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Patrick Chatelard, Laurent Laborde. Synthesis of the ASTEC V2.2 code validation vs. experimental data. The 10th European Review Meeting on Severe Accident Research (ERMSAR-2022), ERMSAR, 2022, KARLSRUHE, Germany. hal-03677729

**HAL Id: hal-03677729**

**<https://hal.science/hal-03677729>**

Submitted on 24 May 2022

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## SYNTHESIS OF THE ASTEC V2.2 CODE VALIDATION AGAINST EXPERIMENTAL DATA

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### ABSTRACT

Significant efforts are being continuously put for many years into the assessment of the severe accident integral code ASTEC developed by IRSN, through comparison either with results of the most important international experiments or with results of other severe accident simulation codes. These efforts are done in priority by IRSN code developers, and then also by partners, in particular in the frame of the on-going SNETP-NUGENIA ASCOM project. This paper relates to the ASTEC V2.2 version that was released in 2021 to the ASTEC community. It aims at providing a synthesis of its assessment vs. experimental data. For that purpose, the ASTEC validation strategy and ASTEC V2.2 validation matrix are firstly introduced. Then some V2.2 results are discussed for a few representative applications that cover diverse aspects of in-vessel and ex-vessel severe accident phenomenology. Finally, main lessons drawn from this large validation task are summarized, along with an evaluation of the current physical modelling relevance and how it relates to the state-of-the-art. Based on those outcomes, the ASTEC V2.2 validity domain is specified and some prospects for further improvements are put forward.

### KEYWORDS

ASTEC, severe accident simulation code, validation

### 1. INTRODUCTION

The Severe Accident (SA) integral code ASTEC [1], developed by the French Institut de Radioprotection et de Sûreté Nucléaire (IRSN), aims at simulating an entire SA sequence in a nuclear water-cooled reactor from the initiating event up to the release of radioactive elements out of the containment. The 3<sup>rd</sup> major version of the ASTEC V2 series, V2.2 [2], was released in 2021 to the ASTEC community. With respect to former V2.1 [3], main progress was on physical models and new code capabilities, but also on physico-numerical issues (improved robustness and reduced sensitivity to cliff-edge effects). As to the physical models' validation, significant efforts are being continuously put for many years into the assessment of the code through comparison either with data of the most important international experiments or with results of other SA simulation codes. These efforts are done in first priority by IRSN code developers, and then also by partners, notably in the frame of the on-going SNETP-NUGENIA ASCOM collaborative project [4]. In continuity to former validation tasks [5] [6], the ASTEC V2.2 assessment has been carried out against a wide experimental data covering main SA physical phenomena while following up in parallel the full scale code-to-code benchmarks activity on various transients for different types of LWRs.

The present paper is exclusively focused on the validation vs. experiments, meaning that the ASTEC assessment by means of code-to-code benchmarks on reactor SA sequences is not tackled in the following. This paper recalls firstly the general approach for ASTEC V2 validation before displaying the composition of the ASTEC V2.2 validation matrix. Some validation results are then discussed for a few representative applications that cover both in-vessel and ex-vessel processes. Finally, the main lessons drawn from this

quite large validation task are summarized, along with an evaluation of the current physical modelling relevance and how it relates to the current state-of-the-art. Based on those outcomes, the ASTEC V2.2 validity domain is specified and some prospects for further improvements are put forward.

## 2. VALIDATION STRATEGY FOR THE ASTEC V2 SERIES

ASTEC V2.2 benefits of course from the intensive validation of former V2.1, V2.1.1 and V2.2b versions that was carried out between 2015 and 2021 not only by IRSN but also by foreign partners in the frame of the successive CESAM FP7 [7] and NUGENIA ASCOM projects (e.g. [8] [9] [10] [11] [12]). That being said, the ASTEC V2.2 validation is supported by its own large set of French and international experiments that cover most aspects of SA phenomenology. While most of the experiments that were analyzed few years ago with V2.1 have been again recalculated with V2.2, the ASTEC V2 validation matrix was being enlarged from time to time in order to continuously account for the newly available experiments in the field of SA. The V2.2 validation matrix includes three different types of experiments: 1) Separate-Effect Tests (SETs) focused on a single phenomenon; 2) Coupled-Effect Tests (CETs) addressing a few phenomena; 3) integral applications that allow checking the completeness of the modeling with respect to significant phenomena and their coupling. For the latter, one may notably mention the TMI-2 and Fukushima-Daiichi accidents, and four integral experiments of the Phébus FP program that coupled all the modules involved for the primary circuit and the core, and for the containment. Overall, the ASTEC V2.2 validation matrix comprises more than 300 experimental tests conducted at various scales in more than 50 different in-pile and out-of-pile facilities worldwide. The contents of the ASTEC V2.2 validation matrix is displayed below in Tables I and II, for in-vessel and ex-vessel processes, respectively.

**Table I. Main experiments used for the validation of the ASTEC V2.2 in-vessel physical models**

Domain	Physical phenomena	Facility/ Program	Experiments
<b>Thermal-hydraulics in primary and secondary circuits</b>	Two-phase flow, heat transfers, wall friction, interface friction, phase separation, condensation...	Moby Dick, Patricia GV, Rebeca, Cosi, Coturne...	Numerous SETs
	Complete T/H behavior in the RCS	BETHSY	#9.1b ( <i>ISP-27</i> ), #5.2e, #6.4, #6.9
<b>Core degradation</b>	Boron carbide oxidation	VERDI	16 tests
	Zircaloy oxidation under air flow	MOZART	7 tests
	Corium oxidation	SKODA-UJP	18 tests
	Reflooding of intact core	PERICLES	48 tests
	Reflooding in debris bed	PRELUDE	12 tests
	Reflooding in debris bed (larger scale)	PEARL	33 tests
	Core degradation (early & late phase)	PHEBUS FP	FPT1, FPT2, FPT3
	In-core debris bed & molten pool behavior	PHEBUS FP	FPT4
	Core reflooding	QUENCH	#3, #11, #10, #16
<b>Corium behaviour in the lower head</b>	Delayed core reflooding	QUENCH	#17
	Corium-water interaction	FARO	#14 ( <i>ISP-39</i> ), #24
	Late phase degradation	LIVE	L1, L6
	Corium-structure interactions	MASCA	21 tests
<b>RCS and vessel processes</b>	Vessel lower head thermal-mechanical loading	OLHF	#1
	RCS thermal-hydraulics & vessel degradation	TMI-2 real accident	Phases 1 to 4

