Analysis of the heat exchanger tube rupture accident in the XT-ADS reactor with the SIMMER-III code

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Abstract

The consequences of postulated HX tube rupture accidental events in the LBE-cooled XT-ADS reactor are investigated with the SIMMER-III code. The steam formation by water-LBE thermal interaction leads to a pressurisation of the cover gas and additionally could lead to sloshing motion in the LBE pool with impact loads of the heavy liquid on structures. Furthermore, the potential for core void formation due to steam drag into the core is also addressed. Two different accident scenarios were simulated with the SIMMER-III code. First, a single tube rupture event was considered as design-basis accident condition in XT-ADS safety analysis. Second, a multiple tube rupture is taken into account in order to assess the adequacy and limits of the safety systems devoted to mitigate the effects of the accident, e.g. the cover gas safety valve capacity.

Introduction

The objective of the European 6th Framework Programme project EUROTRANS was to demonstrate the technical feasibility of transmutation of high-level nuclear waste using accelerator-driven systems (ADS). Within EUROTRANS, the irradiation facility for Experimental Transmutation in an ADS (XT-ADS) was conceived and designed.

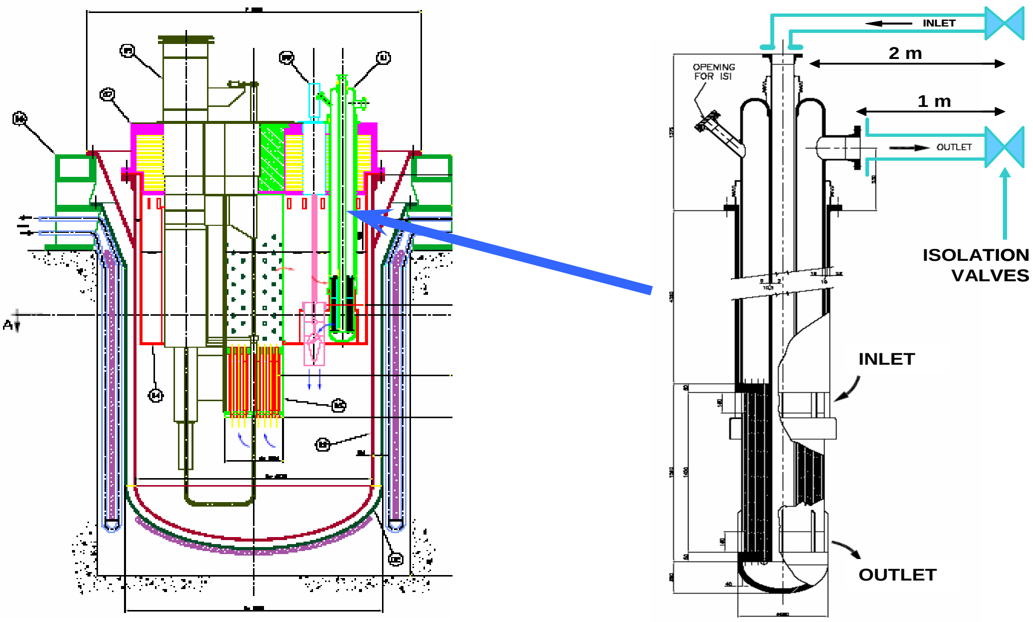
Based on the resulting XT-ADS design, the European 7th Framework Programme project CDT now has the objective to further develop the design of a Fast Spectrum Transmutation Experimental Facility (FASTEF) able to demonstrate efficient transmutation and related technology through a system working in subcritical and/or critical mode. The facility uses lead-bismuth eutectic (LBE) as primary coolant in forced circulation, and saturated water as secondary fluid in natural circulation. The core power is removed by four conventional straight-tube LBE-water heat exchangers (HX) immersed in the hot primary pool. Within the HX the LBE flows shell-side from the upper hot pool downwards to the lower cold pool. On the secondary side, saturated water enters the central inlet pipe at the HX top and flows downwards to the cold collector at the HX bottom; then it flows upwards tube-side and leaves the HX through the hot collector as a steam-water mixture. After separation the steam is condensed through air coolers with power release to the atmosphere.

The present work deals with the HX tube rupture accident and relevant safety issues. The consequences of postulated HX tube rupture accidental events in the LBE-cooled XT-ADS reactor are investigated with the SIMMER-III code.

XT-ADS design and operating conditions

The XT-ADS [1] is a pool-type LBE-cooled subcritical reactor sustained by a proton spallation source. Within the main vessel the hot and cold pools are separated by a diaphragm. Two mechanic axial-flow pumps and four conventional straight-tube steam generators (HX) penetrate the diaphragm wall and transfer the core heat to the secondary loops. The HX design and its arrangement in the primary system of XT-ADS are schematised in Figure 1.

