maximum step size for stable integration of the thermo-hydraulic equations. Details on this subject are compiled in APPENDIX H.

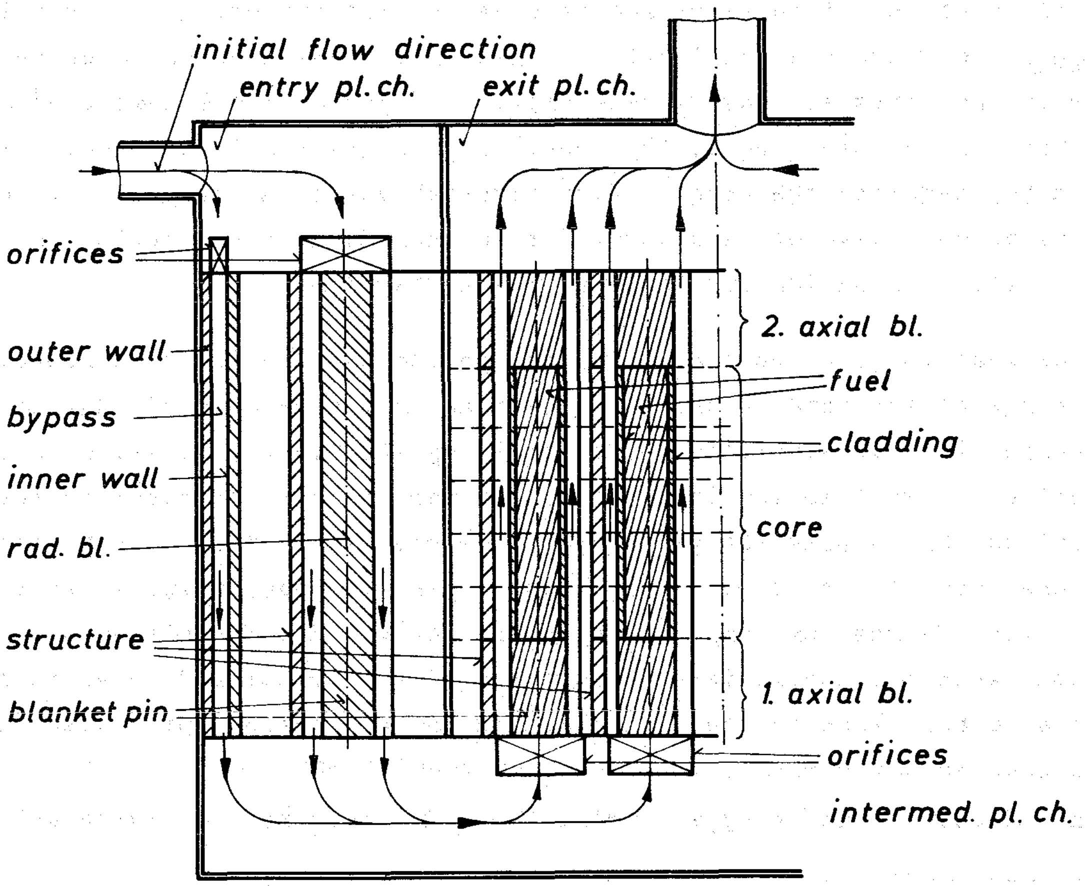


Fig. 5 Nodal Representation of the Reactor for Thermo-Hydraulic Model

II.4 Coolant Hydraulics

Three kinds of pressure losses are distinguished in each flow channel.

a) Pressure loss at the channel entrance:

$$\Delta p_E = 1.5 \cdot \frac{N^2 \cdot V}{2 \cdot g \cdot 10^4} \quad [\text{at}] \qquad (6)$$

It is assumed that no pressure recovery occurs at the channel exit. Note that this pressure loss will occur at the other end of the channel in case of flow reversal.

b) Pressure drop through orifice:

$$\Delta p_T = FT \cdot \frac{N^2 \cdot V}{2 \cdot g \cdot 10^4} \quad [\text{at}] \qquad (7)$$

The coefficient FT may be chosen different for each radial zone and is both purpose and means of controlling the distribution of coolant flow through the various flow paths in parallel.

c) Pressure loss due to friction along the wetted surface of the channels (cladding + equivalent structure) and to acceleration:

$$\Delta p_R = \frac{N^2}{g \cdot 10^4} \left[\frac{FR \cdot \Delta H}{2 \cdot DH} \cdot V + (VA - VE) \right] \quad [\text{at}] \qquad (8)$$

In the present model pressure loss associated with flow of coolant through the plenum chambers is neglected. The condition determining the distribution of coolant mass flow through parallel channels is that of equal pressure drop in all of these channels. For the initial steady state an iterative procedure is used to achieve this. In the transient calculation a scheme of delayed correction is applied to satisfy the criterion of equal pressure drops without need for iterations. APPENDIX C gives a rather detailed account of the pertinent procedures. APPENDIX E is referred to for more information about the calculation of pressure drops in the case of flow stagnation or reversal.

II.5 Coolant Boundary Conditions

There are three links by which this model representing the reactor is coupled to the remaining system. These are:

a) state of coolant at the entrance

b) " " " " " exit

c) disturbances of external excess reactivity (control rods - control system)

Items a) and b) are not entirely independent of each other. In any case it appears practical to prescribe the enthalpy of the coolant as it enters the reactor. The exit enthalpy then is determined directly by the balance of energy. Regarding the hydraulic boundary conditions there is no such unique choice. Therefore, the model was made to accommodate three different choices:

B.C.1 Prescribe:
- pressure at entry, as a function of time;
- coolant mass flow rate through reactor, at initial steady state;
- pressure at the exit relative to the initial value, as a function of time.

Obtain:
- pressure at the exit, at initial steady state;
- coolant mass flow rate, as a function of time.

This particular set of boundary conditions is advantageous in connection with the integration of this model with a corresponding model for the external coolant circuit.

B.C.2 Prescribe:
-pressure at exit, as a function of time;
-coolant mass flow rate, as a function of time;

Obtain:
-pressure at entry, as a function of time.

B.C.3 Prescribe:
- pressure at entry, as a function of time;
- coolant mass flow rate, as a function of time;

Obtain:
- pressure at exit, as a function of time.

For B.C.2 an iterative procedure is required to find the initial steady state solution since in all cases the calculation starts at the entrance where coolant pressure is unknown in this particular instance. For the transient calculation of the same case a scheme of delayed correction is applied thus avoiding time consuming iterative procedures (see APPENDIX C).

III. Neutron Kinetics and Feedback Model

For the description of the transient reactor power the well known point reactor kinetics model is employed. Its solution requires integration of a coupled system of ordinary linear differential equations with time dependent coefficients. This integration is carried out using a semi-analytic method taken over in main parts from the FORE-code /¯1_7 and described in APPENDIX F. The basic scheme of integration outlined in the appendix is augmented by two other schemes. One of them is applied in the vicinity of prompt criticality since the basic scheme is singular at this point. The other scheme corresponds to the prompt jump approximation and is a more efficient scheme of integration which applies when the system is well below prompt critical. Decisions about selecting the proper scheme out of these three are based on the results of certain tests carried out at each step of the step by step-integration. Among other criteria the size of such a step is limited by the relative change of the reactor power during a step,for which upper and lower limit may be prescribed. The step size will be decreased or increased respectively until the actual value of the relative change falls within these limits. A correlation between both, accuracy and stability of this method of integration and this criterion for selection of step size could not be established in the framework of this effort. On the other hand, practical experience gained from its successful application as well as successful application of the same criterion in other methods of integration of point kinetics equations have given enough confidence to validate this approach.

The feedback model, too, draws main features from the FORE-code but it is implemented with a number of significant additions and modifications. In spite of the already great amount of details included in this feedback model it is felt that much more refinement might be required in certain cases. However, at this point such refinement must be left with further development efforts.

Presently, all feedback of reactivity accounted for is associated with temperature and/or density changes in the core only. The reactivity feedback from the Doppler effect is taken to be proportional to the weighted average over the fuel volume in the core of the natural logarithm of the fuel temperature in ^{o}K. Both, axial and radial weights may be specified. These weights may be relative as normalization is carried out in the program. The normalization is such that an isothermal temperature rise $\Delta T = T_1 - T_o$ throughout the fuel in the core will result in a Doppler reactivity change of $\Delta k_D = RCD \cdot \ln(T_1/T_o)$, where RCD is the Doppler constant specified in the input. The basic formula for calculating the Doppler feedback reactivity is

$$\Delta k_D = RCD \frac{\int ARD.AXD.\ln((\overline{TF}+273.16)/(\overline{TF}_o+273.16)\cdot dV_F}{\int ARD \cdot AXD \cdot dV_F} \qquad (9)$$

$$\overline{TF} = \frac{1}{V_z} \cdot \int TF \, dV_z \ \ldots \text{ fuel temperature averaged over the pin volume } V_z \text{ of an axial section}$$

$$V_z = R1^2 \cdot \pi \cdot \Delta H \qquad (10)$$

The effects on reactivity of changes in the density of any core component are treated correspondingly as weighted averages over the component volume in the core of the respective temperatures multiplied by their linear thermal expansion coefficient. As in the case of the Doppler feedback, the weights are assumed to be separable into functions of the axial and radial coordinate (index) respectively (normalization not required). Thus, the product of feedback coefficient times expansion coefficient of each component is equal to the total feedback from this component if a uniform temperature change by 1 °C is imposed throughout the core. Here the basic formula is

$$k_i = -RC_i \frac{\int AR_i \ AX_i \cdot T_i \cdot AE_i \cdot dV_i}{\int AR_i \cdot AX_i \cdot dV_i} \qquad (11)$$

where the index i refers to the three solid components: fuel (F), cladding (C), structure (M). For the coolant density changes can be computed directly as the specific volume V is available:

$$k_s = RCS \cdot \frac{\int ARS \cdot AXS \cdot (1/V) \cdot dV_s}{\int ARS \cdot AXS \cdot dV_s} \qquad (12)$$

The effects of changes in the overall core geometry (height and radius) are also comprised in the feedback model. Increases in the core height are associated with thermal expansion of the fuel and radial increases with lateral expansion of the structural components of the core. Weighting functions have not been incorporated in this part of the model as yet. The pertinent formuli are:

$$k_H = RCH \cdot \frac{\int AEF \cdot \overline{TF} \cdot dV_F}{\int dV_F} \tag{13}$$

$$k_R = RCR \cdot \frac{\int AEM \cdot \overline{TM} \cdot dV_M'}{\int dV_M'} \tag{14}$$

$$V_M' = \Delta H \cdot AN \tag{15}$$

With the general formulations used for the temperature and density feedbacks on reactivity (equation (11), (12)) it is possible to include mechanisms other than the change of smear density of a component caused by a change in its temperature. For instance, one may account for the effect of coolant displacement by cladding expansion and for effective density changes of all components caused by dimensional changes in the supporting core structure due to thermal expansion or contraction. In such cases, the reactivity coefficients (RC_i), the weights (AR_i, AX_i) and the expansion coefficients (AE_i) appearing in equations (11) and (12) must be determined by superposition of the various effects to be included. This is illustrated by a typical example presented in APPENDIX G.

IV. Program Description

IV.1 General Code Structure

Flexibility in operation and application of any complex program is furthered by employing modular programming techniques. This principle was followed here to a large extent. One of the most prominent exceptions is the feedback calculation, which is attached to the thermohydraulic calculations. The reason for this is a gain in computational speed and reduction in storage requirements since all contributions to the feedback originate from changes in thermo-hydraulic variables and may be computed efficiently along with these variables. Another exception is the calculation of the film coefficient of heat transfer to the coolant in the core. Here, too, the calculation is tied in strongly with thermo-hydraulics and an integrated treatment appears advantageous.

The programming language used in all parts is FORTRAN IV compatible with FORTRAN II if all READ and WRITE and COMMON statements are adjusted to comply with FORTRAN II rules. The program has been tested out successfully on the following computers: IBM 7074, 7094, 360/65. The version for IBM 7074 computers requires OVERLAY structure.

Fig. 6 lists all routines required by this program together with their major functional characteristics. Fig. 7 shows a logic flow diagram depicting the interconnections between these routines.

The main program REX is intended for independent application of the model, i.e. for cases where the boundary conditions of the coolant are known functions of time. Provisions are made for linking the present program with a compatible digital program describing the dynamics of the external circuit. In such a case the program may be used without the main program REX as a subroutine called by the name REXION (level 2 in Fig. 7). Guide lines and examples for such applications are given in APPENDIX J. Calls of this subroutine with different values for the last argument (IX) in the list causes execution of various operations such as: reading of input, calculation of initial steady state solution, execution of one step of the transient integration, output of variables. Some of the remaining arguments serve for input of coolant boundary conditions to the subroutine, others return information concerning: actual transient time after last step of integration, size of last step, power, energy and the compliment of coolant boundary conditions upon completion of the last step. Problem termination is also a

Name	Type		Called Subprogram(s)
REX	MAIN	controlling program for indep. applications, input and evaluation of coolant boundary conditions, output frequency control	REXIØN, ZEIT
REXIØN	SUBROUTINE	controlling program, input of parameters for and execution of step size- and termination control	PREP, CØ1, CP1, PØWER, STS, TRS, STEPC, ØUTPUT
PREP	- " -	input of parameters concerning geometry, thermo-hydr., feedback, iteration, output volume control, preparation of const. coefficients	
STS	- " -	solution of initial steady state problem	TPE1, HDV, FLAM1, ETA1, CØ1
TRS	- " -	" " transient problem	TPE1, HDV, FLAM1, ETA1, CØ1, CP1
STEPC	- " -	calculation of max. step size for stable integration of thermo-hydr.	
ØUTPUT	- " -	output of thermo-hydraulic variables and feedback reactivities	
PØWER	- " -	input of point kinetics parameters, integration of point kinetics	RCBE
RCBE	FUNCTION	external (controlled) reactivity disturbance, input of pertinent parameters	
TPE1	SUBROUTINE	temperature and specific heat of coolant from enthalpy and pressure	
HDV	FUNCTION	specific volume of coolant from temperature and pressure	
FLAM1	- " -	thermal conductivity of coolant from temperature and pressure	
ETA1	- " -	dynamic viscosity of coolant from spec. vol. and temperature	
CØ1	- " -	temp. dep. thermal conductivity of fuel, input of pert. parameters	
CP1	- " -	temp. dep. specific heat of fuel, input of pertinent parameters	
ZEIT	- " -	computer clock	

Fig. 6 List and Major Functions of all Routines Comprised by the Complete Program

function of this routine and is signalled to the calling program via the argument IX.

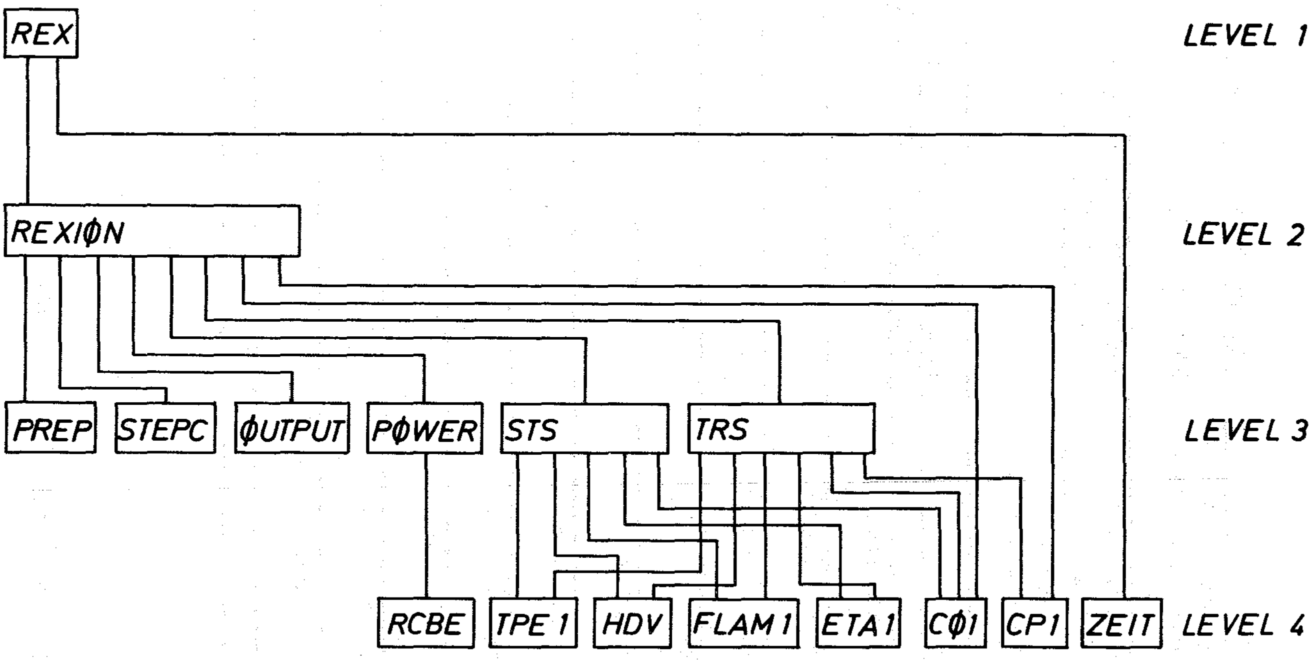


Fig. 7 Logic Flow Diagram

Instead of giving a detailed description or listing of all the routines involved it is considered to be both sufficient and helpful to include flow diagrams of these routines (APPENDIX I). The subprograms of level 4 should be considered non-standard since certain applications may demand individually supplied routines. Guide lines for the construction of such routines are given in the APPENDICES K, L, M, N together with descriptions of the particular versions of those routines which were developed in conjunction with studies for the steam cooled fast breeder project /‾8_7. For the sake of completeness the input required by these specific program versions also is included in the subsequent input description.

IV.2 Input Description

Data input to the program is arranged in blocks. Each block is headed by a card carrying the block number IP (column 3) and a commentary (columns 4 - 75) which will be reproduced in the output. There are nine blocks of data as follows.

IP	Block Significance	Input for
1	system data	REXION
2	coolant enthalpy at entry	REX
3	boundary condition parameter	"
4	pressure	"
5	initial coolant mass flow rate and pressure change	"
6	coolant mass flow rate	"
7	initial reactor power	"
8	output control- and clock termination parameter	"
9	end of job-card	"

Data blocks 2, 4, 5, 6, 7 contain the information concerning all the external conditions (boundary conditions) required for independent application. The only other external condition needed is the external reactivity disturbance, which is specified as part of the system data in block IP = 1. Besides this block 1 contains all the characteristics of the reactor as well as control parameters concerning the computation, output volume, and termination. For convenience block 1 therefore is subdivided into subblocks, each of these headed by a card carrying the subblock number IPT (column 7) and a commentary (columns 8 - 79) which will be reproduced in the output. There are eight subblocks as follows:

IPT	Subblock - Significance
1	geometry and thermo-hydraulic properties
2	temp. dep. fuel properties
3	point kinetics parameters and external reactivity
4	feedback parameters
5	iteration- and output volume control parameters
6	step- and termination-control parameters
7	(not used at present)
8	end of subblock-card

Any particular set of boundary conditions out of the choice of three is specified by the boundary condition parameter IBC (block 3) which may assume one of the values 1, 2, 3 accordingly. In either case the three subsequent blocks have to be used in the following way:

IBC =	1	2	3
block 4	entry pressure	exit pressure	entry pressure
block 5	initial mass flow rate, exit pressure change	omit	omit
block 6	omit	coolant mass flow rate	coolant mass flow rate

A job may consist of several transient problems to be solved successively. For the first problem of any job a full set of data for blocks 1-8 must be supplied in the order indicated by the block numbers. In any further problem only those blocks and/or subblocks need to re-occur in which new data are to replace old values. As an exception to this, the data block 8 must be the last block in the complete set of data for anyone problem. After the data set for the last problem in a job block 9 must appear. An example for block sequence pertaining to a feedback parameter study is given below (subblock numbers in parentheses).

$$\underbrace{1(1,\ 2,\ 3,\ 4,\ 5,\ 6,\ 7,\ 8,),\ 2,\ 3,\ 4,\ 6,\ 7,\ 8,}_{\text{problem No. 1}}\ \underbrace{1(4,\ 8,),\ 8,}_{\text{problem No.2}}\ \underbrace{1(4,\ 8,),\ 8,}_{\text{problem No.3}}\ 9$$

Note, that in each case subblock 8 must appear last in block 1 and block 8 must appear last in each problem.

In an effort to make input as well as output consistent with respect to dimensional units all quantities are measured in terms of the following basic units:

mass:	kg	pressure:	at
length:	m	energy (therm.):	kcal
time:	sec	reactivity:	$
temperature:	°C	power:	MW

Power could be measured in units of kcal/sec, however, this is not at all a customary unit for reactor power and MW are used for this variable instead. The same holds true for pressure which is measured in at (kp/cm^2) instead of kp/m^2. It is possible to apply an entirely different set of basic units for input and output (as long as the set is selfconsistent) after adjusting four conversion factors which are required and defined in subroutine PREP (C1, C3, C4) and subroutine RCBE (C6). They have the following significance:

C1 = 238.89 (kcal/MWsec)
C3 = $9.81 \cdot 10^4$ (kg m/kp sec^2)$\cdot$(kp/m^2 at)
C4 = $1296 \cdot$C3 (kg m/kp h^2)
C6 = 9.81 (kg m/kp sec^2)

Uniform formats are used for all input data:

integer : IP, output volume control parameters ... I3
all others I7

real : .... E 11.4

Restrictions listed in parentheses are imposed by DIMENSIONS specified in the program and may be altered if necessary. In the present version the following values are used:

NRBD = 4, NRD = 5, NXD = 10, NND = 10, NDD = 10,NYD = 50.

card	variable	format	units	significance	restrictions

System data (block 1)

1	IP	I3	-	block identification, columns 4-75 free for commentary	= 1

Geometry and Thermo-Hydraulics (subblock 1)

2	IPT	I7	-	subblock identification, columns 8-79 free for commentary	= 1
3	NRB	I7	-	number of radial zones (incl. bypass zones) in first flow section (= 0 ... no first section)	$0 \leq NRB \leq (NRBD)$
	NBE	"	-	first axial blanket (entrance) (= 0 ... no first axial blanket)	0,1
	NBA	"	-	second axial blanket (exit) (= 0 ... no second axial blanket)	0,1
	NR	"	-	number of radial zones in second flow section (core+ax.bl.)	$0 < NR \leq (NRD)$
	NX	"	-	number of axial sections in core	$0 < NX \leq (NXD)$
	NN	"	-	number of annular zones in fuel pins	$2 \leq NN \leq (NND)$
4	HC	E 11.4	m	height of core	
	HBE	"	m	height of first axial blanket	
	PBE	"	%/100	fraction of total reactor power released in first ax. bl.	
	HBA	"	m	height of second axial blanket	
	PBA	"	%/100	fraction of total reactor power released in second ax. bl.	

For a type 1 channel of the first flow section card 5 is as follows:

5a	BP	"	-	indicator for channel type	= 0
	R2	"	m	breeder pin radius	
	R3	"	m	outer radius of equivalent annular flow channel	
	D4	"	m	thickness of equivalent structure component	
	WP	"	m	wetted perimeter of equivalent structure component	
	AN	"	-	total number of identical pins having these specifications	

For a type 2-channel of the first flow section card 5 has an alternate meaning as follows

5b	BP	E 11.4	-	indicator for channel type	= 1
	R2	"	m	inner radius of annular flow channel	
	R3	"	m	outer radius of " " "	
	D4	"	m	thickness of outer wall	
	WP	"	m	" " inner "	
	AN	"	-	number of identical channels having these specifications	
6	PB	"	%/100	fraction of total reactor power released in this radial zone	
	HA	"	$kcal/m^2 sec ^oC$	equivalent film coefficient of heat transfer to coolant	
	CV	"	$kcal/m^3 {}^oC$	equivalent volumetric specific heat	
	FR	"	-	friction factor for channel walls	
	FT	"	-	orificing factor	

Cards 5 and 6 have to be repeated NRB times for each radial zone and/or bypass zone of the first flow section.

If NRB = 0 cards 5 and 6 must be omitted.

7	R1	"	m	radius of fuel (inner radius of clad)	
	R2	"	m	radius of pin (outer radius of clad)	
	R3	"	m	outer radius of equivalent annular flow channel	
	D4	"	m	thickness of equivalent structural component	
	WP	"	m	wetted perimeter of equivalent structural component	
	AN	"	-	number of identical channels having these specifications	
8	ROF	"	kg/m^3	density of fuel	
	ROC	"	kg/m^3	density of clad	
	ROM	"	kg/m^3	density of structure	
	AEF	"	${}^oC^{-1}$	linear coefficient of thermal expansion of fuel	

	AEC	E 11.4	$^{o}C^{-1}$	linear coefficient of thermal expansion of clad	
	AEM	"	$^{o}C^{-1}$	" " " " " " structure	
9	C0C	"	kcal/m sec°C	thermal conductivity of clad	
	C0M	"	"	" " " structure	
	CPC	"	kcal/kg °C	specific heat of clad	
	CPM	"	"	" " " structure	
	CHC	"	-	coefficient for heat transfer relation: clad-coolant	
	CHM	"	-	" " " " " : structure-coolant	
10	HGP	"	kcal/m^{2}sec°C	film coefficient for heat transfer through fuel-clad gap	
	TM	"	°C	melting point of fuel	
	WM	"	kcal/m^3	latent volumetric heat of fusion in fuel	
	FR	"	-	friction factor for channel walls	
	FT	"	-	orificing factor	
11	AQR	"	-	relative channel power for this radial zone	
	AQF	"	-	relative volumetric power density in fuel	
	AQC	"	-	" " " " " clad	
	AQS	"	-	" " " " " coolant	
	AQM	"	-	" " " " " structure	
12	ARD	"	-	relative weight of this radial zone for Doppler reactivity effects	
	ARF	"	-	relative weight of this radial zone for reactivity effects from fuel density	
	ARC	"	-	relative weight of this radial zone for reactivity effects from clad density	
	ARS	"	-	relative weight of this radial zone for reactivity effects from coolant density	
	ARM	"	-	relative weight of this radial zone for reactivity effects from structure density	

13	HFS	"	kcal/m^{2}sec^{o}C	first axial blanket, equivalent film coefficient of heat transfer pin-coolant	
	CVF	"	kcal/m^3 ^{o}C	first axial blanket, equivalent volumetric specific heat of pin	
	HMS	"	kcal/m^{2}sec^{o}C	first axial blanket, equivalent film coefficient of heat transfer structure coolant	
	CVM	"	kcal/m^3 ^{o}C	first axial blanket, equivalent volumetric specific heat of structure.	
14	HFS	"	"	second axial blanket } - " -	
	CVF	"	"		
	HMS	"	"		
	CVM	"	"		

Card 13 is omitted if NBE = 0., card 14 is omitted if NBA = 0. Cards 7-14 are repeated NR times for each radial zone of the second flow section (core).

