EUR 4673 e

COMMISSION OF THE EUROPEAN COMMUNITIES

COSTANZA (R, Z)

by

E. VINCENTI and A. CLUSAZ

1971

Joint Nuclear Research Centre
Ispra Establishment - Italy

Nuclear Studies Division

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Fuel elements of prismatic shape are considered. Up to 6 groups of delayed neutrons are allowed.

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Inlet temperatures and mass flow in the coolant channels may be varied according to any externally given time table.

Before starting the transient initial calculations put the reactor in criticality conditions at a given power level in equilibrium with the temperature feedback.

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ABSTRACT

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Before starting the transient initial calculations put the reactor in criticality conditions at a given power level in equilibrium with the temperature feedback.

KEYWORDS

FORTRAN
2-DIMENSIONAL CALCULATIONS
CYLINDERS
PROGRAMMING
NEUTRON DIFFUSION EQUATION
HEAT TRANSFER
CANNING
COOLANTS
FUEL PINS
FORCED CONVECTION
TEMPERATURE COEFFICIENT
DOPPLER REACTIVITY
POWER COEFFICIENT
CRITICALITY

Contents:

Purpose *)

The code COSTANZA (R,Z) treats the dynamics of a cylindrical nuclear reactor. Two geometrical dymensions: radius R and hight Z are considered, in the supposition that there is an axial symmetry.
The nuclear time dependent diffusion equations, in two energy groups are solved numerically with the finite-difference approxiamtion.
The heat transfer equation from heating element to coolant in the channel are also solved numerically.
The geometry of the heating element can be of any type, because the element is characterized by thermal resistances and thermal capacities given in input.
Flow rates and inlet temperatures of coolant are externally imposed as input function of time.
The coolant is a single phase fluid which may be liquid or gas, and is not supposed to boil or condense during the transient.
This code has been developed to treat accidents of intermediate gravity in which detailed spatial aspects of the phenomena are essential, but which are not so grave as to produce alterations or damages of the core lattice, or changements of the state in the coolant.

Subdivision of the reactor

The reactor is supposed to be cylindrical with axial symmetry. Therefore only a vertical section of it

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*) Manuscript received on March 15, 1971

will be considered. (Fig.1). This section is a rectangular surface limited by the axis of the cylinder at one side and by the extrapolated boundary of the reactor at the other three sides. This area is subdivided with a cartesian point-lattice. In the radial direction the points may be arbitrarily spaced. In the axial direction the points are located at equal intervals within the core and they may be arbitrarily distributed in the upper and lower reflector. Within the core the axial point lattice is the same for neutronic and thermal calculations.

The outer points are located at the extrapolate boundaries of the reactor. The first two vertical arrays of points are located simmetrically to the axis of the cylinder to obtain the condition of zero space derivative at the axis. The lattice may have a maximum of 400 points, product of the radial and axial points. The radial and axial points cannot be more than 40 each. In Fig. 1 is a point-lattice of 12 axial x 10 radial = 120 points. The core may be subdivided in a maximum number of 30 regions having different core compositions; their boundaries are defined by points of the lattice. The initial criticality condition may be obtained by diffused poison or by the insertion of control rods.

Each region contains a uniformly distributed poison, whose concentration may be varied for criticality search to obtain the initial equilibrium condition, but will remain constant during the transient.
The core is also subdivided in vertical control zones. There can be a maximum number of 10 control zones. They have the same height of the reactor, including top and bottom reflectors if existing. Each zone contains control rods which move in vertical direction independently from the rods of the other zones. Each zone is also characterized by a certain type of cooling channel which may be different from those of the other zones. The coolant and the rods may enter into the core from apposite sides (rod from top and coolant from bottom or viceversa) or they may enter from the same side. Conventionally we assume that the coolant inlet is at the top and the points of the lattice are numerated starting from the top left along the radii down to the bottom right. The entrance side of the rods will be indicated in input.
The vertical boundaries of the control zones are defined by points of the lattice. They may not coincide with the vertical boundaries of the composition regions.
Fig. 1 indicates 5 regions, the first of which includes the top, bottom and radial reflector considered all of the same composition in this case; regions 2,3,4,5 belong to the core. Two vertical central zones (I,II) contain the rods.

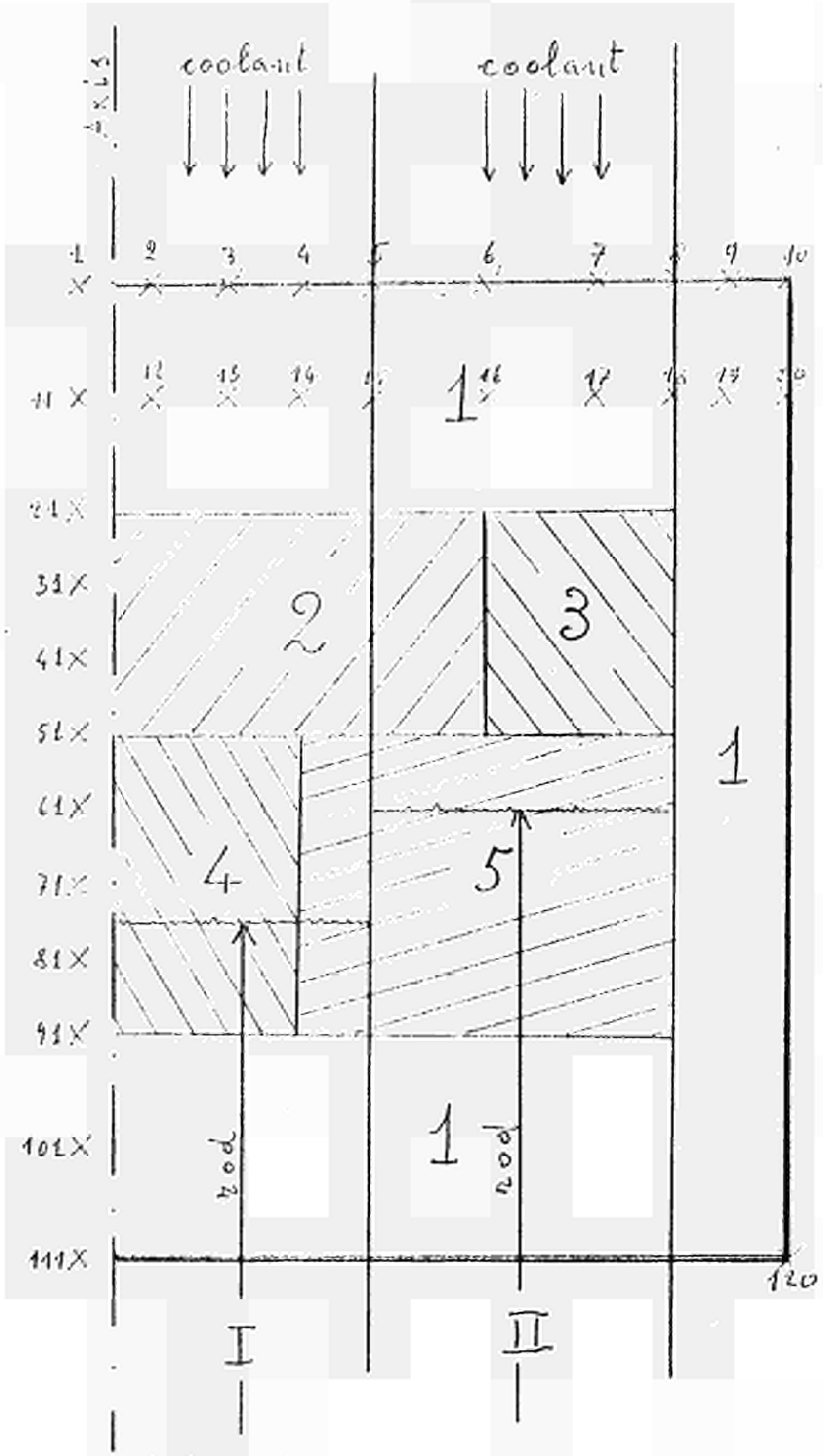


Fig. 1

Fac simile of a core subdivision with a
10 x 12 = 120 point-lattice

5 composition regions (1:reflector; 2,3,4,5:core)
Two vertical control zones I and II
Control rods inserted from bottom

8 axial points in the active part of the core

Control rods

In each control zone the rods move as a bank all together. They are represented by a diffused equivalent poison. The fast and thermal macroscopic cross sections of this equivalent poison are given in input. The poisoned part of the zone is limited by a movable boundary A-B of Fig. 2. When the movable boundary lay between two points of the vertical array, a linearly interpolated value of poison is assigned to the space between the two points.

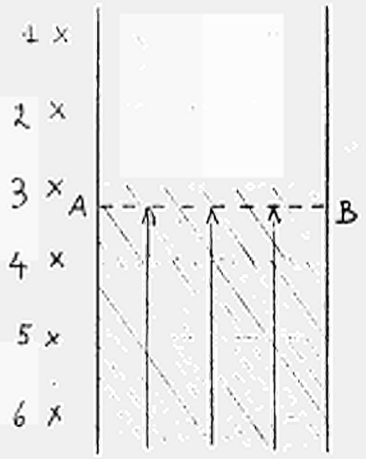


Fig. 2

The initial insertion of the rods in each zone is given in input. However, in all the zones choosen for criticality search, the depth of insertion will be determined by the programme and will be the same for all these zones.
In all other zones not choosen for criticality search, the rods maintain their initial insertion.
During the transient the rods can be moved in any zone arbitrarily chosen. The movement will be specified by a tabulation of insertions versus times given in input for each chosen zone separately. For intermediate times a linear interpolation will be made. To obtain a step-wise movement two tabulated values must be given having times equal to $n \cdot \Delta t$ and $(n+1) \cdot \Delta t$.

If the time of the transient overtakes the last tabulated time, the rods will maintain the last tabulated position.
In all other zones the rods will maintain their initial positions or the positions determined by the criticality search.

Neutronic initialization

The flux calculation starts with flat fluxes. A fixed number of calculations are made (Sub. INIZ) and at every step the fluxes are normalized with the factor

$$F = \frac{\text{Total Power}}{\int_{\text{core}} \varepsilon \left[\Sigma_{\text{fission}}^{\text{fast}} \Psi + \Sigma_{\text{fission}}^{\text{ther.}} \varphi \right] dv}$$

in order to obtain a wanted value of total power. Although the reactor is not critical the distribution of fluxes, thus obtained, is very close to the static distribution.

Criticality search

The criticality search can be made either by varying the concentration of poison in any wanted composition region or by varying the depth of insertion of the

rods in any wanted vertical control zone. The calculation is repeated until the reciprocal of the period of the average thermal flux differs from zero by less than a fixed amount. To accelerate the convergence, only prompt neutrons are considered during this process. The delayed neutron precursor concentrations will be calculated at their equilibrium values once obtained the critical condition.
After every iteration the fluxes are normalized at a wanted power and the temperatures and corresponding feed back on neutronic are calculated.
Once obtained the equilibrium condition at the wanted power the physical constants of the regions may be different from their initial values given in input.

Dynamic Calculations

Starting from the initial equilibrium conditions the code calculates the dynamic behaviour of the reactor in time.
The calculations of the flux distributions and delayed neutrons precursor concentrations will be repeated at every time step of constant length Δt.
The thermohydraulic calculations and the corresponding temperature reactions are calculated at every n time steps, n to be specified in input.

During the transient the power level and flux distributions evolve freely according to the reactivity introduced by any perturbation and to the temperature feed-back. The perturbations may be given by varying the depth of insertion of the rods, or the mass flow, or the inlet temperature in any wanted zone independently. The variation of these parameters as functions of time are given in input in tabular form.
A convenient value of the time interval Δt is given in Appendix B as ratio $\Delta t/T$, where T is the shortest reactor period in the transient to be studied.
The maximum increase of power and the admissible error are considered. It is easy to have an a priori estimate of these values.

