TRACTEBEL Engineering
GDF SUEZ

Use of MELCOR Calculations in the Frame of Level 2 Probabilistic Safety Assessment of the Belgian Plants

4th European MELCOR User Group – 16th to 17th of April, 2012 – Cologne, Germany

C. NGATCHOU

CHOOSE EXPERTS, FIND PARTNERS

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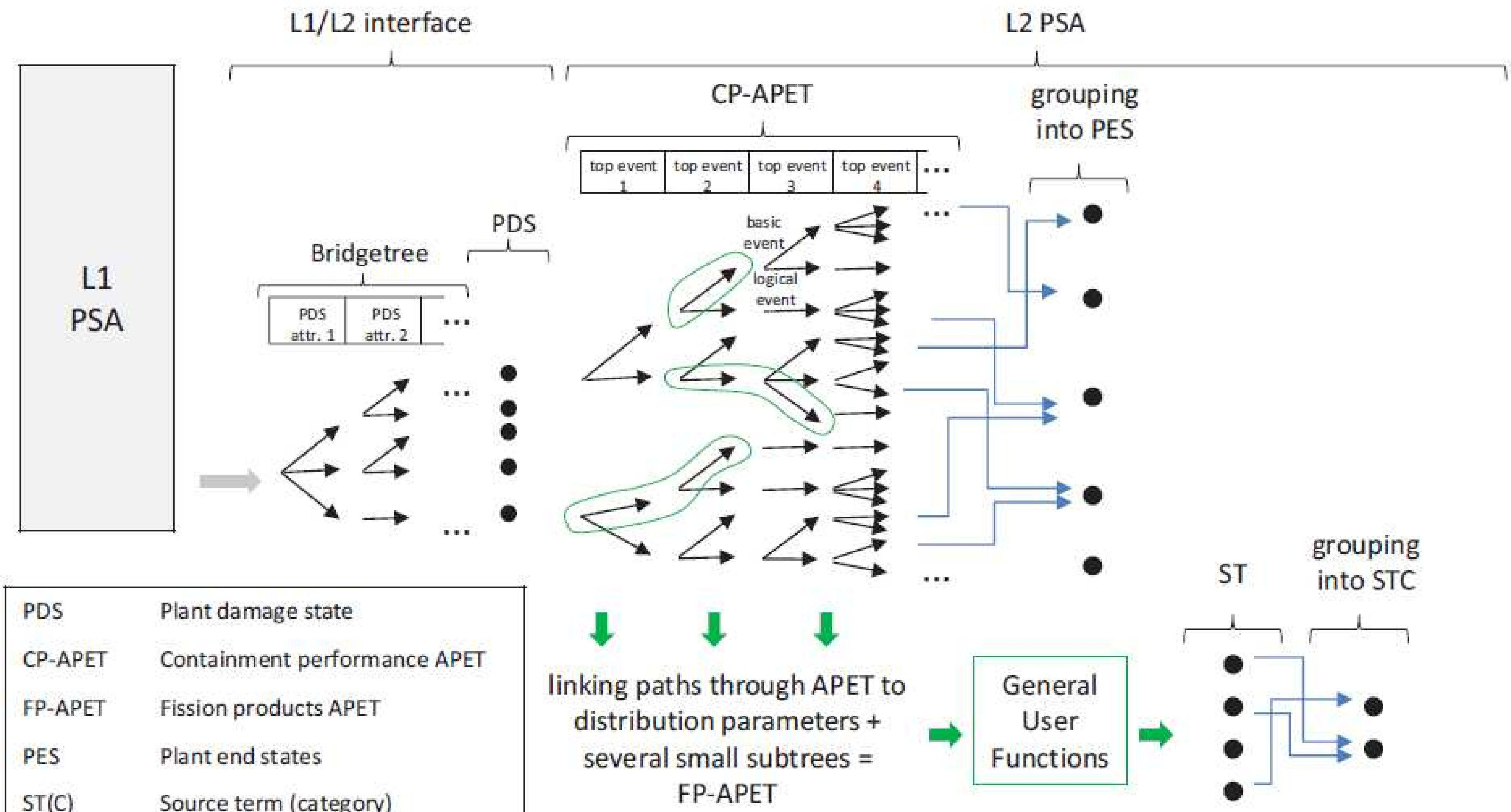
LEVEL 2 PSA OF BELGIAN PLANTS (BACKGROUND)

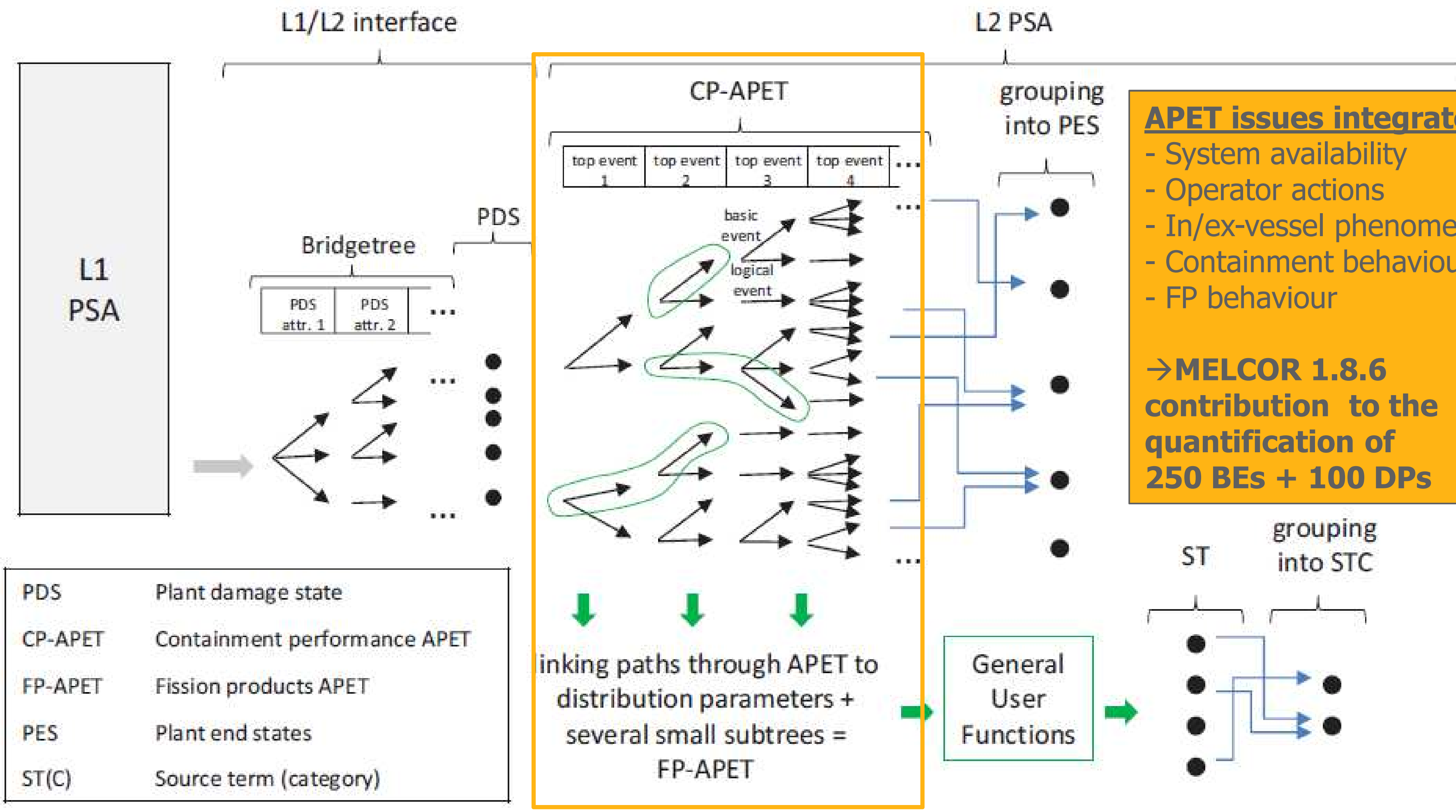
- Previous L2PSA of Belgian units took place in the mid-1990's
  - **Objective was to evaluate the Containment Performance (CP) considering some SAMG actions**
  - **Different Containment Event Tree developed for 2 units (~110 basic events quantified per unit)**
  - **Severe Accident code: MELCOR 1.8.1 & 1.8.2**
- Objectives of the update L2PSA of Belgian units which started in the mid-2000's
  - **Evaluate the CP considering all SAMG actions and Emergency Operating Procedures (FR-C.1)**
  - **Evaluate the Fission Product (FP) Source Term (ST)**
  - **Integrate Human Reliability Analysis (HRA) over Operator Actions (OAs)**
  - **Evaluate shutdown Plant Operating States**
- Update L2PSA of Belgian units
  - **Generic Accident Progression Event Tree (APET) developed for all units**
  - **250 basic events and 100 FP Distribution Parameters (DPs)**
  - **Severe Accident code: MELCOR 1.8.5 & 1.8.6**
  - **Probabilistic code for APET evaluation: EVNTRE**

