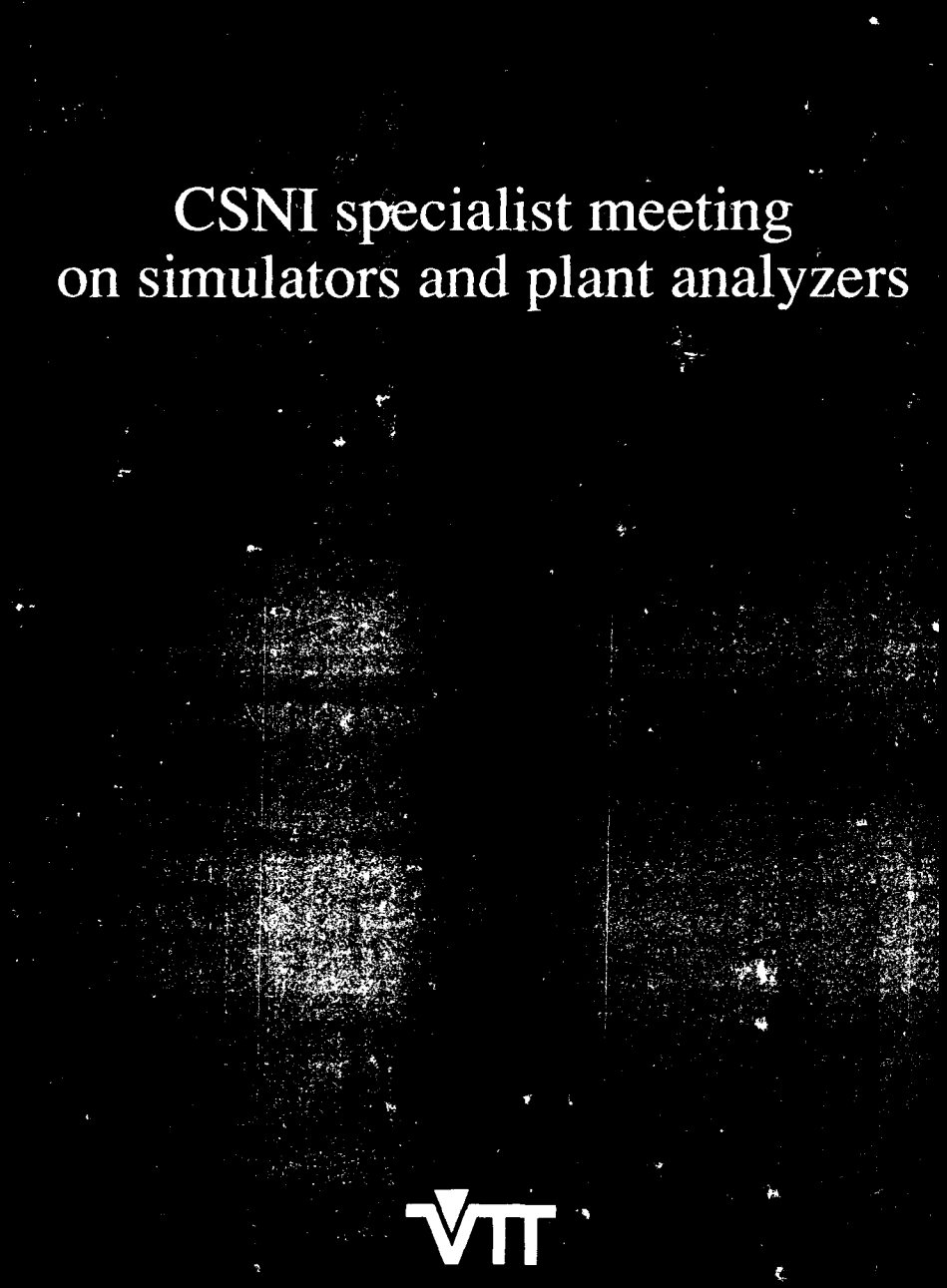
VTT SYMPOSIUM 141

CSNI specialist meeting on simulators and plant analyzers



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A SIMPLIFIED MODEL FOR THE SIMULATION OF OPERATIONAL AND ACCIDENT TRANSIENTS OF PWRs AND PIUS REACTOR.

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ABSTRACT

A simplified but complete simulation model for describing the operational and accident transients of PWRs, of both conventional and PIUS design, has been implemented on the basis of a thermalhydraulic model called TRIP. The model is based on hypotheses valid for liquid water, while two-phase flow effects relating to sonic velocity are disregarded. All components are divided into lumped parameter components and distributed parameter components, depending on their effective behaviour. Calculation examples clearly demonstrate the wide-ranging capabilities of this model, including long term operational transients and stability studies.

1. INTRODUCTION[1]

The analysis of any reactor concept concerns two aspects: safety and operability. Remaining within the framework of a pressurized light water concept, here we consider PWRs (both of conventional and advanced design) and PIUS reactors. Safety aspects in relation to large loss of coolant accidents (LOCA) would appear thoroughly studied and documented: complex computer programs are available for a complete description of these accidents. Moreover, in the case of the PIUS reactor, LOCAs do not seem critical, since the density locks are activated by the strong pressure unbalances caused by these accidents. On the other hand in any reactor system, "slow" accidents are more important than has been previously supposed, both for the delayed triggering of the protection system and the higher effect on the transient of the dynamic behaviour of many components in view also of their control system.
As far as operability is concerned, the analysis of different operating conditions, particularly start-up and stability behaviour, may yield important information about reactor flexibility. The analysis of this latter point is more important for the PIUS reactor than for the PWR, since its behaviour is better known.
These considerations had led us to the conclusion that a simple but complete computation model for plant transients might be a useful tool for both parametric studies during design activity and on-line simulation, when the reactor is in operation.
The slowness of the transients to be analyzed and the limited production of steam inside the primary circuit (this condition is more verified in the PIUS

[1] The conceptual part of this activity was carried out with the financial support of MURST (Ministero dell'Universtà e della Ricerca Scientifica e Tecnologica); computer program implementation and systematic validation for the PIUS reactor were carried out under a research contract sponsored by ENEL/CRTN of Milan.

reactor than in the PWR) allowed us to adopt the hypotheses suitable for an incompressible fluid, and in particular to disregard the sound speed effects. However, two-phase flow is taken into account in a simplified manner, by applying the same equations adopted for the liquid phase, corrected for the increased specific volume.
This model, called TRIP has been implemented in two different computer programs: TRIP (TRansitori Impianto Pius) relevant to the PIUS reactor and TRAP (Transitori Reattore Acqua in Pressione) relevant to the PWR. This model is detailed in this paper, together with some examples of its application to both types of reactor.

