

## Overview of progress of ASTEC Topic

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### SUMMARY

In the 3<sup>rd</sup> SARNET year (called JPA3), 30 partners have assessed the ASTEC V1.2 rev1 code version through validation against experiments and benchmarks with integral and/or mechanistic codes. As to ASTEC validation, more than 20 applications were performed on the following physical phenomena and experiments: circuit thermalhydraulics (PACTEL T2.1 and ISP33, PMK2, LOFT-LP-FP2); core degradation (CORA-13 and W2, QUENCH-11, LOFT-LP-FP2, Phébus FPT4); fission products (FP) release and transport (COLIMA, STORM, Phébus FPT0-1-2); MCCI (ACE L4, BETA, OECD-CCI2); containment thermalhydraulics and aerosol behaviour (LACE LA4, ThAI, PACOS Px1.2, the latter including the spray effects); and iodine in a multi-compartment containment (ThAI). The results are in general good, often close to results of mechanistic codes. Some results reach the limits of present knowledge, for instance on Molten-Corium-Concrete-Interaction and Direct Containment Heating. There is a lack of adequate model, like most codes, for hydrogen production during the reflooding of a degraded core. As to ASTEC benchmarking, the large increase of code robustness allowed performing 18 benchmarks with other codes on plant applications for diverse reactor types: PWR 900, Konvoi 1300, Westinghouse 1000, VVER-1000 and VVER-440. All the calculations reached their normal end, several ones coupling all modules, and various scenarios were analysed: SBLOCA, MBLOCA, LBLOCA, Loss of Steam Generator Feedwater and SBO. The main trends of results are similar to MELCOR or MAAP4 results. Some quantitative differences are due to modelling differences, i.e. on core degradation. First comparison on FP results was done but it will be extended to most scenarios in the next SARNET period. Good results were obtained on comparison with mechanistic codes such as ATHLET-CD, RELAP5-3D or COCOSYS. Exploratory calculations on VVER-440/V213 showed the ASTEC capabilities to evaluate the possibilities of In-Vessel Melt Retention. Physically reliable results were obtained on FP transport and behaviour in CANDU reactors; benchmarks with AECL codes will start in 2007. IRSN and GRS released in Dec.06 the new version ASTEC V1.3. Efforts focused on the first stage of improvements of the documentation as requested by the partners, mainly users manuals and guidelines. CEA specified and implemented in this version improvements of the DIVA models of corium behaviour in the lower head. For ASTEC adaptation to other reactor types than PWR, action plans were defined for CANDU by INR and the new partner AECL, and for BWR by KTH and IKE. Work on detailed specifications is ongoing. In June 06, IRSN organised the 2<sup>nd</sup> ASTEC Users' Club gathering 45 users. Very fruitful discussions took place, including the need to set up assessment guidelines. The V1 code evolution will now focus on feedback from IRSN PSA level2 on 1300 MWe reactors and from SARNET applications, and on a model of reflooding of a degraded core. In parallel, IRSN-GRS will take into account the code evolution needs as expressed by the SARNET users for the general specifications of the future series V2 of ASTEC versions.

## A. INTRODUCTION

The ASTEC Topic, coordinated by IRSN, is composed of 3 different Work-Packages:

- USTIA (**U**Sers Support, **T**raining, **I**ntegration and **A**daptation): IRSN-GRS delivery and maintenance of ASTEC versions, users’ training and support, model developments by partners, in particular for extension to VVER, BWR, CANDU, RBMK,
- PHYMA (**P**HYsical **M**odel **A**ssessment): ASTEC validation against experiments by partners,
- RAB (**R**eactor **A**pplications and **B**enchmarking): ASTEC benchmarks by partners with other codes on plant applications for PWR900-1300, Konvoi 1300, Westinghouse 1000, VVER-440, VVER-1000, CANDU, BWR, RBMK.

Twenty-eight partners (out of IRSN and GRS) worked on ASTEC in the third 18-months period (see Table 1 below).

Table 1: ASTEC Topic partners in JPA3

AECL (Canada)	EDF (France)	IVS (Slovak Rep.)	TRACTEBEL (Belgium)
ARCS (Austria)	ENEA (Italy)	JRC-IE (EC)	TUS-EI (Bulgaria)
AREVA-NP (France)	FZK (Germany)	JSI (Slovenia)	UJD (Slovak Rep.)
BNRA (Bulgaria)	GRS (Germany)	KTH (Sweden)	UJV (Czech Rep.)
BUTE (Hungary)	IKE (Germany)	LEI (Lithuania)	VEIKI (Hungary)
CEA (France)	INR (Romania)	NRG (Netherlands)	VUJE (Slovak Rep.)
CIEMAT (Spain)	INRNE (Bulgaria)	PSI (Switzerland)	
DIMNP (Italy)	IRSN (France)	RUB (Germany)	

## B. STATUS OF USTIA WORK-PACKAGE

### B.1 ASTEC code progress and perspectives

In the last 2 years, two major code versions and two update versions were delivered by IRSN and GRS: ASTEC V1.2rev0 in July 05, V1.2rev1 in Dec.05, V1.3rev0 in Dec.06 and V1.3rev1 in June 07. The main improvements of the V1.3 version focused on:

- The numerical robustness, which allows now all calculations of plant scenarios to reach their normal end,
- The capability of simulation of LBLOCA (Large Break Loss of Coolant Accident) and SGTR (Steam Generator Tube Rupture) scenarios,
- The code documentation as requested in priority by the partners, mainly users manuals and users guidelines.