LEVEL 2 PSA OVERVIEW



PDS	Plant damage state
CP-APET	Containment performance APET
FP-APET	Fission products APET
PES	Plant end states
ST(C)	Source term (category)

LEVEL 2 PSA OVERVIEW



PDS	Plant damage state
CP-APET	Containment performance APET
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APET issues integrate

- System availability
- Operator actions
- In/ex-vessel phenomena
- Containment behaviour
- FP behaviour

→MELCOR 1.8.6 contribution to the quantification of 250 BEs + 100 DPs

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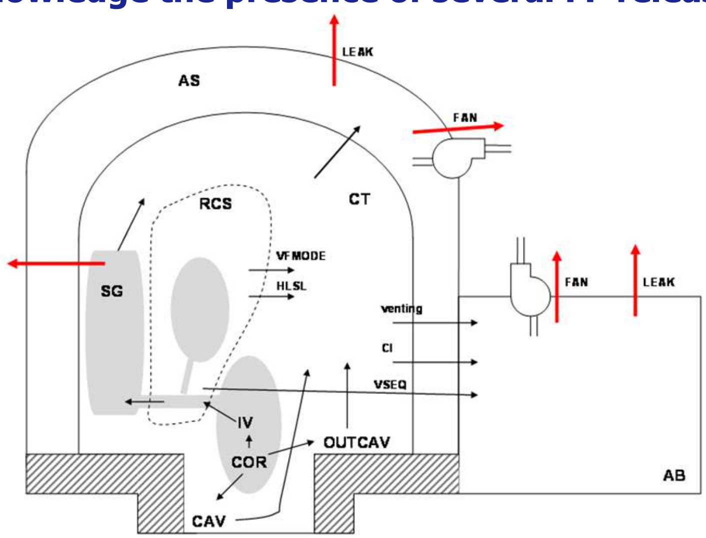
MELCOR CALCULATION SELECTION PROCESS

- MELCOR calculations aim at providing support to the expert performing the quantification:
  - **MELCOR calculations can not match all APET branches**
  - **MELCOR calculations aim at supporting the quantification of the APET phenomenological issues**
  - **Other sources for the quantification are available**
- MELCOR calculation matrix:
  - **Is based on engineering judgment over PDS attributes definition, literature information, and REX**
  - **Should acknowledge the presence of several FP release flow paths**



AB: Auxiliary Building
AS: Annular Space
CAV: Reactor Cavity
CI: Containment Isolation
COR: Core / Corium
CT: Containment
HLSL: Hot Leg / Surge Line creep failure
IV: In-Vessel
OUTCAV: Outside reactor Cavity
VFMODE: Vessel Failure Mode
VSEQ: V-sequence (ISLOCA)

MELCOR CALCULATION SELECTION PROCESS

- Step 1: selection of representative calculations (MELCOR full-scope)
  - **Definition of BC calculations starting from the initiating events as defined in the PDS attributes**
  - **Considering OAs in Emergency Operating Procedures (FR-C.1): RCS depressurization via the PPORVs or via the SG PORVs**
  - **Considering the SAMGs: OAs included in the SA management guidance**
  - **No need to implement all the possible combinations of the safety features**
- Step 2: consideration of specific phenomenological issues (MELCOR stand-alone)
  - **Flashing of the Reactor Coolant System (RCS) content at Vessel Failure (VF)**
  - **Ex-vessel Fuel Coolant Interaction (FCI)**
  - **Containment isolation failure**
  - **Distribution of FP along multiple flow paths**
- Step 3: identification of additional calculations during the quantification process
  - **Additional request once the quantification process is launched (sensitivity calculation)**
- Step 4: consideration of shutdown states

ID	Creep Failure	PPORVs	SG PORVs	AFW	ECCS	CHR	AS VE	AS VI
	No	No	No	No	No	No	No	No
SBO	HLSL	No	No	No	No	No	No	No
	No	No	Total recov. early					
	No	No	No	AF avail.	Early recov.	Early recov.	No	Avail.
	No	No	No	No	No	No	No	No
LossFW	No	Very early 3/3	No	No	LPSI avail. (inj. only) or early HPSI	1 SP avail.	Avail.	Avail.
	No	Early 3/3	No	No	LPSI avail. (inj. only) or early HPSI	No	No	No
	HLSL	No	No	No	No	Early recov.	No	Avail.
	SGTR (2	No	No	No	LPSI avail. (inj. only)	1 SP avail.	Avail.	No
	SGTR (1						No	No
	No						No	No
	No						No	No
VSLOCA	No						No	Avail.
	No						Avail.	No
	No						No	No
	No						No	No
	No						No	No
SLOCA	No						Avail.	Avail.
	No						No	Avail.
	No						Avail.	No
	No						Avail.	Avail.
	No						Avail.	No
	No	Very early 1/3	No	No	No	No	No	No
	No	No	No	No	No	No	No	No
LLOCA	No	No	No	No	Early LPSI (inj. only)	No	Avail.	Avail.
	No	No	No	No	Very early LPSI (inj. only)	1 SP avail.	Avail.	Avail.
	No	No	No	No	No	No	No	No
SGTR	No	Early 3/3	No	No	No	No	No	No
	No	No	Early	Early recov.	No	No	No	Avail.
	No	Early 1/3	Early	Early recov.	No	No	Avail.	No
ISLOCA	No	No	Avail.	AF avail.	HPSI avail.	Avail.	Avail.	Avail.

