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EUROPEAN ATOMIC ENERGY COMMUNITY - EURATOM

**ANALYSIS OF ACCIDENTS IN PULSED
FAST REACTORS : COMPUTER PROGRAMMES
DOPPELAS AND SOREX I**

by

J. RANDLES

1968



Joint Nuclear Research Center
Ispra Establishment - Italy

Reactor Physics Department
Reactor Theory and Analysis

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In this paper, two theories dealing with the two classes of nuclear excursion are sketched and two Fortran 4 computer programmes based on these theories are explained in detail. The first, DOPPELAS, is designed to simulate the «milder» excursions in which the fuel retains its solid state. The second, SOREX 1, simulates the «severe» excursions which destroy the reactor explosively. Detailed examples of the input and output of the programmes are given and the way in which to utilize the input for the analysis of the various types of accident is indicated.

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SUMMARY

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EXCURSIONS
REACTIVITY
REACTOR SAFETY
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D - CODES
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PROGRAMMING

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ANALYSIS OF ACCIDENTS IN PULSED FAST REACTORS :
COMPUTER PROGRAMMES DOPPELAS AND SOREX 1

1. INTRODUCTION (*)

The computer programmes, DOPPELAS and SOREX 1, described in this article have been developed as part of the pulsed fast reactor design project SORA⁽¹⁾, sponsored by Euratom at its research centre at Ispra. Although the immediate need has been to provide methods of analysing accidents in this system alone, the work has been made sufficiently general to permit application to other systems (provided they are not radically different from SORA). Thus, it is hoped that the programmes may be useful to other teams engaged on pulsed fast reactor design work.

In order to systematize the study of pulsed fast reactor safety, it is of great help to classify the various accident conditions under four broad headings, given here in roughly decreasing order of severity:

1. Accidents due to the breakage of the pulsation device.
2. Reactivity accidents with the pulsation device running normally.
3. Fuel melting caused by coolant failure.
4. Reactivity accidents during stationary operation.

The nuclear excursion resulting from any particular accident can vary from "very mild" (small increase in fuel temperature) to "very severe" (large increase), depending on the detailed circumstances. Since the dominating reactivity feedback mechanisms are quite different for an excursion in the "mild" range than for one in the "severe" range, the physical theory used to describe an excursion will depend on its magnitude. The most obvious and logical classification of magnitudes is the following:

Class A Excursion: one of mild or moderate severity in which the fuel remains in the solid state and retains its solid state properties.

Class B Excursion: one which leads to such a large nuclear energy release that the pressure generated in the fuel is able to destroy the core explosively.

(*) Manuscript received on February 27, 1968.

The programme DOPPELAS (in its two slightly differing forms) is designed to treat class A excursions and SOREX 1 deals with class B excursions. The theory and basic equations forming the content of the programmes has already been published^(2,3,4) and it will not be necessary to go deeply into this aspect again. Of more concern here will be the sort of reactor safety problems at which the programmes are aimed, the numerical methods employed to solve the basic equations and the technicalities associated with the practical use of the programmes. For the present introductory chapter it will be sufficient to state that the main variable computed by DOPPELAS and SOREX 1 is the nuclear energy release during an accident and that the accident type (see above list) is important in the theory only in the determination of the time dependent reactivity input $\epsilon_0(t)$.

In accidents of type 1 (which are purely hypothetical and serve only to define a pessimistic upper limit to all hazards) the initiating mechanism is assumed to be a sudden fracture in one of a number of laminar pieces of the pulsation device. The theory by which SOREX 1 computes the consequences of this fracture - the collision of the fragment with the core, the compression of the core into a super prompt critical assembly and the consequent release of a large (class B) fission energy - has already been given in detail⁽⁴⁾. (For a summary, see section 3.2.1).

In accidents of type 2 the base reactivity of the system increases, so that the reactivity pulses are raised bodily to a higher amplitude (without any alteration in shape). This has the effect of generating power pulses with an abnormal fuel temperature rise. If this rise is large the fuel may be damaged, for example, by phase changes or by the thermoelastic shock⁽⁵⁾, and if it is very large it may even destroy the core explosively. To study type 2 accidents, therefore, DOPPELAS and SOREX 1 have been constructed with the option of using a well defined pulse form for the input reactivity $\epsilon_0(t)$ (see sections 2.2.1 and 3.2.2). In the case of SOREX 1, this option is obtained by manipulating the input for a type 1 accident (see section 3.2.2).

In accidents of type 3, fuel melting may commence either before or after the pulsation device has been stopped. (For the SORA reactor it is

always after). If it commences before, it has the effect of raising the level of the reactivity pulses (as above) and the situation becomes similar to a type 2 accident. If melting commences after the stoppage of the pulsation device, however, there arises a situation akin to the maximum accident in a fast power reactor: the core slumps into a prompt critical configuration and a class B excursion is generated. In order to evaluate the energy release for this accident, SOREX 1 is equipped with an option which provides a ramp input form for the reactivity $\epsilon_0(t)$. As for a type 2 accident, this option is obtained by manipulating the input for a type 1 accident (see section 3.2.3).

In accidents of type 4, which can occur only during the relatively few occasions when a pulsed fast reactor is being operated in a steady-state condition, a reactivity drift takes the reactor to prompt criticality. If the drift rate is very large, the resulting excursion will be destructive and the energy release can be calculated by using SOREX 1 in the same way as in a type 3 accident - with the ramp input form for $\epsilon_0(t)$. It is almost certain, however, that reactivity drifts of such a magnitude are unattainable and, even in the worst cases, the excursion will be terminated by the thermal expansion of the fuel well before melting occurs. To analyse this situation, DOPPELAS has also been provided with a ramp input option for $\epsilon_0(t)$ (see section 2.2.2).

DOPPELAS and SOREX 1 have been written in Fortran 4 for both the IBM 7090 and IBM 360/65 machines and are obtainable from the ENEA Computer Programme Library, Casel. Post. 15, Ispra (Varese), Italy. The applications described in the above four paragraphs are illustrative of the main uses to which the programmes have been put in the SORA project. Other uses could also be specified, but the reader will no doubt formulate these for himself in the light of his own needs and problems.

2. CLASS-A EXCURSIONS; THE PROGRAMME DOPPELAS

2.1 Theoretical Basis

A physical and mathematical model for the description of Class A excursions has been developed previously^(2,3) and will therefore only be summarized here. The central point in the theory is the fact that, during a class A excursion, the feedback of reactivity is due almost entirely to the Doppler effect and the axial thermal expansion of the fuel slugs (assumed to be continuous straight bars). Other effects, such as the thermal expansion of the coolant and structure, are too delayed by heat transfer to play a role during the very short times characteristic of pulsed fast reactor excursions.

Hence, it turns out that the feedback processes for a class A excursion can be characterized by two reactor constants: the Doppler coefficient of reactivity γ_{Dopp} and the axial fuel expansion coefficient of reactivity γ_{Exp} . It has been shown⁽³⁾ that, with certain approximations, the feedback reactivities arising from the Doppler effect and the axial thermal expansion of the fuel slugs (which occurs, in general, via the excitation of elastic waves), are given by

$$\tilde{\epsilon}_{\text{Dopp}}(t) = 2 \gamma_{\text{Dopp}} T_A \left\{ 1 - \left(1 + \frac{Q(t)}{HT_A} \right)^{-1/2} \right\} \quad (2.1)$$

and

$$\tilde{\epsilon}_{\text{Elas}}(t) = \frac{4\alpha c}{H} \gamma_{\text{Exp}} \int_0^t J\left(\frac{ct'}{L}\right) Q(t-t') dt' \quad (2.2)$$

respectively. In these expressions T_A is the absolute mean fuel temperature at the beginning of the excursion (at which γ_{Dopp} must be evaluated), H the specific heat of the fuel, α the coefficient of linear expansion of the fuel, c the speed of longitudinal waves propagating axially along the fuel slugs (whose half-length is L) and $Q(t)$ the mean fission energy release

per unit mass of fuel as a function of the time t after the onset of the excursion. The function J is given by

$$J(\theta) = \begin{cases} \theta & \text{for } 0 \leq \theta \leq 1 \\ 2 - \theta & \text{for } 1 \leq \theta \leq 3 \\ \theta - 4 & \text{for } 3 \leq \theta \leq 5 \\ 6 - \theta & \text{for } 5 \leq \theta \leq 7 \\ \theta - 8 & \text{for } 7 \leq \theta \leq 9 \dots \text{etc.} \end{cases} \quad (2.3)$$