15	AQX	E 11.4	-	relative power density of this axial section	
	AXD	"	-	relative weight of this axial section for reactivity effects from Doppler effect in fuel	
	AXF	"	-	relative weight of this axial section for reactivity effects from fuel density changes	
	AXC	"	-	relative weight of this axial section for reactivity effects from clad density changes	
	AXS	"	-	relative weight of this axial section for reactivity effects from coolant density changes	
	AXM	"	-	relative weight of this axial section for reactivity effects from structure density changes	

Card 15 is repeated NX times for each axial section of the core.

16	AL1	E 11.4	-	exponents in heat transfer relation (see eq. (1))	
	AL2	"	-		
	AL3	"	-		
	AL4	"	kcal/m^{2}sec$^\circ$C	constant in heat transfer relation (see eq. (2))	

Parameters Pertaining to the Temperature Dependent Fuel Properties (subblock 2)

17	IPT	I7		subblock identification, columns 8-79 free for commentary	= 2
18	CK1	E 11.4	BTU/ft hr $^\circ$F	coefficients for polynomial representation of thermal conductivity of fuel (APPENDIX K)	
	CK2	"	BTU/ft hr $^\circ F^2$		
	CK3	"	BTU/ft hr $^\circ F^3$		
19	CC1	"	kcal/kg $^\circ$F	coefficients for polynomial representation of specific heat of fuel (see APPENDIX K)	
	CC2	"	kcal/kg $^\circ F^2$		
	CC3	"	kcal/kg $^\circ F^3$		

Cards 18 and 19 refer to the specific form of subroutines C01 and CP1 described in APPENDIX K.

Parameters for Point Kinetics and External Reactivity Function (subblock 3)

20	IPT	I7	-	subblock identification, columns 8-79 free for commentary	= 3
21	OM	E 11.4	sec^{-1}	β/Λ	
	ND	I7	-	number of precursor groups	$\leq$ (NDD)
22	FY	E 11.4	-	β_1/β relative fractional yield and decay constant for precursor groups 1, 2, 3	
	LA	"	sec^{-1}	λ_1	
	FY	"	-	β_2/β	
	LA	"	sec^{-1}	λ_2	
	FY	"	-	β_3/β	
	LA	"	sec^{-1}	λ_3	

Card 22 is to be repeated as necessary to accommodate all parameters for the ND precursor groups.

23				This card (plus eventual following cards) contains parameters required as input to subprogram RCBE defining the external reactivity function. A set of such cards required for the particular version described in APPENDIX L is described in that place.	

Feedback Parameters (subblock 4)

24	IPT	I7	-	subblock identification, columns 8-79 free for commentary	= 4
25	RCD	E 11.4	Ø	Doppler constant	
	RCH	"	Ø	reactivity coefficient related to changes in core height	
	RCR	"	Ø	" " " " " " " radius	
	RCF	"	Ø	" " " " " " fuel temp.	
	RCC	"	Ø	" " " " " " clad "	
	RCS	"	Ø·m^3/kg	" " " " " " coolant density	
26	RCM	"	Ø	" " " " " " structure temp.	
	RC	"	-	coefficient for feedback reactivity (= 0. for elimination of feedback, = 1.0 for normal calc.)	

Parameters for Controlling Iteration in Finding Initial Steady State Solution and for Output Volume Control (subblock 5)

27	IPT	I7	-	subblock identifications, columns 8-79 free for commentary	= 5
28	EST	E 11.4	-	ratio of proposed step size to step size estimate for stable integration (APPENDIX H)	
	EV	"	-	fractional change in spec. vol. of coolant at which steady state iteration is terminated. see APPENDICES C,D	
	ETC	"	-	fractional change in clad temperature at which steady state iteration is terminated	
	ETM	"	-	fractional change in structure temperature at which steady state iteration is terminated	
	EP	"	-	absolute change in pressure drop at which steady state iteration is terminated	

29	IRBN IRBX IRBD	I3 " "	- - -	minimum maximum increment of loop parameter for output of thermo-hydr. variables, concerning radial zones and/or bypasses of first flow section	≤ NRB
	IRN IRX IRD	" " "	- - -	- " - ....., concerning radial zones of second flow section (core + ax.bl.)	≤ NR
	IXN IXX IXD	" " "	- - -	- " - ...., concerning axial sections of core	≤ NX
	IR1N IR1X IR1D	" " "	- - -	minimum maximum increment of loop parameter for output of fuel temperatures concerning radial zones of second flow section (core + ax.bl.)	≤ NR
	IX1N IX1X IX1D	" " "	- - -	- " - concerning axial sections of core	≤ NX
	INN INX IND	" " "	- - -	- " - concerning annular subdivisions of fuel pellet	≤ NN

Parameters for Step- and Termination Control (subblock 6)

30	IPT	I7	-	subblock identification, columns 8-79 free for commentary	= 6
31	NTE NCX	" "	- -	number of steps after which approx. calculation of max. stable step size is repeated number of steps to which integration is limited	

32	XMA	E 11.4	sec	(reactor-) time limit for integration (start at time X = 0.)	
	XIN	"	sec	minimum step size admitted for integration.	
	XIX	"	sec	maximum " " " " "	
	PIN	"	-	minimum relative change in power during step, propose doubling of step size if actual change is less.	
	PIX	"	-	maximum relative change in power during step, halve step size if actual change is higher.	

Parameter space available for purposes as yet undefined (subblock 7)

33	IPT	I7	-	subblock identification, columns 8-79 free for commentary	= 7

If no such parameters are needed card 33 may be omitted. If parameters are specified in accordance with alterations in subroutine REXION they have to be given on cards inserted after card 33

End Card for block 1 (subblock 8)

34	IPT	I7	-	subblock identification, columns 8-79 free for comments, this card indicates the end of the system data	= 8

Inlet Enthalpy (block 2)

35	IP	I3	-	block identification, columns 4-75 free for comments	= 2
36	NY	I7	-	number of points given to define coolant inlet enthalpy (Y) as function of time (X)	≤ (NYD)
37	X	E 11.4	sec	coordinates of first point	= 0.
	Y	"	kcal/kg		
	X	"	sec	" " second "	
	Y	"	kcal/kg		
	X	"	sec	" " third "	
	Y	"	kcal/kg		

Card 37 has to be repeated as to accommodate the coordinates of all NY points.

Coolant Boundary Condition (block 3)

38	IP	I3	-	block identification, columns 4-75 free for comments	= 3
39	IBC	I7	-	indicator for choice of set of boundary conditions	= 1,2,3

Pressure (block 4)

40	IP	I3	-	block identification, columns 4-75 free for comments	= 4
41	NY3	I7	-	number of points given to define pressure (Y) as a function of time (X)	≤ (NYD)
42	X	E 11.4	sec	coordinates of first point	= 0.
	Y	"	at		
	X	"	sec	" " second "	
	Y	"	at		
	X	"	sec	" " third "	
	Y	"	at		

Card 42 has to be repeated as to accommodate the coordinates of all NY points.

Initial Coolant Mass Flow Rate and Deviation of Exit Pressure from Steady State Value as Function of Time (block 5)

43	IP	I3	-	block identification, columns 4-75 free for comments	= 5
44	GO	E 11.4	kg/sec	coolant mass flow rate at initial steady state	> 0.
	NY	I7	-	number of points given to define exit pressure deviation (Y) as function of time (X)	≤ (NYD)
45	X	E 11.4	sec	coordinates of first point	= 0.
	Y	"	at		
	X	"	sec	" " second "	
	Y	"	at		
	X	"	sec	" " third "	
	Y	"	at		

Card 45 has to be repeated as to accommodate the coordinates of all NY points. The coordinate Y of the first point may be different from zero when step changes in the exit pressure are to be studied.

Cards 43-45 are omitted if IBC ≠ 1

Coolant Mass Flow Rate (block 6)

46	IP	I3	-	block identification, columns 4-75 free for commentary	= 6
47	NY	I7	-	number of points given to define coolant mass flow rate (Y) as function of time (X)	≤ (NYD)
48	X	E 11.4	sec	coordinates of first point	= 0.
	Y	"	kg/sec		> 0.
	X	"	sec	" " second "	
	Y	"	kg/sec		
	X	"	sec	" " third "	
	Y	"	kg/sec		

Card 48 has to be repeated as to accommodate the coordinates of all NY points.

Cards 46-48 are omitted if IBC = 1

Initial Reactor Power (block 7)

49	IP	I3	-	block identification, columns 4-75 free for comments	= 7
50	PO	E 11.4	MW	initial reactor power	

Output Frequency Control and Clock Termination Control (block 8)

51	IP	I3	-	block identification, columns 4-75 free for comments, indicates start of computation	= 8
52	NPR	I7	-	number of steps between printed output	
	NCL	I7	-	" " " " interrogation of computer clock	
	CLM	E 11.4	-	maximum computer running time of this problem, in units of computer clock	

End of Job Card (block 9)

53	IP	I3	-	block identification, columns 4-75 free for comments, indicates end of job	= 9

IV.3 Output Description

The first part of the output is a complete and annotated listing of all input data as well as all eventual comments given on block and subblock identification cards.

Next the steady state feedback is printed out (in $ units) which needs to be balanced by external reactivity in order to make the reactor critical at its initial state. The absolute value of this number has no real significance but rather its value relative to values at states with other initial conditions.

The following part of the output gives the time dependent behavior of the most important system variable. A set of values of these variables is printed out every NPR (card 52) steps of the integration, the amount of variables in the output may be controlled by the parameters specified on card 29. Units of all varialbes in the output are consistent with the input and are the same as listed previously. The first set of values always refers to the initial steady state at time X=0.Only in this first set the absolute values of all contributions to the feedback reactivity are given.+) In all further steps the feedback contributions printed out are the deviations from the initial values printed out in the first set referring to time X = 0. Values of the state variables of the coolant at the reactor boundaries (entrance, exit) are printed both, in the first and in the last line of each set. Whenever these may be different, the values in the last line refer to time X given with this set whereas the corresponding value in the first line refers to the time at the beginning of this step. (Note, that X marks the time at the end of a completed step of integration.)

Notations used in this part of the output are listed in the subsequent table. It may be convenient to refer to Fig. 8 for locating most of these variables.

+) These absolute values of the individual contributions may be used in the same sense as mentioned with the total steady state feedback for stability investigations.

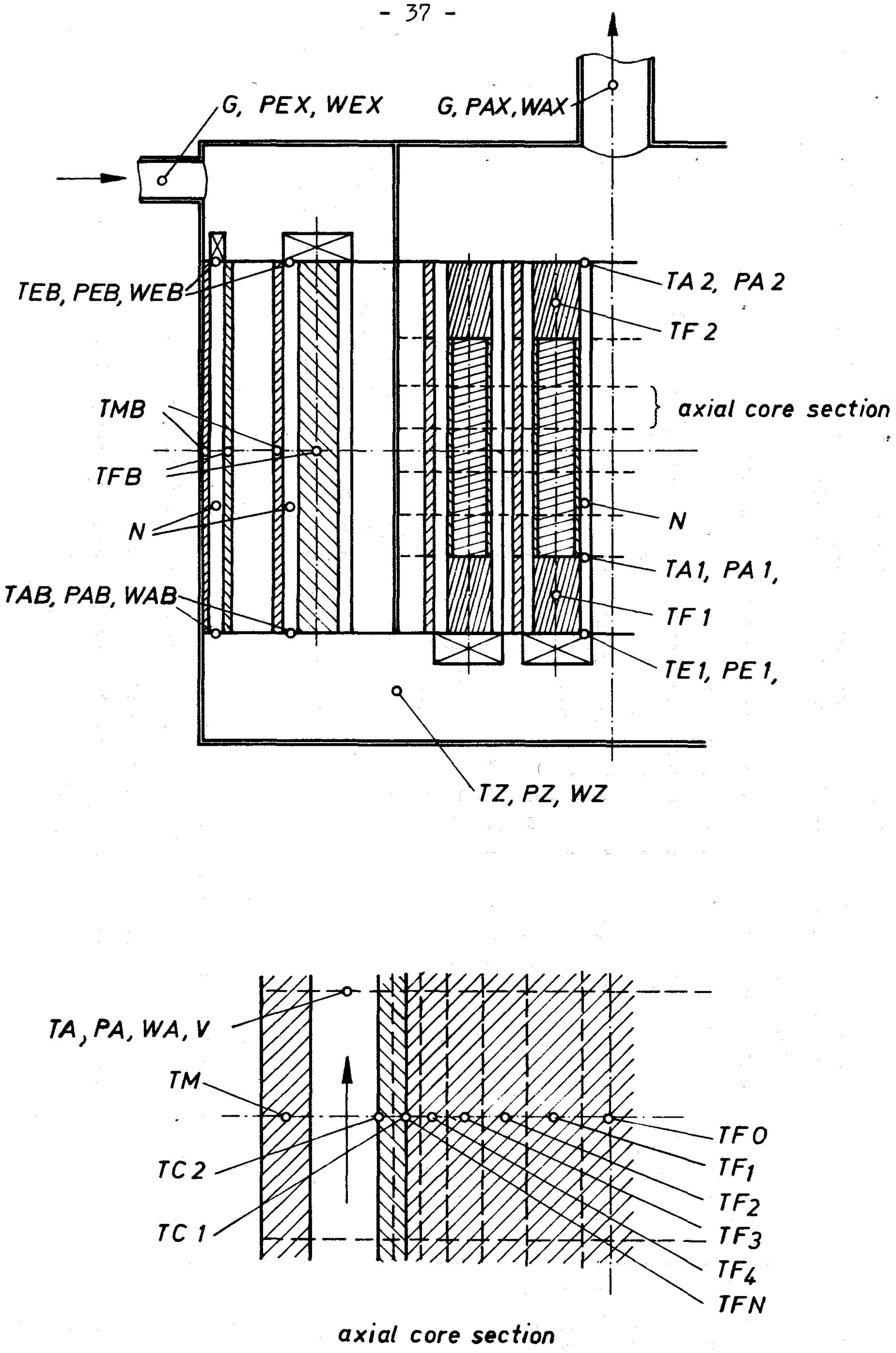


Fig. 8 Schematic Sketch of the Reactor and a Core Channel Section

Variable	Units	Other Notation	Significance	
X	sec	t	time (transient calculation starts at time = 0.)	
I	sec	Δt	time increment, as used for last step completed. Initially (t = 0.):I = increment computed and proposed for first step to be taken.	
P	MW		total reactor power	
E	MWsec	$= \int_0^t P \cdot dt$	total energy released since beginning of transient	
T	%	Δk_T	external (controlled) excess reactivity	
PEX	at		coolant pressure at reactor entrance (first plenum chamber)	
PAX	at		" " " " exit (third " ")	
WEX	kcal/kg		" enthalpy " " entrance (first " ")	
WAX	kcal/kg		" " " " exit (third " ")	
G	kg/sec		coolant mass flow rate	
K	%	Δk_K	total feedback reactivity	steady state (X = 0.): absolute values transient (X ≠ 0.): relative values
D	%	Δk_D	feedback reactivity from Doppler effect	
H	%	Δk_H	" " " change in core height	
R	%	Δk_R	" " " " " " radius	
F	%	Δk_F	" " " " " fuel temp.	
C	%	Δk_C	" " " " " clad temp.	
S	%	Δk_S	" " " " " coolant density	
M	%	Δk_M	" " " " " structure temp.	
IRB	-	-	index for radial zone and/or bypass in first flow section	
IR	-	-	" " " " in second flow section (core + ax.bl.)	
IX	-	-	" " axial section of core	
TEB	°C		coolant temp. at entry to radial zone and/or bypass, after orifice	
TAB	°C		" " " exit from " " " "	

WEB	kcal/kg		coolant enthalpy at entry to radial zone and/or bypass	
WAB	kcal/kg		" " " exit from " " " "	
PEB	at		" pressure " entry to " " " ", after orifice	
PAB	at		" " " exit from " " " "	
TFB	°C		central temperature of pin in rad. zone or inner wall of bypass, resp.	
TMB	°C		temperature of structure " " " " outer " " " "	
N	kg/(sec m^2)		area flow rate of coolant " " " " bypass	
TZ	°C		temperature	of coolant in intermediary (second) plenum chamber
PZ	at		pressure	
WZ	kcal/kg		enthalpy	
TE1	°C		coolant temp. at entry to first axial blanket, after orifice	
TA1	°C		" " " " " " " section of core	
TA2	°C		" " " exit from second axial blanket	
PE1	at		" pressure at entry to first axial blanket, after orifice	
PA1	at		" " " " " " " section of core	
PA2	at		" " " exit from second axial blanket	
TF1	°C		central temperature of pin in first axial blanket	
TF2	°C		" " " " " second " "	
N	kg/(sec m^2)		area flow rate of coolant in this radial zone of the core	
TFO	°C		central fuel temperature	taken at midplane of axial section IX
TFN	°C		fuel edge temperature	
TC1	°C		clad temperature, inner edge	
TC2	°C		" " , outer "	
TM	°C		structure temperature	
TA	°C		coolant temperature	taken at exit of axial section IX
WA	kcal/kg		" enthalpy	
PA	at		" pressure	
V	m^3/kg		" spec. volume	

NC	-		step counter
CL	-		computer time consumed since beginning of this problem

At the end of each problem the total number of steps and the (reactor-) time at the end of the transient are printed in the output.

Other messages:

A certain check on input data is carried out by way of the block- and subblock identification parameters IP and IPT, respectively. If the block (subblock) identification card required at the beginning of any block (subblock) is missing or if the parameter IP (IPT) is incorrect (out of permissible range) a message: INPUT ERROR is printed out together with the incorrect value of IP (IPT). After this the job is terminated.

If the step size required by the criteria for numerical stability and/or limited relative power changes is smaller than the specified lower limit XIN a message appears: STEP SIZE TOO SMALL, together with the last value of the time variable X. After this the job is terminated.

If the reading of a computer clock is made available through the function ZEIT (see APPENDIX N) a message appears (COMPUTING TIME CONSUMED) at the end of the output only if termination of the problem was caused by computation time exceeding the specified value CLM. After this computation continues with the next problem (if any).

If the specific version of function RCBE is used, which is described in APPENDIX L, a message will appear (SCRAM AT X = ...) whenever a scram situation is encountered; the current value of the time parameter is printed after the equal sign. A scram situation arises when at any step the actual reactor power exceeds for the first time the scram level PSC = PO · SCR. The message is printed at this event and comes before any other eventual output with this step.

IV.4 Storage- and COMMON-Requirements, Computing Time

COMMON-storage is required by five of the subprograms on level 3. These are PREP; STS; TRS; STEPC; ØUTPUT. In the case of integrating the program as subroutine REXION with another program already having its own COMMON requirements it is suggested to use block-common-statements whenever FORTRAN IV is available. Otherwise collation of the COMMON-requirements of both program sections is necessary.

Storage restrictions of the IBM 7074 require ØVERLAY structure of the program. The following structure is suggested (structure A):

RØUTSEGMENT: REX, REXIØN, PØWER, RCBE, STEPC, ØUTPUT, ZEIT,
TPE1, HDV, FLAM1, ETA1, CØ1, CP1

ØRIGIN A : PREP
ØRIGIN A : STS
ØRIGIN A : TRS

In case ØVERLAY procedures do not permit back-references to the next higher level,a different structure should be used (structure B):

RØUTSEGMENT: REX, REXIØN, PØWER, RCBE, STEPC, ØUTPUT, ZEIT,
CØ1, CP1

ØRIGIN A : PREP
ØRIGIN A : STS, TPE1, HDV, FLAM1, ETA1, CØ1
ØRIGIN A : TRS, TPE1, HDV, FLAM1, ETA1, CØ1, CP1

The present version of the program has the following approximate total storage requirements:

10 K with ØVERLAY (structure B)
21 K without ØVERLAY

Computing times of individual problems depend on the number of nodes, output volume and frequency, complexity of subprograms on level 4, step size and range of integration. The following example (see also APPENDIX Ø) should give an indication of typical computing times.

Problem: see APPENDIX Ø (subprograms as in APPENDICES K, L, M)
Number of nodes: NRB = 2, NR = 2, NBE = NBA = 1, NX = 5, NN = 4
Output frequency: NPR = 5, 10, 20
Stable step size: 0,5 - 5,0 milliseconds
computation time per step (average): 0,9 sec IBM 7074
0,2 sec IBM 7094
0,07 sec IBM 360/65 (FØRTRAN ØPT = 1)

V. Comments, Suggestions for Further Development

The models, methods and codes described in this report have proved to be useful and efficient tools for fast breeder analysis. Even though a relatively short time has elapsed since completion of the program a number of applications to accident analysis has provided significant results. Among these are:

- calculation of power reactivity coefficients for various reactor states of equilibrium;
- calculation of transient reactor behavior in blow down accidents (rupture of main steam pipes);
- parametric studies relating to scram characteristics, applied to blow down accidents.

Aside from these applications to specific systems many other studies can be envisaged including also investigations of a more general nature. The detailed and realistic features of the hydraulic model could - for example - serve as the basis for studies concerning both, design and analysis of reactors.

This report shall be not complete without pointing out weaknesses and areas which will require further development in order to improve efficiency and applicability of this analytical tool. The remainder of this section is dedicated to a discussion of the more important ones of these items.

The Model

The main deficiency of the model is the fact that it does not cover the coolant circuit and other pertinent components external to the reactor. Although certain analyses can be carried out with such a restricted model (for example: rapid excursions extending over a few seconds only) most practical cases will require an integral treatment of the whole reactor system. Therefore, the development of a consistent dynamics model and code for the external circuit is an essential implementation needed and is an immediate goal for further efforts in this area.

Another shortcoming of the model is seen in the treatment of the feedback. The great variety encountered in reactor core designs entails an almost equal variety in feedback mechanisms and virtually precludes the establishing of a general feedback model covering all possible cases. Feedback mechanisms which cannot be accommodated by the ones already included in the present model will have to be added in individual cases, preferrably in the form of subprograms.

A third part of the model potentially requiring additional development is channel orificing. The orificing coefficients FT are determined by criteria related to channel temperature rise, channel power, channel pressure drops, e.t.c., all of these being characteristics of the static reactor design. Since most of the static design calculations do not yield directly the coefficients FT trial and error procedures have to be used with the present program which turns out to be quite time consuming. This could be avoided by developing a program consistent with the underlying model and code, which would calculate these coefficients on the basis of the pertinent criteria mentioned above.

Further areas for development of the model are identified with heat transfer through the fuel cladding-gap and with the plenum chambers. Provisions have already been made for a more sophisticated treatment of the gap coefficient as it might become available.

Methods

The approximate nature of the criteria determining the step size for integration may require special caution in certain cases such as

- during rapid changes in the coolant boundary conditions;
- reactor power near prompt criticality.

Similarily, the nodal representation of the fuel and the treatment of fuel melting need consideration when temperature dependence of thermal conductivity of the fuel and fuel melting are of importance. In all of these cases recourse may be taken to either one or both of the following means:

- increasing the number of nodes;
- limiting the step size to values considerably below the stability limit.

In either case the associated penalty in computation time has to be considered and may be severe. To overcome these problems different methods of treating fuel melting, thermo-hydraulics and point kinetics will have to be devised. Some available methods /¯9,10_7 which feature good numerical stability as well as high accuracy were discarded because of the complexities introduced by them. However, there is sufficient incentive to develop new and efficient methods for treating the problems mentioned above:

- fuel heat transfer;
- fuel melting;
- coolant thermo-hydraulics;
- integration of point kinetics;
- determination of max. step size for numerically stable integration.

At this point it cannot be clear to what extent any such innovation might be incorporated in the present program.

Program

Experience gained up to date has indicated that computation time will not be a limiting factor with normal cases. The calculation of a typical transient arising with a reactor accident as described in APPENDIX 0 requires about one minute computer time on an IBM 360/65 system to cover a range of interest of about 10 seconds of reactor time. Systems with a greater number of nodes will increase computation time accordingly as will be the case when using slower computers (IBM 7094: ca. 3 minutes; IBM 7074 ca. 12 minutes for the same problem). Computer storage practically does not impose limitations; COMMON and DIMENSION statements are formulated in such a way as to facilitate adjustments in special cases.

VI. APPENDICES

APPENDIX A : Notation Equations

The following list of notations is complete only in conjunction with the lists for input and output given in sections IV.2 and IV. 3.