Base Case calculations (no OAs and no safety systems recovery)

- **Very Early refers to time phase between core damage and SAMGs opening**
- **Early refers to time phase between SAMGs opening and VF**
- **Late refers to the phase after VF**

All Base Case calculations can be useful to assess:

- **In-vessel melt progression**
- **Grace time to VF**
- **Operator response time within the SAMGs**
- **Containment challenges**
- **FP behaviour**

AS VE: Annular Space Extraction Ventilation
AS VI: Annular Space Internal Ventilation

ID	Creep Failure	PPORVs	SG PORVs	AFW	ECCS	CHR	AS VE	AS VI
SBO	No	No	No	No	No	No	No	No
	HLSL	No	No	No	No	No	No	No
	No	No	Total recov. early					
	No	No	No	AF avail.	Early recov.	Early recov.	No	Avail.
LossFW	No	No	No	No	No	No	No	No
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	No	Early 3/3	No	No	LPSI avail. (inj. only) or early HPSI	No	No	No
	HLSL	No	No	No	No	Early recov.	No	Avail.
	SGTR (2 tubes)	No	No	No	LPS			
	SGTR (10 tubes)	No	No	No	LPS			
	No	No	No	No	LPS			
VSLOCA	No	No	No	No	No			
	No	No	No	AF avail.	No			ail.
	No	No	Very early	AF avail.	Early HPSI (inj. only)	No	Avail.	No
	No	No	Early	AF avail.	No	1 SP avail.	No	No
	No	Early 1/3	No	No	No	No	No	No
SLOCA	No	No	No	No	No	No	No	No
	No	No	Very early	AF avail.	Early recov. (inj. only)	1 SP avail.	Avail.	Avail.
	No	No	Early	AF avail.	Early LPSI (inj. only)	1 SP avail.	No	Avail.
	No	Early 3/3	No	No	Early recov. (inj. only)	1 SP avail.	Avail.	No
	No	Very early 3/3	No	No	Very early recov. (inj. only)	No	Avail.	Avail.
	No	Early 1/3	No	No	Late LPSI	No	Avail.	No
	No	Very early 1/3	No	No	No	No	No	No
LLOCA	No	No	No	No	No	No	No	No
	No	No	No	No	Early LPSI (inj. only)	No	Avail.	Avail.
	No	No	No	No	Very early LPSI (inj. only)	1 SP avail.	Avail.	Avail.
SGTR	No	No	No	No	No	No	No	No
	No	Early 3/3	No	No	No	No	No	No
	No	No	Early	Early recov.	No	No	No	Avail.
	No	Early 1/3	Early	Early recov.	No	No	Avail.	No
ISLOCA	No	No	Avail.	AF avail.	HPSI avail.	Avail.	Avail.	Avail.

Assessment of the impact of primary or secondary depressurization on the accident progression

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AS VI: Annular Space Internal Ventilation

ID	Creep Failure	PPORVs	SG PORVs	AFW	ECCS	CHR	AS VE	AS VI
SBO	No	No	No	No	No	No	No	No
	HLSL	No	No	No	No	No	No	No
	No	No	Total recov. early					
	No	No	No	AF avail.	Early recov.	Early recov.	No	Avail.
LossFW	No	No	No	No	No	No	No	No
	No	Very early 3/3	No	No	LPSI avail. (inj. only) or early HPSI	1 SP avail.	Avail.	Avail.
	No	Early 3/3	No	No	LPSI avail. (inj. only) or early HPSI	No	No	No
	HLSL	No	No	No	No	Early recov.	No	Avail.
	SGTR (2 tubes)	No	No	No	LPSI avail. (inj. only)	1 SP avail.	Avail.	No
			No	No	LPSI avail. (inj. only)	1 SP avail.	No	No
			No	No	LPSI avail.	1 SP avail.	No	No
			No	No	No	No	No	No
			No	AF avail.	No	No	No	Avail.
			Very early	AF avail.	Early HPSI (inj. only)			
			Early	AF avail.	No			
			No	No	No			
	No	No	No	No	No			
	No	No	Very early	AF avail.	Early recov. (inj. only)			
	No	No	Early	AF avail.	Early LPSI (inj. only)			
SLOCA	No	Early 3/3	No	No	Early recov. (inj. only)			
	No	Very early 3/3	No	No	Very early recov. (inj. only)			
	No	Early 1/3	No	No	Late LPSI			
	No	Very early 1/3	No	No	No			
LLOCA	No	No	No	No	No			
	No	No	No	No	Early LPSI (inj. only)			
	No	No	No	No	Very early LPSI (inj. only)			
SGTR	No	No	No	No	No			
	No	Early 3/3	No	No	No			
	No	No	Early	Early recov.	No			
	No	Early 1/3	Early	Early recov.	No			
ISLOCA	No	No	Avail.	AF avail.	HPSI avail.	Avail.	Avail.	Avail.

LossFW_1
PPORVs efficiency + Impact of fast RCS injection on core degradation

LossFW_2
Bounding scenario to assess H2 risk

VSLOCA
Very slow accident progression: fast SG depressurization + early RCS injection

SLOCA_1
Bounding scenario to assess in-vessel H2 production

SLOCA_2
Late containment overpressurization

AS VE: Annular Space Extraction Ventilation
AS VI: Annular Space Internal Ventilation

ID	Creep Failure	PPORVs	SG PORVs	AFW	ECCS	CHR	AS VE	AS VI
SBO	No	No	No	No	No	No	No	No
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	No	Early 3/3	No	No	LPSI avail. (inj. only) or early HPSI	No	No	No
	HLSL	No	No	No	No	Early recov.	No	Avail.
	SGTR (2 tubes)	No	No	No	LPSI avail. (inj. only)	1 SP avail.	Avail.	No
	SGTR (10 tubes)	No	No	No	LPSI avail. (inj. only)	1 SP avail.	No	No
	No	No	No	No	LPSI avail.	1 SP avail.	No	No
VSLOCA	No	No	No	No	No	No	No	No
	No	No	No	AF avail.	No	No	No	Avail.
	No	No	Very early	AF avail.	Early HPSI (inj. only)	No	Avail.	No
	No					1 SP avail.	No	No
	No					No	No	No
SLOCA	No	No	No	No	No	No	No	No
	No	No	Very early	AF avail.	Early recov. (inj. only)	1 SP avail.	Avail.	Avail.
	No	No	Early	AF avail.	Early LPSI (inj. only)	1 SP avail.	No	Avail.
	No	Early 3/3	No	No	Early recov. (inj. only)	1 SP avail.	Avail.	No
	No	Very early 3/3	No	No	Very early recov. (inj. only)	No	Avail.	Avail.
	No	Early 1/3	No	No	Late LPSI	No	Avail.	No
	No	Very early 1/3	No	No	No	No	No	No
LLOCA	No	No	No	No	No	No	No	No
	No	No	No	No	Early LPSI (inj. only)	No	Avail.	Avail.
	No	No	No	No	Very early LPSI (inj. only)	1 SP avail.	Avail.	Avail.
SGTR	No	No	No	No	No	No	No	No
	No	Early 3/3	No	No	No	No	No	No
	No	No	Early	Early recov.	No	No	No	Avail.
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ISLOCA	No	No	Avail.	AF avail.	HPSI avail.	Avail.	Avail.	Avail.