Denoting the prompt reactivity input generating the excursion by $\epsilon_p(t)$ as in the introduction (section 1), the total instantaneous prompt reactivity is given by

$$\epsilon(t) = \epsilon_o(t) + \tilde{\epsilon}_{\text{Dopp}}(t) + \tilde{\epsilon}_{\text{Elas}}(t) \quad (2.4)$$

The energy release Q is assumed⁽⁶⁾ to be governed by the point reactor kinetics equation

$$\tau \ddot{Q} = \epsilon \dot{Q} + \epsilon_{oo} S \quad (2.5)$$

where τ is the prompt neutron lifetime and $-\epsilon_{oo}$ and S are respectively the prompt reactivity and mean power per unit mass of fuel at the beginning of the excursion. Because the excursion is very short in comparison with the decay time of the delayed neutron emitters, S can be considered as a constant. Assuming the system to be initially in a steady state, the boundary conditions to the problem are

$$Q(0) = 0, \quad \dot{Q}(0) = S \quad (2.6)$$

which imply that $\tilde{\epsilon}_{\text{Dopp}}(0) = \tilde{\epsilon}_{\text{Elas}}(0) = 0$ and $\epsilon_o(0) = -\epsilon_{oo}$.

For purposes of numerical analysis, the integral in (2.2) can be eliminated⁽³⁾ to give

$$\ddot{\epsilon}_{Elas} = \frac{4\alpha c^2}{HL} \delta_{Exp} \left[Q(t) - 2 \sum_{m=0}^{\infty} (-1)^m Q\left(t - (2m+1)\frac{L}{c}\right) \right] \quad (2.7)$$

where now it is assumed that $Q(t) = 0$ if $t \leq 0$. It is of interest to note that L/c is the wave transit time along the fuel slug half-length.

2.2 Reactivity Input

2.2.1 Pulse Form of Input-DOPPELAS 1

In order to simulate the reactivity input of a pulsed fast reactor under all conditions where the pulsation device is operating normally, the first version of DOPPELAS adopts the following formulae^(3,4)

$$\epsilon_o(t) = \max \left[\epsilon_p(t-t^*); -\epsilon_{oo} \right] \quad (2.8)$$

where

$$\epsilon_p(t') = \begin{cases} rt' + \epsilon_m + \frac{r^2}{4B} & \text{for } t' \leq -t_o \\ \epsilon_m - Bt'^2 & \text{for } -t_o \leq t' \leq t_o \\ -rt' + \epsilon_m + \frac{r^2}{4B} & \text{for } t' \geq t_o \end{cases} \quad (2.9)$$

$$t^* = \frac{1}{r} \left(\epsilon_{oo} + \epsilon_m + \frac{r^2}{4B} \right) \quad (2.10)$$

and

$$t_0 = \frac{r}{2B}$$

Here, $-\epsilon_{00}$ is again the base reactivity from which the pulse begins at $t = 0$, t^* is a half of the total duration of the pulse, r the ramp rate of rise (fall) of the pulse during its initial (final) stage, ϵ_m the maximum prompt reactivity and B a sharpness parameter. The idea of using a parabolic approximation at the peak originated with the Russian IBR reactor⁽⁷⁾ but the inclusion of linear sides resulted from studies in the SORA project⁽⁸⁾. In the above formulation, the duration of each of the ramp parts of the pulse is $t_{\text{ramp}} = t^* - t_0$, i.e.

$$t_{\text{ramp}} = \frac{1}{r} \left(\epsilon_{00} + \epsilon_m - \frac{r^2}{4B} \right) \quad (2.11)$$

The duration of the parabolic part is $t_{\text{para}} = 2t_0$, i.e.

$$t_{\text{para}} = \frac{r}{B}$$

2.2.2 Ramp/Step Form of Input-DOPPELAS 2

In order to simulate an accidental drift or step change in reactivity during steady operation when the pulsation device is stationary, the second version of DOPPELAS uses the expression

$$\epsilon_0(t) = \begin{cases} rt - \epsilon_{00} & \text{for } 0 \leq t \leq t'_{\text{ramp}} \\ \epsilon_m & \text{for } t \geq t'_{\text{ramp}} \end{cases} \quad (2.12)$$

where r is the ramp rate of increase of the reactivity to the constant maximum ϵ_m and

$$t'_{\text{ramp}} = \frac{\epsilon_{00} + \epsilon_m}{r} \quad (2.13)$$

is the duration of this ramp. The initial reactivity, $-\epsilon_{00}$, will normally represent the delayed critical condition and will therefore be different from the $-\tilde{\epsilon}_{00}$ for the pulsed condition.

It will be noted that, for the pulse input (2.8), the dominant mechanism for terminating an excursion is the die-away of the input $\epsilon_0(t)$ itself. For the ramp/step input (2.12), on the contrary, the shut-down comes entirely from the inherent feedback processes ($\tilde{\epsilon}_{\text{Dopp}}$ and $\tilde{\epsilon}_{\text{Elas}}$).

2.3 Numerical Method

The problem for DOPPELAS is essentially that of simultaneously solving equations (2.5) and (2.7), equations (2.1), (2.4) and (2.6) being only supplementary. As described in a previous paper⁽³⁾ the method adopted is a simple application of the standard method of finite difference representation. By introducing a uniform chain of time points $t_n = n \Delta t$, where Δt is some suitably small interval, the differential equations (2.5) and (2.7) can be written approximately in terms of the discreet values of $Q(t)$ and $\tilde{\epsilon}_{\text{Elas}}(t)$ at these points. For (2.5) we have

$$\tau \frac{Q(t_{n+1}) - 2Q(t_n) + Q(t_{n-1}))}{\Delta t^2} = \epsilon(t_n) \frac{Q(t_{n+1}) - Q(t_{n-1}))}{2\Delta t} + \epsilon_{00} S \quad (2.14)$$

where

$$\epsilon(t_n) = \epsilon_0(t_n) + \tilde{\epsilon}_{\text{Dopp}}(t_n) + \tilde{\epsilon}_{\text{Elas}}(t_n) \quad (2.15)$$

and for (2.7)

$$\begin{aligned} & \tilde{\epsilon}_{Elas}(t_n) - 2\tilde{\epsilon}_{Elas}(t_{n-1}) + \tilde{\epsilon}_{Elas}(t_{n-2}) \\ &= \frac{4\alpha c^2 \Delta t^2}{HL} \gamma_{Exp} \left[Q(t_{n-1}) - 2 \sum_{m=0}^{\infty} (-1)^m Q(t_{n-1} - (2m+1)\frac{L}{c}) \right] \end{aligned} \quad (2.16)$$

$\gamma_{Dopp}(t_n)$ is evaluated from (2.1) and $\epsilon_o(t_n)$ from (2.8) in DOPPELAS 1 and (2.12) in DOPPELAS 2.

Considering the boundary conditions in the form

$$\begin{aligned} Q(0) &= 0, & Q(\Delta t) &= S \Delta t \\ \tilde{\epsilon}_{Elas}(0) &= 0, & \tilde{\epsilon}_{Elas}(\Delta t) &= \frac{4\alpha c^2 S \Delta t^3}{3HL} \gamma_{Exp} \end{aligned} \quad (2.17)$$

it is clear that $Q(t)$ and $\tilde{\epsilon}_{Elas}(t)$ can be evaluated step-by-step from (2.14) and (2.16) for as large a value of n as is necessary.

