PERFORMANCE OF PASSIVE HEAT REMOVAL SYSTEM UNDER ACCIDENT CONDITIONS: A STUDY CASE.

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ABSTRACT

In many innovative LWR designs, passive safety systems are widely envisaged. In general, their behaviour involves natural and simple physical events as free convection, thus entailing an higher safety degree of the plant, inversely proportional to the necessity of human intervention or energized devices to prime the safety system.

A thorough behaviour's knowledge of this kind of systems requires experimental campaigns as well as numerical simulations: both the Regulatory Commissions and the Utilities are engaged to verify the effectiveness and reliability of these systems.

From the simulation view point, a different choice in nodalization, heat transfer correlation and system dimensions could lead to different system performance during accident transients. This problem is pointed out in this paper: as test case, a Passive Heat Removal loop under Steam Line Break accident conditions is concerned.

The results obtained show that thick circuit nodalization, consistent with a value of the Courant number close to unity, is a necessity to find out the correct system's behaviour. Besides they confirm the need of experimental facilities, in particular to investigate the circuit's activation, and of parametric studies for optimization design; for the last issue, computer codes that hold fast-running feature even with a large number of circuit nodes are very useful tools.

INTRODUCTION

In the current state of reconsideration of the nuclear plant methodology, particular attention is devoted to the reactor safety systems and criteria, aimed at ensuring an ever-increasing certainty and effectiveness of intervention of the safety systems appointed to limit and bound the accidents.

In this framework the tendency is prevailing to equip new reactors with passive grade circuits and components, that are able to remove the residual heat and to mantain the core covered, with no need of human intervention and with exclusion or maximum limitation of activated or energized devices for the process primer. For this reason all new reactor designs, above all LWRs both of the innovative type and of the evolutive type, are provided with passive components as check valves (AP-600), density valves or density-locks (PIUS), accumulators, pools and circuits generally acting in natural circulation (AP-600, PIUS, SBWR, SWR-1000 et al.).

If simple are the physical principles above which the working of these systems is based, not so easy could be both the knowledge of the exact behaviour during the accidents and the precise system configuration and dimensioning in order to achieve the best effectiveness. Because of this condition, a noticeable effort is in progress to evaluate their reliability and efficiency, from the experimental side by testing single components with full scale facilities and whole circuits at reduced scale, and from the simulation side by using pre-existent codes, validating them for the new reactor configurations, or by creating new codes specially devoted to the aim.

It is the purpose of this work to investigate what kind of problems could arise from the numerical simulation view point, by considering a fully passive safety system as an example and finding out its typical behaviour under accident conditions. The choice has been taken on the Emergency Core Cooling System (ECCS) of the MARS reactor (Caira et al., 1986) (Univ. of Rome "La Sapienza", 1989). The sensitivity analysis of the passive circuit has

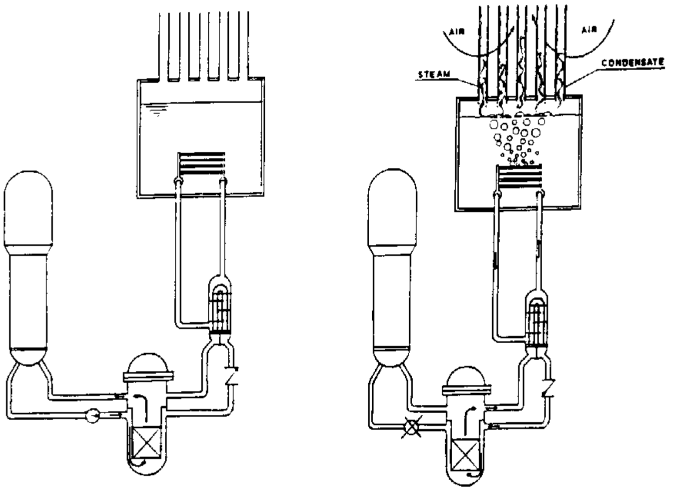

Fig. 1 Activation of the natural circulation loops in MARS.

TABLE I

MARS Reactor Main Data		
General Data		
Thermal power	600	MWth
Core inlet temperature	214	°C
Core outlet temperature	254	°C
Primary pressure	75	bar
Primary flow rate	3227.5	kg/s
Steam flow rate	277.3	kg/s
Secondary pressure	18.8	bar
Feedwater temperature	150	°C
Average core thermal flux	3.29×10^5	W/m^2
ECCS Main Data		
Primary temperature	70	°C (same as CPP temp.)
Secondary temperature	10÷40	°C (environ. temp.)
Pool temperature	10÷40	°C (environ. temp.)
Primary pressure	same as reactor primary system	
Secondary pressure	75	bar
Pool pressure	1	bar (atmosph. pressure)
Water reserve in each pool	280	m^3
Water volume above HEX #2 tube bank	230	m^3
Water elevation above HEX #2 tube bank	2.8	m

been carried out with TRAP/2M (Brega et al., 1992) (Ricotti, 1994), a fast-running code properly implemented for new reactor designs and passive circuits analysis; the code is currently under validation by comparison with RELAP5/mod2.5 results for MARS transients (ENEA, 1994) and with experimental tests of the SPES-2 facility, a scaled plant of AP-600. The steps we are following to perform the code accuracy evaluation are the same belonging to the methodology proposed by D'Auria et al. (1993), Ambrosini et al. (1990). For the sake of simplicity, a single design basis accident has been selected to perform the tests, the Steam Line Break (SLB) one.

In a second section, the main safety features of MARS reactor are briefly described. Section third outlines the code used for the analysis. In section fourth, the typical behaviour of ECCS circuits during SLB accident is sketched; the results are obtained with the same ENEA/RELAP nodalization and are considered as reference case. The sensitivity analysis on ECCS Secondary Loop is presented in the fifth section, including parametric studies on: circuit nodalization, selected heat transfer correlations, circuit dimensions.

