SIMULATION OF MOLTEN CORE CONCRETE INTERACTION FOR CANDU ACCIDENT LATE PHASE BY MEDICIS MODULE

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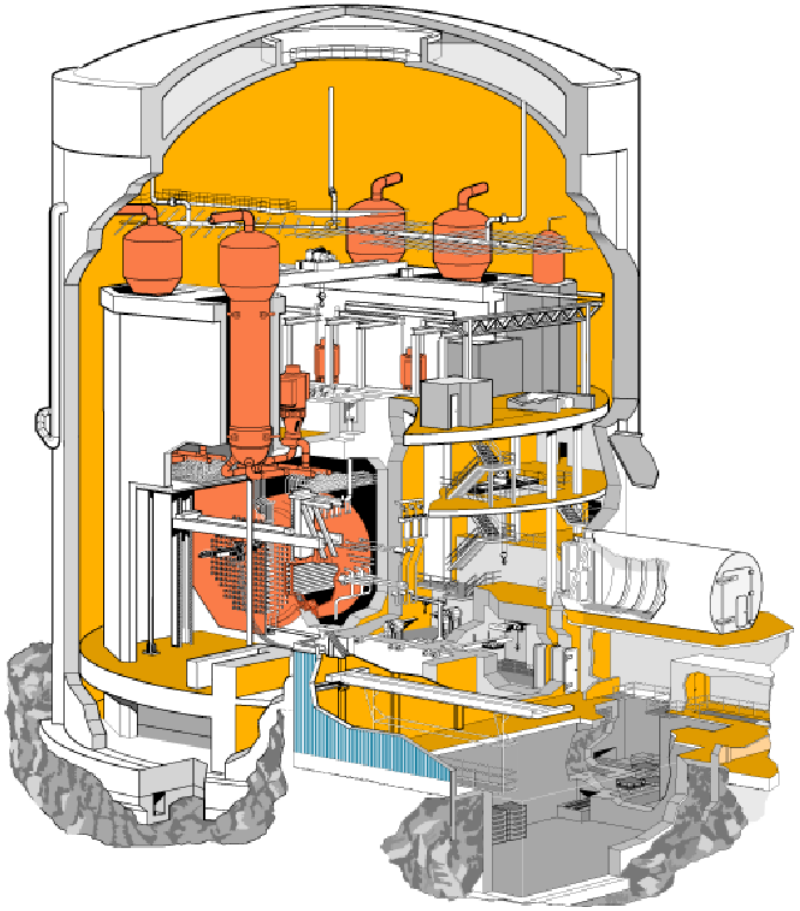


OUTLINE

- INR involvement in SA research activities
- CANDU specificities for SA & accidents (MCCI)
- ASTEC computer code
- **M**odel of **E**rosion **D**ue to **I**nteraction of **C**or**I**um with basement **S**ubstance
- Results on simulation of MCCI for CANDU accident late phase by MEDICIS module
- Conclusions

INR involvement in SA research activities

- National R&D Programme

- International Euratom projects

  - FP5 PHEBEN2
    - Familiarization with ASTEC code
    - Simulation of PHEBUS experiments for ASTEC validation on experimental problems
  - FP6 SARNET
    - investigations for development of an ASTEC version for CANDU
    - validation of ASTEC versions (based on experiments)
    - ASTEC aplication at NPP level
  - FP7 SARNET2
    - to extend the use of ASTEC for CANDU type reactors
  - H2020 FASTNET (ongoing project)
    - source term calculation - relevant accidents for the radiological emergency

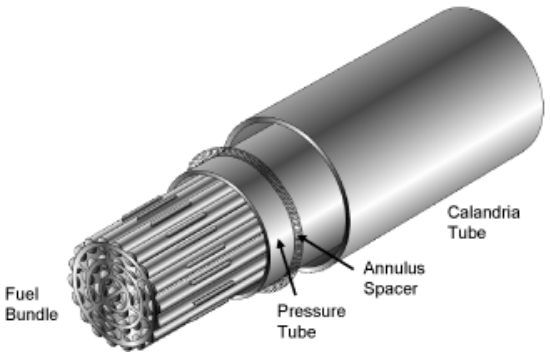
CANDU specificities for SA

- ✓ The fuel channel (CANDU specific)

