Recent progress in source term research and evaluations with the ASTEC code

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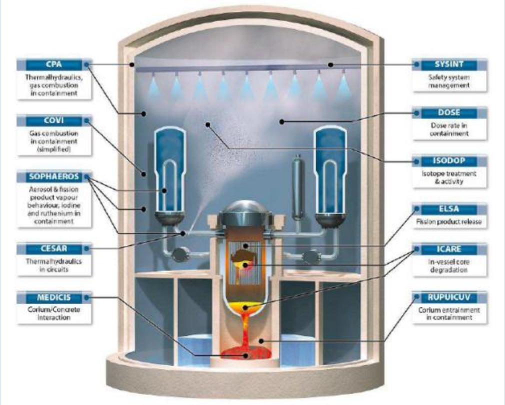
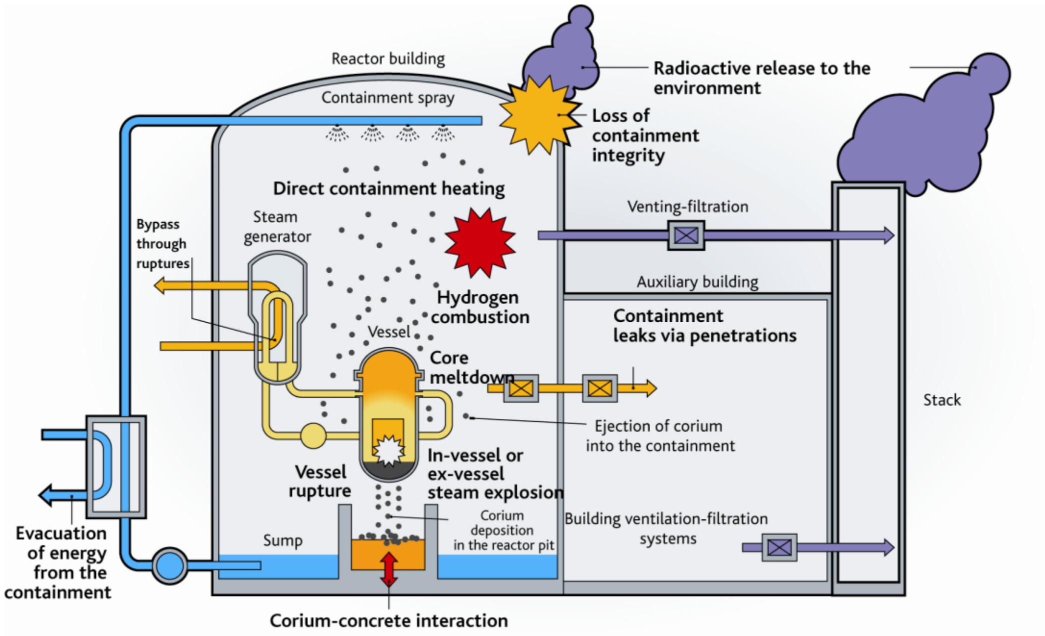


8th International Experts' Meeting on Strenghtening Research and Development Effectiveness in the Light of the Accident of the Fukushima Daiichi Nuclear Power Plant (IEM 8) Vienna, Austria, February 16-20, 2015

Approach and safety objectives for French reactors

Assessment of:
- Containment failure risks
- Associated consequences (source term - releases)
- Efficiency of protection and release mitigation measures



Focus on iodine, ruthenium and cesium releases

- Elimination of accidents conducive of short term containment failure - ***avoid large uncontroled releases at short term***
- Prevent the containment concrete basemat failure by MCCI - ***avoid uncontroled releases through the ground at mid-term***
- Reduce ***releases at mid-term*** during authorized filtered venting aiming at preserving the containment integrity

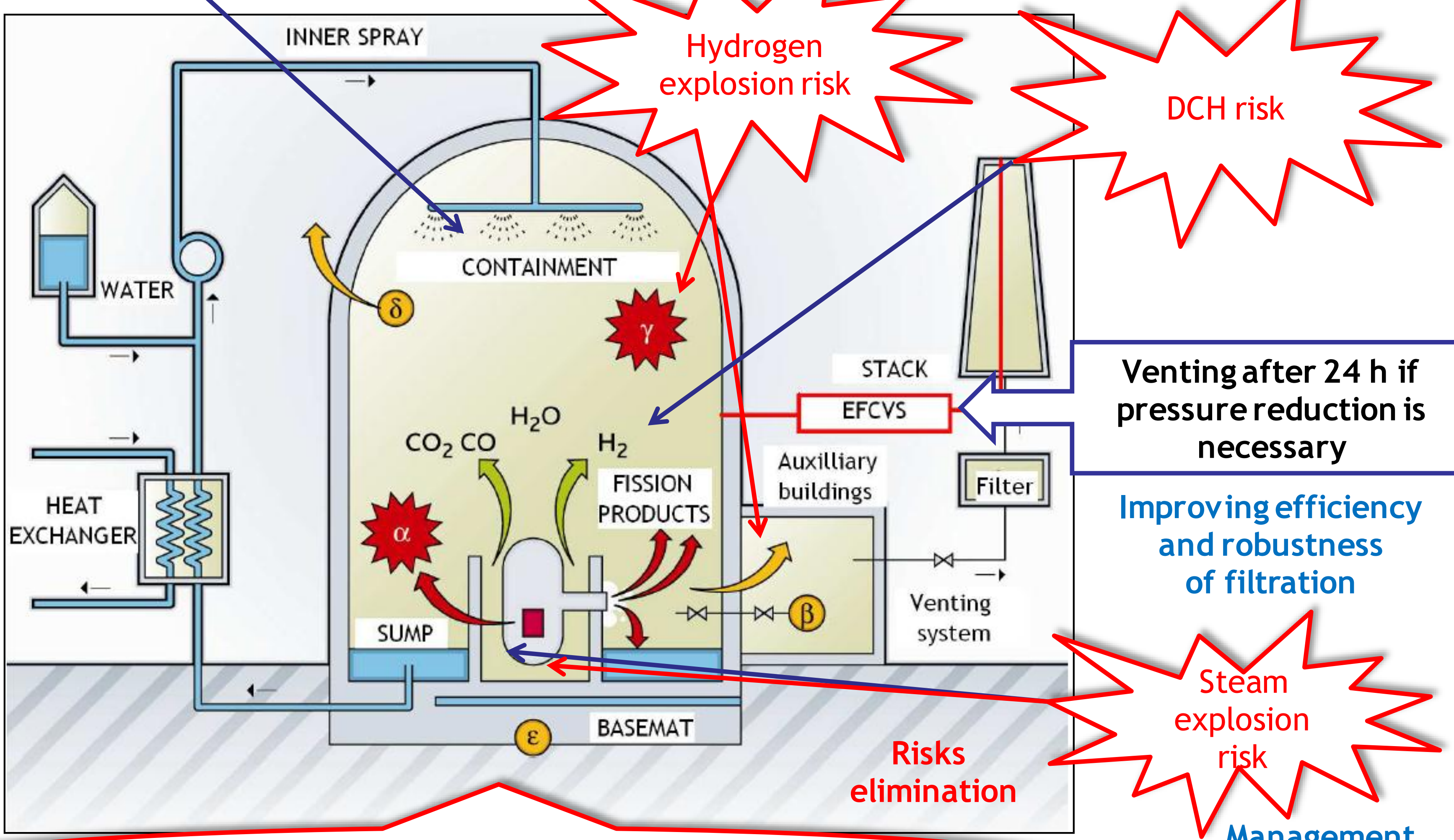
Safety objectives, revised orientations after Fukushima