Assessment of different release paths for fission product

AS VE: Annular Space Extraction Ventilation
AS VI: Annular Space Internal Ventilation

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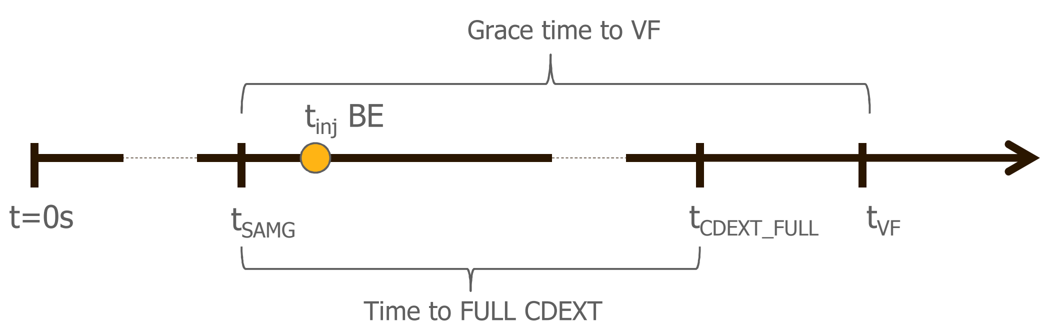
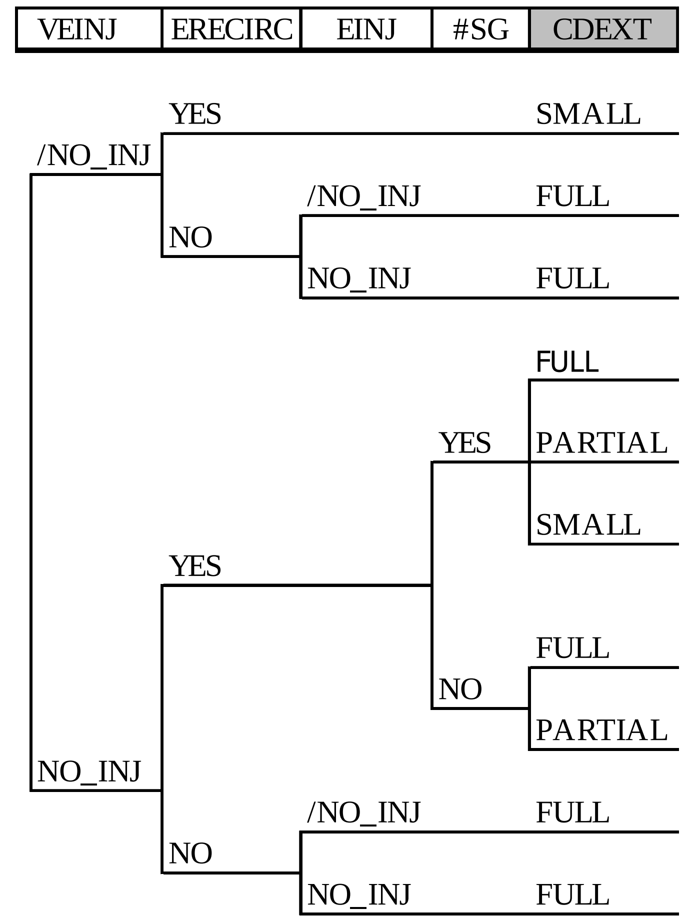
CORE DAMAGE EXTENT

- SMALL: CDEXT < 5% total core mass
- PARTIAL: 5% < CDEXT < 35% total core mass
- FULL: CDEXT > 35% total core mass



- Quantification approach
  - **BC calculation gives the time frame in which water injection might be efficient to avoid full CDEXT**
  - **Likelihood of core degradation mitigation is determined by comparing this time frame to b.e. injection timing**
  - **b.e. injection: at least 20' after SAMGs opening**



(V)EINJ: (Very) Early RCS injection
ERECIRC: Early cooled RCS recirculation
#SG: Status of SGs at core damage

CORE DAMAGE EXTENT

- SMALL: CDEXT < 5% total core mass
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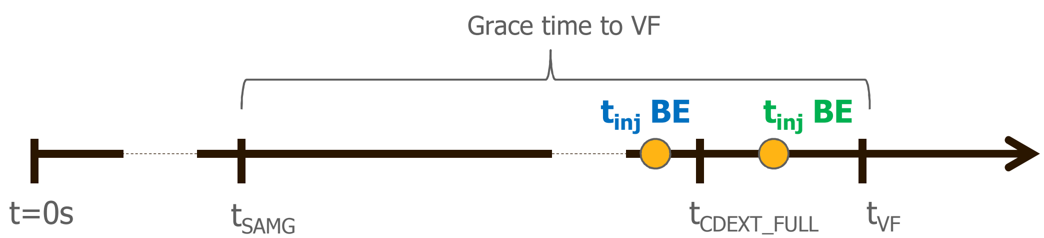
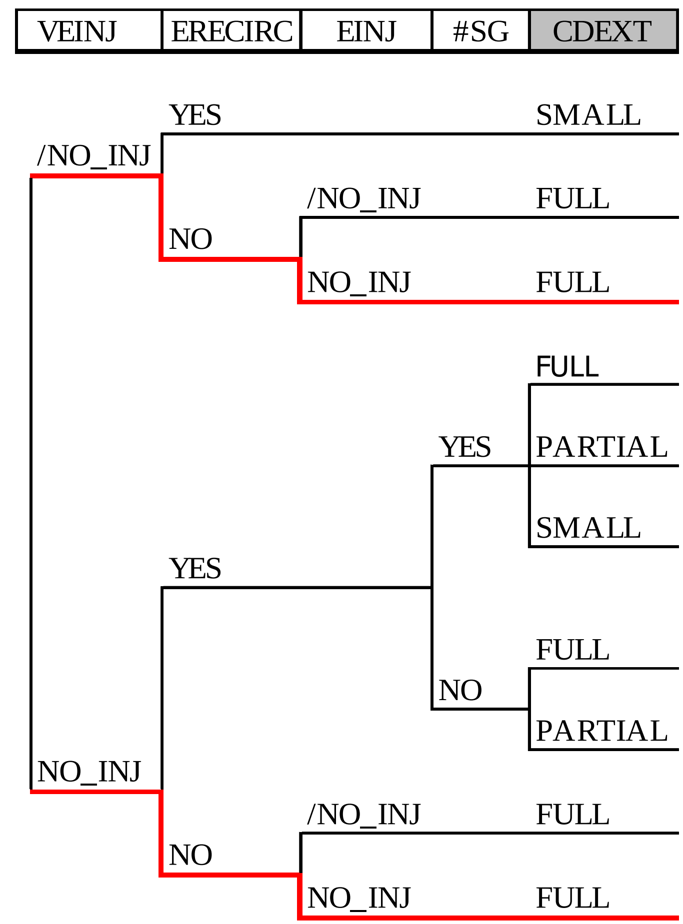


ID	AFW	E (s)	t_inj_SI (s)	t_CDEXT_Partial (s)	t_CDEXT_Full (s)
ID_1_BC	No	20000	–	20500	20600
ID_1_P1	Yes	47100	–	169600	169800
ID_2_BC	No	2600	–	10500	17400
ID_2_P1	Yes	2600	3800	4200	10700
ID_2_P2	Yes	2600	–	8500	10000
ID_2_P3	No	2600	4100	5000	–