The main new or improved models are:

- In CESAR module for Reactor Coolant System (RCS) thermalhydraulics: reflooding of a quasi- intact core; new model on condensation in pressuriser; general pump model for any Nuclear Power Plant (NPP); numerical implicitation of primary-secondary heat and flow exchanges; improvements of the sub-critical break flow correlation; new model for pressuriser spray,

- In DIVA module for core degradation: model improvement of corium behaviour in lower plenum (Ref.[1]); improved model for vessel mechanical failure; new simple model to account for slump of corium through the holes of the core lower plates; corium fragmentation during slump into lower plenum,
- In ELSA module for FP and structure materials release: improvements for Mo semi-volatile FP; improvements for structure (Fe, Ni, Cr, Zr) and control rod materials (Silver, Indium, Cadmium or SIC) during candling and from a corium molten pool in the vessel lower plenum; improvements for UO<sub>2</sub> fuel oxidation in air conditions,
- In SOPHAEROS module for FP/aerosol transport in RCS: improvements of gas chemistry database in MDB library (mainly for Mo, Te, Ru elements); FP vapour nucleation at arrival in containment; simulation of deposits in the RCS intact closed loops and account for multi-source as in parallel hydraulic channels like the core thanks to a new numerical solver,
- In CPA module for thermalhydraulics and aerosols in containment: new model for H<sub>2</sub> combustion in regime of fast turbulent deflagration; preliminary models of FP/aerosols retention through filters and leakage and retention through concrete walls; extension to 50 aerosol size classes for a better coupling with SOPHAEROS; model extension of junctions for water overflow via a lateral opening; extension of DRASYS zone model (for simulation of pressure suppression systems) by consideration of evaporation, condensation, dry heat transfer and fog depletion at pool water surface,
- In MEDICIS module for Molten-Corium-Concrete-Interaction (MCCI): improved coupling with CPA, accounting for radiative heat transfers in a semi-absorbent atmosphere in the cavity and thermal evolution of cavity walls.
- In IODE module for iodine in containment: revision of model of radiolytic oxidation of iodide into iodine in sump; model improvements on I<sub>2</sub> interaction with air radiolysis products.

The latest version V1.3rev1 can be considered as a reference version for applications within the next 2 years, both for IRSN PSA2 on French PWR1300 MWe reactors and for SARNET JPA4 period. Large efforts were done by IRSN and GRS on code validation in 2006, especially on RCS thermalhydraulics and on MCCI. Several current benchmarks by IRSN with CATHARE2 French reference thermalhydraulics code on diverse scenarios in PWR 1300 show a good agreement.

New V1.3 update versions may be released in 2007-08 depending on the feedback of users. Efforts will go on about the documentation improvement and about the users' tools, with Graphic User Interfaces for pre-processing of input decks and with visualisation of results with the GRS tool ATLAS. But the main significant model improvements are from now on done by IRSN and GRS in the future series of versions ASTEC V2. IRSN and GRS are currently working on the requirements and the specifications of this V2 series, accounting for the SARNET partners' needs as expressed in [Ref.2]. The plans are to aim at releasing the 1<sup>st</sup> version ASTEC V2.0 end of 2008, with, as main features, the models of the ICARE2 IRSN mechanistic code for core degradation and the capabilities for EPR applications.

## **B.2 Code maintenance and users' support**

The ASTEC page of the Advanced Communication Tool (ACT) on the SARNET Web portal was intensively used: periodic news on code progress, forums of discussion, surveys,

description of models, code input decks, technical reports, access to code updates... For support to the users, the use of the MARCUS Maintenance tool, based on Web and e-mails, has proved to be very efficient to make easier the dialogues between users and developers and to keep the full tracks of all users' requests and of solutions given by the Maintenance team. A new user-friendlier version of this tool will be released in May 07.

The 2<sup>nd</sup> Users' Club was organized by IRSN at Aix-en-Provence during 4 days in June 06. It gathered 45 participants from 27 organizations and 15 members of the IRSN-GRS ASTEC team. Very fruitful discussions took place between the users and the ASTEC team. A complete status of all current ASTEC applications done in the 3 WP was presented. The main user requests were discussed and the IRSN-GRS team presented the trends of code evolution in the short and long term. A questionnaire of satisfaction on the code was distributed to the partners during this meeting. It allowed underlining the needs of improvements: on a scale from 1 ("inadequate") to 4 ("very good"), code capabilities (models, validation) were evaluated as "good", as well as maintenance (reactivity, users support). Ease of code use (installation, post-processing, robustness) was evaluated as a little below "good". The lowest evaluation concerned code documentation as "medium". Training was organised by GRS in Nov.06 on the use of the ATLAS GRS graphic simulator for visualisation of ASTEC results.

### **B.3 Model developments by partners**

The CEA improvements of the models of corium behaviour in the lower head were included in ASTEC V1.3 (see more details in Ref.[1]). Validation of these improvements is planned in PHYMA in the next period (see § C). CEA is currently working on the capability to simulate the vessel external cooling for in-vessel melt retention (Ref. [1]).

### **B.4 Model adaptations to simulate other NPPs**

Progress was obtained on ranking of model adaptations to VVER-440, VVER-1000, CANDU, BWR and RBMK reactors:

- VVER-440 and VVER-1000: very few model adaptations are necessary since ASTEC has been applied to these reactors since several years. The main difficulty remains the precise representation of the complex VVER-440 in-vessel geometry with canisters around fuel bundles (as for BWR: see below). Some other specific needs will be solved by the current IRSN merging between DIVA and ICARE2, thus in ASTEC V2 versions.
- BWR: the KTH ranking underlined the priorities on DIVA model adaptations such as fuel channels and bypass (canisters), core support structures, geometry of B<sub>4</sub>C control blades, and vessel lower head with numerous penetrations. Other main evolution needs concern the CESAR module with for instance jet pumps. A preliminary analysis of other phenomena shows that the existing ASTEC models would be mostly applicable, so validation on BWR-specific experiments will be done in PHYMA. Note that, for all above reactor types, a generic need, valid also for PWR, concerns the implementation of models for behaviour of lower core structures such as plates with holes, which will be achieved in future V2 versions through the ICARE2 models.
- CANDU: the ASTEC applications in RAB frame to fission product behaviour in primary system and in containment showed the applicability of existing models. Some small adaptations of IODE module may be necessary. Meanwhile, INR investigations focused on the hard point that is the core degradation in a very specific geometry (horizontal cores, calandria...), especially in the early-phase before full core collapse and

debris/corium formation. Specifications of model adaptations have started but they will be reinforced by the AECL knowledge of MAAP4-CANDU models.

- RBMK: specifications of model adaptations wait for the outcomes of the exploratory CESAR-DIVA calculations that are going on in RAB frame for the early-phase of the accident before any melt interaction with graphite. The confinement CPA model adaptations that were identified as necessary in JPA1 are currently done by GRS.