PASSIVE SAFETY SISTEMS IN MARS REACTOR

The key issue of residual heat evacuation in case of accident, in the 600 MWth MARS (Multipurpose Advanced Reactor Inherently Safe) one single loop reactor is solved through a passive Emergency Core Cooling System (ECCS) which consists of two independent circuits based on natural circulation, triggered by passive check valves activated by the primary pump trip (Fig.1). Each train is made up by:

- an ECCS Primary Loop directly connected to the primary vessel through 16" piping filled with 70°C cold water at the same pressure as the primary system; during normal operation the circulation inside it is prevented by special check valves which are kept closed by a suitable pressure drop provided by the primary pump;
- an ECCS Secondary Loop at the same temperature and pressure as the ECCS Primary;
- a tertiary Pool and Condenser Loop consisting of a water reservoir (Pool) at the environmental temperature and pressure and an air-condenser connected to the pool, which rejects the heat via evaporation to the atmosphere and returns the condensate to the pool.

Other main passive features are the back up scram system activated by passive mechanisms based on thermal differential expansion of materials and the pressurized Containment for Primary system Protection (CPP) which houses the primary system working at 234 °C and 75 bar, in a low enthalpy water filled and pressurized containment at 70 °C and same pressure as the primary system. The CPP is aimed to prevent large LOCA and control rejection accidents, while making the primary system operating in absence of primary stresses. The main plant data are reported in Table I.

The attention of present work has been focused on the Secondary Loop of the double ECCS circuit operating in natural circulation, in order to find out, from a thermalhydraulic view, its typical behaviour during accident conditions and, also from a numerical view, the sensitivity of the system simulation. The choice has been taken on this loop because it seems to represent a typical passive circuit belonging to Class 2 (based only on motion of fluids), according to the IAEA (1990) proposed classification of passive systems, while circuits of other projects belong to a lower Class, involving also the motion of mechanical devices as valves, even energized or not.

TRAP/2M CODE MAIN FEATURES

Because of the purpose of this study, that is to say a parametric analysis of multi-loop system with accurate description of the spatial distribution of thermalhydraulic parameters, a faster but simpler code than a best-estimate one was adopted to perform the analysis. The program utilized is TRAP/2M, a code developed at the Department of Nuclear Engineering for the investigation of different reactor types, which allows the simulation of passive systems (as the Core Make Up Tank of AP-600 design or the Density-Locks in the PIUS reactor) in a modular way.

The target is a thermalhydraulic model not too complex, so leading to high computation speed even on personal computers, but rather detailed so owning a correct description of the displacement of density/temperature/boron fronts along the circuits. For these reasons the TRAP model has been framed with the following main features, from a physical view point:

- incompressible but thermally expandable fluid;
- both 3 eqs. (mass, energy, momentum balance for homogeneous mixture in thermal equilibrium) and 5 eqs. (2 mass, 2 energy, 1 momentum for two fluids in thermal non-equilibrium) models for simulation of plant components;
- both zero and monodimensional neutron kinetics, with multi-radial zone fuel subdivision for heat transfer calculation;
- monodimensional geometry, with multi-loop (connected or parallel) circuits simulation;

and from a numerical solution view point:

- for 5 eqs. model: lumped parameter form of the balance eqs. and finite difference method for solution of those volumes where large and turbulent mixing occur, like plena, or components where homogeneous mixture in thermal equilibrium is not acceptable, as the pressurizer;
- for 3 eqs. model: distributed parameter eqs. form and method of characteristics (MOC) solution to avoid or strongly reduce numerical diffusion problem, typical of finite difference schemes with upwind ("donor cell") technique - for this reason in other safety codes has been already resolved the superposition of a MOC grid to the staggered grid of the upwind scheme (Paulsen et al., 1992) (Dodge, 1992); the nodalization of circuit components is available both with a "fixed grid" and with an "adaptive or mobile grid" in space step in order to keep closed to unity the Courant number for each nodal cell; this solution frame is applied to components as reactor, pipes, steam generators, heat exchangers;
- iterative solution with implicit and semi-implicit methods.

The code can perform:

- accident analysis, excluding large LOCA and sudden large depressurization - this set of transients has already found its right tools (best-estimate codes such as ATHLET, CATHARE, RELAP, TRAC, RETRAN et al.);
- operation transients, as hot and cold startup, load following, shut-down;
- parametric studies, to quickly provide the designer with responses about reactor sensitivity to component dimension variations, thermalhydraulic parameter or plant procedure modifications, and about reactor stability.

TRAP/2M is written in Fortran language and runs on personal computers. The user can take advantage of the interactive feature (plant parameters modification by keyboard input in the course of program run) besides the graphic output.

ECCS BEHAVIOUR UNDER STEAM LINE BREAK ACCIDENT CONDITIONS

The initiating event is the double end guillottine rupture of the steam line down of the Steam Generator Isolation Valve (SGIV), on the reactor in hot standby conditions. It has been assumed that the rupture cannot be produced before the SGIV being this part of secondary piping designed to withstand 83 bar pressure as the primary loop, while the secondary pressure is 20 bar.

TABLE II

Time [s]	Sequence of event of Steam Line Break accident
0.	Double end guillotine rupture
$0.^+$	Automatic reactor scram (*)
$0.^+$	Primary pump trip (*)
$0.^+$	SGIV starts closing
5.	On/off MIVs start closing
10.	SGIV completely closed
12.	ECCS check valve starts open
15.	MIVs completely closed
17.	ECCS check valve completely open
50.	ECCS primary flow rate at max. value
750.	ECCS operating in stable regime

(*) *SG low pressure or high steam flow rate signal*

The immediate consequence of this accident is a very strong increment of the steam flow rate with the contemporary rapid depressurization of the steam generator. The equilibrium isotherm drops down according to the pressure decrease, all resulting in a remarkable increase in the thermal transfer between the primary and secondary loop. The primary fluid is therefore subjected to an overcooling which together to the negative moderator temperature coefficient determines a positive reactivity insertion. This feature in the MARS case is even more relevant because of the presence of the ECCS Primary circuit at 70°C. So the most severe scenario is that one which leads to the maximum cooling of the primary fluid, situation corresponding to the maximum reactivity recovery. To this purpose the most conservative conditions have been identified to be the Hot Standby coupled to the minimum pool and ECCS Secondary Loop temperature value in the year (10°C) and in addition the hypothesis is made that both the ECCS trains intervene and the decay power is negligible.

