RELAP5/MOD3.2 POST TEST SIMULATION AND ACCURACY QUANTIFICATION OF LOBI TEST A1-93

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ABSTRACT

The present paper deals with the Relap5/Mod3.2 post test analysis of the small break LOCA test A1-93 from LOBI/Mod2 Facility.

LOBI/Mod2 is a non-nuclear two loop, high-pressure integral system test facility for PWR safety research, installed at JRC in Ispra Establishment (Italy). Volume and core power scaling factors are 1/712, with respect to the KWU Siemens 1300 MW_e (3900 MW_t) standard PWR.

The test A1-93 is originated by a 2% small break in the cold leg without the actuation of the high pressure injection system. An enhanced depressurization is obtained by actuating the pressurizer PORV and SRV. When primary system pressure reaches 27 bar, accumulator injection begins.

The Relap5/Mod3.2 nodalization of LOBI facility considered is one that has already been used and qualified at University of Pisa.

The experimental main parameters are compared with the calculated results, showing good agreement in all phases of transient. Qualitative and quantitative code accuracy evaluation has been performed using the Fast Fourier Transform-Based Methodology.

1. INTRODUCTION

Thermal hydraulic computer codes, like Relap5/Mod3.2 (R5M3.2) code [1], have been developed to predict the behavior of Nuclear Power Plants (NPP) during transient and accident conditions. As part of the development of these codes assessment studies are included in order to demonstrate the qualification level and to determine the accuracy in the prediction of the system performance, of the safety margins and of design parameters for accident management procedures of Light Water Reactors (LWR).

The LOBI/Mod2 Facility is an integral test facility (ITF) available at the European Community Joint Research Center (JRC) of Ispra, Italy. The Test A1-93 [2,3] is an experiment characterizing a small break loss-of-coolant accident (LOCA) through an equivalent 2% cold leg break without high pressure injection system (HPIS), with enhanced depressurization achieved by actuating the pressurizer power operated relief and safety relief valves (PORV and SRV, respectively). When the primary system pressure reaches 27 bar, the accumulator (ACC) injection begins.

The main results of the post test analysis performed by R5M3.2 code for the small break LOCA test A1-93, carried out in LOBI/Mod2 facility, are presented. The purpose of this paper is to evaluate the performance of the R5M3.2 for the mentioned experiment through a quantitative and qualitative accuracy evaluation. The quantitative analysis has been performed adopting a method [4], developed at University of Pisa, which has the capability to quantify the errors in code predictions related to the measured experimental signal. The Fast Fourier Transform (FFT) is used with the purpose of having an integral representation in the frequency domain of the discrepancies between measured and calculated time trends.

2. DESCRIPTION OF THE LOBI A1-93 TEST

The experiment A1-93 [2,3] is a small break LOCA originated by an equivalent 2% cold leg break without HPIS actuation but with ACC's active after an enhanced primary system depressurization by pressurizer PORV and SRV. The test aims at observing: (a) the core boil-off and dryout at relatively high pressure in the primary system, (b) the phenomena during enhanced depressurization and (c) the effectiveness of the hot leg ACC injection into the partially uncovered rod bundle and the core rewet. The experiment starts with the facility at full power.

The transient scenario can be derived from Figs. 1 and 2, which were subdivided in four phenomenological windows, as summarized in Table 1. The specified and the measured initial conditions for the test are shown in Table 2. The transient setpoint imposed and the resulting sequence of events are reported in Tables 3 and 4.

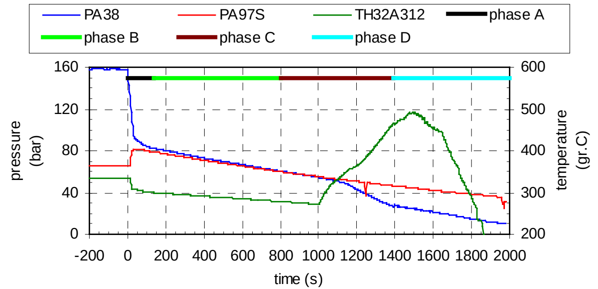

Fig. 1 - Measured trends of primary pressure (PA38), secondary pressure (PA97S) and rod surface temperature (TH32A312)

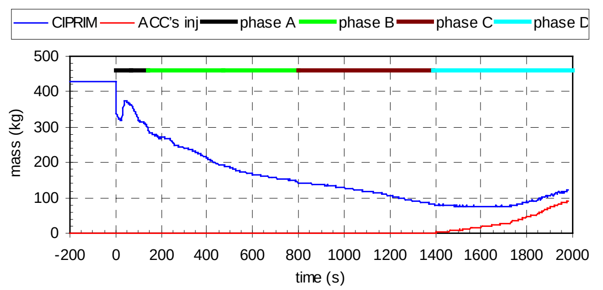

Fig. 2 - Measured trends of primary mass (CIPRIM) and ACC delivered total mass (ACC's inj)

Table 1 – Phenomenological windows

Phase	Characterization	Time Interval (s)
A	subcooled blowdown (until break uncovering)	0 – 140
B	saturated blowdown until primary system pressure reaches secondary pressure	140 – 800
C	continuous saturated blowdown, beginning of core dryout, enhanced primary system depressurization (until ACC's start)	800 – 1393
D	primary system mass depletion, begin of core refill, end of core dryout	1393 – 1892