2. THE THERMOHYDRAULIC MODEL

The TRIP thermohydraulic model is based on a subdivision of the circuit components in two categories: those described by distributed parameters (constant cross-section pipes, including the reactor and the steam generators) and those described by lumped parameters (transition cross-section between two different components, density locks, plena, pumps, containment vessel, pressurizer).
Temperature changes move through pipes essentially as a front; that is, the incoming fluid does not mix with the fluid within the particular region, but only displaces it. Instead in plena an almost complete mixing of the incoming with the existing fluid inside the plena occurs. Thus the scheme detailed below correctly describes this different physical behaviour. In particular correct timing of temperature and boron changes in the primary system is very important in simulating plant transients, because of the reactivity effects.
For distributed parameter analysis, the three conservation equations of mass, momentum and energy are written by applying different simplifying hypotheses. The pipe component is assumed to be monodimensional, disregarding the lateral exchange. Then the three conservation equations, for a constant cross-section pipe, take the following form:

$$\frac{\partial \rho}{\partial t} + \frac{\partial G}{\partial x} = 0 \qquad \text{(mass)} \qquad (1)$$

$$\frac{\partial G}{\partial t} + \frac{\partial}{\partial x}\left(\frac{G^2}{\rho}\right) = -\frac{\partial p}{\partial x} - f\frac{G|G|}{2D\rho} - \rho g \qquad \text{(momentum)} \qquad (2)$$

$$\rho\frac{\partial h}{\partial t} + G\frac{\partial h}{\partial x} = \frac{\phi\,\Pi}{\Omega} + \frac{\partial p}{\partial t} + \frac{G}{\rho}\left(\frac{\partial p}{\partial x} + f\frac{G|G|}{2D\rho}\right) \qquad \text{(energy)} \qquad (3)$$

where the unknowns are five: G mass flux, ρ fluid density, p pressure, h specific enthalpy, f friction factor, while the assigned variables are: Ω cross-section area, D equivalent diameter, Π heated perimeter, ϕ heat flux; g is the gravity acceleration.
Two further equations are given by the fluid density state equation and the empirical correlation for the friction factor:

$$\rho = \rho(h,p) \quad ; \quad f = f(h,p,G,\text{geometry}) \qquad (4)$$

where the dependence on h comes about because of the need to determine the fluid viscosity μ. The fluid is assumed incompressible, but thermally expandable, and calculated as if it were at saturation condition, then:

$$\frac{\partial \rho}{\partial p} = 0 \quad ; \quad \rho = \rho(h)\big|_{p=p_{sat}} \qquad (5)$$

In the energy equation, the terms connected to the pressure variation and the friction losses are neglected;

$$\frac{\partial p}{\partial t} = 0 \quad ; \quad \frac{\partial p}{\partial x} = 0 \quad ; \quad f\frac{G|G|}{2D\rho} = 0 \tag{6}$$

therefore the energy and the momentum equations are decoupled.
In the mass conservation equation, the term $\partial\rho/\partial t$ is neglected, by assuming slow transient conditions:

$$\frac{\partial \rho}{\partial t} = \frac{\partial \rho}{\partial h}\frac{\partial h}{\partial t} = 0 \quad \Rightarrow \quad \underset{\text{(thermal expandability)}}{\frac{\partial \rho}{\partial h} \neq 0} \quad \text{and} \quad \underset{\text{(slow transients)}}{\frac{\partial h}{\partial t} = 0} \tag{7}$$

This yields:

$$\frac{\partial G}{\partial x} = 0 \Rightarrow G(x,t) = G(t) \tag{8}$$

then, the acceleration term in the momentum equation becomes:

$$\frac{\partial}{\partial x}\left(\frac{G^2}{\rho}\right) = G^2\frac{\partial}{\partial x}\left(\frac{1}{\rho}\right) \tag{9}$$

By substituting the total flow rate Γ and the linear power w to G and ϕ, i.e.:

$$\Gamma = G\,\Omega \quad ; \quad w = \phi\,\Pi \tag{10}$$

and taking into account the above-mentioned simplifying hypotheses, eqs. (1), (2) and (3) become:

$$\Gamma = \Gamma(t) \tag{11}$$

$$\frac{\partial p}{\partial x} = -f\frac{\Gamma^2}{2\Omega^2 D\rho} - \rho g - \frac{\Gamma^2}{\Omega^2}\frac{\partial(1/\rho)}{\partial x} - \frac{1}{\Omega}\frac{\partial \Gamma}{\partial t} \tag{12}$$

$$\rho\Omega\frac{\partial h}{\partial t} + \Gamma\frac{\partial h}{\partial x} = w \tag{13}$$

Obviously Γ can vary stepwise when connected to lumped parameter components, and in particular when fluid is injected into or extracted from the circuit, as through the density locks and the pressurizer.
For lumped parameter components, except for the pressurizer, a zero dimension solution of mass, momentum and energy equations is carried out as follows:

$$\frac{dM}{dt} = \Gamma_{in} - \Gamma_{out} \quad \text{(mass)} \tag{14}$$

$$p_{in} - p_{out} = \rho g\Delta z + \frac{d\Gamma}{dt}\frac{L}{\Omega} + K\frac{\Gamma|\Gamma|}{2\rho\Omega^2} + \frac{\Gamma^2}{2\rho}\left(\frac{1}{\Omega^2_{out}} - \frac{1}{\Omega^2_{in}}\right) \quad \text{(momentum)} \tag{15}$$

$$\frac{dU}{dt} = \Gamma_{in}\,h_{in} - \Gamma_{out}\,h_{out} \quad \text{(energy)} \tag{16}$$

where Ω, L, Δz and K are the component cross-section, length, elevation, and total form loss coefficient respectively, while M and U are the mass and the internal energy of the fluid contained within the component. When the volume V is constant, another conservation equation is provided by:

$$\frac{dV}{dt} = \frac{d(M/\rho)}{dt} = 0 \quad \text{(volume)} \tag{17}$$

The time derivative of internal energy is equal to:

$$\frac{dU}{dt} = \frac{dH}{dt} - p\frac{dV}{dt} - V\frac{dp}{dt} \qquad (18)$$

where H is the available fluid enthalpy. The second term on the right side of the equation is zero for all components with constant volume; for those where it is different from zero (the funnel and the containment vessel in the case of PIUS), it is in any case a small quantity. For this reason it is always neglected. The third term is small for accidents which can be analyzed by this program (i.e. accidents where pressure changes slowly), and is neglected too.
For the pressurizer, a two-zone model (steam plus water) is adopted. For both zones, mass and energy balance equations are written, while the momentum balance is disregarded. All mass exchanges between the two zones, caused by the disequilibrium effects between pressure and temperature (liquid evaporation or steam condensation) are taken into account, as well as the masses coming from the circuit through the surge line and the spray system (the latter for control purposes). The surge line is the line which connects the pressurizer to the main circuit. If present, it is divided into several stretches taken as lumped parameter components, according to the above-indicated model. This assumption is made in alternative to viewing it a distributed parameter component: in fact the irregular flow rate trend and the limited liquid speed value should facilitate the axial fluid mixing, as assumed in lumped parameter components; however the adoption of a higher number of stretches should reduce any difference between the two hypotheses. For a detailed description of this model reference is made to [1].