The speed and accuracy of this calculation depend on the assumed value of Δt . Since the wave transit time L/c appears explicitly in (2.16), it is convenient to choose Δt so that $L/c \Delta t$ is an exact integer. Apart from this, it is only necessary to ensure that Δt is not so large as make the finite difference solution inaccurate or so small as to introduce parasitic solutions. Extensive numerical studies have shown that a value lying well away from both limits can be selected by taking

$$\Delta t \approx \min \left(\frac{0.03 T}{|E_m|}, 10^{-6} \right) \text{ sec.} \quad (2.18)$$

Thus, DOPPELAS first computes Δt from (2.18) and then rounds it off slightly so that $L/c \Delta t$ is integral.

2.4 Programme Data

The physical data (with units) required before the above analysis can be made to calculate a nuclear excursion are given in Table 2.1. Except for one parameter (the sharpness B), the quantities shown are used in both versions of DOPPELAS. The parameter shown at the bottom of the table, the

Table 2.1

DOPPELAS Input Data

Prompt neutron generation time, τ	sec
Maximum prompt reactivity, ϵ_m	Δk
Axial fuel expansion coefficient of reactivity, γ_{Exp}	$\Delta k/cm$
Doppler coefficient of reactivity at T_o °C, γ_{Dopp}	$\Delta k/^\circ C$
Specific heat of fuel, H	J/gm $^\circ C$
Coefficient of linear expansion of fuel, α	strain/ $^\circ C$
Speed of waves along fuel slugs, c	cm/sec
Half-length of fuel slugs, L	cm
Mean specific power just before excursion, S	W/gm fuel
Pulse sharpness, B (redundant in DOPPELAS 2)	$\Delta k/sec^2$
Initial ramp rate, r	$\Delta k/sec$
Base reactivity (without negative sign), ϵ_{∞}	Δk
Initial mean fuel temperature, T_o ($= T_A - 273$)	$^\circ C$
Desired printing interval, δt	μsec

printing interval δt (μsec), is used to instruct the programme when to interpolate and print lines of results. The solution: $Q(t)$, $\tilde{\epsilon}_{Elas}(t)$, ... etc, is printed at $t = 0, \delta t, 2 \delta t, 3 \delta t, \dots$ right up to the end of the excursion, the latter being measured by the levelling-off of $Q(t)$. For details of the programme output, see section 2.5.

Typical values of the above parameters for a SORA type reactor operating in the pulsed mode (i.e. for DOPPELAS 1) are given in Table 2.2. The pulse maximum $\epsilon_m = 0.0018 \Delta k$ represents an accident in which the thermoelastic stresses fall just short of breaking the cladding of the highest rated fuel elements. The print-out interval of 20μ sec is enough in this case to reveal all details of the excursion without generating excessive output.

Table 2.2

Typical Numerical Values for DOPPELAS Input Data

$\tau = 2 \times 10^{-8} \text{ sec}$	$\epsilon_m = 0.0018 \Delta k$	$\gamma_{\text{Exp}} = -0.0184 k/cm$	$\gamma_{\text{Dopp}} = 2 \times 10^{-6} \Delta k/^{\circ}C$
$H = 0.14 \text{ J/gm}^{\circ}C$	$\alpha = 1.4 \times 10^{-5} \text{ str./}^{\circ}C$	$c = 2.6 \times 10^5 \text{ cm/sec}$	$L = 12 \text{ cm}$
$S = 1.43 \text{ W/gm}$	$B = 4.805 \times 10^5 \Delta k/\text{sec}^2$	$r = 93 \Delta k/\text{sec}$	$\delta t = 20 \mu \text{ sec}$
$\epsilon_{\infty} = 0.038 \Delta k$	$T_o = 400 \text{ }^{\circ}C$		

The manner in which the above data is prepared on cards for input to the IBM 360/65 or 7090 is illustrated in Table 2.3. The first row of this table indicates the relevant column numbers of the cards and the first four cards represent the first case. Columns 1-10 of each card serve to specify storage locations. Thus, for example, the c-1-4 shown punched respectively in columns 1, 5 and 10 of the first card means: "Take the four numbers punched in ranges 11-25, 26-40, 41-55 and 56-70 and store them in c(1), c(2), c(3) and c(4) respectively". Similarly, the c-5-8 in columns 1, 5 and 10 of the second card signifies that the subsequent four numbers in ranges 11-25, 26-40, 41-55 and 56-70 of this card are to be stored in c(5), c(6), c(7) and c(8) respectively. In all, 16 parameters are read and stored in this way in registers c(1)-c(16). Of

1	5	10	25	40	55	70
C	1	4	2.0 E-8	180.0 E-5	-0.018	2.0 E-6
C	5	8	0.14	1.4 E-5	2.6 E-5	12.0
C	9	12	1.43	4.805 E-5	93.0	20.0
C	13	16	0.038	400.0		
CAL						
C	2	2	170.0 E-5			
CAL						
C	2	2	410.0 E-5			
C	9	9	1.43 E-8			
CAL						
C	2	2	420.0 E-5			
CAL						
C	1	2	4.0 E-8	180.0 E-5		
C	9	9	1.43			
CAL						
C	1	4	2.0 E-8	180.0 E-5	0.0	0.0
CAL						
C	3	4	-0.018	2.0 E-6		
C	12	13	40.0	0.03		
CAL						
STP						

TABLE 2.3

these, the first 14 represent the physical parameters in exactly the same order and format as in Table 2.2 while the last two registers, c(15) and c(16), are functionless and can be left blank. (For clarity and convenience, the exact correspondence between the programme C(J) registers and the physical parameters is given in Table 2.4). The card with CAL punched in columns 1, 2 and 3 directs the programme to the execution of case 1.

Table 2.4

Correspondence between the Programme Storage
Registers and the Physical Parameters

c(1) = τ	c(2) = ϵ_m	c(3) = γ_{Exp}	c(4) = γ_{Dopp}
c(5) = H	c(6) = α	c(7) = c	c(8) = L
c(9) = S	c(10) = B	c(11) = r	c(12) = δt
c(13) = ϵ_{oo}	c(14) = T_o		

The remainder of Table 2.3 illustrates the manner in which a series of cases are assembled. After the execution of the first case described above, the programme automatically searches for new data. In the example given, the programme finds that it has to read only one number and store it in c(2). The old value of ϵ_m is then overwritten by the new and execution is carried out with this new value of ϵ_m (= 0.0017 Δk) but with all other parameters preserved as in case 1. On completion of the second case, the programme then finds two cards, each with one parameter. The first goes into c(2) and the second into c(9). Thus, case 3 is executed with a new value of ϵ_m (= 0.0041 Δk) and a new value of S (= 1.43x10⁻⁸ W/gm). Case 4 is a repetition of case 3, but with ϵ_m = 0.0042 Δk . In case 5 the prompt neutron generation time τ is increased from 2x10⁻⁸ to 4x10⁻⁸ sec and ϵ_m and S are restored to the values which they had in case 1. The 6'th case

repeats case 1, but with all reactivity feedback effects removed ($\gamma_{\text{Exp}} = \gamma_{\text{Dopp}} = 0$). The 7'th and last case restores the feedback effects but increases the print-out interval δt from 20 to 40 μsec and investigates the effect of a higher base reactivity - ϵ_{00} . All further execution is terminated by the card with STP punched in columns 1, 2 and 3 respectively.

The above examples have been designed to give a complete coverage of the input capabilities of DOPPELAS. Both versions of the programme are identical except that, in DOPPELAS 2, the register c(10) (= B) is redundant and can be filled with any number whatever without effect.

2.5 Programme Output

The output of the two versions of DOPPELAS, 1 and 2, is illustrated in Figures 2.1 and 2.2 respectively. These figures are copied directly from the output delivered by the IBM 360/65 printer, the input data being precisely that given in Table 2.2, i.e. the first case of Table 2.3.

The first line in the output of any case defines the version of the programme being used (pulse or ramp/step input) and the case number. Then follows four lines, each containing four numbers, which gives a complete listing (in the same format as in Tables 2.2 and 2.4) of the data being used in the case. In DOPPELAS 1, there then follows a line of four numbers giving respectively t_{ramp} (eq. (2.11)), t^* (eq. (2.10)), L/c (the wave transit along the slug half-length) and Δt (the finite difference interval, eq. (2.18)). In DOPPELAS 2, the line contains only three numbers: t'_{ramp} (eq. (2.13)), L/c and Δt , since t^* is meaningless in this case. All of these times are stated in μsec .