<b>Fission products and aerosols behaviour in the RCS</b>	FP release from fuel	VERCORS	#4, #5
	FP release from fuel	VERDON	#1, #5
	Diffusiophoresis aerosol deposition	TUBA	TD07
	Interaction between FP vapor & aerosols	FALCON	#18 (ISP-34)
	Deposition & resuspension of aerosols	STORM	#11 (ISP-40)
	Iodine transport & chemical behavior (speciation) in the RCS	CHIP/CHIP+	12 tests
	Ruthenium transport & chemical behavior (speciation) in the RCS	START	6 tests

Table II. Main experiments used for the validation of the ASTEC V2.2 ex-vessel physical models

Domain	Physical phenomena	Facility/Program	Experiments
<b>Th.-hydraulics in ERVC circuit</b>	Th.hydraulics in vessel external cooling circuit ( <i>case of IVR strategy implementation</i> )	ULPU V	#10
<b>Thermal-hydraulics in containment</b>	Containment T/H and H <sub>2</sub> distribution	TOSQAN	ISP-47
	Cont. T/H and H <sub>2</sub> distribution	MISTRA	ISP-47
	Filmwise condensation on containment walls	TOSQAN	#1, #9b
	Contain. T/H with spray activation	TOSQAN	#115
	Contain. T/H, H <sub>2</sub> stratification with spray	PANDA	PE1
	Contain. T/H and H <sub>2</sub> stratification	THAI HM	#2
	Contain. T/H and H <sub>2</sub> deflagration	THAI HD	#22 (ISP-49)
	Contain. T/H and H <sub>2</sub> PAR behavior	THAI HR	#1, #11, #12, #22
	Flame propagation (H <sub>2</sub> -air mixture)	ENACCEF	#153
	Flame propagation (H <sub>2</sub> -air-steam mixture)	ENACCEF	ISP-49, XH2
<b>Th.-hydraulics and aerosols in containment</b>	Cont. T/H and aerosols behavior	VANAM	M3 (ISP-37)
	Cont. T/H and aerosols behavior with spray	CSE	A10
	Filtration by pool scrubbing	PSI	6 tests
<b>Iodine and Ruthenium chemistry in containment</b>	I <sub>2</sub> formation in sump and adsorption surfaces	CAIMAN	#97-02 (ISP-41)
	Iodine volatility in the containment	PHEBUS RTF	#1, #3, #6
	I <sup>-</sup> radiolytic oxidation, mass transfer on paints	SREAS	#01
	Iodine release from Epoxy paint under irradiation	EPICUR LD	#1, #2, #3, #5, #6
	CH <sub>3</sub> I desorption from Epoxy paints	BIP2	RAD-EPICUR-A1
	Interaction of I <sub>2</sub> with stainless steel	BIP	G1
	Iodine mass transfer & adsorption on steel wall	THAI	#9
	Silver/iodine interactions in sumps	SIEMENS-IPSN	6 tests
	RuO <sub>2</sub> decomposition on paint under irradiation	IRSN	4 tests
	AgI decomposition	EPICUR MC	Aer1
	IOx formation	PARIS	2 tests
	IOx decomposition	STEM2	6 tests
	All iodine & ruthenium chemistry-related phenomena	Phébus FP	FPT1 (ISP-46), FPT2, FPT3
<b>DCH</b>	Dispersion of hot corium from the reactor pit	DISCO	FH03
<b>Corium Concrete Interaction</b>	LCS concrete (8 wt. %)	CCI	#2, #8
	Siliceous concrete (15 and 6 wt. %)	CCI	#3, #7
	Siliceous concrete (14 wt. %)	VULCANO	VBU5, VBU6

### 3. OVERVIEW OF THE ASTEC V2.2 VALIDATION

This section aims to provide a comprehensive picture of the ASTEC V2.2 validation achievements. For that purpose, results of some simulations are depicted for a few experiments. Those peculiar code-to-data comparisons are selected to be representative of the ASTEC V2.2 whole validation process. However, since those few examples concern only a sub-set of the entire set of ASTEC V2 modules, this chapter is itself sub-divided into separate sub-sections (each one being focused on a SA key physical phenomenon) in order to provide a somewhat exhaustive view of the ASTEC V2 whole validation process, independently from the provision or not within the paper of an illustration of related results.

#### 3.1. Thermal-Hydraulics in the Reactor Cooling System (RCS)

In ASTEC, CESAR is the module dealing with the two-phase thermal-hydraulics in the primary (including the vessel) and secondary circuits. The validation matrix that was considered to evaluate the physical relevance of the ASTEC V2.2 CESAR models to cope with RCS phenomena (see Table I) covers both DBA basic phenomena (including tests addressing shut-down states) and, to some extent, SA conditions. A brief summary of the main lessons drawn from the code-to-data assessment in the field of RCS thermal-hydraulics is provided later in Section 4. Details about these various ASTEC V2.2 CESAR simulations may be found in [13] [14] [15] [16].