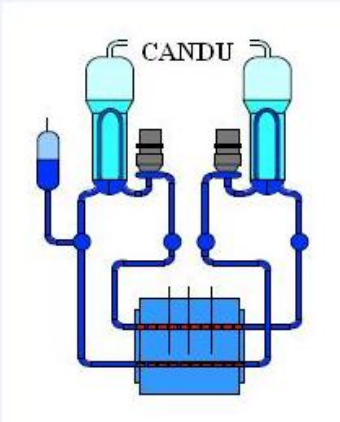
  -CANDU fuel bundles lie inside the pressure tube

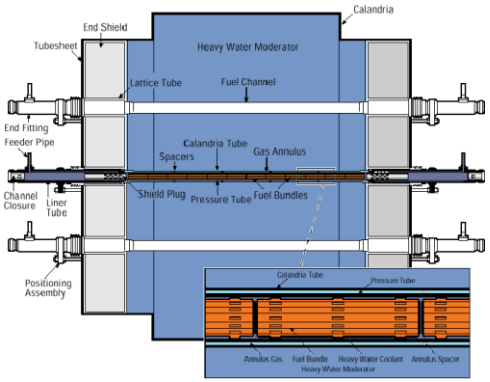
  -a Calandria tube separates the pressure tube from the moderator

  -a gas gap between pressure and Calandria tube provide thermal insulation



- ✓ The horizontal orientation of fuel channels in calandria (important from the failure mode point of view)





When the long fuel channels are heated , they will sag and dislocate to the lower rows where deformation of channel configuration would occur, leading to severe core damage

CANDU specificities for SA (cont.)

✓ Moderator system (own circuit)

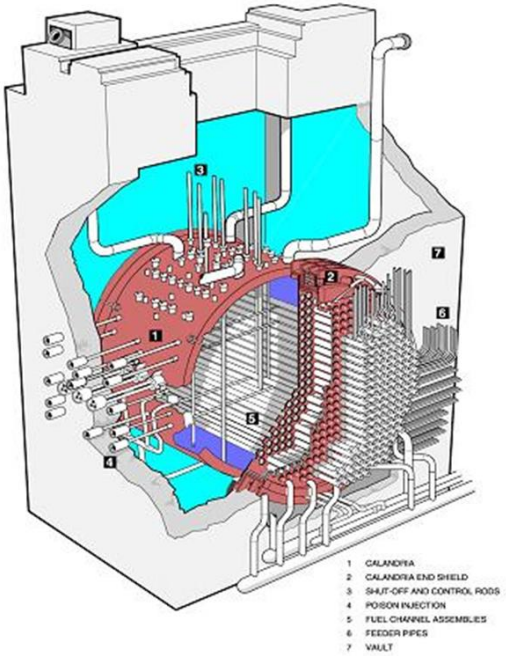
- 230 t

The moderator system is fully independent of the heat transport system

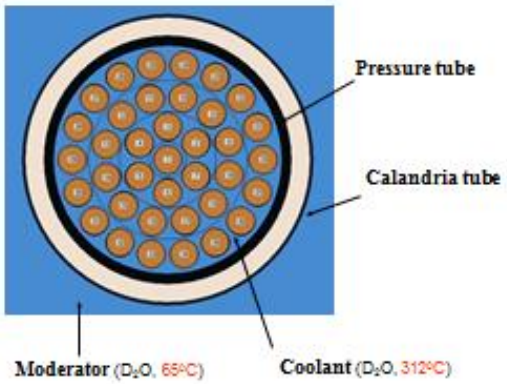
- The heavy water moderator in the calandria is a unique CANDU feature which provides a passive heat sink for some accident scenarios (LOCA+unavailability of ECCS)

✓ Light water from the calandria vault

- 500 t
- a biological shield under normal operating conditions
- a passive heat sink under certain severe accident scenarios
  e.g. if hot dry debris is collected in the bottom of calandria after core disassembly and heats up, the calandria vault water will remove the decay heat from the calandria through the calandria wall.