Method

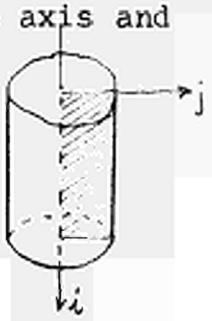
The two-groups time-dependent diffusion equations and the equation of the delayed neutron precursors are:

$$1)\quad D_1 \nabla^2 \psi - \Sigma_R \psi + (1-\beta)(\Sigma_{f1}\psi + \Sigma_{f2}\varphi) + \sum_{i=1}^{N} \lambda_i C_i = \frac{1}{v}\frac{\delta \psi}{\delta t}$$

$$2)\quad D_2 \nabla^2 \varphi - \Sigma_a \varphi + \Sigma_R \cdot p \cdot \psi = \frac{1}{v}\frac{\delta \varphi}{\delta t}$$

$$3)\quad \frac{\delta C_i}{\delta t} = \beta_i (\nu \Sigma_{f1}\psi + \nu \Sigma_{f2}\varphi) - \lambda_i C_i$$

As the reactor is cylindrical, with axial symmetry, a calculation of the fluxes and other physical magnitudes made in a vertical section delimited by the axis and outer boundaries, as shown in fig.3, describes completely the behaviour of the whole reactor.

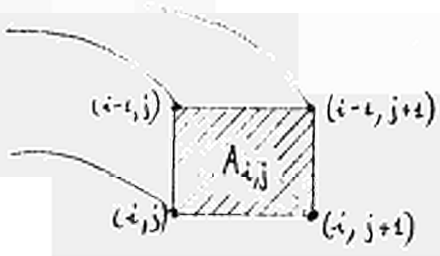


This section is covered with a point lattice. The reactor volume is subdivided into cylindrical annuli each of which is delimited by four points of the lattice.

j = is the radial index increasing from the axis outwards

i = is the axial index increasing from the upper boundary downwards

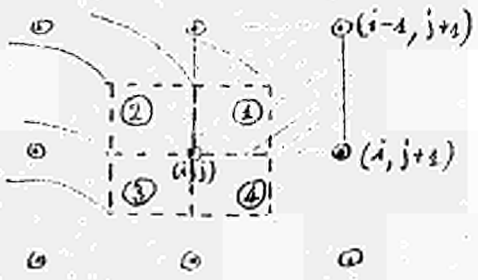
fig. 4



The physical constants of the equations 1) 2) 3), generally indicated with Aij, may have different values for each annular part of the space, but are constant within the annulus. There is a correspondabce of indexes between the part of the space and the lower left of the four points which delimit it.

The equations 1) 2) 3) are integrated over the volume corresponding to the point (i,j) which is subdivided into four sub-volumes

see fig. 5



Each sub-volume belongs to a different part of space, which may have different physical constants. Thus for every point of the lattice, the integrated equations are averaged over the surrounding parts of space. This is evidently significant for points on the interferences of different regions, but it is also significant for the internal points of a region, because the variations of the physical constants due to the temperature reaction are calculated pointwise. By this method the formal expression of the integrated equations results to be the same everywhere with a considerable simplification of the programme.

For the details of the integration see Appendix A.

The general form of the integrated equation for the generic point (i,j) is:

$$4)\quad -\alpha_{ij}\,\varphi_{i-1,j} - \beta_{ij}\,\varphi_{i,j-1} - \gamma_{ij}\,\varphi_{i+1,j} - \delta_{ij}\,\varphi_{i,j+1} + \varepsilon_{ij}\,\varphi_{ij} = b_{ij}\,\psi_{ij} + c_{ij}$$

This is the eq. corresponding to the thermal flux and contains, in the known term of the right side the source term $b_{ij}\,\psi_{ij}$ with the fast flux ψ_{ij} . The equation corresponding to the fast flux ψ is formally the same and contains a source term with the thermal flux φ .
There are two systems of n linear equations, one for each energy group; n is the number of the points of the lattice.

Note

The boundary condition $\frac{d\varphi}{dr} = 0$ at the axis of the cylindrical core, is obtained by putting all the points (i,1) and (i,2) of the first two vertical columns, symmetrically to the axis. i.e. r(1) = -r(2) (r (j) being the radial distance of the point (i,j) from the axis), and by imposing $\varphi_{i,1} = \varphi_{i,2}$. This is obtained by putting $\beta_{i,1} = 0$. In fact the equation corresponding to the first point of each radius is of the type:

$$8)\quad -\alpha_{i,2}\,\varphi_{i,2} - \beta_{i,2}\,\varphi_{i,1} - \gamma_{i,2}\,\varphi_{i+1,2} - \delta_{i2}\,\varphi_{i,3} + \varepsilon_{i2}\,\varphi_{i,2} = b_{i2}\,\psi_{i2} + c_{i2}$$

if $\varphi_{i1} = \varphi_{i,2}$ then the equation can be written:

$$9)\quad -\alpha_{i2}\,\varphi_{i2} - \gamma_{i2}\,\varphi_{i+1,2} - \delta_{i2}\,\varphi_{i,3} + [\varepsilon_{i,2} - \beta_{i,2}]\,\varphi_{i,2} = b_{i2}\,\psi_{i2} + c_{i2}$$

as β_{i2} is also contained in ε_{i2} with the + sign the equation 9) can be obtained from 8) by simply putting $\beta_{i,2} = 0$.
The outer boundary conditions are obtained by imposing $\varphi = 0$ and $\psi = 0$ in all the points of the outer boundary.

In a first version of the code we have used the Gauss-Seidel iterative method with overrelaxation factor for the solution of each groups separately, using than the obtained solution as source for the other groups and iterating between the groups.
This way of proceeding has been abandoned for a much faster method in part direct and in part iterative.
In eq. 4) the fluxes $\varphi_{i-1,j}$ and $\varphi_{i+1,j}$ correspond to points belonging to the radius (i-1) above and to the radius (i+1) below the point (i,j).
Let us consider the values $\varphi_{i-1,j}$ and $\varphi_{i+1,j}$ as already known.
All the equations of the i^{th} radius form a system of JMAX equations (JMAX = number of points of the radius), which has a tridiagonal matrix of coefficients. In fact each equation contains only three incognita. This could be solved with the well known method of forward elimination and backward substitution, for each group separately.
However by intercalating the equation of the fast with those of the thermal group and rearranging the terms, it is possible to obtain a system of 2 x (IMAX) equations for both groups, with a pentadiagonal matrix of coefficients. This can be partitioned into (2x2) submatrices and considered as a tridiagonal matrix with entries consisting of (2x2) submatrices. The method of forward elimination on backward substitution can be applied operating on these (2x2) submatrices and the direct solution can be obtained for both groups at the same time. (See: Finite Difference Method for solving the Spatio-Temporal Diffusion Equation in the Two-group Approximation - EUR 596 by B.Monterosso and E.Vincenti).

All the point lattice has to be scanned by repeating this direct calculation at each radius. For $\varphi_{i-1,j}$ will be used the value obtained in the calculation of the $(i-1)^{th}$ radius. In the actual iteration, and for $\varphi_{i+1,j}$ will be used the value obtained in the preceeding iteration. The scanning of the lattice will be repeated alternatively downard and upward until convergence is reached.
This method which is direct in radial direction and iterative in axial direction eliminates the iterations between the groups and in the normal cases reduces the computing time of a factor 3 compared to the usual overrelaxation method.

Thermal calculation

The reactor is subdivided in a number of vertical zones (max. 10). Each zone contains many vertical cooling channels of the same type. Channels belonging to different zones may however be of different types. For channel is meant here a fuel rod with the corresponding coolant. The channels go through the reactor from top to bottom including the reflectors, but only the part contained in the active core is considered for thermal calculation. The part is subdivided with a point-lattice of constant mesh ΔZ, which coincides with the axial lattice for neutronic calculation.

To determine the power developped in a fuel rod, in any zone, in a part ΔZ between the $(i-1)^{th}$ and the $(i)^{th}$ level, the power is integrated in the volume A (Fig.6) of the zone between (i-1) and (i) and this is divided by the number of rods of the zone.

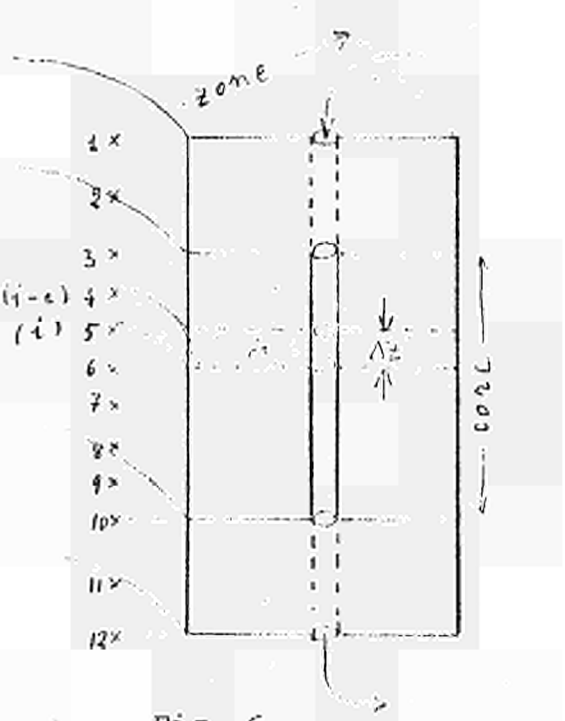


Fig. 6

$$\frac{\int_A \varepsilon \left(\Sigma_f f_{sf} \psi + \sum f_{tl.} \varphi \right) dv}{\text{number of rods in the zone}}$$

The heat is generated in the rod and propagates to the coolant into which it is injected at the point (i). The fuel rod is subdivided in a number of concentrical shells (5 10). The relative distribution of power among the shells is given in input and remains constant during the transient, although the total power varies with time. The time-dependent heat balance equation, transformed with the finite-difference method, is solved in implicit way at each level (i) and gives the temperature distribution at a given instant in the shells of the fuel and in the coolant. The results obtained at level (i) will be used as input for the calculation at level (i+1). A complete description of this procedure is in the report EUR 3171 by A.Agazzi, G.Forti, E.Vincenti, pages 8 14.

Temperature reaction

Eight physical constants are allowed to vary with the temperature, i.e.:

D_{fast}; $\Sigma_{removal}$; $\nu\Sigma_{fission\ fast}$; p (~~reserve~~ res. esc. prob.)

$D_{thermal}$; $\Sigma a_{th.}$; $\nu\Sigma_{fission\ th.}$; Σ poison

this temperature dependence has been expressed in the form of a Taylar expansion:

$$C = C_0 + \alpha (T_f - T_{f0}) + \beta (T_m - T_{m0}) + \gamma (T_f - T_{f0})^2 + \delta (T_m - T_{m0})^2$$

where

C_0 = initial value of the physical constant

$\alpha, \beta, \gamma, \delta$ = temperature coefficients

T_{f0} and T_{m0} = Reference temperatures of fuel and moderator corresponding to the initial value C_0 (1)

All these magnitutes are given in input region wise.

T_f and T_m = New values of the fuel and moderator temperatures. (1)

---

(1) Note This version of the code is made for pressurized water reactors where the moderator and coolant are at the same temperature. Another version of the code has been made for HTG pebble-bed reactors, where the moderator (graphite) is contained in the fuel element mixed with the fuel.

Although all other values, including the reference temperatures T_{fo} and T_{mo}, are given for each composition region, the temperatures T_f and T_m are calculated in each vertical control zone. The calculation is made at every thermal time step. T_f and T_m are values of temperatures averaged over that part of the radius within the control zone, they have however distinct values at every axial level. The temperature reaction is therefore made pointwise in axial direction, and zonewise in radial direction.

Programme Composition

The code consists of a Main and 19 Subroutines of which 5 belong to the first Overlay and the remaining 14 belong to the second Overlay.
The 5 routines of the first group are called only once. They calculate all the coefficients which will not be changed anymore and will be transfered to the second overlay in order to make available the rest of the memory.

First overlay :

1) MAIN - Calls the first routines of the first group and PRINC 2, control routine of the second group.

2) INPUT - Reads the vector DATA from cards or tape.

3) PRINC - It takes the data which are read region-wise in Input and transforms them into point-wise data. Calls GEOM and DCAN.

4) DCAN - Calculates all the thermohydraulic coefficients which will remain unchanged during the transient.

5) GEOM - Calculates all the coefficient depending from the geometry of the core and the point lattice.

6) AZER 1 - Called from Input, before reading the data. Puts equal zero all the commons of the first Overlay.