#### 3.2. Core Degradation

In ASTEC, all in-vessel degradation processes (i.e. in the core and in the vessel lower head) are simulated by the ICARE module. The validation matrix that was considered to evaluate the suitability and capability of the ASTEC V2.2 ICARE core degradation models (see Table I) includes both ICARE stand-alone applications and CESAR/ICARE coupled applications.

To illustrate such validation tasks, attention is directed hereafter at one of the works that was performed to assess the CESAR/ICARE coupled modules vs. the PEARL debris bed reflooding tests. Being part of the PROGRES experimental program [17], the IRSN PEARL facility aims at improving the understanding of the factors governing the coolability of large heated debris beds. The PEARL test section (Fig. 1a) is composed of a long quartz tube (diameter 540 mm) filled with a 500 mm high debris bed made of stainless steel balls. It is surrounded by a bypass zone made of twice larger quartz balls representing a quasi-intact region at the periphery of a degraded core. The bed is heated by induction with a specific power of 150 W/kg, representative of the decay heat one hour after SCRAM in a generic PWR. In the tests presented hereafter, water is injected at the bottom of the test section (bottom flooding).

The device is modelled in ASTEC by 3 axial channels for the debris bed plus one channel for the bypass, surrounded by an adiabatic wall, and a 50 mm axial nodalization is applied. The bed initial temperature is set to the experimental value measured at the reflooding onset ( $t=0$ s). A constant pressure boundary condition is applied at the top while water is injected from the bottom following experimental conditions. Figures 1b and 1c indicate examples of comparison between ASTEC calculation and experiments [18]. The presented tests D5-2 and D1-7 are both performed with the same debris bed geometry, water velocity and initial temperature, and only differ by the imposed pressure (respectively 5 bars and 1 bar). The evolution of the steam mass flow rate at the test section outlet is well reproduced in both tests, as well as the quench front progression in the bed centre ( $R=0$  mm) and periphery ( $R=220$  mm). In particular, the impact of pressure on the reflooding is well captured: while a flat quench front profile is observed in the D5-2 test with a short reflooding time, the quench front progression in D1-7 is faster in the periphery compared to the centre, and the reflooding time is much longer.



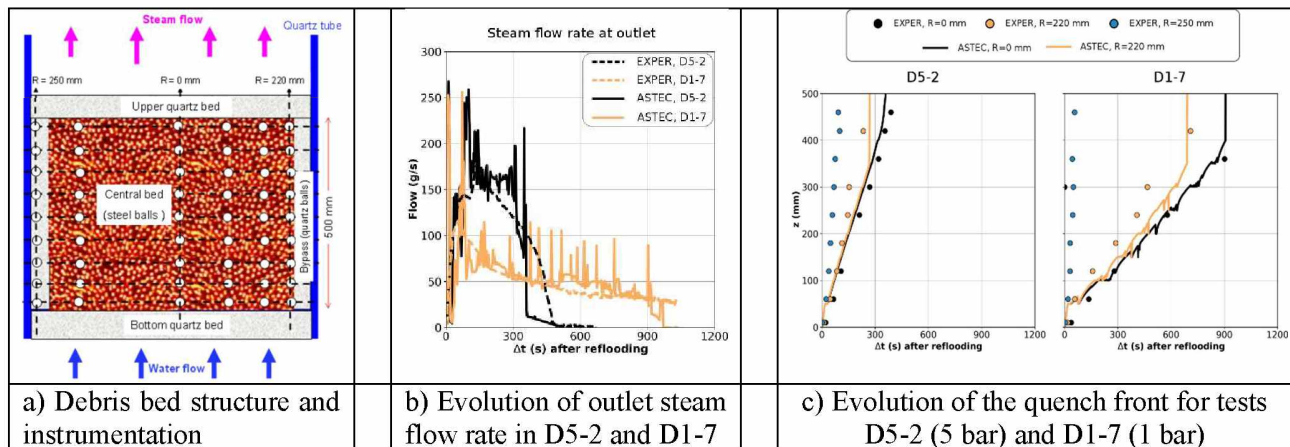


Figure 1. PEARL

Besides this example, a summary of the main lessons which have been drawn from the whole code-to-data assessment in the field of core degradation is provided later in Section 4. To get more details about these numerous ASTEC V2.2 CESAR/ICARE simulations, one may refer to [15] [16] [18] [19].

### 3.3. Corium Behavior in the Vessel Lower Head and ERVC issues

As already mentioned, the ICARE module also deals with the corium behavior after its slumping into the lower head. Besides, in case of situations with an In-Vessel Retention (IVR) strategy implementation, the CESAR module is also of interest to model the external reactor vessel cooling (ERVC) circuit. The main lessons that were drawn from the code-to-data assessment relating to the corium behavior in lower head are summarized in Section 4. More details about these ASTEC V2.2 analyses are given in [15] [16] [20].

### 3.4. Fission Products Release from the Core

In ASTEC, the fission products (FP) release from the core components is simulated by the ELSA module that is tightly coupled with the ICARE module. The validation matrix that was considered to evaluate the physical relevance of the ASTEC V2.2 FP release models remains today limited to a few VERCORS and VERDON tests [16]. Indeed, apart from these two experiments, the validation status of the ASTEC V2.2 ELSA models today still relies upon the one issued from the validation of the V2.1 former series, keeping in mind that only very few modelling evolutions were implemented in the ELSA module from V2.1 to V2.2. The main lessons that had been drawn from that V2.1 assessment are summarized in [15].

### 3.5. Fission Products and Aerosols Transport and Chemistry in RCS

In ASTEC V2.2, all FP/aerosols phenomena (i.e. transport and chemistry of FPs/aerosols in both RCS and containment) are simulated by the SOPHAEROS module. The validation matrix that was considered to evaluate the physical relevance of the SOPHAEROS models in the RCS domain is shown in Table I.