Figure 1: HX design and its arrangement in the primary system of XT-ADS reactor



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In the HX the LBE flows shell-side from the upper hot pool downwards to the lower cold pool. On the secondary side, saturated water enters the central inlet pipe at the HX top and flows downwards to the cold collector at the HX bottom; then it flows upwards tube-side and leaves the HX through the hot collector as a steam-water mixture. Ferruling is provided at tube inlet in order to stabilise the flow.

Different normal operating conditions are foreseen for the XT-ADS depending on the selected core power level in the range 50-70 MW. In particular, the saturated steam pressure levels in the secondary circuit are dictated by the wish to limit the pressure in the secondary circuit and by the design choice to control the reactor power removal by adjusting the mean temperature difference between primary coolant and saturated water in the HX. The pressure limitation is a provision intended for mitigation of the consequences of the design-basis HX tube rupture accident.

Since the FASTEF core power is 100 MW, the operating condition at the maximum XT-ADS power of 70 MW is taken as a reference in the present analysis. Besides the condition at the beginning of cycle (BOC) is assumed, owing to the greatest secondary side HX pressure which maximises the water discharge into the primary coolant. The main primary and secondary circuit operating parameters of XT-ADS are listed in Table 1.

Table 1: Main XT-ADS operating parameters

Parameter	Unit	Value
Core power at BOL	MW	70
LBE cold temperature	°C	300
LBE hot temperature	°C	369
Core mass flow rate	kg/s	4 772
Core bypass mass flow rate	kg/s	2 228
LBE mass flow rate in one HX	kg/s	1 750
Feedwater pressure	bar	30.03
Feedwater temperature	°C	233
Secondary pressure at HX outlet	bar	29.67
Equilibrium quality at HX outlet	–	0.408

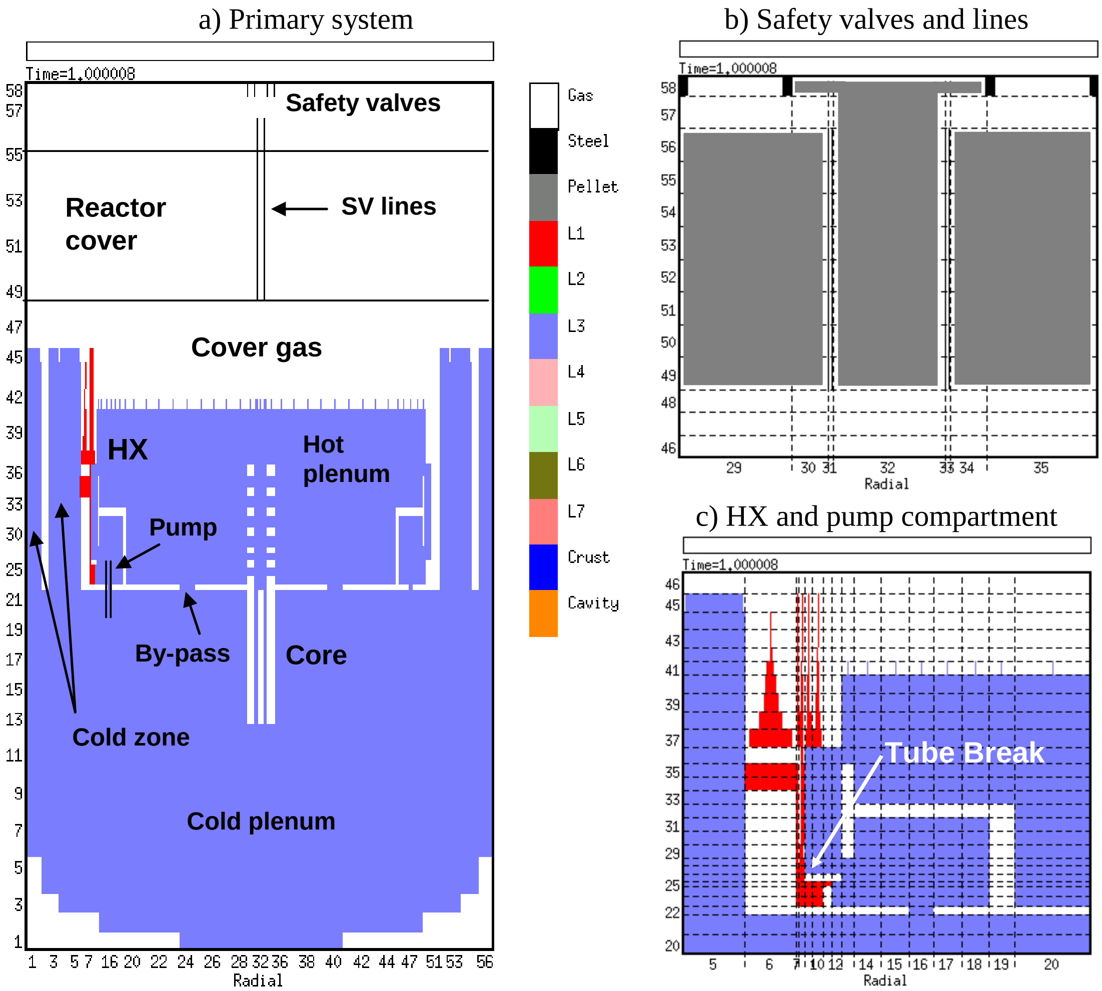
SIMMER-III simulation of postulated accidents