Second Overlay :

7) PRINC-2 - In its first part, before label 1000, this routine determines the initial conditions. It calls AZER 2 to put equal zero all the commons belonging only to the second Overlay. Puts the control rod in the initial position. Calls INIZ to give a first approximate distribution of the fluxes. Calls CRITIC to calculate the initial equilibrium distributions of fluxes and temperatures.
In the second part after the label 1000 it determines the transient behaviour.
At every time step it calls BARRE to determine the rod position; it calls Flussi to calculate the flux distribution; optionally it calculates the accumulated energy per cm^3 at every point; it calculates the delayed neutrons precursors concentrations at every point.
At every KPC (see input key) time steps it calls the thermal routines CANPALL and CØVAR to determine the temperature reactions.
Calls STAMPA to print according to the orders given in input.
Controls the restart operations to store on tape the results at the end of a calculation and to start from tape an interrupted calculation (see Restart Instructions).

8) AZER 2 - Puts equal zero all the commons belonging only to the second Overlay.

9) INIZ - It calls FLUSSI a number of times specified in input. Starting from and initial flat distribution determines a first approximate distribution of the fluxes. In these calculations the delayed neutrons are not considered. It normalizes the fluxes at a given initial power level. Uses a neutronic time step DELTI which may be different from DELTC used in CRITIC, and from DELT used for the transient calculation.

10) FLUSSI - It solves directly along each radius the two-group system of linear equations. (see Method). It scans axially the point lattice, in alternate directions, until the residuals of each group

$$\frac{\sum_{i=1}^{N} |\Delta \varphi_i|}{\sum_{i=1}^{N} \varphi_i} < EP1 \quad \text{and} \quad \frac{\sum_{i=1}^{N} |\Delta \varphi_i|}{\sum_{i=1}^{N} \varphi_i} < EP2$$

are smaller of the quantities EP1 and EP2 given in input.
It calculates the fast and thermal flux average values and the reciprocal of the period.

11) MAT1 - It calculates the coefficients of the system of linear eq. to be solved by Flussi. This calculation is made using the invariant coefficients transfered from the first overlay and variable physical magnitudes depending from the temperature reaction and the rod position.
This routine will be called at every thermal calculation, from Princ 2 and from Critic.
When only the poison concentration is varied it is enough to call MAT2, because, as the routine contains the Entry Mat 2, the first part of it will be bypassed.

12) STAMPA - It prints the output. Any wanted result may be printed in several optional types of print (see input instructions).

13) CRITC - searches the criticality by varying iteratively either the concentration of poison in any wanted region, or the insertion of the rod in any wanted zone. In the first part of this iterative method, from two values of poison and the corresponding values of reciprocal period, it determines, by extrapolation, the next value of poison and so on. When the reciprocal period is below a given value it variates the poison at each iteration of one thausand of the last concentration, until the convergency criterium is satisfied or the reciprocal of period changes of sign.
The same proceeding is followed when the criticality is searched with rod movement. After a first part with the extrapolation method, the rod are displaced of 1 millimeter at each iteration.
In both cases at each iteration the thermohydraulic routines are called to determine the temperature reaction.
The calculation is made without considering the delayed neutrons.

14) BARRE - This routine calculates the new coefficients of the system of linear equations only where a new condition of poison was determined by the displacement of the rods e.g. see M and N of Fig. 7....
The recursive coefficients of the forward elimination

and backword substitution method however are calculated by BARRE in all the points of the region A B C D of Fig. 7 determined by the rods displacement and the outer boundary.

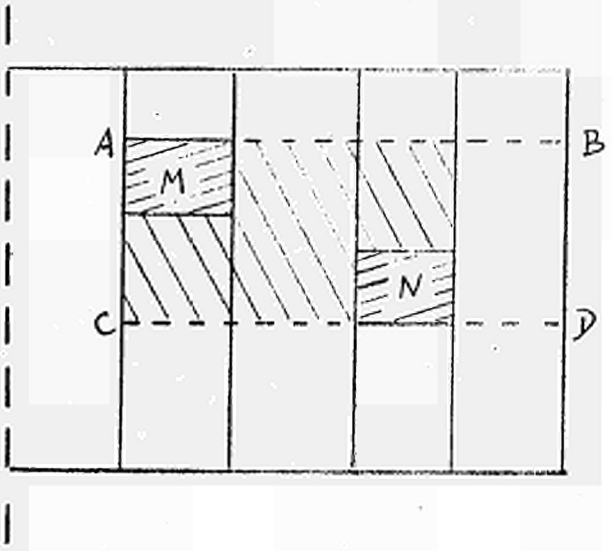


Fig. 7

It is called from Critic and Princ 2. When called from Princ 2 it determines the rod position by interpolation of the tabulation given in input.

15) TEST - This is a dummy routine which contains all the commons and may be used to introduce any new statement in the programme. It is called at every time step from Princ 2.

16) CANPAL - This routine calculates from each channel the temperature distribution in the fuel rod and in the coolant at all axial levels (see thermal calculation). It is called during the transient from Princ 2 at every KPC time step, and from Critic to determine the equilibrium initial condition.

17) VINIZ - Determines for each channel the coolant inlet temperatures and mass flow at every time step, interpolating the values given in input as function of time in tabulated form.

18) INTEGR - Calculates for each channel independently at every axial level the fuel and coolant average temperatures.

19) COVAR - calculates the new values of the physical constants given by Integr. (See temperature reaction).

20) RESTAR - stores on tape the results at a given time. It restarts an interrumpted calculation, reading the results stored on tape (See restant instructions).

Input Instructions

A title card is the first input card of each problem.
A vector of 10000 memory positions : DATA (1).....
DATA (10000) contains all the data.
Since entire groups of memory positions are zero, it is possible to read separate sets of significant data; each set of data must be preceeded by a card containing the integers Ki_1, Ki_2, Ki_3, written in Format (2I6, I12) where Ki_1 is normally zero, Ki_2 and Ki_3 are the indexes of the first and last datum of the set.
Only in the last set of a problem Ki_1 must be any positive integer number. The data are in floating form, six per card (Format 6 E 12.8).
Any number of problems may be run in sequence; for all the subsequent problem only the data different from the corresponding data of the first problem need to be given. The vector DATA of the first problem must be memorized on an auxiliary tape. (See Restart Instructions).

Input Key

Title card : Columns 1-2-3 if left blank the data are read from cards and the results will not be stored on tape. Numbers in these columns correspond to store and restart (see Restart Instructions). Columns 4-5-6. If only one problem is treated they must contain any positive integer. If a series of problems are to be treated in the same run, only the last title card of the last problem must have any positive integer, in the preceeding title cards these columns must be blank. Columns 7-70 may contain any alphanumerical information which will be printed in output.

	DATA Number	Variable Name	DESCRIPTION	Allowable Values	NOTES
First card	1	TEMAC	Computer time (min.)		Only if the first three columns of the title card contain a number see Restart Instructions.
	2	DELT	Neutronic time step Δ t for transient calculation (sec.)		
	3	DELTC	Neutronic time step Δt for criticality search (sec.)		
	4	IMAX	Number of axial mesh points	≤ 40	$(IMAX * JMAX) \leq 400$
	5	JMAX	" " radial " "	≤ 40	
	6	NREG	Number of regions with different composition	≤ 30	
Second card	7	NRIT	Number of delayed neutron groups	≤ 6	
	8	ITMAX	Maximum allowable number of axial iterations	suggested value = 30	
	9	IDST	Number of initial iterations before criticality search	Suggested value = 20	
	10		blank		
	11		blank		
	12	DELTI	Neutronic time step Δt for the initial iterations before criticality		

	DATA Number	Variable Name	DESCRIPTION	Allowable Values	NOTES
third card	13		Blank		
	14	EP1	Convergence criterium for the fast group	s.v.=0,01	
	15	EP2	Same for the thermal group	s.v.=0,01	
	16	SI	Initial reactor power (Watts)		
	17	KPC	The thermal calculation is done every KPC neutronic steps		
	18	NCAN	Number of radial zones containing channels		
	19		Blank		
	20		Blank		
	21	KTE	If KTE > 0 Subroutine TEST will be called.		
	22	ICA	Axial index of the points laying on the upper core boundary. (Reflector excluded)		
	23	ICB	Same for the lower boundary		
	24	JCI	Radial index of the points laying on the inner core boundary		Usually the central part of the reactor belongs to the core, then JCI=2
	25	JCE	Radial index of the points laying on the outer boundary of the core. (Radial reflector excluded)		

DATA Number	Variable Name	DESCRIPTION	Allowable values	NOTES
26	W	Fast group neutron velocity ($\frac{cm}{sec}$)		
27	V	Thermal " " " "		
28	SPRG	First guess of control poison concentration		Blank if critically search is made with rod movement
29	DAPF	Convergence criterion for reciprocal of period in criticality search	s.v.=0.1	
30	LF	Maximum allowable number of criticality iterations	s.v.=30	
31	IDIR	= 1 if the control rods enter into the core at the same side as the coolant. = 2 if they enter at the opposite side		
32	IBCR	= 0 criticality search made with diffused poison = 1 criticality search made with rod movement		
33	NZB	Number of the vertical zones	≤ 10	The vertical zones have the same height of the reactor. Each zone is characterized by the same rod depth of insertion and by the same typical channel.

DATA Number	Variable Name	DESCRIPTION	Allowable values	NOTES
34	SPB1	Microscopic control poison (barn) cross section for the fast groups.		they are multiplied by SPR in each region to obtain the correspondin macroscopic cross section
35	SPB2	Same for the thermal group		
201-206	BETA	β_i delayed neutrons yield per fission		
211-216	DL	λ_i delayed neutrons precursors decay constants		
231	INTG	= 1 The power will be integrated in the time at every mesh point = 0 No integration will be effectuated		
232	NUSO	Number of thresholds of integrated energies	≤ 10	only if INTG = 1
233-242	SØLEN	Thresholds of the integrated energies in increasing order from the lower to the higher	$\left[\frac{\text{Joule}}{\text{cm}^3}\right]$	(See printing order N° 8 and 9)
301	I1	Index of the upper boundary of the first region		This group of data for energy regions is included in one card. For the region bounded by the axis of cylinder J1=1
302	I2	Index of the lower boundary of the first region		
303	J1	Index of the left (inner) boundary of the first region		
304	J2	Index of the right (outer) boundary of the first region		
305	-	blank		
306	-	blank		
307-312		for the second region		
375-480		for the 30th region		

DATA Number	Variable Name	DESCRIPTION	Allowable values	NOTES
1001	D1	Diffusion coefficient fast group	One card for each region	
1002	SR	Removal cross section		
1003	SF1			
1004	P	Resonance escape probability		
1005	-	blank		
1006	-	blank		
1007-1012		Second region		
1175-1180		30th region		
1601	D2	Diffusion coefficient thermal group	One card for each region	If IBCR = 0 SPR will be varied to obtain criticality in the control regions
1602	SA	thermal absorption cross-section		
1603	SF2			
1604	SPR	Poison concentration; it is multiplied by SPB1=Data (34) and SPB2=Data (35)		
1605	-	blank		
1606	-	blank		
1607-1612		Second region		

DATA Number	Variable Name	DESCRIPTION	Allowable values	NOTES
2201	EQUi1	Thermal equivalent of fission (fast) [Watt-sec]		
2202	EQUi2	Thermal equivalent of fission (thermal) [Watt-sec]		
2203	FNU	ν Neutron yield per fission		
2204	KV	KV= order number of the region, then in that region SPR will be varied for criticality search KV= Zero, SPR will not change		Only if IBCR=0
2205 2206	TRU TMU	The initial values of the physical constants given in input were calculated according to a fuel temperature = TRU and a moderator temperature = TMU for each composition region.		
2207-2212		for the second region		
2375-2380		for the 30th region		
2801	KB	KB= order number of the zone, this zone contains control rods KB= 0, no rods		See note of Data (33)
2802	KBC	KBC= order number of the zone, the rods of the zone are used for criticality search KBC= zero, no movement of rod for criticality search	Only if IBCR=1	The order number of the zone, must increase from left to right

DATA Number	Variable Name	DESCRIPTION	Allowable values	NOTES
2803	J1B	Index of the left (inner) boundary of the zone		For the region bounded by the axis of cylinder J1B = 1
2804	J2B	Index of the right (outer) boundary of the zone		
2805	KCA	KCA= order number of zone, the zone contains channels KCA= zero, no channel		
2806	-	blank		
2807-2812		Second zone		
2855-2860		10^{th} zone		
2861	VEBA1	Macroscopic cross section of the rod equivalent poison (fast)		
2862	VEBA2	Macroscopic cross section of the rod equivalent poison (thermal)		
2863	-	blank		
2864	-	blank		
2865	-	blank		
2866	-	blank		
2867-2872		Second zone		
2915-2920		10^{th} zone		