After the above preliminaries, the output gives the solution computed according to the method in section 2.3. There are eight columns of numbers. The 1'st column gives the time in μsec at intervals of δt (= 20 μsec in the examples). The 2'nd, 3'rd, 4'th, 5'th, 6'th, 7'th and 8'th columns give respectively $\tilde{\epsilon}_{\text{Elas}}$, $\tilde{\epsilon}_{\text{Dopp}}$, $\tilde{\epsilon}_{\text{Elas}} + \tilde{\epsilon}_{\text{Dopp}}$, ϵ_0 , the average fuel temperature rise (in $^{\circ}\text{C}$), the average energy release per gram of

DOPPELAS-PULSE REACTIVITY INPUT CASE 1

0.20000D-07	0.18000D-02	-0.01800	0.20000D-05
0.14000	0.14000D-04	0.26000D 06	12.000
0.1430D 01	0.48050D 06	93.000	20.000
0.03800	400.00000	0.0	0.0
379.57	476.34	46.15	0.3344D 00

T(MICS)	ELAS. FBK	DOPP. FBK	TOTAL FBK	INPUT REACT.	AV.DELT(DEG.C)	AV.ENERGY(J/GM)	AV.PWR.(W/GM)	5
0.0	0.0	0.0	0.0	-0.38000D-01	0.0	0.0	0.14300D 01	
20.0	-0.78257D-10	0.41836D-09	0.34010D-09	-0.36140D-01	0.20918D-03	0.29285D-04	0.15011D 01	
40.0	-0.63373D-09	0.85875D-09	0.22502D-09	-0.34280D-01	0.42937D-03	0.60112D-04	0.15825D 01	
60.0	-0.21151D-08	0.13236D-08	-0.79145D-09	-0.32420D-01	0.66181D-03	0.92654D-04	0.16733D 01	
80.0	-0.44409D-08	0.18159D-08	-0.26251D-08	-0.30560D-01	0.90794D-03	0.12711D-03	0.17752D 01	
100.0	-0.71904D-08	0.23389D-08	-0.48515D-08	-0.28700D-01	0.11695D-02	0.16373D-03	0.18881D 01	

FIGURE 2.1

DOPPELAS-RAMP/STEP REACTIVITY INPUT CASE 1

0.20000D-07	0.18000D-02	-0.01800	0.20000D-05
0.14000	0.14000D-04	0.26000D 06	12.000
0.1430D 01	0.48050D 06	93.000	20.000
0.03800	400.00000	0.0	0.0
427.96	46.15	0.3344D 00	

T(MICS)	ELAS. FBK	DOPP. FBK	TOTAL FBK	INPUT REACT.	AV.DELT(DEG.C)	AV.ENERGY(J/GM)	AV.PWR.(W/GM)	β
0.0	0.0	0.0	0.0	-0.38000D-01	0.0	0.0	0.14300D 01	
20.0	-0.78257D-10	0.41836D-09	0.34010D-09	-0.36140D-01	0.20918D-03	0.29285D-04	0.15011D 01	
40.0	-0.63373D-09	0.85875D-09	0.22502D-09	-0.34280D-01	0.42937D-03	0.60112D-04	0.15825D 01	
60.0	-0.21151D-08	0.13236D-08	-0.79145D-09	-0.32420D-01	0.66181D-03	0.92654D-04	0.16733D 01	
80.0	-0.44409D-08	0.18159D-08	-0.26251D-08	-0.30560D-01	0.90794D-03	0.12711D-03	0.17752D 01	
100.0	-0.71904D-08	0.23389D-08	-0.48515D-08	-0.28700D-01	0.11695D-02	0.16373D-03	0.18881D 01	

FIGURE 2.2

fuel Q (in Joules/gm) and the average power per gram of fuel Q (in Watts (gm)). All reactivities are in units of Δk measured relative to prompt criticality.

The calculation is stopped by a convergence criterion placed on the specific energy Q and this usually operates at the end of an excursion shortly after the total reactivity has fallen below prompt critical. If the solution is of interest beyond this point, as has been the case⁽³⁾ already, it is only necessary to remove the appropriate card from the programme deck. Users will find this a simple problem.

DOPPELAS is written in Fortran 4 language.

3. CLASS-B EXCURSIONS; THE PROGRAMME SOREX 1

3.1 Theoretical Basis

A complex physical-mathematical model for the analysis of destructive excursions in a pulsed fast reactor has recently been published in full detail⁽⁴⁾ and need not be greatly elaborated here. We shall simply sketch the essential ideas and equations. Although the theory is developed explicitly for type 1 accidents, it is easily adapted for the study of types 2-4, as will be seen in section 3.2.

The essential ingredient used in the theory is Nicholson's⁽⁹⁾ version of the Bethe-Tait⁽¹⁰⁾ model. In this, the only available shut-down mechanism is the process of destruction caused by the generation of very large pressures in the core. Shut-down reactivity arises from the fact that core material is accelerated along pressure gradients into regions of lower importance. To describe this, and all other effects, the core is approximated by an equivalent sphere of radius $R_c (= (3 V_c / 4 \pi)^{1/3})$, V_c being the core volume). Denoting the pressure by $p(r, t)$ and the reactivity worth per unit volume of core material by $D(r)$, the basic equation governing the shut-down reactivity $\tilde{\epsilon}$ in this model is^(9,4)

$$\frac{d^2 \tilde{\epsilon}}{dt^2} = - \frac{4 \pi}{\rho_c} \int_0^{R_c} \frac{\partial p}{\partial r} \frac{dD}{dr} r^2 dr \quad (3.1)$$

where ρ_c is the mean density of the core, r the radius variable and t the time.

The integral in (3.1) is evaluated by introducing three approximations. For the pressure, it is assumed that the dependence on the specific energy $Q(r, t)$ (energy release per unit mass of fuel) falls into two linear regions^(4,11). A "low pressure regime":

$$p = \left. \begin{array}{l} 0 \\ \gamma_2 \rho_f (Q - Q_2^*) \end{array} \right\} \begin{array}{l} \text{if } Q \leq Q_2^* \\ \text{if } Q > Q_2^* \end{array} \quad (3.2)$$

(next page)

and a "high pressure regime":

$$p = \gamma_1 \rho_f (Q - Q_1^*) \quad \text{if } Q > Q_0^* \quad \left. \vphantom{p = \gamma_1 \rho_f (Q - Q_1^*)} \right\} \quad (3.2)$$

where ρ_f is the effective density of the fuel (after expansion to fill all voids) and $\gamma_1, Q_1^*, \gamma_2$ and Q_2^* are constants. Q_0^* depends on these constants. Note: with ρ_f in gm/cm³ and Q, Q_1^* and Q_2^* in ergs/gm, γ_1 and $\gamma_2 \sim 1-10$ are dimensionless and p is in dynes/cm².

For the specific energy $Q(r, t)$ and reactivity worth density $D(r)$ are assumed parabolic spatial distribution functions whose shape is unaffected by the excursion⁽⁹⁾:

$$Q(r, t) = Q_0(t) \left(1 - q \frac{r^2}{R_c^2} \right) \quad (3.3)$$

and

$$D(r) = g_0 - \frac{1}{2} g \frac{r^2}{R_c^2} \quad (3.4)$$

where $Q_0(t)$ is the energy per unit mass of fuel at the core centre and q, g_0 and g are determined by matching these formulae with the results of neutron transport theory.