Table 2 – Initial conditions for Lobi test A1-93

	Unit	Specified	Actual	R5M3.2
PRIMARY SYSTEM				
Upper plenum pressure	bar	158.0	158.0	157.91
Primary mass inventory	kg		430.5	435.71
Reactor pressure vessel:				
. Core power	MW	5.28	5.17	5.17
. Core mass flow rate	kg/s(%)	26.684(95.3)		26.407(95.37)
. Core bypass mass flow rate	kg/s	1.316(4.7)		1.280(4.62)
. Upper plenum temperature	°C	300.82		300.82
Intact(IL) / Broken(BL) loop:				
. Mass flow	kg/s	21.0/7.0	20.6/7.1	20.591/7.096
. Vessel inlet temperature	°C	294.0/294.0	295.0/295.0	293.87/293.78
. Vessel outlet temperature	°C	326.0/326.0	327.0/326.0	325.64/325.51
. Pump speed	rad/s			499.92/408.44
Pressurizer:				
. Water level	m	4.8	4.9	4.90
. Temperature	°C	346.0	346.0	346.01
Accumulator of the intact loop:				
. Water volume	m^3	0.224	0.247	0.247
. Gas volume	m^3	0.056	0.033	0.0329
. Liquid temperature	°C	30.0	113.4	113.4
. Gas pressure	bar	27.0	27.0	27.0
Accumulator of the broken loop:				
. Water volume	m^3	0.0723	0.082	0.082
. Gas volume	m^3	0.0217	0.012	0.0123
. Liquid temperature	°C	30.0	58.1	58.1
. Gas pressure	bar	27.0	27.0	27.0
MCP seal water injection:				
. Mass flow into intact loop	kg/s	-	0.00913	0.00913
. Mass flow into broken loop	kg/s	-	0.00913	0.00913
. Temperature	°C	-	30.0 [c.]	30.0
SECONDARY SYSTEM				
Steam generator of intact loop:				
. Steam dome pressure	bar	64.5	65.5	65.50
. Mass flow	kg/s	2.0	1.98	1.980
. Inlet/outlet temperature	°C	210.0/280.0	211.0/281.0	211.0/281.33
. Downcomer water level	m	8.0	8.15	8.07
. Recirculation ratio	-	-	4.6 [c]	3.95
Steam generator of broken loop:				
. Steam dome pressure	bar	64.5	65.5	65.50
. Mass flow	kg/s	0.67	0.68	0.680
. Inlet/outlet temperature	°C	210.0/280.0	211.0/281.0	211.0/281.33
. Downcomer water level	m	8.4	8.5	8.44
. Recirculation ratio	-	-	4.6 [c]	4.56
HEAT LOSS				
Reactor pressure vessel	kW		19.4	18.82
Intact loop	kW		42.0	41.95
Broken loop	kW		30.0	29.80
Steam generator secondary side (IL)	kW		7.2	6.72
Steam generator secondary side (BL)	kW		5.0	4.95

[c] Circa

Table 3 – Imposed sequence of trips for Lobi test A1-93 (actual data)

Event	Time and/or set point values
- Break opening	0 s
- Secondary side lines connected	upper plenum pressure < 132 bar (13 s)
- Shut-off valves of feedwater and steam lines	upper plenum pressure < 132 bar (13 s)
- Cooldown curve of –100 K/h through steam generator relief valve	upper plenum pressure < 132 bar (13 s)
- Scram	upper plenum pressure < 132 bar (13 s) plus delay of 0.5 s
- Pump coastdown initiation	23 s
- Auxiliary feedwater of intact loop SG	IL SG level < 5 m or 701 s
- Auxiliary feedwater of broken loop SG	BL SG level < 5 m or 1007 s
- Accumulators start	upper plenum pressure < 27 bar (1393 s)
- End of transient	1982 s

Table 4 – Sequence of events for Lobi test A1-93

EVENT	TIME (s)	
	Test	**R5M32**
- Steady state	-200.0→0.0	-100.00→0.0
- Start of blowdown transient (leak starts to open) (*1)	0.0	0.00
- Secondary side steam lines connected (*1)	0.0	12.5
- Primary system (upper plenum) pressure reaches 132 bar (*1,2)	13.0	12.5
- Cooldown curve of -100 K/h becomes active on secondary side through steam generator relief valve (*1)	13.0	12.5
- Shut-off valves in secondary loop feedwater and steam lines start to close (*1)	13.0	12.5
- Heating power starts to drop (up. pl. pressure = 132 bar + delay of 0.5 s) (*1)	13.5	13.05
- Intact and broken loop main coolant pumps start to decrease (23 s after transient beginning, up. pl. pressure = 110 bar) (*1,2)	23.0	23.0
- Pressurizer emptied		29.7
- Pressurizer surge line uncovers	26.0	30.5
- Saturation in upper plenum and hot legs	34.0	39.7
- Saturation in cold legs	80.0	216.5
- Saturation in lower plenum	91.0	132.1
- Intact and broken loop main coolant pumps are stopped	93.0	93.0
- Insertion of broken loop locked rotor resistance simulator	97.0	97.0
- Break orifice uncovers	140.0	198.0
- Auxiliary feedwater (AFW) inlet valve of intact loop steam generator starts to open (6s) and remains open (*1)	701.0	701.13
- Clearance of broken loop seal	780.0	870.1
- BL/IL loop seal clearing	780.0/ -	784.0/ 925.0
- Primary system pressure drops below secondary system pressure	800.0	628.7
- Core dryout initiates	1000.0	1259.9
- AFW inlet valve of BL steam generator starts to open (6s) and remains open (*1)	1007.0	1007.123
- Pressurizer power operated relief valve (PORV) is opened (*1)	1151.0	1151.13
- Start of ACC injections into IL and BL hot legs (up. pl. pressure < 27 bar) (*1)	1393.0	1378.69
- Pressurizer additional relief valve (SRV) is opened (*1)	1492.0	1545.50
- Minimum primary system mass inventory / value (kg)	1589.0 (73.)	1389.9 (94.)
- Heater rod temperature at level 8 exceeds 650°C (*1)	1646.0	-
- Maximum heater rod temperature at level 8 / value (K)		1640.2 (630.43)
- Power off (*1)	1646.0	1646.0
- End of test (*1)	1982.0	1970.0

(*1) Condition of the test (*2) Circa

3. ADOPTED CODE AND NODALIZATION

3.1 Relap5/Mod3.2 Code

The light water reactor transient analysis code, Relap5, was developed at Idaho National Engineering Laboratory (INEL) for the U.S. Nuclear Regulatory Commission (USNRC). Specific applications of the code have included simulations of transients in LWR system such as loss-of-coolant, anticipated transients without scram, and operational transients such as loss of feedwater, loss of offsite power, station blackout and turbine trip.