AE_i	linear coefficient of thermal expansion	component i (= F, C, M)
AR_i	heat source density, coefficient for rad. zone-distribution	
AX_i	heat source density, coefficient for axial section-distribution	
C_i	precursor concentrations (i = 1, 2, ... ND)	
C1	= 238,89 kcal/MWsec	
C01	thermal conductivity of fuel (function)	
CP	specific heat (at constant pressure)	
CP1	specific heat of fuel (function)	
CP3	specific heat of coolant, average over axial section	
CPA	" " " " , exit of axial section	
CPE	" " " " , entry of axial section	
DH	hydraulic diameter, wetted surface includes cladding + structure	
DH2	" " , wetted surface of cladding only	
DH4	" " , wetted surface of structure only	
DP	coolant pressure drop in axial section	
DX	step size, time increment (≡ I)	
ETA ETA1	dynamic viscosity of coolant /¯kps/m^2 _7	
FC	factor, indicator for flow direction	
FLAM FLAM1	thermal conductivity of coolant /¯kcal/m h ^{o}C _7	
FQ	net area for coolant flow in a radial zone	
g	9.81 m/sec^2, acceleration of gravity	

GF	net flow rate per unit area of coolant in channel ($\equiv$ N)
ΔH	height of axial section
H3	film coefficient of heat transfer between coolant and channel walls
H23	" " " " " " " " cladding
H34	" " " " " " " " structure
HT	total core height
IR	index, for radial zones
IX	index, for axial sections
	argument, mode control of subroutine REXION
IV	argument, " " " function RCBE
Δk	excess reactivity
Δk_T	" " , external, ($\equiv$ T)
Δk_K	" " , feedback (total), ($\equiv$ K)
Δk_D	" " , Doppler effect, ($\equiv$ D)
Δk_H	" " , change in core height, ($\equiv$ H)
Δk_R	" " , change in core radius, ($\equiv$ R)
Δk_F	" " , change in fuel density, ($\equiv$ F)
Δk_C	" " , " " clad " , ($\equiv$ C)
Δk_S	" " , " " coolant " , ($\equiv$ S)
Δk_M	" " , " " structure density, ($\equiv$ M)
K_o	total steady state feedback (relative value, output)
$\overset{*}{Nu}$	generalized Nusselt's number
NRBD	dimension, maximum value for NRB
NRD	" , " " " NR
NXD	" , " " " NX
NND	" , " " " NN
NDD	" , " " " ND
NYD	" , " " " NY
PC	fraction of total reactor power released in core
PE	coolant pressure at entry of axial section

PI	= 3.14 15 927	
Pr	Prandtl's number	
PS	power level for reactor scram	
P3	coolant pressure	
Δp_E	coolant pressure loss due to entry	
Δp_T	" " " due to orifice	
Δp_R	" " " due to friction	
Δp_A	" " " due to acceleration	
q	heat source density	
RC_i	feedback coefficient, component i (= F, C, S, M)	
Re	Reynolds number	
T_i	temperature in component i (= F, C, M)	
TA	coolant temperature, exit of axial section	
TE	" " , entry of axial section	
T3	" " , average over axial section	
TF	fuel temperature	
TM1	structure temperature in first axial blanket	
TM2	" " " second axial blanket	
TSB	temperature of structure in rad. bl. " " outer wall in bypass	} first flow section
TW	channel wall temperature	
U	variable, representing heat of fusion assoc. with a node	
UH	hypothetical change of enthalpy during a step of integration	
v	coolant velocity	
VA	specific volume of coolant, exit of axial section	
VE	" " " " , entry of axial section	
V_i	volume of component i (= F, C, M)	
V_F	total volume of fuel in core	
V_S	total volume of coolant in core	

WA	enthalpy of coolant, exit of axial section
WE	" " " , entry of axial section
WI	" " " , average over axial section
WA_L	enthalpy of coolant at channel exit
Z	axial coordinate of core geometry
α	reciprocal of generalized friction factor
β	total fraction of delayed neutrons
η	dynamic viscosity of coolant [kps/m^2]
λ	thermal conductivity of coolant [kcal/m h °C]
Λ	prompt neutron generation time
ρ	density of coolant (= 1./V)

Equations

Balance of total power:

$$PC + PBE + PBA + PB = 1.0$$

$$PB = \sum_{IRB} (PB)$$

Heat source density in various components:

$$\left.\begin{array}{ll} \text{radial blanket: pin} \\ \text{bypass} \quad \text{: inner wall} \end{array}\right\} \quad R2M = \begin{cases} R2 \\ 2.0 \cdot WP \end{cases}$$

$$q_{RB} = \frac{P \cdot C1 \cdot PB}{AN \cdot PI \cdot R2 \cdot R2M \cdot HT}$$

$$\left.\begin{array}{ll} \text{radial blanket:} & \text{structure} \\ & \text{coolant} \\ \text{bypass:} & \text{outer wall} \end{array}\right\} \text{ no source}$$

---

axial blanket: pin

first blanket

$$q_{B1} = \frac{P \cdot C1 \cdot PBE}{PI \cdot HBE} \cdot \frac{AQR}{\sum_{IR} (AQR \cdot AN)} \cdot \frac{1}{R2^2}$$

second blanket

$$q_{B2} = \frac{P \cdot C1 \cdot PBA}{PI \cdot HBA} \cdot \frac{AQR}{\sum_{IR} (AQR \cdot AN)} \cdot \frac{1}{R2^2}$$

$$\left.\begin{array}{ll} \text{axial blanket:} & \text{structure} \\ & \text{coolant} \end{array}\right\} \text{no source}$$

Core:

$$q_E = \frac{P \cdot C1 \cdot PC}{HC/NX} \cdot \frac{1}{SAQ \cdot \sum_{IX} (AQX) \cdot \sum_{IR} (AQR \cdot AN)}$$

$$SAQ = AQF + AQC + AQS + AQM$$

fuel:

$$q_F = q_E \, \frac{AQF \cdot AQX \cdot AQR}{R1^2 \cdot PI}$$

clad:

$$q_C = q_E \, \frac{AQC \cdot AQX \cdot AQR}{(R2^2 - R1^2) . PI}$$

coolant:

$$q_S = q_E \cdot \frac{AQS \cdot AQX \cdot AQR}{(R3^2 - R2^2) \cdot PI}$$

structure:

$$q_M = q_E \cdot \frac{AQM \cdot AQX \cdot AQR}{WP \cdot D4}$$

Steady State Temperatures

core:

fuel: $$TF_{n-1} = TF_n + q_F \cdot \frac{R1^2}{4 \cdot NN \cdot C01(TF_n)} \qquad n = 1, \ldots\ldots N$$

$$TFN = TF_N = TC1 + q_F \frac{R1}{2 \cdot HGP}$$

cladding: $$TC1 = TC2 + q_F \frac{R1^2}{C02} \cdot \frac{R2-R1}{R2+R1} + q_C \frac{(R2-R1)^2}{2 \cdot C02}$$

$$TC2 = T3 + q_F \cdot \frac{R1^2}{2 \cdot R2 \cdot H23} + q_C \frac{(R2^2-R1^2)}{2 \cdot R2 \cdot H23}$$

structure: $$TM = T3 + q_M \cdot \frac{D4}{H34'} \qquad \text{where} \quad H34' = H34 \frac{1}{1 + \frac{D4 \cdot H34}{3 \cdot C04}}$$

coolant: $$WA = WE + \frac{HC/NX}{GF} \cdot \left(q_S + q_F \frac{R1^2}{(R3^2 - R2^2)} + q_C \frac{R2^2-R1^2}{R3^2-R2^2} + q_M \frac{WP \cdot D4}{(R3^2-R2^2) \cdot PI}\right)$$

$$WI = (WA + WE) \cdot 0,5$$

$$TA = f_T(PA, WA)$$

$$T3 = (TA + TE) \cdot 0,5$$

---

first axial blanket (second ax.bl. correspondingly):

pin: $$TF1 = T3 + q_{B1} \frac{R2}{2 \cdot HFS}$$

structure: $$TM1 = T3$$

coolant: $$WA = WE + q_{B1} \cdot \frac{HBE \cdot R2^2}{(R3^2-R2^2) \cdot GF}$$

$$WI = (WA + WE) \cdot 0,5$$

$$TA = f_T(PA, WA)$$

$$T3 = (TA + TE) \cdot 0,5$$

$$\left.\begin{array}{l}\underline{\text{radial blanket}}\\ \underline{\text{bypass}}\end{array}\right\} \quad R2M = \begin{cases} R2 \\ 2\cdot WP \end{cases}$$

$$\left.\begin{array}{l}\text{pin:}\\ \text{inner wall:}\end{array}\right\} TFB = T3 + q_{RB}\cdot\frac{R2M}{2\cdot HA}$$

$$\left.\begin{array}{l}\text{structure:}\\ \text{outer wall:}\end{array}\right\} TSB = T3$$

coolant:

$$WA = WE + q_{RB}\,\frac{HT\cdot R2\cdot R2M}{(R3^2-R2^2).GF}$$

$$WI = (WA + WE)\cdot 0{,}5$$

$$TA = f_T(PA,WA)$$

$$T3 = (TA + TE)\cdot 0{,}5$$

Transient Temperatures

Core:

fuel:

$$\begin{aligned} TFO = TFO + \frac{DX}{R01\cdot CP1(TFO)} \cdot \Big\{ q_F + \frac{4.NN}{R1^2} \cdot \Big[\\ - (TFO-TF_1)\cdot C01\ (TF_1)\Big]\Big\} \end{aligned}$$

$$\begin{aligned} TF_n = TF_n + \frac{DX}{R01\cdot CP1(TF_n)} \cdot\Big\{ q_F + \frac{4.NN}{R1^2} \cdot \Big[(n-0.5)\cdot(TF_{n-1}-TF_n)\cdot \\ \cdot\ C01(TF_n)-(n+0.5)(TF_n-TF_{n+1})\cdot C01(TF_{n+1})\Big]\Big\} \end{aligned}$$

$$n = 1, \ldots.\ N-1$$

$$\begin{aligned} TFN = TFN + \frac{DX}{R01\cdot CP1(TFN)} \cdot\Big\{ q_F+ \frac{4.NN}{R1^2} \Big[(2\cdot NN-1)\cdot \\ (TF_{N-1}-TFN)\cdot C01(TFN)-(TFN-TC1)\cdot R1\cdot HGP \Big]\Big\} \end{aligned}$$

cladding:

$$\begin{aligned} TC1 = TC1 + \frac{DX}{R02\cdot CP2} \Big\{ q_C+ \frac{4}{R2^2-R1^2} \Big[R1\cdot HGP.(TFN-TC1)- \\ - (TC1-TC2)\cdot\frac{R2+R1}{2\cdot(R2-R1)} \cdot C02\Big]\Big\} \end{aligned}$$

$$\begin{aligned} TC2 = TC2 + \frac{DX}{R02\cdot CP2} \Big\{ q_C + \frac{4}{R2^2-R1^2} \cdot\Big[\frac{R2+R1}{2\cdot(R2-R1)}\cdot \\ \cdot(TC1-TC2)\cdot C02-(TC2-T3)\cdot R2\cdot H23 \Big]\Big\} \end{aligned}$$

structure:
$$TM = TM + \frac{DX}{R04 \cdot CP4} \cdot \left\{ q_M - \frac{H34'}{D4} (TM-T3) \right\}$$

coolant:
$$WA = WA + DX \cdot V \cdot \left\{ q_S + \frac{2 \cdot H23 \cdot R2}{R3^2-R2^2} (TC2-T3) + \frac{H34 \cdot WP}{PI \cdot (R3^2-R2^2)} \cdot \right.$$
$$\left. \cdot (TM-T3) + \frac{GF}{HC/NX} (WE-WA) \right\}$$

$$WI = (WA + WE) \cdot 0{,}5$$
$$TA = f_T(PA,WA)$$
$$T3 = (TA + TE) \cdot 0{,}5$$

<u>first axial blanket</u> (second ax.bl. accordingly):

pin:
$$TF1 = TF1 + \frac{DX}{CVF} \left\{ q_{B1} - \frac{2 \cdot HFS}{R2} \cdot (TF1-T3) \right\}$$

structure:
$$TM1 = TM1 + \frac{DX}{CVM} \left\{ - \frac{HMS}{D4} \cdot (TM1-T3) \right\}$$

coolant:
$$WA = WA + DX \cdot V \left\{ \frac{2 \cdot HFS \cdot R2}{R3^2-R2^2} (TF1-T3) + \frac{HMS \cdot WP}{PI \cdot (R3^2-R2^2)} \cdot \right.$$
$$\left. \cdot (TM1-T3) + \frac{GF}{HBE} (WE-WA) \right\}$$

$$WI = (WA + WE) \cdot 0{,}5$$
$$TA = f_T(PA,WA)$$
$$T3 = (TA + TE) \cdot 0{,}5$$

$$\left. \begin{array}{l} \underline{\text{radial blanket}} \\ \underline{\text{bypass}} \end{array} \right\} \quad WPM = \begin{cases} WP \\ 2 \cdot R3 \cdot PI \end{cases}$$

$$\left. \begin{array}{l} \text{pin} \\ \text{inner wall} \end{array} \right\}: \quad TFB = TFB + \frac{DX}{CV} \left\{ q_{RB} - \frac{2 \cdot HA}{R2} (TFB-T3) \right\}$$

$$\left. \begin{array}{l} \text{structure} \\ \text{outer wall} \end{array} \right\}: \quad TMB = TMB + \frac{DX}{CV} \left\{ - \frac{HA}{D4} (TMB-T3) \right\}$$

coolant:
$$WA = WA + DX \cdot V \left\{ \frac{2 \cdot HA \cdot R2}{R3^2-R2^2} (TFB-T3) + \frac{HA \cdot WPM}{PI (R3^2-R2^2)} \cdot \right.$$
$$\left. \cdot (TMB-T3) + \frac{GF}{HT} (WE-WA) \right\}$$

$$WI = (WA + WE) \cdot 0{,}5$$

$$TA = f_T(PA, WA)$$

$$T3 = (TA+TE) \cdot 0{,}5$$

Orifices: conservation of enthalpy when passing orifice is assumed.

Plenum Chambers:

zero pressure loss of coolant
zero residence time of coolant in chamber
instantaneous mixing of all entering streams of coolant:

$$WI = \frac{\sum_{IR} (FQ \cdot GF \cdot WA_L)}{\sum_{IR} (FQ \cdot GF)}$$

where: $FQ = PI \cdot (R3^2 - R2^2) \cdot AN$

Fuel Melting

The basic model for treating fuel melting and recrystallization is the same as in /¯1_7. However, the computational technique differs and admits all possible cases (fuel partially or entirely molten at initial steady state, partial and/or total melting and/or recrystallization during transient). Melting point and recrystallization point are assumed to be identical (TM) as are the values of heat of fusion and heat of recrystallization (UM, /¯kcal/m^3_7).

In the calculation a variable U is associated with each fuel node, which is a record of the latent heat of fusion of this node:

$U = 0.$ .... solid
$U = UM$ .... molten
$0 < U < UM$ ...... partially molten

If in the steady state calculation the temperature of any fuel node TF is such that

$TF > TM$ $U = UM$
$TF < TM$ $U = 0.$

During the transient calculation fuel temperatures first are calculated according to the equations given before. Then a hypothetical enthalpy change is calculated:

$$UH = (TF - TM) \cdot R01 \cdot CP1\ (TM)$$

which may be $\gtrless$ 0 depending on TF $\gtrless$ TM. This enthalpy change if added to U yields a new quantity UN

$$UN = U + UH$$

which is subject to decisions on further procedures:

$$UN < 0 \begin{cases} U = 0 \ldots \text{ the node was solid and remained solid, set } TF = TF \\ U > 0 \ldots \text{ the node just solidified entirely, } TF = TF+U/(R01 \cdot CP1(TM)) \\ \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad U = 0. \end{cases}$$

$$UN > 0 \begin{cases} UN < UM \ldots \text{ fuel is partially molten, set } TF = TM \\ \qquad\qquad\qquad\qquad\qquad\qquad\quad U = UN \\ UN > UM \ldots \begin{cases} U = UM \text{ the node was molten, set } TF = TF \\ U < UM \text{ the node just melted entirely, set} \\ \qquad TF = TF-(UM-U)/(R01 \cdot CP1(TM)) \\ \qquad U = UM \end{cases} \end{cases}$$

Fig. A1 should help to illustrate this scheme.

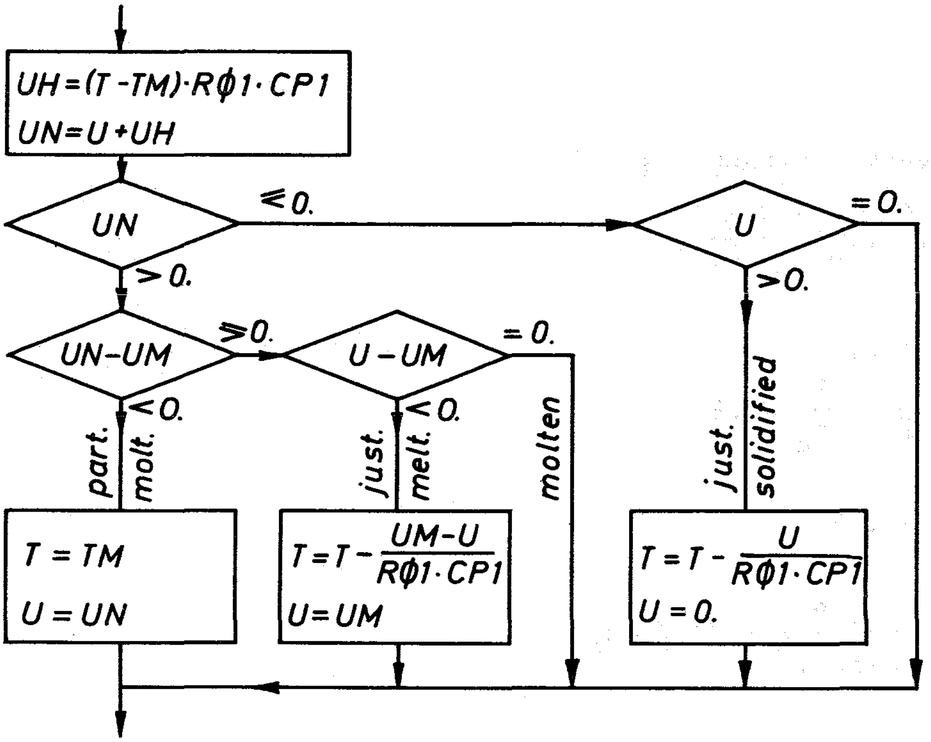


Fig. A1 Flow Diagram for Calculations Regarding Fuel Melting

Film Coefficient of Heat Transfer to Coolant:

from cladding:

$$H23 = AL4 + \frac{CH2}{DH2^{(1-AL1)}} \cdot (GF)^{AL1} \cdot \left(\frac{FLAM^{(1-AL2)} \cdot CP3^{AL2}}{ETA^{(AL1-AL2)}} \right) \cdot$$

$$\cdot \left(\frac{T3+273.16}{TC2+273.16} \right)^{AL3}$$

from structure:

$$H34 = AL4 + \frac{CH4}{DH4^{(1-AL1)}} \cdot (GF)^{AL1} \cdot \left(\frac{FLAM^{(1-AL2)} \cdot CP3^{AL2}}{ETA^{(AL1-AL2)}} \right) \cdot$$

$$\cdot \left(\frac{T3+273.16}{TM+273.16} \right)^{AL3}$$

with $DH2 = \frac{2 \cdot (R3^2 - R2^2)}{R2}$ $\qquad DH4 = \frac{4 \cdot PI \cdot (R3^2 - R2^2)}{WP}$

$FLAM = f_{\lambda}\ (PA,T3)$

$ETA = f_{\eta}\ (V,T3)$

$CPA = f_{cp}(PA,TA)$

$CP3 = (CPA + CPE) \cdot 0,5$

Hydraulic Model

Pressure Losses:

pressure loss at channel entrance ($\rho = 1/V$):

$$\Delta p_E = \left[\left(\frac{v_1}{\varphi}\right)^2 - (v_o)^2 \right] \frac{\rho}{2g}$$

with: $v_o = 0.$

$v_1 \cdot \rho = \frac{\dot{m}}{F_q} = GF$

$\frac{1}{\varphi^2} = 1,5$

$$\Delta p_E = 1,5 \cdot \frac{GF^2}{2 \cdot g \cdot 10^4} \cdot V \quad [at]$$

pressure loss through orifice:

$$\Delta p_T = FT \cdot \frac{GF^2}{2g \cdot 10^4} \cdot V \quad [\mathrm{at}]$$

pressure loss in channel due to friction and acceleration

$$\text{channel length } \Delta H = \begin{cases} HT \text{ ...... radial blanket} \\ HT \text{ ...... bypass} \\ HBE \text{ ..... first axial blanket} \\ HBA \text{ ..... second " "} \\ HC/NX \text{ ... axial section in core} \end{cases}$$

hydraulic diameter:

$$DH = \frac{4 \cdot PI \cdot (R3^2 - R2^2)}{WPM + 2 \cdot PI \cdot R2}$$

wetted perimeter:

$$WPM = \begin{cases} WP \text{ ...... radial blanket} \\ 2 \cdot R3 \cdot PI \text{.. bypass} \\ WP \text{ ...... first, second ax.bl., core} \end{cases}$$

$$\Delta p_R = \frac{GF^2}{g \cdot 10^4} \cdot \left[\frac{FR \cdot \Delta H}{2 \cdot DH} \cdot V + (VA - VE) \right] \quad [\mathrm{at}]$$

$$VA = f_V(PA, TA)$$

$$V = (VA + VE) \cdot 0{,}5$$

Feedback Equations

$$\text{subscript } x = \begin{cases} 0 \text{ ... steady state value} \\ T \text{ ... transient value} \end{cases}$$

Doppler feedback:

$$D_x = RCD \cdot \frac{\sum\limits_{IX} \cdot \sum\limits_{IR} (ADX \cdot ADR \cdot AN \cdot R1^2 \cdot \ln (\overline{TF}_x + 273.16))}{\sum\limits_{IX} \cdot (ADX) \cdot \sum\limits_{IR} (ADR \cdot AN \cdot R1^2)}$$

$$\overline{TF}_x = \frac{1}{NN} \cdot \sum_{IN} (TF_x)$$

core height feedback:

$$H_x = \mathrm{RCH} \cdot \frac{\sum\limits_{IX} \cdot \sum\limits_{IR} (\mathrm{AN} \cdot \mathrm{R1}^2 \cdot \mathrm{AEF} \cdot \overline{\mathrm{TF}}_x)}{\mathrm{NN} \cdot \sum\limits_{IR} (\mathrm{AN} \cdot \mathrm{R1}^2)}$$

core radius feedback:

$$R_x = \mathrm{RCR} \cdot \frac{\sum\limits_{IX} \cdot \sum\limits_{IR} (\mathrm{AN} \cdot \mathrm{AEM} \cdot \mathrm{TM}_x)}{\mathrm{NN} \cdot \sum\limits_{IR} (\mathrm{AN})}$$

fuel density feedback:

$$F_x = -\mathrm{RCF} \frac{\sum\limits_{IX} \cdot \sum\limits_{IR} (\mathrm{AXF} \cdot \mathrm{ARF} \cdot \mathrm{AN} \cdot \mathrm{R1}^2 \cdot \mathrm{AEF} \cdot \overline{\mathrm{TF}}_x)}{\sum\limits_{IX} \cdot (\mathrm{AXF}) \cdot \sum\limits_{IR} (\mathrm{ARF} \cdot \mathrm{AN} \cdot \mathrm{R1}^2)}$$

cladding density feedback:

$$C_x = -\mathrm{RCC} \frac{\sum\limits_{IX} \cdot \sum\limits_{IR} (\mathrm{AXC} \cdot \mathrm{ARC} \cdot \mathrm{AN} \cdot (\mathrm{R2}^2 - \mathrm{R1}^2) \cdot \mathrm{AEC} \cdot \overline{\mathrm{TC}}_x)}{\sum\limits_{IX} (\mathrm{AXC}) \cdot \sum\limits_{IR} (\mathrm{ARC} \cdot \mathrm{AN} \cdot (\mathrm{R2}^2 - \mathrm{R1}^2))}$$

$$\overline{\mathrm{TC}}_x = (\mathrm{TC1}_x + \mathrm{TC2}_x) \cdot 0{,}5$$

structure density feedback:

$$M_x = -\mathrm{RCM} \frac{\sum\limits_{IX} \cdot \sum\limits_{IR} (\mathrm{AXM} \cdot \mathrm{ARM} \cdot \mathrm{AN} \cdot \mathrm{WP} \cdot \mathrm{D4} \cdot \mathrm{AEM} \cdot \mathrm{TM}_x)}{\sum\limits_{IX} (\mathrm{AXM}) \cdot \sum\limits_{IR} (\mathrm{ARM} \cdot \mathrm{AN} \cdot \mathrm{WP} \cdot \mathrm{D4})}$$

coolant density feedback:

$$S_x = -\mathrm{RCS} \frac{\sum\limits_{IX} \cdot \sum\limits_{IR} (\mathrm{AXS} \cdot \mathrm{ARS} \cdot \mathrm{AN} \cdot (\mathrm{R3}^2 - \mathrm{R2}^2)/V_x)}{\sum\limits_{IX} (\mathrm{AXS}) \cdot \sum\limits_{JR} (\mathrm{ARS} \cdot \mathrm{AN} \cdot (\mathrm{R3}^2 - \mathrm{R2}^2))}$$

Total steady state feedback:

$$K_o = (D_o + H_o + R_o + F_o + C_o + S_o + M_o)$$

This total steady state feedback is assumed to be compensated by external reactivity.

Transient feedback

$D = D_x - D_o$

$H = H_x - H_o$

$R = R_x - R_o$

$F = F_x - F_o$

$C = C_x - C_o$

$S = S_x - S_o$

$M = M_x - M_o$

Total transient feedback

$$K = (D + H + R + F + C + S + M) \cdot RC$$

APPENDIX B : Decay Time Constants for Nodal Temperatures in Cylindrical Fuel Pin

Taking fuel temperatures relative to the temperature TC1 of the inner edge of the cladding we can write the system of equations for the nodal fuel temperatures as follows:

$$R01 \cdot CP1 . \frac{d\ TFO}{dx} = q_F + \frac{4 \cdot C01 \cdot NN}{R1^2} \left[\qquad - (TFO - TF_1) \right]$$

$$R01 \cdot CP1 \cdot \frac{d\ TF_n}{dx} = q_F + \frac{4 \cdot C01 \cdot NN}{R1^2} \left[(n-0.5) \cdot (TF_{n-1} - TF_n) - (n+0.5) \cdot (TF_n - TF_{n+1}) \right]$$

$$n = 1, \ldots, N-1$$

$$R01 \cdot CP1 \cdot \frac{d\ TFN}{dx} = q_F + \frac{4 \cdot C01 \cdot NN}{R1^2} \left[(2 \cdot NN-1) \cdot (TF_{N-1} - TFN) - \frac{R1 \cdot HGP}{C01} \cdot TFN \right]$$

All parameters except for volumetric heat source q_F are assumed to be invariants for this consideration. Fictitious subdivisions separate the cylindrical fuel pin into NN-1 concentric annuli of equal volume, as well as a central cylinder and an outer most annulus having only half of this volume. In the case of steady state the temperatures TF_1, TF_2, ... TF_{N-1} represent the volume average temperature of each annulus, respectively. TFO and TFN represent the temperature at the center axis and on the surface edge, respectively.

We assume that starting from a steady state equilibrium the heat source q_F vanishes at time x = 0. Consequently, all temperatures eventually will drop to the reference level ($TFO = TF_n = TFN \Rightarrow 0.$). The asymptotic solution of the temperature transients may be found by means of Laplace transformation as follows:

$$\frac{R1^2}{4 \cdot NN} \cdot \frac{R01 \cdot CP1}{C01} \cdot s \cdot \widetilde{TFO} = \qquad - (\widetilde{TFO} - \widetilde{TF}_1)$$

$$\frac{R1^2}{4 \cdot NN} \cdot \frac{R01 \cdot CP1}{C01} \cdot s \cdot \widetilde{TF}_n = (n-0.5) \cdot (\widetilde{TF}_{n-1} - \widetilde{TF}_n) - (n+0.5) \cdot (\widetilde{TF}_n - \widetilde{TF}_{n+1})$$

$$n = 1,2 \ldots N-1$$

$$\frac{R1^2}{4 \cdot NN} \cdot \frac{R01 \cdot CP1}{C01} \cdot s \cdot \widetilde{TFN} = (2 \cdot NN-1) \cdot (\widetilde{TF}_{N-1} - \widetilde{TFN}) - \frac{R1 \cdot HGP}{C01} \cdot \widetilde{TFN}$$

This is a linear and homogeneous system of equations for the temperatures TF_n with all negative Eigenvalues s_n. The asymptotic behavior is characterised by the Eigenvalue s_N with the smallest magnitude. It is evident that this Eigenvalue as all others is a function only of three parameters:

$$s_N = s_N(NN, \frac{R1 \cdot HGP}{C01}, R1^2 \cdot \frac{R01 \cdot CP1}{C01})$$

where the last parameter appears as a scaling factor only.