Using (3.2), (3.3) and (3.4) in equation (3.1) it follows that

$$\frac{d^2 \tilde{\epsilon}}{dt^2} = -\frac{8\pi}{5} q q' R_c Q_0(t) \left[\gamma_1 \left(\frac{S_1}{R_c} \right)^5 + \gamma_2 \frac{S_2^5 - S_1^5}{R_c^5} \right] \quad (3.5)$$

where S_1 and S_2 are functions of $Q_0(t)$ ⁽⁴⁾ and

$$q' = \frac{\rho_f}{\rho_c} g \quad (3.6)$$

In addition to the shut-down reactivity $\tilde{\epsilon}$, the theory also includes the Doppler effect. The feedback reactivity coming from this effect is represented by the same formula as in DOPPELAS, i.e.

$$\tilde{\epsilon}_{\text{Dopp}} = 2 \gamma'_{\text{Dopp}} T_A \left[1 - \left(1 - \frac{\bar{Q}}{HT_A} \right)^{-1/2} \right] \quad (3.7)$$

where \bar{Q} is the average specific energy release:

$$\bar{Q} = \left(1 - \frac{3}{5} \rho \right) Q_0(t) \quad (3.8)$$

H is the average specific heat of the fuel over the range of interest⁽⁴⁾, T_A the absolute mean fuel temperature before the excursion and γ'_{Dopp} the Doppler coefficient of reactivity at temperature T_A .

Denoting, once again, the prompt reactivity input due to the accident conditions by $\epsilon_0(t)$, the total prompt reactivity is given by

$$\epsilon = \epsilon_0(t) + \tilde{\epsilon}_{\text{Dopp}}(t) + \tilde{\epsilon}(t) \quad (3.9)$$

In conjunction with this reactivity, it is again assumed⁽⁶⁾ that the point neutron kinetics model is applicable:

$$\tau \ddot{Q}_0 = \epsilon \dot{Q}_0 + \epsilon_{00} S_0 \quad (3.10)$$

where $-\epsilon_{00}$ is the prompt reactivity just before the excursion ($\epsilon_0(t_b) = -\epsilon_{00}$) and S_0 is the initial specific power at the core centre, i.e.

$$S_0 = \frac{S}{1 - \frac{3}{5} \rho} \quad (3.11)$$

S being the mean initial power per unit mass of fuel. The boundary conditions to (3.10) are $Q_0(t_b) = 0$ and $\dot{Q}_0(t_b) = S_0$, where t_b is the time point when the reactivity begins to rise above $-\epsilon_{00}$ (see section 3.2).

If the input reactivity $\beta_o(t)$ is given, it will now be noted that equations (3.5), (3.7), (3.9) and (3.10) form a closed set with a unique solution, $Q_o(t)$. During the course of an excursion, $Q_o(t)$ at first rises slowly at a rate depending on S but accelerates very sharply when $\beta_o > 0$. After arrival at the threshold Q_2^* of the low pressure regime, the shut-down reactivity $\tilde{\beta}$ becomes dominant very quickly and $Q_o(t)$ converges to its final limit $Q_o(\infty)$. If M_f is the total mass of fuel in the core, it follows from (3.3) that the total energy release is given by

$$Q_{tot}(t) = \left(1 - \frac{3}{5} \rho\right) M_f Q_o(t) \quad (3.12)$$

the final value, $Q_{tot}(\infty)$, being very insensitive to the value of S .

In order to calculate the mechanical energy which may become available for the creation of blasts and projectiles within the containment of the reactor, an approximation similar to equation (3.2) is made. For a unit mass of fuel with internal energy Q it is assumed that the available work, W_s , is given by^(4,11)

$$W_s = \begin{cases} 0 & \text{if } Q \leq W_2^* \\ k(Q - W_2^*) & \text{if } W_2^* \leq Q \leq W_o^* \\ l(Q - W_1^*) & \text{if } Q > W_o^* \end{cases} \quad (3.13)$$

where k , W_2^* , l , W_1^* and W_o^* are constants. It follows that the total available work corresponding to the specific energy $Q_o(t)$ at the centre of the core is

$$W(t) = M_f \left\{ k \left[(Q_o - W_2^*) \frac{r_2^3 - r_1^3}{R_c^3} - \frac{3}{5} \rho Q_o \frac{r_2^5 - r_1^5}{R_c^5} \right] + l \left[(Q_o - W_1^*) \frac{r_1^3}{R_c^3} - \frac{3}{5} \rho Q_o \frac{r_1^5}{R_c^5} \right] \right\} \quad (3.14)$$

where r_1 and r_2 are functions of $Q_0(t)$ ⁽⁴⁾. The final available work $W(\infty)$ is given by putting $Q_0 = Q_0(\infty)$ in (3.14).

3.2 Reactivity Input

3.2.1 Reactivity Input due to Rotor Breakage

In the absence of a grossly abnormal accident of the type to be outlined in this section, the reactivity input is given by equations (2.8) and (2.9), which, for convenience, are repeated here (with t measured relative to the peak):

$$\epsilon_0(t) = \max[\epsilon_{p_0}(t); -\epsilon_{00}] \quad (3.15)$$

where

$$\epsilon_{p_0}(t) = \begin{cases} rt + \frac{r^2}{4B} + \epsilon_m & \text{for } t \leq -t_0 \\ \epsilon_m - Bt^2 & \text{for } -t_0 \leq t \leq t_0 \\ -rt + \frac{r^2}{4B} + \epsilon_m & \text{for } t \geq t_0 \end{cases} \quad (3.16)$$

ϵ_m , B and r being respectively the normal maximum prompt criticality, the sharpness and the ramp rate of rise (fall) of the pulse. (For the definition of the other parameters, see section 2.2.1).

The effect of a rotor breakage accident (type 1) is, mathematically, to replace the above single reactivity pulse by a superposition of three separate pulses⁽⁴⁾. This occurs because the different trajectories followed by the broken and unbroken parts of the moving reflector lead to a time delay between their passage near the core, so splitting equation (3.15) into two components, while the compression and decompression of the core accompanying the collision of the broken fragment injects a third reactivity component.

In the theory, the amplitudes of and time differences between these three pulse components depend on: the angle θ of the pulsation device at the instant of fracture relative to its position when the normal reactivity is a maximum, the radius R_0 of the outer tip of the pulsation device, the speed V of the outer tip of the pulsation device, the effective mass $m^{(4)}$ of the fragment, the "reduced compressibility" $\kappa'^{(4)}$ of the coolant, the "rigidity" $\beta^{(4)}$ of the fuel assembly, the "looseness" $\alpha'^{(4)}$ of the core, the volume fraction f_0 of the coolant, the volume of the core, the total area A_0 of the moving reflector presented to the core and the normal gap h separating the moving reflector from the core.

The above kinematic and dynamical parameters are not the only quantities to determine the reactivity input $\epsilon_0(t)$ from the three pulse components. There is also the number of laminar pieces n built into the pulsation device (only one of which is assumed to break), the volume coefficient of reactivity $\eta^{(4)}$ and "wobble" coefficient of reactivity $\epsilon'^{(4)}$.

All of these parameters provide the context for a description of the processes following a pulsation device breakage accident. In mathematical terms, this description boils down to the following set of equations⁽⁴⁾:

$$\begin{aligned} \epsilon_0(t) = & a_n \max[\epsilon_{p_0}(t); -\epsilon_{o_0}] + b_n \left\{ \max[\epsilon'_{p_0}(t-t_3); -\epsilon_{o_0}] \right. \\ & \left. + \epsilon_{gap}(t) \right\} + \left(\eta + \frac{n b_n \epsilon' V_c}{A_0} \right) y(t) \end{aligned} \quad (3.17)$$

where a_n and b_n are the relative reactivity worths of the unbroken and broken parts of the pulsation device respectively (i.e. in the simplest approximation $b_n = 1/n$, $a_n = 1 - b_n$); $y(t)$ is the fractional decrease in core volume satisfying

$$\ddot{y} = -G_c(y) - G_s(y) \quad (3.18)$$

with $y = 0$ for $t \leq t_2$ and $\dot{y} = \frac{A_0 V}{n V_c} \sin \theta$ for $t = t_2$,

$$G_c(y) = \frac{A_o^2 \kappa'}{nm f_o V_c} y \quad (3.19)$$

being proportional to the force due to the compression of the coolant,

$$G_3(y) = \begin{cases} 0 & \text{for } y \leq \alpha'/n \\ \frac{\frac{\beta A_o}{nm V_c} (y - \alpha'/n)}{2 - \ln n - \ln(y - \alpha'/n)} & \text{for } y \geq \alpha'/n \end{cases} \quad (3.20)$$

proportional to that due to the compression of the fuel slugs and t_2 is the instant of impact; $\epsilon'_{po}(t) = \epsilon_{po}(t \cos \theta)$ and

$$\epsilon_{gap}(t) = \begin{cases} 0 & \text{if } t \leq t_g \\ \epsilon' V \sin \theta (t - t_g) & \text{if } t_g \leq t \leq t_2 \\ \epsilon' h & \text{if } t \geq t_2 \end{cases} \quad (3.21)$$

The times t_2 , t_3 and t_g are given by

$$t_2 = \frac{h}{V \sin \theta} - \frac{R_o}{V} (\theta - \tan \frac{\theta}{2})$$

$$t_3 = \frac{R_o}{V} (\tan \theta - \theta)$$

$$t_g = \frac{R_o}{V} (\theta - \tan \frac{\theta}{2})$$

and, for completeness, the breakage occurs at

$$t_1 = - \frac{R_o \theta}{V}$$

The instant t_b regarded as the starting point of an excursion, is given when (3.17) begins to rise above $-\epsilon_{oo}$.