### C. STATUS OF PHYMA WORK-PACKAGE

This activity consists of comparisons between ASTEC and experimental results (see Table 2).

Table 2 – Validation tasks performed in JPA3

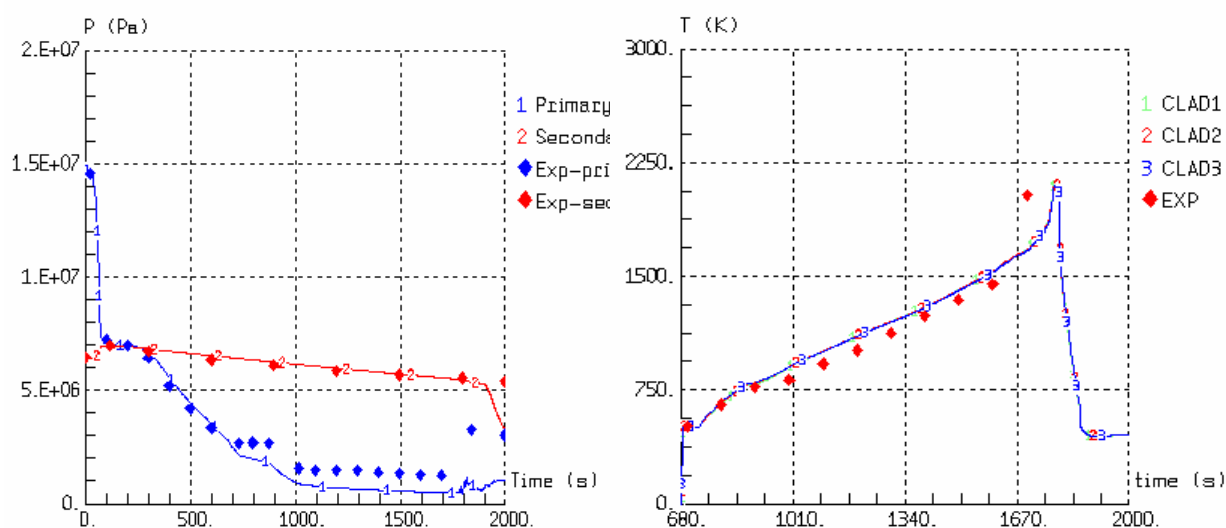
Module	Phenomena	Partner	Experiment
CESAR	RCS thermalhydraulics	IVS	PACTEL ISP 33 and T2.1
		ENEA	LOFT-LP-FP2
		BUTE	PMK2
DIVA	Core degradation	IKE	CORA13 and Phébus FPT4
	Core degradation (VVER)	INR	CORA-W2
	Core reflooding	FZK	QUENCH-08, 11
	Core reflooding	INRNE	QUENCH-11
	Corium fragmentation	IRSN	FARO L14-L28
	Vessel lower head mechanics	IRSN	OLHF-1
ELSA	FP release	JRC	Phébus FPT0-FPT1
	FP release from molten pool	CEA	COLIMA
	FP release	ENEA	LOFT-LP-FP2
MEDICIS	MCCI	ARCS	ACE L4
		IRSN-GRS	OECD-CCI2, BETA 2.1, 2.3, 5.2
		UJV	OECD-CCI2
SOPHAEROS	FP transport in RCS	JRC	Phébus FPT0-1
		UJV	Phébus FPT1-2
		TUS	COLIMA
		JRC	STORM SR
CPA	Containment thermalhydraulics and aerosols	RUB	PACOS Px1.2
		JRC	Phébus FPT0-1
		JSI	LACE LA4
IODE	Iodine in containment	CIEMAT	Phébus FPT2
		GRS	ThAI Iod10-11-12
All	Integral experiment	INR	Phébus FPT2
		TUS-EI	Phébus FPT1

The main conclusions on ASTEC V1.2 validation are summed up below.

The total volume of partners' work represents about 7 persons/year. Five domains are covered: In-vessel phenomena (thermalhydraulics and degradation phenomena); ex-vessel corium (MCCI, corium cooling, DCH); containment behaviour; source term; and Phébus FP integral experiments. ASTEC results are also compared to results of detailed codes such as ICARE/CATHARE, ATHLET-CD, SCDAP/RELAP5, COCOSYS, TONUS, CONTAIN...

### *RCS thermalhydraulics (CESAR module)*

Good results have been obtained on the integral test LOFT-LP-FP2 (Fig.1) and on two PACTEL experiments in geometry of VVER-440 circuits. This is important since LOFT is an integral test, thus near the reactor conditions, and since the PACTEL facility covers various thermalhydraulic flow regimes. A discrepancy remains on PMK2 SBLOCA transient after hydro-accumulator injection: investigations must go on to clarify the origin of this difference. These good results have been confirmed by the results of the very intensive validation work by IRSN and ENEA on 3 BETHSY CEA integral tests (Ref.[3]) and by IRSN on analytical CEA experiments (SUPER-MOBY-DICK, PATRICIA GV, COSI...).



**Fig.1:** CESAR-DIVA ENEA application to LOFT-LP-FP2: primary and secondary pressure **Fig.2:** CESAR-DIVA ENEA application to LOFT-LP-FP2: clad temperature at axial mid-level

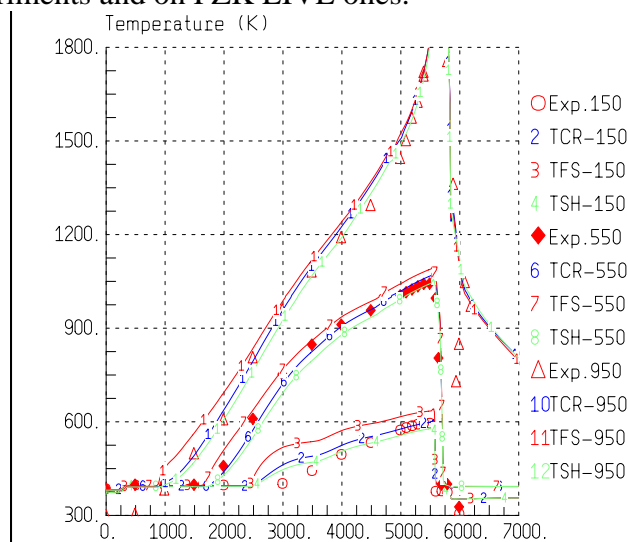
### *Core degradation (DIVA module)*

Many partners' efforts focused on core degradation validation. The results are good for early-phase models of core heat-up, oxidation and hydrogen total production (before quenching) on CORA-13 and W2, QUENCH-11, and LOFT-LP-FP2 experiments (Fig.2). But model improvements are needed for the reflooding phase where the hydrogen production is largely underestimated, like with all other codes.