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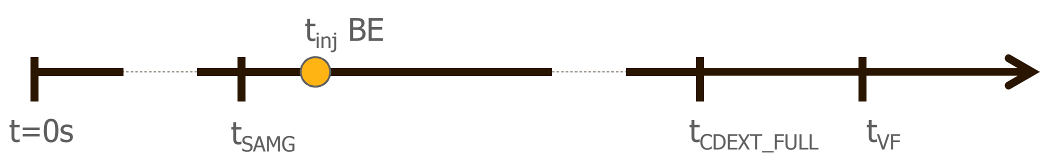

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ID_1_BC	No	20000	–	20500	20600
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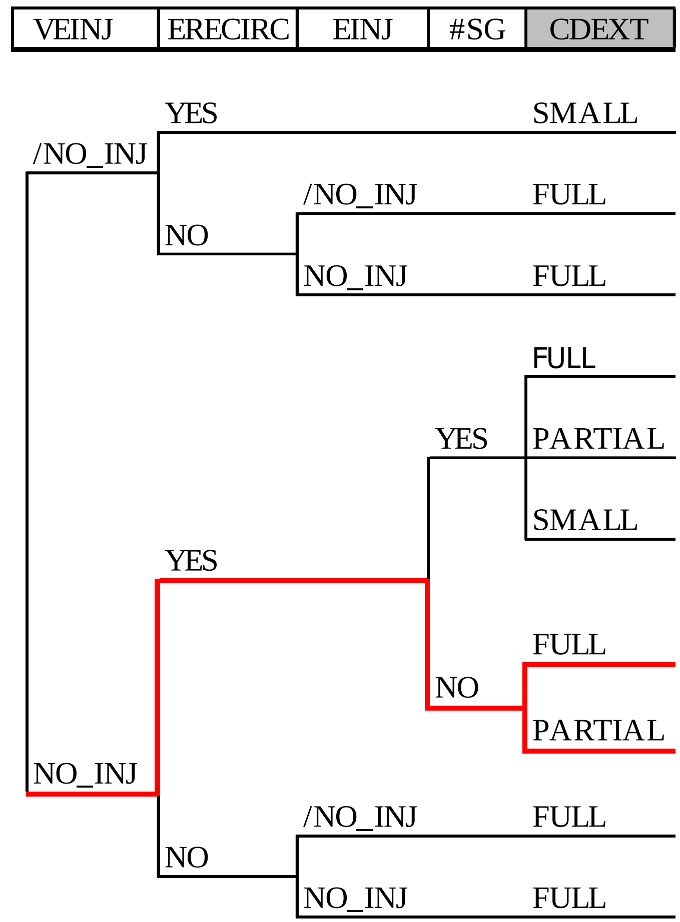
ID_2_BC	No	2600	–	10500	17400
ID_2_P1	Yes	2600	3800	4200	10700
ID_2_P2	Yes	2600	–	8500	10000
ID_2_P3	No	2600	4100	5000	–



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CORE DAMAGE EXTENT

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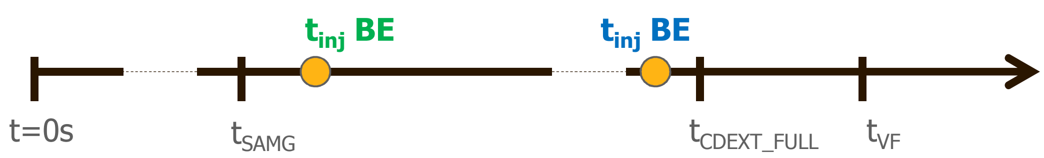
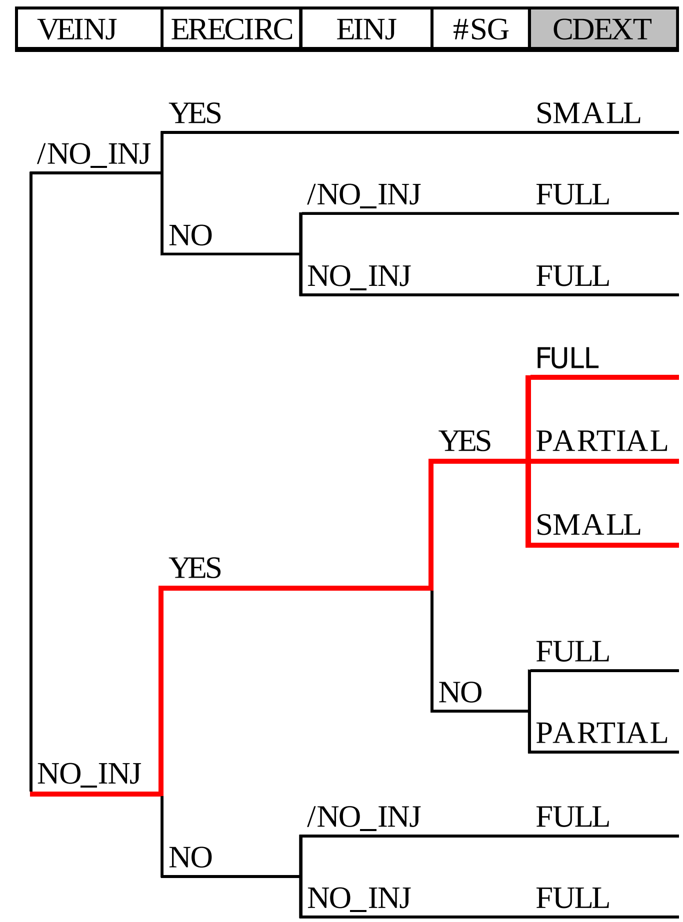
- FULL: CDEXT > 35% total core mass



ID	AFW	E (s)	t_inj_SI (s)	t_CDEXT_Partial (s)	t_CDEXT_Full (s)
ID_1_BC	No	20000	–	20500	20600
ID_1_P1	Yes	47100	–	169600	169800
ID_2_BC	No	2600	–	10500	17400
ID_2_P1	Yes	2600	3800	4200	10700
ID_2_P2	Yes	2600	–	8500	10000
ID_2_P3	No	2600	4100	5000	–



