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The influence of Core Bypass Flow during SBLOCA

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Abstract

Many parameters affect the behavior of a NPP during a Small Break Loss of Coolant Accident (SBLOCA). The bypass flow between the core side and the downcomer is one of them. Different PWRs have different values of core bypass flow.

In spite of the complexity of the real situation in the primary system during SBLOCA, some fundamental details of the phenomena can be explained with simplified mathematical models, which relate on basic parameters of the primary coolant. These models define the conditions for loop seal clearance and final results are confirmed with measured values.

The analysis presented in the paper refers to Bethsy Test 9.1.b SB LOCA scenario, with variation of core bypass flow. Basic RELAP5 input model calculation results show very good agreement with the experimental data.

The core liquid level depression before loop seal clearance is lower in case of smaller core bypass flow. This affects the fuel clad temperature because of different heat transfer mechanisms. Time of loop seal clearance is delayed with larger core bypass flow and consequently lower differential pressure between downcomer and core.

1. Core Bypass Flow

Core bypass flow is the part of primary coolant flow, which does not pass the through core. The core bypass flow is considerd in this paper only direct flow from downcomer to upper plenum of the reactor vessel. It consists of flow through the connection between the cold leg and reactor vessel, reactor vessel head coolant flow and in some particular reactors the flow through a vent valve, which is opened only during safety injection phase.

Calculated results and observations of the experimental tests showed the influence of total core bypass flow value on the SBLOCA scenario. The core bypass flow, due to the connection between the upper core region and cold leg, decreases differential pressure between downcomer and upper plenum of the reactor vessel. It allows steam entering from the upper part of the reactor vessel into the cold leg and than further to the break.

A core bypass flows in commercial PWRs usualy vary from 0,5% up to 4% of total loops RCS flow rate [1].

In the two-loop Krško NPP, a 0,5% amount of primary coolant flow avoids the core through the junction of the hot leg and reactor vessel, another 0,5% passes through the spray nozzles for reactor vessel head cooling [2].

Standard four-loop Westinghouse NPPs have through the stated junction a doubled flow

rate, while the same one passes through spray nozzles (comparison with the Krš NPP) [3].
More details about values of the core bypass flows are listed in Table 1.

Nuclear Power Plant	Core bypass flow in %
NEK-Westinghouse (two loops)	1
Westinghouse (four loops)	1.5
French NPP	2
Doel 2 - Belgium (two loops)	0,24
Doel 4 - Belgium (three loops)	0,35

Table 1. Core bypass flows in different NPPs

2. Physical interpretation of fundamental phenomena during SBLOCA

All the parameters affecting the SBLOCA scenario cannot be considered in simplified mathematical models. However some basic principles and phases of the accident can be very well predicted by simplified mathematical equations. They lead to results, which are confirmed by large computer codes and by experimental simulations.
The core cooling is most interfered just before the loop seal clearance. The core coolant level is then at the lowest elevation. Natural circulation is stopped and coolant from safety injection has not jet reached the core.

Physical parameters:
p ...... pressure
ρ ...... density
z ...... elevation
g ...... gravitational acceleration

Subscript:
$_c$ .... core
$_d$ .... downcomer

Table 2. Explanation of used nomenclature

2.1 Conditions for loop seal clearance

Figure 2.1 presents the conditions in the reactor vessel when the natural circulation stops. Only steam is present on the primary side of steam generators. Core coolant level is equal to the level in loop seals. Core coolant level in Figure 2.1 is collapsed coolant level, meaning that coolant below this level is in liquid phase without steam bubbles. Actual core coolant level is much higher because of the fruit. In this simplified model we neglect the presence of steam in the primary system and we assume constant density of the primary coolant. With these assumption, we can write:

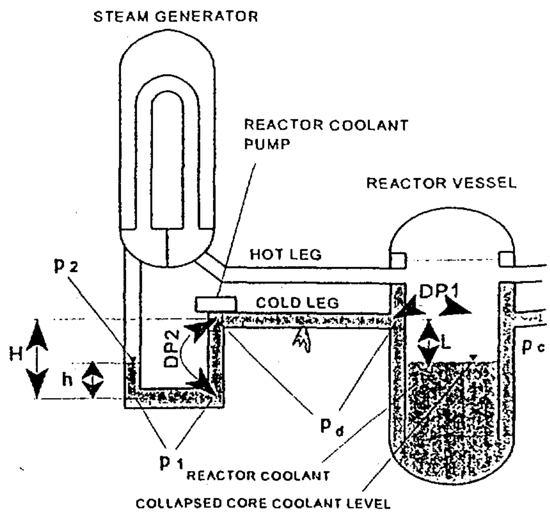

Figure 2.1 Model of primary circuit after natural circulation stop

$$p_2 = p_c \tag{1}$$

The pressure at the bottom of the cold leg p_1 is:

