

Severe accident code ASTEC development and validation

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1 Introduction

The integral code ASTEC (Accident Source Term Evaluation Code) is being developed by IPSN (Institut de Protection et de Sûreté Nucléaire), France, and GRS (Gesellschaft für Anlagen- und Reaktorsicherheit), Germany, since 1994. The aim of this close co-operation of both companies is the creation of a fast running integral code which allows the calculation of the entire sequence of a severe accident in a light water reactor from the initiating event up to the release of fission products into the environment, covering all important in-vessel and ex-vessel phenomena. The main fields of application of this code are probabilistic safety analysis level 2 studies, accident sequence studies, uncertainty and sensitivity studies and support to experiments.

Since the 1980s, a two tier approach has been applied by IPSN and GRS based on the simultaneous but independent development of both integral and detailed mechanistic codes. During this time IPSN has developed the integral code ESCADRE and GRS has modelled the containment behaviour using two codes, RALOC for the thermal hydraulics and the hydrogen distribution and FIPLOC for the aerosol behaviour. For the first ASTEC version (called V0), it has been decided to gather in the same system the best candidates which can be provided by the two companies. Thus, ASTEC V0 consists in a combination of some modules of ESCADRE (for the reactor cooling system, core degradation, fission product release and transport, corium ejection from the vessel, direct containment heating and iodine chemistry in the containment), and of the module CPA (Containment Part of ASTEC), which combines the RALOC and FIPLOC codes.

GRS has the responsibility for the modules dealing with the containment except for the iodine chemistry. IPSN retains the responsibility for the overall code structure and the other modules. Nevertheless, a close collaboration exists for the development and the validation for most of several modules like SOPHAEROS or WECHSL.

This document briefly presents the status of development and validation of the code ASTEC. It focuses on the progress made since the status reported at the

Fachgespräch 1998 in Berlin and on the joint development of the module SOPHAEROS, dealing with the fission product transport in the primary circuit. Results of recent applications of ASTEC V0 to a German PWR 1300 MWe (GRS) and a French REP 900 (IPSN) will be presented. Finally, an outlook on the ongoing development of the next ASTEC version V1 and on the validation of ASTEC by external users within the project EVITA (European Validation of the Integral code ASTEC) of the 5th European framework programme will be given.

2 Status of ASTEC V0

The version V0.1 was used intensively in 1998. A general feed-back came from multi-compartment reactor calculations and from the overall validation performed by IPSN and GRS on:

- 25 separate-effect tests,
- the FPT1 experiment of the Phebus.FP programme implying most of the code modules in a coupled mode.

This intensive use led to a recent version, V0.2, released in October 1999 to internal IPSN and GRS users, which includes the following improvements:

- higher robustness of the new VULCAIN module (version 7.1 block2) for RCS thermal hydraulics and core degradation, up to vessel lower head failure,
- feed-back from the synthesis of the VULCAIN module validation on 6 experiments (PHEBUS B9+, CORA-13, PBF SFD 1-4, Phebus.FP FPT0 and FPT1, ACRR MP-1),
- improvement of the treatment of semi-volatile Fission products (FP) in ELSA module,
- validation of the RUPUICUV module for DCH on air-water and thermite (Surtsey facility, KAERI experiments),
- integration of the latest version 4.2 of the IODE module, which includes the Ag-I reactions in the sump,
- implementation of all the main safety systems for Severe Accident management, especially an extension of the SYSINT module to account for the containment systems or events:

- spray, either in direct or recirculation mode,
- water overflow from one compartment into another, e.g. from sump to cavity.
- improvement of modelling of several phenomena in CPA: spray systems, hydrogen combustion, hydrogen recombiners.

The whole documentation of the V0.2 is now ready, and gathered on a Web site:

- description of all the physical models (one Technical Report by module),
- on-line hypertext user's manual,
- minimal validation report.

Other improvements are under way, in order to lead to the version ASTEC V0.3 mid-2000:

- extension of the IODE module capability to deal with several independent compartments, each possibly including a sump (the V0.2 version allows an average treatment of iodine among all the containment compartments) ;
- new chemistry models in the IODE version: formation of organic iodides from gas-phase painted walls, sump iodine radiolysis at high temperature ;
- integration of the latest version of the SOPHAEROS module, which will replace the current version developed in 1994, and thus will bring a lot of new models (gas phase chemistry, homogeneous nucleation, aerosol mechanical resuspension,...).