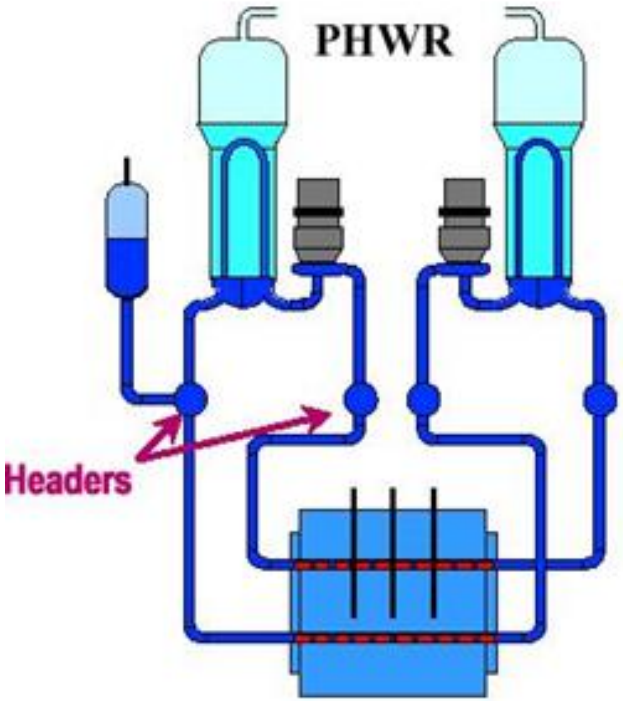
CANDU 6 Reactor Assembly



CANDU specificities for SA (cont.)

✓ Primary circuit complexity

- each channel is individually connected to collectors (headers) located above the core
- each particle of fluid goes through the core twice before it gets back to where it started
- CANDU6 two loops – after a LOCA, loops are isolated, the inventory being maintained into intact loop
- operating pressure ~10 MPa



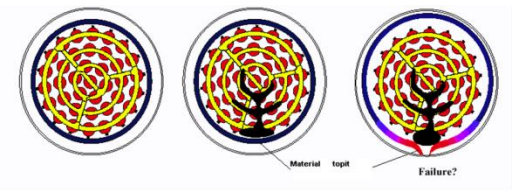
Evolution of core degradation during SA progression

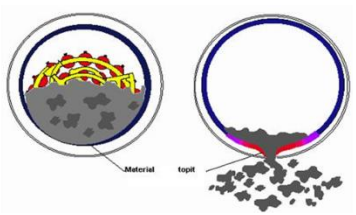
SA require a significant loss of moderator

SA:
✓LOCA+LOECCS+LOMCS
✓SBO
✓Multiple SGTR+LOECCS+ Loss of SG Feedwater+LOMCS

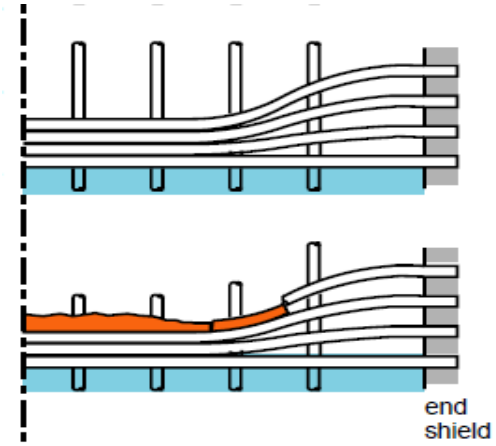
Phenomena occuring during SA progression:

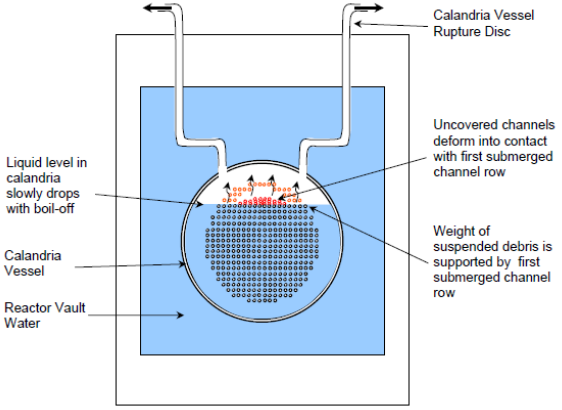
➢Fuel bundle heat up and disassembly





➢Fuel channel heat up, sagging, perforation and melt-through



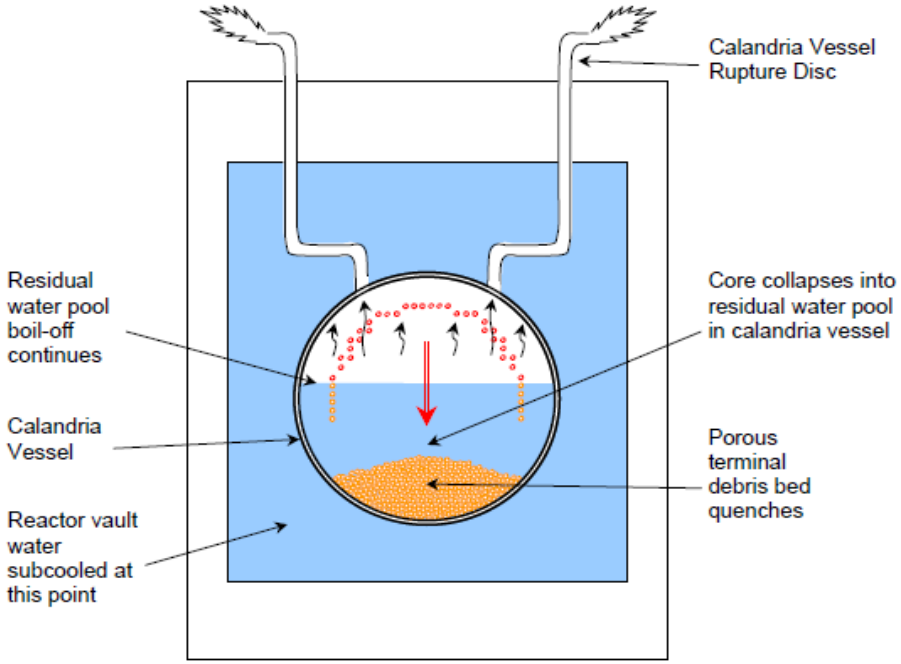


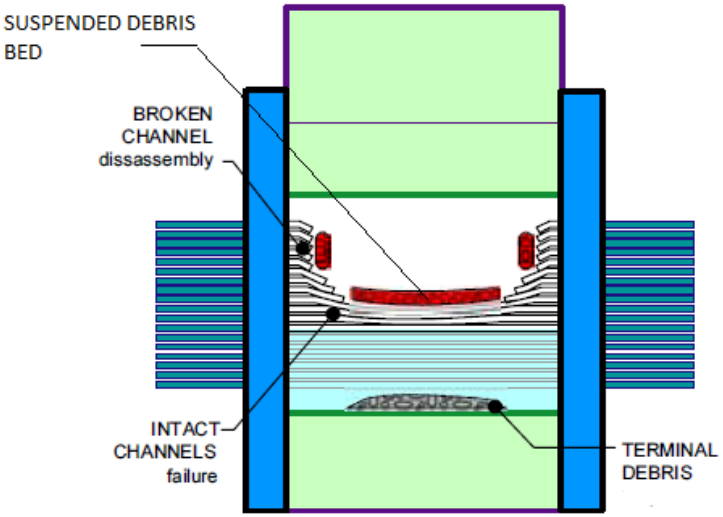
Evolution of core degradation during SA progression (cont.)