$$p_1 = p_2 + \rho g h \tag{2}$$

and the pressure of the downcomer inlet:

$$p_d = p_1 - \rho g H \tag{3}$$

After joining the equations (1), (2) and (3), we have:

$$p_d = p_2 - \rho g(H-h) = p_c - \rho g(H-h) \tag{4}$$

The differential pressures DP1 and DP2 are defined as follows:

$$DP1 = p_d - p_c = -\rho g(H-h) = -\rho g L \quad DP2 = p_1 - p_d = \rho g H \tag{5}$$

Figure 2.2 shows the conditions before the loop seal clearance. The lowest cold leg point is almost dried out. We can write:

$$h = 0 \qquad L \geq H \tag{6}$$

It is also

$$|DP1| \doteq \rho g L \tag{7}$$

and

$$DP2 \doteq \rho g H \tag{8}$$

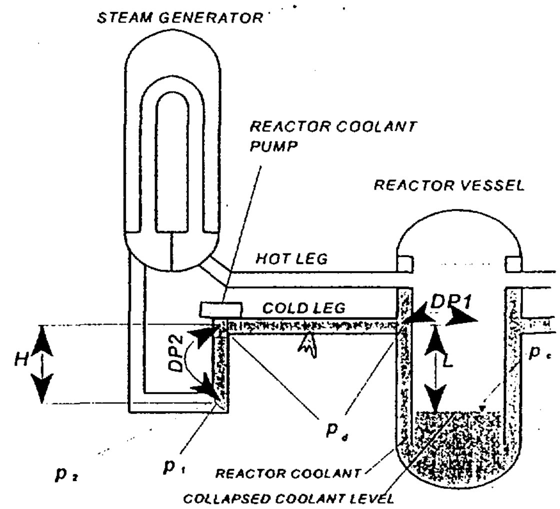

Figure 2.2 *Model of primary circuit just before loop seal clearance*

When the coolant covers just the cold leg lowest point, the DP2 is constant and equal to ρgH. Differential pressure between the core and downcomer DP1 depends on the core coolant level. It becomes zero with fulfillment of the condition: h=H.

Dry out of the horizontal pipe of loop seal ($L \geq H$) defines the condition for loop seal clearance, according to the differential pressures DP1 and DP2:

$$|DP1| \geq DP2 \text{ at } L \geq H \tag{9}$$

Experiments showed presence of liquid core coolant in the U tubes of steam generators at the moment just before loop seal clearance [4]. A difference between coolant levels of the hot and of the cold primary side of steam generator was observed. Considering this, we can add this term to the equation (9):

$$|DP1| \geq DP2+DP3 \qquad \textbf{(10)}$$

where DP3 (Figure 2.3) is given by the equation:

$$DP3=\rho g(h_2-h_1) \qquad \textbf{(11)}$$

A positive difference between the coolant levels in the steam generators (h_2-h_1) additionally reduces the core coolant level below the lowest cold leg point.

Core bypass flow presenting direct connection between downcomer and upper plenum impacts on the differential pressure DP1. The increase of DP1 during SBLOCA is slow with larger core bypass flow and loop seal clearance is delayed.

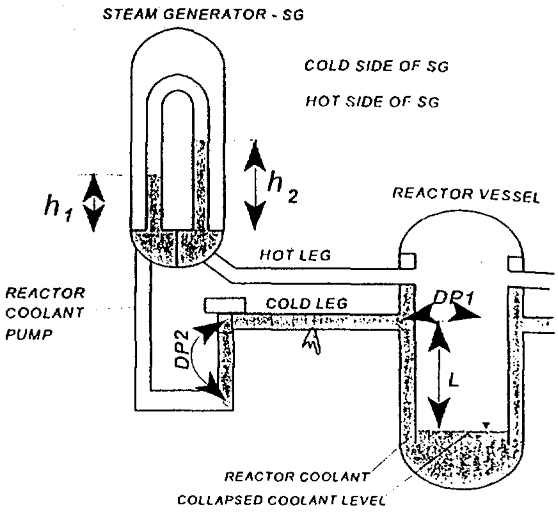

Figure 2.3 *Model of primary circuit just before loop seal clearance with coolant in SG tubes*