On the other hand the solution of this particular problem may be obtained analytically without discretization /‾11_7. The Eigenvalue with the smallest magnitude is given by:

$$s_\infty = (\frac{R1}{\alpha})^2 \cdot \frac{R01 \cdot CP1}{C01}$$

where α is the smallest value satisfying the transcendental equation

$$\alpha \cdot \frac{J_1(\alpha)}{J_o(\alpha)} = \frac{R1 \cdot HGP}{C01}$$

In much the same way as above the Eigenvalue s_∞ is a function of two parameters:

$$s_\infty = s_\infty (\frac{R1 \cdot HGP}{C01} , R1^2 \cdot \frac{R01 \cdot CP1}{C01})$$

Fig. B1 is a plot of the function s_N and s (multiplied by the scaling factor $R1^2 \cdot \frac{R01 \cdot CP1}{C01}$) versus $\frac{R1 \cdot HGP}{C01}$. These were obtained numerically using a separate program written for this purpose.

As may be expected, the function s is the asymptotic function to s_N, as NN goes to infinity. Thus, for any given set of values for the characteristic parameters one may obtain from this plot

a) the asymptotic behavior of the correct solution,

b) the asymptotic behavior of the approximate solution resulting for NN+1 nodes,

c) the required number of nodes to obtain a predetermined accuracy in the asymptotic solution for this case

Although vanishing of the heat source in conjunction with the simplifying assumptions made constitute a rather specific case of transient behavior, it may be considered typical for fast transients. The simplicity of the diagram in Fig. B1 renders this a useful tool in selecting a proper mesh for a variety of pertinent problems.

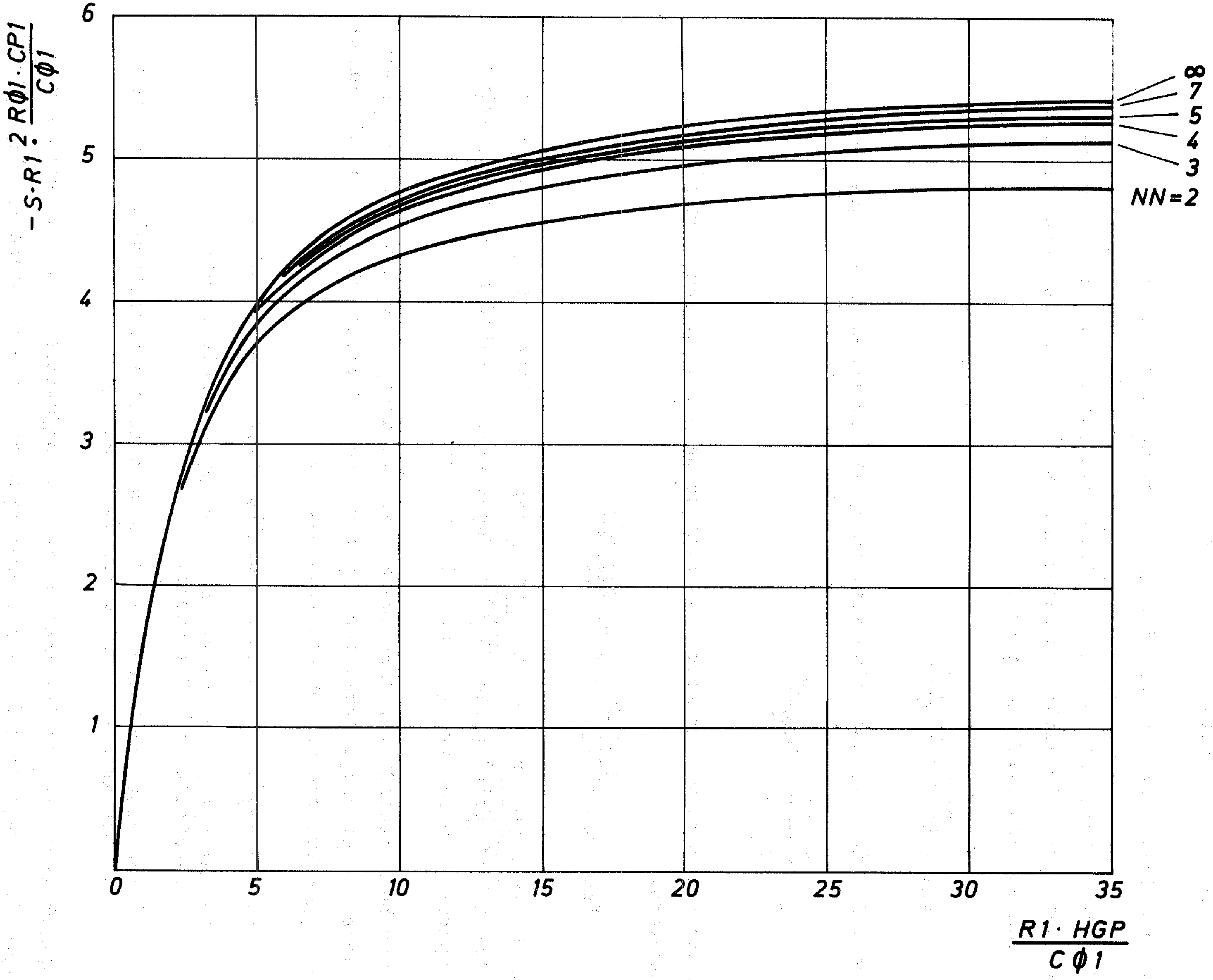


Fig. B1 Asymptotic Time Constants for Temperature Decay in Cylindrical Fuel Pin

APPENDIX C : Predictor-Corrector-Schemes Applied in Solving the Hydraulics Problem.

The general expression for the pressure drop in a flow channel (index i) is

$$\Delta p_i = \Delta p_{Ei} + \Delta p_{Ti} + \Delta p_{Ri} + \Delta p_{Ai}$$

$$= \frac{1}{g} GF_i^2 \cdot \left\{ \frac{1.5+FT_i}{2.0} VE + \frac{FR_i}{2 \cdot DH_i} \Sigma \Delta H_j V_{ij} - (VA_i - VE_i) \right\}$$

The first term in parantheses represents entry and orifice losses, the second term frictional losses and the last term acceleration loss. If one assumes the specific volume to be constant throughout the channel **and** moreover to be the same in all (parallel) channels

$$V_E = V_{ij} = VA_i = \overline{V}$$

one may write the total pressure drop in a simpler form:

$$\Delta p_i = \frac{1}{g} GF_i^2 \left\{ \frac{1.5+FT_i}{2.0} + \frac{FR_i \cdot HT}{2. \cdot DH_i} \right\} \cdot \overline{V} = \frac{1}{g} GF_i^2 \cdot \frac{1}{\alpha_i^2} \cdot \overline{V}$$

where

$$\frac{1}{\alpha_i^2} = \left\{ \frac{1.5+FT_i}{2.0} + \frac{FR_i \cdot HT}{2. \cdot DH_i} \right\}$$

is a generalized coefficient of friction associated with each channel. The second relevant equation is obtained from the mass balance of the coolant:

$$\sum_i \left[(GF_i) \cdot (AN_i \cdot (R3_i^2 - R2_i^2) \cdot PI) \right] = \sum_i \left[(GF_i) \cdot (FQ_i) \right] = G$$

where

$$FQ_i = AN_i \cdot (R3_i^2 - R2_i^2) \cdot PI$$

a) Steady State Equilibrium

Calculation of flow distribution in parallel channels:

The condition that all Δp_i be equal in all parallel channels, together with the approximate expression for Δp_i and the mass balance yields the predictor formula:

$$GF_i = G \cdot \frac{\alpha_i}{\sum_i (FQ_i \cdot \alpha_i)}$$

With these estimates for the area net flow rates GF_i the associated pressure drops Δp_i may be calculated. A correction formula is obtained by assuming that the correct pressure drop Δp^* is related to the correct net flow rates GF_i^* by

$$\Delta p_i^* = \Delta p_i \cdot (\frac{GF_i^*}{GF_i})^2$$

Combination of this relation with the mass balance yields the correction formula:

$$GF_i^* = GF_i \frac{G/\sqrt{\Delta p_i}}{\sum_i (FQ_i \cdot GF_i/\sqrt{\Delta p_i})}$$

This correction is applied iteratively until the maximum difference between any two values Δp_i is less than a specified number DP. When this condition is satisfied one may compute a pressure drop $\overline{\Delta p}$ from the relation:

$$G = \sum_i (GF_i \cdot FQ_i) = \sum_i (GF_i^* \cdot FQ_i) = \sum_i (GF_i \cdot \sqrt{\frac{\overline{\Delta p}}{\Delta p_i}} \cdot FQ_i)$$

as

$$\overline{\Delta p} = \left[\frac{\sum_i (GF_i \cdot FQ_i)}{\sum_i (GF_i \cdot FQ_i/\sqrt{\Delta p_i})} \right]^2$$

This pressure drop $\overline{\Delta p}$ will be a good approximation of the actual pressure drop between the two plenum chambers.

Calculation of the entry pressure (B.C.2):

From the predictor formula and the approximation for the pressure drop Δp_i, both given previously in this appendix, we can derive:

$$\Delta p_i = \Delta p = \frac{1}{g} \cdot \left[\frac{G}{\sum_i (FQ_i \ \alpha_i)} \right]^2 \cdot \overline{V}$$

For the case of two flow sections connected in series (radial blanket, axial blankets + core) the corresponding formula is:

$$\Delta p = \frac{1}{g} \left[\frac{G}{(\sum_i(FQ_i\alpha_i))_{RB}+(\sum_i(FQ_i\alpha_i))_{AB+C}} \right]^2 \cdot \overline{V}$$

A good estimate for $\overline{V}$ is obtained by taking the average of VE and VA which in turn are determined by enthalpy and pressure at entrance and exit. Since the entrance pressure is not known an iterative procedure might be applied. This is not done here in the light of the fact that the expression for Δp is itself only an approximation. This pressure drop Δp and the given exit pressure p^{*}_{out} are combined to give the entry pressure p_{in}:

$$p_{in} = p^{*}_{out} + \Delta p$$

Using this entry pressure we proceed to compute pressure drops as indicated. Finally, we obtain an exit pressure p_{out}, in general, will differ from the given value p^{*}_{out}. The difference is used directly and iteratively for a correction of the entry pressure:

$$p^{*}_{in} = p_{in} - (p_{out} - p^{*}_{out})$$

until the magnitude of the difference becomes less than a specified number DP.

b) Transient Calculations

The dominating requirement of short computing times together with the experience obtained from applications of this model to many practical cases have prompted the scheme of deferred correction as regarding the calculation of transient hydraulics. It implies that all necessary corrections are deferred to the consecutive step of the integration. The accuracy of this scheme shall not be discussed here but has been found satisfactory in all cases.

The correction is carried out in two consecutive parts. The first correction consists in a proportional change of all area net flow rates GF_i so as to affect the total flow rate of coolant G but not the relative distribution through parallel channels. This correction is applied in order to meet the boundary conditions across the reactor (prescribed pressure drop, or prescribed total coolant flow rate). Thus, for the latter case of prescribed total coolant flow rate the correction obviously is:

$$GF_i^* = GF_i \cdot \left(\frac{G}{\sum_i (GF_i \cdot FQ_i)}\right)$$

whereas in the case of prescribed pressure drop Δp^* the corresponding formula is:

$$GF_i^* = GF_i \cdot \left(\sqrt{\frac{\Delta p^*}{\Delta p}}\right)$$

where

$$\overline{\Delta p} = \left[\frac{\sum_i (GF_i \cdot FQ_i)}{\sum_i (GF_i \cdot FQ_i/\sqrt{\Delta p_i}}\right]^2$$

in analogy to the corresponding equation derived for the steady state calculations. For the case of two flow sections in series the pressure drop $\overline{\Delta p}$ is computed for either section from this formula and added to give

$$\overline{\Delta p} = \overline{\Delta p_1} + \overline{\Delta p_2}$$

The second correction is such that the channel net flow rates GF_i are altered while the total coolant flow rate G remains constant. This correction is applied in order to achieve equality of pressure drops in parallel flow paths. It is derived directly from the mass balance equation and the relation for the correct pressure drop Δp^* given earlier:

$$GF_i^{**} = GF_i^* \cdot \sqrt{\frac{\Delta p}{\Delta p_i}}$$

where

$$\overline{\Delta p} = \left[\frac{\sum_i (GF_i^* \cdot FQ_i)}{\sum_i (GF_i^* \cdot FQ_i/ \sqrt{\Delta p_i}}\right]^2$$

The logic flow diagrams presented in Fig. C1 and Fig. C2 illustrate the procedures described in this appendix.

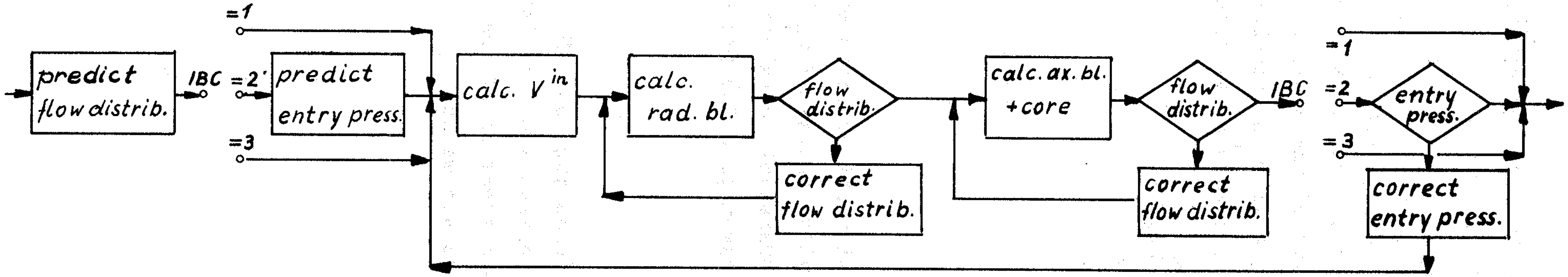


Fig. C1 Flow Diagram for Steady State Hydraulics Calculations

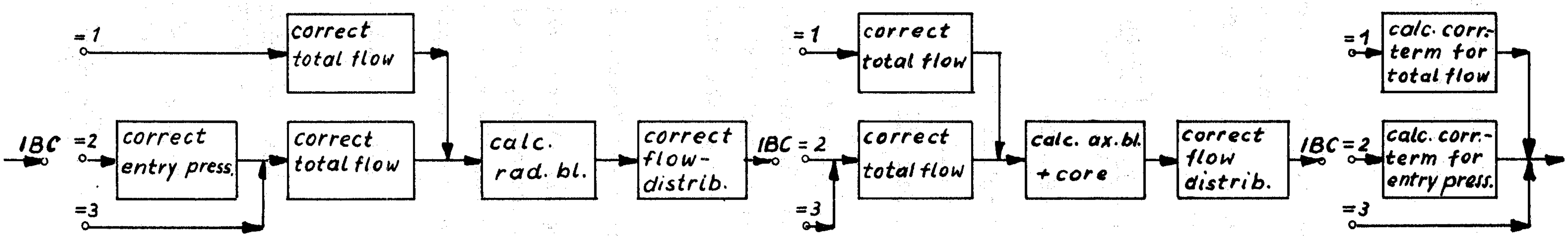


Fig. C2 Flow Diagram for Transient Hydraulics Calculations

APPENDIX D : Other Iterative Procedures Applied in Solving the Steady State Problem

a) Pressure Drop

Calculating the pressure drop from the given formuli requires knowledge of the specific volume of the coolant at the exit of the section under concern. Since this is a function of pressure (as well as enthalpy) the following iteration is devised for obtaining the steady state solution:

$$DP = \frac{(GF)^2}{2 \cdot g} \cdot \left\{ \frac{FR \cdot \Delta H}{2 \cdot DH} (1. + 0.5 \cdot \varepsilon_v) + \varepsilon_v \right\} VE$$

$$PA = PE - DP$$

$$TA = f_T(PA, WA)$$

$$VA = f_V(PA, TA)$$

$$\varepsilon_v = \frac{VA - VE}{VE}$$

The starting guess for ε_v is zero; the termination criterion is on the magnitude of the difference between two consecutive values of ε_v being smaller than a prescribed quantity EV. In the transient calculation the specific volume at the exit of the section is taken from the preceeding time step.

b) Heat Transfer and Channel Wall Temperatures

Determining the channel wall temperatures TC2 (cladding) and TM (structure) from the equations given in APPENDIX A requires another iterative procedure since the film coefficient itself is a function of the wall temperature. For the temperature TM of the structure we have:

$$H34 = \widehat{H34} \cdot \left(\frac{1}{1 + \varepsilon_T}\right)^{AL3} + AL4$$

$$H34' = H34 \cdot \frac{1}{1 + \frac{D4 \cdot H34}{3 \cdot C04}}$$

$$TM = T3 + q_M \cdot \frac{D4}{H34'}$$

$$\varepsilon_T = \frac{TM - T3}{T3 + 273.16}$$

Initialization and termination are done similarily as in case a) using the prescribed quantities ETC and ETM respectively for the wall temperature of cladding and structure. For the transient calculation the values of these two temperatures from the preceeding step are taken to calculate the film coefficients.

APPENDIX E : Stagnation and Reversal of Flow

Although there is only one minor modification required to adjust the model for accommodating flow reversal the numerical methods are affected extensively. The adjustment in the model concerns the shift in location of the entry pressure loss with flow reversal. This applies to both the radial blanket flow section as well as the core flow section. Thus, reversed flow experiences pressure losses from entry, friction and orificing, in this order.

Many of the numerical procedures used in similar context elsewhere are not suited for the treatment of flow reversal as they are numerically unstable at reversed flow direction. Also, it appears desirable to maintain the original sequence in which the calculation computes enthalpies and pressures, the sequence thus being independent of the direction of flow. This sequence was chosen to coincide with the initial direction of flow which was also used as a basis for the nomenclature and sequence of the various flow sections in series (entrance plenum chambers - rad. bl. - intermediary plenum chamber - first ax. bl. - core - second ax. bl. - exit plenum chamber). For both of these reasons - stability and simplicity - the method selected here is well suited.

a) Hydraulics

Aside from the adjustment for shift in location of entry losses there is no significant change required in the hydraulics-model and -calculation in the program. Reversed flow is indicated by a negative coolant flow rate. All other pressure losses (friction, acceleration) may be computed by the original formuli if the change in sign is accounted for by a factor FC = ± 1 as in the following example.

$$\Delta p_i = p_{i+1} - p_i = FC \cdot \frac{(GF)^2}{2g} \cdot \left[\frac{FR \cdot \Delta H}{2 \cdot DH} \cdot \overline{V}_i + (V_{i+1} - V_i) \right]$$

where

$$FC = \begin{cases} +1 & \text{for normal flow} \\ -1 & \text{for reversed flow} \end{cases}$$

and i,i+1 refers to two consecutive axial nodes along the flow path the order of which does not change with change of flow direction. In case of stagnation of flow $(G = GF_i = 0)$ all pressure drops Δp_i would also vanish. Hence, a fictitious and very small flow rate must be maintained

(10^{-8} kg/sec) in order to avoid deviding by zero in the correction formuli given in APPENDIX C.

b) Thermodynamics

Flow reversal does not affect the equations for enthalpy balance in the coolant if WE and WA stands for the coolant enthalpy entering and leaving the node, respectively, and irrespective of flow direction. The schematic diagram in Fig. E1 shows how the nodal enthalpies are interrelated. A node entered by one arrow only indicates, that this enthalpy is transferred directly from one node to the other. If such a connection occurs between two nodes at different times (t_j and t_{j+1})this is equivalent to a transport delay of the length of the time increment I. It can be seen from this figure that there is in effect such a transport delay applied between all neighbouring nodes, including the nodes representing the plenum chambers+). In as much as the step size of the integration approaches the transport time Δt_T this method will account for the actual transport effects (see APPENDIX H).

c) Boundary Conditions

When using program REX, flow reversal is achieved by appropriate choice of the boundary conditions. With B.C.1. flow reversal occurs when the specified exit pressure exceeds the entry pressure, which is also specified. In the case of B.C.2 and B.C.3 flow reversal occurs when the total coolant flow rate G becomes negative. The present version of the main program REX is such that for all three cases the enthalpy of the coolant entering the reactor under conditions of reversed flow is constant and equal to the value at this point (exit plenum chamber) just before flow reversal. Thus, the enthalpy values specified in data block 2 become irrelevant in case of flow reversal.

+) To be quite exact at this point the prior assumption of zero residence time of the coolant in the plenum chambers must be corrected to state that a delay of a length I is included, which in general however will be small and may be neglected relative to actual residence times.

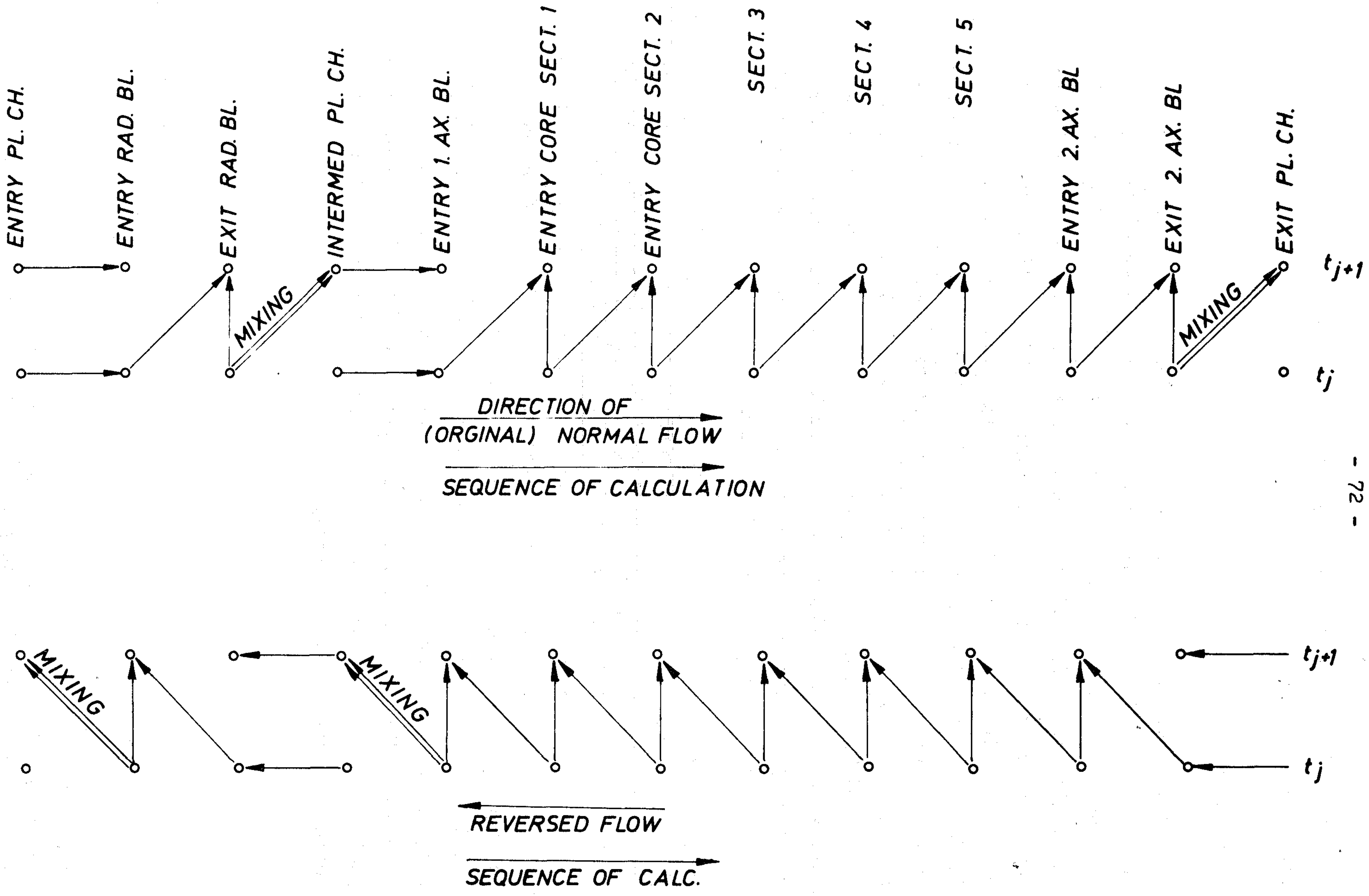


Fig. E1 Nodal Mesh for Transient Calculation of Coolant Enthalpy (Flow Reversal)

APPENDIX F : Integration of the Point Kinetics Equations

Equations:

$$\frac{dP}{dt} = \frac{1}{\Lambda}\cdot\left[\beta\cdot\Delta k - \beta\right]\cdot P + \sum_i \lambda_i C_i$$

$$\frac{dC_i}{dt} = \frac{1}{\Lambda}\cdot\beta_i\cdot P - \lambda_i C_i \qquad i = 1,2,\ldots ND$$

$$\Delta k = \Delta k_T + \Delta k_K \qquad [\$\text{-units}|$$

Substitutions:

$$Y_i = \frac{\Lambda\lambda_i}{\beta_i}\cdot C_i$$

$$f_i = \frac{\beta_i}{\beta}$$

$$\omega = \frac{\beta}{\Lambda}$$

Yield:

$$\frac{dP}{dt} = \omega\cdot\left[(\Delta k - 1)\cdot P + \sum_i f_i\cdot Y_i\right]$$

$$\frac{dY_i}{dt} = \lambda_i\cdot\left[P - Y_i\right]$$

The basic assumption facilitating efficient integration by a semi-analytic method is that changes in the variables Y_i may be neglected relative to the change in P during a short time interval. Furthermore, the reactivity also is to remain constant during this interval. We introduce the following two quantities

$$\frac{1}{\tau_0} = \omega\cdot(\Delta k_0 - 1)$$

$$S_0 = \frac{1}{\Delta k_0 - 1}\cdot\sum_i f_i Y_{i0}$$

where the subscript 0 refers to (known) values at the beginning of an interval Δt over which we want to integrate. With this we now can write:

$$\frac{dP}{dt} = \frac{1}{\tau_0}\left[P + S_0\right]$$

which under the assumption made above can be integrated to give

$$P = (P_0 + S_0)\cdot e^{\frac{\Delta t}{\tau_0}} - S_0$$

Integrating again yields the energy release:

$$\Delta E = \int^{\Delta t} P dt = (P_0 + S_0)\cdot \tau_0 \cdot \left(e^{\frac{\Delta t}{\tau_0}} - 1\right) - S_0 \cdot \Delta t$$

and

$$E = E_0 + \Delta E$$

The variables Y_i corresponding to the concentration of the precursors are obtained from integration of the corresponding equations:

$$Y_i = Y_{i_0} + \lambda_i \left[\Delta E - Y_{i_0}\cdot \Delta t\right]$$

Assuming equilibrium at the power level P_0 as the initial condition, the starting values of all variables have to be:

$$\begin{array}{ll} \rho_0 = 0 & S_0 = -P_0 \\ \frac{1}{\tau_0} = -\omega & Y_{i_0} = P_0 \\ & E_0 = 0 \end{array}$$

Although the scheme is complete at this point two special cases shall be considered:

a) Prompt Criticality

Condition: $\left|\frac{\Delta t}{\tau_0}\right| \leqslant \varepsilon_1 \ll 1$

If this inequality is satisfied for an appropriate value of ε_1, it is acceptable to approximate the exponential function by the first two terms of its Taylor expansion:

$$P = (P_0 + S_0)\cdot\left(1 + \frac{\Delta t}{\tau_0}\right) - S_0 = P_0\cdot\left(1 + \frac{\Delta t}{\tau_0}\right) + S_0\cdot\frac{\Delta t}{\tau_0}$$

For sufficiently small values of ε_1($= 10^{-6}$) we may simplify further and write:

$$P = P_0 + S_0\cdot\frac{\Delta t}{\tau_0}$$

For the energy increment ΔE we get in the same manner:

$$\Delta E = (P_0 + S_0)\cdot\tau_0\cdot\left(\frac{\Delta t}{\tau_0} + \left(\frac{\Delta t}{\tau_0}\right)^2\cdot\frac{1}{2}\right) - S_0\cdot\Delta t = \left(P_0 + S_0\cdot\frac{1}{2}\cdot\frac{\Delta t}{\tau_0}\right)\cdot\Delta t$$

The inequality above may be rewritten as:

$$\left|\Delta k_0 - 1\right| \leqslant \frac{10^{-6}}{\Delta t\cdot\omega}$$

which normally will be satisfied only when the excess reactivity Δk_o is very nearly equal to unity (one dollar) (prompt criticality).

b) Prompt Jump Approximation

Condition:

$$\frac{\Delta t}{\tau_0} \leqslant \varepsilon_2 < 0$$

If this condition is satisfied for sufficiently large values of ε_2 (e.g.-18.4) it is acceptable to neglect the experimental function relative to unity. Thus we get:

$$P = - S_0$$

$$\Delta E = -(P_0 + S_0)\cdot\tau_0 - S_0\cdot\Delta t \;=\; P_0\cdot\tau_0 + S_0\cdot(\tau_0 - \Delta t)$$

$$= \left[-P_0 - S_0\cdot\left(1 + \frac{\Delta t}{\tau_0}\right)\right]\cdot\tau_0$$

The inequality above may be rewritten as:

$$\Delta k_0 \leqslant 1 - \frac{18.4}{\omega\cdot\Delta t}$$

which is satisfied whenever the reactor is sufficiently below prompt critical. The approximate solution obtained in this case is equivalent to the well-known prompt jump approximation.