Improvements on the thermalhydraulic phase of reflooding of quasi-intact bundles have been observed on QUENCH and CORA experiments with respect to ASTEC V1.1 version. ASTEC V1.2 is able to simulate the QUENCH-11 experiment reasonably, especially using a reduced corium candling velocity with respect to the default value. But despite the good agreement on temperatures (Fig.3) and partially on bundle damage, the total hydrogen mass is less than half of the experimental value due to an under-prediction in the reflooding

phase, similarly to the other codes (cf. the current benchmark in the CORIUM Topic). This is also the conclusion of work on CORA-13 and LOFT-LP-FP2 experiments.

For late-phase models, the results are good: debris bed melting (Phébus FPT4, using the magma-debris models for 2D corium relocation instead of 1D candling), corium fragmentation at slump into vessel lower plenum (FARO), and vessel lower head mechanics (OLHF1). Validation work will go on in 2007 in PHYMA frame by CEA on KTH SIMECO experiments and on FZK LIVE ones.

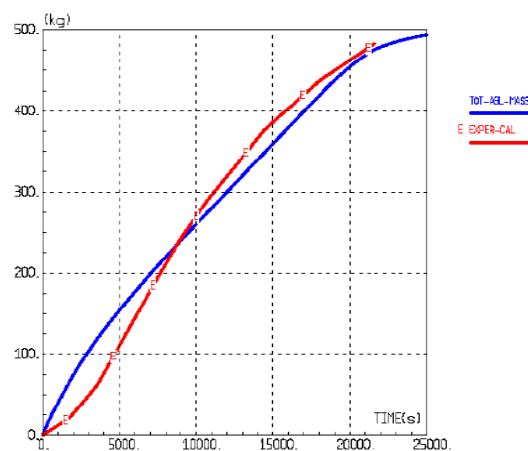


**Fig.3:** Comparison of ASTEC and experimental (symbols) QUENCH-11 temperatures at different axial levels (FZK work)

Note that the three independent DIVA applications on the CORA experiments show the absence of user-effect since all results are very close together.

#### **MCCI (MEDICIS module)**

MEDICIS has proven to be robust, flexible and fast running. The module is now able to simulate most of the relevant phenomena. The validation on ACE, BETA and OECD-CCI2 experiments (Fig.5) shows that using a fixed set of model parameters, in particular the corium solidification temperature near the liquidus one and using standard heat transfer correlations, consistent results can be obtained.



**Fig.4:** Comparison of ASTEC and experimental OECD-CCI2 mass of ablated concrete (UJV work)

CCI2-2-Var.WOB

For experiments with stratified thermite melts such as BETA, the correct behaviour can be simulated by defining the heat transfer coefficients as function of inclination of the

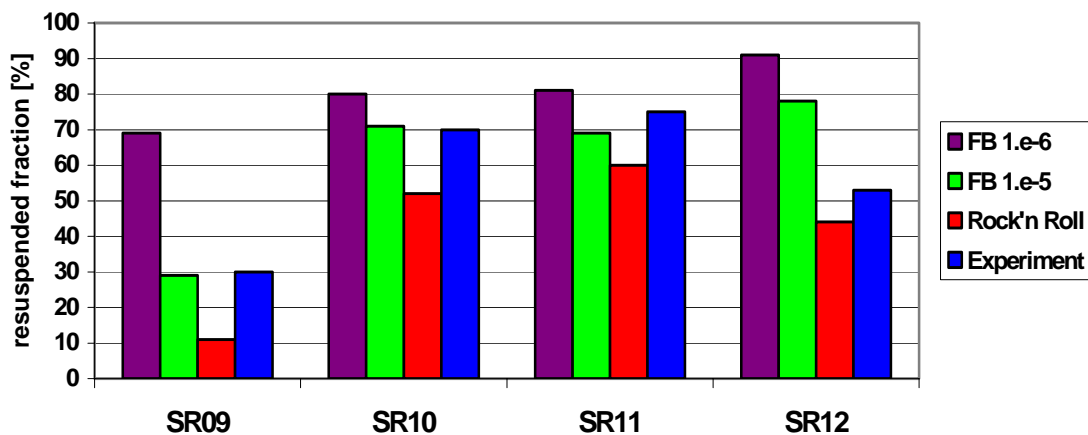
interface. A benchmark on COMET-L2 and L3 experiments was carried out in the Corium Topic, involving MEDICIS (Ref.[4]). The application to the ACE L4 experiment shows the module applicability to VVER concrete and to a two-layer substrate. The limits of knowledge are now reached in the MEDICIS validation where the models have reached the state of the art. Further experimental results are necessary to progress, in particular on heat flux spatial distribution (radial/axial) and on oxide/metal heat flux. IRSN interpretation of CEA ARTEMIS (stimulant corium) and VULCANO (real corium) experiments is under way. Analysis work is also under way in the frame of the Corium Topic.

*FP and structure material release from the core (ELSA module)*

The integral release of volatile FP is well reproduced on Phebus FPT0 and FPT2, but the kinetics are overestimated. Sensitivity studies were done on FPT0 and FPT2 about the influence of the distribution of fuel grains on release of volatile and semi-volatile FP: they concluded to a weak influence of a polydisperse distribution, which is not surprising at least for FPT0 since release is not governed by intra-granular diffusion. A reasonable agreement was obtained for FP release from a degraded geometry such as debris bed and molten pool in Phebus FPT4. The same conclusion can be drawn from the application to LOFT-LP-FP2 for the transient phase before bundle reflooding.