2.2 Impact of the core bypass flow to the core coolant level

On the bases of the results of simplified mathematical model [5], we can estimate the relation between core coolant level and core bypass flow. Figure 2.4 displays the situation in the reactor vessel just before loop seal clearance. It can be simplified as follows: kinetic energy in the primary system can be neglected, considering the absence of natural circulation and constant density of primary coolant. These lead to equilibrium equation for core (region c; where $\bar{\rho}_c$ is average water density in the core) and junction of downcomer and cold leg (region d):

$$p_c+\bar{\rho}_c g z_c=p_d+\rho_d g z_d \qquad \textbf{(12)}$$

After restructuring the last equation, we have:

$$z_c=\frac{1}{\bar{\rho}_c}(\rho_d z_d-\frac{p_c-p_d}{g}) \qquad \textbf{(13)}$$

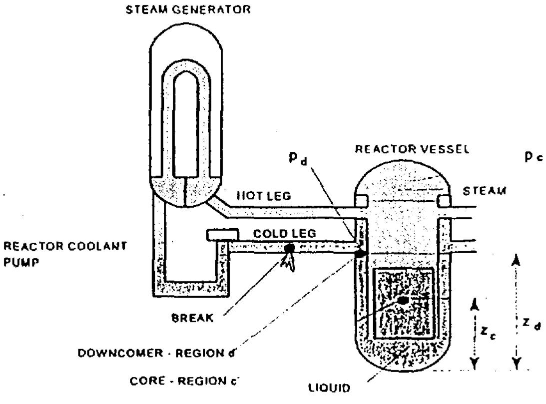

Figure 2.4 *Impact of the core bypass flow on core coolant level in a model of primary circuit*

Elevation z_d is taken as a reference value (0). Therefor the equation for coolant level difference between regions c and d is:

$$z_c' = z_c - z_d = -\frac{1}{\bar{\rho}_c}\frac{p_c - p_d}{g} \qquad \textbf{(14)}$$

We assume a 30% void factor for the core region, the average core coolant density at [illegible] bars in core is:

$$\bar{\rho}_c = 514\,\frac{kg}{m^3} \qquad \textbf{(15)}$$

Finally, we can write the relation between the elevation of core coolant (in cm) and differential pressure (in Pa) across the downcomer and core:

$$z_c' = -0.02(p_c - p_d) \quad [cm] \qquad \textbf{(16)}$$

Equation (16) means: every differential pressure across downcomer and core of 100 Pa leads to additionally 2 cm lower core coolant level in the period just before loop seal clearance.
Nuclear power plants with smaller core bypass flow have larger differential pressure between downcomer and upper plenum during SBLOCA. Mathematically:

$$(p_c - p_d)_{larger\ core\ bypass\ flow} < (p_c - p_d)_{smaller\ core\ bypass\ flow} \qquad \textbf{(17)}$$

Reference [5] states that the differential pressure (p_c-p_d) can be up to 13 000 Pa under same SBLOCA conditions and power plants with different core bypass flow. That can cause (equation 16) more than 2m difference of core coolant level before loop seal clearance.

3. Results of RELAP calculations on Bethsy 9.1.b SB LOCA experiment

Based on modeling of Bethsy scaled model of the three-loop french nuclear power plant, IJS-OR4 division tried to prove stated theoretical conclusions. Different scenarios were analyzed and compared with experimental data. First, the calculated core bypass flow was assumed equal to the experimental one (1,18% of the primary coolant flow).
The core bypass flow was increased to the value of 1,94% in a second scenario. Table 2 presents values of maximum core level depression before the time of loop seal clearance and maximum fuel clad temperature occurrence during the calculated scenarios.
Figure 3.1 presents core coolant collapsed liquid level for the calculated 1.18%, 1.94% and experimental core bypass flow. A delay (24 min) of the loop seal clearance is evident with increased core bypass flow. Other scenarios with even smaller bypass were calculated. They showed, that decreasing the bypass flow under 1% does not contribute much to sooner appearance of seal clearance. We concluded, that the relation between

	time (s)	minimum collapsed core level (m)	time (s)	maximum fuel clad temperature (K)
1,18% core bypass flow	3230	1,76	3310	1047
1,94% core bypass flow	4680	1.99	4800	972

Table 2 Values of modeled core bypass flow for Bethys scaled model

the amount of core bypass flow and appearance of loop seal clearance of RELAP runs is not linear.