Improving robustness of systems to evacuate containment residual heat (without FCVS)

Mitigation: recombiners implemented

Risks elimination

RCS depressurization: robust systems implemented



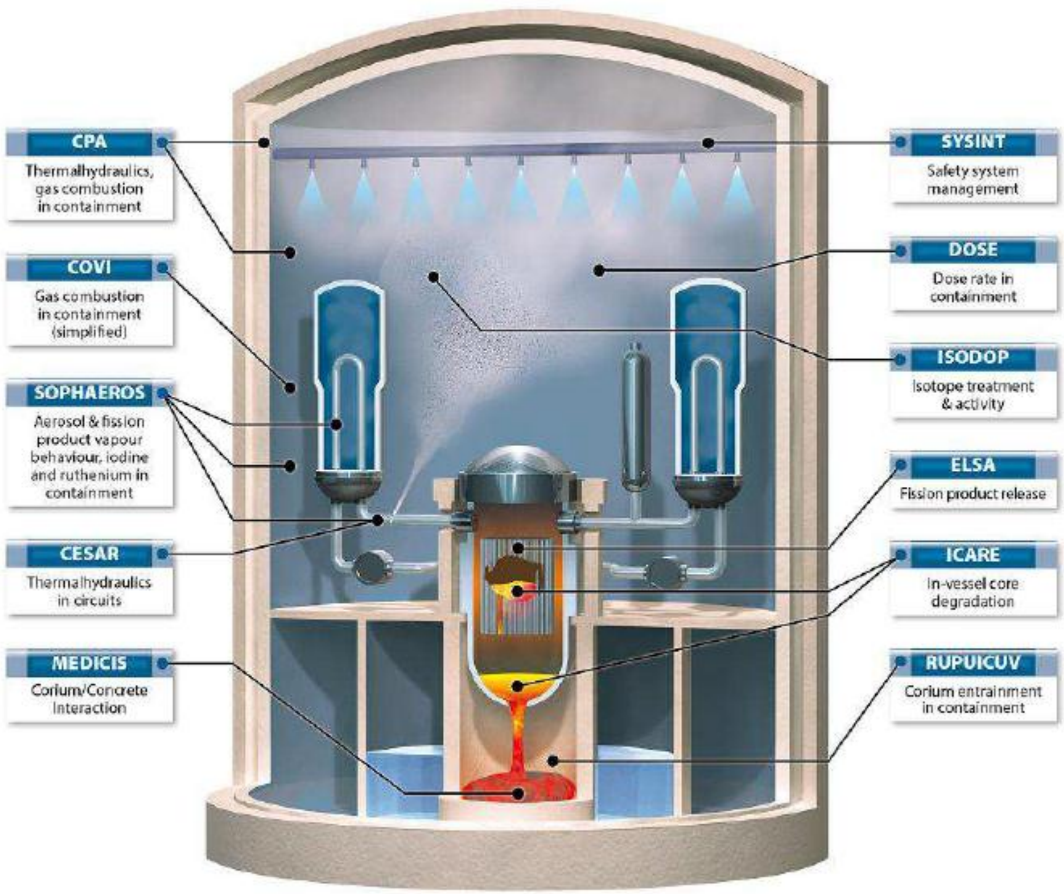
Venting after 24 h if pressure reduction is necessary

Improving efficiency and robustness of filtration

Risk of containment failure by erosion of the concrete basemat by MCCI, potential releases through the ground after 24 h

Management of water supplies under revision

ASTEC code (joint IRSN/GRS development since 1996)



Code main features

- Complete accident sequence calculation from initiating event to releases (<12 h CPU)
- Safety systems considered
- Validation and update of models using SOA knowledge from R&D

Specific to releases (ST) calculations

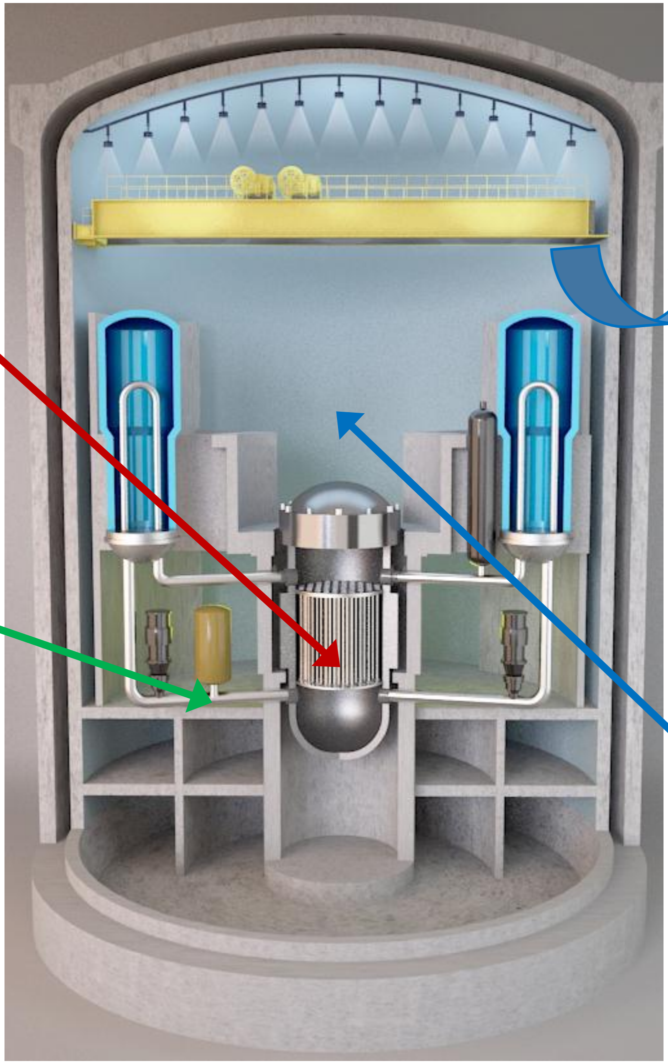
- Consideration of containment failure modes, leak-paths and filtered venting (DFs for solid filter, scrubbing module for liquid filter)
- Modules dealing with FP release from fuel, transport in the RCS and behaviour in the containment - detailed modelling of physico-chemical processes, including dose effects

ASTEC used for ST evaluations, in support to L2 PSA and emergency response tools

Main on-going or recently concluded experimental programs and models improvements done or projected for ASTEC