*FP/aerosol transport in RCS (SOPHAEROS module)*

The application to STORM experiments shows that the 2 ASTEC existing models encompass the measurements of the final resuspended fraction (Fig.6): there is the need of further improvement of aerosol mechanical resuspension model (under way in the Source Term Topic).



**Fig.5:** SOPHAEROS application to STORM SR experiments: comparison of different models with experimental data (JRC-IE work)

Validation on Phebus FPT0, FPT1 and FPT2 shows a general agreement on the total amount of deposits in the circuit. But, despite a slight improvement with respect to the previous code version, there is an overestimation of deposits in the Steam Generator and an underestimation in the hot leg. The crucial importance of gas phase chemistry has been underlined in the Phebus applications, in particular for iodine behaviour (Ref.[5]). SOPHAEROS has proven to be a very useful tool for such analyses of aerosols and vapour behaviour simultaneously with speciation. A very preliminary validation on the COLIMA experiment concerning FP release and transport from a VVER corium was performed; work will go on in 2007. The main need of model improvement is RCS iodine chemistry in general.

IRSN work goes on continuously about MDB gas databank review and about modelling of kinetics of iodine chemistry, in close relation with the CHIP IRSN new experiment.

***Thermalhydraulics and aerosol behaviour in containment (CPA module)***

Good general results are obtained for CPA module validation (see Ref.[6] for more details). For containment thermalhydraulics, good agreement is obtained on the LACE LA4 test. The thermalhydraulic processes including the distribution of the helium tracer were also correctly calculated with CPA for 3 ThAI multi-compartment tests. For effect of containment spray systems on thermalhydraulics, CPA reproduces in a satisfactory way the temperatures and pressure in the large-scale PACOS Px1.2 experiment. It confirms the results obtained previously by IRSN and GRS on CSE-A10 and NUPEC M7.1 spray experiments.

For aerosol depletion, agreement on dry aerosol concentration in the LACE LA4 test vessel is correct, using voluntarily a very rough containment nodalisation. However, the simulated trend of the decrease of the soluble (CsOH) aerosol concentration is different from the trend as observed in the experiment: this decrease is very sensitive to the correct simulation of atmosphere saturation, which was not perfectly reached in the calculation. JRC/IE investigated on the Phebus applications the influence of the solubility factor on the average aerosol diameter.

***Iodine behaviour in containment (IODE module)***

In essence, IODE results show no major differences with respect to Phebus FPT2 data (see Ref.[7] for more details). The module is able to capture the iodine evolution in the gas phase when the radiolytic oxidation of gaseous  $I_2$  is considered. For the first time, validation of adsorption/desorption IODE models was done in multi-compartment large-scale experiments such as ThAI. Qualitatively, the distribution of  $I_2$  in the vessel is calculated correctly for all tests, especially the concentration differences of several orders between the compartments in the stratification phases. The significantly slower or incomplete homogenisation of  $I_2$  as compared to the helium behaviour in the vessel during the mixing phase is also well reproduced. Quantitatively, the agreement is good under dry conditions but ASTEC overestimates the gaseous  $I_2$  concentrations when the relative humidity is high.

***Next stage of work***

The next work in 2007 will extend to In-vessel late-phase experiments SIMECO and LIVE, to iodine validation on Phébus FP and to BWR-specific experiments. Work will continue on spray (TOSQAN, MISTRA) and on MCCI (OECD-CCI and COMET).

**D. STATUS OF RAB WORK-PACKAGE**

A comparison of 18 ASTEC V1.2rev1 plant applications was performed with integral codes MELCOR and MAAP and detailed codes such as ATHLET-CD and SCDAP/RELAP5 (Table 3). They concerned 7 different reactor types: PWR 900, Westinghouse 1000, Konvoi 1300, VVER-1000, VVER-440/V213, CANDU and RBMK. The total volume of work by partners represents about 10 persons/year. A first outcome of these 18 benchmarks is the significant increase of code numerical robustness, in particular the CESAR and DIVA modules. All applications reached their normal end in a once-through calculation. In some cases, a specific management of time step was necessary for accounting for the intense hydro-accumulator injection after primary circuit depressurisation. ASTEC computing time is globally around real accident time. Some cases run below real time (about half of real time for PWR 900 reactors) while Konvoi 1300 cases run much above real time. Some sensibility

studies have showed the consistency of ASTEC results: on core axial meshing and on some model parameters on core degradation. The other conclusions of RAB calculations are summed up below.

Table 3 – Benchmarking tasks performed in JPA3

Reactor	Sequence	Partner	Modules	Code for comparison
West.1000	SBLOCA	TRACTEBEL	CPA (containment)	MELCOR
Konvoi 1300	MBLOCA 200 cm <sup>2</sup>	GRS	All	MELCOR
		IKE	All (focus on In-vessel)	ATHLET-CD
	NRG	All	MAAP4	
	MBLOCA 80 cm <sup>2</sup>	GRS	All	MELCOR
PWR 900	Loss of SG Feedwater	AREVA-NP	All	MAAP4
		ENEA	All	MELCOR
	SBO, MBLOCA	EDF	All	MAAP4
VVER- 1000	LBLOCA	UJV	CPA (containment)	MELCOR
	SBO	INRNE, TUS	All	MELCOR
VVER- 440/213	SBO, MBLOCA	VUJE	All	MAAP4/VVER
	SBO	IVS	All	RELAP5-3D, MAAP4/VVER
	SBO	UJD	CESAR-DIVA- SOPHAEROS-CPA	MELCOR
	SBLOCA	VEIKI	CESAR-DIVA-CPA	MAAP4/VVER
	MBLOCA	BUTE	CESAR-DIVA-CPA	APROS
CANDU	LOCA 20%	INR	SOPHAEROS-CPA-IODE	-