The SIMMER-III code [2] has been used to simulate the accidental transients. SIMMER-III is two-dimensional, multi-velocity-field, multi-phase, multi-component, Eulerian fluiddynamics code coupled with a neutronic kinetics model. It is a flexible tool which can deal with various problems consistent with his modelling framework such as safety analysis in advanced fast reactors up to the new accelerator-driven systems, steam explosions, fuel coolant interaction problems and, more generally, multi-phase flow problems. Based on wide code assessment efforts it can be stated that SIMMER-III is well applicable to integral multi-phase thermal-hydraulic problems including transient fuel-coolant interaction phenomena. The validation on specific phenomena related to steam generator tube rupture in a LBE environment is mainly based on the simulation of some small-scale experiments [3] and on the simulation of first experiments conducted on the large-scale LIFUS facility at ENEA/Brasimone centre in the framework of the EU EUROTRANS project [4,5]. The code has been employed for the evaluation of a postulated steam generator tube rupture accident in the accelerator-driven system with lead-cooling EFIT [3].

The whole primary system of the XT-ADS reactor is represented by SIMMER-III in 2-D Cartesian X-Z geometry using 56 horizontal and 58 vertical meshes as illustrated in Figure 2. This Cartesian geometry was preferred to the cylindrical geometries (HX or core-centred) used in the preliminary analysis, since it seems to best simulate all the phenomena closer to the real XT-ADS geometrical configuration. The results of the code assessment on LIFUS experiments give confidence on the validity of the SIMMER-III simulation, despite the necessary simplification adopted in the models due to the 2-D features of the code [5].

The XT-ADS model used in the SIMMER-III transient analysis is depicted in Figure 2. All main components and volumes are simulated by representative slabs of constant thickness in the Cartesian geometry.

Figure 2: XT-ADS model used in the SIMMER-III transient analysis



The initial temperature conditions in hot and cold plenum of the LBE pool is reproduced, but the core power is neglected. This is consistent with a scenario in which early HX failure is detected and the reactor is automatically shut down by proton beam trip. However, since the calculated transients are very short (few tenths of seconds), core power neglecting is also retained as a valid assumption in case there is no reactor trip. In any case, the reactor kinetics model is not activated and thus core void effects on reactivity and eventual nuclear power excursion could not be taken into account.

The nominal forced circulation in the primary circuit is established by simulating a DP of +1.5 bar (total pressure drop in the primary circuit) through the pump duct. The bypass flow rate through the diaphragm is represented calibrated orifices. The pressure losses in the HX both shell- and tube-side and through the ferruling at tube inlet are simulated by calibrated orifice coefficients. The resistance to gas flow in the pump duct by the impeller is neglected for a conservative analysis against steam ingress to the core inlet under transient conditions.

HX water inventory by RELAP5 code

The right evaluation of HX water inventory is necessary to well predict the discharge of water in the primary circuit. Since the power operation of HX is not simulated with SIMMER-III, the water inventory under normal operation has been calculated with the RELAP5 code. In particular, RELAP5 provides the mean void fractions in the tube bundle and hot collector which dictates the total mass of water inside the HX. Volume, mean void fraction and water mass in the different zones of HX are given in Table 2 below. The length of the pipes between the HX isolation valves and the HX inlet/outlet is taken into account as schematised in Figure 1.

Table 2: HX water inventory

Component	Volume [m^3]	Mean void fraction	Liquid mass [kg]	Steam mass [kg]	Total H_2O mass [kg]
Inlet pipe	0.162	1	133	0	133
Cold collector	0.086	1	71	0	71
Tube bundle	0.084	0.54	32	1	33
Hot collector + tube outlet	1.348	0.77	255	15	270
Total	1.68	–	491	16	507

In the analysed transients the early detection of HX failure with prompt actuation of isolation valves is supposed. The detection system could be based on secondary side depressurisation signal in case of large break (multiple tube rupture) or the presence of steam in the cover gas is case of small break (one tube rupture). However, the conclusions of the present analysis remain valid even without HX isolation.

Cover gas circuit and safety valve simulation

The main cover gas circuit and safety valve parameters are summarised in Table 3. The cover gas volume inside the vessel is of 36 m^3, while the cover gas circuit volume outside the vessel is neglected for conservative analysis against the maximum amplitude of cover gas pressure rise in transient conditions.

The lines to safety valves (SV) are separated from the lines to cover gas treatment circuit. The automatic opening/closure of safety valves during the transient phase cannot be simulated with SIMMER-III due to the lack of a specific model. Therefore, partial or full valve opening is stated in code input, at the instant in which the cover gas pressure reaches the opening pressure set-point. Once opened the safety valve never close in the present simulation.