To illustrate such validation tasks, attention is directed hereafter at some of the works performed to assess the SOPHAEROS modeling for iodine gaseous phase chemistry kinetics in the RCS vs. the CHIP and CHIP+ data. The CHIP experimental program, operated at IRSN as part of the International Source Term Program [21], aimed to obtain data on iodine speciation under different circuit boundary conditions in presence of other FPs (Cs, Mo) and control rod materials (Ag, In, Cd, B). The CHIP experiments consist in analyzing the behavior of selected elements transported in a controlled thermal gradient tube flow. The

test line is composed of a high temperature alumina tube at the entrance followed by a stainless steel tube where the fluid is cooled down and where chemical reactions take place, producing aerosols and gases.

Validation results are displayed in Table III for two tests (tests “Cd-Mo-Cs-I” and “Ag-Cd-B-Mo-Cs-I”) that were part of the CHIP+ program. For each injected element, the comparison between the ASTEC prediction and the experimental data is focused on the deposited masses in the alumina and steel tubes, respectively, and thus the transported mass flowing out from the test line. In both tests, the SOPHAEROS kinetic modelling implemented in ASTEC V2.2 gives a satisfactory estimation of the iodine total transport (gas+aerosols) along the CHIP+ test line. Cesium and molybdenum transport is also reasonably predicted, though a bit overestimated, notably for the second test loaded with several control rod materials. On the contrary, the transport of Cadmium (Cd) and Silver (Ag) is largely overestimated by ASTEC in the second test because of a large underestimation of the Cd and Ag deposited masses in the high temperature zone.

**Table III. Deposition & Transport of Elements along the CHIP Line (in % of element mass injected)**

Experiment and selected elements	Deposited in high temperature zone (% ii.)		Deposited in transport zone (stainless steel tube) (% ii.)		Released at the outlet of the test line (% ii.)	
	Experiment	ASTEC	Experiment	ASTEC	Experiment	ASTEC
<b>“CdMoCsI”</b>						
<b>Iodine</b>	0.00%	0.00%	13.20%	19.28%	86.80%	80.72%
<b>Cesium</b>	10.00%	1.66%	16.50%	16.06%	73.50%	82.28%
<b>Molybdenum</b>	30.60%	11.18%	10.30%	28.44%	59.10%	60.38%
<b>“AgCdBMoCsI”</b>						
<b>Iodine</b>	0.00%	2.70%	7.20%	11.76%	92.80%	85.53%
<b>Cesium</b>	14.30%	1.47%	10.10%	10.99%	75.60%	87.54%
<b>Molybdenum</b>	25.50%	3.25%	9.10%	10.68%	65.40%	86.06%
<b>Cadmium</b>	33.10%	0.00%	24.20%	18.50%	42.70%	81.50%
<b>Silver</b>	48.50%	17.16%	7.80%	9.01%	43.70%	73.83%
<b>Boron</b>	1.00%	0.03%	1.80%	1.51%	97.20%	98.46%

Overall, the good results obtained for the iodine transport in most CHIP/CHIP+ experiments confirm the physical relevance of the current iodine gaseous phase chemistry kinetics modelling in the RCS. For other elements, results alternate among reasonable (e.g. fuel elements) and inadequate (control rod elements). Improvements are expected from IRSN on-going modelling works to ensure SOPHAEROS accounting for non-congruent condensation phenomena. A summary of the main lessons that have been drawn from the code-to-data assessment relating to the FP/aerosols behavior in the RCS is provided later in Section 4. More information about those ASTEC V2.2 SOPHAEROS analyses are displayed in [15] and [16].

### 3.6. Thermal-Hydraulics in Containment

In ASTEC, CPA is the module dealing with containment thermal-hydraulics, including all phenomena related to hydrogen risk (H<sub>2</sub> distribution, combustion and recombination). The validation matrix that was considered to evaluate the suitability of the CPA models to address those issues is supplied in Table II.

To briefly illustrate the numerous validation tasks relating to containment thermal-hydraulics, attention is directed hereafter at the work that was performed to assess the CPA module vs. the TOSQAN ISP-47 test. This experiment, operated by IRSN, aimed to study steam condensation on walls, notably in presence of non-condensable gas. For that purpose, the ISP-47 test included three steady states with air-steam mixture and one steady state with air-steam-helium mixture [22].

The global thermal-hydraulics behavior of the TOSQAN ISP-47 test is mainly governed by steam injection and wall condensation (pressurization due to steam and helium injection and depressurization due to condensation on cold wall). Each steady state, characterized by a pressure level (Fig.2a), is reached when the condensation mass flow rate (Fig.2b) is equal to the steam injection mass flow rate. As shown on those figures, the ISP-47 thermal-hydraulics behavior is very well captured by the ASTEC V2.2 CPA simulations for the four steady-states. The fluid temperature evolution is also reasonably predicted during both the pressurization and depressurization phases.