The Relap5/Mod3.2 [1] is based on a non-homogeneous, non-equilibrium set of six partial differential balance equations for the steam and the liquid phases. A non-condensable component in the steam phase and a non-volatile component (boron) in the liquid phase can be treated by the code. A fast, partially implicit numeric scheme is used to solve the equations inside control volumes connected by junctions. Heat flow paths are also modeled in a one-dimensional sense, using a staggered mesh to calculate temperatures and heat flux vectors. Several specific models are included in the code to simulate special components like pumps, valves, steam separators, etc.

3.2 LOBI/Mod2 nodalization description

A detailed nodalization reproducing each geometrical zone of the loop has been developed in such way that is suitable for the analysis of different types of transients. The general methodology adopted here for the nodalization can be found in ref. [5], based upon the use of the Relap5/Mod2 code. The recommendations of the R5M3.2 manuals, ref. [1], are considered, too.

The LOBI/Mod2 nodalization scheme, shown in Fig. 3, has been used and qualified (at the steady state and the ‘on-transient’ levels) at the University of Pisa. Minor changes and adaptations were introduced in the present framework, including the initial and boundary conditions of the LOBI A1-93 test.

A nodalization representing an actual system (ITF or NPP) can be considered qualified when: (a) it has geometrical fidelity with the involved systems, (b) it reproduces the measured nominal steady state condition of the system, and (c) it shows a satisfactory behavior in time dependent conditions.

Taking into account these statements, a standard procedure to obtain a “qualified nodalization” can be seen in ref. [6]. This process consists of two steps: a qualification at the steady state level and the qualification at the “on transient” level.

4. ANALYSIS OF POST TEST CALCULATION RESULTS

This analysis includes two parts. The first part consists of 100 s of a null transient (steady state calculation with transient option) to check the correctness of the initial conditions. In the second part, the time dependent results of the code calculation are compared with the experimental time trends. If necessary, proper sensitivity analysis changing the initial or boundary conditions and/or specific parameter data within their own uncertainty ranges can be planned from and performed, based on the results of the mentioned analysis.

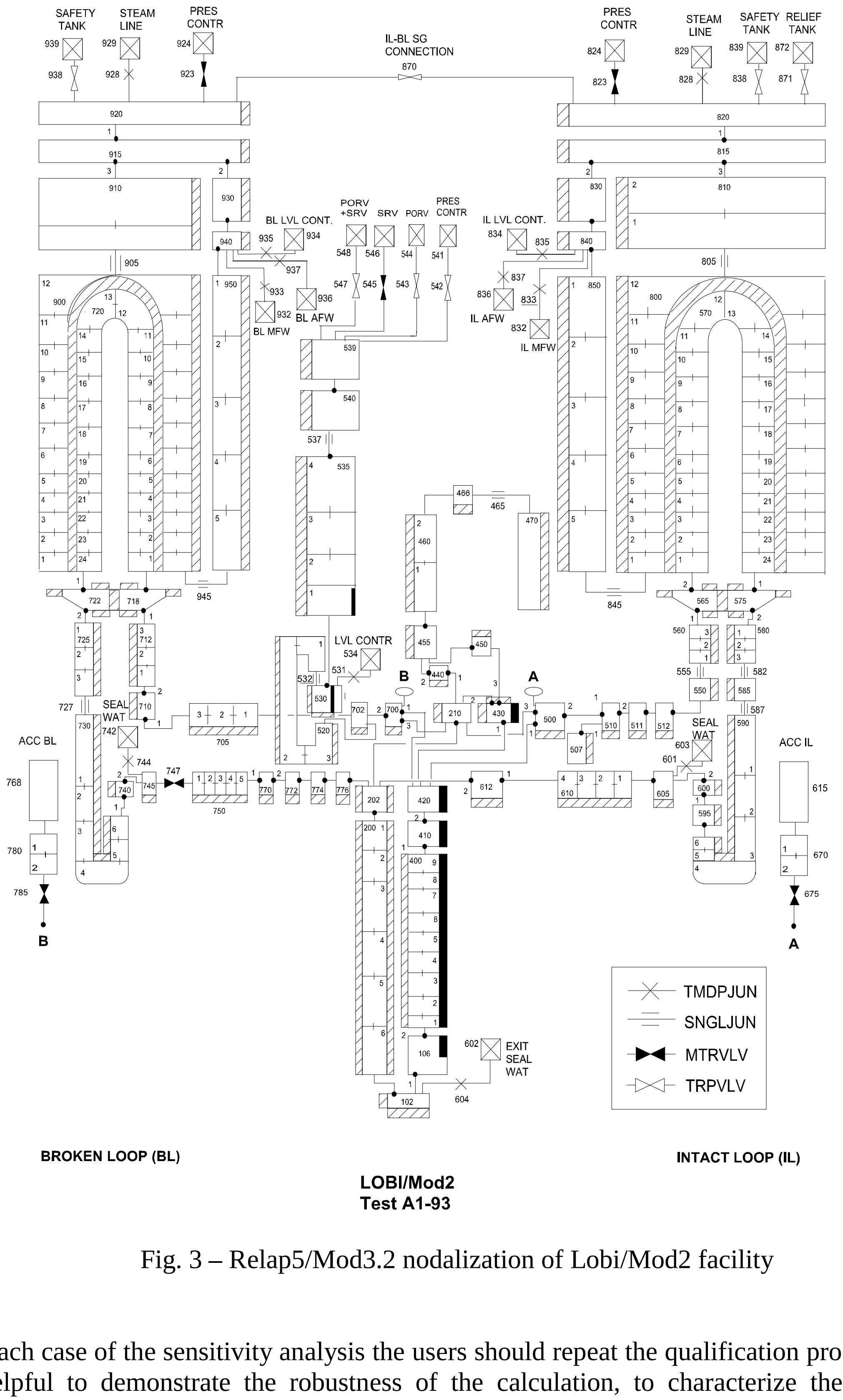

Fig. 3 – Relap5/Mod3.2 nodalization of Lobi/Mod2 facility

For each case of the sensitivity analysis the users should repeat the qualification process. These cases are helpful to demonstrate the robustness of the calculation, to characterize the reasons of possible discrepancies between measured and calculated trends, to optimize code results and user option choices and to improve the knowledge of the code by the user.