#### *Front-end thermalhydraulic phase*

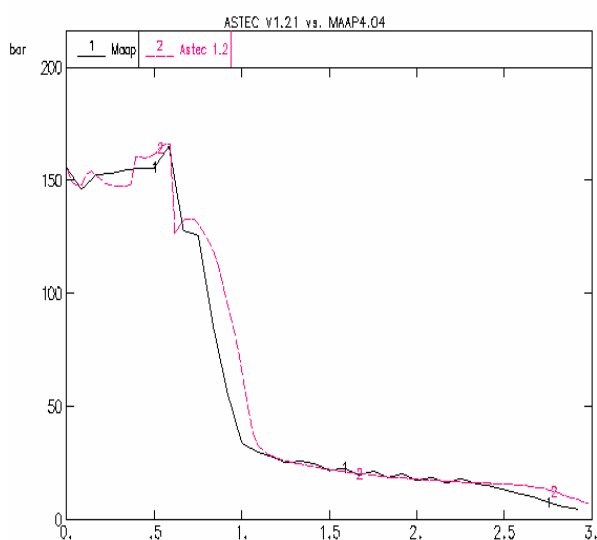
The agreement is good in most cases on evolution of primary and secondary pressure (Fig.6, 7, 8 and 10), in particular with mechanistic codes such as RELAP5-3D or ATHLET-CD (Fig.8). The remaining differences between the integral codes may come from differences on the initial water inventories, i.e. on differences between input decks, which could not be totally suppressed. For VVER case, the IRSN recommendation to users to adopt a more detailed nodalisation of the SG (3 horizontal volumes for the primary side) led to a large improvement in the results. A too simple SG nodalisation (1 volume in secondary side) led to an earlier SG dryout with respect to results of mechanistic codes such as RELAP5-3D for instance. In a few cases, differences on the start of core heat-up were observed: the reason was larger primary coolant leaks from primary circuit in the ASTEC calculation that need to be investigated further. Results on pressuriser level should likely be improved with the latest models in V1.3rev1.

#### *Core degradation phase*

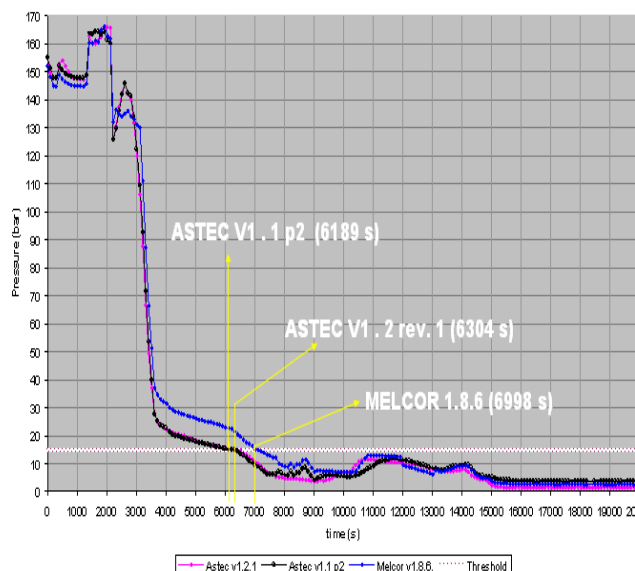
In most cases, the agreement was good on core heat-up until the start of strong fuel rod oxidation, and also on the early-phase of core degradation. Some users indicated an

earlier start of core degradation and faster progress in ASTEC than in MELCOR. This was sometimes due to differences in the core water inventories, which remains to be investigated further. Divergences appear on kinetics of late-phase core degradation, mainly due to different models (candling in ASTEC, mixed 1D/2D relocation in MELCOR and MAAP4). For instance, with respect to MAAP4, core degradation processes were more gradual in ASTEC than in MAAP (with the latter, corium accumulation in a molten pool within the core and then instantaneous slump into the lower plenum). The absence in ASTEC of modelling of corium retention on core support plates influences too the characteristics of the core slump into the lower plenum. Nevertheless, differences on time and location of vessel failure were not significant in most cases: mostly within a difference by  $\pm 15\%$ . In some VVER cases, due to the complexity of vessel geometry with fuel followers, the differences were higher (up to 30%). The conclusion is the same for corium masses in lower plenum at time of vessel failure. For instance on PWR900 cases, the agreement on corium composition for the first pour was very good.

A successful use of 2D magma-debris relocation models was obtained in a VVER-440 application up to RPV failure. Note that these models cannot be recommended for extended use because they are being updated in ASTEC V2 frame by IRSN. Their use gave a much later time of RPV failure (8 hours later) than with candling. But this conclusion must not be considered yet as applicable for all scenarios and all reactor types. The capability of ASTEC to simulate the in-vessel melt retention (IVR) was showed through applications to the VVER-440 case (Ref.[1]).