The main phases of the accident sequence are reported in Table II. The complete set of related to the significant parameters results as obtained with TRAP/2M code simulation is reported elsewhere (ENEA, 1994), (Ricotti et al., 1995); here we summarize the main steps of the accident.

Up to 15s into the transient the ECCS Primary and Secondary Loops are isolated. The primary pump trip, contemporary to the reactor scram, provokes the sharp drop down of the primary flow rate and the openings of the passive check valves giving activation to the natural circulation in the ECCS under the forcing head resulting from coolant density differential between hot leg (reactor side) and cold leg (ECCS primary). The started operation of ECCS restores quickly the flow rate in the core which had dropped down around the zero value at the instant of the primary loop interception. The steep drop down of the primary flow rate within the first 15s from beginning of transient, coupled to the circulating time of cold front for reaching the core zone, makes the cooling effect due to rapid depressurization of the secondary loop, practically ininfluent. Also the auxiliary feedwater flow rate at 40°C temperature appears to have no influence. The moderator temperature in the first 20s remains substantially at the initial value of 214°C.

Instead the entry of the cold water of the ECCS Primary at 70°C starts to strongly cool off the core, particularly in the initial phase when the flow rate reaches a peak of about 420kg/s. The

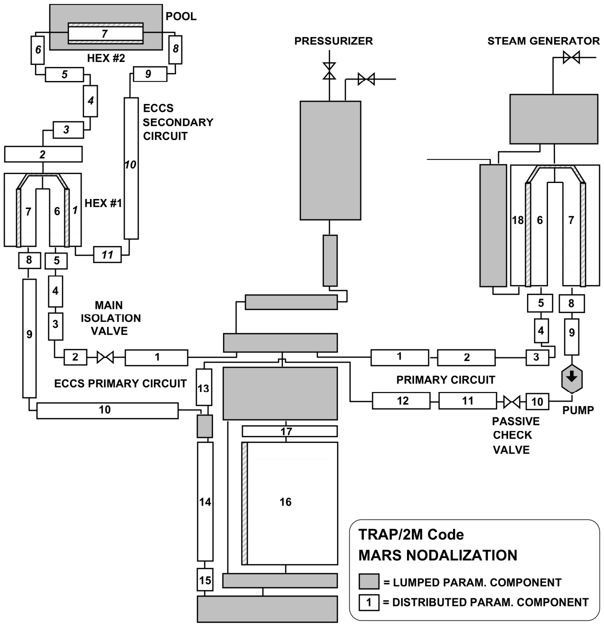

Fig. 2 Nodalization scheme of MARS plant for TRAP/2M code.

ECCS Secondary Loop activates when the hot front enters the ECCS Primary heat exchanger (here named HEX #1) and the secondary fluid is warmed up by the core coolant: the Secondary Loop flow rate have a peak of 320kg/s and during the first 500s shows the same damped oscillating behaviour of the Primary Loop but shifted in time due to the startup of the natural circulation. Both the flow rates are always positive, with the secondary flow rate always greater then the primary one after 180s about.

Later on, the moderator temperature continues to slow down smoothly compared to the initial phase, according to the ECCS Primary flow rate, which is a function of the continuously decreasing forcing head as the difference of temperature between ECCS Primary and Secondary is reduced, as a result of the pool heating up via the secondary heat exchanger (HEX #2). At the time 1000s into the transient the thermalhydraulic regime is stabilized and goes monotonically towards equilibrium; at this point the moderator temperature is decreased to about 80°C and the pool is heated up to 20°C. The positive reactivity insertion due to the coolant temperature feedback is about 800pcm, figure not susceptible of significant increasing in the mid-long term when the system goes towards the equilibrium pool temperature. The conclusion is that within 15s from the beginning of the transient the plant reaches the safe state on the shut down reactor and isolated primary loop and the ECCS enters in operation to provide the core cooling by natural circulation. The reactivity recovery, as a consequence of fuel and moderator cool off lies however far under the criticality conditions even in the highly conservative assumptions that have been made for the case. Finally, given the temperature trends in coolant, cladding and fuel no hazard for the fuel rod integrity is evidentiated.

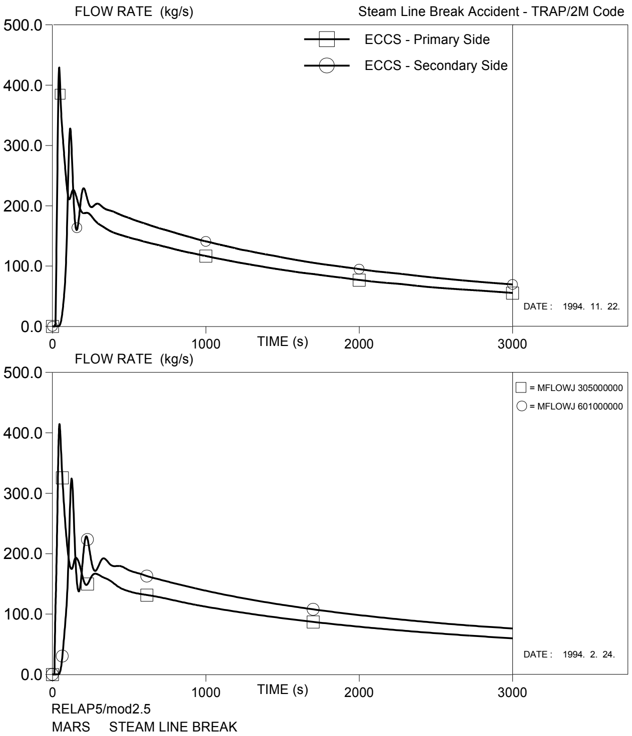

Fig. 3 Comparison between TRAP/2M (top graph) and RELAP5/mod2.5 (bottom graph) results: ECCS Primary and Secondary flow rates during SLB.