Note, that both inequalities given under a) and b) depend on the step size Δt of the integration. The flow chart given in Fig. F1 illustrates the integration scheme described above.

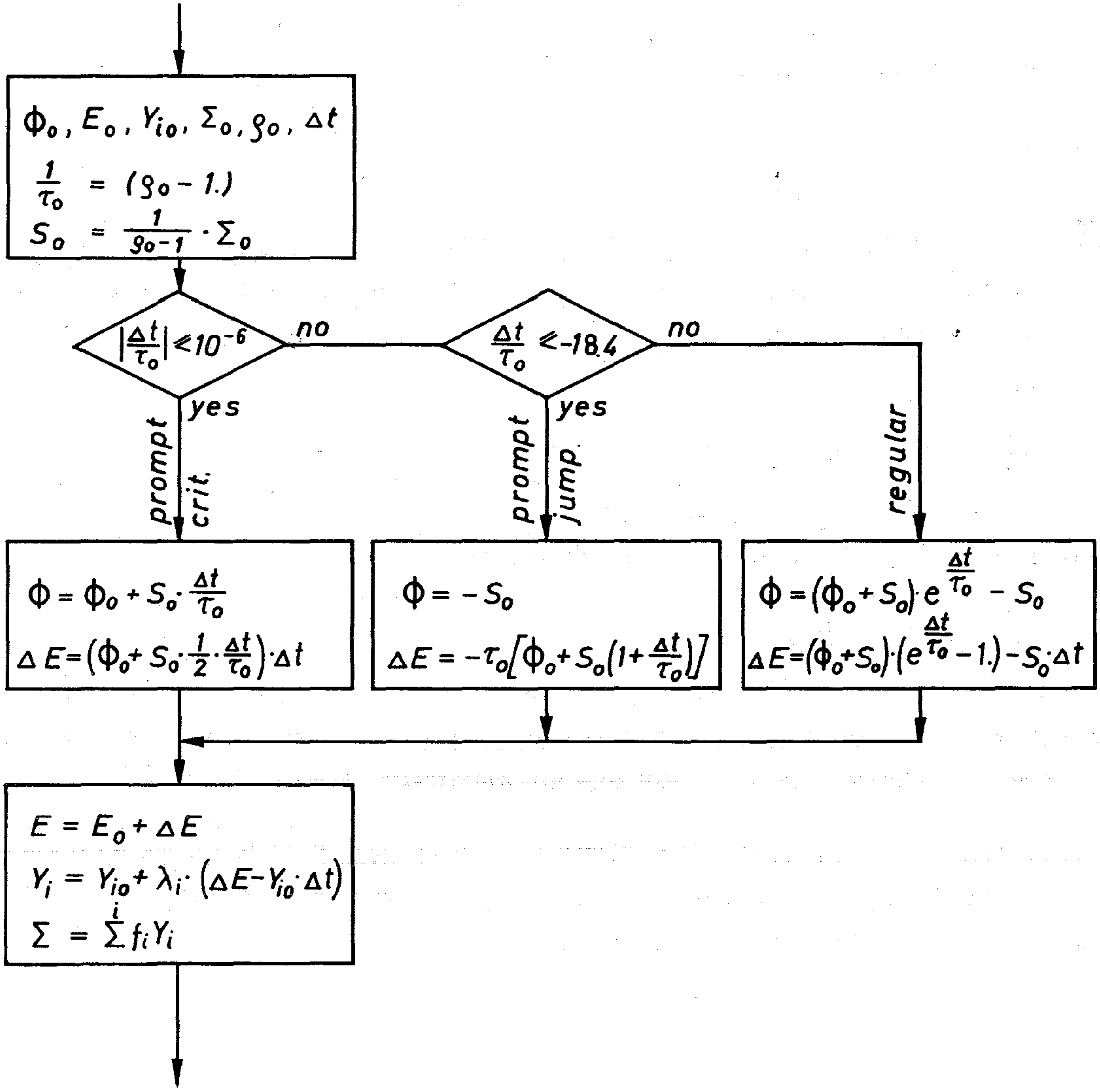


Fig. F1 Flow Diagram of the Integration Scheme for Point Kinetics

APPENDIX G : Sample for Calculating Feedback Parameters from Results of Perturbation Calculations

The example given below is based on feedback models employed by the FORE-code [1] and also by [12]. These models are slightly modified and restricted to space dependence in axial direction only. Consequently, the radial distribution coefficients ARD, ARF, ARC, ARS, ARM are insignificant and may be assigned arbitrary values ($\neq 0$). Axial subdivisions are introduced at equal intervals along the vertical axis of the core.

A set of basic reactivity coefficients is assumed to be available, for instance, from one dimensional perturbation calculations for the particular case of interest:

$\left(\frac{\partial k}{k} \Big/ \frac{\partial \rho_n}{\rho_n}\right)_{IX}$	rel. change in reactivity resulting from a relative change in density of material n (= F,C,S,M) in axial section IX,
$\left(\frac{\partial k}{k} \Big/ \frac{\partial HC}{HC}\right)$	relative change in reactivity resulting from a relative change in core height HC,
$\left(\frac{\partial k}{k} \Big/ \frac{\partial R}{R}\right)$	relative change in reactivity resulting from a relative change in core radius R,
$\left(\partial k / \partial TF\right)_{IX}$	change in reactivity resulting from a change in fuel temperature TF by 1 ^oK in axial section IX due to the Doppler effect (Doppler coefficient)(fuel reference temperature 900 ^oK)
β	fraction of delayed neutrons

Additional parameters appearing in the following equations are

α_S.....volume fraction of coolant per axial channel section

$$= \frac{R3^2 - R2^2}{R3^2 + WP \cdot D4/PI}$$

β_1......volume fraction of spacers per axial channel section

β_2...... " " " subassembly cans per axial channel section

Before presenting the formuli special mention shall be made of some of the mechanisms and associated assumptions (indexing code refers to subsequent paragraphs):

a 3), b 1), d 1) : the effective density of each of the components: fuel, clad and structure is not changed by the radial expansion of the respective component;

d 2), d 3), d 4) : radial expansion of the core in any point is assumed to be a linear function of the local structural temperature alone.

a) Fuel Temperature Effects

a 1) Doppler effect:

$AXD = (\partial k/\partial TF)_{IX}$ ...... axial distribution coefficients (unnormalized)

$RCD = \frac{900}{\beta}\sum_{IX}(AXD)$ ...... Doppler constant, $-units,

a 2) Change in core height due to axial expansion of fuel:

$$RCH = \frac{1}{\beta}\left(\frac{\partial k}{k} \Big/ \frac{\partial HC}{HC}\right)$$

a 3) Change in effective fuel density due to axial expansion of fuel:

$$AXF = \left(\frac{\partial k}{k} \Big/ \frac{\partial \rho_F}{\rho_F}\right)_{IX}$$

$$RCF = \frac{1}{\beta} \cdot \sum_{IX}(AXF)$$

b) Cladding Temperature Effects

b 1) Change in effective cladding density due to axial expansion of cladding:

$$AXC_1 = \left(\frac{\partial k}{k} \Big/ \frac{\partial \rho_c}{\rho_c}\right)_{IX}$$

b 2) Change in effective coolant density due to radial expansion of cladding:

$$AXC_2 = \left(\frac{\partial k}{k} \Big/ \frac{\partial \rho_s}{\rho_s}\right) \cdot \frac{\frac{d\rho_s}{\rho_s} / dTC}{\frac{d\rho_c}{\rho_c} / dTC} = \left(\frac{\partial k}{k} \Big/ \frac{\partial \rho_s}{\rho_s}\right) \cdot \frac{-2 \cdot AEF \cdot \frac{1-\alpha_s-(\beta_1+\beta_2)}{\alpha_s}}{-AEC}$$

Total:

$$AXC = AXC_1 + AXC_2$$

$$RCC = \frac{1}{\beta} \cdot \sum_{IX}(AXC)$$

c) Coolant Density Effect:

$$AXS = \left(\frac{\partial k}{k} \Big/ \frac{\partial \rho_s}{\rho_s}\right) \cdot \frac{1}{\rho_s}$$

$$RCS = \frac{1}{\beta} \cdot \sum_{IX} (AXS)$$

d) Structure Temperature Effects

d 1) Change in effective structure density due to axial expansion of structure:

$$AXM_1 = \left(\frac{\partial k}{k} \Big/ \frac{\partial \rho_M}{\rho_M}\right)$$

d 2) Change in effective fuel density due to radial expansion of (supporting) structure

$$AXM_2 = \left(\frac{\partial k}{k} \Big/ \frac{\partial \rho_F}{\rho_F}\right) \cdot \frac{\frac{d\rho_F}{\rho_F} \Big/ dTM}{\frac{d\rho_M}{\rho_M} \Big/ dTM} = \left(\frac{\partial k}{k} \Big/ \frac{\partial \rho_F}{\rho_F}\right) \cdot \frac{-2 \cdot AEM}{-AEM} = \left(\frac{\partial k}{k} \Big/ \frac{\partial \rho_F}{\rho_F}\right) \cdot 2$$

d 3) Change in effective cladding density due to radial expansion of (supporting) structure

$$AXM_3 = \left(\frac{\partial k}{k} \Big/ \frac{\partial \rho_c}{\rho_c}\right) \cdot \frac{\frac{d\rho_c}{\rho_c} \Big/ dTM}{\frac{d\rho_M}{\rho_M} \Big/ dTM} = \left(\frac{\partial k}{k} \Big/ \frac{\partial \rho_c}{\rho_c}\right) \cdot \frac{-2 \cdot AEM}{-AEM} = \left(\frac{\partial k}{k} \Big/ \frac{\partial \rho_c}{\rho_c}\right) \cdot 2$$

d 4) Change in effective coolant density due to radial expansion of (supporting) structure

$$AXM_4 = \left(\frac{\partial k}{k} \Big/ \frac{\partial \rho_s}{\rho_s}\right) \cdot \frac{\frac{d\rho_s}{\rho_s} \Big/ dTM}{\frac{d\rho_M}{\rho_M} \Big/ dTM} = \left(\frac{\partial k}{k} \Big/ \frac{\partial \rho_s}{\rho_s}\right) \cdot \frac{2 \cdot AEM \frac{1-\alpha_s}{\alpha_s}}{-AEM} = \left(\frac{\partial k}{k} \Big/ \frac{\partial \rho_s}{\rho_s}\right) \cdot \left(-\frac{2(1-\alpha_s)}{\alpha_s}\right)$$

d 5) Change in effective coolant density due to expansion of structure (spacers and subassembly cans)

$$AXM_5 = \left(\frac{\partial k}{k} \Big/ \frac{\partial \rho_s}{\rho_s}\right) \cdot \frac{\frac{d\rho_s}{\rho_s} \Big/ dTM}{\frac{d\rho_M}{\rho_M} \Big/ dTM} = \left(\frac{\partial k}{k} \Big/ \frac{\partial \rho_s}{\rho_s}\right) \cdot \frac{-AEM \frac{3\beta_1 + 2\beta_2}{\alpha_s}}{-AEM} = \left(\frac{\partial k}{k} \Big/ \frac{\partial \rho_s}{\rho_s}\right) \cdot \frac{3\beta_1 + 2\beta_2}{\alpha_s}$$

Total: $AXM = \sum_{i=1}^{5} AXM_i$

$$RCM = \frac{1}{\beta} \sum_{IX} AXM$$

d 6) Change in core radius due to radial expansion of structure

$$RCR = \frac{1}{\beta} \left(\frac{\partial k}{k} \Big/ \frac{\partial R}{R}\right)$$

APPENDIX H : Determination of Integration Step Size, Numerical Stability of Integration of the Thermo-Hydraulic Equations

a) Estimation of the Maximum Stable Step Size for Integration of the Thermo-Hydraulic Equations

Numerical instabilities occurring during integration by nodal approximation of problems of heat transfer and heat transport impose a dominating limitation on the step size of integration. With the nodes fixed at their spatial coordinates there is a maximum stable step size for the integration which depends on both the physical parameters involved as well as the particular method of discretization and mesh spacing. A classic approach to determine the maximum stable step size is the one of small perturbations which in general leads to an Eigenvalue problem. Computer storage requirements and considerations of computing speed preclude such an approach in most practical cases. To achieve the same purpose a much simpler technique is employed here which yields a conservative (too small) maximum step size granting numerical stability of the integration. A certain amount of flexibility is maintained by multiplying this step size estimate by a given constant coefficient EST before applying it to the integration. Furthermore, re-evaluation of the maximum stable step size may be restricted to every NTE'th step during the integration and keeping it unaltered for all the steps in between. This facilitates savings in computing time for step size determination in case of slowly varying transients. If the maximum stable step size (MSS) comes out to be smaller than the current step size, the latter will be halved until it in turn is smaller than MSS. If MSS is larger than twice the current step size the latter may be doubled for the following step of the integration if other tests are satisfied. These tests are listed under b) in this appendix.

The perturbation method consists of introducing small perturbances ε_i in all variables of the pertinent system of equations. These must not grow for any of the variables from any one step to the next in order for the system to be stable. Since we require the true solution to hold along with the perturbation solution we may subtract the(unpertubed) original system of equations from the perturbed one. In the case of a linear system - as we are dealing with - the remaining equations on the right hand side are linear and homogeneous in the perturbations ε_i which were introduced at the beginning of the step. The components of the left hand vector are the perturbations ε_i^* at the end of the step.

Application of this scheme to the pertinent equations for transient temperatures in all components of one axial section (see APPENDIX A) we get the following system of equations:

$$\begin{aligned}
\varepsilon_1^* &= \varepsilon_1 \cdot (1 - \Delta t \cdot \alpha_{11}) + \varepsilon_2 \cdot \Delta t \cdot \alpha_{12} \\
\varepsilon_2^* &= \varepsilon_1 \cdot \Delta t \cdot \alpha_{21} + \varepsilon_2 \cdot (1 - \Delta t \cdot \alpha_{22}) + \varepsilon_3 \cdot \Delta t \cdot \alpha_{23} \\
&\vdots \\
\varepsilon_j^* &= \varepsilon_{j-1} \cdot \Delta t \, \alpha_{j,j-1} + \varepsilon_j \cdot (1 - \Delta t \cdot \alpha_{jj}) + \varepsilon_{j+1} \cdot \Delta t \cdot \alpha_{j,j+1} \\
&\vdots \\
\varepsilon_J^* &= \varepsilon_{J-1} \cdot \Delta t \cdot \alpha_{J-1,J} + \varepsilon_J \cdot (1 - \Delta t \cdot \alpha_{JJ})
\end{aligned}$$

where all of the coefficients $\alpha_{i,j}$ are positive. Note, that some of these coefficients are functions of time as they contain temperature dependent fuel properties, coolant net flow rate and film coefficients.

Instead of solving the Eigenvalue-problem associated with the requirement of decreasing perturbations we apply a criterion of the form /‾13_7:

$$\sum_{i=1}^{J} |A_{ji}| \leqslant 1 \qquad j = 1, 2, \ldots J$$

where A_{ji} are the elements of the coefficient matrix in the system of equations above. Guarding against numerical instabilities of oscillatory nature this criterion yields a conservative estimate for the maximum stable step size in the following manner:

$$\sum_{i=1}^{J} |A_{ji}| = \Delta t_j \alpha_{j,j-1} + (-1 + \Delta t_j \alpha_{jj}) + \Delta t_j \cdot \alpha_{j,j+1} = 1$$

$$\Delta t_j = \frac{2}{\alpha_{j,j-1} + \alpha_{jj} + \alpha_{j,j+1}}$$

$$\Delta t_{MAX} = \mathrm{MIN}\,(\Delta t_j)$$

In view of the last equation not all Δt_j need to be evaluated since certain ones always are larger than certain other ones by nature of the expressions from which they are computed. For instance, this is the case for the fuel nodes in any particular axial section, where only the surface node (TFN) needs to be considered here.

With regard to the equations for the coolant it is convenient to replace the enthalpy perturbations by temperature perturbations using the relations:

$$\varepsilon_{WA} = CPA \cdot \varepsilon_{TA}$$

$$\varepsilon_{T3} = 0.5 \cdot \varepsilon_{TA}$$

The last equation follows from the assumption of a linear profile for the coolant temperature over anyone axial section.

Applying the equation for Δt_j to our particular system we get the following set of equations (core):

fuel edge:

$$\Delta t_1 = \frac{R01 \cdot CP1 \cdot R1^2}{4 \cdot NN \cdot \left[(2 \cdot NN-1) \cdot C01 + R1 \cdot HGP\right]}$$

cladding, inner edge:

$$\Delta t_2 = \frac{R02 \cdot CP2 \cdot (R2^2 - R1^2)}{4 \cdot \left[R1 \cdot HGP + \frac{(R2+R1)}{2 \cdot (R2-R1)} \cdot C02\right]}$$

cladding, outer edge:

$$\Delta t_3 = \frac{R02 \cdot CP2 \cdot (R2^2 - R1^2)}{4 \cdot \left[\frac{(R2+R1)}{2 \cdot (R2-R1)} \cdot C02 + R2 \cdot H23\right]}$$

coolant:

$$\Delta t_4 = \frac{2}{\left[\frac{2 \cdot H23 \cdot R2}{CP3 \cdot (R3^2 - R2^2)} + \frac{H34' \cdot WP}{CP3 \cdot PI \cdot (R3^2 - R2^2)} + \frac{GF}{\Delta H}\right] \cdot V}$$

structure:

$$\Delta t_5 = \frac{R04 \cdot CP4 \cdot D4}{H34'}$$

Corresponding equations are obtained for blankets and bypasses. The proposed step size then is obtained from

$$\Delta t = EST \cdot MIN\ (\Delta t_j)$$

The last term in parentheses of the denominator in the expression for Δt_4 is the reciprocal of the transport time Δt_T of the coolant through the distance ΔH. In cases where this term dominates the maximum stable step size is approximately twice the transport time Δt_T:

$$\Delta t_M = 2 \cdot \Delta t_T$$

b) Step Size Limitations from Relative Changes of Total Power

Another criterion for the selection of the step size is applied in conjunction with the relative change in total power:

$$\Delta P = \frac{P_{n+1} - P_n}{P_n}$$

where the subscript refers to successive instances in time.

If $\Delta P > \Delta P_{Max}$ the step size is halved and integration of the point kinetics equations is repeated until $\Delta P < \Delta P_{Max}$.

If $\Delta P < \Delta P_{Min}$ the step size may be doubled for the consecutive step.

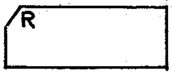
The values for ΔP_{Max} and ΔP_{Min} are chosen from experience to be in the order of about 0.1 to 0.01.

c) Further Limitations

Finally, arbitrary limits may be set for the maximum and minimum value of the step size (XIX, XIN). If a step size smaller than XIN is required by either criterion given under a) and b) the computation is terminated. If a step size larger than XIX is permissible, the computation will continue using the most recent step size just below this upper limit. If, for the first step of integration, the stability criterion results in a step size larger than the upper limit XIX, then this value (XIX) will be taken as the size of the initial step of integration.

APPENDIX I: Flow Diagrams

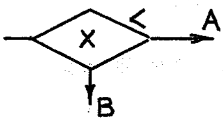
The subsequent flow diagrams cover all routines on levels 1,2, and 3 as well as the reactivity function RCBE. Conventional symbols are employed to a large extent. Unconventional symbols are explained as follows:



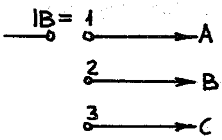
READ statement

WRITE statement

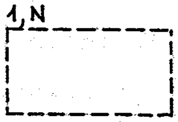
READ & WRITE statement



if: X 0 ..... go to A IF statement
X 0 ..... go to B



if: IB=1 ..... go to A computed GO TO statement
IB=2 ..... go to B
IB=3 ..... go to C



DO statement; loop index goes from 1 to N.
For simplicity, the loop index is omitted inside the loop.
Examples: T(,,NN) corresponds to T(IX,IR,NN)
WI0(IX1,) corresponds to WI0(IX1,IR)
S corresponds to S(IX,IR)

Variable names in the flow diagrams are the same as in the actual routines and may differ from the names used elsewhere in this report.

Vertical dashed lines appearing in the flow diagram of subroutine STS signify iterative procedures as described in APPENDICES C and D.