3 Applications of ASTEC-V0

Several reactor applications are currently being performed, on the one hand to "consolidate" the code, and on the other hand to compare its results with reference integral codes:

- Numerous applications to a French 900 MWe reactor allow to check all models and their coupling in various conditions and range of physical parameters, as well as to check the activation and correct behaviour of main safety systems.
- The comparisons with reference integral codes are performed:

- with ESCADRE on single-compartment configurations of the containment. All the 20 ESCADRE delivery cases were run again and compared with ASTEC. The differences are consistent with the code and modeling uncertainties;
- with MELCOR on German Konvoi PWR 1300 MWe and on VVER-1000 in a containment multi-compartment configuration ;
- with MAAP4 on VVER-440 (needing the DRASYS model of condensing bubble tower to be checked and improved).

As a first example of current application, a comparison is presented with existing results of GRS investigations with the MELCOR 1.8.3 version on a German Konvoi PWR 1300 MWe. MELCOR calculations at GRS were performed for severe accidents like 2F-break of the main coolant line, large break LOCA with break off of the surge line, small break LOCA and failure of the steam generator feed water supply.

The comparison with MELCOR was first restricted to RCS and in-vessel behaviour, on a scenario of a guillotine break in the hot leg (figure 1), using a nodalization of 28 axial nodes in the core, and 27 volumes in the containment. The successive events such as meltdown, flow down and vaporisation of the control rods were reasonably simulated by VULCAIN. Swelling and collapse of the fuel rods with bursting and release of fission products, UO₂ fragmentation and forming of a pool with crust were observed. Corium flow through the molten parts of the baffle occurred. The agreement for the instant of vessel failure is good : 5800 s with MELCOR and 6200 s with ASTEC.

In a second step the application is being extended to the containment simulation, using now all modules of ASTEC. For a detailed comparison of ASTEC and MELCOR, a scenario of a double-ended break of the surge line was considered, using injection data from MELCOR. Since the input database has to be improved further, the results below are only preliminary. The instants of the phenomena occurring until vessel rupture are in good accordance (within approximately 10 % of deviation) with MELCOR (see Table 1). The course of the temperatures in the centre of the core (figure 2) corresponds to the MELCOR results until core melting is assumed in MELCOR. Core melting starts at 2100 K in MELCOR and at 2800 K in ASTEC.

Table 1: Comparison between MELCOR and ASTEC for characteristic phenomena occurring until vessel failure for a German PWR 1300 MWe.

Phenomena	ASTEC (seconds)	MELCOR (seconds)	Comments
Beginning of fission product release	1163	1320	
First fuel cladding rupture	2040	1800	
First lateral corium slump in vessel lower head	6472	6000	MELCOR: failure of the core support plate
Vessel rupture	6555	6300	
Beginning of molten core-concrete interaction	6619	7200	

Some large differences appear on steam production (figure 3): the steam injection calculated by VULCAIN is too low compared to MELCOR, particularly during the peak caused by the final corium slump into the lower vessel head. The analysis of these differences is under way.

As a second example of current application, a high-pressure reactor-case for a French 900 MWe PWR is presented in the Figures 4 to 8. The reactor nodalization is the following one:

- core: 24 axial meshes and 5 radial rings,
- RCS: 35 volumes,
- containment: 11 compartments (Fig.4).

The scenario is a TMLB sequence, characterized by a total loss of SG feedwater, PORV regulation, no accumulator discharge, and ECCS not available. The hydrogen and steam source is injected in the compartment where is the pressurizer relief tank zone (number C10 on Fig.4).

The results show (RDP in the Figures means pressurizer relief tank zone):

- pressure peak of almost 6 bars from DCH after vessel lower head rupture (Fig.5), where hot gas dispersal into the different compartments is supposed,
- activation of spray system above 2.4 bars, first in direct mode then in recirculation mode (see the slight effect on containment pressure in Fig.5 at about 19000 s.),

- large amount of H₂ production after DCH in the containment, where more than 11 t. of Zr from the non-dispersed corium are rapidly oxidized during MCCI (see Fig.7 at about 14000 s.),
- transport of FP and aerosols through the containment compartments, first in the pressurizer relief tank zone then in the other compartments (see Fig.8).

The hydrogen combustion model is not activated in this calculation.

These two applications show that the code behaviour is satisfactory, involving the main phenomena and the main safety systems. They will continue during the next months on PWR, in particularly with calculations on some selected sequences in support to IPSN PSA2, as well as on VVER.

4 Joint development of the module SOPHAEROS

The SOPHAEROS code simulates the physico-chemical behaviour of fission products (FPs), released by the fuel at high temperature in the form of vapours, between the core and the breach in the reactor coolant system (RCS). IPSN produced the first official version of SOPHAEROS, version 1.1, in 1994. This version deals with the behaviour of a small number of fixed vapour species as well as extensively modelling aerosol phenomena. Since 1994 the code has evolved considerably benefiting from concerted development and validation by IPSN and GRS in the context of a collaboration which parallels that of ASTEC itself.