4.1 Steady state calculation

The last column of Table 1 shows the results obtained by the R5M3.2 calculation in the LOBI Test A1-93 after 100 s of a steady state condition using the “TRANSNT” (transient) code option. These values can be compared with the actual data of the test in the same table. To illustrate the reproducibility of the data, Figs. 4 to 11 show calculated relevant parameters of the test.

Fig. 4 shows the primary and secondary system pressure profiles compared with the related experimental results. Calculated and experimental time trends of core power can be found in Fig. 5. Fig. 6 shows the good reproducibility and adequate values of the intact and broken loop mass flow rate. The comparison between calculated and experimental values of the collapsed liquid levels of the pressurizer and of the intact and broken loop steam generators, during the steady state, are given in Fig. 7. Fig. 8 shows the steady state trends of the outlet and inlet fluid temperature of the reactor pressure vessel. Fig. 9 shows the mass flow rates of intact loop steam generator. The steady state value of the primary system mass inventory can be derived from Fig.10. The surface clad temperature for the heater rod at middle position can be seen at Fig. 11, again related to the steady state period.

From these results, the following overall remarks can be mentioned:

- the process of the nodalization qualification on steady state level was followed and the criteria of acceptability were verified,
- the calculated values are stable and adequate,
- some discrepancies in heater rod temperatures can be explained considering the position of the thermocouples (the calculated temperature refers to the surface of the rod simulators and the experimental data are taken slightly inside the surface).

4.2 Transient calculation

The calculated sequence of main events can be seen in Table 3: experimental values are also reported. Figs. 12 to 19 show the comparison of calculated and experimental time profiles for several relevant parameters of the test.

The four phenomenological windows already mentioned can be identified from the calculated results. At a qualitative level one may conclude that the main phenomena occurring during the test are reproduced by the calculation.

Fig. 12 shows the trends of the primary and secondary side pressures: a quite good agreement in all phases of the transient can be observed. From the sequence of events (Table 3), it results that the time when the calculated primary pressure reaches the secondary one occurs earlier than in the experiment. This difference is related to the small underestimation of the primary side pressure that appears to be in connection with the break discharge in saturated condition, as presented in Fig. 13 (first two parameters, left axis). However, this difference can be considered within the typical unavoidable uncertainty bands that affect a related system calculation. The calculated integral of mass flow rate exiting from the break is similar to the experimental one (Fig. 13, last two parameters, right axis).

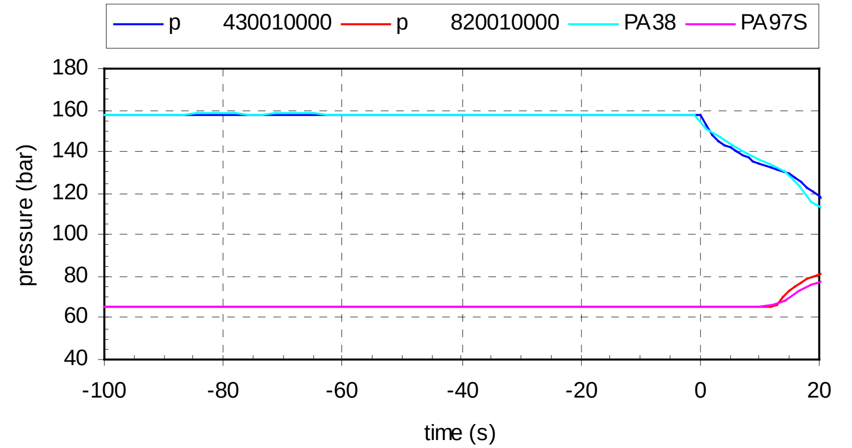

Fig. 4 - Primary and secondary pressure

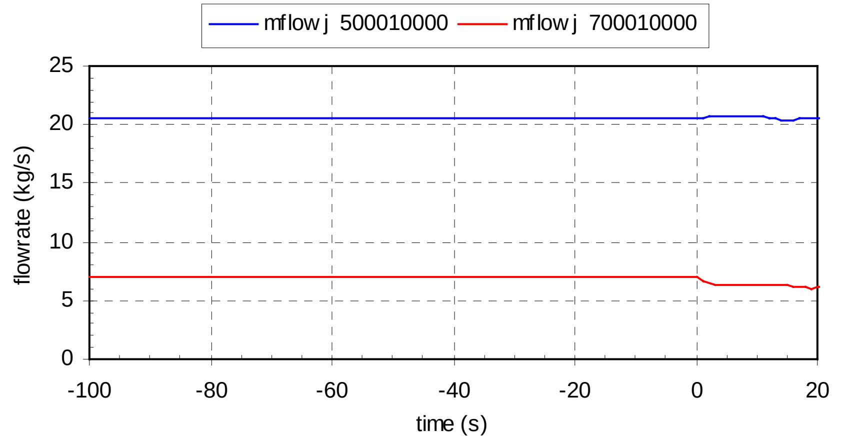

Fig. 6 - Hot leg mass flow rate

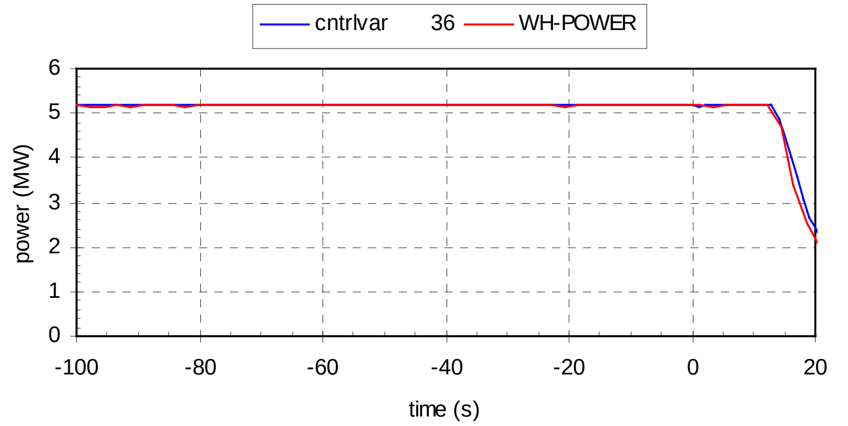

Fig. 5 - Core exchanged power (calc.) and core power (exp.)