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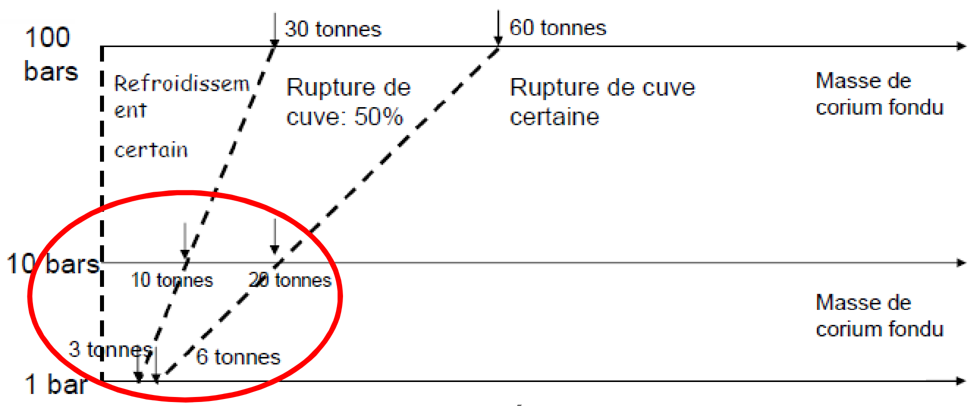
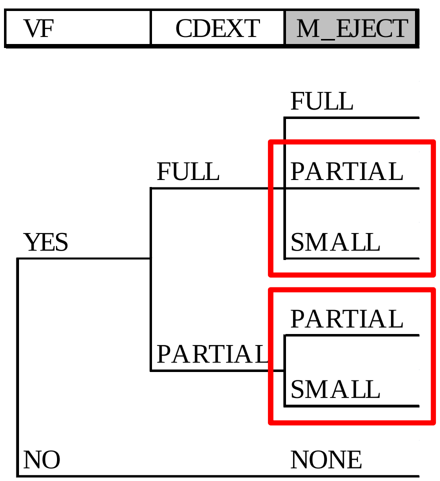
CORE DEBRIS EJECTION AT VESSEL FAILURE

- M_EJECT FULL /PARTIAL /SMALL
  - **100% /60% /30% of total core mass ejected at VF**
- Supporting calculations + Engineering Judgment
  - **Every MELCOR calculation with VF is used**
  - **Every calculation with PARTIAL CDEXT and no VF (successful core reflooding after RCS injection)**



J.-M. Seiler (CEA) et al., "La Rétention du Corium", SFEN 2009

Refroidissement certain: In-vessel retention
Rupture de cuve: Vessel failure
Masse de corium fondu: Molten corium mass



- Assignment of probabilities
  - **All debris relocated in LP is ejected at VF**
  - **Low confidence level on tools to assess debris ejection at VF**
  - **Very unlikely that total core mass be ejected at VF**
  - **If PARTIAL CDEXT → debris mass in LP is lower**

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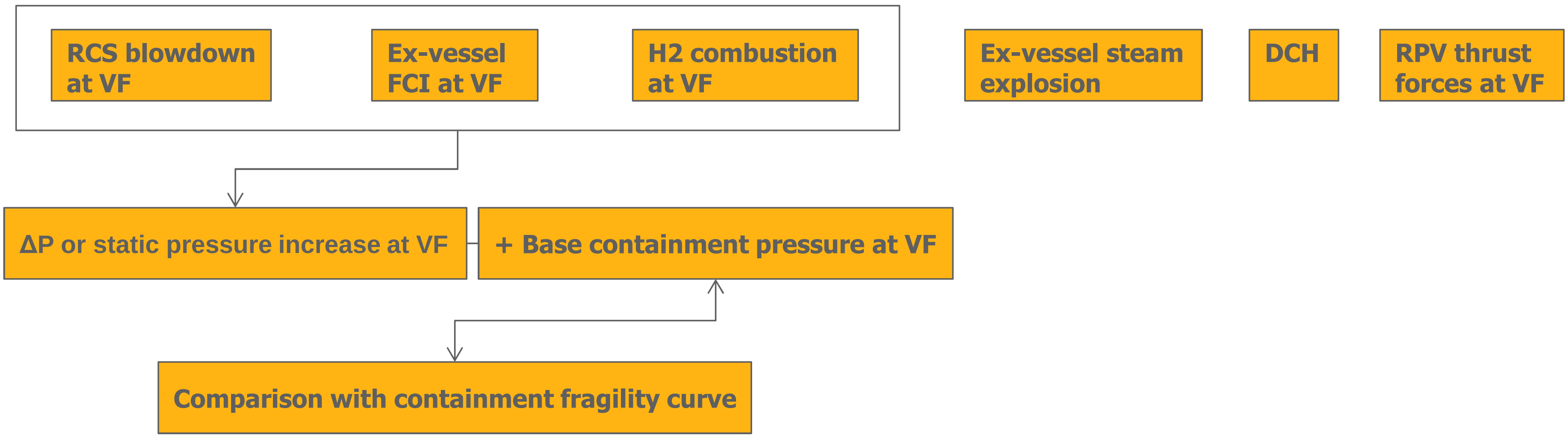
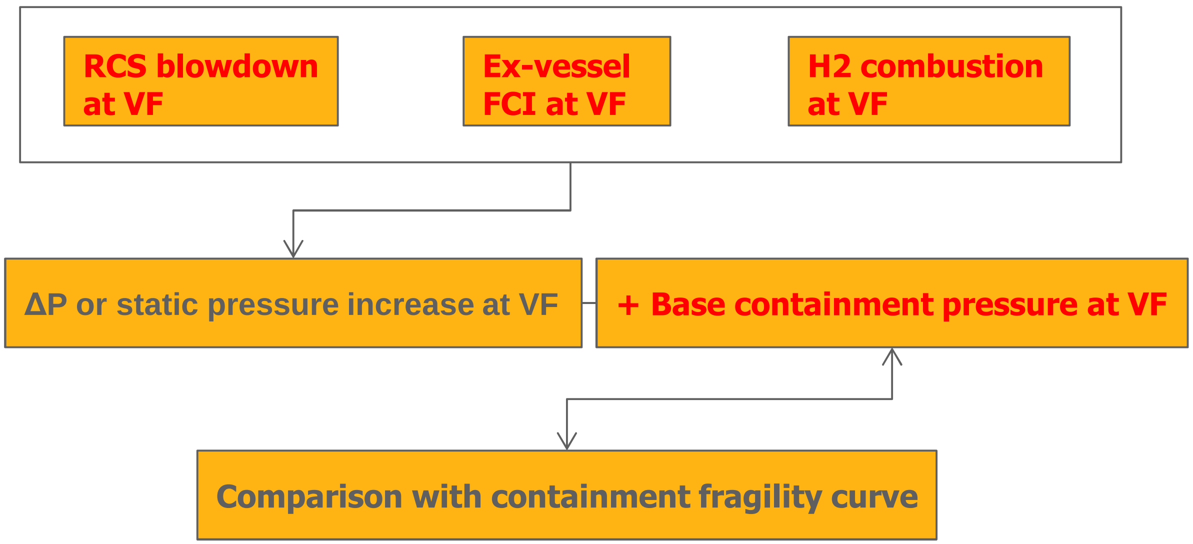
CONTAINMENT FAILURE DUE TO PRESSURE RISE AT VF



- Assign split fraction to basic events linked to containment failure due to static pressure rise at VF
- Do not include loads induced by DCH, dynamic pressure wave of a steam explosion, or vessel rocketing which happen at a shorter time scale

CONTAINMENT FAILURE DUE TO PRESSURE RISE AT VF



- Assign split fraction to basic events linked to containment failure due to static pressure rise at VF
- Do not include loads induced by DCH, dynamic pressure wave of a steam explosion, or vessel rocketing which happen at a shorter time scale

Ex-vessel steam explosion | **DCH** | **RPV thrust forces at VF**

- H2 risk assessment
  - **Based on conditions prevailing in containment just before VF**
  - **Expert Judgement process + H2 risk analyser routine**
  - **H2 Recombiners are installed in all Belgian units**

  → **No H2 risk at VF; gas mixture in containment not flammable in all control volumes**
- Uncertainties treated with Crystal Ball
  - **Applying distribution probabilities on results**