The latest official version of SOPHAEROS, version 2.0 finalized in March 1999, models vapour-phase chemical reactions using a database of 107 species, chemisorbtion of certain FP vapours, condensation (including homogenous nucleation in favourable conditions) and all the main aerosol transport phenomena, i.e. agglomeration, deposition and resuspension. Table 2 shows the current test matrix describing the validation studies which have been carried out with SOPHAEROS. Considerable effort has also been devoted to improving the program itself by full conversion of all units to S.I. and extending portability to six platforms, viz. Sun, PC, HP, DEC, Silicon Graphics, IBM, on each of which a carefully-chosen set of 11 calculations was performed.

As for the next version of SOPHAEROS, version 2.1 due to appear next year, IPSN is pursuing improvement of vapour-phase chemistry modelling coupled to validation on experiments of the Phebus FP and VERCORS experiments. An optional mechanical resuspension model, developed by JRC/Ispira in the context of the STORM programme, will also be implemented. GRS will complete coupling of the pool scrubbing module SPARC-B to SOPHAEROS allowing version 2.1 to model the trapping of aerosols in volumes of water that can exist in the RCS. GRS is focusing its validation work on mechanical resuspension before switching to examination of homogeneous nucleation.

Table 2 : validation matrix of the SOPHAEROS code

EXPERIMENT	TESTS STUDIED	MAIN PHENOMENA
LACE (intern. consortium)	• LACE3B	• eddy and bend impaction • settling
TUBA-T (IPSN)	• TT14, 22, 24-31	• thermophoresis
TUBA-D (IPSN)	• TD01-TD12	• diffusiophoresis • thermo-diffusiophoresis
TRANSAT (IPSN)	• TR1, 2, TR4-TR8	• eddy and bend (90°) impaction • settling
ADPFF (AEA-T)	• WT10-23, WT25	• eddy and bend (90°) impaction • settling
DEPAT (IPSN)	• DEPAT 01-04 • DEPM 01-03	• turbulent diffusion • eddy impaction
STORM (CEC-ENEL)	• SD 04, ISP 40 • SR (in progress)	• thermophoresis • eddy impaction • mechanical resuspension
DEVAP (IPSN)	• 8, 13-15, 17, 18, 20	• vapour condensation • sorbtion (CsI, CsOH, Te)
AERODEVAP (IPSN)	• 01, 02, 04	• vapour condensation • homogeneous nucleation • vapour-aerosol interaction
Falcon (AEA-T)	• FAL17, 18 • ISP	• chemistry, condensation • vapour-aerosol interaction
REVAP-ASSESS (E.U. 4th Framework)	• 2 VTT tests, Fal-25	• revaporization
PHEBUS-FP (IPSN-CEC-EDF)	• FPT0, FPT1 (in progress)	• integral phenomena

5 Development of ASTEC V1

A main drawback of ASTEC V0 is the absence of a model for the front end phase of a severe accident, i.e. the phase from the initiating event through vessel blow-down up to the beginning of core uncovering. This leads to the necessity of calculating the reactor coolant system behaviour during the front end with an adequate thermalhydraulic code, like CATHARE or ATHLET, in order to obtain the initial conditions at the beginning of core uncovering and the sources to the containment during the front end phase.

The development activities for the ASTEC version V1 are concentrated on overcoming this drawback. Feasibility studies have led to the following solution: the module VULCAIN, dealing with the primary circuit thermal hydraulics and core degradation in version V0, will be replaced by two new modules: CESAR (Circuit Evolution under Severe Accidents in Reactors) and DIVA (Degradation In-Vessel during Accidents).

The module CESAR is based on a plant simulator French code whose specifications were derived from the CATHARE code. This module covers the 2phase thermal hydraulics in the reactor coolant system. It is based on a lumped parameter approach with zero- and one-dimensional nodes and with 5 conservation equations for the liquid and gas mass and energy and for the mixture momentum. Extensions of this module are currently underway regarding the treatment of non-condensable gases, the simulation of the reactor control system, the introduction of a reflood model and the introduction of a time step management.

The module DIVA is based on ICARE2 V3, the mechanistic reference code for core degradation during severe accidents at IPSN. To fulfil the fast running requirements of ASTEC, CPU-time intensive models of ICARE2 will be omitted and replaced by simple models if necessary. Current activities in the DIVA development are the extension of the thermal hydraulics model, the development of models for the relocation of molten corium into the lower head, and the behaviour of corium in the lower head.

Most efforts are currently focusing on the coupling of both modules, which is a very important and difficult point: different strategies are under study.