DATA Number	Variable Name	DESCRIPTION	Allowable values	NOTES
3001-3030	TOBA	Times of the rod movement tabulation for the first zone sec	DATA (3001) must always be zero	
3031-3060	PRIN	Corresponding depth of rod insertion in the tabulation for the first zone cm		
3061-3090		Same for the second zone	DATA (3061) = 0	
3091-3120		etc.	DATA (3541) = 0	
4001-4040	X(J)	Distance of mesh points from the axis		
4101-4140	Y(I)	Distance of mesh points from the upper boundary.		The upper boundary is for definition the side from which the coolant enters. The first distance is Y(1) = 0.0

DATA Number	Variable Name	DESCRIPTION	Allowable values	NOTES

CHANNEL DATA

5001	DZ	Constant axial mesh distance cm	
5002	SEZ	Section of channel cm^2 (Coolant corresponding to a fuel rod)	
5003	SC	Coolant specific heat $\frac{Joule}{g\ °C}$	
5004	RO	Coolant density g/cm^3	
5005		blank	
5006	-	blank	

DATA Number	Variable Name	DESCRIPTION	Allowable values	NOTES
5007	N1 (KC)	Number of shells in the fuel rod	N1 $\leq$ 9	
5008	PALN1 (KC)	Number of fuel rods in the zone KC		
5009		blank		
5010	ØSE1	Outer surface of a part of rod of height DZ		
5011	-	blank		
5012	-	blank		
		——— • ———		
5013-5018		These six DATA contained in one card correspond to the first shell of the rod.		
5013	RES1	Thermal resistence between the shell and the next one [°C/Watt]		
5014	CPT1	Thermal capacity of the shell [Joules/°C]		
5015	VOS1	Shell volume [cm^3]		
5016	PZO1	Power fraction corresponding to the shell		Relative values are significant. Normalization is performed by the code.

DATA Number	Variable Name	DESCRIPTION	Allowable values	NOTES
5019–5024		Same data for the second shell etc.....		
5061–5066		Same data for the nineth shell		
		——— · ———		
5190	VITE	Inlet temperature of coolant at equilibrium initial conditions (Put zero if inlet temperature is tabulated as function of time) [°C]		
5191	STEPT	Step of coolant inlet temperature		Only if VITE ≠ 0
5192	RAMPT	Value of dT/dt for ramps in coolant inlet temperature [°C/sec]		"
5193	VIPO	Iniatial value of coolant mass-flow (put zero if tabulated) [g/sec]		
5194	STEPPO	Step of coolant mass flow		Only if VIPO ≠ 0
5195	RAMPO	Value of $\frac{dW}{dt}$ for ramp in mass flow [g/sec^2]		"
		——— · ———		

DATA Number	Variable Name	DESCRIPTION	Allowabl Values	NOTES
5201-5329		SECOND CHANNEL DATA		
6801-6999		TENTH CHANNEL DATA		

NOTE: All the cards must be repeated for every channel. The order number of the existent channel must be the same of the order number of the radial zone in which the channel is contained.
(Ex. Suppose that zone one and three contain channel and zone two do not contain any channel, then the channel of zone three must be considered as the third and its data are in the group Data (5401) ....(5599).)

7001-7060		Tabulation of inlet temperatures and mass flow for the first channel. Each point of the tabulation for both magnitudes is contained in one card (4 data), as follows:		
7001	TOTE	Time of the temperature tabulation (Zero in the first card)		
7002	TENT	Value of the corresponding temperature		
7003	TOPO	Time of the mass-flow tabulation (zero in the first card)		
7004	PENT	Value of the corresponding mass flow		
7005	PENT	blank		
7006	PENT	blank		

DATA Number	Variable Name	DESCRIPTION	Allowable values	NOTES
7007-7012		Second card of the tabultation etc.		
7061-7120		Same for the second channel etc.		
7541-7600		Same for the 10th channel		

TEMPERATURE COEFFICIENTS (8001 → 8960)

The temperature dependence of the physical constants is expressed in the form of a Taylor expansion

$$C = C_c + \alpha_1 (T_f - T_{f\circ}) + \alpha_2 (T_m - T_{mc}) + \alpha_3 (T_f - T_{fc})^2 + \alpha_4 (T_m - T_{mc})^2$$

The variable physical constants are 8 in the following order :

1	D1 = D_1
2	SR = Σ_R
3	SF1 = $\nu \Sigma_{f1}$
4	P = p
5	D2 = D_2
6	SA = Σ_{a2}
7	SF2 = $\nu \Sigma_{f2}$
8	SPR = Σ poison

The algoritm giving the position of the temperature coefficient in the reactor DATA is as follows:

$$CTN(K,L,N) = DATA[8000 + 32*(N-1) + 8*(L-1) + K]$$

DATA Number	Variable Name	DESCRIPTION	Allowable values	NOTES

where K (1,...8) = order number of the physical constant

L (1,...4) = order number of α_i in the Taylor series

N (1,...30)= order number of the composition region

PRINTING ORDERS

9901-9960 It is possible to give in input up to 5 different printing orders. Each order is contained in two cards (12 data)

9901-9912 First order

9913-9924 Second "

" "

9949-9960 Fifth "

In each group of 12 data (two cards) corresponding to an order the first datum = n1 indicates that the printing order is valid up to the n_1^{th} time-step.

DATA Number	Variable Name	DESCRIPTION	Allowable values	NOTES
		The other data of the group $n_i \leq n1$ (i= 2,3,...12) indicate that the corresponding type of printing will be made at every n_i time-step. If some of the data = n_i are left blank the corresponding type of printing will not be made.		

Ex. For the first order :

9901	n1	The first printing order will be performed up to the $n1^{th}$ time step.	First card
9902	n2	Flux core average, reciprocal period and total power	
9903	n3	Flux map	
9904	n4	Map of rod insertions	
9905	n5		
9906	n6	Map of the concentrations of the delayed neutron precursors	

DATA Number	Variable Name	DESCRIPTION	Allowable values	NOTES
9907	n7	Maximal fuel temperature, max. cladding temperature, max. heat flux, inlet and outlet temperature, mass flow.	Second card	
9908	n8	Map of temperatures		
9909	n9	Percent of core (in volume) below a given integrated energy threshold		
9910	n10	Map of integrated energies		
9911		nothing		
9912				

It is possible to give as many order as wanted up to five.
The calculation stops at the time-step indicated by the first datum = n1 of the last printing order.

Restart an interrupted calculation

Two dimensional calculations require long computer time. It may be interesting to have the possibility of restarting an interrupted calculation, without repeating it from the beginning. In particular it may be interesting to have the possibility to initiate again a calculation from the equilibrium condition, without repeating the criticality search. For this purpose it is necessary to store on tape the results already obtained.

It is possible after a restart to change the printing orders. The first card of the new printing orders must contain in the first twelve columns the number IT of the time steps at which the calculation was interrupted; this card is blank in all other columns. A second blank card must follow, then groups of two cards must follow containing the new printing orders.

It is also possible to change the tabulations given in input for the rod movements, inlet temperatures, and mass flow. Of course only changements after the instant t of restart have a meaning.

The new tabulations must contain a first point at time zero, with any value of the variable, the second point will be at the instant t and the value of the variable (insertion of rod, inlet temperature, mass flow) must be that indicated in the output of the results which were stored on tape. From t on any new point may be introduced in the tabulation.

At any subsequent restart after having changed the original tabulation, it is necessary to use the cards of the new tabulation, otherwise the programme will calculate according

to the original one which remains stored on tape.

It is also possible in a restarted calculation to introduce a new value of the time step Data (2). In this case a new printing order must be given, as described in the preceeding page. The original vector Data is stored on tape, only the new changed values must be given by cards.
The orders of restart are given in the fisrt three columns of the title card:

Titel Card:

Blank = Input data read from card, no storing of results on tape

001 = Input data read from cards, three files are stored on tape

file 1	input data
file 2	results of criticality search
file 3	results of instant t.

002 = Only if more than one problem is treated. Input data corresponding to the first problem are read from tape, file 1. Only those input data of the new problem which differ from those of the first problem are read from cards. At every new restart of the problem the cards corresponding to changement of the input data must be introduced, because on tape will always remain stored the input of the first problem.

003 = Restart from equilibrium conditions after criticality search, and store results at the end of calculation at time t.

004
005 = restart from results stored on file
006 (n-1) and store results on file n.
00n

-03
-04 Restart from the results stored in any file without destroying the subsequent files. This in case of temptative changements of rods, inlet temperature, mass flow tabulation and time step in any part of the transient.
-05
-On

First data card:

In addition to the titel card the first data card, containing DATA (1) to (6) must always be present.
In DATA (1) = TEMAC is indicated the computer time (minutes). At every thermal calculation the programme will compare the remaining computer time with the computer time necessary to make a thermal time step. If it will not be possible to make the next thermal calculation, then the results will be stored on tape.

If no thermal calculations are made then the programme makes this check at every 100 steps.

In the control cards are DD statements. At every file stored on tape corresponds a DD statement. When in the third column of the title card there 1 or 2 or 3 the DD statements are three, otherwise the number of the DD statements is the same as the number contained in column three of the Title card.

Every DD statement corresponding to a file stored on tape must contain the parameter DISP = (NEW, DELETE), and every DD st. corresponding to a file read from tape must contain the parameter DISP = (ØLD, DELETE).

DATA (Zones de 10 colonnes)

PROBLEM | DATE | PAGE | OF

Sample Problem Input and Control Cards
First calculation. Input data read from cards

```
TIME
LINES
$       TAPES
//      Identification Card
//          EXEC  FTLG,ØV=ØVLY
//LKED SYSIN    DD *
  Main Binary :
ØVERLAY A
  Binary  1st Overlay
ØVERLAY A
  Binary  2nd Overlay
/*
//GØ.FT09F001   DD UNIT=L91,VØLUME=(PRIVATE,SER=EU2747),                C
//                LABEL=(1,SL),DSNAME=EU2747(1),                        C
//                DISP=(NEW,DELETE)
//GØ.FT09F002   DD UNIT=L91,VØLUME=(PRIVATE,SER=EU2747),                C
//                LABEL=(2,SL),DSNAME=EU2747(2),                        C
//                DISP=(NEW,DELETE)
//GØ.FT09F003   DD UNIT=L91,VØLUME=(PRIVATE,SER=EU2747),                C
//                LABEL=(3,SL),DSNAME=EU2747(3),                        C
//                DISP=(NEW,DELETE)
//GØ SYSIN      DD *
```

PROBLEM Vincent DATE PAGE 1 OF

```
1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20  21  22  23  24  25  26  27  28  29  30  31  32  33  34  35  36  37  38  39  40  41  42  43  44  45  46  47  48  49  50  51  52  53  54  55  56  57  58  59  60  61  62  63  64  65  66  67  68  69  70  71  72  73  74  75  76  77  78  79  80
1       1       1                                                   SAMPLE      PROBLEM
2                           1                                                   36
3           5.0                     0.001                           0.001                                   12.0                    10.0                    5.0
4           6.0                         30.0                            20.0                                                    0.001
5                                   0.01                            0.01                        500.0   +06         100.0               2.0
6                                                                               3.0                 10.0                    2.0
7           8.0                     0.1             +10             0.26        +06     0.2     +21     0.1                 30.0
8           1.0                         0.0                         2.0         0.2     -23     0.8     -23
9                       201                         206
10  0.218       -03     0.1116      -02             0.972       -03     0.1687  -02     0.455   -03     0.185   -03
11                      211                         216
12  0.125       -01     0.319       -01             0.123       +00     0.312   +00     0.115   +01     0.274   +02
13                      231                         233
14      1.0                 1.0                         10.0
15                      301                         330
16      1.0                 12.0                    1.0                 10.0
17      3.0                 6.0                     1.0                 6.0
18      3.0                 6.0                     6.0                 8.0
19      6.0                 10.0                    1.0                 4.0
20      6.0                 10.0                    4.0                 8.0
21                  1001                        1030
22      1.37                0.91            -02                 1.0
23      1.35                0.838           -02                 1.0
24      1.35                0.838           -02                 1.0
25      1.35                0.838           -02                 1.0
```