3. THE SOLVING METHOD

The solving procedure is based on the usual finite difference method, once a space-time grid has been defined. For the time derivatives of the above-mentioned equations, the grid is obtained by a fixed time interval Δt. Then the solving procedure differentiates, according to lumped or distributed parameter components.
The lumped parameter components are divided into five categories: I) transition cross-section components and pumps; II) plena; III) density locks; IV) containment vessel; V) pressurizer. The transition component cross-section represents the boundary between two adjacent components; their axial length is zero.
For first category components, only the momentum equation (15) is solved: the pressure is modified by an amount equal to the concentrated friction pressure drops and the kinetic term (the head term in the case of the pump).
For all three other components, the calculation procedure is as follows (see eqs. (5), (14), (16) and (17), taking into account the simplifications indicated at the end of the previous paragraph):

$$M^{n+1} = M^n + (\Gamma_{in}^{n+1} - \Gamma_{out}^{n+1})\,\Delta t \qquad (19)$$

$$h^{n+1} = \frac{1}{M^{n+1}}\left[M^n h^n + \left(\Gamma_{in}^{n+1} h_{in}^n - \Gamma_{out}^{n+1} h_{out}^n\right)\Delta t\right] \qquad (20)$$

$$\rho^{n+1} = \rho(h^{n+1}) \qquad (21)$$

$$\frac{M^{n+1}}{\rho^{n+1}} = V = \frac{M^n}{\rho^n} \qquad (22)$$

where the superscripts n and n+1 represent the variable value at time t and t+Δt respectively. Γ_{in}^{n+1} is known, as explained below, while Γ_{out}^{n+1}, h^{n+1}, ρ^{n+1} and M^{n+1} are obtained by solving the above four equations through a rapidly converging iterative procedure. Then the outlet pressure is determined by the momentum equation (15) as:

$$p_{out}^{n+1} = p_{in}^{n+1} - \rho^{n+1} g\Delta z - \frac{\Gamma_{out}^{n+1} - \Gamma_{out}^{n}}{\Delta t}\frac{L}{\Omega} - \frac{\Gamma_{out}^{2}}{2\rho^{n+1}}\left(\frac{1}{\Omega_{out}^{2}} - \frac{1}{\Omega_{in}^{2}}\right) \qquad (23)$$

For the density lock component (in the case of the PIUS reactor alone) the above equations are applied by taking into account the presence of a separation level between cold and hot water (see next paragraph). The inertia term of eq. (23) is particularly important in this component where the flow rate may undergo sharp accelerations, due to continuous changes in direction. Some simplifications have been adopted for the containment vessel, as explained in the next paragraph.

The pressurizer model differs from the above components and is solved by applying the Eulero-Cauchy method to the four resulting differential equations.

The time step may be smaller than that used for the other components; in this case the system parameters are assumed unchanged during the time step interval.

For distributed parameter components the energy equation is solved by adopting the "method of characteristic"; recalling that:

$$\frac{\partial h}{\partial x} = \frac{dh}{dx} - \frac{\partial h}{\partial t}\frac{dt}{dx} \qquad (24)$$

$$\frac{dx}{dt} = v \qquad (25)$$

where v is the fluid speed, and substituting eqs. (24) and (25) in eq. (13), one obtains:

$$\frac{dh}{dx} = \frac{w}{\Gamma} \qquad (26)$$

which is solved by the finite difference method along the "characteristic line", defined by eq. (25).

The variables at the time t^{n+1} are calculated by an implicit method. The space-time grid is obtained by the same fixed time interval Δt of lumped parameter components, and a variable space interval Δx ("mobile grid"), as defined below. A constant Δx spacing solution is currently under study.

Eqs. (25) and (26) turn into:

$$\frac{\Delta x}{\Delta t} = \langle v \rangle \qquad (27)$$

$$\frac{\Delta h}{\Delta x} = \frac{\langle w \rangle}{\langle \Gamma \rangle} \qquad (28)$$

where <v>, <w>, <Γ> are the values averaged along the characteristic line assuming a linear trend. The stability condition, which is equal to:

$$\Delta t \leq \min\left\{\frac{\Delta x}{|v|}\right\} \qquad (29)$$

is satisfied by eq. (27), which defines the value of the Δx interval variable

in time and space. The division of pipe components according to this mobile grid is shown in fig.1.
The solving equations become:

$$\frac{x_p^{n+1} - x_s^n}{\Delta t} = \langle v \rangle \quad ; \quad \frac{h_p^{n+1} - h_s^n}{x_p^{n+1} - x_s^n} = \frac{\langle w \rangle}{\langle \Gamma \rangle} \tag{30}$$

subscripts P and S refer to the corresponding points of fig.1. $\langle \Gamma \rangle$ is constant versus x, as previously assumed (eq. (11)); $\langle w \rangle$ is obtained by the neutron kinetic equation and/or heat transfer equation; $\langle v \rangle$ is the arithmetic mean of the values obtained in S and P (see fig.1):

$$\langle v \rangle = \frac{v_p^{n+1} + v_s^n}{2} \tag{31}$$

and h_s^n is obtained through a linear interpolation between the corresponding values in x_i^n and x_{i+1}^n.

Space interval Δx is determined by $\langle v \rangle$, which depends on Δx through the enthalpy h_p^{n+1} and the corresponding ρ_p^{n+1}. Thus, a short iterative process is implemented upon the relative speed difference, within a fixed convergence error (typically 10^{-4}).
The momentum equations (12) and (23) are integrated spatially, by using the same space grid assumed for the energy equation for distributed parameter components, and by adopting fluid density and viscosity values obtained by the energy balance in each component. The friction term of eq. (12) includes both the distributed pressure drops and the concentrated ones (if present).
The integral of $\partial p/\partial x$, when extended to the whole circuit, must be zero, since the initial cross-section coincides with the last one. This is obtained through an iterative procedure on Γ, which remains the last unknown to be determined.
In conclusion, at t^{n+1}, Γ is initially assumed equal to the value of the previous t^n time step; then equations (30) and (19) through (22) are solved; with the resulting ρ and μ values eqs. (12) and (23) are integrated and the value of integral of $\partial p/\partial x$ is determined; if this integral is not zero within a prefixed convergence error (typically 10^{-5} kPa), the procedure is repeated assuming a more correct Γ value adopting the null method. The procedure is repeated until the convergence is reached.
In line with the above hypotheses and in particular that to keep constant the flow rate along the distributed parameter components (eq.8), the solution is affected by an error, which is essentially due to the non-conservation of the volume for these components, or in other words, fluid thermal expansion or contraction is not taken into account by shifting a given mass of fluid forward in the circuit into the pressurizer and viceversa. This is reflected in a difference between the space integrals of mass and energy ("photographic") and the corresponding time integrals ("historic"), normalized to the same initial conditions. Being binding the historic integrals, the photographic ones undergo an ongoing correction adding the historic-photographic difference to the circuit in each time step. This difference is introduced in the pressurizer (funnel). In conclusion the pressurizer (funnel) is fed by two flow rates (both positive and negative): the first one is given by the balance between the outgoing flow rate (starting value in each iteration) and the incoming flow rate; the second one is the

above mentioned correction.
When present the two-phase mixture is treated in a simplified way. Steam quality is determined by the excess of fluid enthalpy over saturation enthalpy which is checked in every cross-section of the cell ends or inside the lumped parameter components, by referring to the pressure calculated at the previous time step. Mixture specific volume is calculated from the homogeneous model assuming slip ratio equal to one. Pressure drops are obtained by using the same equations adopted in single phase and corrected for mixture specific volume, without referring for the time being to specific correlations valid in this condition.
The mobile spatial grid implies that the final cell of each distributed parameter component does not, in general, coincide with the actual component end. Thus, the abscissa of the starting point S is shifted upstream, as indicated in fig.2, until achieving convergence.
The boron moves along the distributed parameter components in strict coherence with flow rate, without any axial mixing. When it enters a concentrated parameter component, it is instantaneously mixed into the whole volume. Boron distribution along the density lock is described in the next paragraph.