FP Release from fuel
- *Phébus FP, ISTP (VERDON)*
- *effects of fuel type, BU, oxygen potential (pO_2)*

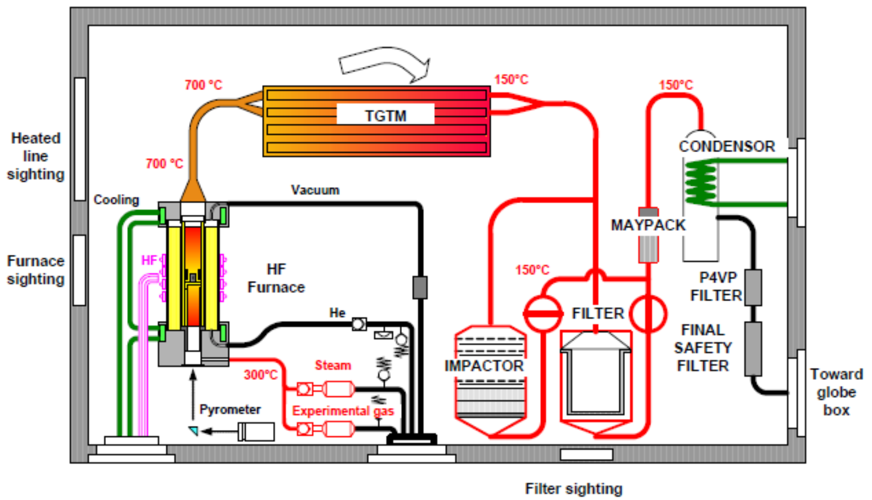
FP behaviour in RCS
- *Phébus FP, ISTP (Ru, CHIP), SARNET (AEKI, VTT Ru), OECD/STEM, CHIP+(IRSN)*
- *gaseous iodine at the break, effects of B, Mo, Ag, In, Cd on iodine speciation*
- *Ru transport and deposition*
- *I, Cs and Ru revaporisation*



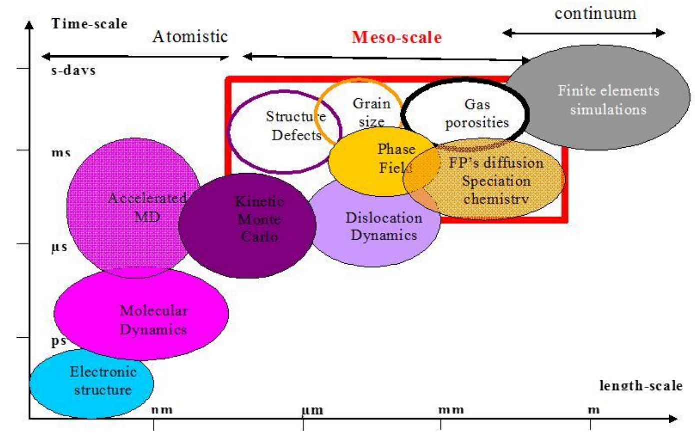
FP retention and reemission in FCVS and in pools
- *ANR MIRE, EU PASSAM*
- *DFs in solid filters for SA conditions*
- *Pool hydrodynamics and DFs in liquid filter*

FP behaviour in containment
- *Phébus FP, ISTP (Ru, EPICUR), OECD/STEM, BIP (1-2), THAI (1-2)*
- *focus on chemistry in atmospheric compartment (Org-I, I_xO_y, I_2 interactions with paints and aerosols)*
- *stability of surface deposited iodine aerosols*
- *gaseous ruthenium (RuO_4)*

VERDON tests (ISTP)



Development of multiscale approach to support MFPR and ASTEC models development



Developed knowledge and tools

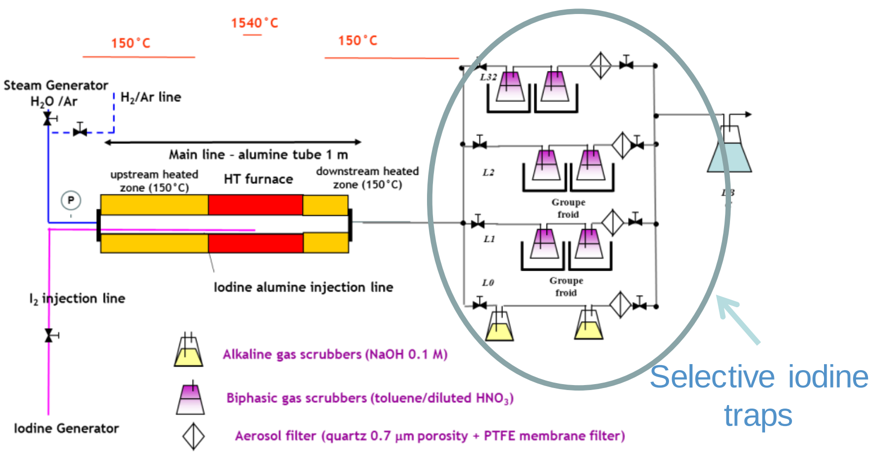
- Large consistent database (Phébus FP, VERCORS, VERDON) on FP volatility used for the development/validation of mechanistic (MFPR), simplified (ELSA/ASTEC) modelling
- Volatile FP: larger release than expected from MOX at intermediate T (1200°C)
- "Semi-volatile" FP: release highly sensitive to fuel oxidation (Ru) and pO_2 in flow (Ba, Mo)

Perspectives

Development of predictive mechanistic models including for specific conditions and new fuels (H2020 INFORMS project)

- Inclusion of effects of fuel BU and oxidation
- Releases before significant fuel melting (DBA, margin to intervention in SFP)
- Ru release at short term (failed vessel, SFP)
- Releases for new fuel

CHIP tests (ISTP)
Iodine chemistry in RCS
Gaseous iodine at the RCS break



ASTEC models developed with the support of theoretical chemistry (thermo-kinetics models of gas phase reactions)

I Cs Mo Cd B ...