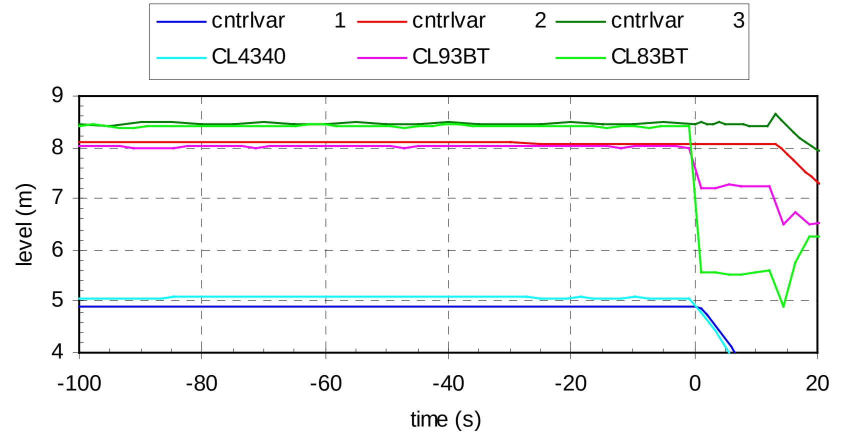

Fig. 7 - Pressurizer and steam generators water level

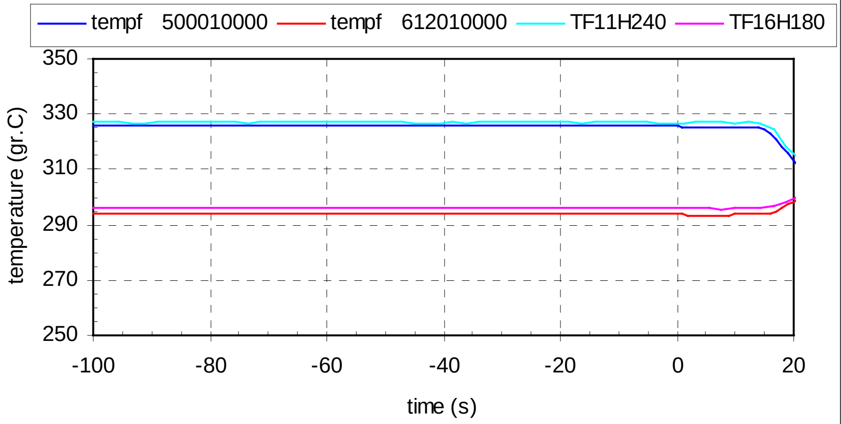

Fig. 8 - Outlet and inlet fluid temperature of intact loop RPV

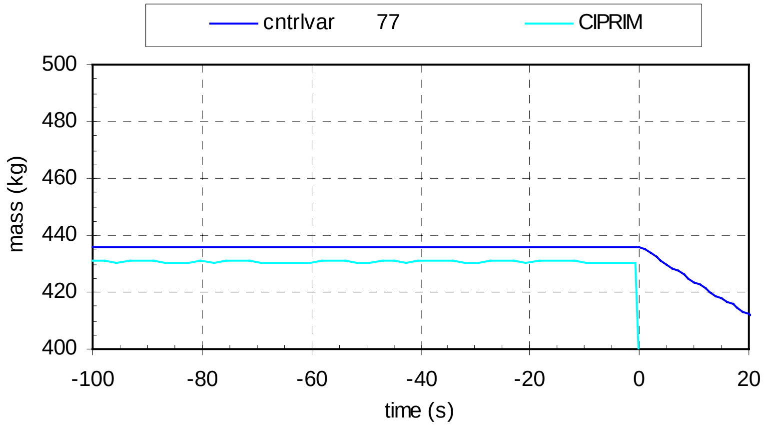

Fig. 10 - Primary side total mass

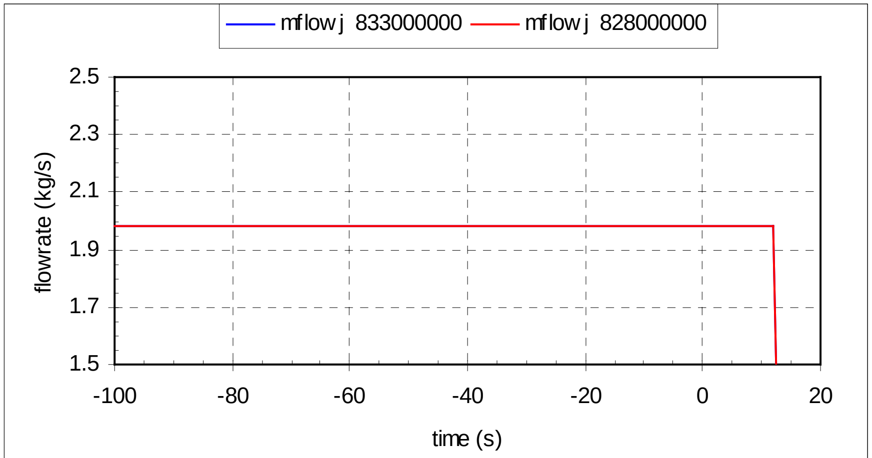

Fig. 9 - Intact loop SG feedwater and steam outlet mass flow rates

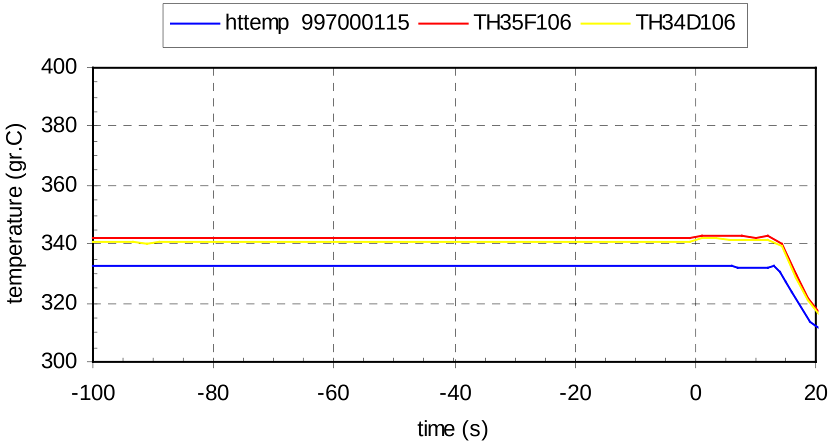

Fig. 11 - Heater rod temperature (middle level)