Although (3.17), supplemented by all the other equations above, has been formulated with a particular view to the simulation of type 1 accidents in SOREX 1, other types of accident can be simulated very easily.

3.2.2 Reactivity Pulse Input

A pure pulse form of reactivity input (for the study of type 2 and possibly type 3 accidents) can be obtained in SOREX 1 by making Θ very small (e.g. $\Theta = 0.1^\circ$) and setting $\epsilon' = 0$. It is easy to see physically, that, provided the gap h is non-zero, such a small angle fracture is unable to lead to a collision and that the terms in $\epsilon_{\text{gap}}(t)$ and $y(t)$ must therefore be absent from (3.17). Mathematically, it is even more obvious since, with $\Theta = 0.1^\circ$, $\epsilon' = 0$ and $h > 0$, the delay t_2 in the collision pulse is very large (i.e. the reactivity input due to collision is excluded until much too late) while $\epsilon_{\text{gap}} \approx 0$. On the other hand, $t_3 = 0$ and $\epsilon'_{\text{po}}(t) = \epsilon_{\text{po}}(t)$. From this, it follows immediately that (3.17) reduces to (3.15) as required.

3.2.3 Reactivity Ramp Input

A ramp form of reactivity input (for the study of accident types 3 and 4) can be achieved by first performing the above adjustments ($\Theta = 0.1^\circ$, $\epsilon' = 0$, $h > 0$) to give an input of the form (3.15) and then by raising ϵ_m to a high value, e.g. $\epsilon_m = 1$. The effect of the latter adjustment is to ensure that the ramp part of (3.16) extends well into the super-critical region and that the parabolic part can never be attained before destruction occurs.

3.3 Numerical Method

The problem for SOREX 1 is essentially that of simultaneously solving the differential equations (3.5), (3.10) and (3.18), all other equations being regarded as supplementary to these three. As for the class A excursions treated by DOPPELAS, this is accomplished by expanding the equations over a sequence of time points t_n . There is one feature of class B excursions

sions, however, which makes this procedure more critical, namely, the much larger fission powers generated. The quantities \dot{Q}_0 and \ddot{Q}_0 vary so rapidly when the excursion is at its peak that, in order to maintain good accuracy, it is necessary to decrease the spacing of the points t_n in this region.

Thus, defining

$$\Delta t_n = t_{n+1} - t_n \quad (3.22)$$

we take

$$\Delta t_n = \begin{cases} 10^{-6} \text{ sec} & \text{if } \epsilon(t_n) \leq 0 \\ \min [10^{-6}; 0.005\tau / \epsilon(t_n)] \text{ sec} & \text{if } \epsilon(t_n) > 0 \end{cases} \quad (3.23)$$

until the smallest value is reached and then keep Δt_n fixed at that value until the end of the excursion (disassembly). In (3.23), $\epsilon(t_n)$ is given by (3.9) with $t = t_n$.

With the above time sequence, the finite difference representation of the kinetics equation (3.10) assumed in SOREX 1 is

$$\begin{aligned} \tau & \frac{\frac{Q_0(t_{n+1}) - Q_0(t_n)}{\Delta t_n} - \frac{Q_0(t_n) - Q_0(t_{n-1})}{\Delta t_{n-1}}}{\frac{1}{2}(\Delta t_n + \Delta t_{n-1})} \\ & = \epsilon(t_n) \frac{Q_0(t_{n+1}) - Q_0(t_{n-1})}{\Delta t_n + \Delta t_{n-1}} + \epsilon_{00} S_0 \end{aligned}$$

(3.24)

Since $Q_0(t_0) = 0$ and $Q_0(t_1) = S_0 t_1$ (where t_0 is the zeroth time point), this equation leads to a step-by-step evaluation of the whole excursion provided $\tilde{\epsilon}(t_n)$ is known.

To evaluate $\tilde{\epsilon}(t_n)$, however, requires finite difference representations also of equations (3.5) and (3.18). Equation (3.5) is approximated by

$$\frac{\frac{\tilde{\epsilon}(t_n) - \tilde{\epsilon}(t_{n-1})}{\Delta t_{n-1}} - \frac{\tilde{\epsilon}(t_{n-1}) - \tilde{\epsilon}(t_{n-2})}{\Delta t_{n-2}}}{\frac{1}{2}(\Delta t_{n-1} + \Delta t_{n-2})} = F_{n-1} \quad (3.25)$$

where F_n is given by

$$F_n = -\frac{8\pi}{5} \gamma \gamma' R_c Q_0(t_n) \left[\gamma_1 \left(\frac{S_{1n}}{R_c} \right)^5 + \gamma_2 \frac{S_{2n}^5 - S_{1n}^5}{R_c^5} \right]$$

And S_{1n} and S_{2n} are known in terms of $Q_0(t_n)$ ⁽⁴⁾. From (3.2) it is obvious that $\tilde{\epsilon}(t_n) = 0$ for all t_n satisfying $Q_0(t_n) < Q_2^*$ and this condition makes possible, with (3.25), a complete evaluation of $\tilde{\epsilon}$ for all t_n .

The finite difference representation of equation (3.18) is based on the second order Taylor expansion:

$$y(t_n) = y(t_{n-1}) + \dot{y}(t_{n-1}) \Delta t_{n-1} + \frac{1}{2} \ddot{y}(t_{n-1}) \Delta t_{n-1}^2$$

Writing $y(t_n) = y_n$, $\dot{y}(t_n) = \dot{y}_n$ and $\ddot{y}(t_n) = \ddot{y}_n$, this becomes

$$y_n = y_{n-1} + \dot{y}_{n-1} \Delta t_{n-1} + \frac{1}{2} \ddot{y}_{n-1} \Delta t_{n-1}^2 \quad (3.26)$$

and defining

$$f(y) = G_c(y) + G_s(y) \quad (3.27)$$

it follows immediately from (3.18) that

$$\ddot{y}_{n-1} = -f(y_{n-1}) \quad (3.28)$$

while the first derivative \dot{y}_{n-1} can be evaluated by multiplying (3.18) by \dot{y} :

$$\dot{y}\ddot{y} = -f(y)\dot{y}$$

and integrating over the interval (y_{n-2}, y_{n-1}) :

$$\frac{1}{2}(\dot{y}_{n-1}^2 - \dot{y}_{n-2}^2) = - \int_{y_{n-2}}^{y_{n-1}} f(y') dy'$$

If the integrand in this formula is now expanded to first order in $(y' - y_{n-1})$, i.e.

$$f(y') = f(y_{n-1}) + (y' - y_{n-1}) f'(y_{n-1})$$

then we get

$$\dot{y}_{n-1} = \pm \left[\dot{y}_{n-2}^2 - 2(y_{n-1} - y_{n-2})f(y_{n-1}) + (y_{n-1} - y_{n-2})^2 f'(y_{n-1}) \right]^{1/2} \quad (3.29)$$

Equations (3.26), (3.28) and (3.29) are now sufficient to evaluate y_n step by step if we introduce the starting conditions that $y = 0$ for $t \leq t_2$ and $y = A_0 V \sin \theta/n V_c$ for $t = t_2$. The + sign in (3.29) is used during the compression part of the collision and the - sign during decompression.