Damaged fuel

- I
- HI
- I_2

Kinetics: I, O, H

Radiolysis of H_2 and H_2O

- $Cd + 2 I \rightarrow CdI_2$
- $Cs + I \rightarrow CsI$
- $Cs + OH \rightarrow CsOH$

+ Cd

+ Cs

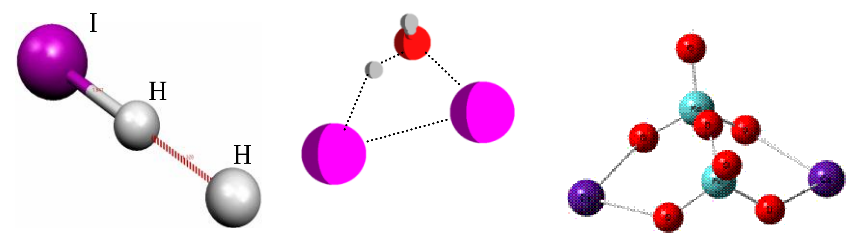
Caesium molybdates

Molybdenum chemistry — Equilibrium

Caesium borates — Kinetics

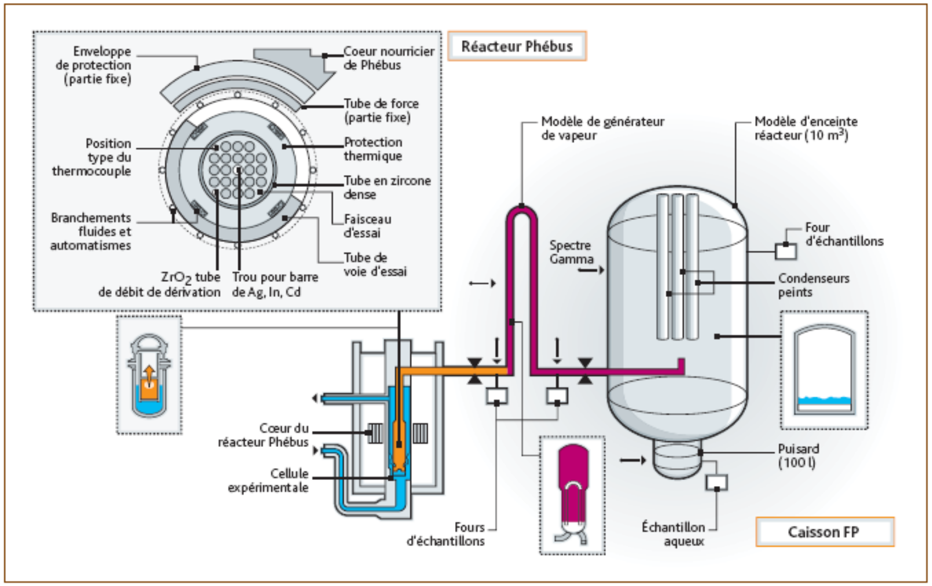
Boron chemistry — Equilibrium

Thermodynamic and kinetic constants for main species and reactions of interest



Transition compound

Progress and perspectives for iodine and ruthenium behaviour in RCS

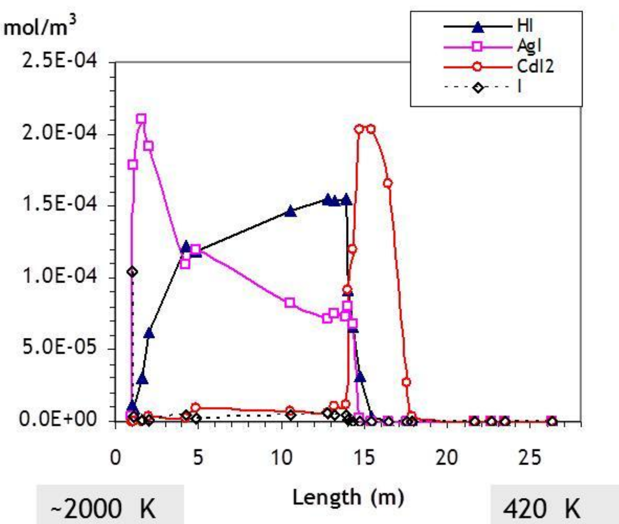


Gaseous iodine % at the RCS break in Phébus integral tests

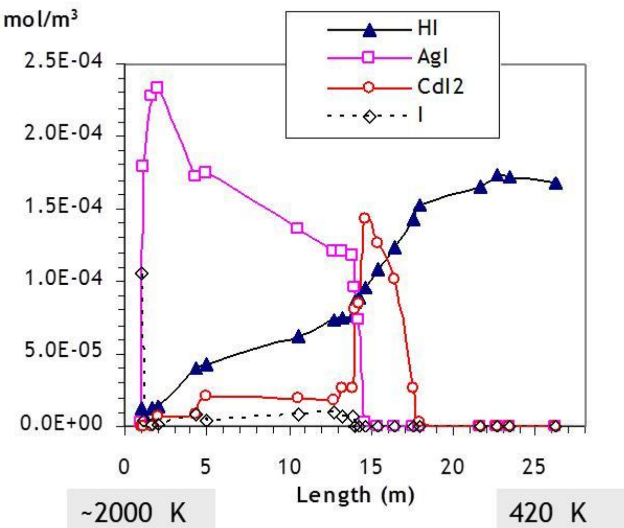
	Exp.	Thermo.	+ Kinetics
FPT1	1	0	2
FPT3	88	26	41*

* Close to exp. value considering the B blockage at the SG entrance in FPT3

Necessity to treat properly Mo and Cd chemistry and kinetic limitations to calculate observed gaseous iodine %



Thermodynamic equilibrium



Accounting for iodine kinetics

FPT1 calculation showing effect of kinetic limitations (HI maintained at cold leg break)

CHIP tests

START tests (OCDE/STEM)

Developed knowledge and tools

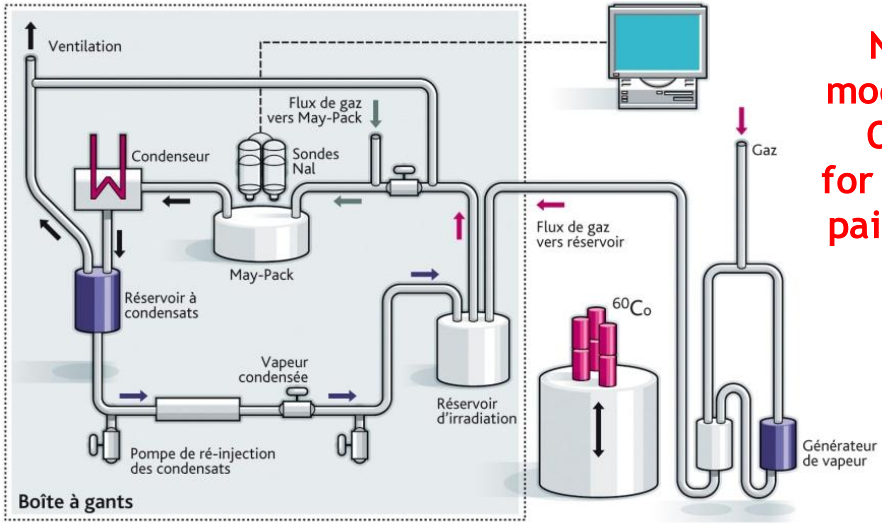
- Large database (Phébus FP, ISTP/CHIP, VTT/EXSI, AEKI/Ru, OECD/STEM/START) on FP transport in RCS (focus on I and Ru chemistry) used for models development in ASTEC
- Support of theoretical chemistry calculations
- Large progress in modelling of integral tests results (gaseous iodine % at the break)