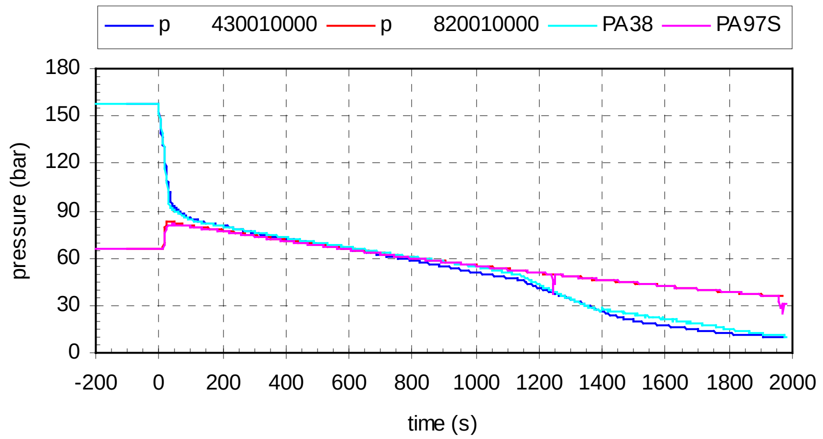

Fig. 12 - Primary and secondary pressure time profile

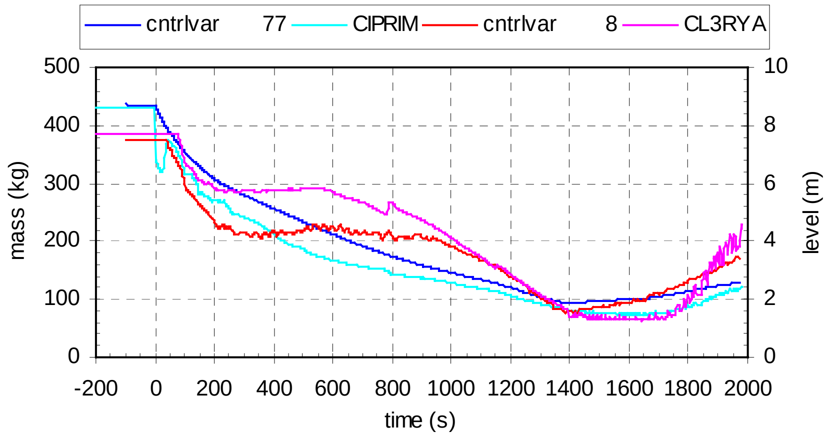

Fig. 14 - Primary side total mass and RPV riser level

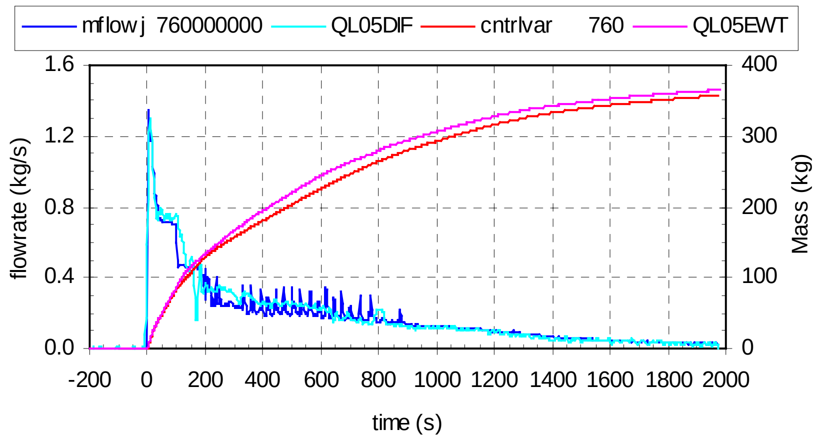

Fig. 13 - Break flow rate and integrated mass

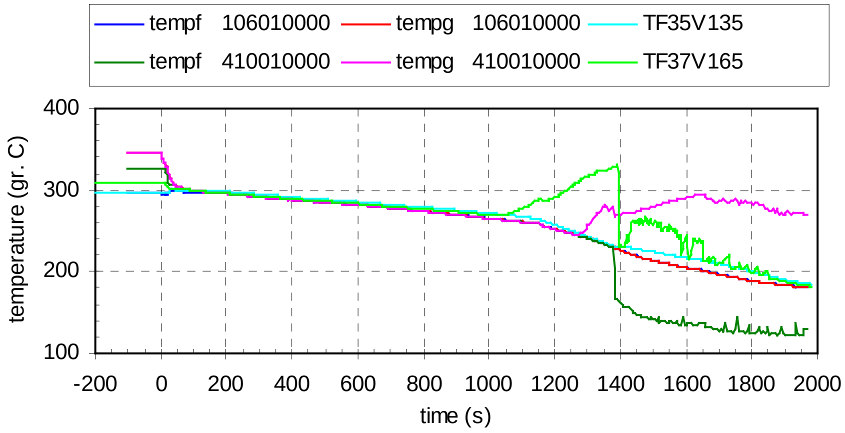

Fig. 15 - Core inlet and outlet fluid temperature

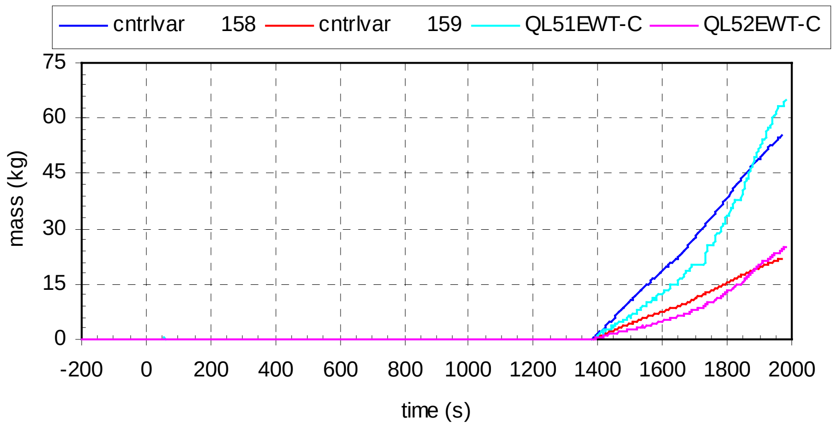

Fig. 16 - IL & BL hot leg accumulator integral of mass injected

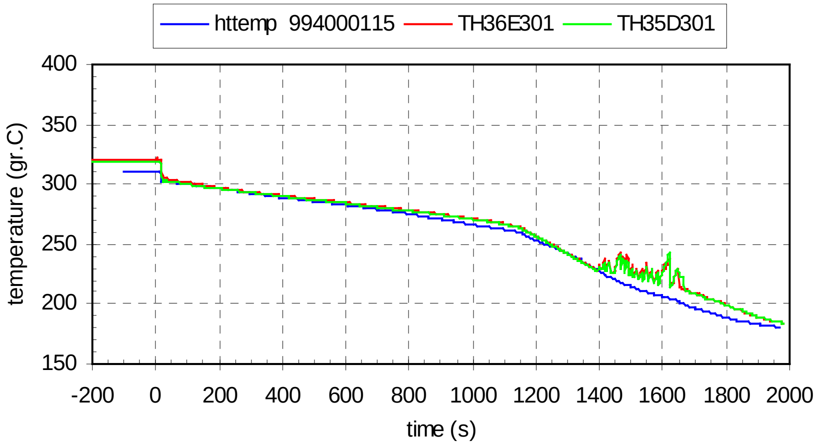

Fig. 17 - Heater rod temperature (bottom level)

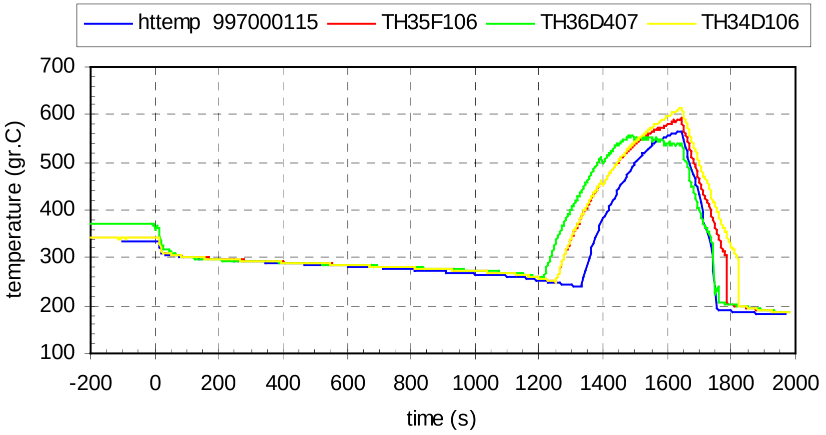

Fig. 18 - Heater rod temperature (middle level)

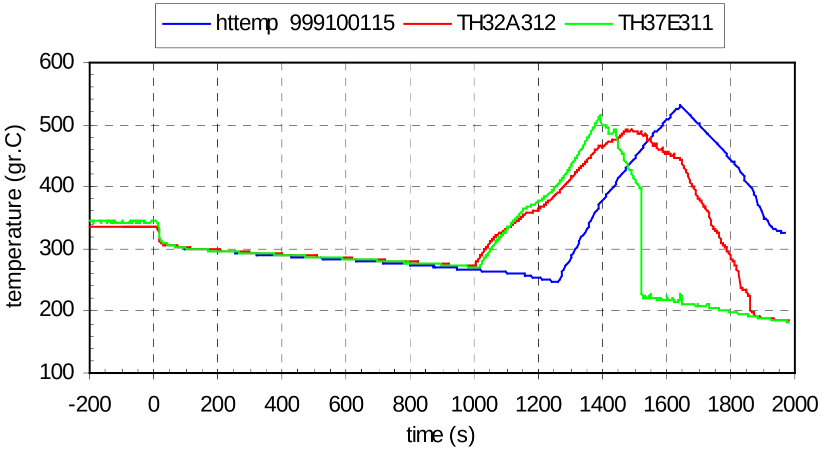

Fig. 19 - Heater rod temperature (high level)

Fig. 14 presents the integral of mass from the primary system (first two parameters, left axis) and the reactor pressure vessel (RPV) riser level (last two parameters, right axis), respectively. The higher calculated primary side mass is due to the reduced integrated mass lost through the rupture. The discrepancies in the prediction of the RPV riser level are a consequence of the misprediction of the pressure and the flow distributions inside the vessel and of the heat transfer inside the core. Experimental uncertainties that characterize pressure drop measurements (therefore level measurements) play also a role for explaining the detected discrepancies.