4. THE CIRCUIT COMPONENTS

The PIUS primary circuit is segmented as shown in fig.3. The PWR circuit is conceptually similar to the PIUS one if the density locks are eliminated. The external loops are lumped together, so that dissymmetry effects between the loops are simulated in an approximate way. When one loop (or two, or three) goes out of service (loss of flow accident), the total cross-section area of the external circuit is progressively reduced to that of the remaining operating loops, and a possible flow reversal in the failed loop(s) can be assigned as input datum (see below).
Some components require a special model: i.e. the reactor, the steam generator, the pump, the density lock, the siphon breaker, the pressurizer and the containment vessel. The reactor core model is rather complex and will be presented in the following paragraph.
The power exchanged in the steam generator is calculated by assigning the temperature of the secondary fluid. This is uniform along the whole steam generator and it corresponds to the steam saturation temperature; its value might not be constant over time, but in this case it is assigned as an input. Overall total heat resistance is normalized in order to exchange the nominal reactor power with the actual heat exchange surface. Its value is then broken down into two terms: a constant one, representing the thermal resistance of the tube thickness, crud deposition and the secondary side boiling, and a variable one, representing the primary side heat transfer, which is proportional to the flow rate to an exponent of 0.8.
The pump characteristic is assumed as having the following form:

$$\frac{H}{H_0} = A_1\left(\frac{Q}{Q_0}\right)^2 + A_2\frac{n}{n_0}\frac{Q}{Q_0} + A_3\left(\frac{n}{n_0}\right)^2 \qquad (32)$$

where H, Q, n are the head, the volumetric flow rate and the revolutions per minute respectively, while A_1, A_2, A_3 are characteristic constants of the pump, and subscript (o) indicates nominal values.
The pump is described in three different conditions: normal condition, loss of energy condition, cavitation condition.
In normal condition the pump volumetric flow rate is obtained by the value of Γ calculated during the previously explained procedure, while the revolutions

per minute are constant during the time step. Their value is calculated by setting the lower density lock flow rate to zero, or optionally setting the interface level between cold and hot water in the lower density lock within a prefixed interval, always referring to the previous time step conditions. Thus, at the end of each time step, the rotation speed is adjusted through an approximate procedure. Maximum speed cannot exceed nominal speed (typically 5%) by an assigned quantity; a pump inertia effect is taken into account in this adjustment by assigning the maximum allowable acceleration value. In the loss of energy condition, the pump decay speed is calculated by solving the usual dynamic equation, where the pump is characterized by an assigned overall rotational inertia and an efficiency kept constant during the transient. Loss of energy may involve 1, 2, 3 or 4 pumps of the circuit. The model accounts for the behaviour of a system, with some pumps working in parallel regularly fed by external energy, and some pumps without power supply. Cavitation condition is obtained when the assigned NPSH (Net Positive Suction Head) value is reached at pump entry. In this case the head is set to zero.

The density lock is a vertical cylinder filled by a bundle of open tubes. At a certain elevation there is a separation interface between hot and cold water. Across this interface, the water temperature and boron concentration undergo a stepwise change: no turbulence mixing is considered herein.

Density lock flow rate is determined through eq.(23), where the inertia term is augmented to allow for the contribution of the movement of the water mass surrounding the density lock. The density lock flow rate, when entering the plenum to which it is connected, mixes instantly with the water contained in the plenum itself. The incoming water remains at the temperature and boron concentration values existing above the density lock separation interface until this is displayed beyond the highest section of the density lock. Beyond this point, cold and borated water (containment vessel water) enters the plenum. When the water is flowing in the direction from the primary circuit to the containment vessel, the conditions above the interface are obtained by an instantaneous mixing of the incoming water and that already present in this zone.

The siphon breaker is simulated by a localized pressure drop alone. The small coolant bypass flow rate between the riser and the downcomer, is an input datum, since its variation is rather complex to calculate on-line.

The pressurizer model is solved out-of-line, assuming as surge line flow rate and enthalpy, the values calculated by the main circuit model at the end of each time step. In turn the main circuit model adopts the values calculated at the end of the previous time steps input data from the pressurizer (pressure, surge line flow rate and enthalpy) . Let us recall that the circuit dynamic behaviour is slightly affected by its absolute pressure and the surge line flow rate is always a tiny fraction of the circuit one. In the PWR, the surge line is physically present; in the PIUS, it is practically non-existent and the interested zone is divided into three volumes (see fig.3): the funnel (F), the upper plenum (A_2) and the vertical annular connection to the upper density lock (C). Each volume is treated separately in line with the above detailed procedure adopted for plena. During start up operation, the A_2 and C enthalpies may differ somewhat and in this case a rather complex heat transfer process should take place mainly between the downcomer (12) and volume C. For the time being, a simplified model has been adopted, which only implies heat exchange between A_2 and C and between A_2 and F, calculated with a term proportional to their temperature difference (temperature being uniform in each volume according to our model).

The funnel and the containment vessel levels are correctly calculated by evaluating any spill-over between the funnel and the containment vessel and the density lock flow rates. The containment vessel water temperature and boron concentration are assumed constant in space and time. Therefore, the containment vessel is assumed to have its actual volume for level calculation and an infinite volume for enthalpy and boron calculation.

5. THE REACTOR CORE

The reactor core model presents three aspects: channel thermohydraulics, fuel rod behaviour and neutron power kinetics.
From a thermohydraulic viewpoint the core may be approximately described as a bundle of separate channels, each containing one fuel element. With their different power inputs, these channels also have also slightly different flow rates in order to satisfy the boundary condition in obtaining the same core pressure drop. During transient conditions a steam-water mixture may be obtained in the hottest channel and this would imply a slightly higher asymmetry in channel flow rate distribution and above all a "void" generation, which involves a negative reactivity feedback. A thorough description of this thermohydraulic configuration is really too complicated for our program aims and so a simplification has been adopted.
The reactor core is described through a single power channel representing the core average channel. This is viewed as a "pipe" with constant cross-section, and a power input derived from the fuel rod subroutine. However at the end of each time step and maintaining the already calculated core boundary conditions constant, the parallel channel behaviour is determined out-of-line. Three channels are examined, each representative of those of the central, intermediate and peripheral zones respectively. In this way, a more precise temperature and void distribution can be calculated to determine reactivity feedback data. This out-of-line calculation follows an iterative procedure to correct the flow rate of each channel at the same overall flow rate and in order to converge on the same pressure drop. To check the importance of this procedure two hypothetical conditions were calculated: saturation conditions are obtained at the outlet of the average channel, either by halving nominal flow rate or doubling nominal power. The negative reactivity feedback, due to moderator temperature and void, is calculated for the average channel, or as the average of the three channels: 512 pcm against 1369 pcm and 779 pcm against 2150 pcm were obtained in the first and second cases respectively. This example clearly reveals the need, when calculating reactivity effects, to consider three different channels in parallel. In reality, the overall effect on the transient is dampened, because a higher void reactivity feedback reduces the reactor power more rapidly which in turn, reduces void formation (inherent feedback phenomenon).
The fuel rod temperature distribution is only described in the radial direction. The cross-section is divided into five annular zones: three in the fuel zone, one in the gap and one in the cladding, and their temperatures are the unknowns. The general Fourier equation was solved by referring to these five temperatures. The boundary conditions are: the power generated in each zone, which is proportional to its area (deriving from the neutron kinetic subroutine), the coolant temperature and the corresponding heat transfer coefficient. In conclusion, five linear algebraic equations are obtained, the solution of which yields the desired temperature distribution and thus the thermal power transferred to the coolant, plus a suitable mean fuel temperature for Doppler reactivity calculation.
The thermal conductivities and specific heats of zircaloy and uranium oxide