Comparing the experimental data of ROSA-IV [4] and MOD-2C [1] models we expected larger influence of increased core bypass flow to the core level depression just before the loop seal clearance. The difference in minimum collapsed core coolant level in the two calculations was approximately 20 cm.

Because of delayed loop seal clearance, the core level depression appears, when the decay heat is lower. Fuel clad is less exposed to interfered heat transfer and maximum fuel clad temperature is increasing with decreasing core bypass flow (enclosed figures to the article; A.1 and A.2).

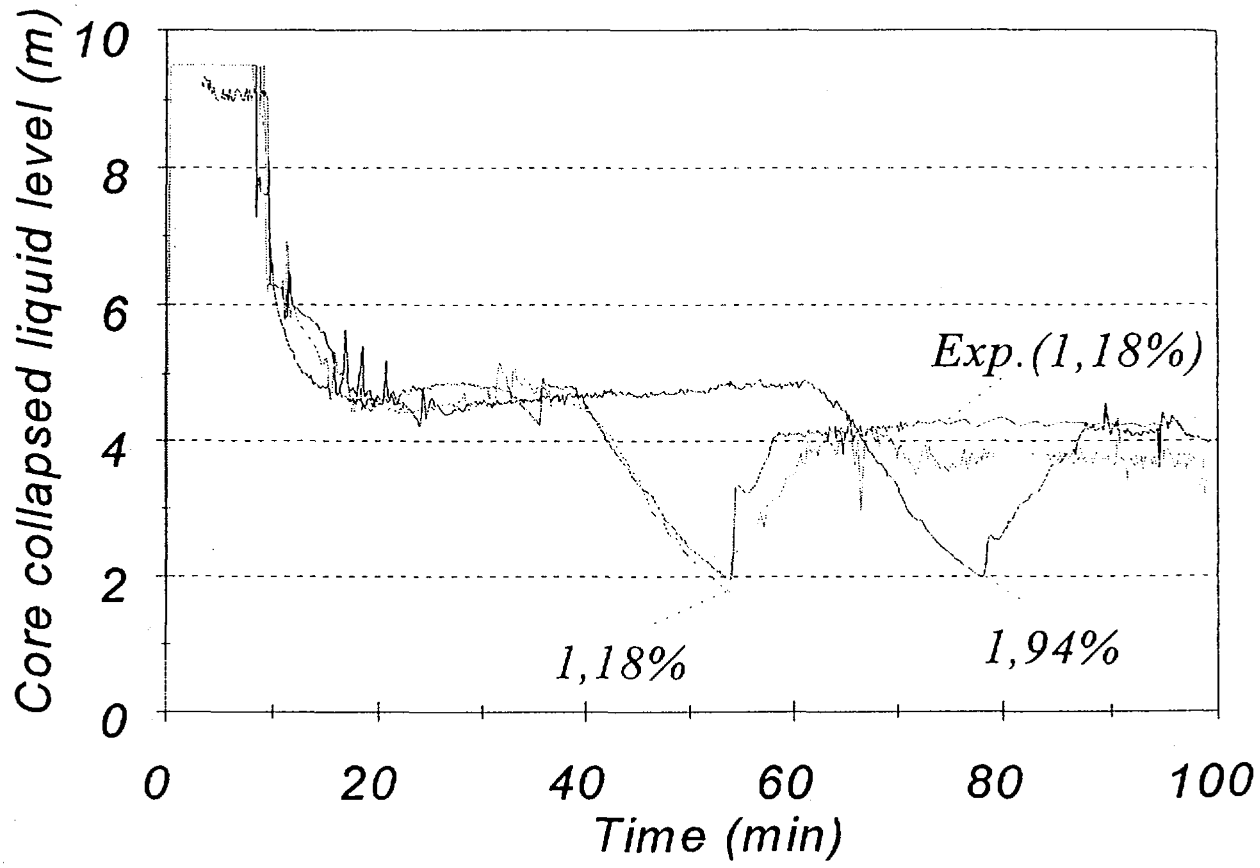

Figure 3.1 *Core collapsed liquid level of two RELAP runs with 1,18%, with 1,94% and of experiment with 1,18% core bypass flow*

The depressurization of the primary coolant system strongly depends on the time of loop seal clearance. In both scenarios (enclosed figures to the article; A.1 and A.2), depressurization under 6 MPa took place after the loop seal clearance, but this had no impact on fuel clad temperature excursions.