**Fig.6:** LFW-SG PWR 900 primary pressure ASTEC/MAAP4 (AREVA-NP work)

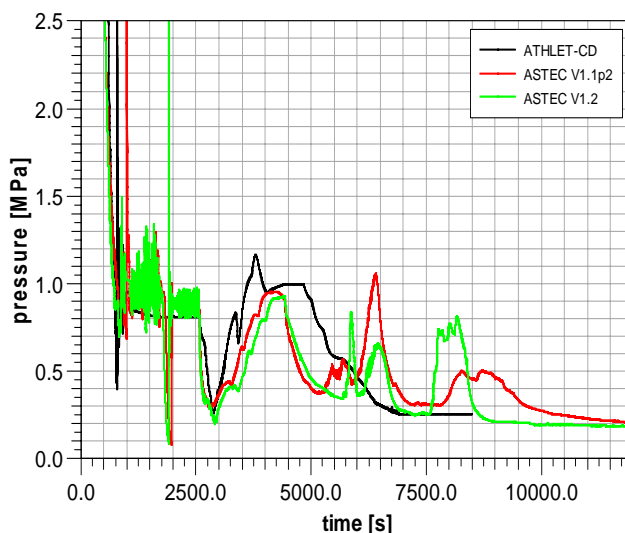


**Fig.7:** LFW-SG PWR 900 primary pressure ASTEC/MELCOR (ENEA work)

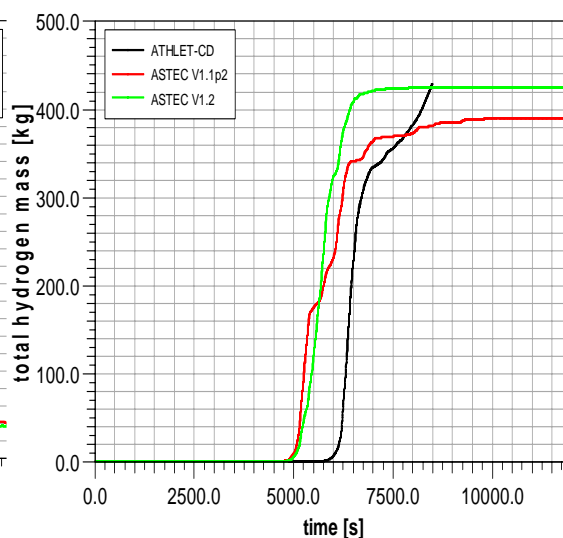
### ***Hydrogen production***

The agreement between all codes was much better than with previous ASTEC versions that clearly underestimated the hydrogen production. In general, the differences on the total amount of hydrogen in-vessel production are limited (Fig.9 in PWR case and 11 in VVER-440 case), mostly lower than  $\pm 15\%$ . The maximal difference reached 30% in one application. A missing model in ASTEC V1.2 of corium fragmentation during slump into lower plenum (but now in ASTEC V1.3) leads to not calculate a supplementary production (around 30 to 50

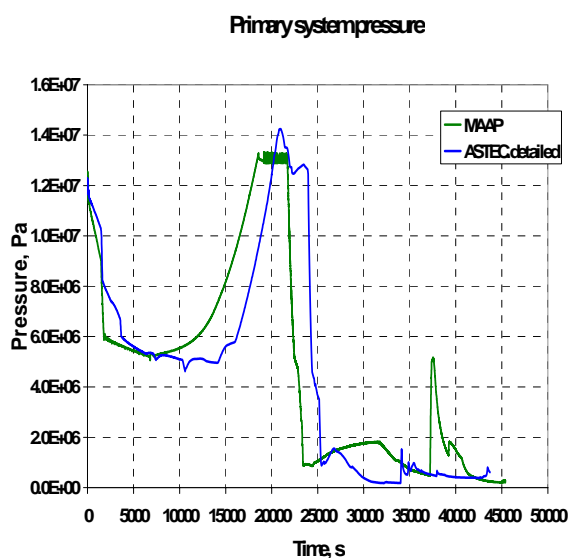
kg). Steel oxidation was not considered in the PWR900 calculations: its account (already possible with V1.2 version but not selected by the users) will increase the ASTEC results. On hydrogen production kinetics, in most cases the rate of production is similar in ASTEC and MELCOR, and higher in MAAP4. Some differences on time of start of oxidation appeared between the code results on PWR900 scenarios: in some calculations, oxidation does not start because the core is cooled by discharge of hydro-accumulators before it is heated up significantly. These differences seem linked to different nodalizations or model options (such as isothermal or adiabatic hydro-accumulators discharge) that will have to be further investigated.



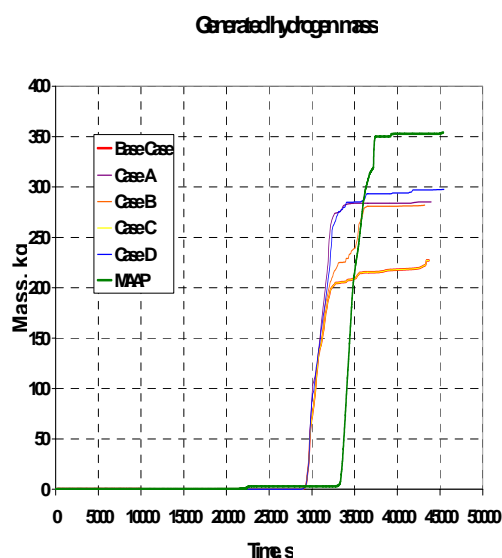
**Fig.8:** MBLOCA Konvoi 1300 primary pressure ASTEC / ATHLET-CD (IKE work)



**Fig.9:** MBLOCA Konvoi 1300 in-vessel  $H_2$  ASTEC / ATHLET-CD (IKE work)



**Fig.10:** SBLOCA VVER-440 primary pressure ASTEC / MAAP4-VVER (VEIKI work)



**Fig.11:** SBLOCA VVER-440 in-vessel  $H_2$  ASTEC / MAAP4-VVER (VEIKI work)

### *Containment behaviour*

The results of CPA stand-alone or coupled calculations show in general a good agreement with other codes on thermalhydraulics in the containment. In some cases,

improvements of input decks and nodalisation allowed to improve considerably the results. The remaining differences can be considered as acceptable. Several users investigated their origin through an analysis of the heat transfer models (convection, condensation/evaporation) but no firm conclusion was yet obtained. The numerical difficulties that were seen when using with ASTEC V1.1 the DRASYS models for VVER-440/V213 have disappeared. For non-condensable gases injected to the containment, the agreement with MELCOR was excellent. The agreement for deposition of aerosol fission products was not so good, due to the differences in thermalhydraulic results.

### ***FP behaviour***

Half of the applications activated the FP modules and reached their normal end but only few have detailed FP results and compared them with other code results. Note that the problems with code crashes that occurred with SOPHAEROS in ASTEC V1.1 have totally disappeared due to improvements of SOPHAEROS numerical solver. The available comparisons show a good agreement on volatile FP release and a less good agreement on semi-volatile FP such as Ba and Mo. Note that in the latest version ASTEC V1.3, models for release of semi-volatile FP have been improved; they lead to a much higher Mo release and the Ba results are consistent with the whole interpretation of Phebus FP experiments. Higher values of aerosols release were observed with ASTEC in one Konvoi 1300 calculation than with MELCOR but also higher deposits in RCS, which finally led to the same order of magnitude of aerosols in containment. Such comparison will be completed for other calculations in the next months.

### ***MCCI***

The main outcome is the difference that is observed for once-through scenario calculations on the mass of corium involved in MCCI in the cavity. Since ASTEC V1.2rev1 stops the core degradation calculation at time of vessel failure, the corium mass involved in MEDICIS calculations is often much lower than the one in the other integral codes where this core degradation calculation goes on. ASTEC V1.3rev1 allows continuing the DIVA calculation after vessel failure, which will imply much higher and realistic corium masses in MCCI. Let us indicate that a MCCI reactor benchmark is planned in the Corium Topic in the next period.