Additionally, the ASTEC version V1 will bring improvements in the following areas:

- Updates of the modules ELSA, SOPHAEROS and IODE: new releases of these modules, which are developed outside the ASTEC environment, will be implemented into ASTEC in order to benefit from the progress made in their development. These improvements are mainly release of fission products from degraded geometries, pool scrubbing in the reactor coolant circuit and formation of iodides from painted walls.

- The modularity of the module CPA will be increased. Furthermore, the combustion and catalytic recombiner models will be improved.
- The physical basis of the module RUPUICUV, dealing with the direct containment heating, will be improved.
- The module WECHSL, dealing with the molten corium-concrete interactions, will be replaced by the module WEX, a reengineered and improved version of WECHSL, which was created by GRS in the frame of the development of their mechanistic containment code COCOSYS (COntainment COdE SYStem).
- The material properties used by each module will be standardised by the introduction of a common material data bank.
- The user interface will be improved with respect to pre-processing, online-visualisation and post-processing.
- The restart capability will be extended to any instant of the calculation.

6 External use and validation of ASTEC

Beyond the concerted efforts of IPSN and GRS, there exists in the two companies a policy of ease of access to their codes for other organizations in order to get feed-back experience from various users and improve the quality of the code.

ESCADRE, RALOC have been widely distributed, especially in the frame of TACIS programmes. The international distribution of ASTEC V0 has already been initiated, with a release to ENEA (Italy), VUJE (Slovaquia), KI and GAN (Russia).

A larger international contribution to the ASTEC code validation is expected within the 5th EC framework programme, in the frame of a shared cost action entitled EVITA (European Validation of the InTegral Code ASTEC). This project has been successfully evaluated by the community, the project consortium will consist of 16 partners from 8 countries plus JRC Ispra. EVITA final objective is to provide European end-users like licensing authorities, vendors and utilities with a well validated European integral code for the simulation of severe accident sequences in nuclear power plants. The integral code ASTEC will be distributed to European partners in order to apply the validation strategy issued from the VASA project (4th EC framework programme, just ended) on ASTEC.

Key experiments and severe accidents sequences, which form the basis of analysis, will be selected and defined. Following the risk-oriented approach of the VASA project, a guidance for the ASTEC validation process fitting for specific end-user needs as well as for research requirements will be established. Both of the ASTEC developing organisations have to supply the other project partners with the code. Then the validation process of ASTEC based on the experiments defined before will be performed. The experiments may be taken from the test series PBF-SFD, LOFT, STORM, BETA, HDR, VANAM, PHEBUS and others. Furthermore, plant applications with ASTEC for the severe accident sequences defined before, and for the demonstration of the capability for studying accident management measures will be performed. The sequences should be representative for different types of reactors like PWR, BWR, VVER and future concepts like EPR. After discussion of the results, the various European ASTEC users will give their feedback to the developing organisations.

EVITA will increase the extension and quality of the ASTEC validation considerably. The validation status reached and the needs for further ASTEC development will be defined by the partners with special attention to specific end-users needs.

Among the ASTEC modules, one may notice the specific case of SOPHAEROS which is used (in a stand alone version) on the other side of the Atlantic. Following requests for the latest version, SOPHAEROS v2.0 has been delivered in 1999 to the Candu Owners Group (COG), a consortium of Atomic Energy of Canada Limited, Ontario Power Generation, Hydro Quebec and New Brunswick Power. COG intend using SOPHAEROS as a reference code in their safety studies of CANDU reactors including a wide-ranging and rigorous validation exercise during the three years to come.

7 Outlook

The reactor applications will continue in 2000, on PWR (German 1300 MWe, French 900 MWe in support to IPSN PSA2) and on VVER. These will allow fruitful comparisons with reference codes such as ESCADRE, MELCOR and MAAP4.

The EVITA Project, devoted to ASTEC validation by European partners, will be an important step in the code progress.

In parallel to ASTEC V0 use and improvement, milestones in the development of the next version ASTEC V1 are the release end of 2000 of a first version including all new modules for internal use, and the release end of 2001 of a version for external use.

8 References

- [1] H.J. Allelein and J.P. Van Dorselaere
ASTEC code development and first applications for PSA level 2.
Fachgespräch 98, Berlin, 26 - 27 November 1998



Figure 1: Nodalisation scheme for German PWR 1300 MWe.