Table 3: Main cover gas circuit and safety valve parameters

Parameter	Unit	Value
Safety valves number	–	2
Opening pressure set-point	bar	6
Valve cross-flow area	m^2	0.39
Valve capacity (saturated steam)	kg/s	6
Inner diameter of line to SV	M	0.154
Length of line to SV above reactor cover	M	1
In-vessel cover gas volume	m^3	36
Cover gas pressure	bar	1
Out-of-vessel cover gas circuit volume	–	Neglected

Analysis of accident scenarios

Two different accident scenarios were simulated with the SIMMER-III code. First, a single tube rupture event was considered as a design-basis accident condition in XT-ADS safety analysis. Second, a multiple tube rupture is taken into account in order to assess the limits of the safety systems devoted to mitigate the effects of the accident, e.g. the cover gas safety valve capacity. The break characteristics in the analysed HX tube rupture events are summarised in Table 4.

Table 4: Break characteristics in the analysed HX tube rupture events

Event	Break type	Diameter [m]	Flow area [m^2]	Initial leakage flow rate [kg/s]
Single tube rupture	Guillotine break of 1 tube at the inlet	0.0137	0.000295	2.3 (by RELAP5 [1])
Multiple tube rupture	Guillotine break of 5 tubes at the inlet	0.0137	0.001475	11.5 (by RELAP5 [1])

Single tube rupture

The 2-D representation of the whole primary system with SIMMER-III does not allow the detailed simulation of a single tube bundle and then the reliable calculation of the water discharge through the ruptured tube. Therefore, the water leakage rate calculated by ANSALDO with the RELAP5 code [1] for the operating condition under investigation (2.3 kg/s, see Table 4) is taken into account in the present SIMMER-III simulation as the initial leakage rate. Besides, as a conservative assumption with regard to potential drag of steam at the core inlet through the pump duct, the maximum leakage rate calculated by RELAP5 at the tube outlet is located at the lowest elevation, i.e. at tube inlet in the SIMMER-III simulation.

After tube break at t = 1 s, the pressurised saturated water entering the primary system at much lower pressure suddenly vaporises, also due to thermal interaction with the hot primary coolant. This induces LBE movements inside the pump compartment, while the steam tends to flow upwards through the HX by buoyancy towards the cover gas as illustrated in Figure 3, which represents material fractions and gas velocity field during the transient phase.

The time evolution of main parameters which illustrate the behaviour of the system is shown in Figure 4. Water discharge into the primary circuit is represented in Figure 4(a). The break mass flow rate reduces slowly with time according to the progressive pressure increase in the primary system [Figure 4(b)], while the secondary pressure remains almost constant [Figure 4(c)], owing to the low leakage rate against the large mass of saturated water inside the HX. The cumulated discharge after 42 s (stop of calculation) is of 90 kg [Figure 4(a)], less than one-fifth of the total HX water inventory.

Just after break opening, a maximum pressure peak of 8-10 bar lasting approximately one-tenth of a second is observed within the pump compartment and shell-side into the HX [Figure 4(d)]. The continuous flow of steam towards the cover gas leads to progressive primary pressure rise up to reaching the safety valves opening set-point (6 bar) after 29 s [Figure 4(a)].

The consequent steam release through the partially opened safety valves at a rate of about 1 kg/s per valve [Figure 4(e)], much less than the valve capacity value (6 kg/s), is sufficient to terminate the cover gas pressure increase.

Sloshing motion in the LBE pool in not of concern, since it involves the region close to the break only. Limited fluctuations are calculated at the LBE free level as shown in Figure 3; therefore, no LBE flow through the lines to the safety valves, which could compromise their efficiency, is predicted. The likelihood for steam drag into the core is very remote, as confirmed by the maximum void fraction calculated in the active core in Figure 4(f), which remains well below 1%. No risk of core power excursion due to positive void worth is then expected.

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Figure 3: Material fractions and gas velocity field during the transient phase

a) t = 2 s (1 s after break opening) b) t = 30 s (1 s after SV opening)