The core inlet and outlet fluid temperature trends are shown in Fig. 15. The difference observed in the core outlet temperature is connected with the time where the core dryout began (1000 s (experimental) and 1200 s (R5M3.2) → see Table 3). After ACC injection (Fig. 16) the boiling is reduced and so, fluid temperature continues to decrease. The ACC appears more effective in the calculated case.

It is important to keep in mind that thermocouple position strongly affects the values of the reported curves. The thermocouple gives a measure of wall temperature when void fraction is high (larger than about 80%).

After the ACC's actuation, see Fig. 16, the calculated integral of mass injected in primary system is a little higher than the experimental one. As consequence, the RPV riser level and the primary side mass inventory (Fig.14) begin to recover earlier. The ACC's actuation stopped the dryout causing the decrease of heater rod temperatures (see Figs. 17, 18 and 19, respectively for bottom, middle and top levels).

4.3 Code accuracy evaluation

In order to investigate the qualitative accuracy evaluation for the calculated results, ref. [7] presents a systematic procedure consisting of the identification of phenomena (CSNI list) and of Relevant Thermal-hydraulic Aspects (RTA). For this, an engineering judgement (Excellent, Reasonable, Minimal, Unqualified and Not Applicable) is adopted. A positive overall qualitative judgement is achieved if “Unqualified” is not present in the procedure.

For the present study, although not presented and discussed here, the evaluation on the identification of phenomena and on relevant thermal-hydraulic aspects point of view are adequate and satisfactory.

When the positive point of view from the qualitative judgement is obtained, it is possible to address the quantitative accuracy evaluation. In this framework, a special methodology, developed at University of Pisa, based upon the use of the Fast Fourier Transform [4] can be used.

Table 5 presents the results obtained from the application of the methodology above mentioned. The main remark from the qualitative accuracy evaluation analysis is that the acceptability threshold is attained both in relation to the calculated overall accuracy amplitude (AA_{tot}) that is equal to 0.26 (it is well below the acceptability limit of 0.4) and also to the primary system pressure where the calculated accuracy amplitude (AA) is equal to 0.06 (which is below the acceptability limit of 0.1).

Table 5 – Summary of the results obtained by FFT Method application to the selected parameters.

PARAMETER (exp/calc)	**WF**	**AA**
1) Upper plenum pressure (pa38/p 430-01)	0.07	0.06
2) SG secondary side pressure (pa97s/p 820-01)	0.08	0.10
3) Core inlet fluid temperature (tf35v135/tempf106-01)	0.04	0.05
4) Core outlet fluid temperature (tf37v165/tempf 410-01)	0.06	0.53
5) Upper head fluid temperature (tf39/tempf 460-01)	0.06	0.47
6) Integral of mass break flow rate (ql05ewt/cntrlvar 760)	0.04	0.03
7) Break flow rate (ql05dif/mflowj 760-00)	0.17	0.62
8) Heater rod temperature – bottom level (th36e301/httemp 9940-15)	0.05	0.11
9) Heater rod temperature – middle level (th35f106/httemp 9970-15)	0.02	0.30
10) Heater rod temperature – high level (th32a312/httemp 9991-15)	0.06	0.63
11) Primary side mass inventory (ciprim/cntrlvar 077)	0.05	0.23
12) RPV riser level (cl3rya/cntrlvar 008)	0.03	0.23
13) SG downcomer level (cl93bt/cntrlvar 002)	0.04	0.34
14) SG bottom downcomer fluid temperature (tf93f2/tempf 850-05)	0.08	0.05
15) ACC integral of injected mass in il hot leg (ql51ewt-c/cntrlvar 158)	0.04	0.13
16) ACC's integral of injected mass (ql51ewt-c + ql52ewt-c / cntrlvar 161)	0.04	0.13
17) Core power (wh-power/cntrlvar 036)	0.12	0.13
18) DP inlet-outlet il SG (pd9092aa/cntrlvar 028)	0.08	0.72
19) DP loop seal (asc. side bl) (pd2724/ cntrlvar 024)	0.04	0.51
20) DP loop seal (desc. side) (pd8227a/cntrlvar 030)	0.04	0.35
21) DP il SG inlet plenum – U tubes top (pd90bpx2/cntrlvar 031)	0.07	0.46
22) DP across downcomer – upper head bypass (pd3d3rba/cntrlvar 187)	0.05	0.17
23) PZR level (cl4340/cntrlvar 001)	0.05	0.22
	WFtot	**AAtot**
	0.06	0.26

5. CONCLUSIONS

The analyzed transient LOBI Test A1-93 is a small break LOCA experiment originated by an equivalent 2% cold leg break without HPIS but with ACC's actuation when the primary system reaches 27 bar. Just one dryout situation occurred and it was quenched by the intervention of ACC's into the hot legs from intact and broken loops.

A qualified R5M3.2 nodalization has been used for this post test analysis. A good agreement was obtained in general between the code predictions and the experimental data in all phases of the transient. The phenomena that occurred in all selected phenomenological windows were also identified in the calculated results. These remarks lead to the conclusion that the code is able to predict all the significant aspects of the transient in a satisfactory way.

Basically, the general main conclusions are:

- the R5M3.2 code has full capability in predicting the relevant thermal-hydraulic aspects that characterize the transient, and
- some minor discrepancies between measured and calculated trends were judged to be reasonable and acceptable since they can be considered within the uncertainty bands.

The present paper represents a part of a Ph.D. thesis development at COPPE/UFRJ [8] in order to make an independent assessment of a Code with capability of Internal Assessment of Uncertainty (CIAU) now in development at University of Pisa [9]. This is in the framework of accident analysis for licensing purposes with the use of best estimate thermal hydraulic system codes, like R5M3.2, where it is required the application of an acceptable methodology to quantify the uncertainties obtained from the simulations.

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