are taken as temperature dependent while their density is assumed constant. Gap conductivity is assumed to be burnup and linear-power dependent and so an empirical correlation based on a rather complex fuel performance model was developed.
This model is applied to the average fuel cross-section of the reactor. The coolant boundary values are taken under the average conditions as well. This conclusion was reached after a number of calculations showed that the adoption of several fuel cross-sections (six for each of the three above-mentioned channels) yielded a reactivity feedback value which varied by a few percentage points from the single cross-section value.
The neutron power is calculated out-of-line at the end of each time step; the resulting value is the power input for the calculation of the fuel rod temperature distribution in the next time step. The reactivity is calculated as the sum of four terms due to: fuel temperature (Doppler effect), moderator temperature, moderator voids, boron coolant concentration. Each one is calculated by multiplying the corresponding parameter variation with respect to a reference condition, by a given input value (reactivity coefficient), which can be a function of the parameter itself. As for Doppler reactivity, an effective fuel temperature is defined as:

$$\theta = \ln\left(\frac{4}{9}\,\theta_0 + \frac{5}{9}\,\theta_2 + 669\right) \qquad (33)$$

where θ_0 and θ_2 are the fuel centre and peripheral temperatures respectively.

In the PWR, the scram rods are simulated by an assigned curve reactivity time, triggered when a given plant parameter reaches a limiting value (e.g. recirculation flow rate below 87% of the nominal value).
The neutron kinetic equations (Nordheim-Fuchs) are written for six delayed neutron groups and solved by the simplified Runge-Kutta method, according to the procedure indicated in ref. [2]. The solution is obtained by a shorter time step to the one used in the thermohydraulic part of the program (typically 10 ms against 100 ms). Therefore the neutron kinetic integration is carried out with constant input data throughout the whole thermohydraulic time step. The delayed neutron decay time constants and their fractions are input data, burnup dependent. When a reactor moderator parameter (temperature, void, boron) is averaged, it can be done by weighing the quantity in a linear or quadratic mode versus the actual neutron flux (axially and radially).
Significant improvements of TRIP model are in progress concerning steam generator secondary side modeling, the adoption of an axial core kinetics and the elimination of hypothesis (7).
The TRIP and TRAP programs are currently run on a PC, IBM compatible; a main frame version exists as well.

6. CALCULATION EXAMPLES

This paragraph shows some examples of the program capabilities concerning both PIUS and PWR. These results do not intend to provide systematic informations about safety and operational features of these reactors: that will be detailed elsewhere.
The results are shown in figs.4,5,6,7,8: the first three concern the PIUS reactor and the rest, the PWR.
Fig.4 shows a loss of flow in one pump out of four and stop of feedwater pump, in terms of plant characteristic parameters versus time. This transient may represent a reactor scram. The results obtained by considering the flow reversal through the out-of-service loop are shown on the same plot.
Fig.5 shows a hot standby start-up at 1000 s, following a reactor scram

obtained according to the above procedure.
Fig.6 shows the amplification effects of pump speed oscillation on core reactivity and reactor thermal power, in order to show the program capabilities in studying plant stability. The results have been synthesized plotting the relative amplitude of the parameter under consideration divided by the relative amplitude of the pump rotation speed oscillation. Calculations have been carried out both with density locks open and closed.
Fig.7 refers to a PWR as a AP600; it represents a loss of flow accident in all reactor pumps followed by a reactor scram. Different parameter transients are shown in six plots.Fig.8 highlights the same transient without the intervention of the scram system.
All these examples clearly demonstrate the wide capabilities of these two programs based on the TRIP model, under all conditions in which liquid water or low quality mixtures are maintained within the primary circuit. These capabilities cover the analysis of reactor accidents (with exception of LOCA), reactor stability and long term operational transients.

NOMENCLATURE

Symbols

D : equivalent diameter
f : friction factor, frequency
g : gravity acceleration
G : mass flux
h : specific enthalpy
H : total enthalpy, pump head
K : total form loss coefficient
L : component length
M : fluid mass
n : pump revolutions per minute
p : pressure
Q : volumetric flow rate
t : time
U : internal energy
v : fluid speed
V : component volume
z : elevation
x : axial coordinate
w : linear power
Δ : difference
ϕ : heat flux
γ : relative amplitude of a parameter/ relative amplitude of disturbance
Γ : total mass flow rate
Π : heated perimeter
Ω : cross-section area
ρ : fluid density
μ : fluid viscosity

Subscripts

b : boron concentration
i : generic space grid position
in : inlet
l : density lock interface elevation
o : nominal value
out : outlet
p : point P of fig.1
s : point S of fig.1
sat : saturation
w : reactor power
ρ : reactivity

Superscripts

n : at time t
n+1 : at time t+Δt

REFERENCES

1. G.P.Invernali, C.Lombardi: *Simulation of PWR Pressurizer in Transient Conditions* - X Heat Transfer National Congress, Genoa, Italy, 25/27 June 1992.

2. Yung-An Chao, A.Attard: *A Resolution of the Stiffness Problem of Reactor Kinetics* - Nuclear Science and Engineering, N.90, 1985.

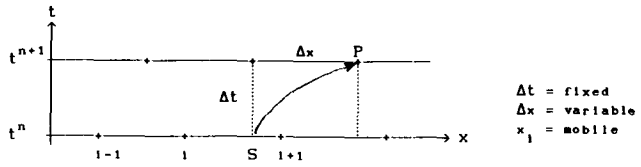

Fig.1 - Subdivision of pipe components according to mobile grid.

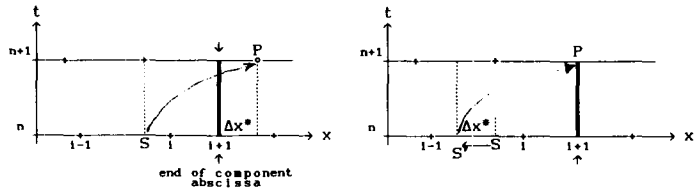

Fig.2 - Procedure to shift upstream point S in order to coincide with component end.