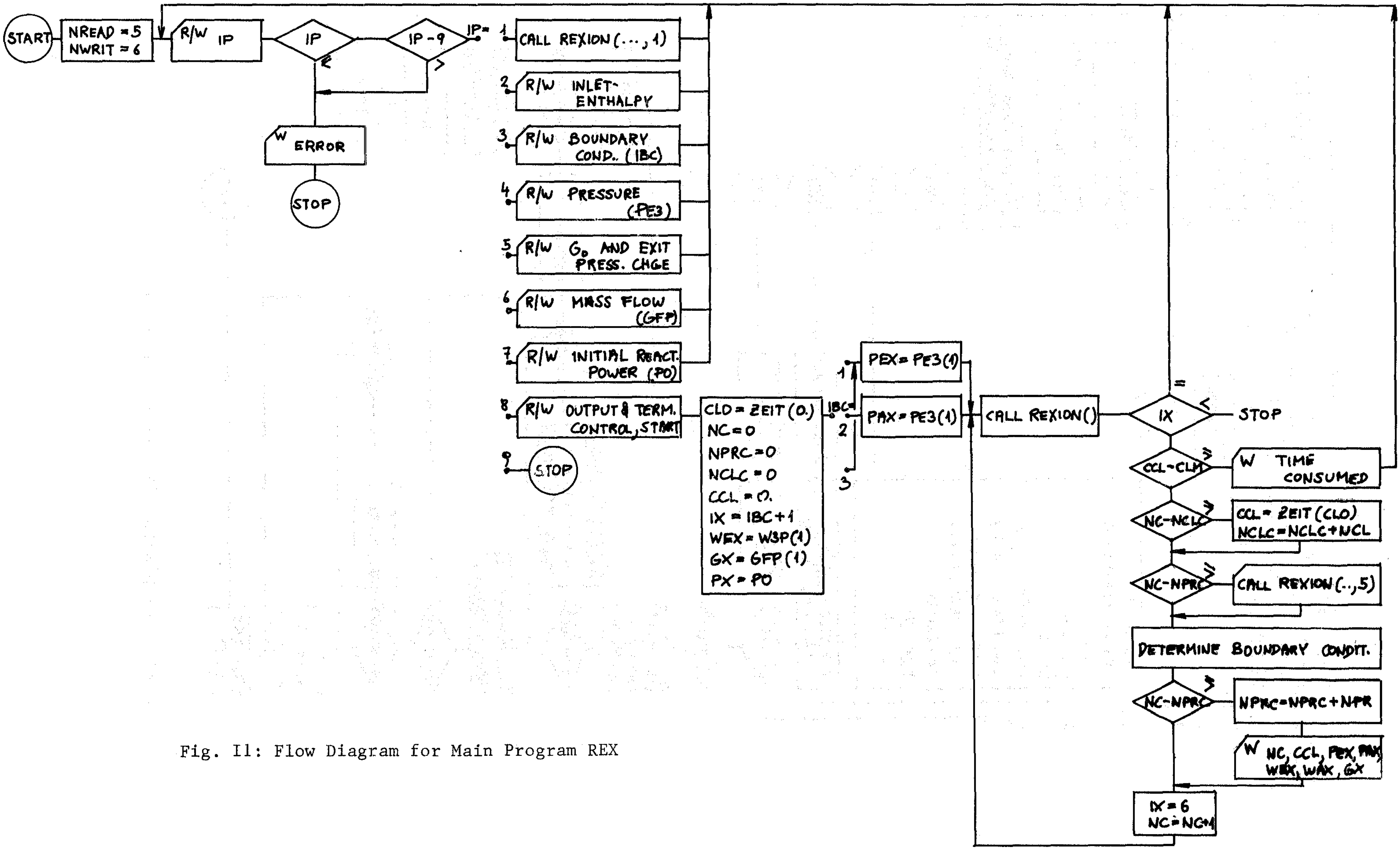


Fig. I1: Flow Diagram for Main Program REX

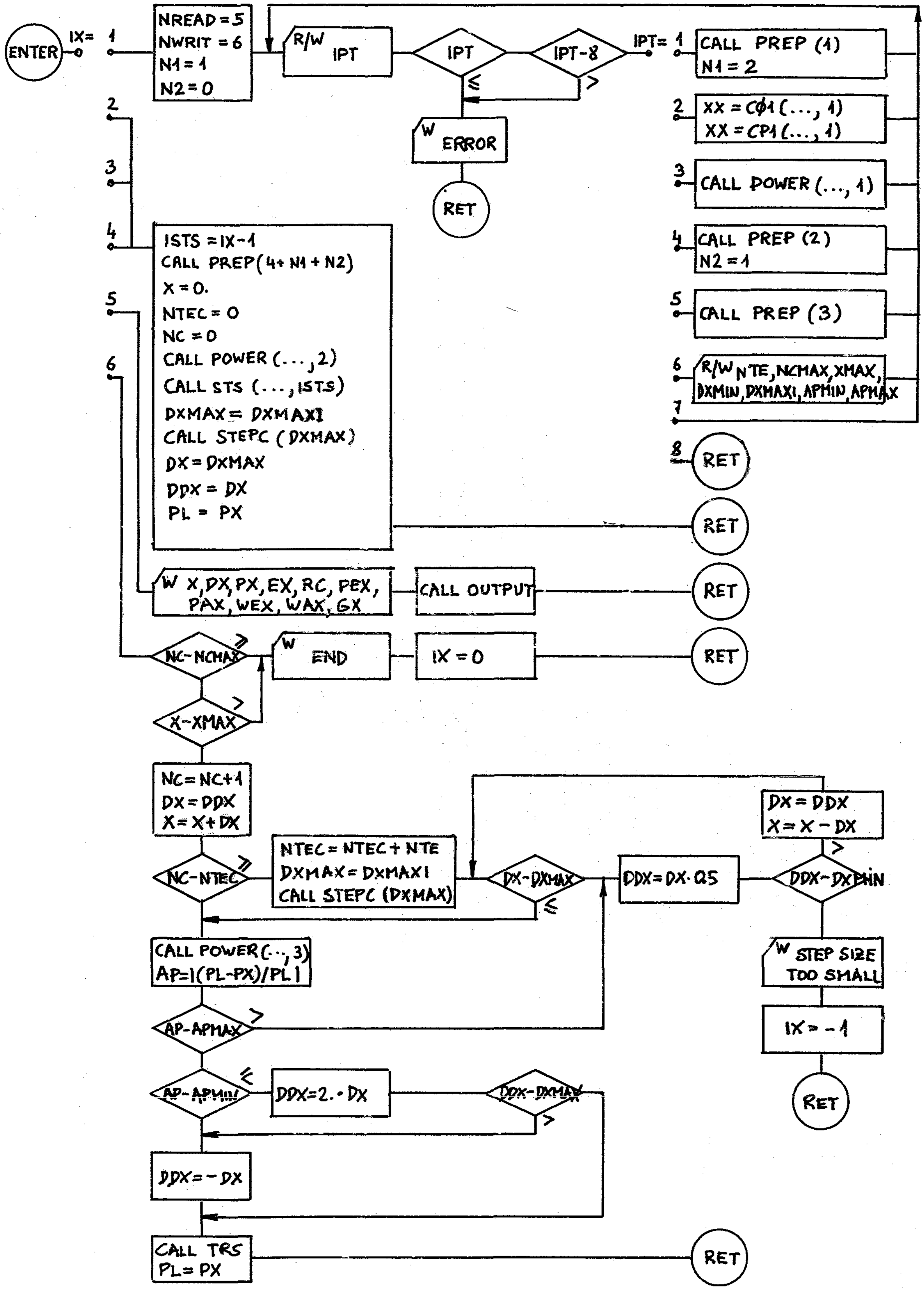


Fig.I2: Flow Diagram for Subroutine REXION

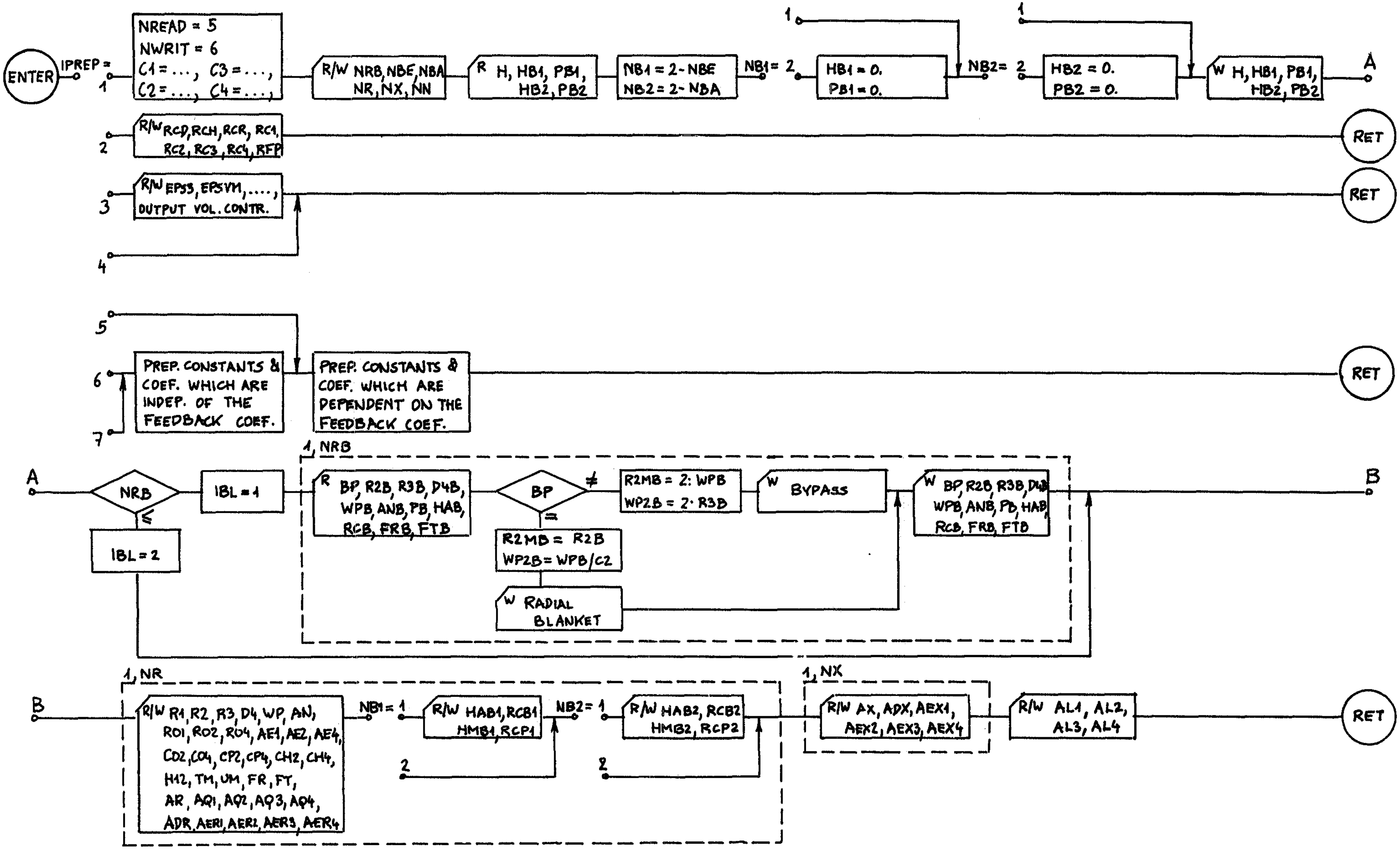


Fig.I3: Flow Diagram for Subroutine PREP

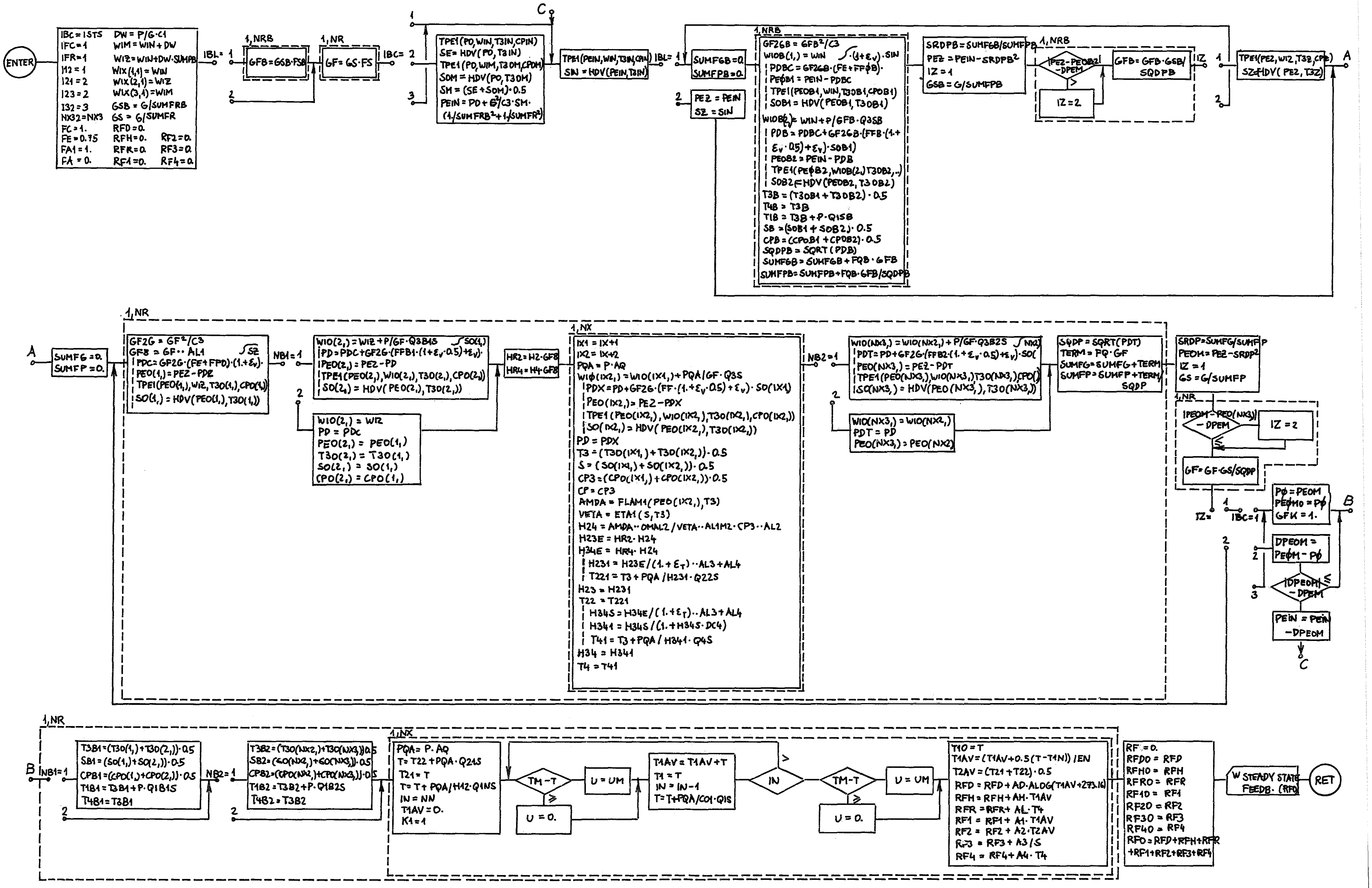


Fig. I4: Flow Diagram for Subroutine STS

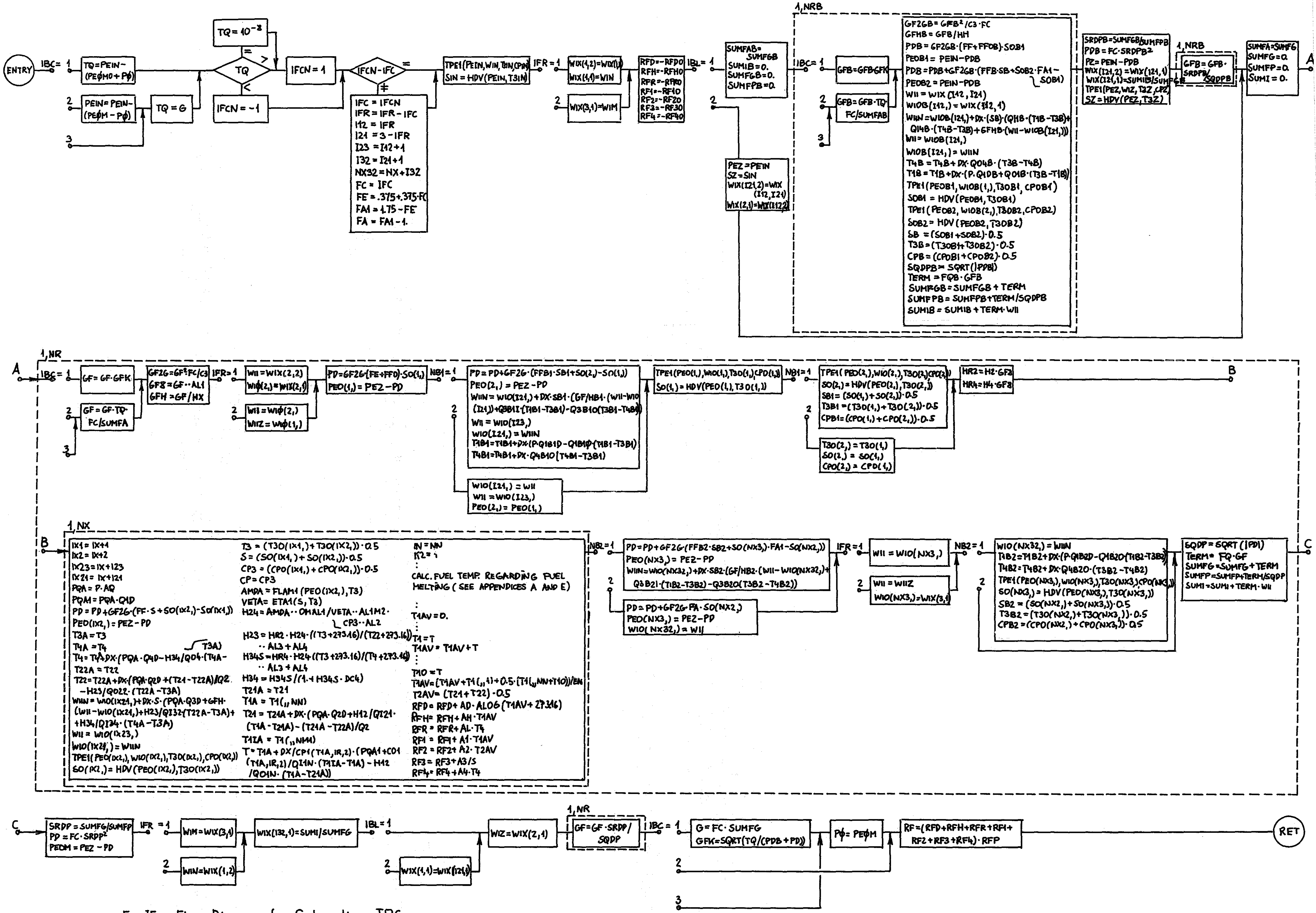


Fig. 15: Flow Diagram for Subroutine TRS

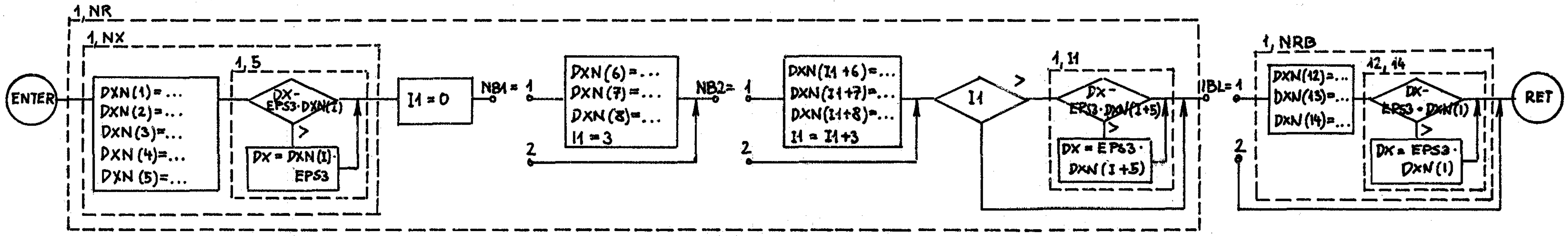


Fig.I6: Flow Diagram for Subroutine STEPC

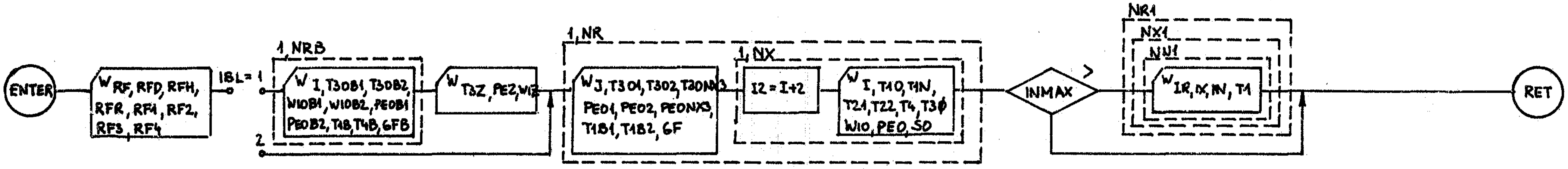


Fig.I7: Flow Diagram for Subroutine OUTPUT

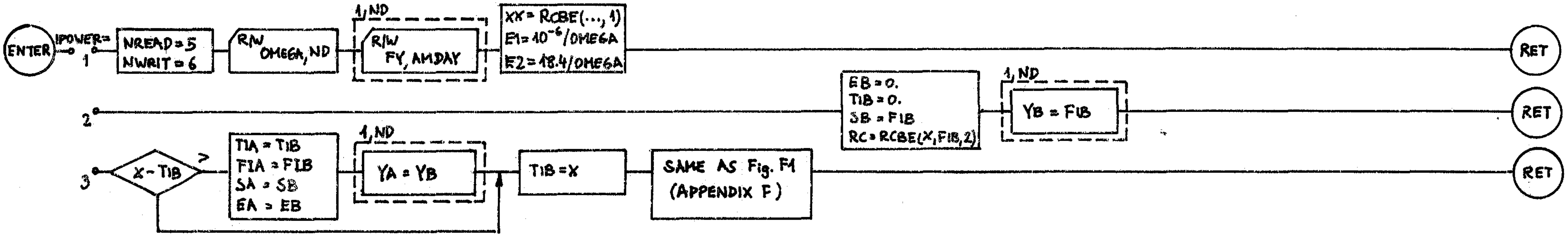


Fig.I8: Flow Diagram for Subroutine POWER

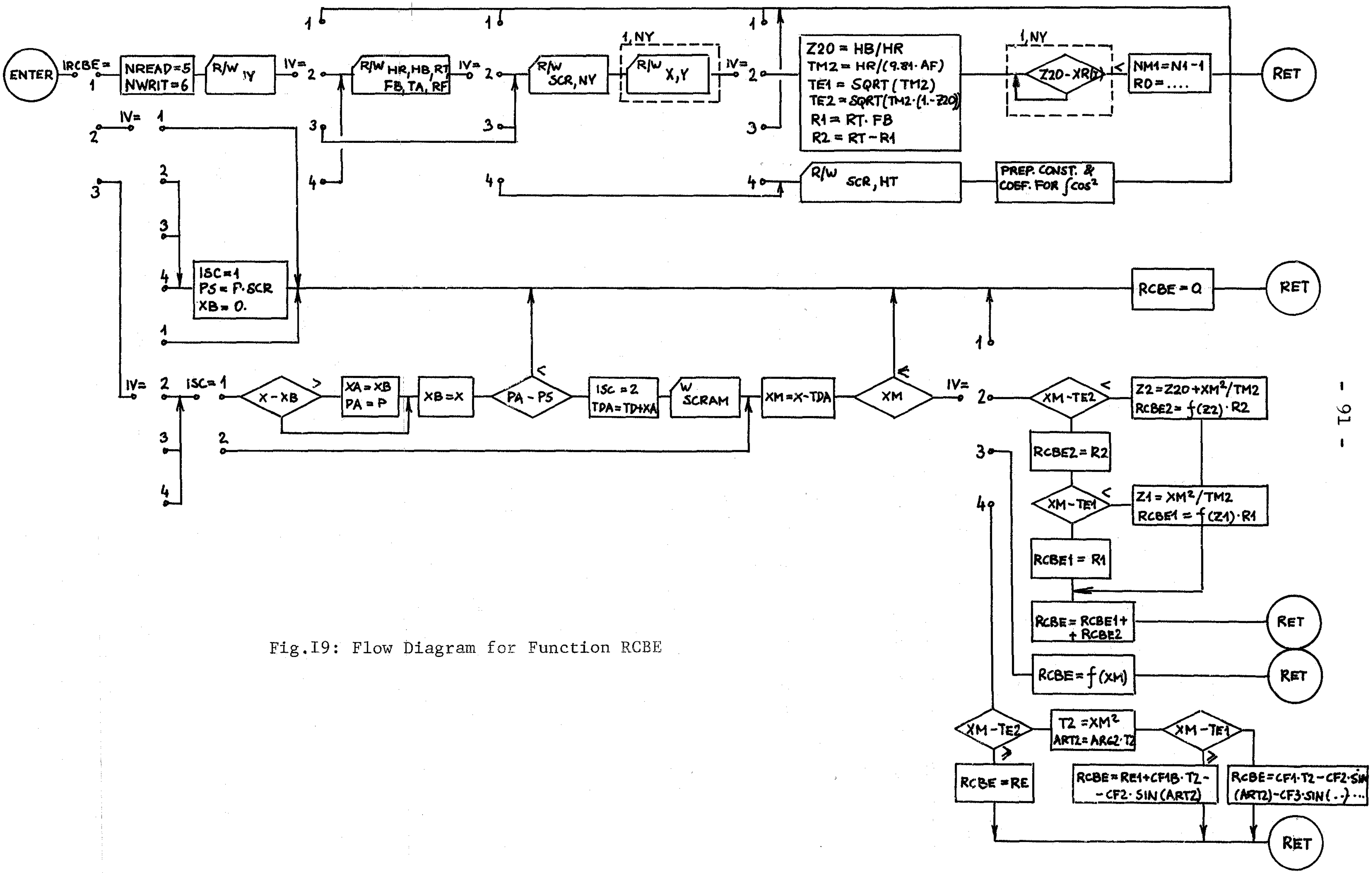


Fig.I9: Flow Diagram for Function RCBE

APPENDIX J : Subroutine REXION: Description and Instructions for Use

The program described in this report can be used without the mainprogram REX by simply calling the subroutine REXION. The calling program must provide information specifying time dependent coolant boundary conditions et.c. The following rules should be observed:

The subroutine is called by:

```
CALL REXION (X, DX, P, E, G, PEX, PAX, WEX, WAX, IX)
```

The last argument in the list IX is used both as a parameter controlling the mode of operation of the subroutine as well as an error indicator. Calling the subroutine with different values for IX indicates the following operations:

IX = 1 ... reading of all data required by the subroutine; these data are the ones designated SYSTEMS DATA constituting subblocks 1-8 as described in Chapter IV.2. A replica of this input is printed as first part of the output.

IX = 2 ... calculation of the initial steady state solution, boundary condition B.C.1

IX = 3 ... calculation of the initial steady state solution, boundary condition B.C.2

IX = 4 ... calculation of the initial steady state solution, boundary condition B.C.3

IX = 5 ... output of all system variables, pertaining to time X, as described in Chapter IV.3

IX = 6 ... integration of the transient problem over one step of length DX. The step length is determined internally from considerations presented in APPENDIX H.

After calling the subroutine with IX = 6, one out of three possible returns is made to the calling program:

IX = 6 ... (value unchanged) successful completion of the step of integration

IX = 0.... successful completion of the transient problem (internal termination criterion satisfied)

IX = -1 .... integration not successful, step size required for stable and accurate integration is smaller than permitted minimum value XIN.

The remaining arguments in the list of the subroutine are explained in the input description, Chapter IV.2, and the list of notations, APPENDIX A. Which of these are input (I) and which are output (Ø) depends on the operational mode and is described in the following table:

IX	X	DX	P	E	G	PEX	PAX	WEX	WAX	Comment	
2	Ø$^{(1)}$	Ø$^{(3)}$	I	Ø$^{(1)}$	I	I	Ø	I	Ø	B.C.1	
3	Ø$^{(1)}$	Ø$^{(3)}$	I	Ø$^{(1)}$	I	Ø	I	I	Ø	B.C.2	steady state
4	Ø$^{(1)}$	Ø$^{(3)}$	I	Ø$^{(1)}$	I	I	Ø	I	Ø	B.C.3	
6(2)	Ø$^{(2)}$	Ø$^{(4)}$	Ø	Ø	Ø	I	I/Ø$^{(5)}$	I	Ø	B.C.1	
(3)	Ø$^{(2)}$	Ø$^{(4)}$	Ø	Ø	I	Ø	I	I	Ø	B.C.2	transient
(4)	Ø$^{(2)}$	Ø$^{(4)}$	Ø	Ø	I	I	Ø	I	Ø	B.C.3	

(1) ... quantity is set equal to zero

(2) ... time at the end of last step of integration

(3) ... is set equal to the maximum step size for stable integration as calculated from initial steady state conditions - or to the maximum permissible step size XIX - which ever is smaller

(4) ... step size used for the last step of integration

(5) ... when calling the subroutine this argument has to be equal to the difference Δp of the current exit pressure and its initial value: $\Delta p = P_{ex} - P_{ex,o}$. Upon return this argument will be set equal to the acutal current exit pressure PAX.

None of the parameters listed with Ø in the last three lines (IX = 6) must be altered in the calling program during integration of anyone transient problem. Also, it should be noted that all arguments listed with I in the last three lines are evaluated at time X_{j-1} at the beginning of the step whereas the remaining arguments listed with Ø refer to the time $X_j = X_{j-1} + DX$.

The flow diagram in Fig. 31 gives an example for the integrated use of subroutine REXION. This flow diagram is essentially identical with the one of the main routine REX.