CONTAINMENT FAILURE DUE TO PRESSURE RISE AT VF

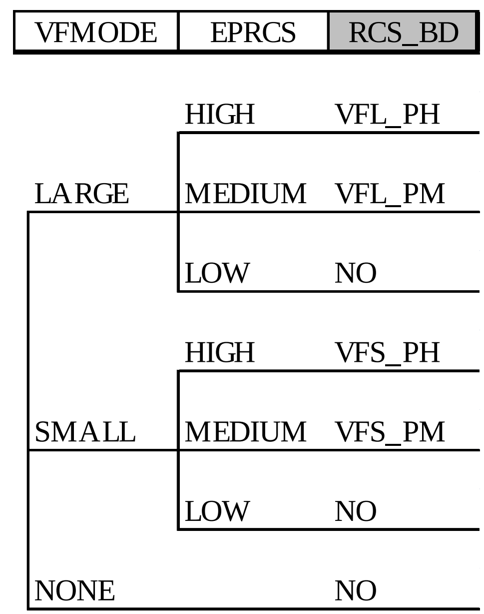
> Steam spike due to blowdown of the RCS content at VF

- In case of early water in reactor cavity → difficult to isolate ΔP induced by RCS blowdown at VF

→ Stand-alone calculations performed with a simplified input deck

- Characteristics of steam flow at VF given by MELCOR calculations
- Stand-alone calculations performed for both small and large VF

VFMODE	Breach (m^2)	EPRCS	$P_{RCS\ at\ VF}$ (bar)	ID	Pressure rise period Δt (s)	Δp (bar)
SMALL	0.037	HIGH	160	ID_1	47	-
	0.031		160	ID_2	43	-
	0.024	MEDIUM	76	ID_3	70	-
	0.044		69	ID_4	80	-
LARGE	3.14	HIGH	160	ID_1	4	-
	3.14		160	ID_2	4	-
	3.14	MEDIUM	76	ID_3	6	-
	3.14		69	ID_4	8	-



VFMODE: Vessel Failure mode
EPRCS: RCS pressure (end early phase)

CONTAINMENT FAILURE DUE TO PRESSURE RISE AT VF

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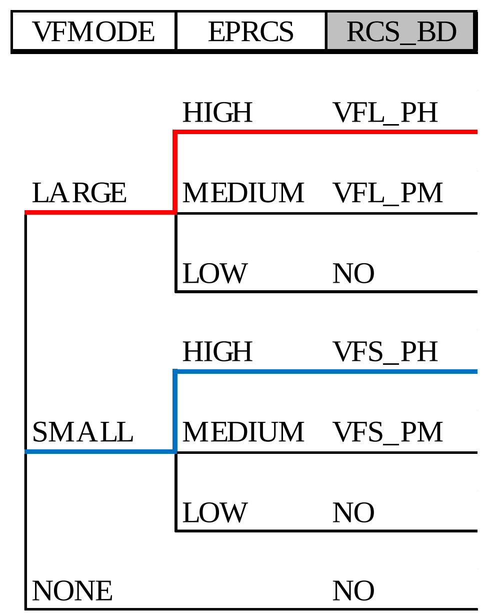
LARGE	3.14	HIGH	160	ID_1	4	-
	3.14		160	ID_2	4	-
	3.14	MEDIUM	76	ID_3	6	-
	3.14		69	ID_4	8	-



VFMODE: Vessel Failure mode
EPRCS: RCS pressure (end early phase)

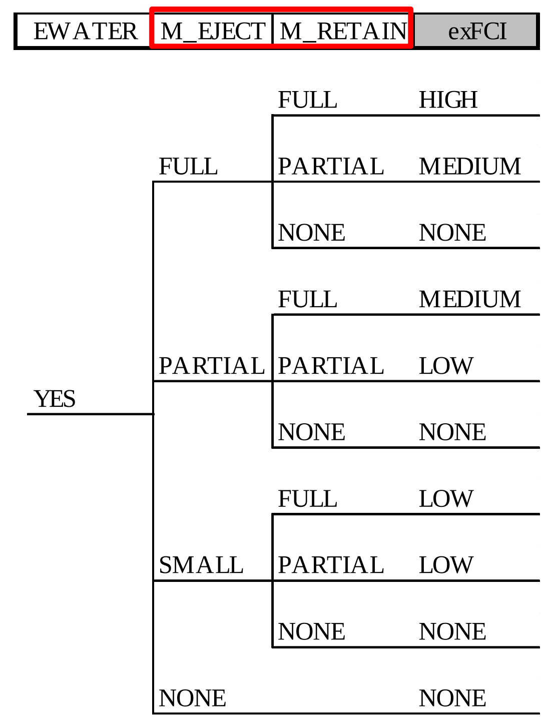
CONTAINMENT FAILURE DUE TO PRESSURE RISE AT VF

> Steam spike due to ex-vessel Fuel Coolant Interaction

- Full-scope run → difficult to isolate ΔP induced by quenching at VF
- Stand-alone calculations → ΔP induced by quenching at VF
- Approach consists in the assessment of the:
  - **Corium mass participating in FCI**
  - **Energy released during corium quenching**
  - **Characteristic time of debris ejection**

$$E_{Quench}(t) = \left(x_{no}^{Zr} . Q_{ox}^{Zr} + x_{no}^{Fe} . Q_{ox}^{Fe} + x_{frag} . E_{FCI}\right) m_{FCI} . f(t, T_r)$$

exFCI	m_tot (%)	T_r(s)	E_Quench (GJ)	Δp (bar)
LOW	15	3	19.6	-
	30	6	39.2	-
MEDIUM	45	9	58.8	-
	60	12	78.4	-
HIGH	80	16	105	-
	100	20	131	-



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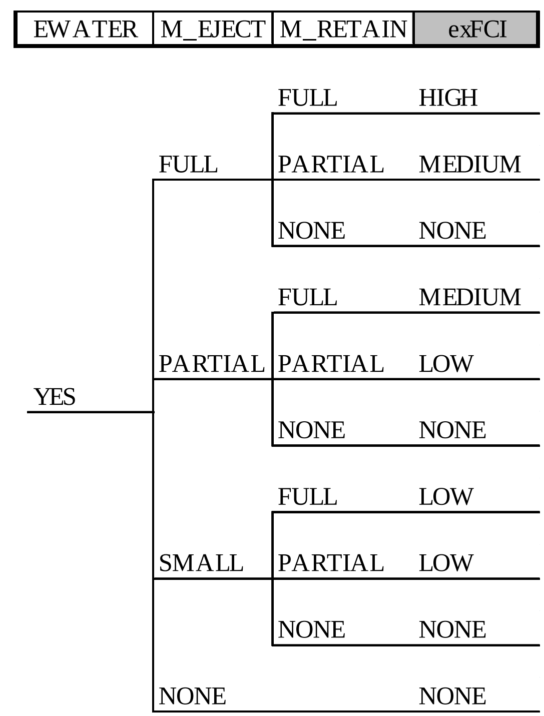

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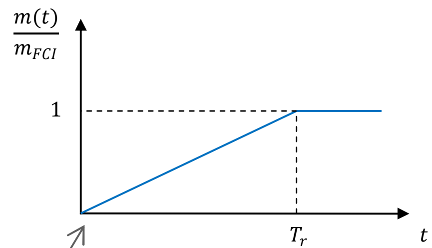