Perspectives

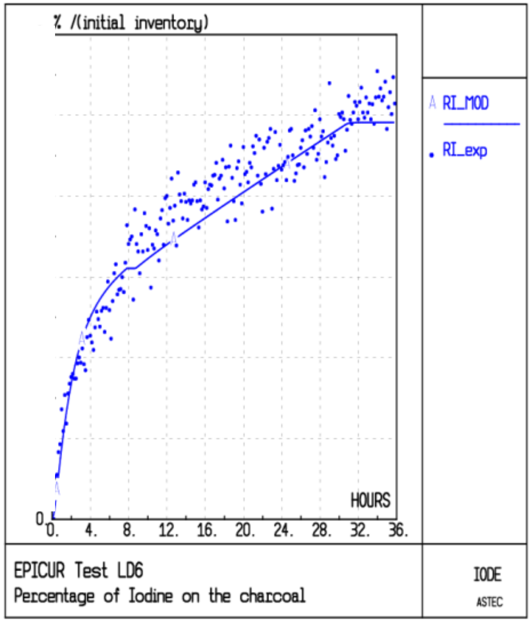
Finalize predictive models for I and Ru transport in RCS (CHIP follow-up, OECD/STEM1 and 2, MIRE)

- Complete modelling of control rod elements (Ag, In, Cd) effect on iodine chemistry
- FP resuspension from RCS deposits (focus on Ru, I and Cs) – « delayed » ST

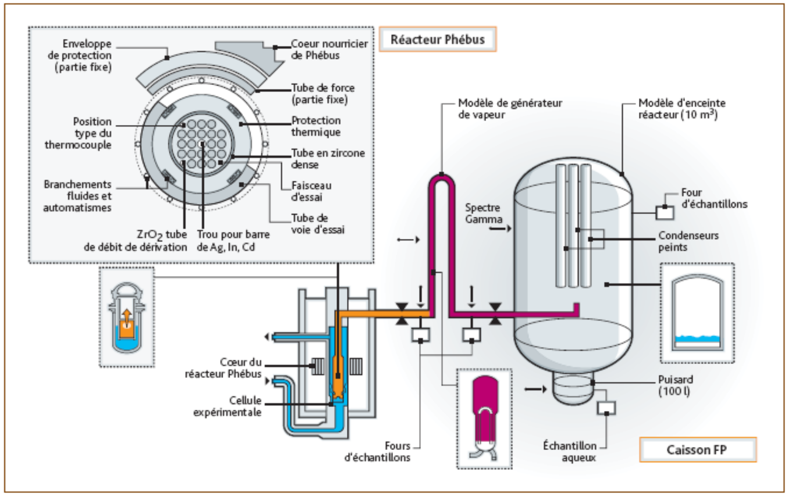
EPICUR tests (ISTP, OECD/STEM)



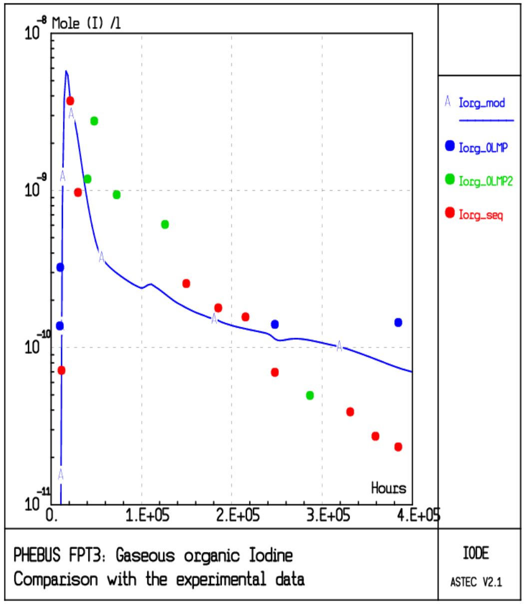
New ASTEC kinetic models developed from OECD/STEM results for org-I formation from paints and in gas phase



Phébus FP tests

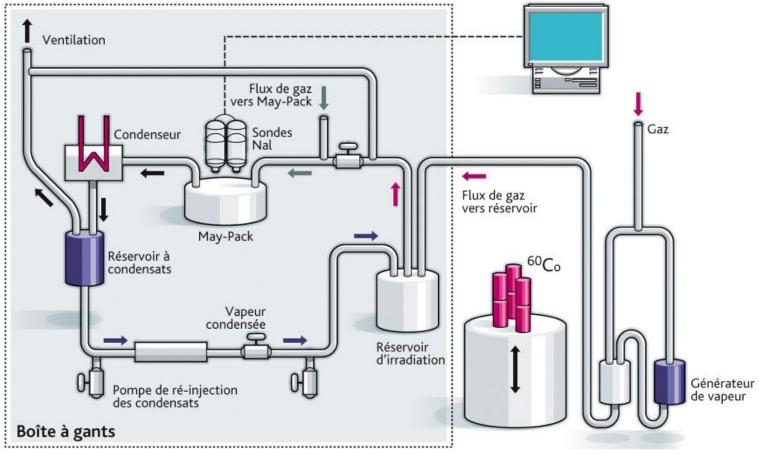


Calculations with new model show better prediction of gaseous org-I concentration in containment for Phébus tests, notably for FPT3

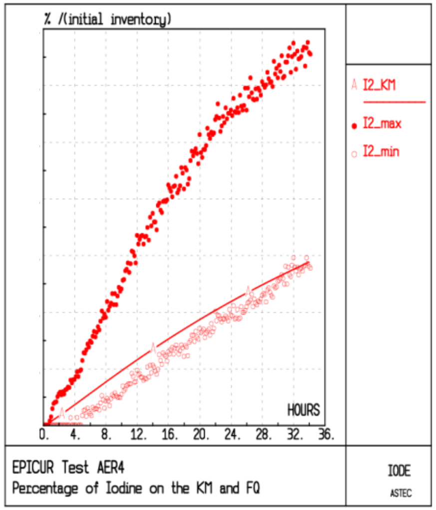


Progress and perspectives for iodine behaviour in containment

EPICUR tests (OECD/STEM)



OECD/STEM test evidencing large iodine aerosol decomposition by irradiation



Developed knowledge and tools

- Large database (Phébus FP, ISTP/EPICUR, OECD BIP, THAI, STEM, …) on I and Ru behaviour in containment used for kinetic models development in ASTEC
- Importance of processes involving org-I, I_xO_y formation/destruction in gas phase and iodine aerosols decomposition for ST

Perspectives

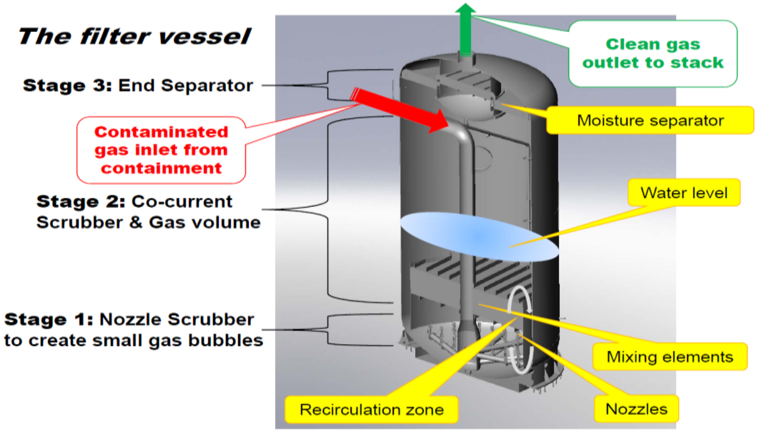
Importance of remobilisation processes at mid and long term (OECD/STEM2, BIP3, THAI3, MIRE, EU PASSAM) – « delayed ST »