Differential pressure of the upstream line of loop seal was a good indicator of loop seal clearance during the experiment. At least one of the three upstream differential pressures was zero just after the loop seal clearance. Calculated results (enclosed figures to the article; A.1 and A.2) did not predict this. RELAP's calculated differential pressures of the upstream lines are based on the average density of the coolant in that area. During the loop seal clearance, iner surface of the primary pipe could be still wetted, while inside the pipe could be already steam. RELAP differential pressure measurement simplifications do not represent real physical measurements of differential pressure values in upstream lines of loop seal.

4. Conclusions

After analyzing the impact of core bypass flow on SBLOCA scenarios we can give the following conclusions:

- In general, the larger core bypass flow leads to smaller break flow. This is due to larger void fraction in broken cold leg.
- The amount of core bypass flow has impact on the appearance of loop seal clearance. The increase of differential pressure between upper plenum and downcomer during SBLOCA is prolonged due to larger core bypass flow and delay of loop seal clearing.
- The core coolant level just before the loop seal clearance depends on the differential pressure between core and downcomer. A larger core bypass flow causes smaller differential pressure and core level depression.
- The maximum fuel clad temperature is lower with delayed loop seal clearance due to larger core bypass flow and at the same time lower decay heat power.

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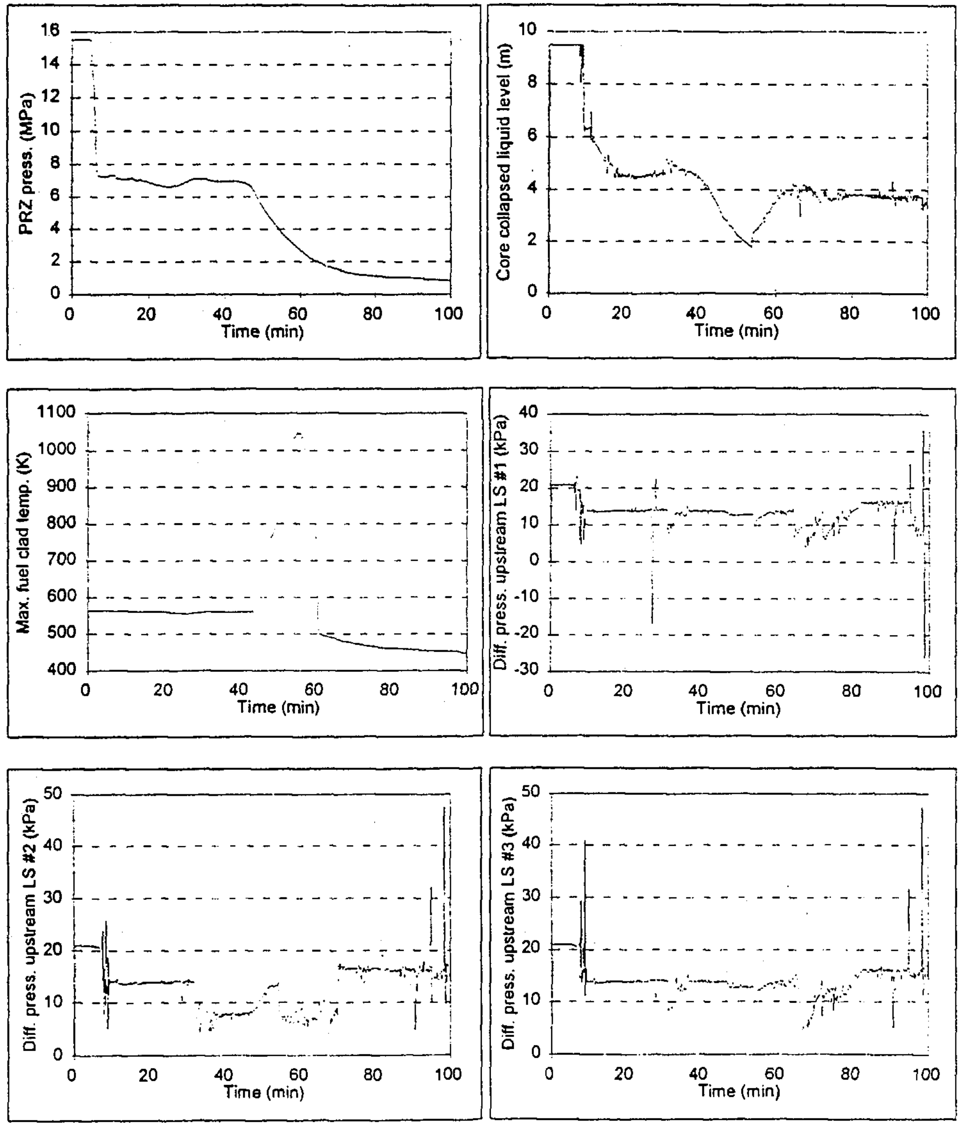