SENSITIVITY STUDY ON ECCS BEHAVIOUR

To obtain the initial reference test case for the sensitivity study, the same plant nodalization used by ENEA (1994) for RELAP5/mod2.5 code has been adopted for TRAP/2M code. The input translation has been made coherently with the model of TRAP code that uses distributed parameter balance equations to solve tubes, heat exchangers and the reactor core. Therefore, each volume of RELAP is defined for TRAP as a length of duct included between two sections, equivalent to the inlet and outlet cross sections of the volume: a linear behaviour of the thermalhydraulic parameters is assumed within the two sections. This led to a total of 38 distributed parameter components subdivided into 108 sections plus 14 lumped parameter components, constituting the input set of TRAP and corresponding to the 109 volumes used by ENEA/RELAP. The nodalization scheme looks as reported in Fig.2. As far as the ECCS is concerned, 28 sections have been utilized for the Primary Loop and 26 sections for the Secondary Loop, equivalent to the 18 and 15 volumes used for RELAP, respectively.

Besides the number of nodes, the same heat transfer correlations and selection criteria of RELAP5/mod2.5 have been adopted to obtain the reference case.

Both in the Steam Line Break accident and in the other design basis accidents the TRAP simulations are in good agreement with the RELAP results, as shown in the example of Fig.3 and more

TABLE III

EMERGENCY CORE COOLING SYSTEM (ECCS) DATA

Primary Heat Exchanger (HEX #1)	
tube type	U-tubes ¾" BWG 18
(tube internal diameter)	16.56 mm
(tubes total cross section area)	0.19386 m^2
number of tubes	900
tube bundle total height	4000 mm
tube bundle diameter	1100 mm
shell outer diameter	1500 mm
inclination ***(vertical-up=+90°)***	+20°
Secondary Heat Exchanger (HEX #2)	
tube type	Straight tubes 1" BWG 18
(tube internal diameter)	22.91 mm
(tubes total cross section area)	0.3174 m^2
number of tubes	770
tube lenght	7000 mm
inclination ***(vertical-up=+90°)***	-5°
Piping	
operating pressure	72 bar
internal diameter	406.4 mm
(cross section area)	0.1297 m^2
ECCS circuit overall height	12.3 m
ECCS circuit overall lenght	52.4 m

fully in ENEA (1994), thus allowing to start from a sound basis for the parametric study.

The selected procedure involved modifications of the ECCS Secondary Loop with regard to its number of sections, the heat transfer correlations of the ECCS primary heat exchanger (HEX#1) and the dimensions of the circuit, but keeping untouched the corresponding parameters of the ECCS Primary Loop, of the reactor core and of the reactor primary and secondary circuit, in order to avoid the superposition of different effects and to better point out the sensitivity of the ECCS Secondary passive circuit. The main ECCS design data are reported in Table III.

The transients lasting 500s were carried out on a Pentium/60MHz personal computer, with a time step of 0.1s.

A - Nodalization

This first step aimed at verifying the sensitivity of the ECCS Secondary Loop behaviour to the number of sections adopted for its discretization, starting from the initial ENEA/RELAP nodalization. The attention has been focused mainly on the response of the secondary and the primary flow rates of the ECCS.

The SLB accident has been repeated using different nodalizations with an ever increasing number of sections. The results are summarized in Fig.4.

By doubling the number of volumes of the ECCS Secondary Loop (from 26 to 41 sections) we noted a lower damping of the oscillating time profile for both the flow rates. This trend is confirmed as the number of sections is multiplied, as far as to invert the flow in the ECCS Secondary Loop when the number of volumes is quadrupled (61 sections). This irregular behaviour from one nodalization to another that leads even to the flow rate inversion is undoubtedly chargeable to the numerical diffusion, stronger in the reference case, which have the unphysical effect of increasing the transmission speed of the temperature front along the circuit. In the first case (26 sections) this allows a more rapid activation of the heat exchanger to the pool (HEX #2) and maintains the right half of the loop cooler than the left one, thus supporting a clockwise natural circulation, whereas in the third case (61 sections) after 150s about the mean density of the left half of the circuit remains higher than that of the right half, so giving rise to a stable counter-clockwise flow.

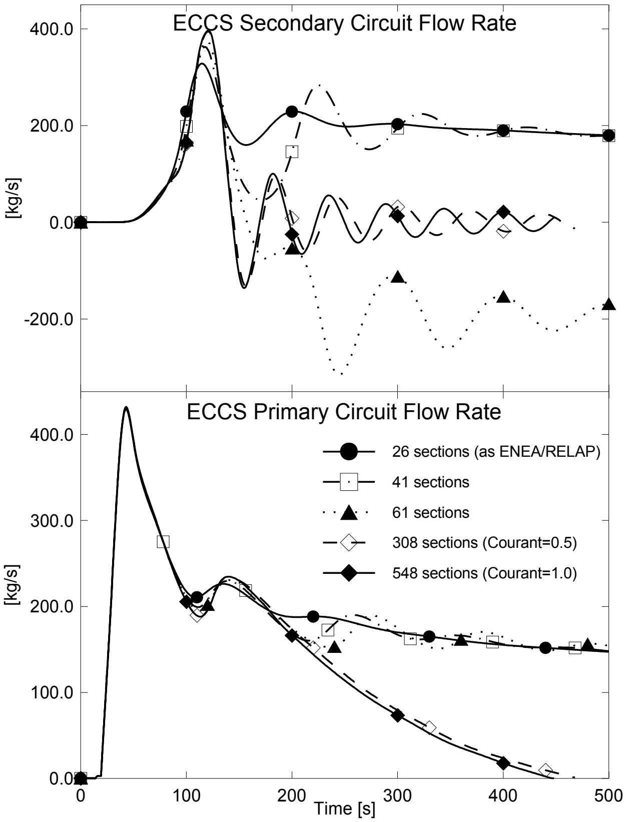

Fig. 4 SLB accident: results for different ECCS Secondary Loop nodalizations.