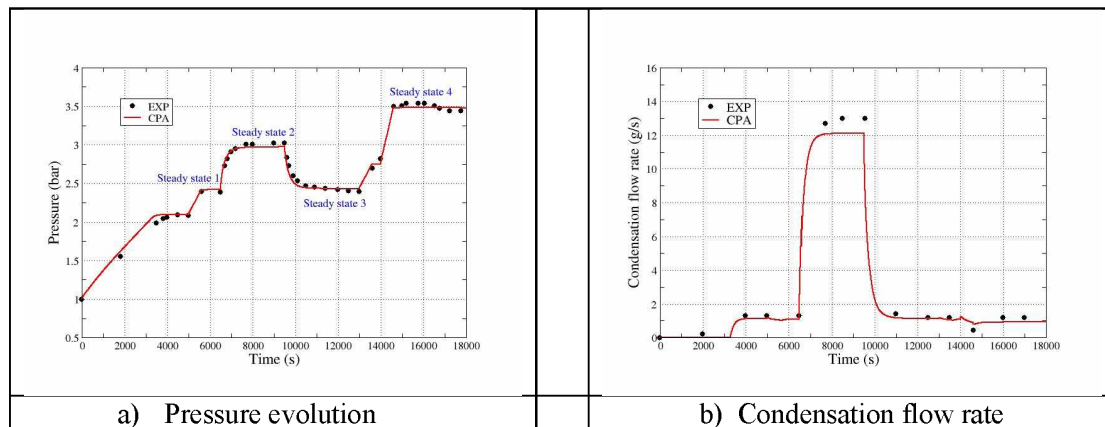


Figure 2. TOSQAN ISP-47

A summary of the main lessons that have been drawn from the code-to-data assessment in the field of the containment thermal-hydraulics is provided later in Section 4. To get more details about these numerous and rather different ASTEC V2.2 CPA simulations, one may refer to [15] and [16].

### 3.7. Thermal-Hydraulics and Aerosols Behavior in Containment

As already mentioned, the SOPHAEROS module also deals with the behavior of FPs and aerosols in the containment, in addition to the RCS domain. The validation matrix that was used to evaluate the physical relevance of the SOPHAEROS models to cope with those containment phenomena is supplied in Table II. The CPA/SOPHAEROS coupling was activated to simulate the integral tests while pool-scrubbing SETs have been analyzed using SOPHAEROS in its stand-alone running mode. A summary of the main lessons that have been drawn from the code-to-data assessment related to behavior of FPs and aerosols in the containment, along with their coupling to the thermal-hydraulics, is provided later in Section 4. More details about these ASTEC V2.2 CPA/SOPHAEROS analyses may be found in [15] and [16].

### 3.8. Iodine and Ruthenium Chemistry in Containment

In ASTEC V2.2, the SOPHAEROS module also addresses in a detailed manner the chemical behavior of iodine and ruthenium compounds (vapors and aerosols) in containment. The validation matrix that was assumed to assess the suitability of the SOPHAEROS iodine models is given in Table II.

To illustrate very shortly such validation extended tasks, attention is directed hereafter at the work that was performed to assess the SOPHAEROS containment iodine chemistry models vs. the PHEBUS RTF1 test. The RTF1 test, that had been operated at AECL at the end of the 90s as a part of the ISP-41 [23], dealt notably with the radiolysis of iodide ions  $I^-$ , leading to the formation of  $I_2$  in the sump and its transfer



to the gaseous phase where it was adsorbed on a dry paint surface. So, the main issue of this validation task was to check how fast iodide ions  $I^-$  were converted into gaseous  $I_2$  and how much gaseous organic and inorganic iodine remained in gaseous phase all over the irradiation. As shown on Fig.3, the ASTEC V2.2 prediction of the iodine distribution in aqueous phase, gaseous phase and on painted surfaces was quite good using recommended values for steel and paint adsorption rate constants.

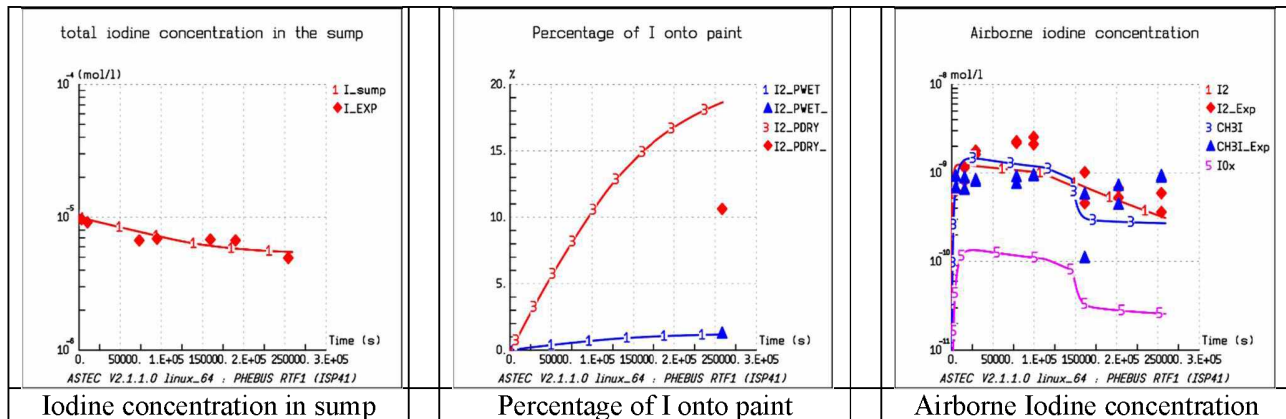


Figure 3. PHEBUS RTF

Main lessons that have been drawn from the code-to-data assessment relating to the iodine and ruthenium chemistry in the containment are summarized later in Section 4. To get more details about these diverse ASTEC V2.2 SOPHAEROS simulations, one may refer to [15] and [16].

### 3.9. Direct Containment Heating

In ASTEC the Direct Containment Heating (DCH) is modelled in a rather simple manner, with main goal to limit the number of user parameters that are unknown particularly in reactor cases. The ASTEC V2.2 DCH models were validated on five tests from the KIT DISCO experimental program, focusing on the DISCO-HOT FH series addressing French 1300 MWe PWRs. A brief summary of the main issues learnt from this assessment is provided in Section 4. More details may be found in [15] and [16].