- Effect of paint ageing on volatile iodine release
- Iodine re-suspension/re-vaporisation from sumps, pools and surfaces deposits during transient phases (depressurisation due to venting, hydrogen combustion, dose effects …)

Progress and perspectives for releases mitigation (FCVS)

Sand bed filter on a French 900 MWe PWR

Example of liquid scrubber FCVS



After Fukushima:

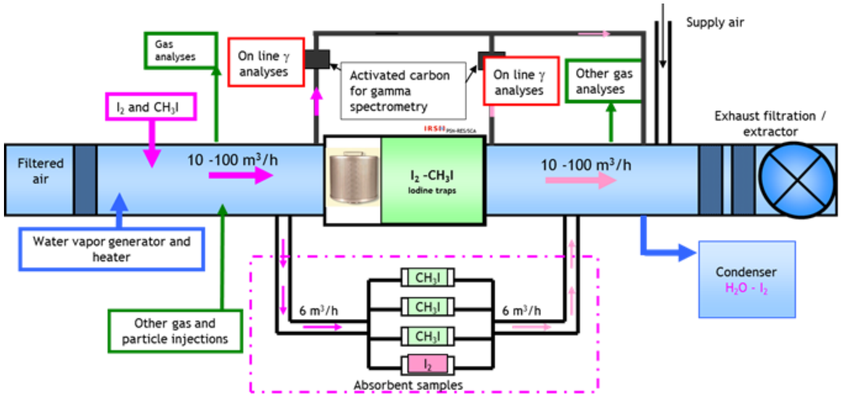
- containment venting appears as a crucial SAMM
- many countries have decided to implement FCVS on NPP or reassess functionning of existing ones in SA
- <u>but</u>, more challenging operating conditions are envisaged (e.g. prolonged use)
- Interrogations on performances of available systems
- large on-going and future R&D initiatives to test existing systems functioning and develop new systems (MIRE, EU PASSAM, many national programs)

Focus on filtration of species which may significantly contribute to the dose (Org-I, I_xO_y and RuO_4) - not considered at design of systems implemented after TMI2

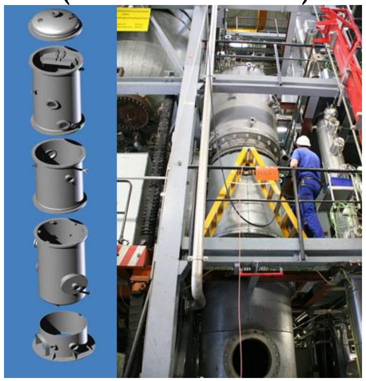
R&D orientations in phase with conclusions of OECD « Status Report » on FCVS (NEA/CSNI/R(2014)7)

Progress and perspectives for releases mitigation (FCVS)

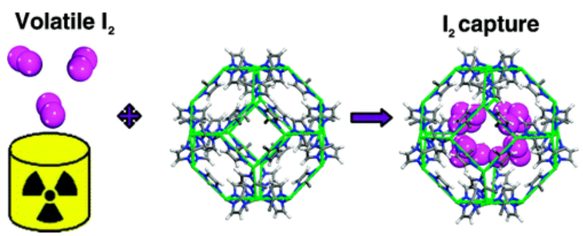
IRSN PERSEE test loop (MIRE/PASSAM)



AREVA combined filter prototype for tests (MIRE/PASSAM)



Innovative filtration media MOFs/Zeolite AgX (MIRE/PASSAM)



Developed knowledge and tools

- Liquid filters: (1) large database on hydrodynamics and aerosols filtration efficiency (DFs) but scrubbing models need development and validation (2) strong coupling between hydrodynamics and aerosols filtration and between chemistry and gaseous iodine species filtration
- Solid filters: large qualification database (DFs) for existing systems for initially prescribed conditions (post TMI2)

Perspectives

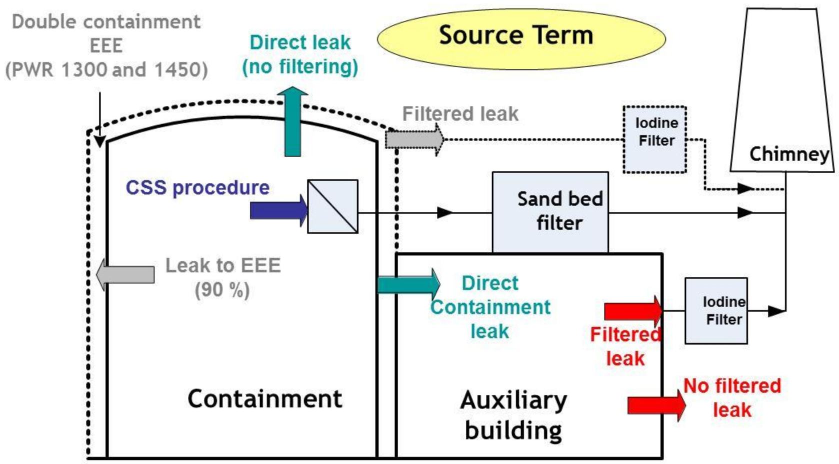
Filtration of species not initially considered, FCVS long term efficiency, efficiency for prolonged use (MIRE, PASSAM)

- Org-I, I_xO_y, RuO_4 filtration
- FCVS efficiency for prolonged use
- Innovative filtration systems (zeolites and MOFs medias, combined systems)

Examples of recent calculations, focus on releases determination

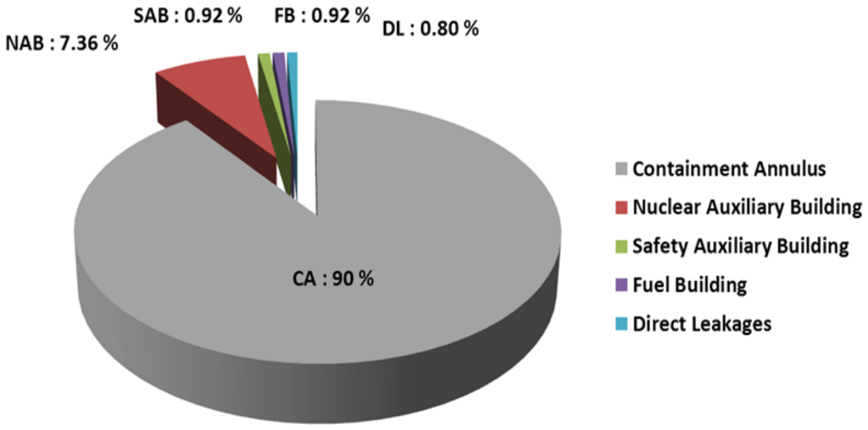
- Releases calculations using ASTEC for various accident sequences, supplemented by sensitivity and uncertainty analyses
- Type and extent of releases with corresponding frequencies, assessment of radiological consequences using L2 PSA
- Fast running calculation tools used for emergency response