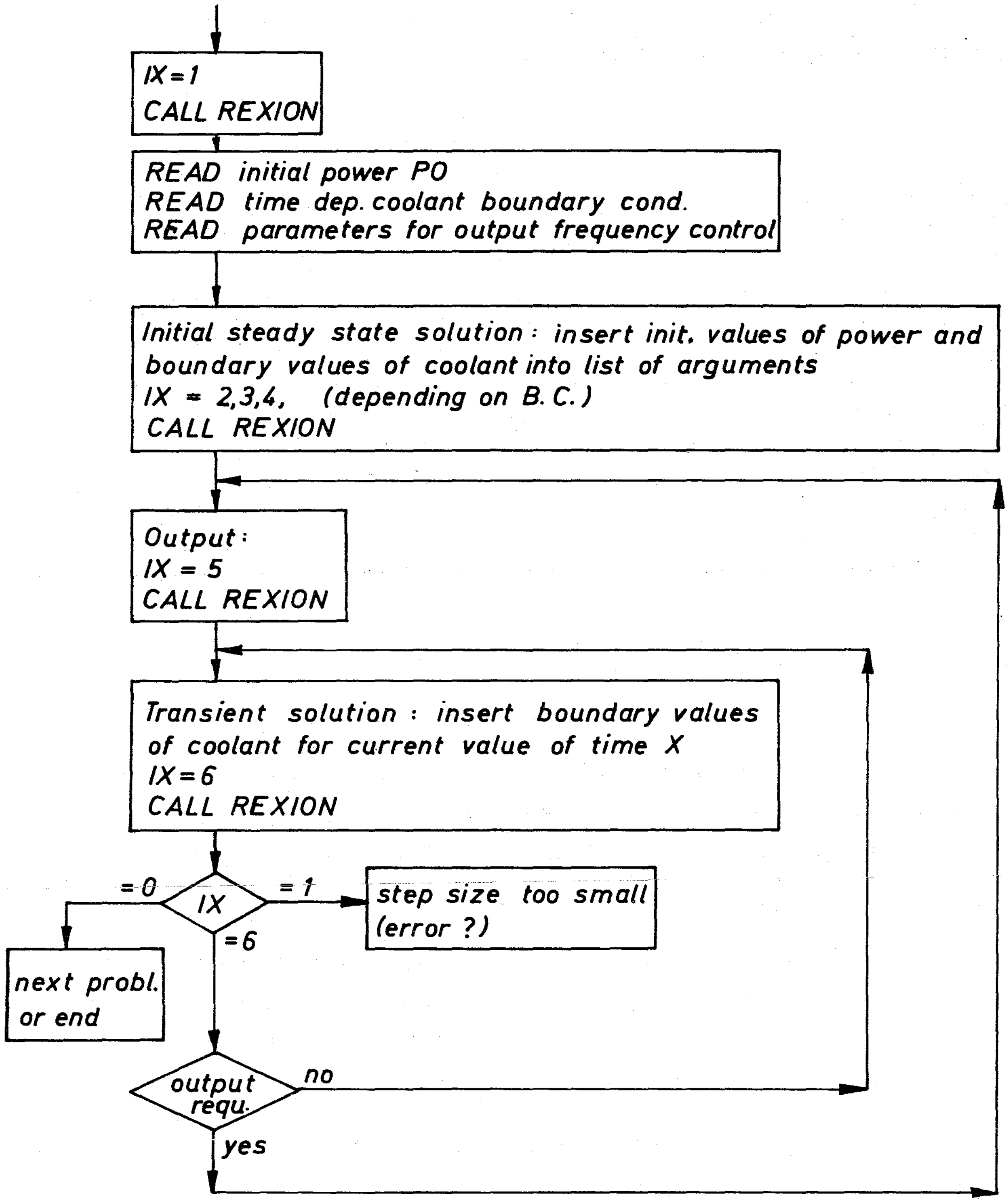


Fig. J1 Sample Flow Diagram for Application of Subroutine REXION

APPENDIX K : Functions C01 and CP1

The functions C01 and CP1 are to compute the temperature dependent thermal conductivity and specific heat of the fuel. Both of these two functions have three arguments:

C01 (T, IR, IC)
CP1 (T, IR, IC)

where T ... temperature of the fuel
IR .. index of the radial of the second flow section
IC .. parameter for mode control: $\begin{cases} = 1 \text{ ... input, preparation} \\ = 2 \text{ ... calculation} \end{cases}$

If input data are required for either of the two functions, they may be supplied in subblock 2 of the SYSTEM DATA. If data card 17 is inserted then each of the two functions is called just once, in the order C01 and CP1, with IC = 1. Thus, the required data cards must follow directly after card 17, such as card 18 and 19 shown in Chapter IV.2. For the routine calculation of the functional values the functions are called with IC = 2. If neither function C01 nor CP1 require input the corresponding data cards 17, 18, 19 may be omitted and the parameter IC may be ignored.

The second argument IR may be significant in the case that fuel with different thermal properties in different radial core zones is specified.

Second order polynomials are used at present for both functions:

$$T^{*} = a \cdot T - b$$

$$C01 = (CK1 + T^{*} \cdot (CK2 + T^{*} \cdot CK3)) \cdot CK0$$

$$CP1 = (CC1 + T^{*} \cdot (CC2 + T^{*} \cdot CC3)) \cdot CC0$$

With a = 1.8 and b = 38.0 the transformation from T to T^{*} corresponds to a transformation from ^{o}C to ^{o}F with a reference temperature of 70 ^{o}F ($\cong$ 21 ^{o}C). The coefficients CK0 and CC0 may be used for converting to different units (see /‾1_7).

APPENDIX L : Function RCBE

The function RCBE is to compute the external excess reactivity as a function of time and the total reactor power. The latter variable is included for providing the possibility of scram functions initiated by power level signals. If other system variables are to be used in controlling the reactor by external excess reactivity appropriate adjustments must be made in the present version of the program (CALL-statements).

The function is called by:

RCBE (X, P, IC)

where

X ... time (sec)
P ... total reactor power (MW)
IC .. mode control parameter $\begin{cases} = 1 \text{ ... input} \\ = 2 \text{ ... steady state} \\ = 3 \text{ ... transient} \end{cases}$

If input data to this routine are required they may be supplied in subblock 3 of SYSTEM DATA (when the function RCBE is called once with IC = 1) directly after reading of the delayed neutron parameters. Thus, eventual data cards (cards numbered 23) must follow right after the last card numbered 22.

For calculating the steady state solution the function RCBE is called once with IC = 2 and with the second argument P equal to the initial power level PO. Preparatory calculations involving PO can be carried out during this step (e.g. setting of a scram level relative to the initial power). Upon returning the function should be set equal to zero, as the initial excess reactivity is equal to zero as required by the equilibrium condition.

Calls of RCBE with IC = 3 are the standard type in the transient case and are to give external excess reactivity as a function of the arguments: time (X) and power (P). It is essential for this mode of the routine that it may be called with decreasing values for X. This is the case when the step size has to be halved as a result of failing the test concerning maximum relative power change.

Description of the present version of RCBE

The present version of RCBE is intended specifically to supply excess reactivity as a function of time in case of a reactor scram. Three different ways of specifying such functions are offered. One of them employs linear interpolation between points in the $\Delta k_{ext}/t$-plane and thus it also is suited to represent quite general functions not necessarily relating to an emergency shut down.

a) Mode 1:

The external excess reactivity remains zero at all times

b) Mode 2:

The external excess reactivity as a function of rod position is described by straight lines interconnecting points in the $\Delta k_T/Z$-plane. This function must be given in a normalized form $(\Delta k_T^*/Z^*)$ where

$$\Delta k_T^* = \Delta k_T/RT$$

$$Z^* = Z/HR$$

Thus, the last point in the $\Delta k_T^*/Z^*$-plane should be (1,1) which corresponds to the total external excess reactivity RT being inserted at the end position HR of the rods. The first point should have the coordinates (0,0) since zero excess reactivity is required for the initial equilibrium.

Scram action is triggered by the power reaching the excess level PS given by

$$PS = PO \cdot SCR$$

After this instant in time (XS) rod motion sets in with a time delay TD. Assuming constant acceleration by a multiple AF of the earths gravity g the rod position Z is obtained from:

$$Z = XM^2 \cdot (g \cdot AF)$$

where:

$$XM = X - (XS + TD).$$

Furthermore, it may be assumed that a fraction FB of all rods starts its motion from the edge of the reactor (Z = 0.) whereas the remaining rods (1.-FB) start at Z = HB (in particular: edge of core of axial blanket). The total reactivity is divided proportionately; the initial value of Δk_{ext} being zero the value at the final rod position becomes

$$\Delta k_{T,\ final} = RT - RT \cdot (1-FB) \cdot \Delta k_{T(Z=HB)}$$

c) Mode 3

Scram triggering and rod delay are treated the same way as in mode 2. However, in this mode the external excess reactivity may be specified directly as a function of time after start of the rod motion:

$$\Delta k_T = \Delta k_T \text{ (XM)}$$

d) Mode 4

Scram triggering as well as rod delay and rod motion are treated the same way as in mode 2. However, in this mode the spatial distribution of the external excess reactivity over the axial direction Z of the reactor (height HT) follows a $\cos^2$-law. Note that the distance of total rod travel HR must be less than or equal to HT. Thus, the unnormalized function Δk_T is obtained by direct integration:

$$\Delta k_T = \frac{1}{2} \left[\frac{2 \cdot Z}{HT} - \frac{1}{PI} \cdot \sin \left(PI \frac{2 \cdot Z}{HT}\right) \right]$$

If a fraction (1. - FB) of all rods starts from a point Z = HB the excess reactivity at the end position will no longer be RT but will be

$$\Delta k_{T,final} = RT\text{-}RT\cdot(1.0\text{-}FB)\cdot\Delta k_{T(Z\,=\,HB)}$$

Input description

card	name	format	units	comments	restrictions
23/1	IV	I7	-	mode parameter	1, 2, 3, 4

No other card is required if IV = 1. If IV = 2 or IV = 4 the next card is 23/2:

card	name	format	units	comments	restrictions
23/2	HR	E 11.4	m	total distance of travel for rod fraction FB	
	HB	"	m	Z = HB is starting position for rod fraction (1.0-FB)	
	RT	"	%	total reactivity inserted when all rods at end position (only if FB = 1.0)	
	FB	"	-	fraction of rods starting from Z = 0. (remainder from Z=HB)	
	TD	"	sec	time delay between power level trip and start of rod motion.	
	AF	"	-	AF•g is acceleration for rod motion	
23/3	SCR	E 11.4	-	PS = PO•SCR is power level at which scram is triggered	
	N	I7	-	number of points in {$\Delta k^*/Z^*$-plane (IV = 2) Δk /XM-plane (IV = 3)	≤ (NYD)
23/4	X	E 11.4	- sec	coordinates of first point } this card is to be repeated as required by parameter N on card 23/3 (maximum number of cards is 17)	= 0.
	Y	"	- %		
	X	"	- sec	" " second "	
	Y	"	- %		
	X	"	- sec	" " third "	
	Y	"	- %		
23/5	SCR	E 11.4	-	PS = PO•SCR is power level at which scram is triggered	
	HT	"	m	length of half wave for $\cos^2$-distribution of reactivity over Z-coordinate (in particular: total reactor height)	

The input cards must be arranged according to the following table.

mode IV =	1	2	3	4
	23/1	23/1	23/1	23/1
		23/2		23/2
		23/3	23/3	
		23/4	23/4	23/4

APPENDIX M : Subroutines and Functions Concerning Coolant Properties: TPE1, HDV, FLAM1, ETA1

Calculations concerning heat transfer to the coolant as well as coolant pressure drop require certain variables, the functional relationships of which are derived from the equations of state of the coolant medium:

$T = f_T(P3, WI)$ ...... temperature $[{}^\circ C]$

$CP = f_{CP}(P3, WI)$ ..... specific heat $[kcal/kg\ {}^\circ C]$

$V = f_V\ (P3, T)$ ..... specific volume $[m^3/kg]$

$\lambda = f_\lambda\ (P3, T)$ ..... thermal conductivity $[kcal/m\ h\ {}^\circ C]$

$\eta = f_\eta\ (V, T)$ ..... dynamic viscosity $[kps/m^2]$

It is convenient to combine the computation of T and CP since

$$CP = \frac{\partial WI}{\partial T}\bigg|_{P3=const}$$

With this the following subprograms are introduced

```
SUBROUTINE  TPE1 (P3, WI, T, CP)
FUNCTION    HDV  (P3, T)
FUNCTION    FLAM1 (P3, T)
FUNCTION    ETA1 (V, T)
```

A particular set of these functions is described below which pertains to superheated steam. In other cases where the coolant may be approximated by an ideal gas the pertinent relations are quite simple:

$$T = a + b \cdot WI$$

$$CP = 1/b$$

$$V = c \cdot \frac{(T-273.16)}{P3}$$

In the case of an incompressible coolant (e.g. liqu. sodium) the last equation can be simplified to:

$$V = const.$$

If - as in the case of liquid sodium - the film coefficient of heat transfer to the coolant is approximately an invariant the values of λ and η are irrelevant and the corresponding functions may consist of simple statements such as

```
FLAM1 = 1.0
ETA1  = 1.0
```

Functions for Superheated Steam

The present analysis puts a premium on computational speed. In contrast to this the development of subprograms for state variables of superheated steam has been guided up to now by considerations of accuracy and range of applicability of a single expression. Using such conventional subprograms [6] it turned out that about 75 % of the computer time needed for a typical transient problem was used by these subprograms alone. Consequently, a new set of subprograms was developed using simpler and faster methods yet having sufficient accuracy for transient problems in concern. The most severe restriction lies with the range of applicability. Using techniques indicated below one may choose position and size of this range with accuracy being a function primarily of the latter. In order to guarantee accuracies better than 1 - 3 % it is necessary to limit the range to pressures between 50 and 200 at.

The technique adopted for generating efficient representations of the functions f_T, f_V, f_λ was least squares fitting of polynomials of varying order in two variables. The functions of [6] were used as reference. In this manner the following expressions were used for the approximation of f_T:

$$T = a_N \cdot WI^N + a_{N+1} \cdot WI^{N+1} + \ldots \quad a_{N+M} \cdot WI^{N+M}$$

$$a_{N+i} = a_{N,K} \cdot P3^K + a_{N,K+1} \cdot P3^{K+1} + \ldots \; a_{N,K+L} \cdot P3^{K+L}$$

where

$i = 0, 1, 2, \ldots. M$

$N,K = -3, -2, \ldots.. +2, +3$

$M,L = 0, 1, \ldots... 5, 6$

The choice of a suitable set of parameters N, M, K, L for the range and order of the polynomials was based on the magnitude of the residue as well as on the magnitude of M and L, i.e. if two approximations had residues of comparable magnitude the favored choice was the polynomial of lower order. The fitting procedure was carried out in two successive steps, first fitting the function at discrete values of one argument (e.g. pressure P3). The coefficients $a_{n(P3)}$ which are obtained from these fits are functions of the pressure P3 known only at a number of discrete points and may be fitted in turn by polynomials in this variable. The specific heat CP can be obtained analytically by differentiation of the polynomial with respect to enthalpy WI and taking the reciprocal.

Corresponding procedures were employed for fitting the other two functions f_V and f_λ .

Extension of the range of applicability to higher enthalpies and temperatures (within the same range of pressure: 50 - 200 at) is possible by taking the following approach (ideal gas):

for $WI > 900$ kcal/kg

$$\text{use} \quad T = T_{(WI=900)} + \frac{WI - 900}{CP_{(WI=900)}}$$

The corresponding relations for specific volume and thermal conductivity are:

for $T > 700$

$$\text{use } V = V_{(T=700)} + \frac{T-700}{P3} \cdot 0.0051$$

$$\text{and } FLAM = FLAM_{(T=700)} + (T-700) \cdot 1.2 \cdot 10^{-4}$$

No least square fitting procedure was necessary with the function f_η since an analytic expression was already available /¯6_7for approximation of this function in a range very nearly identical with the one required in this program.

APPENDIX N : Function ZEIT

With most computer facilities the user has access to the computer clock by way of a subprogram. If this is the case it may be used with the present program to monitor computation time as well as for problem termination. To this purpose the input parameter CLM specifies the maximum computation time allotted to a transient problem. The units of CLM must be the same as the ones used by the clock. In order to avoid excessive time consumption the frequency of clock interrogation may be restricted to every NCL'th step of the integration.

By definition the function ZEIT (CLO) must yield the computer clock reading CL minus the current value of the argument CLO

$$ZEIT = CL - CLO$$

If the computation time for any one transient problem in a job exceeds its allotted time CLM, this problem is terminated, a comment is printed out (C0MPUTING TIME C0NSUMED) and the next problem is started.

If no clock-subprogram is available a dummy function should be supplied, which returns a constant value to the calling program. In this case the parameter CLM is irrelevant.

The function ZEIT is called by the main program REX only and therefore it is not required if subroutine REXION alone is used.

APPENDIX O : Annotated Sample Problem

The sample problem presented in this appendix is taken from a study /¯14_7 of reactivity parameters in conjunction with a steam cooled fast breeder reactor /¯8_7.

The reactor system is represented by two flow sections. The first flow section consists of two (radial) zones, one of them representing an annular bypass around the perimeter of the core, the other representing the radial blanket. The second flow section represents the core with an axial blanket at each end. The core is subdivided into two radial zones and five axial sections. The first radial zone represents the average core channel whereas the second radial zone comprises a single channel only which is identified with the central channel of the core (nominal hot channel). Geometry and properties of this channel are the same as in the average channel, however, the power density is higher (310 vs. 266).

Power release is assumed to be distributed as follows: radial blanket 10 %, axial blankets 2,5 % each, core 85 %. Power is released in the fuel only (no heat sources in cladding, coolant, structure).

No orifices are assumed for the first flow section (FT = 0). Average channel and central channel of the second section (core) are orificed so as to achieve nearly equal exit temperatures for the coolant (i.e. 538.99 vs 548.32 at steady state).

Feedback coefficients and weighting factors were computed as indicated in APPENDIX G. External reactivity was calculated from mode IV = 4 of the function RCBE described in APPENDIX L ($\cos^2$-distribution of reactivity weight, constant rod acceleration). Total reactivity insertion is $-25.00, all rods start from the edge of the core and are accelerated by 2 g. Scram is initiated when power exceeds 25 % of the starting value (2320 MW, nominal reactor power) and rod motion follows after a 100 msec delay.

The reactor transient arises from a rupture of a steam pipe carrying superheated steam from the reactor. Mass flow and pressure transients for this accident were calculated with a different model representing the entire reactor circuit /¯15_7.

Output is printed every 100 steps and indicates the main features of the transient: Scram occurs at X = 0.050 sec, rod motion starts at X = 0.150 sec, full insertion is completed at about 0.38 sec. Total excess reactivity $\Delta k = K + T$ reaches a maximum of about \$ 0.98, peak power is about P_{Max} = 100 000 MW at X_M = 0.18 sec, total energy release (up to X = 1.9 sec) is about 10 500 MWsec.