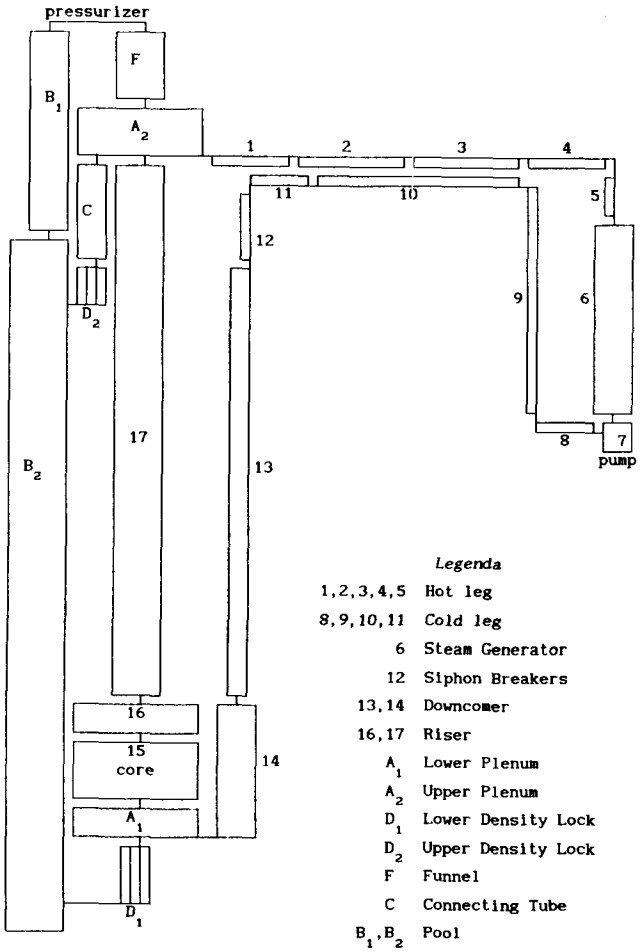

Fig.3 - Discretization of PIUS reactor system in TRIP model.

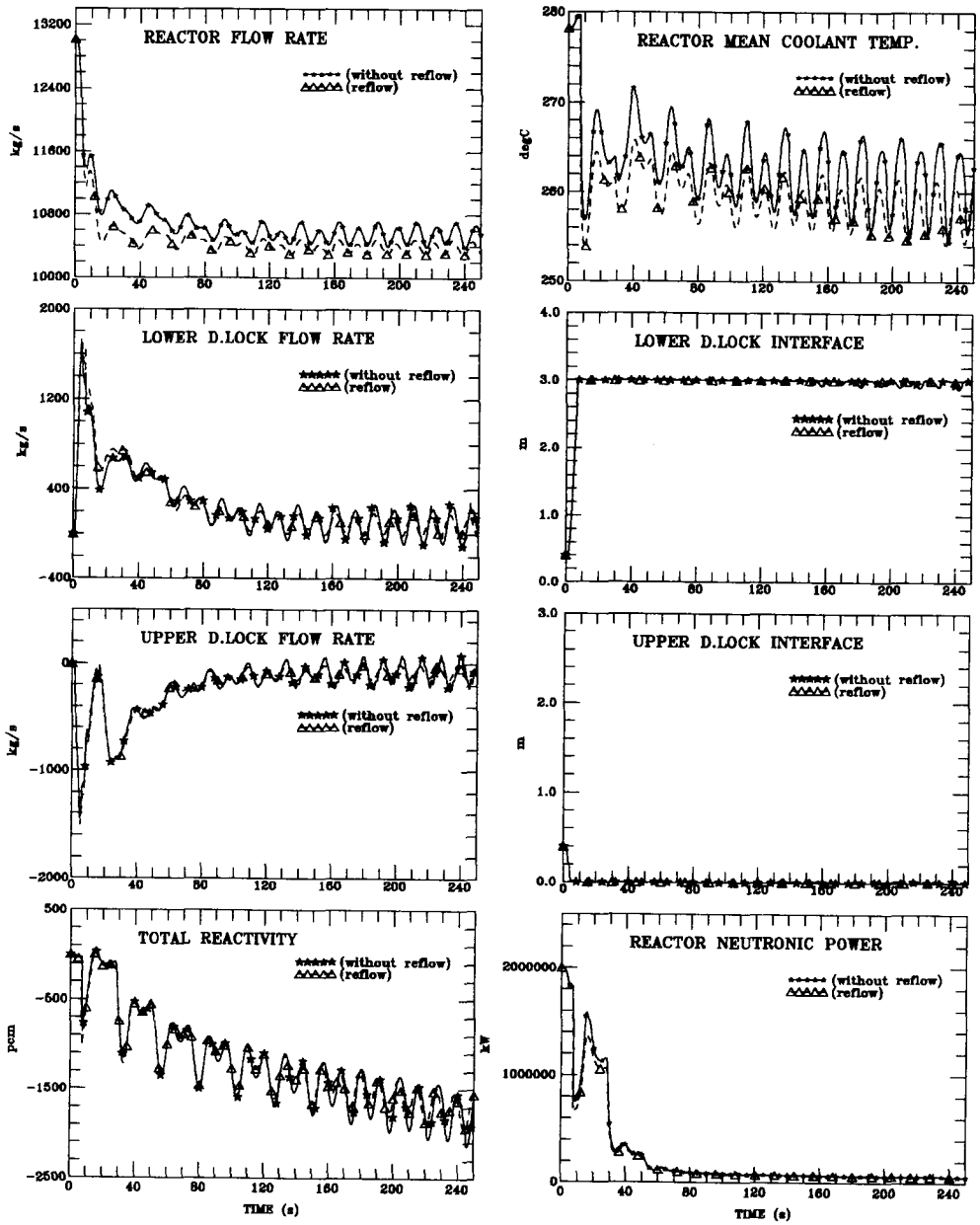

Fig. 4 - Loss of flow in one pump out of four and feedwater pump stop for PIUS; results obtained by considering the flow reversal through the out-of-service loop are shown on the same plots (TRIP program).