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PROBLEM			DATE	PAGE 2	OF

	Col. 1–12	Col. 13–24	Col. 25–36	Col. 37–48	Col. 49–60	Col. 61–72
1	1.35	0.838 -02		1.0		
2	1601	1630				
3	0.966	0.62 -04	0.0			
4	0.977	0.452 -02	0.520 -02			
5	0.977	0.469 -02	0.518 -02			
6	0.977	0.423 -02	0.505 -02			
7	0.977	0.477 -02	0.515 -02			
8	2201	2230				
9				1.0		
10	0.3172 -10	0.3172 -10	2.46	2.0	800.0	290.0
11	0.3172 -10	0.3172 -10	2.46	3.0	800.0	290.0
12	0.3172 -10	0.3172 -10	2.46	4.0	800.0	290.0
13	0.3172 -10	0.3172 -10	2.46	5.0	800.0	290.0
14	2801	2812				
15	1.0		1.0	5.0	1.0	
16	2.0		5.0	8.0	2.0	
17	2861	2872				
18	0.4 -04	0.45 -03				
19	0.4 -04	0.45 -03				
20	3001	3002				
21	0.0	0.2				
22	3031	3032				
23	612.0	367.0				
24	3061	3063				
25	0.0	0.2	1.0			

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PROBLEM | DATE | PAGE 3 OF

1–12	13–24	25–36	37–48	49–60	61–72	73–80
3091	3093					
0.0	245.0	612.0				
4001	4010					
30.0	30.0	60.0	90.0	120.0	160.0	
200.0	230.0	240.0	250.0			
4101	4112					
0.0	20.0	40.0	116.0	192.0	268.0	
344.0	420.0	496.0	572.0	592.0	612.0	
5001	5048					
76.0	1.5	5.4	0.8			
6.0	2479.0		286.0			
0.0775	0.0447	11.9383	0.2			
0.0283	0.0447	11.9383	0.2			
0.01847	0.0447	11.9383	0.2			
0.01393	0.0447	11.9383	0.2			
0.00686	0.0447	11.9383	0.2			
0.00377	0.0591	12.5324	0.0			
5190	5193					
270.0			585.0			
5201	5248					
76.0	1.5	5.4	0.8			
6.0	6628.0		286.0			
0.0775	0.0447	11.9383	0.2			
0.0283	0.0447	11.9383	0.2			
0.01847	0.0447	11.9383	0.2			

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Line	Col. 1–12	Col. 13–24	Col. 25–36	Col. 37–48
1	0.01393	0.0447	11.9383	0.2
2	0.00686	0.0447	11.9383	0.2
3	0.00377	0.0591	12.5324	0.0
4	5390	5393		
5	270.0			585.0
6	8036	8036		
7	1.256 -06			
11	8068	8068		
12	1.256 -06			
16	8100	8100		
17	1.256 -06			
21	8132	8132		
22	1.256 -06			

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```
    1   9901        9924
  400.0          10.0         200.0          50.0
  100.0         100.0          50.0         200.0
 3000.0          10.0         200.0          50.0
  200.0         500.0         200.0         500.0
/*
7/8
                Restart from equilibrium conditions
                after criticality search.
  TIME
  LINES
$     TAPES
//      Identification Card
//          EXEC  FTLG,ØV=ØVLY
//LKED SYSIN  DD*
 Main Binary
ØVERLAY A
 Binary 1st Overlay
ØVERLAY A
 Binary 2nd Overlay
/*
//GØ.FT09F001    DD UNIT=L91,VØLUME=(PRIVATE,SER=EU2747),                       C
//                  LABEL=(1,SL),DSNAME=EU27471,                                C
//                  DISP=(ØLD,DELETE)
//GØ.FT09F002    DD UNIT=L91,VØLUME=(PRIVATE,SER=EU2747),                       C
```

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PB

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```
//             LABEL=(2,SL),DSNAME=EU27472,                          C
//             DISP=(ØLD,DELETE)
//GØ.FT09F003   DD UNIT=L91,VØLUME=(PRIVATE,SER=EU2747),              C
//             LABEL=(3,SL),DSNAME=EU27473,                          C
//             DISP=(NEW,DELETE)
//GØ SYSIN     DD *
  3  1                  SAMPLE   PRØBLEM
      1      1          1
   3.0
/*
7/8
                Restart from results stored on file 3 at time t = 0.2 sec. with
                a new Δt DATA(2) = 0.002, new real time schedule and print ordres
  TIME
  LINES
$      TAPES
//              Identification Card
//          EXEC   FTLG,ØV=ØVLY
//LKED SYSIN    DD *
  Main Binary
ØVERLAY A
  Binary 1st overlay
ØVERLAY A
 Binary 2nd overlay
/*
```


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```
//GØ.FT09F001       DD UNIT=L91,VØLUME=(PRIVATE,SER=EU2747),                  C
//                LABEL=(1,SL),DSNAME=EU27471,                               C
//                DISP=(ØLD,DELETE)
//GØ.FT09F002       DD UNIT=L91,VØLUME=(PRIVATE,SER=EU2747),                  C
//                LABEL=(2,SL),DSNAME=EU27472,                               C
//                DISP=(ØLD,DELETE)
//GØ.FT09F003       DD UNIT=L91,VØLUME=(PRIVATE,SER=EU2747),                  C
//                LABEL=(3,SL),DSNAME=EU27473,                               C
//                DISP=(ØLD,DELETE)
//GO.FT09F004       DD UNIT=L91,VØLUME=(PRIVATE,SER=EU2747),                  C
                  LABEL=(4,SL),DSNAME=EU27474,                               C
                  DISP=(NEW,DELETE)
//GØ SYSIN        DD *
  4  1                          SAMPLE   PRØBLEM
           1        6
     5.0        0.002       0.001       12.0        10.0        5.0
        3061        3063
     0.0         0.2        0.5
        3091        3093
     0.0      245.0      612.0
     1  9901        9936
  200.0
       Blank Card
  300.0         5.0     100.0       25.0
   50.0        50.0      25.0      100.0
```


VI - CET 002

PROBLEM | DATE | PAGE 8 OF

```
      600.0          5.0          100.0          25.0
      100.0        950.0          100.0        250.0
1*
7/8
```

COSTANZA R.Z.

SAMPLE PROBLEM

```
    1  0.5000000E 01     2  0.1000000E-02     3  0.1000000E-02     4  0.1200000E 02     5  0.1000000E 02     6  0.5000000E 01
    7  0.6000000E 01     8  0.3000000E 02     9  0.2000000E 02    10  0.0              11  0.0              12  0.1000000E-02
   13  0.0              14  0.1000000E-02    15  0.1000000E-02    16  0.5000000E 09    17  0.1000000E 03    18  0.2000000E 01
   19  0.0              20  0.0              21  0.0              22  0.3000000E 01    23  0.1000000E 02    24  0.2000000E 01
   25  0.8000000E 01    26  0.1000000E 10    27  0.2600000E 06    28  0.2000000E 21    29  0.1000000E 00    30  0.3000000E 02
   31  0.1000000E 01    32  0.0              33  0.2000000E 01    34  0.2000000E-23    35  0.8000000E-23    36  0.0

  201  0.2180000E-03   202  0.1116000E-02   203  0.9770000E-03   204  0.1687000E-02   205  0.4550000E-03   206  0.1850000E-03

  211  0.1250000E-01   212  0.3190000E-01   213  0.1230000E 00   214  0.3120000E 00   215  0.1150000E 01   216  0.2740000E 01

  231  0.1000000E 01   232  0.1000000E 01   233  0.1000000E 02

  301  0.1000000E 01   302  0.1200000E 02   303  0.1000000E 01   304  0.1000000E 02   305  0.0              306  0.0
  307  0.3000000E 01   308  0.5000000E 01   309  0.1000000E 01   310  0.6000000E 01   311  0.0              312  0.0
  313  0.3600000E 01   314  0.5000000E 01   315  0.6000000E 01   316  0.8000000E 01   317  0.0              318  0.0
  319  0.6000000E 01   320  0.1000000E 02   321  0.1000000E 01   322  0.4000000E 01   323  0.0              324  0.0
  325  0.6000000E 01   326  0.1000000E 02   327  0.4000000E 01   328  0.8000000E 01   329  0.0              330  0.0

 1001  0.1370000E 01  1002  0.3100000E-02  1003  0.0              1004  0.1000000E 01  1005  0.0              1006  0.0
 1007  0.1350000E 01  1008  0.3380000E-02  1009  0.0              1010  0.1000000E 01  1011  0.0              1012  0.0
 1013  0.1350000E 01  1014  0.3380000E-02  1015  0.0              1016  0.1000000E 01  1017  0.0              1018  0.0
 1019  0.1350000E 01  1020  0.3380000E-02  1021  0.0              1022  0.1000000E 01  1023  0.0              1024  0.0
 1025  0.1350000E 01  1026  0.3380000E-02  1027  0.0              1028  0.1000000E 01  1029  0.0              1030  0.0

 1601  0.3660000E 00  1602  0.2200000E-04  1603  0.0              1604  0.0              1605  0.0              1606  0.0
 1607  0.9770000E 00  1608  0.4520000E-02  1609  0.5200000E-02  1610  0.0              1611  0.0              1612  0.0
 1613  0.9770000E 00  1614  0.4690000E-02  1615  0.5130000E-02  1616  0.0              1617  0.0              1618  0.0
 1619  0.9770000E 00  1620  0.4230000E-02  1621  0.5050000E-02  1622  0.0              1623  0.0              1624  0.0
 1625  0.9770000E 00  1626  0.4770000E-02  1627  0.5150000E-02  1628  0.0              1629  0.0              1630  0.0

 2201  0.0              2202  0.0              2203  0.0              2204  0.1000000E 01  2205  0.0              2206  0.0
 2207  0.3172000E-10  2208  0.3172000E-10  2209  0.2460000E 01  2210  0.2000000E 01  2211  0.8000000E 03  2212  0.2900000E 03
 2213  0.3172000E-10  2214  0.3172000E-10  2215  0.2460000E 01  2216  0.3000000E 01  2217  0.8000000E 03  2218  0.2900000E 03
 2219  0.3172000E-10  2220  0.3172000E-10  2221  0.2460000E 01  2222  0.4000000E 01  2223  0.8000000E 03  2224  0.2900000E 03
 2225  0.3172000E-10  2226  0.3172000E-10  2227  0.2460000E 01  2228  0.5000000E 01  2229  0.8000000E 03  2230  0.2900000E 03

 2801  0.1000000E 01  2802  0.0              2803  0.1000000E 01  2804  0.5000000E 01  2805  0.1000000E 01  2806  0.0
 2807  0.2000000E 01  2808  0.0              2809  0.5000000E 01  2810  0.8000000E 01  2811  0.2000000E 01  2812  0.0

 2861  0.9000000E-04  2862  0.3300000E-03  2863  0.0              2864  0.0              2865  0.0              2966  0.0
 2867  0.9000000E-04  2868  0.3300000E-03  2869  0.0              2870  0.0              2871  0.0              2972  0.0

 3001  0.0              3002  0.2000000E 00

 3031  0.6120000E 03  3032  0.3670000E 03

 3061  0.0              3062  0.2000000E 00  3063  0.1000000E 01
```

Input Data

Input Data

```
3091  0.0             3092  0.2450000E 03 3093  0.6120000E 03

4001 -0.3000000E 02 4002  0.3000000E 02 4003  0.6000000E 02 4004  0.9000000E 02 4005  0.1200000E 03 4006  0.1600000E 03
4007  0.2000000E 03 4008  0.2500000E 03 4009  0.2400000E 03 4010  0.2500000E 03

4101  0.0             4102  0.2000000E 02 4103  0.4000000E 02 4104  0.1160000E 03 4105  0.1920000E 03 4106  0.2680000E 03
4107  0.3440000E 03 4108  0.4200000E 03 4109  0.4960000E 03 4110  0.5720000E 03 4111  0.6920000E 03 4112  0.6120000E 03

5001  0.7600000E 02 5002  0.1000000E 01 5003  0.5400000E 01 5004  0.8000000E 00 5005  0.0           5006  0.0
5007  0.6000000E 01 5008  0.2477500E 04 5009  0.0           5010  0.2860000E 03 5011  0.0           5012  0.0
5013  0.7750000E-01 5014  0.1177000E-01 5015  0.1193833E 02 5016  0.2000000E 00 5017  0.0           5018  0.0
5019  0.2330000E-01 5020  0.1177000E-01 5021  0.1193833E 02 5022  0.2000000E 00 5023  0.0           5024  0.0
5025  0.1347000E-01 5026  0.1177000E-01 5027  0.1193833E 02 5028  0.2000000E 00 5029  0.0           5030  0.0
5031  0.1393000E-01 5032  0.1177000E-01 5033  0.1193833E 02 5034  0.2000000E 00 5035  0.0           5036  0.0
5037  0.6360000E-02 5038  0.1177000E-01 5039  0.1193833E 02 5040  0.2000000E 00 5041  0.0           5042  0.0
5043  0.3770000E-02 5044  0.1181000E-01 5045  0.1253213E 02 5046  0.0           5047  0.0           5048  0.0