Maximum fuel temperature rise (nominal hot channel) is about 2678 °C (just below melting point) at X = 0.293 sec. Maximum cladding temperature (nominal hot channel) is about 1317 °C at X = 1.15 sec.

```
1   SYSTEM DATA (SAMPLE PROBLEM, SEE REF.(8) AND REF.(14))
     1   GEOMETRY AND THERMODYN.
              NRB 2                NBF 1                NBA 1                NR  2                NX  5                NN  4
              HC   0.15300E 01     HBF  0.35000E 00     PBF  0.25000E-01     HBA  0.35000E 00     PBA  0.25000E-01
          BYPASS,  IPB=1
              BP   0.10000E 01     R2   0.18000E 01     R3   0.18600E 01     D4   0.85000E-01     WP   0.30000E-01     AN   0.10000E 01
              PB   0.0             HA   0.50000E 00     CV   0.77000E 03     FR   0.19830E-01     FT   0.0
          RAD.BL., IPB=2
              BP   0.0             R2   0.62500E-02     R3   0.71650E-02     D4   0.30000E-02     WP   0.36400E-02     AN   0.20280E 05
              PB   0.10000E 00     HA   0.50000E 00     CV   0.77000E 03     FR   0.19830E-01     FT   0.0
          RAD.CORE ZONE IR=1
              R1   0.31000E-02     R2   0.35000E-02     R3   0.42850E-02     D4   0.30000E-02     WP   0.15800E-02     AN   0.76446E 05
              RCF  0.94000E 04     ROC  0.83500E 04     ROM  0.83500E 04     AFF  0.12000E-04     AFC  0.14000E-04     AFM  0.14000E-04
              COC  0.45390E-02     COM  0.45390E-02     CPC  0.97940E-01     CPM  0.97940E-01     CHC  0.24750E-01     CHM  0.24750E-01
              HGP  0.17917E 01     TM   0.27000E 04     WM   0.62824E 06     FR   0.19830E-01     FT   0.13000E 02
              AOP  0.26600E 03     AQF  0.10000E 01     AOC  0.0             AQS  0.0             AQM  0.0
              ARD  0.10000E 01     ARF  0.10000E 01     ARC  0.10000E 01     ARS  0.10000E 01     ARM  0.10000E 01
              AX.BL. -ENTRANCE     HFS  0.50000E 00     CVF  0.77000E 03     HMS  0.20000E 01     CVM  0.81780E 03
              AX.BL.      -EXIT    HFS  0.50000E 00     CVF  0.77000E 03     HMS  0.20000E 01     CVM  0.81780E 03
          RAD.CORE ZONE IR=2
              R1   0.31000E-02     R2   0.35000E-02     R3   0.42850E-02     D4   0.30000E-02     WP   0.15800E-02     AN   0.10000E 01
              ROF  0.94000E 04     ROC  0.83500E 04     ROM  0.83500E 04     AFF  0.12000E-04     AFC  0.14000E-04     AFM  0.14000E-04
              COC  0.45390E-02     COM  0.45390E-02     CPC  0.97940E-01     CPM  0.97940E-01     CHC  0.24750E-01     CHM  0.24750E-01
              HGP  0.17917E 01     TM   0.27000E 04     WM   0.62824E 06     FR   0.19830E-01     FT   0.60000E 01
              AOP  0.31000E 03     AQF  0.10000E 01     AOC  0.0             AOS  0.0             AOM  0.0
              ARD  0.10000E 01     ARF  0.10000E 01     ARC  0.10000E 01     ARS  0.10000E 01     ARM  0.10000E 01
              AX.BL. -ENTRANCE     HFS  0.50000E 00     CVF  0.77000E 03     HMS  0.20000E 01     CVM  0.81780E 03
              AX.BL.      -EXIT    HFS  0.50000E 00     CVF  0.77000E 03     HMS  0.20000E 01     CVM  0.81780E 03
          AX.CORE ZONE  IX=1
              AOX  0.94940E 00     AXD  0.15790E 01     AXF  0.25600E 01     AXC  0.20670E 00     AXS  0.49400E 00     AXM  0.53260E 00
          AX.CORE ZONE  IX=2
              AOX  0.15980E 01     AXD  0.43810E 01     AXF  0.60050E 01     AXC  0.74900E 00     AXS  0.20000E 01     AXM  0.12438E 01
          AX.CORE ZONE  IX=3
              AOX  0.18383E 01     AXD  0.56840E 01     AXF  0.80800E 01     AXC  0.10365E 01     AXS  0.32170E 01     AXM  0.16620E 01
          AX.CORE ZONE  IX=4
              AOX  0.15980E 01     AXD  0.43010E 01     AXF  0.67180E 01     AXC  0.78750E 00     AXS  0.28120E 01     AXM  0.13738E 01
          AX.CORE ZONE  IX=5
              AOX  0.94940E 00     AXD  0.16440E 01     AXF  0.32300E 01     AXC  0.24910E 00     AXS  0.10150E 01     AXM  0.67250E 00
          EXPONENTS FOR HEAT TRANSFER RELATION
              AL1  0.80000E 00     AL2  0.60000E 00     AL3  0.57500E 00     AL4  0.0
     2   TEMP.DEP.FUEL PROPERTIES
              CK1  0.13882E 01     CK2  0.0             CK3  0.0
              CC1  0.81940E-01     CC2  0.0             CC3  0.0
     3   POINT KINETICS AND CONTROLLED REACTIVITY
              OM   0.73150E 04     ND  6
              FY   0.24500E-01     LA   0.12700E-01     FY   0.22400E 00     LA   0.30100E-01     FY   0.18860E 00     LA   0.12400E 00
              FY   0.35470E 00     LA   0.32500E 00     FY   0.14970E 00     LA   0.11120E 01     FY   0.58500E-01     LA   0.26970E 01
              CONTR.REACT.PROGR.NO.4
              HR   0.13700E 01     HB   0.35000E 00     RT  -0.25000E 02     FB   0.0             TD   0.10000E 00     AF   0.20000E 01
              SCP  0.12500E 01     HT   0.22300E 01
     4   FEEDBACK PARAMETERS
              RCD -0.33255E 01     RCH  0.20900E 02     RCR  0.0             RCF  0.82640E 02     RCC -0.94097E 02     RCS -0.29632E 00
              RCM  0.17040E 03     RC   0.10000E 01
     5   ITERATION AND OUTPUT VOLUME CONTROL
              EST  0.10000E 01     EV   0.10000E-01     ETC  0.10000E-01     ETM  0.10000E-01     EP   0.10000E-01
              IPR    1   2   1     IR     1   2   1     IX     1   5   1     IP1    0   0   0     IX1    0   0   0     IN     0   0   0
     6   STEP AND TERMINATION CONTROL
              NTE  10              NCX     900
              XMA  0.18999E 01     XIN  0.10000E-05     XIX  0.50000E 00     PIN  0.10000E-01     PIX  0.50000E-01
     7   NOT USED
     8   END OF SYSTEM DATA
2    INLET ENTHALPY
              NY    2
              X    0.0             Y    0.65500E 03     X    0.60000E 02     Y    0.65500E 03     X
3    BOUNDARY CONDITION
              IBC 2
4    PRESSURE
              NY  10
              X    0.0             Y    0.17000E 03     X    0.20000E-01     Y    0.17000E 03     X    0.40000E-01     Y    0.16977E 03
              X    0.60000E-01     Y    0.16944E 03     X    0.20000E 00     Y    0.16588E 03     X    0.34000E 00     Y    0.16293E 03
              X    0.80000E 00     Y    0.15478E 03     X    0.11000E 01     Y    0.15032E 03     X    0.14000E 01     Y    0.14640E 03
              X    0.19000E 01     Y    0.14070E 03     X
6    MASS FLOW
              NY  10
              X    0.0             Y    0.35000E 04     X    0.20000E-01     Y    0.33600E 04     X    0.10000E 00     Y    0.26200E 04
              Y    0.32000E 00     Y    0.10850E 04     X    0.40000E 00     Y    0.59600E 03     X    0.45000E 00     Y    0.45400E 03
              X    0.86000E 00     Y    0.74000E 03     X    0.10800E 01     Y    0.87300E 03     X    0.15600E 01     Y    0.11970E 04
              X    0.19000E 01     Y    0.12270E 04     X
7    INITIAL POWER
              PO   0.23200E 04
8    OUTPUT CONTROL AND START
              NPR      100         NCL     5000         CLM  0.10000E 02
```

```
STEADY STATE FEEDBACK= $ -0.43643280E 02

  X 0.0           I 0.7071E-02 P 0.2320E 04 E 0.0          T 0.0             PFX  182.64  PAX  170.00  WFX  655.00  WAX  813.35 G 0.3500E 04
 FEEDBACK         K 0.0        D-0.2368E 02 H 0.2289E 00 R 0.0           F-0.9544E 00 C 0.6820E 00 S-0.1884E 02 M-0.1081E 01
  IRB=1             TFB  376.16  TAB  376.01  WFB  655.00  WAB  655.00  PFB  181.61  PAB  181.36  TFB  376.09  TMB  376.09 N 0.3674E 04
  IRB=2             TFB  376.68  TAB  419.45  WFB  655.00  WAB  712.40  PFB  182.52  PAB  181.36  TFB  460.48  TMB  398.06 N 0.1235E 04
                     TZ  385.72   PZ  181.36   WZ  670.83
   IR=1             TF1  382.96  TA1  385.25  TA2  538.99  PF1  176.63  PA1  175.91  PA2  170.00  TF1  431.20  TF2  583.41 N 0.2385E 04
          IX= 1     TFO  890.19  TFN  507.43  TC1  428.41  TC2  416.69   TM  392.09   TA  398.93   WA  693.22   PA  175.19 V 0.1269E-01
          IX= 2     TFO 1259.24  TFN  614.98  TC1  481.98  TC2  462.25   TM  413.15   TA  427.37   WA  724.25   PA  174.34 V 0.1459E-01
          IX= 3     TFO 1430.81  TFN  689.67  TC1  536.66  TC2  513.97   TM  447.41   TA  467.45   WA  759.94   PA  173.38 V 0.1669E-01
          IX= 4     TFO 1348.15  TFN  703.90  TC1  570.89  TC2  551.16   TM  487.61   TA  507.77   WA  790.96   PA  172.33 V 0.1847E-01
          IX= 5     TFO 1033.01  TFN  650.24  TC1  571.22  TC2  559.50   TM  520.70   TA  533.63   WA  809.39   PA  171.24 V 0.1958E-01
   IR=2             TF1  383.97  TA1  386.28  TA2  548.32  PF1  178.34  PA1  177.45  PA2  170.00  TF1  440.01  TF2  600.41 N 0.2662E 04
          IX= 1     TFO  971.57  TFN  525.49  TC1  433.40  TC2  419.74   TM  393.41   TA  400.54   WA  694.21   PA  176.55 V 0.1264E-01
          IX= 2     TFO 1397.18  TFN  646.35  TC1  491.35  TC2  468.36   TM  415.48   TA  430.42   WA  726.59   PA  175.49 V 0.1463E-01
          IX= 3     TFO 1591.98  TFN  728.25  TC1  549.94  TC2  523.49   TM  451.59   TA  472.75   WA  763.84   PA  174.28 V 0.1681E-01
          IX= 4     TFO 1491.44  TFN  740.61  TC1  585.61  TC2  562.62   TM  494.08   TA  515.40   WA  796.23   PA  172.95 V 0.1868E-01
          IX= 5     TFO 1122.61  TFN  676.53  TC1  584.44  TC2  570.78   TM  529.06   TA  542.73   WA  815.47   PA  171.57 V 0.1987E-01
                                              NC=       0   CL=    0.0  PFX  182.64  PAX  170.00  WEX  655.00  WAX  813.35 G 0.3500E 04

  SPCAM AT X=   0.5015919E-01
  X 0.1328E 00 I 0.4419E-03 P 0.3821E 05 E 0.8935E 03 T 0.0             PFX  173.84  PAX  167.60  WFX  655.00  WAX  821.70 G 0.2394E 04
 FEEDBACK         K 0.9416E 00 D-0.1280E 00 H 0.1098E-01 R 0.0           F-0.4790E-01 C 0.1745E-01 S 0.1089E 01 M-0.4694E-03
  IRB=1             TFB  371.20  TAB  371.14  WFB  655.00  WAB  655.03  PFB  173.32  PAB  173.20  TFB  376.07  TMB  376.07 N 0.2517E 04
  IRB=2             TFB  371.49  TAB  422.44  WFB  655.00  WAB  720.02  PFB  173.78  PAB  173.20  TFB  463.75  TMB  398.02 N 0.8411E 03
                     TZ  382.26   PZ  173.20   WZ  672.87
   IR=1             TF1  380.84  TA1  384.54  TA2  550.80  PF1  170.88  PA1  170.53  PA2  167.61  TF1  435.60  TF2  588.05 N 0.1631E 04
          IX- 1     TFO  920.56  TFN  534 46  TC1  434.57  TC2  422.70   TM  392.09   TA  401.60   WA  699.80   PA  170.17 V 0.1348E-01
          IX= 2     TFO 1310.36  TFN  660.96  TC1  494.01  TC2  474.57   TM  413.26   TA  435.24   WA  733.98   PA  169.74 V 0.1556E-01
          IX= 3     TFO 1489.62  TFN  742.89  TC1  551.68  TC2  529.76   TM  447.63   TA  480.21   WA  771.51   PA  169.26 V 0.1774E-01
          IX= 4     TFO 1399.28  TFN  750.39  TC1  584.79  TC2  566.07   TM  487.89   TA  522.68   WA  802.53   PA  168.75 V 0.1950E-01
          IX= 5     TFO 1063.38  TFN  678.14  TC1  580.52  TC2  569.81   TM  520.98   TA  546.41   WA  818.77   PA  168.22 V 0.2045E-01
   IR=2             TF1  381.36  TA1  385.29  TA2  562.43  PF1  ~~171.72  PA1  171.28  PA2  167.61  TF1  445.14  TF2  605.82 N 0.1816E 04~~
          IX= 1     TFO 1006.96  TFN  556.95  TC1  440.44  TC2  426.56   TM  393.41   TA  403.47   WA  701.47   PA  170.83 V 0.1352E-01
          IX= 2     TFO 1456.77  TFN  699.93  TC1  505.31  TC2  482.63   TM  415.67   TA  439.42   WA  737.48   PA  170.30 V 0.1571E-01
          IX= 3     TFO 1660.53  TFN  790.28  TC1  567.45  TC2  541.89   TM  451.86   TA  487.52   WA  776.91   PA  169.70 V 0.1799E-01
          IX= 4     TFO 1551.03  TFN  794.81  TC1  601.87  TC2  580.06   TM  494.43   TA  532.82   WA  809.41   PA  169.04 V 0.1984E-01
          IX= 5     TFO 1158.01  TFN  709.08  TC1  595.41  TC2  582.97   TM  529.41   TA  557.82   WA  826.26   PA  168.37 V 0.2084E-01
                                              NC=     100   CL=    0.0  PFX  173.84  PAX  167.59  WFX  655.00  WAX  821.70 G 0.2391E 04
  X 0.1914E 00 I 0.8839E-03 P 0.1070E 06 E 0.5445E 04 T-0.2533E 00   PFX  170.64  PAX  166.12  WFX  655.00  WAX  836.33 G 0.1989E 04
 FEEDBACK         K 0.1222E 01 D-0.9346E 00 H 0.9103E-01 R 0.0           F-0.3971E 00 C 0.8509E-01 S 0.2380E 01 M-0.1553E-02
  IRB=1             TFB  369.28  TAB  369.25  WFB  655.00  WAB  655.05  PFB  170.28  PAB  170.19  TFB  376.04  TMB  376.05 N 0.2099E 04
  IRB=2             TFB  369.49  TAB  432.23  WFB  655.00  WAB  730.99  PFB  170.60  PAB  170.19  TFB  488.29  TMB  398.02 N 0.6918E 03
                     TZ  382.32   PZ  170.19   WZ  675.65
   IR=1             TF1  381.33  TA1  387.90  TA2  573.81  PF1  168.54  PA1  168.29  PA2  166.15  TF1  468.47  TF2  621.39 N 0.1355E 04
          IX= 1     TFO 1146.50  TFN  710.08  TC1  467.78  TC2  445.39   TM  392.19   TA  411.81   WA  712.24   PA  168.02 V 0.1441E-01
          IX= 2     TFO 1690.66  TFN  957.42  TC1  552.21  TC2  515.84   TM  413.56   TA  456.43   WA  753.23   PA  167.70 V 0.1687E-01
          IX= 3     TFO 1927.11  TFN 1084.63  TC1  620.65  TC2  579.94   TM  448.13   TA  511.09   WA  794.83   PA  167.34 V 0.1924E-01
          IX= 4     TFO 1779.58  TFN 1047.99  TC1  646.31  TC2  611.78   TM  488.51   TA  556.55   WA  825.75   PA  166.96 V 0.2099E-01
          IX= 5     TFO 1289.31  TFN  855.60  TC1  618.98  TC2  599.53   TM  521.57   TA  573.59   WA  836.86   PA  166.58 V 0.2166E-01
   IR=2             TF1  381.71  TA1  388.88  TA2  590.36  PF1  169.15  PA1  168.83  PA2  166.14  TF1  483.44  TF2  644.70 N 0.1500E 04
          IX= 1     TFO 1270.28  TFN  761.54  TC1  478.89  TC2  452.66   TM  393.52   TA  415.25   WA  715.47   PA  168.50 V 0.1457E-01
          IX= 2     TFO 1899.97  TFN 1045.37  TC1  572.94  TC2  530.46   TM  415.98   TA  464.26   WA  759.43   PA  168.10 V 0.1718E-01
          IX= 3     TFO 2170.39  TFN 1188.54  TC1  647.71  TC2  600.20   TM  452.47   TA  524.09   WA  803.81   PA  167.65 V 0.1970E-01
          IX= 4     TFO 1994.23  TFN 1141.66  TC1  673.56  TC2  633.33   TM  495.20   TA  573.20   WA  836.48   PA  167.17 V 0.2156E-01
          IX= 5     TFO 1421.32  TFN  915.97  TC1  640.42  TC2  617.87   TM  530.16   TA  590.52   WA  847.59   PA  166.69 V 0.2225E-01
                                              NC=     200   CL=    0.0  PFX  170.64  PAX  166.10  WFX  655.00  WAX  836.33 G 0.1983E 04
  X 0.2598E 00 I 0.4419E-03 P 0.1098E 05 E 0.9948E 04 T-0.2779E 01   PFX  167.51  PAX  164.63  WFX  655.00  WAX  878.11 G 0.1508E 04
 FEEDBACK         K 0.3218E 01 D-0.1530E 01 H 0.1640E 00 R 0.0           F-0.7156E 00 C 0.2522E 00 S 0.5053E 01 M-0.5804E-02
  IRB=1             TFB  367.34  TAB  367.36  WFB  655.00  WAB  655.09  PFB  167.29  PAB  167.24  TFB  376.02  TMB  376.03 N 0.1603E 04
  IRB=2             TFB  367.47  TAB  458.22  WFB  655.00  WAB  754.89  PFB  167.48  PAB  167.24  TFB  511.88  TMB  398.13 N 0.5136E 03
                     TZ  384.88   PZ  167.24   WZ  681.64
   IR=1             TF1  384.28  TA1  397.41  TA2  640.23  PF1  166.25  PA1  166.09  PA2  164.64  TF1  499.56  TF2  654.22 N 0.1027E 04
          IX= 1     TFO 1366.90  TFN  815.30  TC1  538.57  TC2  509.43   TM  392.72   TA  446.85   WA  745.98   PA  165.90 V 0.1663E-01
          IX= 2     TFO 2061.64  TFN 1137.22  TC1  679.00  TC2  633.00   TM  414.77   TA  530.67   WA  808.85   PA  165.68 V 0.2021E-01
          IX= 3     TFO 2353.88  TFN 1293.66  TC1  772.37  TC2  721.88   TM  450.07   TA  619.16   WA  865.64   PA  165.43 V 0.2346E-01
          IX= 4     TFO 2150.55  TFN 1231.48  TC1  783.29  TC2  741.69   TM  490.90   TA  672.15   WA  897.97   PA  165.16 V 0.2538E-01
          IX= 5     TFO 1509.71  TFN  966.86  TC1  707.01  TC2  685.34   TM  523.79   TA  664.28   WA  893.24   PA  164.91 V 0.2514E-01
   IR=2             TF1  384.52  TA1  399.20  TA2  671.13  PF1  166.63  PA1  166.44  PA2  164.64  TF1  519.66  TF2  683.03 N 0.1120E 04
          IX= 1     TFO 1527.13  TFN  883.91  TC1  560.88  TC2  526.59   TM  394.15   TA  455.45   WA  753.04   PA  166.21 V 0.1701E-01
          IX= 2     TFO 2332.31  TFN 1254.72  TC1  720.23  TC2  666.42   TM  417.45   TA  550.94   WA  822.31   PA  165.94 V 0.2093E-01
          IX= 3     TFO 2667.75  TFN 1432.00  TC1  824.10  TC2  765.06   TM  454.88   TA  650.99   WA  885.06   PA  165.62 V 0.2456E-01
          IX= 4     TFO 2426.58  TFN 1355.51  TC1  833.22  TC2  784.74   TM  498.21   TA  709.05   WA  920.31   PA  165.29 V 0.2662E-01
          IX= 5     TFO 1678.18  TFN 1045.90  TC1  743.76  TC2  718.81   TM  532.99   TA  698.12   WA  913.73   PA  164.98 V 0.2633E-01
                                              NC=     300   CL=    0.0  PFX  167.51  PAX  164.62  WFX  655.00  WAX  878.11 G 0.1505E 04
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 X 0.3040E 00 I 0.4419E-03 P 0.1485E 04 F 0.1014E 05 T-0.7713E 01  PEX  165.63  PAX  163.70  WEX  655.00  WAX  901.45 G 0.1199E 04
FEEDBACK       K 0.4602E 01 D-0.1513E 01 H 0.1618E 00 R 0.0          F-0.7059E 00 C 0.3371E 00 S 0.6332E 01 M-0.1075E-01
 IRB=1          TEB  366.15  TAB  366.19  WEB  655.00  WAB  655.12  PEB  165.49  PAB  165.46  TFB  375.99  TMB  376.00 N 0.1281E 04
 IRB=2          TEB  366.23  TAB  477.58  WEB  655.00  WAB  770.87  PEB  165.62  PAB  165.46  TFB  512.05  TMB  398.30 N 0.4033E 03
                 TZ  386.75   PZ  165.46   WZ  685.52
  IP=1          TE1  386.37  TA1  403.26  TA2  678.12  PE1  164.82  PA1  164.71  PA2  163.71  TF1  499.21  TF2  655.99 N 0.8172E 03
       IX= 1    TFO 1371.21  TFN  786.98  TC1  567.89  TC2  543.30   TM  393.31   TA  470.24   WA  765.53   PA  164.58 V 0.1790E-01
       IX= 2    TFO 2068.90  TFN 1092.71  TC1  734.69  TC2  696.89   TM  416.12   TA  582.52   WA  843.00   PA  164.42 V 0.2230E-01
       IX= 3    TFO 2362.24  TFN 1244.89  TC1  841.34  TC2  800.66   TM  452.33   TA  693.43   WA  911.00   PA  164.24 V 0.2629E-01
       IX= 4    TFO 2157.82  TFN 1191.37  TC1  848.53  TC2  816.14   TM  493.71   TA  749.67   WA  945.07   PA  164.06 V 0.2809E-01
       IX= 5    TFO 1514.03  TFN  946.08  TC1  752.96  TC2  737.77   TM  526.38   TA  725.35   WA  930.37   PA  163.89 V 0.2737E-01
  IP=2          TE1  386.53  TA1  405.59  TA2  716.51  PE1  165.07  PA1  164.94  PA2  163.71  TF1  519.23  TF2  685.16 N 0.8856E 03
       IX= 1    TFO 1532.16  TFN  850.68  TC1  594.57  TC2  565.69   TM  394.84   TA  482.05   WA  774.50   PA  164.79 V 0.1839E-01
       IX= 2    TFO 2340.79  TFN 1202.65  TC1  784.68  TC2  740.36   TM  419.10   TA  610.73   WA  860.59   PA  164.59 V 0.2329E-01
       IX= 3    TFO 2677.49  TFN 1374.96  TC1  903.97  TC2  856.27   TM  457.70   TA  735.70   WA  936.57   PA  164.37 V 0.2761E-01
       IX= 4    TFO 2435.05  TFN 1308.75  TC1  909.09  TC2  871.23   TM  501.76   TA  798.58   WA  974.68   PA  164.14 V 0.2960E-01
       IX= 5    TFO 1683.21  TFN 1021.98  TC1  797.91  TC2  780.53   TM  536.28   TA  769.11   WA  956.85   PA  163.93 V 0.2872E-01
                                           NC=    400  CL=    0.0  PEX  165.63  PAX  163.69  WEX  655.00  WAX  901.45 G 0.1196E 04
 X 0.3615E 00 I 0.8839E-03 P 0.3823E 03 F 0.1018E 05 T-0.1998E 02  PEX  163.57  PAX  162.56  WEX  655.00  WAX  915.05 G 0.8368E 03
FEEDBACK       K 0.5771E 01 D-0.1475E 01 H 0.1568E 00 R 0.0          F-0.6842E 00 C 0.4197E 00 S 0.7372E 01 M-0.1831E-01
 IRB=1          TEB  364.80  TAB  364.89  WEB  655.00  WAB  655.18  PEB  163.50  PAB  163.48  TFB  375.97  TMB  375.98 N 0.8987E 03
 IRB=2          TEB  364.85  TAB  502.87  WEB  655.00  WAB  790.16  PEB  163.56  PAB  163.48  TFB  511.28  TMB  398.65 N 0.2773E 03
                 TZ  389.15   PZ  163.48   WZ  690.08
  IP=1          TE1  389.00  TA1  411.67  TA2  699.98  PE1  163.16  PA1  163.10  PA2  162.58  TF1  497.37  TF2  657.72 N 0.5702E 03
       IX= 1    TFO 1366.51  TFN  772.18  TC1  595.69  TC2  575.89   TM  394.17   TA  495.76   WA  785.20   PA  163.03 V 0.1920E-01
       IX= 2    TFO 2061.01  TFN 1072.43  TC1  788.12  TC2  757.98   TM  418.15   TA  637.22   WA  877.12   PA  162.95 V 0.2449E-01
       IX= 3    TFO 2353.16  TFN 1225.20  TC1  908.46  TC2  876.57   TM  455.79   TA  767.15   WA  955.80   PA  162.85 V 0.2886E-01
       IX= 4    TFO 2149.93  TFN 1178.15  TC1  913.53  TC2  888.87   TM  498.07   TA  825.86   WA  991.33   PA  162.76 V 0.3072E-01
       IX= 5    TFO 1509.33  TFN  943.57  TC1  801.04  TC2  790.73   TM  530.35   TA  783.19   WA  965.53   PA  162.67 V 0.2940E-01
  IP=2          TE1  389.08  TA1  415.03  TA2  742.93  PE1  163.29  PA1  163.22  PA2  162.58  TF1  517.05  TF2  687.28 N 0.6148E 03
       IX= 1    TFO 1526.69  TFN  833.16  TC1  626.63  TC2  603.37   TM  395.86   TA  511.38   WA  796.27   PA  163.14 V 0.1982E-01
       IX= 2    TFO 2331.59  TFN 1178.66  TC1  846.29  TC2  810.86   TM  421.58   TA  673.58   WA  899.15   PA  163.04 V 0.2578E-01
       IX= 3    TFO 2666.91  TFN 1351.64  TC1  981.44  TC2  943.90   TM  462.01   TA  820.42   WA  988.02   PA  162.92 V 0.3052E-01
       IX= 4    TFO 2425.85  TFN 1293.19  TC1  984.42  TC2  955.54   TM  507.25   TA  886.19   WA 1027.83   PA  162.80 V 0.3260E-01
       IX= 5    TFO 1677.74  TFN 1019.46  TC1  854.50  TC2  842.75   TM  541.32   TA  836.09   WA  997.53   PA  162.69 V 0.3105E-01
                                           NC=    500  CL=    0.0  PEX  163.57  PAX  162.55  WEX  655.00  WAX  915.05 G 0.8314E 03
 X 0.9422E 00 I 0.7071E-02 P 0.2414E 03 F 0.1034E 05 T-0.2416E 02  PEX  153.83  PAX  152.77  WEX  655.00  WAX  997.60 G 0.7854E 03
FEEDBACK       K 0.9022E 01 D-0.1264E 01 H 0.1303E 00 R 0.0          F-0.5674E 00 C 0.7345E 00 S 0.1011E 02 M-0.1259E 00
 IRB=1          TEB  357.90  TAB  358.31  WEB  655.00  WAB  655.72  PEB  153.76  PAB  153.74  TFB  375.78  TMB  375.90 N 0.8530E 03
 IRB=2          TEB  357.95  TAB  569.31  WEB  655.00  WAB  836.91  PEB  153.82  PAB  153.74  TFB  506.55  TMB  406.17 N 0.2518E 03
                 TZ  392.62   PZ  153.74   WZ  701.19
  IP=1          TE1  392.37  TA1  420.47  TA2  838.54  PE1  153.42  PA1  153.37  PA2  152.76  TF1  481.68  TF2  695.51 N 0.5351E 03
       IX= 1    TFO 1295.42  TFN  780.65  TC1  688.43  TC2  673.86   TM  405.13   TA  567.56   WA  835.91   PA  153.29 V 0.2351E-01
       IX= 2    TFO 1942.08  TFN 1115.94  TC1  978.88  TC2  958.10   TM  445.82   TA  803.46   WA  978.83   PA  153.19 V 0.3197E-01
       IX= 3    TFO 2216.97  TFN 1304.95  TC1 1164.66  TC2 1144.29   TM  505.47   TA 1015.23   WA 1106.34   PA  153.08 V 0.3905E-01
       IX= 4    TFO 2032.18  TFN 1289.21  TC1 1191.81  TC2 1179.23   TM  560.82   TA 1112.07   WA 1164.66   PA  152.96 V 0.4231E-01
       IX= 5    TFO 1440.23  TFN 1068.06  TC1 1045.13  TC2 1045.08   TM  587.35   TA 1044.68   WA 1124.09   PA  152.85 V 0.4009E-01
  IP=2          TE1  392.46  TA1  424.53  TA2  909.09  PE1  153.56  PA1  153.49  PA2  152.76  TF1  498.24  TF2  732.48 N 0.5677E 03
       IX= 1    TFO 1443.79  TFN  841.27  TC1  732.74  TC2  715.57   TM  408.84   TA  592.64   WA  851.53   PA  153.41 V 0.2445E-01
       IX= 2    TFO 2192.93  TFN 1225.39  TC1 1063.38  TC2 1038.70   TM  455.22   TA  858.83   WA 1012.16   PA  153.29 V 0.3379E-01
       IX= 3    TFO 2508.14  TFN 1439.20  TC1 1272.57  TC2 1248.15   TM  523.46   TA 1100.32   WA 1157.57   PA  153.14 V 0.4186E-01
       IX= 4    TFO 2288.61  TFN 1419.96  TC1 1304.60  TC2 1289.48   TM  585.40   TA 1212.53   WA 1225.14   PA  153.00 V 0.4565E-01
       IX= 5    TFO 1597.28  TFN 1166.11  TC1 1139.87  TC2 1139.81   TM  612.76   TA 1138.09   WA 1180.32   PA  152.87 V 0.4320E-01
                                           NC=    600  CL=    0.0  PEX  153.83  PAX  152.67  WEX  655.00  WAX  997.60 G 0.7897E 03
 X 0.1649E 01 I 0.7071E-02 P 0.1774E 03 F 0.1049E 05 T-0.2416E 02  PEX  145.96  PAX  143.64  WEX  655.00  WAX 1065.22 G 0.1136E 04
FEEDBACK       K 0.8905E 01 D-0.1062E 01 H 0.1071E 00 R 0.0          F-0.4641E 00 C 0.6551E 00 S 0.9950E 01 M-0.2810E 00
 IRB=1          TEB  351.86  TAB  352.26  WEB  655.00  WAB  655.72  PEB  145.82  PAB  145.78  TFB  375.45  TMB  375.78 N 0.1228E 04
 IRB=2          TEB  351.97  TAB  539.26  WEB  655.00  WAB  819.64  PEB  145.95  PAB  145.78  TFB  500.12  TMB  412.96 N 0.3690E 03
                 TZ  383.76   PZ  145.78   WZ  697.39
  IP=1          TE1  383.25  TA1  401.71  TA2  946.46  PE1  145.09  PA1  144.97  PA2  143.63  TF1  463.46  TF2  765.22 N 0.7740E 03
       IX= 1    TFO 1191.42  TFN  706.84  TC1  612.88  TC2  597.29   TM  416.90   TA  508.48   WA  799.66   PA  144.83 V 0.2257E-01
       IX= 2    TFO 1772.44  TFN 1022.65  TC1  881.56  TC2  858.05   TM  480.62   TA  710.72   WA  924.19   PA  144.63 V 0.3066E-01
       IX= 3    TFO 2026.87  TFN 1228.73  TC1 1083.92  TC2 1059.75   TM  572.65   TA  919.60   WA 1049.46   PA  144.38 V 0.3810E-01
       IX= 4    TFO 1873.24  TFN 1268.05  TC1 1166.31  TC2 1149.22   TM  654.30   TA 1060.93   WA 1134.19   PA  144.12 V 0.4317E-01
       IX= 5    TFO 1354.60  TFN 1128.13  TC1 1106.14  TC2 1102.45   TM  686.97   TA 1078.58   WA 1144.78   PA  143.87 V 0.4387E-01
  IP=2          TE1  383.45  TA1  403.85  TA2 1027.22  PE1  145.38  PA1  145.25  PA2  143.63  TF1  476.70  TF2  813.89 N 0.8227E 03
       IX= 1    TFO 1322.23  TFN  754.31  TC1  644.16  TC2  625.90   TM  422.40   TA  524.07   WA  809.95   PA  145.07 V 0.2319E-01
       IX= 2    TFO 1994.64  TFN 1113.52  TC1  947.23  TC2  919.52   TM  495.96   TA  750.43   WA  947.98   PA  144.84 V 0.3202E-01
       IX= 3    TFO 2285.84  TFN 1343.75  TC1 1171.52  TC2 1142.77   TM  603.06   TA  984.37   WA 1088.27   PA  144.55 V 0.4034E-01
       IX= 4    TFO 2103.03  TFN 1388.30  TC1 1266.20  TC2 1245.62   TM  696.95   TA 1145.44   WA 1184.85   PA  144.23 V 0.4612E-01
       IX= 5    TFO 1497.82  TFN 1231.35  TC1 1203.46  TC2 1198.63   TM  733.14   TA 1170.01   WA 1199.58   PA  143.92 V 0.4710E-01
                                           NC=    700  CL=    0.0  PEX  145.96  PAX  143.56  WEX  655.00  WAX 1065.22 G 0.1138E 04
END OF TRANSIENT,   NC=   736 X= 0.19037781E 01
 9    END OF THIS PROBLEM
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