### 3.10. Molten Core Concrete Interaction

In ASTEC, MEDICIS is the module dealing with Molten Core Concrete Interaction (MCCI). The validation matrix that was considered to evaluate the physical consistency of the ASTEC V2.2 MEDICIS models is shown in Table II. A summary of the main outcomes that have been drawn from the code-to-data assessment in the field of MCCI (either dry CCI or CCI with top flooding) is provided in the next section. To get more details about these ASTEC V2.2 MEDICIS analyses, one may refer to [15] and [16].

## 4. MAIN OUTCOMES FROM ASTEC V2.2 VALIDATION vs. EXPERIMENTS

For primary and secondary circuit thermal-hydraulics, the ASTEC V2.2 models have been successfully reassessed vs. numerous SETs (Moby-Dick, Coturne, Rebeca, Cosi, Patricia, Takeuchi...) covering basic key phenomena such as critical flow-rate, flashing, interfacial friction, wall heat transfer, interfacial heat transfer and reflooding of a full-scale western-PWR fuel rod assembly (PERICLES). Good results have been also obtained on several BETHSY integral tests with RCS loops as well as on the TMI-2 scenario.

For core degradation early phase phenomena such as core heat-up, oxidation and hydrogen production, results of the ASTEC V2.2 simulations of several Phébus FP and QUENCH integral experiments are quite good. Furthermore, the core final state is also rather well estimated for all Phébus FP and QUENCH transients. Those results show the overall consistency of the updated early-to-late transition phase modeling now available in V2.2 to trigger the fuel rod embrittlement and subsequent relocation of materials combining the flowdown of solid/liquid melts with the possible formation and collapse of fragmented debris. ASTEC V2 results are also satisfactory on TMI-2 up to the final quenching. Conversely, the large hydrogen peak observed during the quenching phase is still underestimated by ICARE. As concerns air ingress transients, while promising results could be obtained against two QUENCH air tests using a preliminary nitriding model, modelling efforts in that field shall continue.

Focusing on late degradation phase models, nice results have been achieved on Phébus FPT4 (test starting in a debris bed geometry), using the combined magma-debris models in the core region. Good results have been also obtained against PRELUDE and PEARL data addressing the reflooding of severely damaged cores, thus confirming the global physical consistency of the ASTEC new model dealing with two-phase flows in porous media. The ICARE modelling for the corium behavior in the lower head is relevant too, as exhibited by the satisfactory simulations of several LIVE and MASCA tests that were focused on heat transfers in corium molten pools and interaction between corium and structural materials, respectively. Finally, the ASTEC V2.2 lower head failure model was also successfully validated vs. the OLHF-1 experimental data, providing a consistent evaluation of the rupture time and localization.

For FP release from core components, good V2.2 results (and even excellent for volatile species) have been obtained on a few VERCORS and VERDON tests, while the planned update of the ELSA models validation vs. other SETs as well as vs. Phébus FP integral tests had to be postponed to mid-2022.

Regarding FP/aerosol behavior in the primary circuit, the ASTEC V2.2 results are reasonable on FP transport and deposition, as experienced on TUBA, FALCON and STORM tests. As concerns physical processes that directly drive the amount of iodine to be released under a gaseous form into the containment, suitable results have been also obtained in the field of element chemical speciation in the RCS. In particular, the {Cs-Mo-I-O-H} new models implemented in SOPHAEROS enabled a good prediction of the CHIP PL experimental trends. Those promising results have been then confirmed vs. several tests of the CHIP+ program with control rod materials, apart from the Ag behavior. So, the numerous simulations that have been performed vs. the CHIP and Phébus FP experimental data have clearly highlighted the significant progress that has been brought by the implementation in ASTEC V2.2 of an RCS gaseous phase chemistry kinetics dedicated modelling. Nonetheless, R&D works are still being continued at IRSN on the chemical behavior of multi-element compounds (e.g. on {I-O-H-Cs-Mo-Ag-Cd-B} system), while progressively ensuring SOPHAEROS accounting for non-congruent condensation phenomena.

For containment thermal-hydraulics, the relevant simulations of the TOSQAN, THAI-HM and PANDA experiments confirmed the overall consistency of the CPA models to deal with mass and heat transfers (e.g. condensation/evaporation, thermal stratification) or hydrogen distribution in the containment under SA conditions. As to the modelling of the mitigation systems operating in the containment, the simulations of selected TOSQAN and PANDA tests proved the global ability of CPA models to deal correctly with spray condensation phenomena. The simulations of several THAI-HR tests showed that CPA can rather well predict the behavior of concurrent types of operating PARs under various transient conditions. Regarding hydrogen combustion, reasonable results could also be obtained vs. THAI-HD and ENACCEF tests using the flame front propagation model. However, open questions still exist applying this model to real plants, as the CPA-FRONT model parameters were determined in relatively small test facilities. So, their application in rougher nodalization with larger control volumes requires to be further assessed.

Regarding the behavior of FPs and aerosols in containment, satisfactory results have been obtained on integral experiments (VANAM, CSE, Phébus FP) using the ASTEC V2.2 SOPHAEROS module. Those rather fair results confirm the physical relevance of the SOPHAEROS containment new modelling that is now replacing the former V2.0 CPA-AFP sub-module. However, these good results concern mostly the evolution of the species in the gaseous atmosphere or on the walls (suspended and depleted) while the predictions of pool scrubbing experiments still exhibited some modelling deficiencies. In that respect, a new pool scrubbing model is being currently under development at IRSN, aimed at removing the observed weakness in that field.