SOREX 1 performs the change-over automatically when y_n reaches its maximum.

The calculation is stopped either when the condition

$$\frac{1}{Q_0} \frac{dQ_0}{dt} < 10^{-4} \text{ sec}^{-1}$$

is satisfied or when the input reactivity $\epsilon_0(t)$ returns to $-\epsilon_{\infty}$ (which is symptomatic of a non-destructive excursion).

3.4 Programme Data

The physical data, along with the Fortran registers used to store them in the programme and the units required, are all listed in Table 3.1. The order in which the parameters appear is not strictly logical but has resulted from the natural evolution of the theory during its development. The quantity Δt (μsec) stored in register A(8) informs the programme at which time point t_n to interpolate and print the solution $Q_0(t)$ and all other quantities of interest. Typical values of the above parameters for a serious pulsation device breakage accident are shown in Table 3.2. This data represents approximately the maximum accident of a SORA type reactor.

The manner in which the above data is prepared on cards for input to the IBM 360/65 or 7090 is illustrated in Table 3.3. The logic is identical to that for DOPPELAS and can be appreciated most readily by a detailed comparison of Tables 3.2 and 3.3. The second card, for example, begins with A, 5, 8 punched respectively in columns 1, 5 and 10. This has the effect of allocating the four numbers on this card in columns 11-25, 26-40, 41-55 and 56-70 to registers A(5), A(6), A(7) and A(8) respectively. Similarly, the B, 17, 20 (punched in columns 1, 4 and 5, 9 and 10) on the 7th card directs the four numbers punched in columns 11-25, 26-40, 41-55 and 56-70 to registers B(17), B(18), B(19) and B(20) respectively. In this way, all 36 numbers on the 9 cards are read by the programme to make a complete case and execution is triggered by the card with CAL punched in columns 1, 2 and 3.

Table 3.1

SOREX 1 Input Data

Physical Parameter	Fortran Register	Unit
Prompt neutron generation time, τ	A(1)	sec
Volume coefficient of reactivity, η	A(2)	Δk
Core volume, V_c	A(3)	liters
Normal pulse ramp rise (fall) rate, r	A(4)	$\Delta k/\text{sec}$
Initial (source) power, S	A(5)	W/gm fuel
Low pressure regime parameter, γ_2	A(6)	-
Number of laminar parts in pulsation device, n	A(7)	-
Printing interval, Δt	A(8)	μsec
High pressure regime parameter, γ_1	B(1)	-
Effective fuel density, ρ_f	B(2)	gm/cm^3
High pressure regime parameter, Q_1^*	B(3)	ergs/gm
Total mass of fuel, M_f	B(4)	Kgm
Effective mass of fragment, m	B(5)	Kgm
Pulsation device breakage angle, θ	B(6)	degrees
Area of moving reflector towards core, A_o	B(7)	cm^2
Corrected coolant compressibility, K'	B(8)	dynes/cm^2
Gap between moving reflector and core, h	B(9)	cm
Wobble coefficient of reactivity, e'	B(10)	$\Delta k/\text{cm}$
Normal pulse maximum, ϵ_m	B(11)	Δk
Normal pulse sharpness, B	B(12)	$\Delta k/\text{sec}^2$
Speed, outer tip of moving reflector, V	B(13)	m/sec
Radius, " " " " " " , R_o	B(14)	cm
Base reactivity (without - sign), e_{oo}	B(15)	Δk
Low pressure regime parameter, Q_2^*	B(16)	ergs/gm
Power shape factor, q	B(17)	-
Reactivity worth shape factor, q' (eq. 3.6)	B(18)	$\Delta k/\text{cm}^3$
Fuel assembly rigidity, β	B(19)	dynes
" " looseness, α'	B(20)	-
Doppler coefficient of reactivity, γ_{Dopp}	B(21)	$\Delta k/^\circ\text{C}$
Initial mean fuel temperature, T_A	B(22)	$^\circ\text{K}$
Mean fuel specific heat, H	B(23)	$\text{ergs}/\text{gm } ^\circ\text{C}$
Available work parameter, k	B(24)	-
" " " " , w_2^*	B(25)	ergs/gm
" " " " , w_1^*	B(26)	ergs/gm
" " " " , l	B(27)	-
Coolant volume fraction, f_o	B(28)	-

Table 3.2

Typical Values for the SOREX 1 Input Data

A(1→4):	$\tau = 2 \times 10^{-8}$ sec	$\eta = 0.37 \Delta k$	$V_c = 5.9$ liters	$r = 93 \Delta k/\text{sec}$
A(5→8):	$S = 1.43 \times 10^{-8}$ W/gm	$\gamma_2 = 36$	$n = 4$	$t = 20 \mu\text{sec}$
B(1→4):	$\gamma_1 = 2.3$	$\rho_f = 14 \text{ gm/cm}^3$	$Q_1^* = 7.3 \times 10^9$ ergs/gm	$M_f = 70$ Kgm
B(5→8):	$m = 2.9$ Kgm	$\theta = 10.5^\circ$	$A_o = 264 \text{ cm}^2$	$\kappa' = 4 \times 10^9$ dynes/cm ²
B(9→12):	$h = 0.45$ cm	$\epsilon' = 0.01 \Delta k/\text{cm}$	$\epsilon_m = 0.00092 \Delta k$	$B = 4.805 \times 10^5 \Delta k/\text{sec}^2$
B(13→16):	$V = 283$ m/sec	$R_o = 90$ cm	$\epsilon_{oo} = 0.038 \Delta k$	$Q_2^* = 9.3 \times 10^9$ ergs/gm
B(17→20):	$q = 0.59$	$q' = 6.8 \times 10^{-4} \Delta k/\text{cm}^3$	$\beta = 8 \times 10^{14}$ dynes	$\alpha' = 0.03$
B(21→24):	$\gamma_{\text{Dopp}} = 2 \times 10^{-6} \Delta K/^\circ\text{C}$	$T_A = 473$ °K	$H = 5.7 \times 10^5$ ergs/cm ⁰ C	$k = 0.676$
B(25→28):	$w_2^* = 9.3 \times 10^9$ ergs/gm	$w_1^* = 15.3 \times 10^9$ ergs/gm	$l = 1$	$f_o = 0.139$

	5	10	25	40	55	70
A	1	4	2.0 E- 8	0.37	5.9	93.0
A	5	8	1.43 E- 8	36.0	4.0	20.0
B	1	4	2.3	14.0	7.3 E 9	70.0
B	5	8	2.9	10.5	264.0	4.0 E 9
B	9	12	0.45	0.01	0.00092	4.805 E 5
B	13	16	283.0	90.0	0.038	9.3 E 9
B	17	20	0.59	6.8 E- 4	8.0 E 14	0.03
B	21	24	2.0 E- 6	473.0	5.7 E 5	0.676
B	25	28	9.3 E 9	15.3 E 9	1.0	0.139
CAL						
B	6	6	11.0			
CAL						
B	6	6	10.0			
CAL						
B	6	6	0.1			
B	10	11	0.0	0.004		
CAL						
A	4	4	10.0			
B	11	11	1.0			
CAL						
A	4	5	20.0	1.43		
CAL						
STP						

TABLE 3.3

The second case illustrated in Table 3.3 is made up by a single card. The B-6-6 punched in columns 1, 5 and 10 has the effect of overwriting the contents of B(6) with the number punched in columns 11-25 while the numbers stored in all the other registers are preserved. The second case is thus the same as case 1 but with the breakage angle set to $\theta = 11^\circ$ instead of 10.5° . Similarly the third case has $\theta = 10^\circ$.