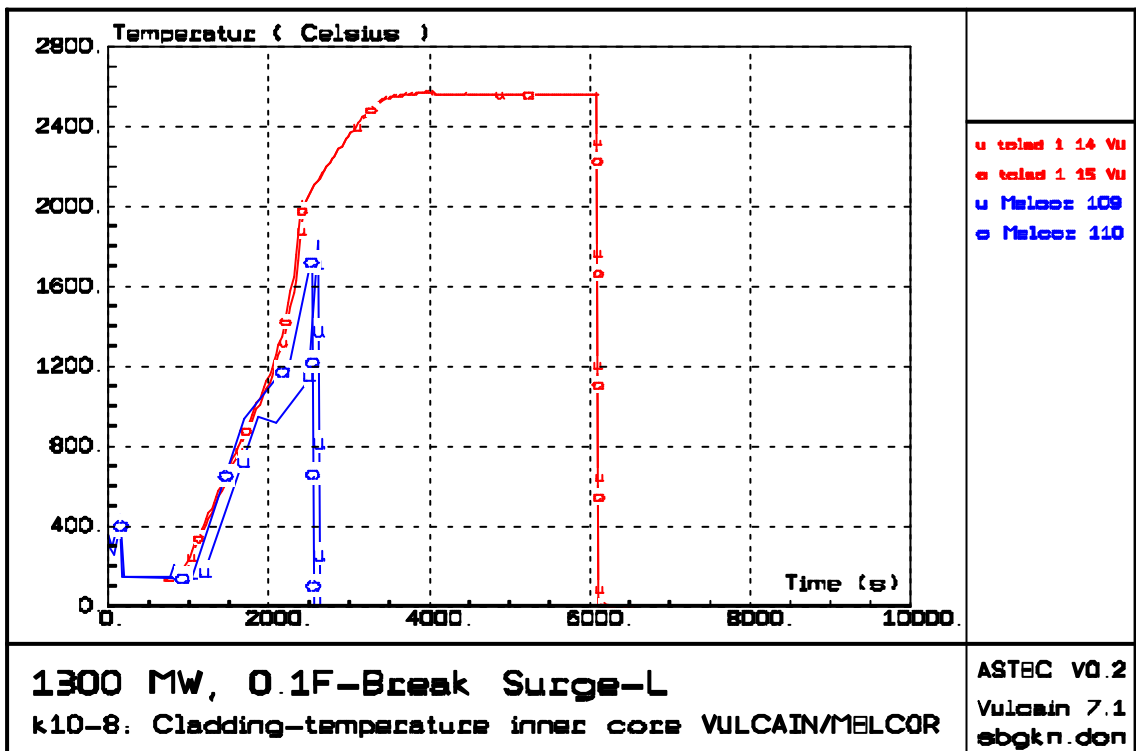


Figure 2: Comparison between MELCOR and ASTEC of cladding temperatures in the centre of the core for a German PWR 1300 MWe.

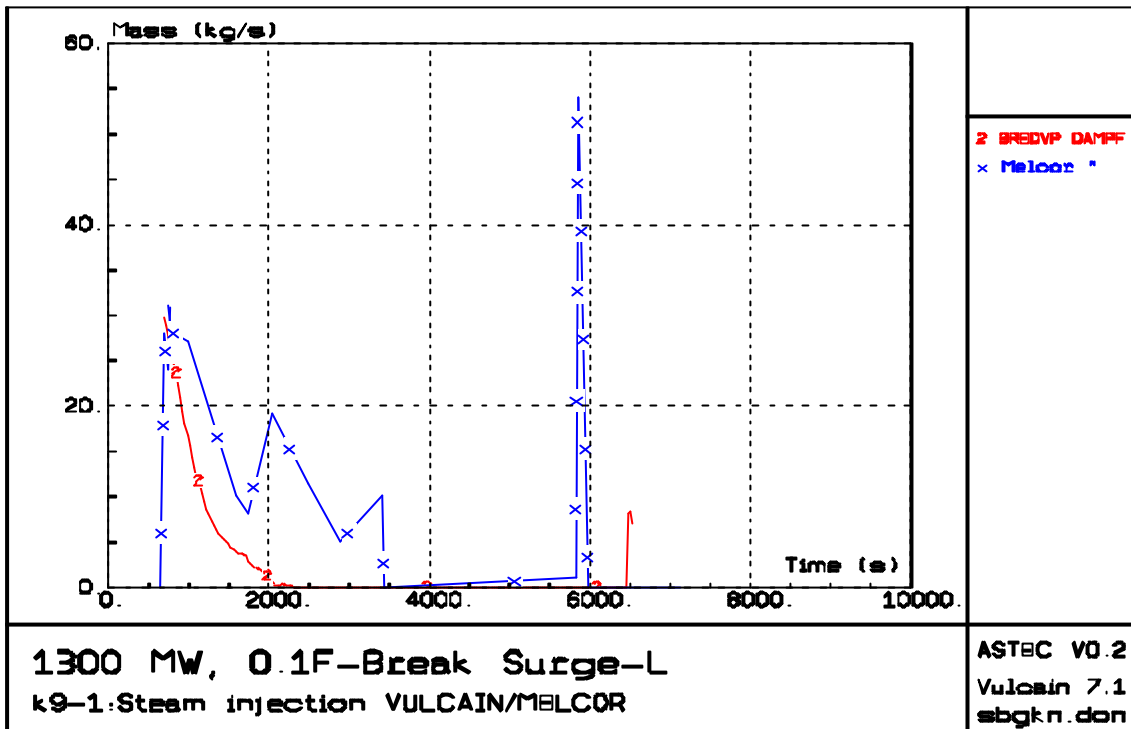


Figure 3: Comparison between MELCOR and ASTEC of the steam mass flow through the break for a German PWR 1300 MWe.