Over the past decade, the ASTEC V2 models dealing with iodine chemistry in containment have been continuously improved in close link with the production of new experimental data successively acquired in the frame of the OECD STEM, STEM2, BIP, BIP2 and BIP3 international projects and the ANR MIRE French domestic project. Most of these SOPHAEROS improvements related to the iodine volatility in gaseous atmosphere aimed to better evaluate the formation/decomposition of inorganic and organic iodine species under irradiation. The treatment of iodine aerosols and oxides was also largely improved. All those modelling evolutions have been then successfully validated vs. numerous SETs. Moreover, in comparison to V2.0, a better agreement with experimental data could notably be achieved for all Phébus FP tests on the evolution of both molecular iodine and organic iodine concentrations in the containment. In summary, those updated validation tasks confirmed that the ASTEC V2.2 modelling of the iodine behavior in the containment is at the state-of-the-art of the R&D knowledge. Finally, though based on a less extended validation matrix in comparison to iodine, the V2.2 modelling of the ruthenium chemistry looked also close to the state-of-the-art, as proved by the quite relevant simulations of IRSN dedicated experiments. That's being said, there are still open issues to be better addressed, such as mid to long term releases.

Regarding DCH, the ASTEC V2.2 new model was successfully assessed vs. DISCO FH experiments. Indeed, despite its simplifications, this new modelling of the DCH process gave satisfactory results while allowing reducing the number of user parameters which are unknown particularly in reactor cases.

For MCCI in dry conditions, the fair agreement noted between ASTEC V2.2 simulations and experimental data on several CCI and VULCANO experiments for the 2-D ablation kinetics and the final cavity shape, as well as for the ablated concrete mass, showed basically the relevance of the set of assumptions and models used for both considered concrete types (LCS and siliceous). The main still unresolved issue for the 2-D ablation in dry conditions remains likely the long-term behavior of the solid accumulation or crust possibly built-up at the cavity bottom very early during MCCI in case of siliceous concrete. For MCCI under water, the CCI-7 and CCI-8 experiments were selected to make a first assessment of the ASTEC MEDICIS new models specifically addressing top quenching phenomena arising during MCCI, such as melt ejection and boiling heat transfer at the corium-water interface, including water ingress. The overall behavior predicted by MEDICIS sounded reasonable, although the analyses need to be thoroughly studied. Nonetheless, one must keep in mind that these top quenching models are a priori poorly adapted to the possible anchored crust process and cannot reflect the intermittency of melt ejection. More R&D is therefore still needed on MCCI top quenching regarding these two processes. In that respect, IRSN currently actively participates with ASTEC in the on-going OECD ROSAU experimental program.

Finally, to complement those huge validation tasks carried out vs. experimental data at different scales, a so-called "validation at plant scale" work is also being realized. In that respect, in addition to the recurrent simulation of the TMI-2 real accident transient, the analyses of the Fukushima-Daiichi accidents are being also periodically updated to further assess the ICARE few specific models that aim to better cope with BWR core geometries [3]. Besides, those analyses emphasized the need for extending the modelling from the short to the long term to better address the delayed releases and resuspension related phenomena [24] [25]. Hence, the ASTEC modelling in those fields will be further improved, accounting for the data that was already obtained from some OECD recent R&D programs (STEM2, BIP3) or could come from the

on-going OECD ESTER project. Moreover, many other ASTEC V2.2 plant analyses are being performed by foreign partners involved in the NUGENIA ASCOM project [4]. These independent plant applications, which often consist of code-to-code benchmark studies, aim at bringing complementary lessons about the ASTEC V2 overall modelling capabilities to calculate complete SA sequences on diverse types of NPPs.

## 5. CONCLUSIONS

The main conclusion that can be drawn from these very extended validation activities of the V2.2 major version is that most ASTEC models are today at the state of the art, in particular FP models that are directly driving the evaluation of the final source term to the environment in case of a severe accident.

ASTEC V2.2 can be considered as a suitable tool to calculate various SA sequences initiated at either reactor power state or shut-down state on different types of NPPs. In particular as demonstrated by both IRSN and many ASCOM foreign partners, ASTEC V2.2 can be used to perform Gen.II PWR and VVER once-through best-estimate calculations, while providing the actual capability for simulations of technical means for mitigation of SA consequences as well as for simulation of typical SAM actions. For BWRs, the V2.2 containment models and source term models are also considered as physically relevant while the core new degradation models, although proved to be rather consistent, likely need to be further assessed. ASTEC V2.2 can also be used to perform best-estimate safety analyses on EPR, as done at IRSN. Moreover, as demonstrated by several partners, ASTEC V2.2 appears to be also a useful tool to investigate the progression of severe accidents in NPPs relying on the in-vessel melt retention strategy.

Modelling efforts will continue to keep ASTEC models at the state of the art and thus further improve the simulations of SA relating to various types of Gen.II and Gen.III plants. Besides, both the development of a few new specific models and the improvement of some existing ones are required to enlarge the scope of best-estimate analyses to other innovative NPPs and nuclear installations, and in particular to consolidate the promising first ASTEC V2.2 applications to SMRs [26] while better addressing accidents occurring in spent fuel pools [27]. Anyhow, ASTEC shall remain a repository of knowledge gained from international R&D for SA phenomenology. For that purpose, physical models will be continuously updated according to the interpretation of current and future experimental programs executed in an international frame. Meanwhile, the ASTEC assessment activities will of course continue both at IRSN and outside IRSN through foreign partners' contributions to be mostly realized in the frame of the ASCOM on-going project.

## ACKNOWLEDGMENTS

The authors would like to associate to this article the whole IRSN ASTEC development team who very actively contributed to the ASTEC V2.2 validation tasks, as well as the foreign organizations who also brought afterward a valuable contribution to the ASTEC V2 assessment tasks in the frame of both the international ASTEC Users' Club network and the SNETP-NUGENIA ASCOM collaborative project.