### ***Applications to CANDU and RBMK reactors***

The exploratory calculations of SA sequences in a CANDU reactor went on with a coupled calculation SOPHAEROS-CPA-IODE of FP behaviour in Primary Heat System (PHT) and in containment. They confirmed the literature results that CANDU PHT works as a filter for a big part of FPs and associated species. Other results were judged as physically reliable: effects in containment of spray system, first in direct mode and then in a recirculation mode, and FP distribution in the containment rooms. As for RBMK, coupled CESAR-DIVA calculations on primary circuit thermalhydraulics and early-phase degradation of a fuel channel for a scenario of Main Circulation Pump header rupture are under way.

### ***Next stage of work***

The next stage of partners' work, using ASTEC V1.3, will mainly be devoted to extend all benchmarks to FP modules (FP release and transport in the RCS) or to activation of other safety systems or procedures than modelled up to now, or possibly to new scenarios like LBLOCA and SGTR. Some studies will focus on parts of the scenario only, e.g. MCCI, using the same well-defined initial and boundary conditions. Sensitivity analyses will also be

performed on the most influent model parameters for a limited set of important sequence results.

#### **E. LINKS WITH OTHER SARNET TOPICS**

Work is going on in the 3 Topics Corium, Containment and Source term to agree on new proposals of modelling to be implemented in next ASTEC versions. Most of them come from the Source Term topic: for instance SIC release from control rod, Ru transport in RCS and iodine mass transfer between containment sump and gas phases. In the PSA2 Topic, general requirements for the use of integral codes in PSA2 will be issued in the next period and the feasibility of ASTEC coupling with dynamic PSA2 will be investigated.

#### **F. CONCLUSIONS**

Noticeable progress was observed on ASTEC results in JPA3. New models were implemented for the first time into the code. Validation has shown good results for most models, except for reflooding of a degraded core, whereas some models (such as MCCI) have reached the limits of the present international knowledge. Benchmarks on plant applications showed the code capability to simulate complete sequences in PWR and VVER, including FP behaviour up to iodine behaviour in containment, as well as parts of sequences in CANDU reactors. Good progress was also observed on ASTEC numerical robustness. The general trends of results are similar for the different integral codes but some differences on results appear due to differences on models. But it must be kept in mind that the objective of these codes is to catch the main trends and the orders of magnitude of phenomena.

In the next period, the analysis will mainly focus on FP results. Comparisons with mechanistic codes will go on since several examples underlined their high importance as references. Concrete action plans were set up for BWR and CANDU model adaptation and benchmarks: work will intensify in 2007-08 on these aspects. Some efforts were made by partners to account for experimental uncertainties in the validation process but these efforts will have to be reinforced in the next period. The Topical Coordinator will soon release a report on assessment guidelines. More sensitivity analyses will also have to be done for benchmarking on plant applications.

The current preparation by IRSN-GRS of the future series of versions V2 accounts for the feedback of the work performed up to now by partners and for their requirements on code evolution. IRSN has now almost finished merging the DIVA module with the ICARE2 IRSN core degradation mechanistic code. The 1<sup>st</sup> version ASTEC V2.0, planned for end of 2008, will include advanced models of core degradation and be applicable to EPR. Meanwhile, some models will be proposed in other SARNET topics for implementation so that ASTEC becomes more and more the European repository for SA knowledge.

#### **ABBREVIATIONS**

ACT	Advanced Communication Tool
BWR	Boiling Water Reactors
EPR	European Pressurised Reactor
FP	Fission Products
ISP	OECD International Standard Problem
JPA	Joint Program of Activities

LBLOCA	Large Break Loss of Coolant Accidents
MBLOCA	Medium Break Loss of Coolant Accident
MCCI	Molten-Corium-Concrete-Interaction
MDB	ASTEC Material Data Bank
NPP	Nuclear Power Plant
PSA2	Probabilistic Safety Analysis level 2
PWR	Pressurised Water Reactors
RBMK	Reaktor Bolshoy Moshchnosti Kanalniy: Russian acronym for Large Power Reactors with Pressure Tubes
RCS	Reactor Coolant System
RPV	Reactor Pressure Vessel
SBLOCA	Small Break Loss of Coolant Accidents
SBO	Station Black-Out scenario
SGTR	Steam Generator Tube Rupture
SIC	Silver-Indium-Cadmium alloy
VVER	Vodo Vodjannyj Energetitcheskij Reaktor: Russian acronym for Water-cooled Water-Moderated Power Reactor

## REFERENCES

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- [1] "ASTEC application to In-vessel Melt retention", D.Tarabelli, G.Ratel, R.Pelisson, P.Matejovic, M.Barnak, ERMSAR-2007, Session "Code and method development activities", Karlsruhe, 12-14 June 2007
- [2] "Synthesis of needs of ASTEC code evolution by SARNET partners", J.P. Van Dorsselaere et al., Report SARNET-ASTEC-D34, March 2006
- [3] "Validation of CESAR thermalhydraulic module of ASTEC V1.2 code on BETHSY experiments", N.Tregourès, G.Bandini, L.Foucher, J.Fleurot, P.Meloni, ICONE-15, Nagoya, 22-26 April 2007
- [4] "Simulation of Molten Corium Concrete Interaction in a Stratified Configuration: the COMET-L2-L3 Benchmark", B.Spindler, K.Atkhen, M.Cranga, J.Foit, M.Garcia, W.Schmidt, T.Sevon, C.Spengler, ERMSAR-2007, Session "Corium issues"
- [5] "Towards a better understanding of iodine chemistry in RCS of nuclear reactors", N.Girault, C.Fiche, A.Bujan, J.Dienstbier, ERMSAR-2007, Session "Source Term issues"
- [6] "Recent activities on validation of modeling of thermal-hydraulic and aerosol phenomena in ASTEC CPA", I.Kljenak, M.Dapper, M.Bendiab, M.K.Koch, J.Dienstbier, L.E.Herranz, J.Fontanet, ERMSAR-2007, Session "Code and method development activities"
- [7] "Interpretation of containment chemistry results from Phebus test FPT2", S.Dickinson, N.Girault, L.E. Herranz, P.Raison, ERMSAR-2007, Session "Source Term issues"