Example of French 1 300 MWe PWR Double-walled containment



Filtered and direct leaks to environment

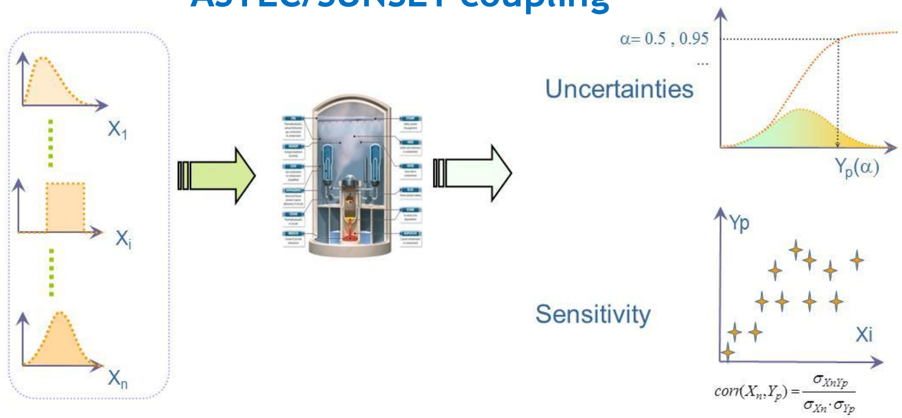
Treatment of leaks to the environment



Primary containment total leakage flow rate:
1.5% volume/day at 5 bar
Leak path from NAB considered
No retention in walls considered

ASTEC releases calculation, sensitivity and uncertainty evaluations

ASTEC/SUNSET coupling

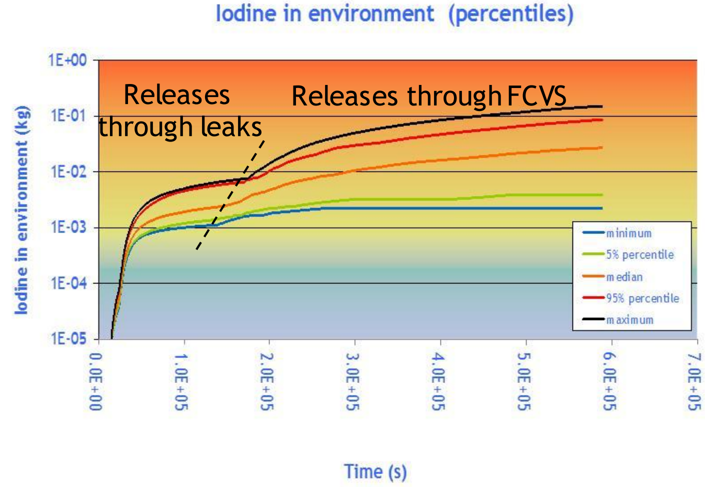


LHS sampling

Astec runs over sampled variables

Sunset uncertainty assessment and sensitivity assessment

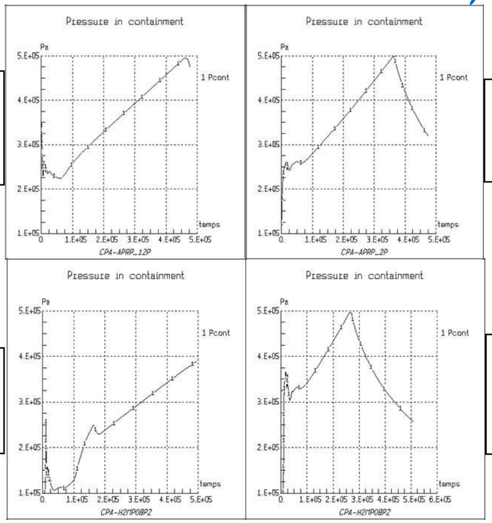
Assessment of variability due to epistemic and stochastic uncertainties



Many sequences considered (≠ physics, SS functioning, containment failure modes)

12" LOCA
FCVS opening at 4 days
Basemat melt-through at 5 days

2" LOCA
FCVS opening at 4 days
Basemat melt-through at 6 days



Loss of FWSG (CSS)
Basemat melt-through at 6 days

Loss of FWSG (no CSS)
FCVS opening at 3 days
Basemat melt-through at 6 days

Identification of main processes affecting ST uncertainties (currently studied in on-going R&D programs)

	1 day	2 days	3 days	6 days
Iodine gaseous mass fraction at primary circuit break	0.72	0.37	0.29	0.35
Iodine oxides deposition rate in containment	-0.75	-0.74	-0.39	-0.21
Organic iodine formation rate in containment atmosphere	0.26	0.30	0.31	0.14
Organic iodine formation rate in containment sumps	-0.04	-0.02	-0.04	-0.03
Organic compound release rate in containment atmosphere	-0.05	-0.02	0.09	0.13
Organic compound release rate from sumps	0.05	0.04	-0.07	-0.09
Ozone formation rate (forward reaction)	0.52	0.29	-0.27	-0.40
Ozone formation rate (backward reaction)	-0.30	-0.05	0.08	0.14

Example of ASTEC releases calculations, L2 PSA results

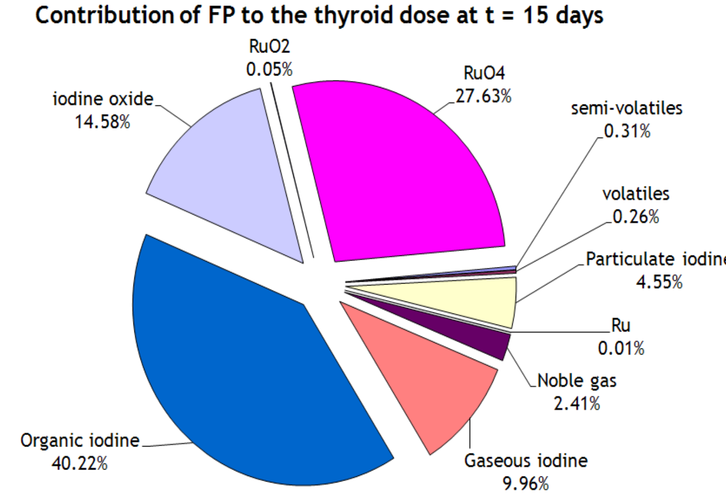
Examples of results obtained for a reference ST evaluation in 2000