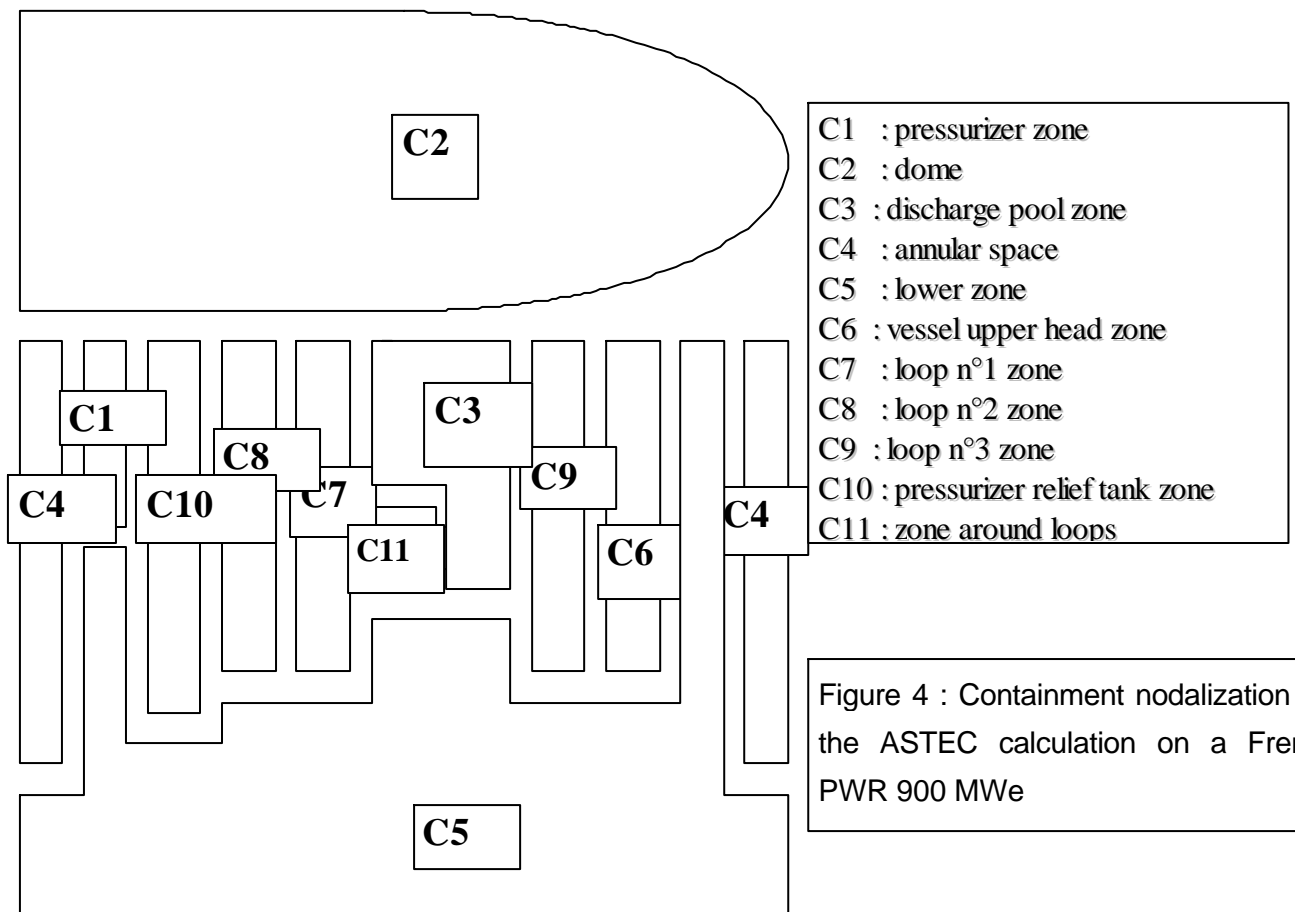


Figure 4 : Containment nodalization for the ASTEC calculation on a French PWR 900 MWe



Figure 5 : containment pressure for a TMLB sequence in a French PWR 900 MWe.