To strongly reduce the numerical diffusion effect, further renodalizations have been carried out by trying to comply with the Courant number condition in the piping and in the heat exchangers, at least in correspondence of the maximum value of the flow rate into the transient. Two other cases have been reported in Fig.4, belonging to nodalizations which respect a value of the Courant number equal to 0.5 (308 sections) and equal to 1.0 (548 sections) at the maximum flow rate reached in the loop. The results, while confirming the oscillating time profile of the ECCS Secondary Loop flow rate, present an asymptotic value near to the null flow. The discrepancy betweeen the last two transients is in the period of the sinusoids. The elimination of the diffusion effects seems to be acquired as shown in Fig.5, where the comparison between the temperature profiles of the reference case and of the 548 sections case are reported. Because of the adiabaticity of the piping and coherently with the monodimensional model assumption, the fluid should transfer the temperature front exactly from the outlet of the primary heat exchanger (HEX #1) to the inlet of the secondary heat exchanger (HEX #2): this is assured if

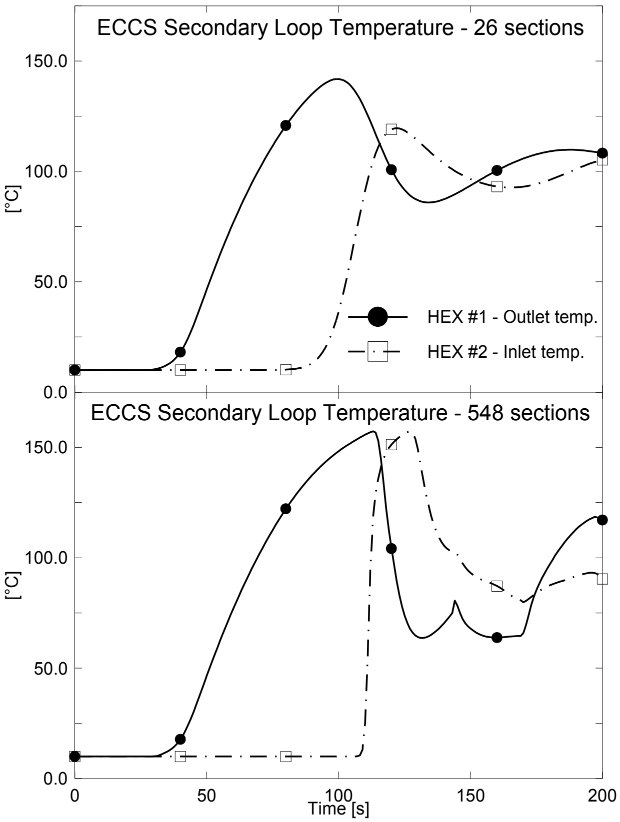

Fig. 5 Numerical diffusion effect during temperature front transmission between primary heat exchanger (HEX #1) outlet and secondary heat exchanger (HEX #2) inlet (top graph) - numerical diffusion avoided with nodalization increased (bottom graph).

the Courant condition is respected, otherwise a reduction in the temperature peak is undergone (equal to 25°C with the 26 sections nodalization).

The non effective functioning of the ECCS Secondary Loop resolves also in a feedback on the Primary Loop: the primary flow rate slows down to zero at 450s about. At this obviously undesired condition the computation has been stopped.

As far as the computing resources are concerned, the CPU time required for the analyses ranged from 2.0 times the real time for the reference nodalization to 7.5 times the real time for the 548 sections case, on a Pentium/60MHz PC.

B - Heat transfer correlations for HEX #1

The second step of the parametric study focused the attention on the heat transfer performance of the primary heat exchanger (HEX #1), that is the thermal link between the ECCS Primary and Secondary Loops, which represents a topical component: here the priming of the natural circulation on the passive circuit occurs.

The HEX #1 is of Tube-Shell type (Fig.6 - corresponding design data already reported in Table III) and is inclined 20° with respect to the horizontal plane. In a second version of the project the HEX #1 has been housed in a completely horizontal position,

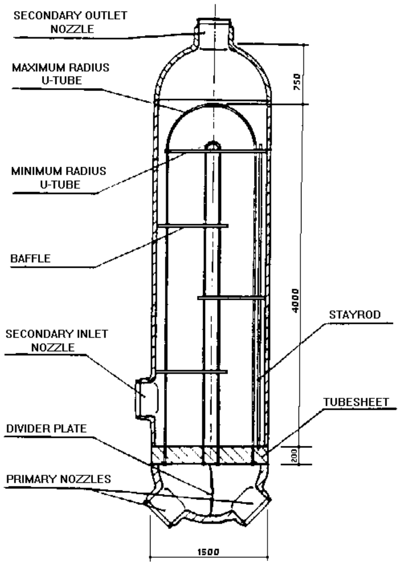

Fig. 6 ECCS Primary heat exchanger (HEX #1).

TABLE IV

AUTHOR FLOW CONDITIONS	HEAT TRANSFER CORRELATION			
(1) Morgan	$Nu_D = C\, Ra_D^n$			
		Ra_D	C	n
		$10^{-10} \div 10^{-2}$	0.675	0.058
		$10^{-2} \div 10^{2}$	1.02	0.148
		$10^{2} \div 10^{4}$	0.850	0.188
external, free (horizontal cylinder)		$10^{4} \div 10^{7}$	0.480	0.250
		$10^{7} \div 10^{12}$	0.125	0.333
(2) Churchill-Chu $10^{-5} < Ra_D < 10^{12}$; external, free (horizontal cylinder)	$Nu_D = \left\{ 0.60 + \frac{0.387\, Ra_D^{1/6}}{\left[1+\left(0.559/Pr\right)^{9/16}\right]^{8/27}} \right\}^2$			
(3) *analytical* laminar flow, uniform surface heat flux, forced	$Nu_D = 4.36$			
(4) Dittus-Boelter $0.7 \le Pr \le 160$, $Re_D \ge 10^5$; forced	$Nu_D = 0.023\, Re_D^{4/5}\, Pr^n$ $n = 0.4$ for $T_s > T_f$ $n = 0.3$ for $T_s < T_f$			
(5) Zhukauskas	$Nu_D = C\, Re_{D,\max}^m\, Pr^{0.36} \left(\frac{Pr}{Pr_s}\right)^{1/4}$			
$0.7 < Pr < 500$,		$Re_{D,\max}$	C	m
$10^3 < Re_{D,\max} < 2 \times 10^6$,		$10 \div 10^2$	0.90	0.40
$N_L \ge 20$; external, forced		$10^2 \div 10^3$	0.51	0.50
(flow across banks of tubes)		$10^3 \div 2 \times 10^5$	0.35	0.60
		$2 \times 10^5 \div 2 \times 10^6$	0.022	0.84
(6) Delaware method Shell-side, crossflow heat exchangers	$h = C\, f(Re) \frac{c_p\, \Gamma}{\Omega} Pr^{-2/3} \left(\frac{\mu}{\mu_s}\right)^{0.14}$ $C = j_c \cdot j_l \cdot j_b \cdot j_s \cdot j_r$			