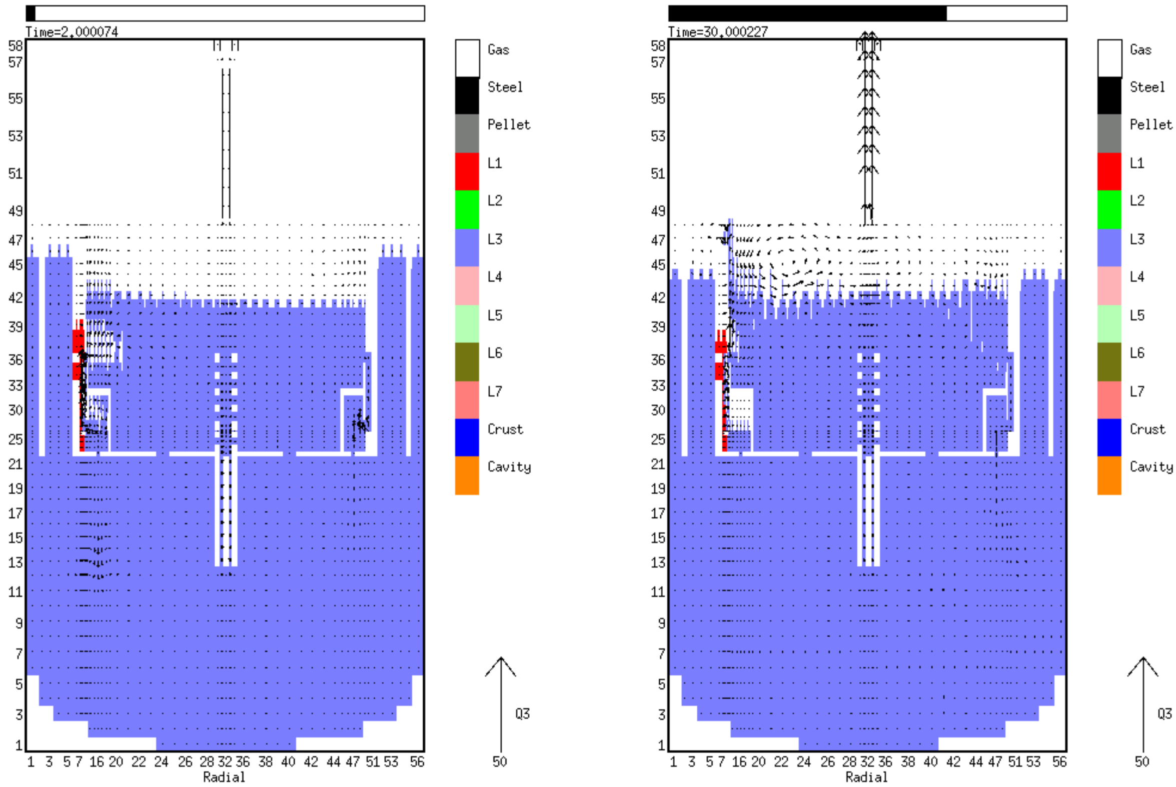


Figure 4: Main results of the single tube rupture simulation

a) Break flowrate and cumulated value b) Cover gas pressure

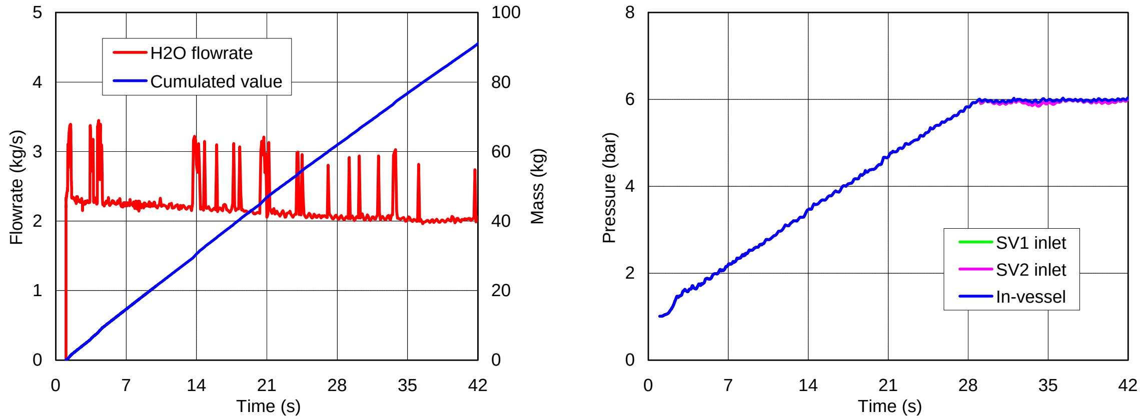
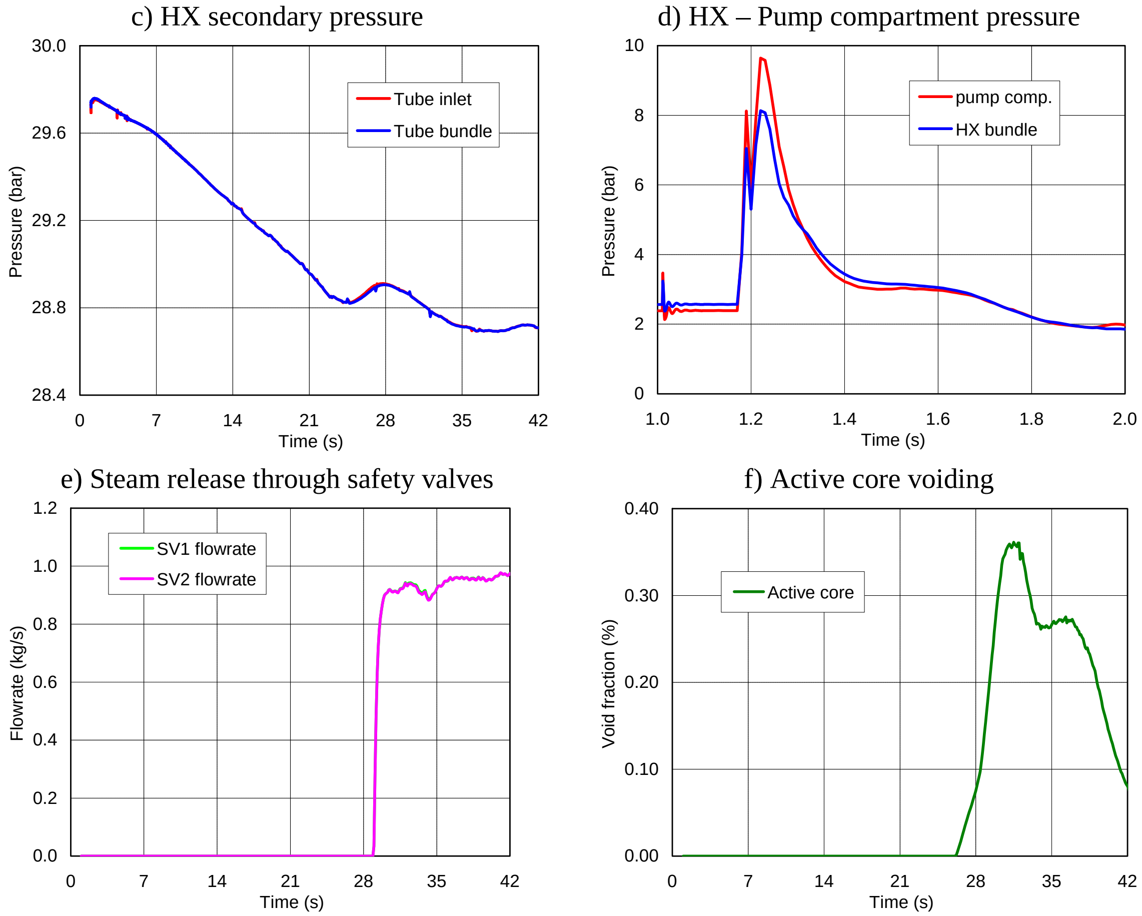