Fractions of initial core activity released in the environment

Fission Product	Representative Isotope	900 MWe PWR		1 300 MWe PWR
		S3 (1990)	S3 (2000)	S3 (2000)
Noble gas	Xe^{133}	7,5E-01	9,5E-01	9,5E-01
Particulate iodine	I^{131}	-	4,2E-05	4,5E-05
Gaseous iodine (I_2)	I^{131}	-	2,5E-07	2,2E-03
Non organic iodine (I_2 and particulate I)	I^{131}	3,0E-03	4,5E-05	2,2E-03
Organic iodine	I^{131}	5,5E-03	4,2E-03	2,2E-02
Cesium	Cs^{137}	3,5E-03	3,5E-05	3,5E-05
Actinides	Pu^{239}	5,0E-05	9,75E-08	1,0E-07

➲ Specific attention to be given to Org-I

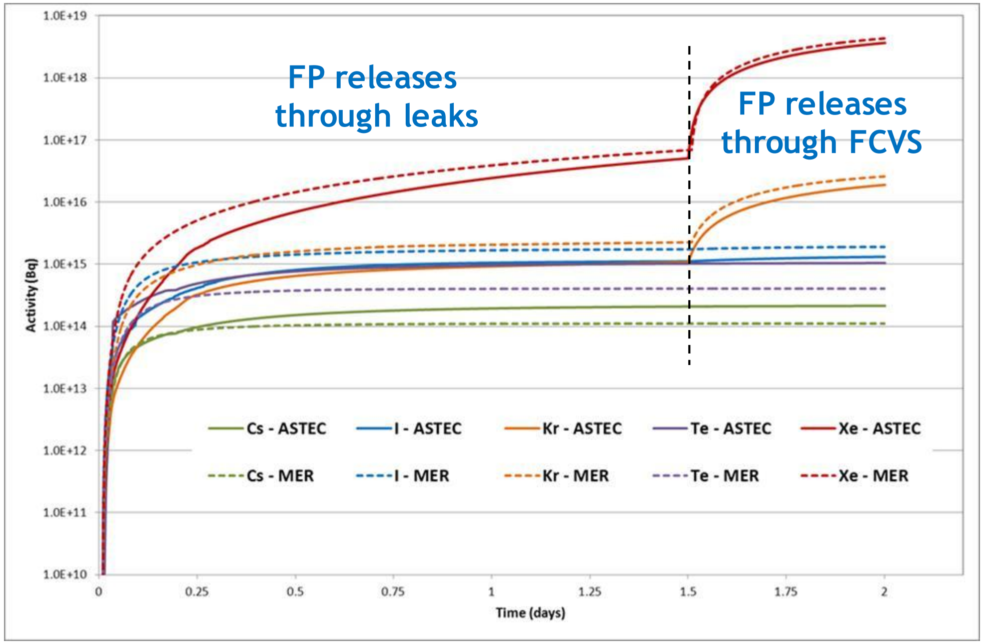
Radiological impact of Ru and I (L2 PSA in 2010) - accident sequence with venting and failure of active safety systems



➲ Ru issue to be further assessed

➲ Continued attention in R&D for Org-I and I_xO_y

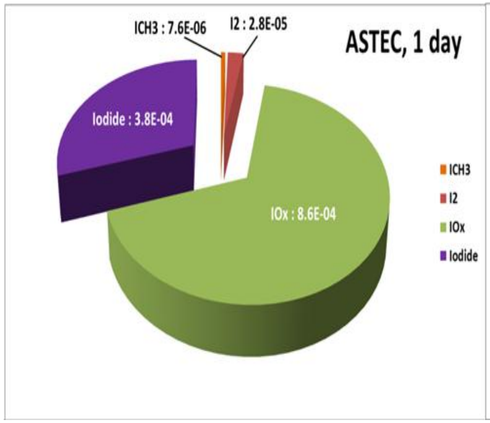
Comparison of ASTEC and fast running code calculations (MER code for L2 PSA) in 2014

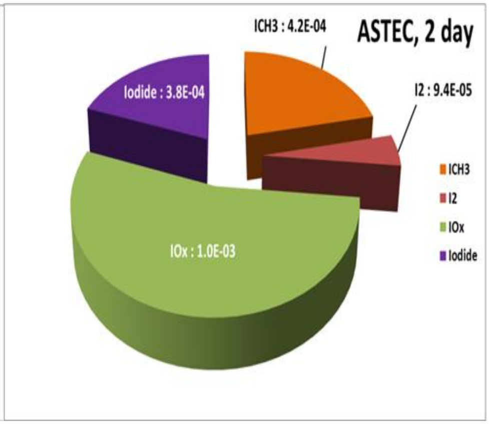


Considered DFs for filtration

Filtration system associated to :	Filters decontamination factor
Annulus containment ventilation	Aerosols : 1000 Oxide iodine (IOx) : 500 * Molecular iodine (I_2) : 100 Organic iodine (CH_3I) : 10
Auxiliary buildings ventilation (except nuclear auxiliary building)	Aerosols : 1000 Oxide iodine (IO_x) : 500 * Molecular iodine (I_2) : 1000 Organic iodine (CH_3I) : 100
FCVS (Filtered Containment Venting System)	Aerosols : 1000 Oxide iodine (IO_x) : 500 * Molecular iodine (I_2) : 10 Organic iodine (CH_3I) : 1

Detailed iodine speciation





➲ Continued attention in R&D for Org-I, I_xO_y and filtration efficiency in SA

Summary of methods and tools used at IRSN and perspectives

- Deterministic and probabilistic approach: ASTEC SA code used in best-estimate calculations, supplemented by sensitivity and uncertainties studies, and as a support to PSA Level-2
- FAST running sofware tools developed based on R&D knowledge (on-going FASTRUN OECD benchmark exercise)
  - Results strongly dependent on ≠ accident scenarios database (e.g. NPP type) and ≠ atmospheric dispersion tools
  - Update of simplified models necessary (consideration of recent R&D results)
- Towards the development of fast emergency response prognosis and diagnosis tools to help the decision making process notably for protection measures (FP7 CESAM and H2020 FASTNET)
  - Development of reference accidental scenarios databases
  - Advanced coupled probabilistic/deterministic approaches
  - Implementation of BBN (Bayesian Network) methods to treat systematically stochastic and epistemic uncertainties

Conclusion and open issues

- Large progress made in ST modelling and evaluations
- Remaining issues and projects under elaboration or evaluation (H2020 and OECD):
  - FP release from fuel for specific accident situations, new fuel types
  - Delayed releases during SA (in relation to venting and long term SAM)
  - Trapping, filtration efficiencies in SA(org-I, RuO_4)
- Databases on FP behaviour (theoretical approach and confirmatory tests when necessary) adequate for the development of predictive modelling
- Consider further in future projects improvement of the on-site and off-site management for the emergency and post-emergency phase
  - Development of prognosis and diagnostic tools for the emergency phase
  - Management of contaminated gaseous and liquid effluents resulting from short-term emergency and post-emergency measures
  - Developing an instrumentation for the optimization of the accident conduct (e.g. opening/closing FCVS, knowledge of in-containment ST and releases, …)