Figure A.1; Main results of RELAP run with 1,18% core bypass flow

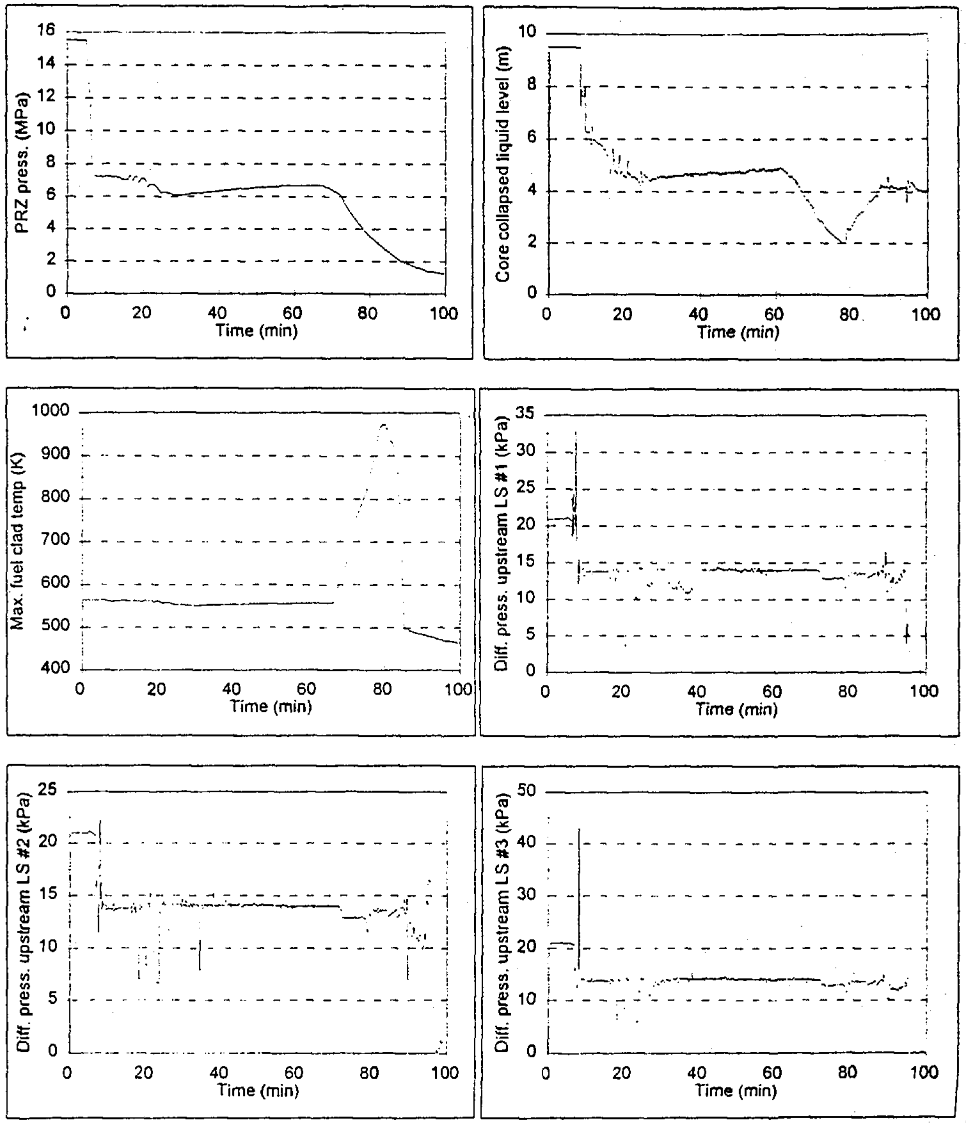

Figure A.2; Main results of RELAP run with 1,94% core bypass flow