5130  0.2700000E 03 5131  0.0           5132  0.0           5133  0.5850000E 03

5201  0.7600000E 02 5202  0.1000000E 01 5203  0.5400000E 01 5204  0.8000000E 00 5205  0.0           5206  0.0
5207  0.6000000E 01 5208  0.2477500E 04 5209  0.0           5210  0.2860000E 03 5211  0.0           5212  0.0
5213  0.7750000E-01 5214  0.1177000E-01 5215  0.1193833E 02 5216  0.2000000E 00 5217  0.0           5218  0.0
5219  0.2330000E-01 5220  0.1177000E-01 5221  0.1193833E 02 5222  0.2000000E 00 5223  0.0           5224  0.0
5225  0.1347000E-01 5226  0.1177000E-01 5227  0.1193833E 02 5228  0.2000000E 00 5229  0.0           5230  0.0
5231  0.1393000E-01 5232  0.1177000E-01 5233  0.1193833E 02 5234  0.2000000E 00 5235  0.0           5236  0.0
5237  0.6360000E-02 5238  0.1177000E-01 5239  0.1193833E 02 5240  0.2000000E 00 5241  0.0           5242  0.0
5243  0.3770000E-02 5244  0.1181000E-01 5245  0.1253213E 02 5246  0.0           5247  0.0           5248  0.0