The fourth case sets $\theta = 0.1^\circ$, $\epsilon' = 0$ and $\epsilon_m = 0.004 \Delta k$. As was explained in section 3.2.2, the values $\theta = 0.1$ and $\epsilon' = 0$ lead to a pure pulse reactivity input, the collision calculation being completely avoided. The value $\epsilon_m = 0.004 \Delta k$ represents an abnormally large pulse and therefore this case evaluates the destructive energy release following a severe type 2 (or 3) accident.

The fifth case retains the "pure pulse" parameters of case 4 but sets the ramp rate $r = 10 \Delta k/\text{sec}$ and raises ϵ_m to $\epsilon_m = 1.0$. As was explained in section 3.2.2, the latter large value has the effect of making the reactivity peak unattainable, the system being destroyed while the input is still following the ramp. Thus, case 5 evaluates the destructive energy release due to a type 3 or 4 accident for which the ramp input is $10 \Delta k/\text{sec}$.

The sixth and last case repeats the latter calculation, but with $r = 20 \Delta k/\text{sec}$ and a greatly increased (factor 10^8) source power of $S = 1.43 \text{ W/gm}$. The card with STP in columns 1, 2 and 3 terminates execution.

The illustrative cases given above are thought to provide an adequate coverage of the SOREX 1 input capabilities. Although none of the cases shown involves changing more than three quantities, the number of allowed changes is unlimited. The approximation $b_n = 1/n$ used in (3.1) can be modified if desired merely by changing a single card in the programme deck.

3.5 Programme Output

The output of SOREX 1 for the data given in Table 3.2 (i.e. case 1 of Table 3.3) is shown in Figure 3.1. Figure 3.2 shows the output for case 2.

These figures are a copy of the output received directly from the IBM 360/65 printer but give only a small part of the solution (up to $t = 80 \mu\text{sec}$) because they are intended only for illustration.

The first lines of the output give the name of the programme and a brief outline of its subject matter followed by the date and time. The latter information is acquired from the clock in the computer by means of a subroutine DATTIM. This subroutine is not built into the 7090 version of SOREX 1 and can easily be removed from the 360/65 version if necessary. It is, however, very useful for daily reference purposes and for preserving a record of the exact machine time used. It will be noted, for example, from Figures 3.1 and 3.2 that the execution time for case 1 was 11.4 sec.

Below the heading is printed a table of all the data used in the case in exactly the same format as in Table 3.2. Below this are printed three lines. The first, consisting of only a single number, gives the value (in cm) of the sphericalized core radius R_c . The second, consisting of three numbers, gives (from left to right) the values of (a) the time (in μsec) at which the broken fragment arrives at the normal gap distance from the core, (b) the time (in μsec) at which a normal reactivity pulse would begin and (c) the time (in μsec) at which the fragment strikes the core. All of these times are measured relative to the instant $t = t_b$ when $\epsilon_o(t)$ (equation (3.17)) begins to rise above $-\epsilon_{oo}$. The third line again consists of three numbers which give (from left to right) the values of (a) the velocity component (in m/sec) of the fragment towards the core, (b) the velocity component (in m/sec) of the fragment tangential to the core and (c) the fractional change in core volume which would occur during the collision if only the coolant (not the fuel slugs) were subjected to compression.

After all of the above preliminaries, the output then states the solution of the problem. This is given in the form of eight columns of numbers. The 1st column gives the time (in μsec) measured from the instant when $\epsilon_o(t)$ begins to rise above $-\epsilon_{oo}$, the 2'nd column gives the input of reactivity (in prompt Δk) due to the compression of the core by the broken fragment (compression pulse⁽⁴⁾), the 3'rd column gives $\epsilon_o(t)$ (in prompt Δk), the 4'th column gives the total reactivity input

SOREX 1

NUCLEAR EXCURSION CAUSED BY A ROTOR BREAKAGE ACCIDENT IN A PULSED FAST REACTOR

CORE DESTRUCTION BASED ON A MODIFIED BETHE-TAIT MODEL

DATE 68/02/08

TIME 17H,05M,04.8SEC

0.20000D-07	0.370	5.900	93.000
0.14300D-07	36.000	4.000	20.000
2.30000	14.00000	0.73000D 10	70.00000
2.90	10.50	264.00	0.4000D 10
0.450000	0.010000	0.000920	0.48050D 06
283.0000	90.0000	0.0380	0.93000D 10
0.59000	0.68000D-03	0.80000D 15	0.03000
0.20000D-05	473.00	0.57000D 06	0.67600
0.93000D 10	0.15300D 11	0.10000D 01	0.13900D 00

FIGURE 3.1

11.210			
176.298	0.0		263.553
51.573	278.261		0.106571D-01

T(MICSEC)	DELK(V)	EPSQ(T)	EPSTOT	P(ATM)	JOULES/GM	-----MEGAJOULES-----	
					Q(T)	TOTAL Q	ADIAB.WORK
0.0	0.0	-0.38000D-01	-0.38000D-01	0.0	0.0	0.0	0.0
20.0	0.0	-0.36117D-01	-0.36117D-01	0.0	0.45355D-12	0.20510D-13	0.0
40.0	0.0	-0.34265D-01	-0.34265D-01	0.0	0.93101D-12	0.42100D-13	0.0
60.0	0.0	-0.32413D-01	-0.32413D-01	0.0	0.14349D-11	0.64887D-13	0.0
80.0	0.0	-0.30561D-01	-0.30561D-01	0.0	0.19684D-11	0.89010D-13	0.0

SOREX 1

NUCLEAR EXCURSION CAUSED BY A ROTOR BREAKAGE ACCIDENT IN A PULSED FAST REACTOR

CORE DESTRUCTION BASED ON A MODIFIED BETHE-TAIT MODEL

DATE 68/02/08

TIME 17H,05M,16.2SEC

0.20000D-07	0.370	5.900	93.000
0.14300D-07	36.000	4.000	20.000
2.30000	14.00000	0.73000D 10	70.00000
2.90	11.00	264.00	0.4000D 10
0.450000	0.010000	0.000920	0.48050D 06
283.0000	90.0000	0.0380	0.93000D 10
0.59000	0.68000D-03	0.80000D 15	0.03000
0.20000D-05	473.00	0.57000D 06	0.67600
0.93000D 10	0.15300D 11	0.10000D 01	0.13900D 00

FIGURE 3.2

26

11.210		
162.544	0.0	245.879
53.999	277.800	0.111585D-01

T(MICSEC)	DELK(V)	EPS0(T)	EPSTOT	P(ATM)	JOULES/GM	-----MEGAJOULES-----	
					Q(T)	TOTAL Q	ADIAB.WORK
0.0	0.0	-0.38000D-01	-0.38000D-01	0.0	0.0	0.0	0.0
20.0	0.0	-0.36123D-01	-0.36123D-01	0.0	0.45349D-12	0.20507D-13	0.0
40.0	0.0	-0.34271D-01	-0.34271D-01	0.0	0.93087D-12	0.42094D-13	0.0
60.0	0.0	-0.32420D-01	-0.32420D-01	0.0	0.14347D-11	0.64876D-13	0.0
80.0	0.0	-0.30569D-01	-0.30569D-01	0.0	0.19680D-11	0.88994D-13	0.0

(equation (3.9) in prompt Δk), the 5'th column gives the pressure generated by the excursion at the core centre (in atmospheres), the 6'th column gives $Q_o(t)$ (in Joules/gm fuel), the 7'th column gives $Q_{tot}(t)$ (equation (3.12) in Mega-Joules) and the 8'th column gives $W(t)$ (equation(3.14) in Mega-Joules).

The time t is selected at intervals of Δt (μsec) until the instant when core disassembly begins. After that the solution is always printed at intervals of 1 μsec to ensure adequate detail in every case.

SOREX 1 is written in Fortran 4 language.

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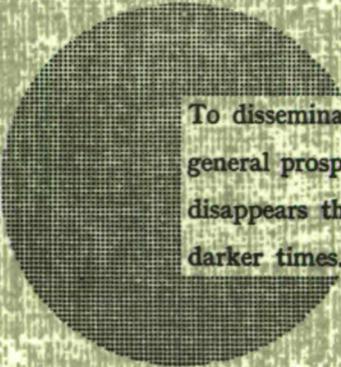
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