TABLE V

HEX #1 Shell-side	**Free Convection**	**Forced Convection**
Correl. Set #1	Morgan (1)	Laminar (3) Dittus-Boelter (4)
Correl. Set #2	Churchill-Chu (2)	Zhukauskas (5)
Correl. Set #3	Churchill-Chu (2)	Delaware method (6)
	Selection Criterium	
Correl. Set #1	$Nu = \max\left\{Nu_{Morgan}, Nu_{laminar}, Nu_{D-B}\right\}$	
Correl. Set #2	$\begin{cases} Gr/Re^2 \le 10^{-2} & Nu = Nu_{Zhuk.} \\ 10^{-2} < Gr/Re^2 < 10^2 & Nu = \sqrt[4]{Nu_{Chu}^4 + Nu_{Zhuk.}^4} \\ Gr/Re^2 \ge 10^2 & Nu = Nu_{Chu} \end{cases}$	
Correl. Set #3	same as Correl. Set #2	

to avoid the formation of air plugs into the U-tubes when filling up the circuit.

In such a situation, where complex geometries and particular flow conditions as the start up in free convection represents some critical states, the problem of a correct evaluation of the heat transfer arises. For example, even the layout together with the flow condition could concur to degradate the performance of an exchanger, as found by Rohsenow (1981), and therefore further difficulties in the simulation in particular with monodimensional codes could be introduced: Rohsenow showed that in horizontal tube-shell heat exchangers in laminar flow, as surely occurs during the start up in the HEX #1, spatial disuniformities of the flow could take place which lead to vertical free convection, with hot fluid returned to the inlet and with a sensible reduction of the heat transfer effectiveness as long as the vertical head term is greater than the friction loss term. But a choice still is needed about the heat transfer correlations to use in the codes, even if it is well known by the designers that only a deep validation with *ad hoc* experimental studies can resolve the problem of the code reliability.

Among a large number of correlations for the shell-side heat transfer coefficient computation, a reduced number of them has been tested in order to verify their effect on the HEX #1 exchanged power and on the ECCS Secondary flow rate. The transients were carried out utilizing the 548 sections nodalization, thus strongly reducing the numerical diffusion. The results here reported (Fig.7) refer to three different correlations sets. Each set is formed by a free convection correlation and a forced convection correlation plus a selection criterium. The correlations are listed in Table IV and the sets description is shown in Table V.

For the free convection flow, those suggested by Morgan (1975) and by Churchill and Chu (1975) have been used, valid for horizontal cylinders. For the forced convection flow, the well known Dittus and Boelter (1930) and the Zhukauskas (1972) for flow across banks of tubes have been singled out. Besides literature correlations as the above mentioned, a specific method were also adopted to evaluate the shell-side heat transfer coefficient in forced convection for tube-shell exchangers, the Delaware method presented by Bell (1981). According to it, the effective heat transfer coefficient is obtained by the product among an ideal value, corresponding to pure crossflow in an ideal tube bank, and various correction factors complying with the others flow paths inside the exchanger, i.e. the correction factor for baffle cut and spacing (j_c), for baffle leakage effects (j_l), for bundle bypass flow (j_b), for variable baffle spacing in the inlet and outlet sections (j_s) and for adverse temperature gradient build-up (j_r). The combined effect of all of these correction factors resolves in a reduction of the ideal heat transfer coefficient.

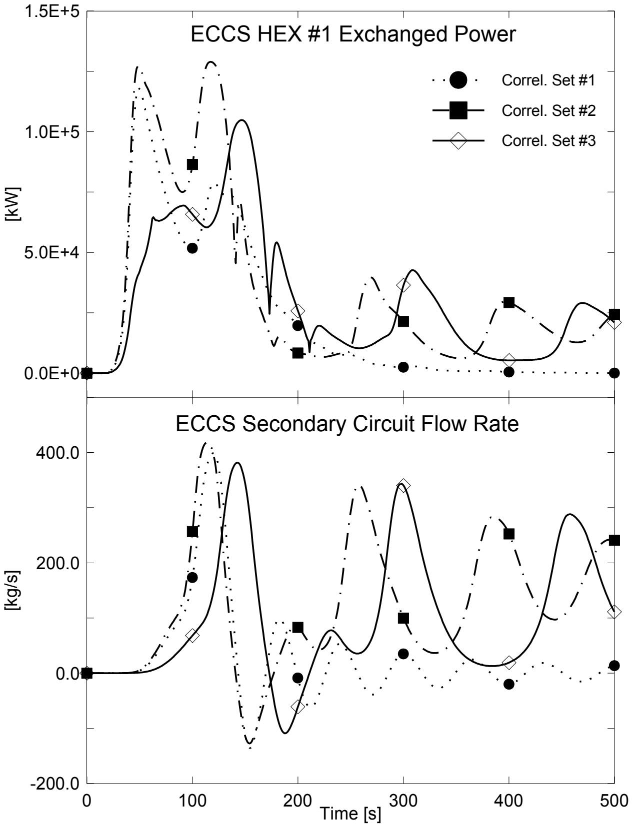

Fig. 7 SLB accident: results for different heat transfer correlation sets for HEX #1.

As far as the selection criterium is concerned, two hypotheses have been followed: the first used by Set #1 is to consider only the maximum contribution to heat transfer among those due to laminar flow, turbulent flow and free convection, the second used by Set #2 and Set #3 is to combine free and forced convection when (Gr/Re^2) ≈ 1 (Incropera and De Witt, 1990).

The results show a sensitivity of the simulated behaviour to the heat transfer correlation choice even if a thick nodalization is used. With the correlation Set #1, a lower effectiveness of the HEX #1 is obtained when compared with that calculated utilizing RELAP5/mod2.5 correlations and selection criterium. With Set #2 a better performance is predicted which brings about the different behaviour of the secondary flow rate, now leaving the null asymptotic value towards a positive one, even if with wide oscillations both in amplitude and in period. Using Set #3 causes an initial delay in establishing the natural convection regime and a worse performance than that of Set #2, but always with a positive secondary flow rate value.