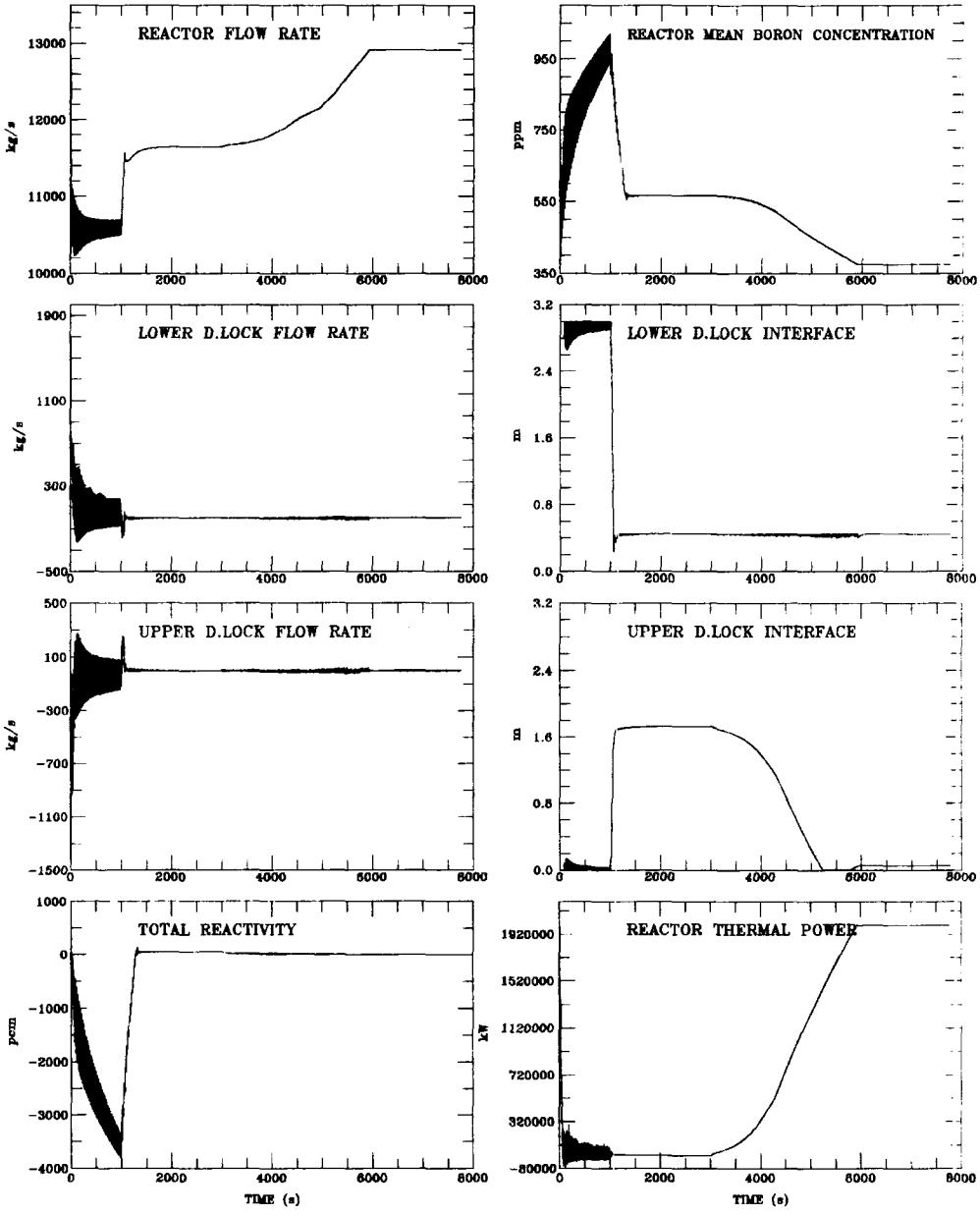

Fig. 5 - A PIUS hot standby start-up at 1000 s, following a reactor scram obtained by 1 pump LOFA and the turbine stop valve closure (TRIP program).

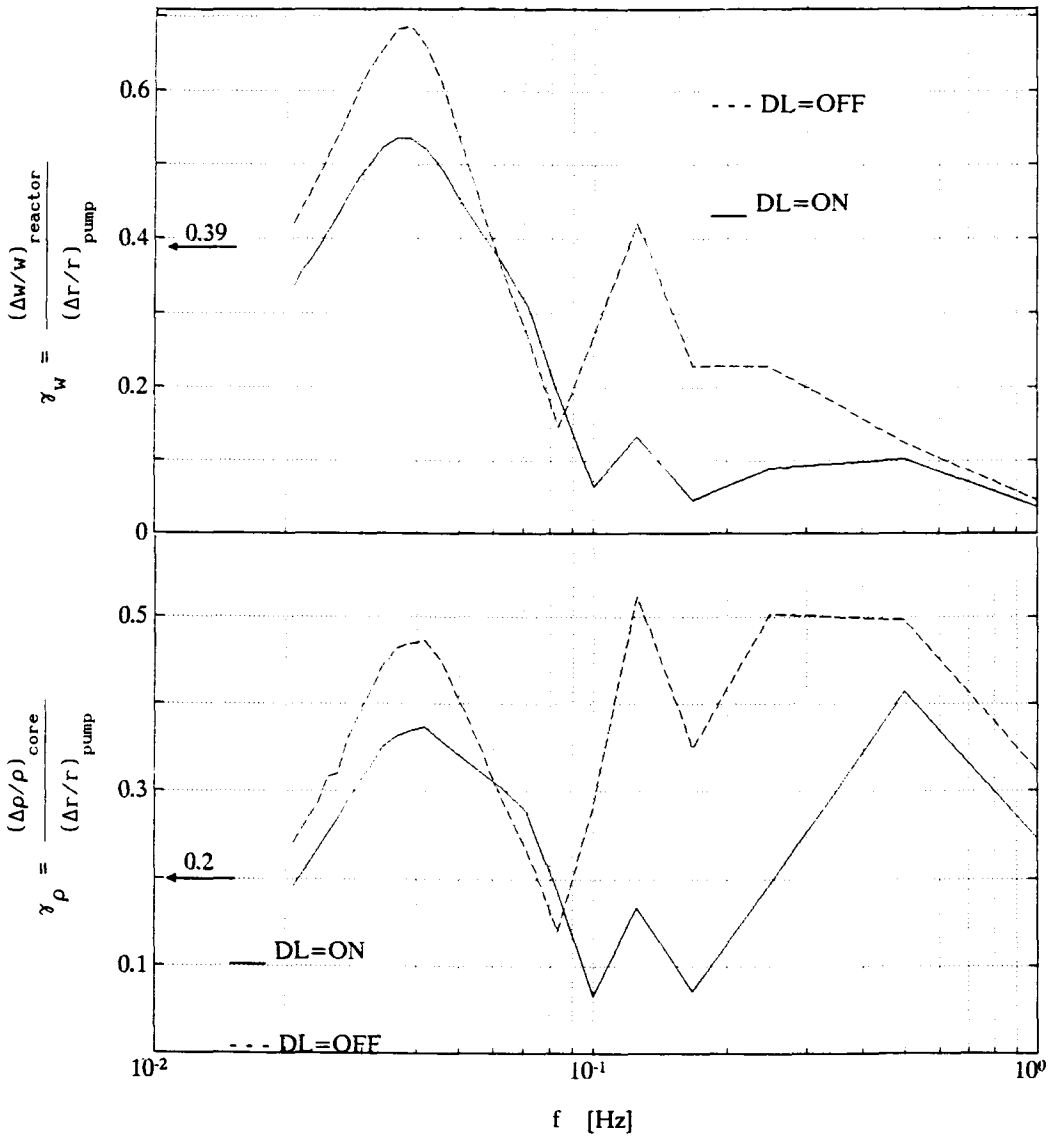

Fig. 6 - Amplification effects in PIUS reactor of a pump speed oscillation on core reactivity and reactor thermal power (TRIP program).