Figure 4: Main results of the single tube rupture simulation (*cont.*)



Multiple tube rupture

The multiple tube rupture accident analysis is intended for investigating a more severe situation in which the pressure spike successive to one tube rupture might induce further damage in the surrounding tubes leading to consistent increase in the water leakage rate into the primary coolant. In the present simulation the equivalent and contemporary rupture of five tubes is taken into account.

After five tubes break at t = 1 s, the sudden water vaporisation and steam release towards the cover gas through the HX leads to enhanced sloshing motion in the upper part of the LBE pool. The heavy liquid moves up and just touching the reactor cover bottom falls back downwards starting fluctuations of the pool free level surface (Figure 5).

Pressure peaks up to 20 bar and elapsing less than 0.1s are calculated within the HX-pump compartment starting from t = 1.1 s [Figure 6(a)]. The amplitude of the peak would be reduced under the assumption that the rupture of the five tubes does not occur at the same instant.

The water discharge into the primary circuit is shown in Figure 6(b). The initial leakage rate (around 12 kg/s) is approximately the one calculated by RELAP5 for one tube multiplied by five. The oscillations observed in the break flow rate are induced by fluctuations of the primary pressure in the vicinity of the break. The leakage rate reduces to about 10 kg/s in the first 6 seconds of transient due to increase of primary pressure; then is reduces much gradually until 40 s according to the slow depressurisation of the secondary system shown in Figure 6(c) (the pressure in the secondary side of HX is sustained by saturated water evaporation). Once the

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Figure 5: Material fractions and gas velocity field during the transient phase

a) t = 2 s (1 s after break opening)   b) t = 20 s (13 s after SV opening)