5330  0.2700000E 03 5331  0.0           5332  0.0           5333  0.5850000E 03

8036 -0.1236000E-05

8063 -0.1236000E-05

8100 -0.1236000E-05

8132 -0.1236000E-05

9901  0.4000000E 03 9902  0.1000000E 02 9903  0.2000000E 03 9904  0.5000000E 02 9905  0.0           9906  0.0
9907  0.1000000E 03 9908  0.1000000E 03 9909  0.5000000E 02 9910  0.2000000E 03 9911  0.0           9912  0.0
9913  0.3000000E 04 9914  0.1000000E 02 9915  0.2000000E 03 9916  0.5000000E 02 9917  0.0           9918  0.0
9919  0.2000000E 03 9920  0.5000000E 03 9921  0.2000000E 03 9922  0.5000000E 03 9923  0.0           9924  0.0
```

NREG=	5	NRIT=	6	NCAN=	2	NZB=	2	KPC=	100
IMAX=	12	JMAX=	10	ICA=	3	ICB=	10	JCI=	2
JCE=	8	DELT=	0.00100	SI=	0.500000E 09	W=	0.100000E 10	V=	0.260000E 06
IDST=	20	INGR=	30	LF=	30	IBCR=	0	IDIR=	1
EP1=	0.0010	EP2=	0.0010	DAPF=	0.1000	DELTC=	0.001000	DELTI=	0.001000
SPRG=	0.200000E 21	SPB1=	0.200000E-23	SPB2=	0.800000E-23	INTG=	1	NUSO=	1

REG	I1	I2	J1	J2
1	1	12	1	10
2	3	6	1	6
3	3	6	6	8
4	6	10	1	4
5	6	10	4	8

REG	D1	SR	P	SF1	SOR	EQUI1	KV
1	0.137000C0E C1	0.3333998E-02	0.100000E 01	0.0	0.0	0.0	1
2	0.134999C0E C1	0.3380000E-02	0.100000E 01	0.0	0.0	0.3171999E-10	2
3	0.134999C0E C1	0.3330000E-02	0.100000E 01	0.0	0.0	0.3171999E-10	3
4	0.134999C0E C1	0.3330000E-02	0.100000E 01	0.0	0.0	0.3171999E-10	4
5	0.134999C0E C1	0.3330000E-02	0.100000E 01	0.0	0.0	0.3171999E-10	5

REG	D2	SA	SPR	SF2	FNU	EQUI2	TRU	TRM
1	0.300000C0E C0	0.6133999E-04	0.0	0.0	0.0	0.0	0.0	0.0
2	0.977000C0E 00	0.4519999E-02	0.0	0.5199999E-02	0.2459999E 01	0.3171999E-10	800.00	290.00
3	0.977000C0E C0	0.4633999E-02	0.0	0.5179998E-02	0.2459999E 01	0.3171999E-10	800.00	290.00
4	0.977000C0E C0	0.4229936E-02	0.0	0.5050000E-02	0.2459999E 01	0.3171999E-10	800.00	290.00
5	0.977000C0E C0	0.4770000E-02	0.0	0.5149998E-02	0.2459999E 01	0.3171999E-10	800.00	290.00

RIT	DL	BETA
1	0.125000C0E-01	0.213000C0E-03
2	0.316000C0E-01	0.111600C0E-02
3	0.123000C0E C0	0.977000C0E-03
4	0.312000C0E C0	0.163700C0E-02
5	0.116000C0E C1	0.933000C0E-03
6	0.274000C0E C1	0.135000C0E-03

X

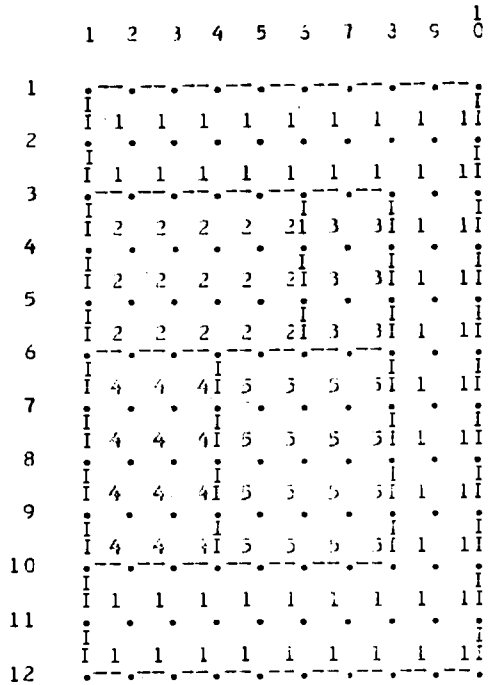
-30.000	30.000	60.000	90.000	120.000	160.000	200.000	230.000	240.000	250.000

Y

0.0 592.000	20.000 612.000	40.000	116.000	192.000	268.000	344.000	420.000	496.000	572.000

ZONE RADIALI

ZONE	J13	J23	KBC	KB	KCA	VEBA1	VEBA2
1	1	5	0	1	1	0.400000E-04	0.4499999E-03
2	5	9	0	2	2	0.400000E-04	0.4499999E-03


1 2 3 4 5 6 7 8 9 10
1 1 1 1 1 1 1 1 1 1
2 1 1 1 1 1 1 1 1 1
3 2 2 2 2 2 3 3 1 1
4 2 2 2 2 2 3 3 1 1
5 2 2 2 2 2 3 3 1 1
6 4 4 4 5 5 5 5 1 1
7 4 4 4 5 5 5 5 1 1
8 4 4 4 5 5 5 5 1 1
9 4 4 4 5 5 5 5 1 1
10 1 1 1 1 1 1 1 1 1
11 1 1 1 1 1 1 1 1 1
12

Core map

CANALE 1

SEZ.CAN.= 0.1300C0E C1 DZ= C.760C00E 02 SC= C.540000E 01 RO= C.800000E 00

PALN1= 2478. N1= 3 CSE1= C.286C00E C3

RES1	CPT1	PZO1	VOL
0.775000E-01	0.447000E-01	0.200000E 00	0.119383E 02
0.283000E-01	0.447000E-01	0.200000E 00	0.119383E 02
0.184700E-01	0.447000E-01	0.200000E 00	0.119383E 02
0.139300E-01	0.447000E-01	0.200000E 00	0.119383E 02
0.686000E-02	0.447000E-01	0.200000E 00	0.119383E 02
0.377000E-02	0.591000E-01	0.0	0.125324E 02

CANALE 2

SEZ.CAN.= 0.130000E C1 DZ= C.760000E 02 SC= C.540000E 01 RO= C.800000E 00

PALN1= 6528. N1= 3 CSE1= C.286000E C3

RES1	CPT1	PZO1	VOL
0.775000E-01	0.447000E-01	0.200000E 00	0.119383E 02
0.283000E-01	0.447000E-01	0.200000E 00	0.119383E 02
0.184700E-01	0.447000E-01	0.200000E 00	0.119383E 02
0.139300E-01	0.447000E-01	0.200000E 00	0.119383E 02
0.686000E-02	0.447000E-01	0.200000E 00	0.119383E 02
0.377000E-02	0.591000E-01	0.0	0.125324E 02

Channel data

TEMPERATURE COEFFICIENTS

REG. 1	ALFA 1	ALFA 2	ALFA 3	ALFA 4
P	C.C	0.0	C.C	0.0
REG. 2	ALFA 1	ALFA 2	ALFA 3	ALFA 4
P	-C.12553338-05	C.0	0.C	0.0
REG. 3	ALFA 1	ALFA 2	ALFA 3	ALFA 4
P	-C.12553998-05	0.0	0.0	C.0
REG. 4	ALFA 1	ALFA 2	ALFA 3	ALFA 4
P	-0.12553998-05	0.0	0.0	0.0
REG. 5	ALFA 1	ALFA 2	ALFA 3	ALFA 4
P	-0.12553998-05	0.0	0.0	0.0

RICERCA CRITICITA

REGIONI AVVELENATE

1 2 3 4 5

ITERAZIONI	DELT	REP	VELENO	IDER
1	0.10000E-02	0.28735D 02	0.0	2
2	0.10000E-02	-0.36366D 03	0.19999999D 21	1
3	0.10000E-02	-0.48248D 01	0.14645926D 20	15
4	0.10000E-02	0.15345D 01	0.12153696D 20	18
5	0.10000E-02	0.31389D 00	0.12755075D 20	31
6	0.10000E-02	0.19258D-01	0.12912832D 20	31
7	0.10000E-02	-0.34035D-02	0.12925745D 20	
8	0.10000E-02	-0.27554D-01	0.12938658D 20	
9	0.10000E-02	-0.52522D-01	0.12951571D 20	
10	0.10000E-02	-0.78658D-01	0.12964483D 20	

TEMPO TOTALE DI CALCOLO SEC. 19.090 TEMPO DI SOLO CRITIC SEC. 11.340

Criticality Search

3 DATI SU NASTRO

FLUX 1 RISULTATI DEL CRITIC

0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.51905E 13	0.51[illegible] 13	0.52621E 13	0.53269E 13	0.53726E 13	0.45240E 13	0.25849E 13	0.96094E 12	0.37967E 12	0.0
0.24241E 14	0.24241E 14	0.24[illegible]33E 14	0.24317E 14	0.25378E 14	0.21462E 14	0.12267E 14	0.39230E 13	0.14363E 13	0.0
0.88432E 14	0.88432E 14	0.89[illegible] 14	0.89389E 14	0.90504E 14	0.75323E 14	0.42674E 14	0.13700E 14	0.50182E 13	0.0
0.11935E 15	0.11935E 15	0.119[illegible]E 15	0.11925E 15	0.11835E 15	0.98239E 14	0.55553E 14	0.17531E 14	0.65332E 13	0.0
0.11990E 15	0.11990E 15	0.11521E 15	0.10310E 15	0.10240E 15	0.83603E 14	0.47727E 14	0.15381E 14	0.56441E 13	0.0
0.10007E 15	0.10007E 15	0.92[illegible]E 14	0.81433E 14	0.72210E 14	0.58357E 14	0.33557E 14	0.10954E 14	0.39884E 13	0.0
0.71489E 14	0.71489E 14	0.65441E 14	0.55302E 14	0.49624E 14	0.39241E 14	0.22476E 14	0.72641E 13	0.26690E 13	0.0
0.41771E 14	0.41771E 14	0.33133E 14	0.32788E 14	0.28672E 14	0.22575E 14	0.12904E 14	0.41680E 13	0.15309E 13	0.0
0.10513E 14	0.10513E 14	0.96[illegible]2E 13	0.84506E 13	0.75400E 13	0.60234E 13	0.34581E 13	0.11111E 13	0.40787E 12	0.0
0.22263E 13	0.22263E 13	0.20505E 13	0.18049E 13	0.16059E 13	0.12742E 13	0.72881E 12	0.24359E 12	0.10754E 12	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Print type n3

Flux map

These flux maps (pages 60 and 61) correspond to the equilibrium conditions after criticality search. Results are stored on tape. The calculation was restarted from this point. See page 49.

FLUX 2

0.0	0.0	0.0	0.0	C.0	C.0	0.C	0.0	0.0	0.0
0.31530E 14	0.31530E 14	0.31887E 14	0.32622E 14	0.34250E 14	0.29805E 14	0.17290E 14	0.68421E 13	0.34206E 13	0.0
0.51329E 14	C.51329E 14	C.5136CE 14	0.52316E 14	0.55098E 14	0.47155E 14	0.27C95E 14	0.114C1E 14	0.62117E 13	0.C
0.145C0E 15	C.14500E 15	0.14536E 15	0.14761E 15	0.15158E 15	C.12722E 15	C.72331E 14	C.3C938E 14	C.17311E 14	0.0
0.19623E 15	C.19623E 15	0.19565E 15	0.19558E 15	0.19878E 15	C.16570E 15	0.94035E 14	0.40210E 14	0.22499E 14	0.0
0.20034E 15	0.20034E 15	0.19223E 15	C.17314E 15	0.17001E 15	0.14033E 15	0.80621E 14	0.34659E 14	0.19437E 14	0.C
0.17072E 15	C.17072E 15	0.15767E 15	0.13488E 15	0.12002E 15	0.97472E 14	0.56571E 14	0.24437E 14	C.13735E 14	0.C
0.12201E 15	C.12201E 15	0.11142E 15	C.93607E 14	C.81797E 14	0.65540E 14	0.37885E 14	0.16354E 14	0.91909E 13	0.0
0.71372E 14	C.71372E 14	C.65003E 14	C.54386E 14	C.47318E 14	0.37751E 14	0.21781E 14	0.93954E 13	0.52792E 13	0.0
0.23101E 14	0.23101E 14	0.21192E 14	0.18113E 14	0.16175E 14	0.13124E 14	0.76C81E 13	0.32215E 13	0.17611E 13	0.0
0.13687E 14	0.13687E 14	0.12613E 14	0.11100E 14	0.10230E 14	0.83839E 13	0.48623E 13	0.193C6E 13	C.96621E 12	0.0
0.0	C.0	0.0	0.0	0.0	C.0	0.C	C.0	C.0	0.0

Print type n_3

ITS = 1 RESIDUAL 0.41390E 12 RE2 0.52446E 16 TO = 0.0 IT = 0

CORE AVERAGE	FLUX 1	FLUX 2	PCWER	DP2	REP	TO
	0.[illegible]E 14	C.34648D 14	C.50000E 09	-0.66795D 13	-0.78558D-01	C.C

Print type n_8

CHANNEL N 1 TIME = 0.100 MASS FLOW = 0.5850000E 03

3	0.0	0.0	0.0	0.0	0.0	0.0	270.000
4	671.836	567.035	491.000	416.971	342.916	297.564	272.617
5	1037.563	838.768	694.205	553.187	411.859	325.152	277.471
6	1206.237	965.557	790.196	618.856	446.878	341.205	283.111
7	1119.143	902.837	745.132	590.818	435.768	340.401	287.982
8	969.476	793.597	665.059	539.177	412.537	334.548	291.690
9	838.803	698.194	595.126	493.920	391.858	328.855	294.248
10	643.919	554.410	488.593	423.798	358.298	317.769	295.517

AVERAGE TEMPERATURES

3	0.0	0.0
4	497.951	272.617
5	707.116	277.471
6	805.545	283.111
7	758.752	287.982
8	675.968	291.690
9	603.580	294.248
10	493.804	295.517

Print type n8

CHANNEL N 2 TIME = C.1CO MASS FLOW = C.5850000E 03

3	0.0	C.C	C.0	0.0	0.C	0.0	270.000
4	486.375	430.033	338.902	349.001	309.226	284.952	271.591
5	716.701	630.734	516.597	434.609	352.552	302.276	274.621
6	816.607	676.034	573.747	473.795	373.508	311.909	278.042
7	733.384	613.948	529.930	445.812	361.311	309.347	280.793
8	620.879	533.C35	468.910	406.109	342.953	304.073	282.706
9	527.331	464.327	418.219	373.002	327.460	299.380	283.953
10	422.485	336.833	36C.793	335.158	309.299	293.332	284.561

AVERAGE TEMPERATURES

3	C.C	C.C
4	362.823	271.591
5	524.245	274.621
6	532.743	278.042
7	537.377	280.733
8	471.381	282.706
9	422.063	283.953
10	362.926	284.561

Print type n8

TIME 0.100 TOTAL ENERGY 0.48166E 08 AVERAGE ENERGY 0.54478E CC

PERCENT OF CORE WITH ENERGY LESS THAN

100.000 C.1CCJCE 02

0.C

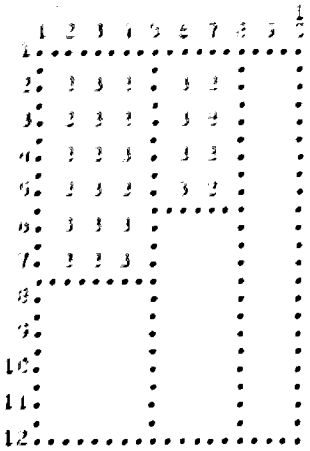
Print type n9

CORE AVERAGE FLUX 1 FLUX 2 POWER DP2 REP TO

[illegible] INSERTION OF TIME 0.200

CRITICAL ZONE 1 2

INJECTION QA. 337.00 343.00



Print type n4

Print type n7

MAX. TEMP. AT TIME 0.200

TYPE 1

CHANNEL	LEVEL	CENTER	LEVEL	SURFACE	LEVEL	H.FLOW	INLET	OUTLET	M.FLOW
1	7	3967.123	9	540.023	9	219.701	270.000	303.881	0.58500E 03
2	9	1390.876	9	358.231	9	66.643	270.000	296.847	0.58500E 03

MAP OF INTEGRATED ENERGIES AT TIME C.4C0

0.2336E 01	C.2333E 01	0.2191E 01	0.1965E 01	0.1667E 01	0.1137E 01	0.5914E 00	0.2470E 00
C.7611E 01	C.7611E 01	0.7124E 01	0.6362E 01	C.5394E 01	0.3660E 01	0.1892E 01	0.8018E 00
0.1563E 02	C.1587E 02	0.1471E 02	0.1232E 02	0.1083E 02	0.7317E 01	0.3782E 01	0.1602E 01
C.3232E 02	C.3202E 02	0.2871E 02	0.2377E 02	0.1914E 02	0.1301E 02	0.6830E 01	0.2902E 01
0.5726E 02	C.5726E 02	0.5080E 02	0.4585E 02	0.3515E 02	0.2367E 02	0.1249E 02	0.5292E 01
0.1151E 03	0.1151E 03	0.9966E 02	0.7534E 02	0.5564E 02	C.3561E 02	0.1834E 02	0.7672E 01
0.1139E 03	C.1133E 03	0.9357E 02	C.7467E 02	0.5346E 02	0.3301E 02	C.1671E 02	0.6946E 01
C.4691E 02	0.4691E 02	0.4056E 02	0.3630E 02	0.2220E 02	0.1364E 02	0.6883E 01	0.2799E 01

Print Type n10

TIME 0.4C0 TOTAL ENERGY C.1820E 10 AVERAGE ENERGY 0.2058E 02

PERCENT OF CORE WITH ENERGY LESS THAN

44.133 C.1CCCOE C2

55.867

Print Type n9

CORE AVERAGE	FLUX 1	FLUX 2	POWER	DP2	REP	TO
	0.8827E 15	0.1534E 16	0.8861E 10	0.5003D 16	0.3254D 01	0.4100E 00
CORE AVERAGE	FLUX 1	FLUX 2	POWER	DP2	REP	TO