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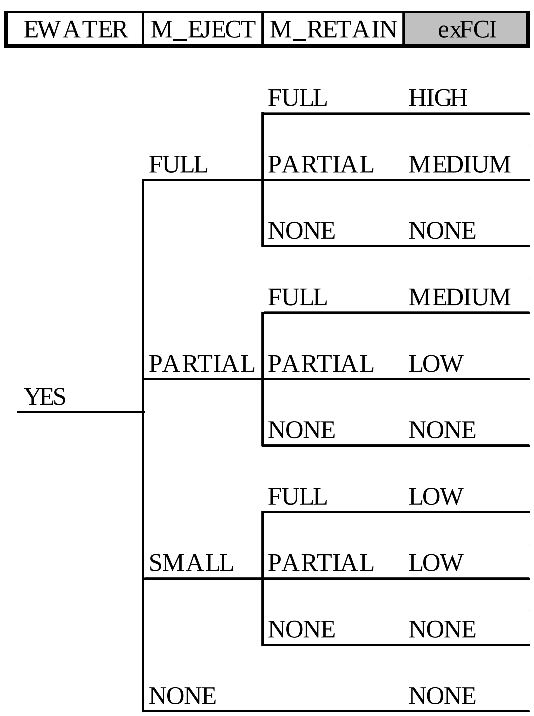

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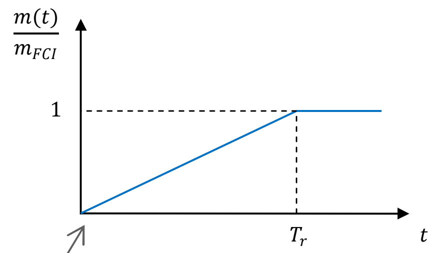

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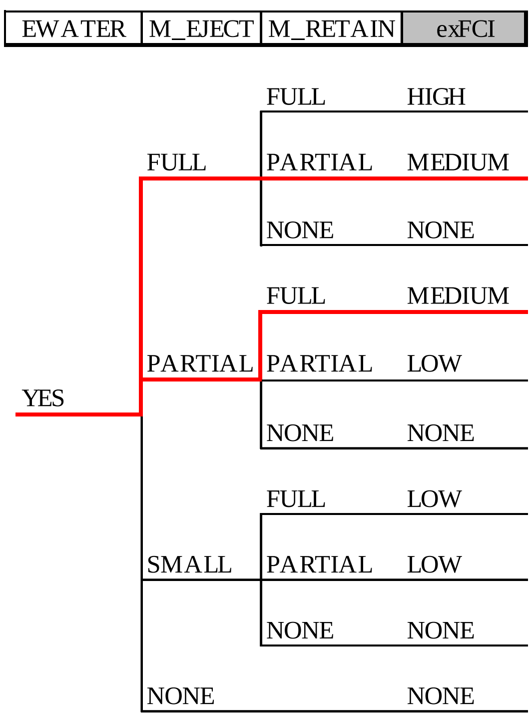

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HUMAN RELIABILITY ANALYSIS

- Assign split fraction to APET basic events linked to AM actions (or HFE = failure to perform task)
- For each BE, probabilities of failure (outcome = NO) based on MELCOR calculations is assessed
  - **A mean value for the available time to perform the task is derived and**
  - **A probability of failure is obtained based on the HRA methodology**
- HRA methodology
  - **Decomposition of each task in successive subtasks**
  - **Quantification of the probability of failure for each subtask**
  - **Assessment of the dependency between HFEs; Sequence of HFEs has to be assigned**
- Expert Judgement process

- $EAM_PPORV
  - **Probability of having an AM action on the opening of at least one PPORV to depressurize the RCS during the early phase**

ID	T_{CET} = 650°C (s)	Open SAMG t_0 (s)	t_{VF} (s)	Δt $t_{650} - t_{VF}$ (s)	Δt $t_0 - t_{VF}$ (s)
ID_1_BC	7900	8800	13500	5600	4700
ID_2_BC	1700	2600	26000	24300	23400

ID	P_{RCS} at t0 (bar)	t_{PPORV} (s)	t_{accu} (s)	$t_{PRCS=12bar}$ (s)	P_{RCS} at VF (bar)	t_{VF} (s)
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Experts #	HEP no dep.	dep. Level	HEP dep.
Expert 1	0.1383	moderate	0.2614
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Expert 3	0.00256	moderate	0.14505
Aggregation	**0.048**	**-**	**0.303**

Expert n°1: very short available time to perform actions + many negative impacts listed but applicability not clearly defined

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FISSION PRODUCT RELEASE FROM CORE/CORIUM

- Assessment of FP release from the core/corium during Early, VF and Late phases
- Quantification of DPs is based on MELCOR calculations and/or literature information
- The main uncertainties are on phenomena appearing during core degradation and MCCI
- Mapping of MELCOR FP classes with NUREG-1465 FP classes
- §x_COR_R_1: value represents % of the initial core inventory of the considered FP class
- §x_COR_R_2: as CDEXT is full, sum of releases during accident progression = sum §x_COR_R_1

CDEXT	VF	E_COR_R	VF_COR_R	L_COR_R
FULL	YES	§E_COR_R	§VF_COR_R	§L_COR_R
	NO	§E_COR_R	0	0
PARTIAL	YES	§E_COR_R	§VF_COR_R	§L_COR_R
	NO	§E_COR_R	0	0
SMALL	NO	§E_COR_R	0	0

_COR_R: FP amount released from the core/corium

Distr. Parameter	Distribution Parameters' Values for each FP Class							
	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	Class 7	Class 8
	Noble Gases	Halogens	Alkali Metals	Tellurium Group	Barium, Strontium	Noble Metals	Lantha-nides	Cerium Group
§E_COR_R_1	-	A	-	-	-	-	-	-
§VF_COR_R_1	-	B	-	-	-	-	-	-
§L_COR_R_1	-	C	-	-	-	-	-	-
§E_COR_R_2	-	D	-	-	-	-	-	-
§VF_COR_R_2	0%	0%	0%	0%	0%	0%	0%	0%
§L_COR_R_2	0%	0%	0%	0%	0%	0%	0%	0%

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CONCLUSION

- Importance of MELCOR for APET quantification
  - **MELCOR contributes to assess ~75% of the APET issues**
- No recipe book for basic event split fractions…
  - **… But engineering judgment over available data + best practices application from SA and L2PSA network**
- MELCOR Validation and Qualification before use
  - **Examples of Tractebel Engineering's benchmarks: RELAP, QUENCH-06, TMI-2, PHEBUS-FPT1, PAKS, ASTEC, TRAPCON, COMET L2/L3**
- The most uncertain phenomenological issues treated with MELCOR
  - **Loss of heat sink due to H2 blockage**
  - **Hot leg / surge line creep failure and induced SGTR**
  - **In-vessel melt retention**
  - **Containment failure due to H2 burn**
- General approach to limit the impact of uncertainties on the APET evaluation results
  - **Detailed Generic Event Tree → Robust L2PSA methodology → Qualitative uncertainty → EJ or not EJ → Use of probabilistic tools for specific issues → APET sensitivity analysis**

THANK YOU !

QUESTIONS