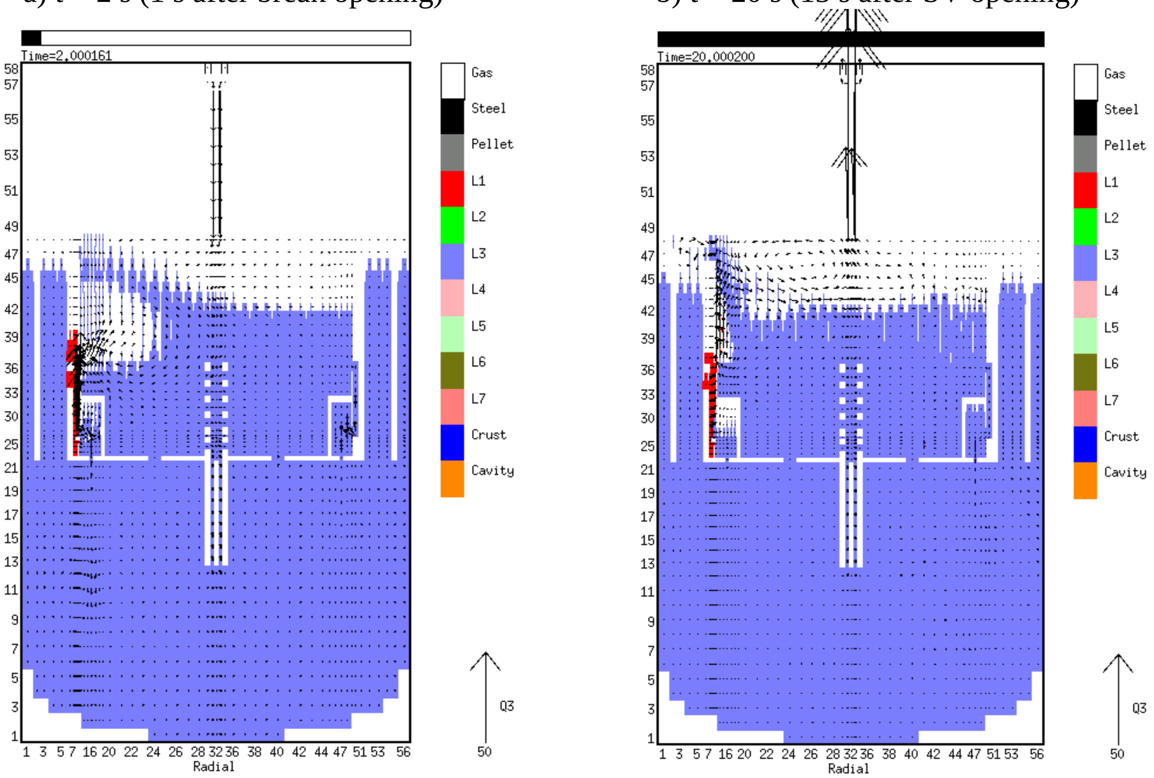


Figure 6: Main results of the multiple tube rupture simulation

a) HX – Pump compartment pressure   b) Break flowrate and cumulated value

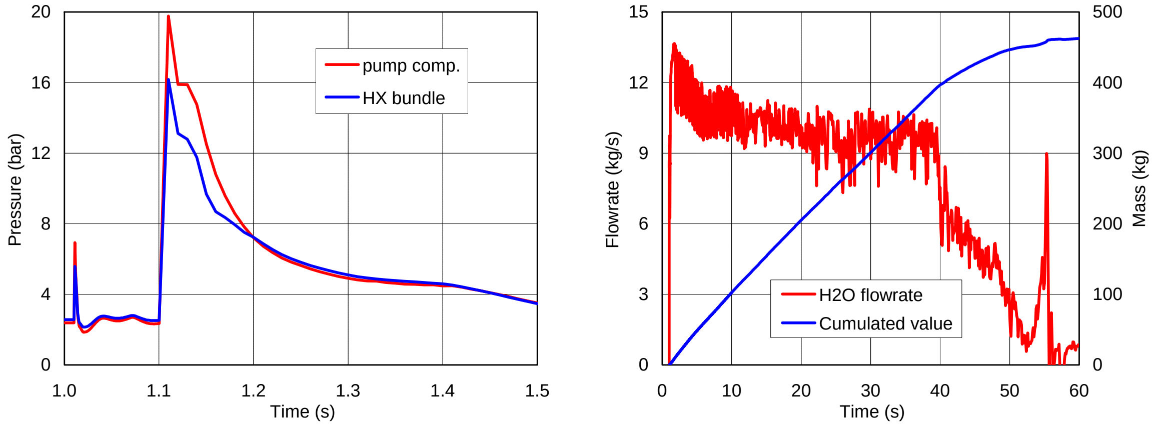
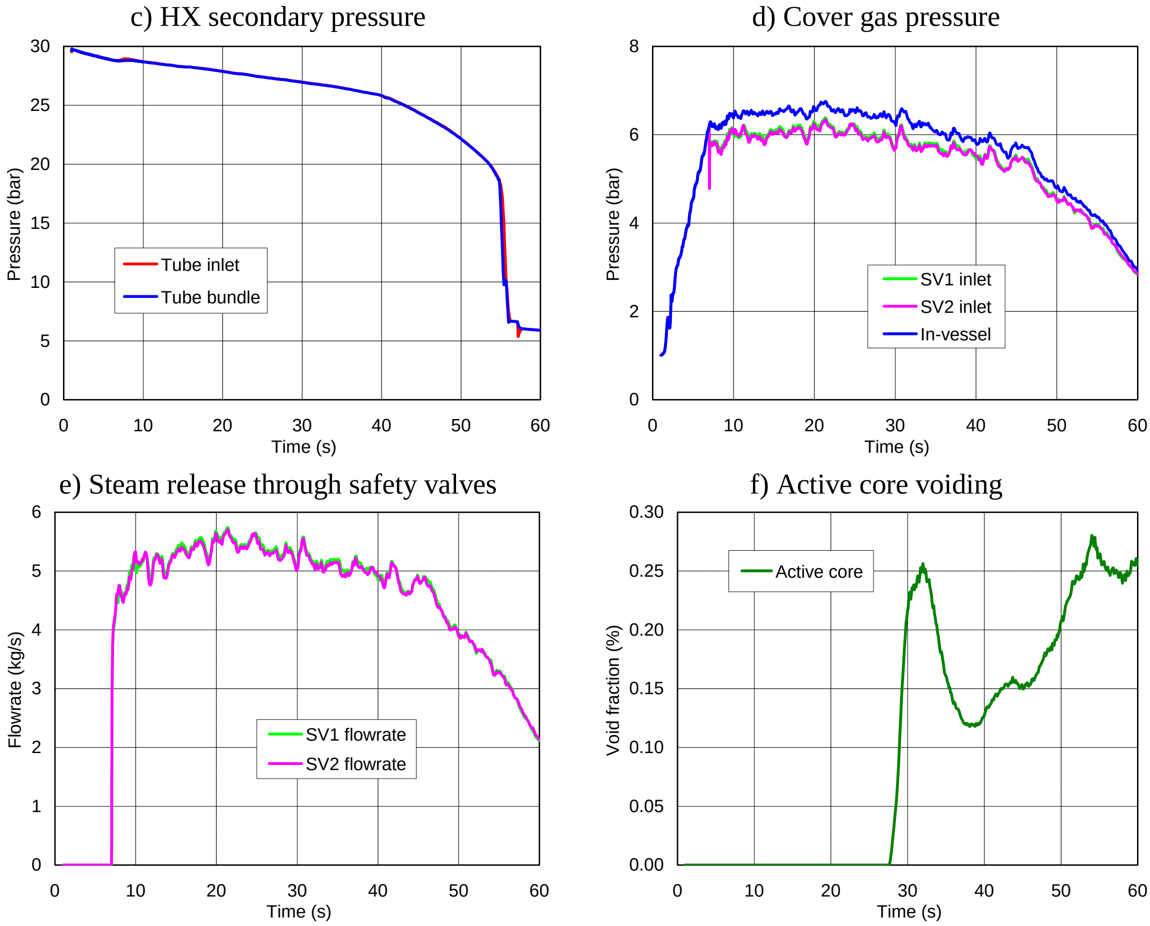


Figure 6: Main results of the multiple tube rupture simulation (*cont.*)



emptying of the HX secondary side becomes significant, the break flow quickly decreases, along with the secondary pressure, terminating at t = 56 s. Approximately 90% of the whole HX water inventory is discharged in the primary circuit at the end of transient.

Following water vaporisation and steam production within the LBE pool, the cover gas pressure rises almost linearly until reaching the safety valves opening set-point at t = 7 s [Figure 6(d)]. The operation of the two safety valves at their full capacity, which is close to 6 kg/s as shown in Figure 6(e), is able to counterbalance the steam production rate and stabilise the cover gas pressure around 6.5 bar, which is about 0.5 bar higher than the pressure calculated at the safety valve inlet [Figure 6(d)], because of pressure losses through the lines to safety valves. As evidenced in Figure 6(d), closure of the safety valves when the cover gas pressure falls down below 6 bar after 30 s is not simulated by the code.

As for the single tube rupture accident, also in this case the sloshing motion in the LBE pool is not of concern and no LBE flow through the lines to safety valves is predicted during the whole transient. Once more the likelihood of steam drag into the core is very remote and the maximum void fraction in the active core remains well below 1% [Figure 6(f)].

Conclusions

HX tube rupture accident scenarios in XT-ADS design have been investigated with the SIMMER-III code, with main emphasis on the evaluation of pressure impact loads and steam drag into the core, in order to assess the adequacy the design solutions adopted to mitigate the consequences of these accidents and safeguard the integrity of the plant. The gained knowledge will be used in the definition of the safety requirements for the next FASTEF design.

For the design basis accident with single HX tube rupture, no relevant pressure impact loads on vessel structures and no significant steam drag into the core is evidenced. Moreover, the pressure rise in the cover gas can be easily accommodated by one safety valve operation.

The analysis of the multiple tube rupture accident has shown that at least up to five tube ruptures can be sustained, without appreciable cover gas over pressure, by prompt and efficient operation of both safety valves. Besides, the sloshing motion in the lead pool and induced impact loads on structures seem still acceptable. Quite significant local and instantaneous pressure loads observed in the HX-pump compartment could be reduced if no contemporary tube failure is assumed. Also in this case the steam drag into the core is not of concern.

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