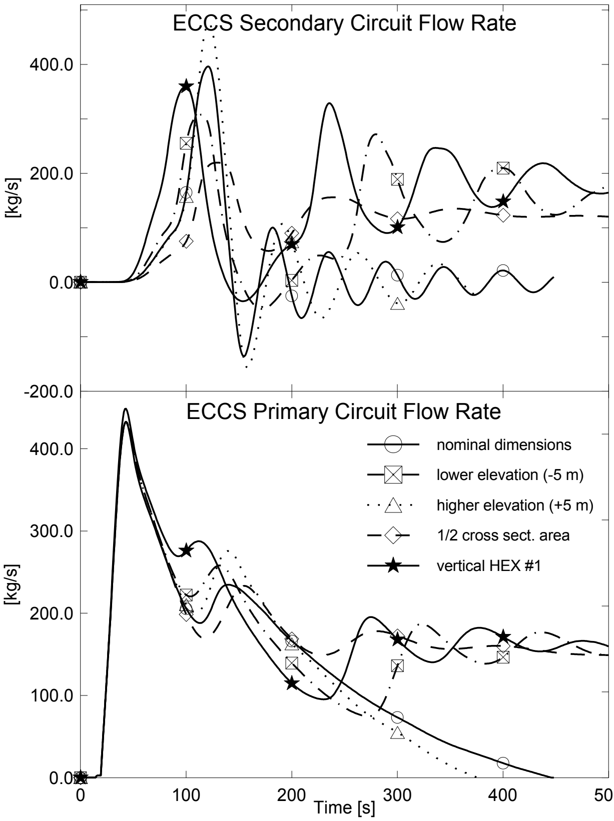

Fig. 8 SLB accident: results for different ECCS Secondary Loop dimensions.

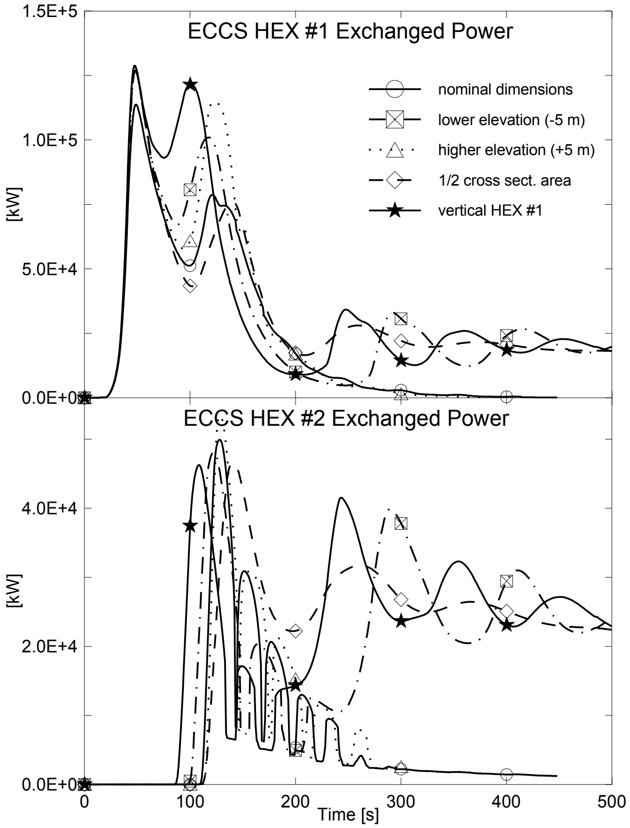

Fig. 9 SLB accident: results for different ECCS Secondary Loop dimensions.

C - ECCS Secondary Loop dimensions

The last step aimed at a first evaluation of the degree of freedom of the circuit dimensioning, dealing with the elevations and the piping size.

The accidental transients were carried out with the thick nodalization (548 sections) and with the reference heat transfer correlations and selection criteria of RELAP5/mod2.5.

The results (Fig.8 and Fig.9) show that a lower height of 5m of the riser piping in the passive circuit with respect to the nominal height is better than an increment of the same length, as would not be considered immediatly evident before the analysis. In the first case a positive flow rate is established in the loop, in the second case the flow rate still keeps a null asymptotic value even if a maximum peak of 480kg/s is reached.

By halving the piping cross sectional area the friction pressure drops are considerably increased, but the result is a more stable behaviour of the passive circuit in term of flow rates and powers exchanged via the HEX #1 and the HEX #2 in spite of a lower value of the asymptotic flow rate and a slower departure from the rest condition.

Finally the vertical housing of the HEX #1 has been adopted, keeping unchanged the nominal height of the loop. As it was to be expected, a more rapid priming of the natural circulation occurs but the oscillating characteristic of the time profiles still remains, with a loss of effectiveness in the HEX #1 from 150s to 220s and in HEX #2 from 120s to 200s.

To summarize, some not obvious behaviours of the main thermalhydraulic parameters of the passive loop have been evidentiated, thus entailing the need of a wide design work in order to find out the best effective circuit configuration.

CONCLUSIONS

The suggestions arising from this parametric study are mainly directed to the designers.

In the simulation of a passive system in natural circulation, is of certain importance to describe in a correct way the spatial distribution of the temperature/density fronts and the heat transfer, which are the forcing parameters of the system. To comply with this request, both a correct adoption of heat transfer correlations, coherently with the particular geometry and flow conditions of the system, and a strongly reduction of the numerical diffusion by the use of nodalizations coping with the Courant limit are needed. The latter issue generally leads to a considerable increase of the number of the discretization nodes which implies more time consuming analyses. It seems to us that the use of codes based on more simple physical models than that used by the safety codes, but with high computing speed and user-friendly features are a good aid to the designer.

As a further notation, the singling out of the design and layout parameters of a passive system for its optimum performance is reached with a wide spectrum analysis, both on the geometric parameters and on the accidental plant configurations, provided the previously mentioned conditions.