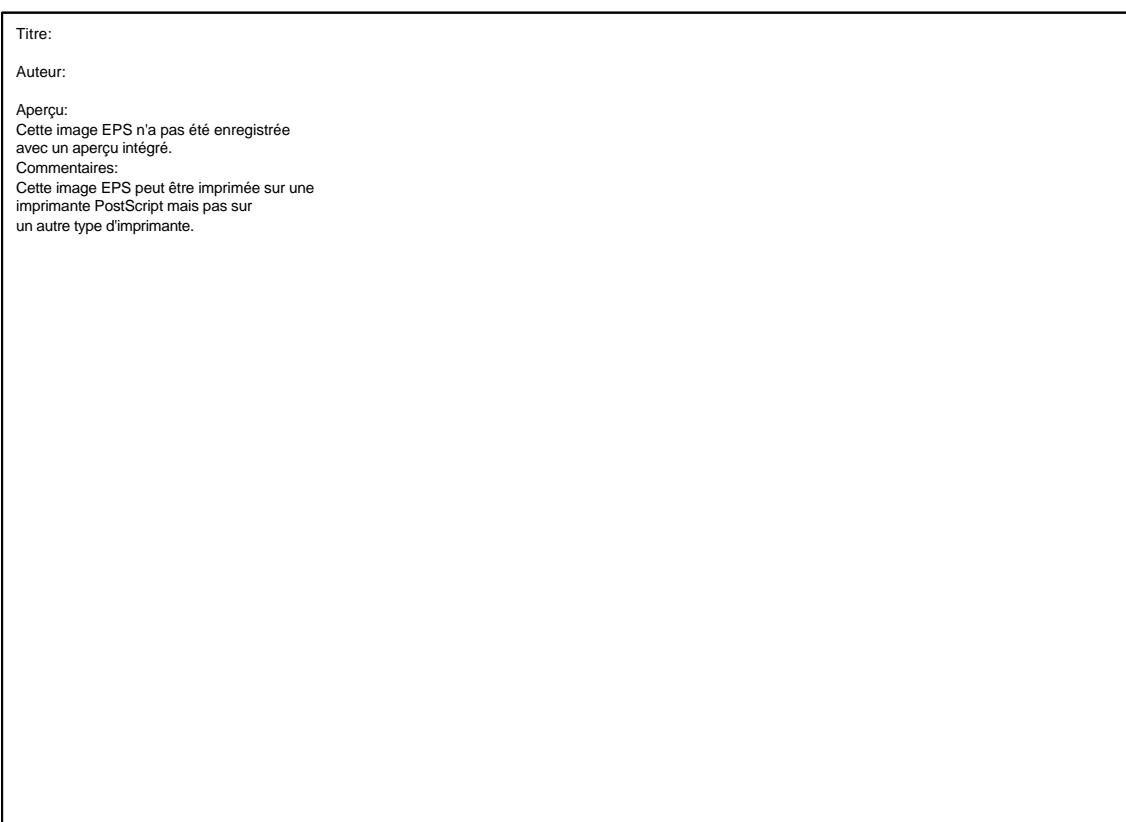


Figure 6 : containment temperature for a TMLB sequence in a French PWR 900 MWe.