## REFERENCES

1. L. Chailan et al., "Overview of ASTEC code and models for Evaluation of Severe Accidents in Water Cooled Reactors", *Proceedings of the IAEA Technical Meeting on Status and Evaluation of Severe Accident Simulation Codes for Water Cooled Reactors*, Vienna (Austria), October 9-12, (2017)
2. L. Laborde et al., "Overview of the ASTEC V2.2 integral code", Report IRSN-2021-00298, (2021)
3. P. Chatelard et al., "Main modelling features of ASTEC V2.1 major version", *Annals of Nuclear Energy*, **93**, pp.83-93, (2016)
4. SNETP NUGENIA TA2 ASCOM, <https://snetp.eu/project-portfolio/>, (2018)
5. P. Chatelard et al., "Overview of ASTEC V2.0r1 validation", *Nuclear Engineering and Design*, **272**, pp.136-151, (2014)



6. M. Buck et al., “Synthesis of validation of ASTEC V2.1rev0 and rev1 versions”, CESAM FP7 Deliverable referred to as “CESAM-D20.25”, (2017)
7. H. Nowack et al., “CESAM - Code for European Severe Accident Management, EURATOM project on ASTEC improvement”, *Annals of Nuclear Energy*, **116**, pp.128-136, (2018)
8. A.K. Mercan et al., “Validation of ASTEC 2.1 using QUENCH-12 for VVER reactors”, *Proceedings of the 9<sup>th</sup> European Review Meeting on Severe Accident Research (ERMSAR-2019)*, Prague, Czech Republic, March 18-20, 2019
9. O. Murat et al., “Preliminary validation of ASTEC V2.2 with the QUENCH-20 BWR bundle experiment”, *Nuclear Engineering and Design*, **370**, (2020)
10. F. Gabrielli et al., “U&S analyses applied to ASTEC results for QUENCH-08 test”, *Annals of Nuclear Energy*, *in press*, (2021)
11. M. Gouëllou et al., “Interaction between Cesium iodide particles and gaseous boric acid in a flowing system through a thermal gradient tube (1030K to 450K) and analysis with ASTEC/SOPHAEROS”, *Progress in Nuclear Energy*, **138**, (2021)
12. M. Kotouc, “Simulation of external reactor vessel cooling with the ASTEC code – Validation on experiments performed at the THS-15 (VVER-1000) facility”, *Proceedings of the 19<sup>th</sup> International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-19)*, Brussels, Belgium, March 6-11, 2022
13. I. Gomez Garcia-Torano and L. Laborde, “Validation of selected CESAR friction models of the ASTECV21 code based on Moby Dick experiments”, *Journal of Nuclear Engineering and Radiation Science*, **5**, (2019)
14. I. Gomez-Garcia-Torano et al., “Overview of the CESAR thermalhydraulic module of ASTEC V2.1 and selected validation studies”, *Proceedings of International Youth Nuclear Congress (IYNC2018)*, Bariloche, Argentina, March 11-17, 2018
15. P. Chatelard, “ASTEC V2.1 final validation report”, Report IRSN-2019-00717, (2019)
16. L. Laborde et al., “ASTEC V2.2 physical validation”, Report IRSN-2021-00272, (2021)
17. PROGRES program, <https://www.irsn.fr/EN/Research/Research-organisation/Research-programmes>
18. I. Gomez-Garcia-Torano et al., “Reflooding of degraded cores in ASTEC V2.1: modelling and validation on PEARL experiments”, submitted to *Nuclear Engineering and Design*.
19. I. Gomez-Garcia-Torano and L. Laborde, “Modelling reflooding of intact core geometries in ASTEC V2.1: Improvements and validation on PERICLES experiments”, *Nuclear Engineering and Design*, **378**, 111157, (2021)
20. L. Laborde et al., “External Reactor Vessel Cooling modelling in ASTEC V2.1 code”, *Proceedings of the 12<sup>th</sup> International Topical Meeting on Nuclear Thermal-Hydraulics, Operation and Safety (NUTHOS-12)*, Qingdao, China, October 14-18, 2018
21. ISTP program, <https://www.irsn.fr/EN/Research/Research-organisation/Research-programmes>
22. J. Malet et al., “OECD International Standard Problem ISP-47 on containment thermal-hydraulics: Conclusions of the TOSQAN part”, *Nuclear Engineering and Design*, **240**, pp. 3209-3220, (2010)
23. J. Ball et al., “International Standard Problem n°41, Containment Iodine Computer Code Exercise Based on a Radioiodine Test Facility (RTF) experiment”, OECD/NEA/CSNI/R(2000)6, Vol 2, (2000)
24. C. Bouillet et al., “OECD/NEA BSAF project (Benchmark on Study of the Accident at the Fukushima Daiichi NPPs), IRSN contribution to BSAF Phase II”, IRSN/PSN-RES/SAG/2018-00065, (2018)
25. P. Chatelard et al., “Contribution of ASTEC numerical simulations to the understanding of the Fukushima accidents”, *Proceedings of the IAEA Workshop on advances in understanding the progression of severe accidents in Boiling Water Reactors*, Vienna, Austria, July 17-21, 2017
26. P. Maccari et al., “Analysis of BDBA sequences in a generic IRIS reactor using ASTEC code”, *Proceedings of the 10<sup>th</sup> European Review Meeting on Severe Accident Research (ERMSAR-2022)*, Karlsruhe, Germany, May 16-19, 2022
27. O. Coindreau et al., “Uncertainty quantification for a severe accident sequence in an SFP in the frame of the H-2020 MUSA Project: first outcomes”, *Proceedings of the 10<sup>th</sup> European Review Meeting on Severe Accident Research (ERMSAR-2022)*, Karlsruhe, Germany, 16-19 May 2022