Above all, is confirmed the need of analyses with experimental facilities which maintain the main parameters of the full scale system relevant to the natural circulation, as the heights, the transit times of the fluid and the heat losses, even for a simple passive loop like the ECCS Secondary of MARS, for a correct knowledge of the system behaviour. Moreover the full scale test of topical components for the system, e.g. the heat exchangers, could point out their behaviour in particular conditions as the start up and could evidentiate unexpected and undesired threedimensional flow effects. This is in agreement with the tendency followed by the Control Authority of the nuclear countries with regard to the new passive safety systems.

The huge effect on the simulation side is the validation of the codes, especially the safety codes which are usually based on monodimensional models: precious informations are extracted from the experiments enabling the designers to conveniently modify the code models, in order to reach the maximum reliability of a necessary tool for costs saving and systems behaviour understanding.

Moreover, all these informations must be suitably examined with a further analysis of the code uncertainties (Boyack et al., 1990), (D'Auria et al., 1994), in order to reach a thorough judgement on the behaviour of the full scale safety system, but this evaluation is beyond the scope of present paper.

Finally, in our opinion the passive circuits should be viewed in a more critical way. The advantage to be "passive" is in some way counterbalanced by the fact that their flow rate is not an independent parameter as for "active" circuits but it is strictly connected to the temperature distribution. This fact introduces the above mentioned system's uncertainties, which may be difficult and time consuming to solve definitely.

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NOMENCLATURE

Symbols:	c_p	specific heat at constant pressure
	f	generic function
	Gr	Grashof number
	h	heat transfer coefficient
	Nu	Nusselt number
	Pr	Prandtl number
	Ra	Rayleigh number
	Re	Reynolds number
	T	temperature
Greeks:	Γ	mass flow rate
	μ	dinamic viscosity
	Ω	cross section area
Subscripts:	D	diameter (refers to cylindrical geom.)
	f	fluid
	s	surface

REFERENCES

Ambrosini, W, Bovalini, R. and D'Auria, F., 1990, "Evaluation of Accuracy of Thermal-Hydraulic Code Calculations", *J. Energia Nucleare*, 7, 2, pp.5-16.

Bell, K. J., 1981, "Delaware Method for Shell-side Design", in Heat Exchangers: Thermal-Hydraulic Fundamentals and Design, Kakaç, S., Bergles, A.E. and Mayinger, F., eds., Hemisphere Publishing Corp., Washington, D.C., pp. 581-618.

Boyack, B.E., Catton, I., Duffey, R.B., Griffith, P., Katsma, K.R., Lellouche, G.S., Levy, S., Rohatgi, U.S., Wilson, G.E., Wulff, W. and Zuber, N., 1990, "An Overview of the Code Scaling, Applicability and Uncertainty Evaluation Methodology", *Nuclear Engineering & Design,* 119.

Brega, E., Lombardi, C., Ricotti, M.E. and Rilli, A., 1992, "A Simplified Model for the Simulation of Operational and Accident Transients of PWRs and PIUS Reactor", *Proceedings, CSNI Spec. Meeting on Simulators & Plant Analyzers,* Lappeenranta, Finland, pp. 156-172.

Caira, M., Cumo, M. and Naviglio, A., 1986, "The MARS Nuclear Reactor Plant: an Inherently Safe, Small, Medium Size Multipurpose Nuclear Plant", *Nuclear Engineering & Design,* 97, 2.

Churchill, S.W. and Chu, H.H.S., 1975, "Correlating Equations for Laminar and Turbulent Free Convection from a Horizontal Cylinder", International Journal of Heat and Mass Transfer, 18, pp. 1049-.

D'Auria, F., Galassi, G.M., Bonuccelli, M. and Debrecin, N, 1993, "A Methodology for the Qualification of Theralhydraulic Code Nodalizations", *Proceedings, NURETH-7,* vol.2, Grenoble.

D'Auria, F., Debrecin, N. and Galassi, G.M., 1994, "Outline of the Uncertainty Methodology based on Accuracy Extrapolation (UMAE)", *CSNI Workshop on Uncertainty Evaluation*, London.

Dittus, F.W. and Boelter, L.M.K., 1930, University of California Publications on Engineering, Berkeley, vol.2, p. 443.

Dodge, R., 1992, "Application of the Method of Characteristics in the VIPRE-02 code", *Proceedings, 7th International RETRAN Conference,* EPRI, Palo Alto, CA, 31.

ENEA, 1994, "MARS project: Safety Evaluation Report", ENEA Nuclear Energy Division Report, MT_GLM_15.

IAEA, 1990, "Safety Related Terms of Advanced Nuclear Plants", Final Report, Vienna.

Incropera, F.P. and De Witt, D.P., 1990, Fundamentals of Heat and Mass Transfer, John Wiley & Sons Inc., New York, pp. 566-567.

Morgan, V.T., 1975, "The Overall Convective Heat Transfer from Smooth Circular Cylinders", Advances in Heat Transfer, Hartnett, J.P. and Irvine, T.F., eds., Academic Press, New York, NY, vol.11, pp. 199-264.

Paulsen, M.P., Shatford, J.G., Westacott, J.L. and Agee, L., 1992, "A Nondiffusive Solution Method for RETRAN-03 BWR Stability Analysis", *Proceedings, 7th International RETRAN Conference,* EPRI, Palo Alto, CA, 4.

Ricotti, M.E., 1994, "TRIP: a Model for Operability and Safety Analysis of Conventional and New Conception PWRs", Ph.D. Thesis, Polytechnic of Milan, Milan.

Ricotti, M.E., Sordi, R. and Vettraino, F., 1995, "Dinamic Response of MARS Reactor under Design Basis Accident conditions", *Proceedings, ICONE-3*, Kyoto, Japan.

Rohsenow, W.M., 1981, "Why Laminar Flow Heat Exchangers can perform poorly", in Heat Exchangers: Thermal-Hydraulic fundamentals and design, Kakaç, S., Bergles, A.E. and Mayinger, F., ed., Hemisphere Publishing Corp., Washington, D.C., pp. 1057-1072.

University of Rome "La Sapienza", 1989, "Multipurpose Advanced Reactor inherently Safe Report", Technical Report.

Zhukauskas, A., 1972, "Heat Transfer from Tubes in Cross Flow", Advances in Heat Transfer, Hartnett, J.P. and Irvine, T.F., eds., Academic Press, New York, NY, vol.11.