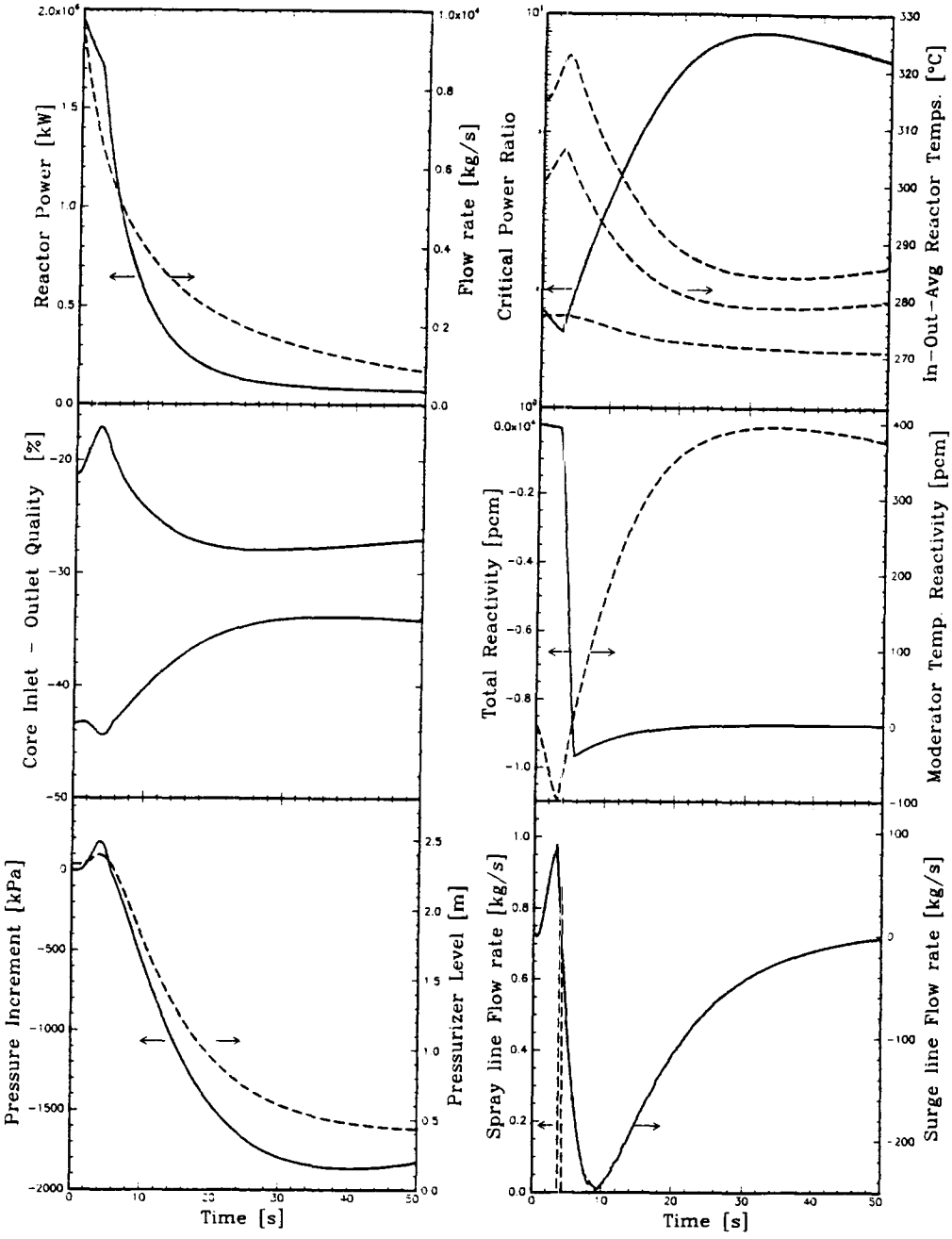

Fig. 7 - Several parameter transients during a loss of flow accident for an AP600 reactor followed by scram as obtained by TRAP program.

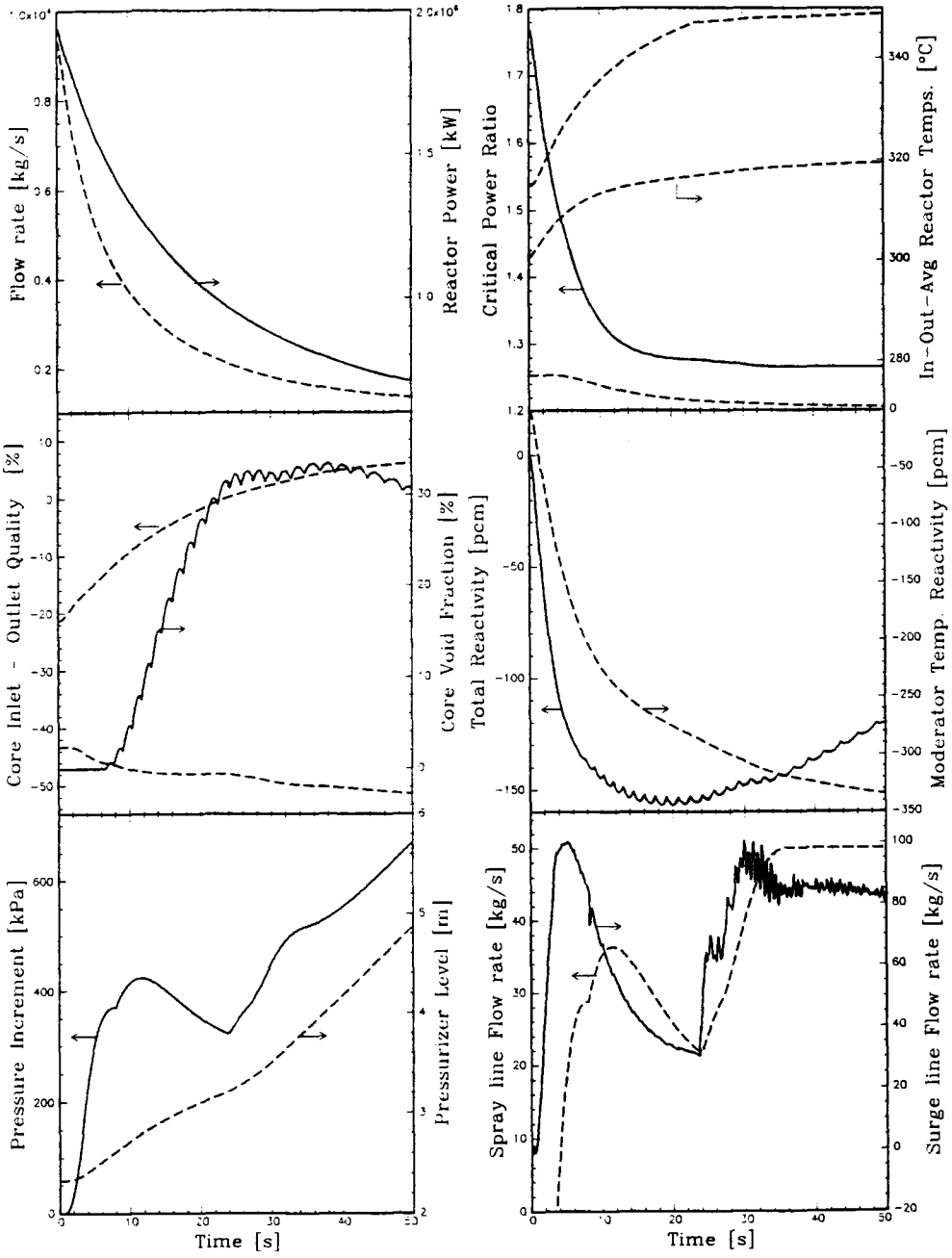

Fig. 8 - Several parameter transients during a loss of flow accident for an AP600 reactor without scram (ATWS) as obtained by TRAP program.