	C.9281E 15	C.1561D 16	0.9239E 10	0.5841D 16	0.3675D 01	C.4200E 00
CORE AVERAGE	FLUX 1	FLUX 2	POWER	DP2	REP	TO
	0.9391E 15	0.1591D 16	0.9626E 10	0.5704D 16	0.3466D 01	0.4300E 00
CORE AVERAGE	FLUX 1	FLUX 2	POWER	DP2	REP	TO

Print Type n2

(4) DATI SU NASTRO

RISULTATI DEL CALCOLC AL TEMPO 0.20C IT = 200

This print indicates that at time 0.2 sec. the results were stored on tape. The number (4) indicates that, to restart from this point, the titel card must contain 4 in the third column and 4 DD statements must be given.
(See pages 42, 50, 51)

Some date were changed, they are printed in the new calculation:

1	0.500000E 01	2	0.200000E-02	3	0.100000E-02	4	0.120000E 02	5	0.100000E 02	6	0.500000E 01	
3061	0.0	3062	0.200000E 00	3063	0.500000E 00							
3091	0.0	3092	0.245000E 03	3093	0.612000E 03							
9901	0.200000E 03	9902	0.0	9903	0.0	9904	0.0	9905	0.0	9906	0.0	
9907	0.0	9908	0.0	9909	0.0	9910	0.0	9911	0.0	9912	0.0	
9913	0.300000E 03	9914	0.500000E 01	9915	0.100000E 03	9916	0.250000E 02	9917	0.0	9918	0.0	
9919	0.500000E 02	9920	0.500000E 02	9921	0.250000E 02	9922	0.100000E 03	9923	0.0	9924	0.0	
9925	0.600000E 03	9926	0.500000E 01	9927	0.100000E 03	9928	0.250000E 02	9929	0.0	9930	0.0	
9931	0.100000E 03	9932	0.250000E 03	9933	0.100000E 03	9934	0.250000E 03	9935	0.0	9936	0.0	

Appendix A

The two diffusion equations are:

1) $$D_1 \nabla^2 \psi - \Sigma_R \psi + (1-\beta)\cdot(\Sigma_{f1}\cdot\psi + \Sigma_{f2}\cdot\varphi) + \sum_{i=1}^{N} \lambda_i C_i = \frac{1}{v}\frac{\partial \psi}{\partial t}$$

2) $$D_2 \nabla^2 \varphi - \Sigma_a \varphi + \Sigma_R \cdot p \cdot \psi = \frac{1}{v}\frac{\partial \varphi}{\partial t}$$

by reordering and substituting the time derivative with its finite-different expression for a time interval Δt, equation 2) takes the new expression

3) $$D_2 \nabla^2 \varphi - A'\varphi + B\psi + C' = \frac{1}{v}\frac{\varphi - \varphi^*}{\Delta t}$$

the new expression for eq. 1) is formally the same, therefore all the following discussions will refer only to eq. 3) as representative for both fast and thermal group.
By putting:

$$A = A' + \frac{1}{v\cdot\Delta t} \quad \text{and} \quad C = C' + \frac{\varphi^*}{v\cdot\Delta t}$$

and reordering, then eq. 3) becomes:

4) $$D\nabla^2\varphi - A\cdot\varphi + B\cdot\psi + C = 0$$

This equation is now integrated over the sector

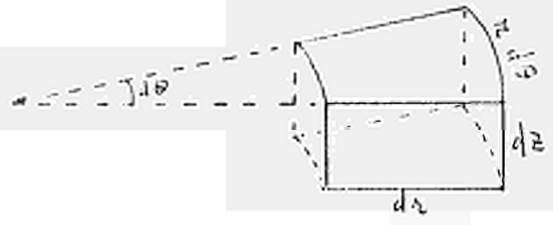


Fig. 5

$$5)\quad D\iiint [\nabla^2 \varphi]\cdot dz\cdot dr\cdot r\,d\theta - \iiint A\varphi + \iiint B\varphi + \iiint C = 0$$

For the theorem of Green the volume integral of the Laplace operator of φ, is equal to the integral over the surface of the volume, of the grädient of φ normal to the surface:

$$D\iiint_V \nabla^2\varphi\cdot dz\cdot dr\cdot r\,d\theta = D\iint_S \frac{\delta\varphi}{\delta n}\,ds$$

Equation 5) then becomes:

$$6)\quad -D\iint_S \frac{\delta\varphi}{\delta n}\,ds + \iiint A\varphi - \iiint B\varphi - \iiint C = 0$$

all the signs have been changed in order to have a coefficient matrix with positive entries in the main diagonal and negative all the other entries.

Each integral term of eq. 6) will now be transformed into a finite-different expression where the flux $\varphi_{i,j}$ is considered constant in the volume corresponding to the point (i,j) of the lattice. This volume has been divided into four sub-volumes Vol. 1,2,3,4; within each sub-volume the physical characteristic of the medium are constant.

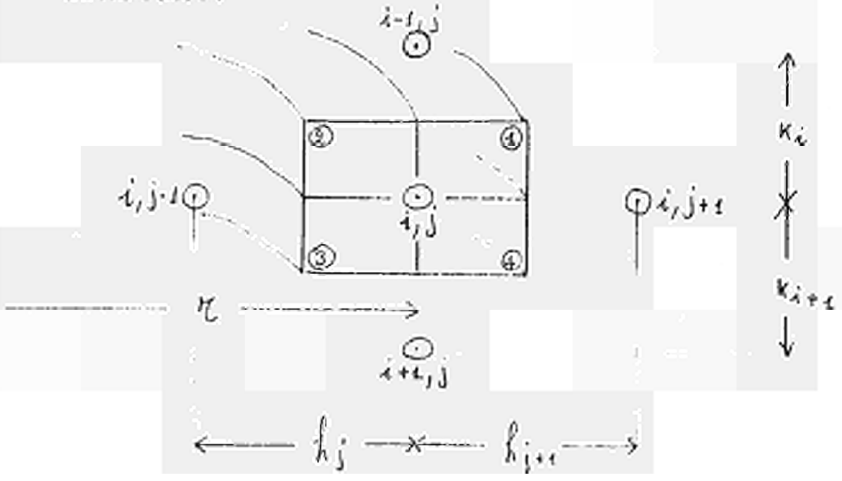


Fig. 6

Here below are the expressions for each term; with the help of fig. 6 they are self explanatory:

7) $$D \iint_S \frac{\partial \varphi}{\partial n} dS = - \frac{\varphi_{ij} - \varphi_{i-1,j}}{h_j} \left[D_2 \frac{k_i}{2} + D_3 \frac{K_{i+1}}{2} \right] \cdot \left(r - \frac{h_j}{2} \right) 2\pi$$

$$+ \frac{\varphi_{i,j+1} - \varphi_{ij}}{h_{j+1}} \left[D_1 \frac{k_i}{2} + D_4 \frac{K_{i+1}}{2} \right] \cdot \left(r + \frac{h_{j+1}}{2} \right) 2\pi$$

$$- \frac{\varphi_{ij} - \varphi_{i-1,j}}{K_i} \left[D_1 \frac{h_{j+1}}{2} \left(r + \frac{h_{j+1}}{4} \right) + D_2 \frac{h_j}{2} \left(r - \frac{h_j}{4} \right) \right] 2\pi$$

$$- \frac{\varphi_{i+1,j} - \varphi_{ij}}{K_{i+1}} \left[D_3 \frac{h_j}{2} \left(r - \frac{h_j}{4} \right) + D_4 \frac{h_{j+1}}{2} \left(r + \frac{h_{j+1}}{4} \right) \right] 2\pi$$

8) $$\iiint A \cdot \varphi \cdot dz \cdot dr \cdot r \, d\theta =$$

$$\varphi_{ij} \cdot A① \left[\frac{k_i}{2} \frac{h_{j+1}}{2} \left(r + \frac{h_{j+1}}{4} \right) \right] \cdot 2\pi$$

$$+ \varphi_{ij} \, A② \left[\frac{k_i}{2} \frac{h_j}{2} \left(r - \frac{h_j}{4} \right) \right] \cdot 2\pi$$

$$+ \varphi_{ij} \, A③ \left[\frac{K_{i+1}}{2} \frac{h_j}{2} \left(r - \frac{h_j}{4} \right) \right] \cdot 2\pi$$

$$+ \varphi_{ij} \, A④ \left[\frac{K_{i+1}}{2} \frac{h_{j+1}}{2} \left(r + \frac{h_{j+1}}{4} \right) \right] 2\pi$$

9) $$\iiint B\,\psi = \psi_{ij}\cdot B_{①}\cdot V\phi L1\cdot 2\pi + \psi_{ij}\cdot B_{②}\cdot V\phi L2\cdot 2\pi + \psi_{ij}\cdot B_{③}\cdot V\phi L3\cdot 2\pi + \psi_{ij}\cdot B_{④}\cdot V\phi L4\cdot 2\pi$$

10) $$\iiint C = C_{ij}\ V\phi L1\cdot 2\pi + C_{ij}\ V\phi L2\cdot 2\pi + C_{ij}\ V\phi L3\cdot 2\pi + C_{ij}\ V\phi L4\cdot 2\pi$$

where VØL 1,2,3,4 . 2π are the subvolumes of fig. 6, or the expressions in parenthesis $\lceil\ \rfloor$ of eq. 8),

the integration in θ has been made over the whole circumference and due to the axial symmetry, it is only a multiplication with 2π. This factor being common to all terms can be eliminated.

The final expression of the equation after reordering is:

11) $$-\alpha_{ij}\cdot\varphi_{i-1,j} - \beta_{ij}\cdot\varphi_{i,j-1} - \gamma_{ij}\cdot\varphi_{i+1,j} - \delta_{ij}\cdot\varphi_{i,j+1} + \varepsilon_{ij}\cdot\varphi_{ij} = b_{ij}\cdot\psi_{ij} + c_{ij}$$

where $$\alpha_{ij} = \frac{D_1 \frac{h_{j+1}}{2}\left(r + \frac{h_{j+1}}{4}\right) + D_2 \frac{h_j}{2}\left(r - \frac{h_j}{4}\right)}{K_i}$$

$$\beta_{ij} = \frac{\left(r - \frac{h_j}{2}\right)\left[D_2 \frac{K_i}{2} + D_3 \frac{K_{i+1}}{2}\right]}{h_j}$$

$$\gamma_{ij} = \frac{D_4 \frac{h_{j+1}}{2}\left(r + \frac{h_{j+1}}{4}\right) + D_3 \frac{h_j}{2}\left(r - \frac{h_j}{4}\right)}{K_{i+1}}$$

$$\delta_{ij} = \frac{\left(r + \frac{h_{j+1}}{2}\right)\left[D_1 \frac{K_i}{2} + D_4 \frac{K_{i+1}}{2}\right]}{h_{j+1}}$$

$$\varepsilon_{ij} = \alpha_{ij} + \beta_{ij} + \gamma_{ij} + \delta_{ij} +$$

$$+ \frac{h_{j+1}}{2}\left(r + \frac{h_{j+1}}{4}\right)\left[A_{①}\frac{K_i}{2} + A_{②}\frac{K_{i+1}}{2}\right] + \frac{h_j}{2}\left(r - \frac{h_j}{4}\right)\left[A_{②}\frac{K_i}{2} + A_{③}\frac{K_{i+1}}{2}\right]$$

$$b_{ij}\psi_{ij} + c_{ij} = \varphi_{ij}\left[B_1 Vol_1 + B_2 Vol_2 + B_3 Vol_3 + B_4 Vol_4\right] +$$

$$+ \left[C_1 Vol_1 + C_2 Vol_2 + C_3 Vol_3 + C_4 Vol_4\right]$$

It can be verified that: $\delta_{ij} = \beta_{i,j+1}$

and $\gamma_{ij} = \alpha_{i+1,j}$

the pentadiagonal matrix of the coefficients is symmetric.
The equation 11) can be written:

11) $$-\alpha_{ij}\cdot\varphi_{i-1,j} - \beta_{ij}\cdot\varphi_{i,j-1} - \alpha_{i+1,j}\cdot\varphi_{i+1,j} - \beta_{i,j+1}\cdot\varphi_{i,j+1} + \varepsilon_{ij}\cdot\varphi_{ij} = b_{ij}\psi_{ij} + c_{ij}$$

it is possible therefore to avoid the storage of the two reactor γ and δ .

4673 c.

Appendix B

Error due to the time discretization in steps of length Δt.

Let us consider the one-group time dependent diffusion equation:

$$D \nabla \varphi - \Sigma_a \varphi + K \Sigma_a \varphi = \frac{1}{v} \frac{\partial \varphi}{\partial t}$$

neglecting the spatial flux distribution and the diffusion term the eq. reduces to:

$$\frac{\delta K}{l} \varphi = \frac{\delta \varphi}{\delta t} \qquad \text{where} \quad l = \frac{1}{v \Sigma_a}$$

let $\frac{\delta k}{l} = \alpha$ substituting the time derivative with its finite-difference expression we have:

$$\alpha \varphi = \frac{\varphi - \varphi^*}{\Delta t}$$

at the time $t = n \cdot \Delta t$ the value of the flux as determined by this approximation will be :

$$\varphi' = \varphi_0 \left(\frac{1}{1 - \alpha \Delta t} \right)^n \qquad a)$$

whereas the exact analytical solution will give :

$$\varphi'' = \varphi_0 \, e^{n\alpha \Delta t} \qquad b)$$

The appropriate solution φ' exceeds the exact one φ'' by an error :

$$\varepsilon = \frac{\varphi' - \varphi''}{\varphi''} = \frac{\left(1 - \frac{\Delta t}{T}\right)^{-n} - e^{n \frac{\Delta t}{T}}}{e^{n \frac{\Delta t}{T}}}$$

In the range of accidents which can be treated by this code, the power level does not become greater than 10^3 the nominal value. A scram or a temperature reaction will interrupt the increase of power, and in the great majority of cases the increase of power is less than 10 times the nominal value.

Here below are calculated the values of ε for various values of the ratio $\Delta t / T$ between the time step and the reactor period, for an increase of power of 10^3 and 10.

Three decades increase

$$e^{n\frac{\Delta t}{T}} = 10^3$$

$$n\frac{\Delta t}{T} = 3 \cdot \ln_e 10 = 6.90776$$

$$n = 6.9\ldots \Big/ \frac{\Delta t}{T}$$

$$\varepsilon = \frac{(1-\frac{\Delta t}{T})^{\frac{-6,9\ldots}{\Delta t/T}} - 1000}{1000}$$

$\Delta t/T$	ε
0.05	19.7 %
0.01	3.18 %
0.005	—

One decade increase

$$e^{n\frac{\Delta t}{T}} = 10$$

$$n\frac{\Delta t}{T} = \ln_e 10 = 2,3026$$

$$n = 2.3 \Big/ \frac{\Delta t}{T}$$

$$\varepsilon = \frac{(1-\frac{\Delta t}{T})^{\frac{-2.3}{\Delta t/T}} - 10}{10}$$

$\Delta t/T$	ε
0.1	13.1 %
0.05	6.2 %
0.01	1 %

Convergence criterium for the fast and thermal flux

The iterations stop when the residual is smaller than a given value of ε, criterium of convergence :

$$\frac{\sum_{i=1}^{N} |\Delta \varphi_i|}{\sum_{i=1}^{N} \varphi_i} < \varepsilon$$

ε should be smaller than the possible variation of φ in Δt

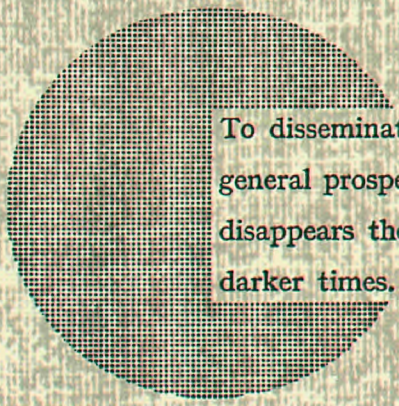
$$\varphi = \varphi_0 \, e^{\frac{\Delta t}{T}}$$

$$\varepsilon < \frac{|\Delta \varphi|}{\varphi} = \left| 1 - e^{\frac{\Delta t}{T}} \right|$$

$$e^{\frac{\Delta t}{T}} = 1 + \frac{\Delta t}{T} + \left(\frac{\Delta t}{T}\right)^2 \frac{1}{2!} + \cdots$$

truncating at the second term and substituting

$$\varepsilon < \frac{\Delta t}{T}$$



To disseminate knowledge is to disseminate prosperity — I mean general prosperity and not individual riches — and with prosperity disappears the greater part of the evil which is our heritage from darker times.

Alfred Nobel

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