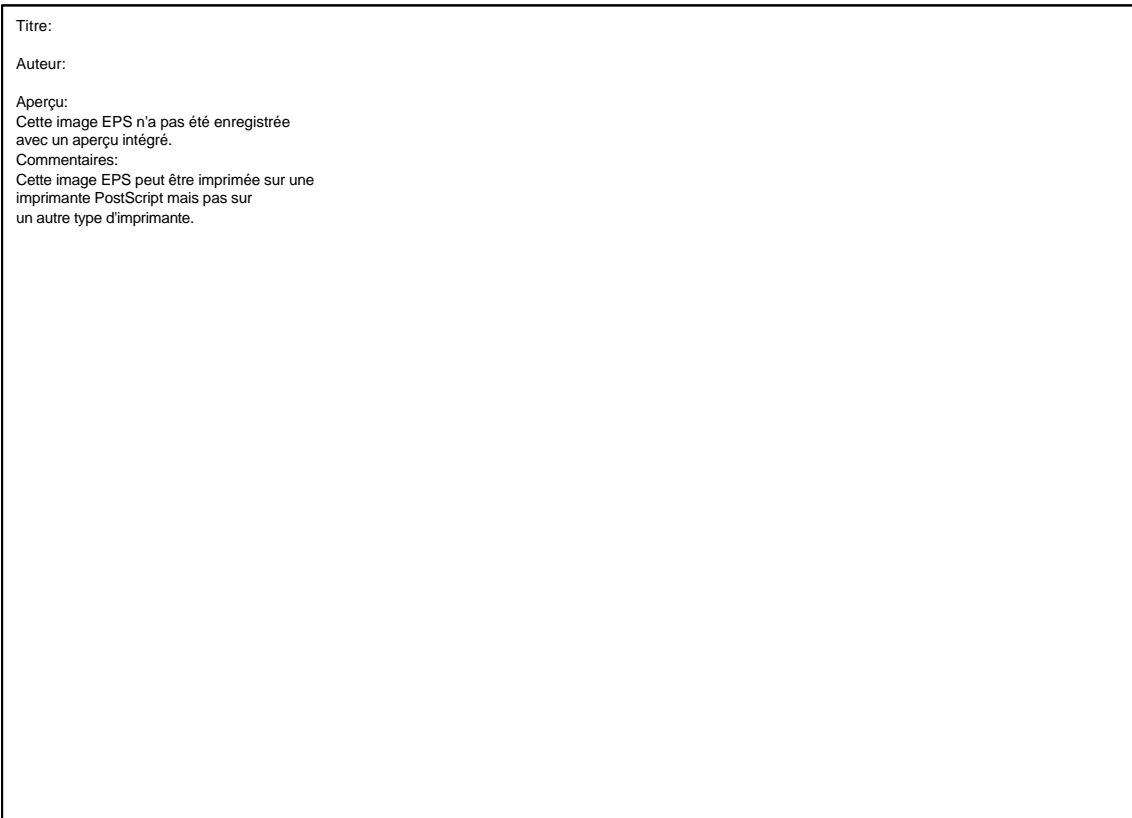


Figure 7 : containment hydrogen distribution for a TMLB sequence in a French PWR 900 MWe.

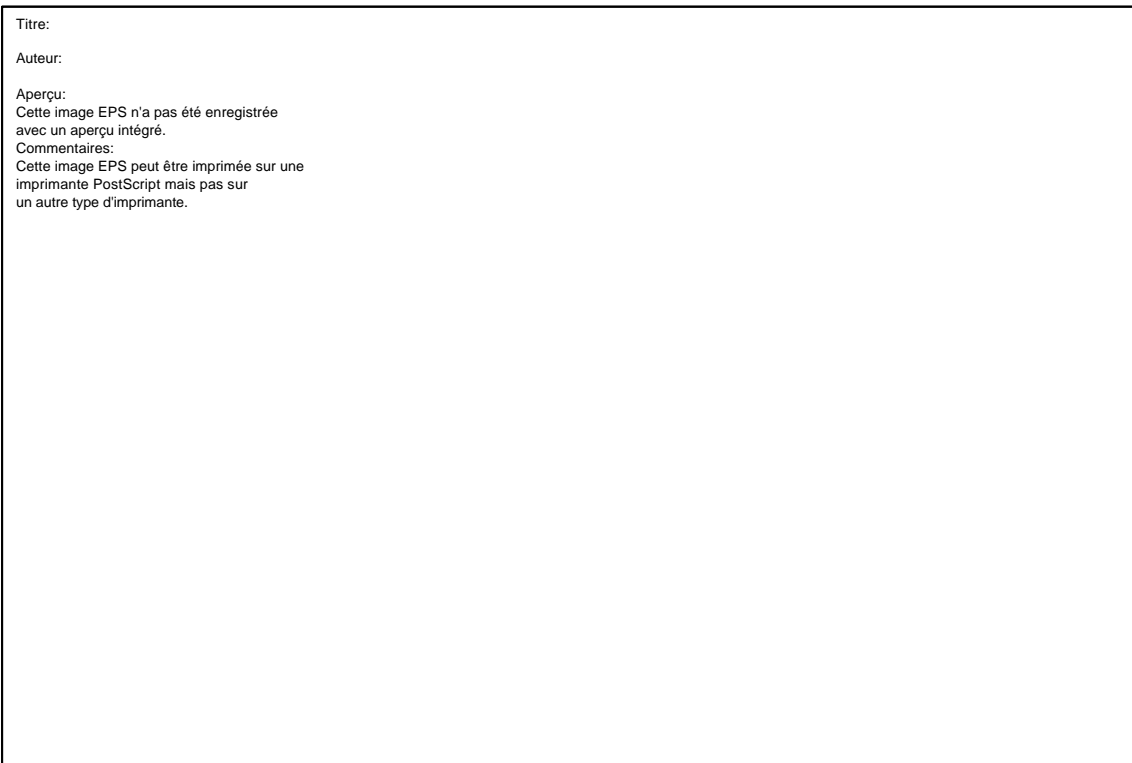


Figure 8 : containment aerosol distribution for a TMLB sequence in a French PWR 900 MWe.