Phenomena occuring during SA progression (cont.):

➢Fuel and fuel channel debris separation from the remaining channel and formation of a suspended debris bed;

➢Suspended debris heat up, core collapse;





➢Terminal debris formation within the calandria vessel;

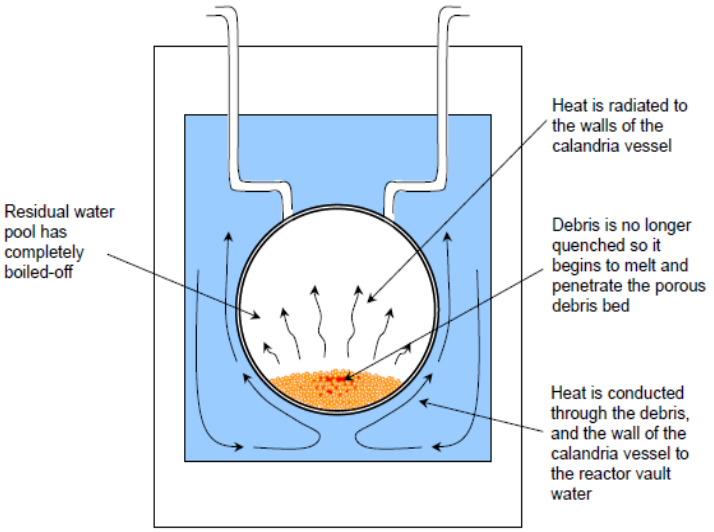
Evolution of core degradation during SA progression (cont.)

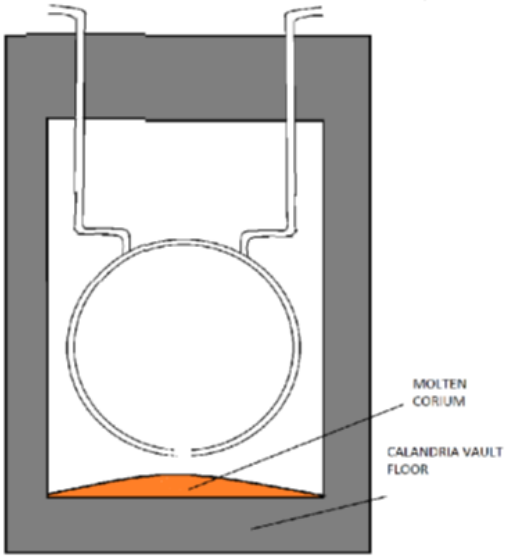
Phenomena occuring during SA progression (cont.):

- Calandria vessel failure;

- Interaction of core debris with the concrete calandria vault;

  - *the interaction leads to release of steam, non-condensable gases such as carbon dioxide and combustible gases such as hydrogen and carbon monoxide*.





- Failure of the containment structure

CANDU6 - Representative accidents (MCCI)

A large LOCA scenario initiated by a guillotine rupture of the reactor outlet header in loop 1, followed by a double-sided blowdown of the PHTS coolant. The break area of the reactor outlet header considered is 0.2594 m2

MAAP4-CANDU

Evolution in time (h)

t=0	t=55.4	t= 58.1	t=122.0
Reactor outlet header guillotine rupture on loop 1	- Calandria vessel bottom wall failed due to creep - Energetic core debris-steam interaction occurred in reactor vault - Containment failed - Corium is discharged into reactor vault	Water is depleted in reactor vault	Reactor vault floor failed due to concrete erosion. The mixture relocates into the basement, where it interacts with the sump water

(Source: IAEA-TECDOC-1594 - Analysis of Severe Accidents in Pressurized Heavy Water Reactors, 2008)

CANDU6 - Representative accidents (MCCI) – cont.

SBO scenario: loss of off-site AC (Class IV) power with a subsequent loss of all on-site standby (Class III) and emergency electric power supplies

MAAP4-CANDU, Version v4.0.5A

Evolution in time (h)

t=0

- AC power loss (Class IV & III)
- Reactor trip due to loss of power

t=46

- Calandria vessel fails
- Energetic core-debris steam interaction occurred in calandria vault

t= 53

Water is depleted inside calandria vault

t=56

Molten corium-concrete interaction begins in calandria vault

t=120.0

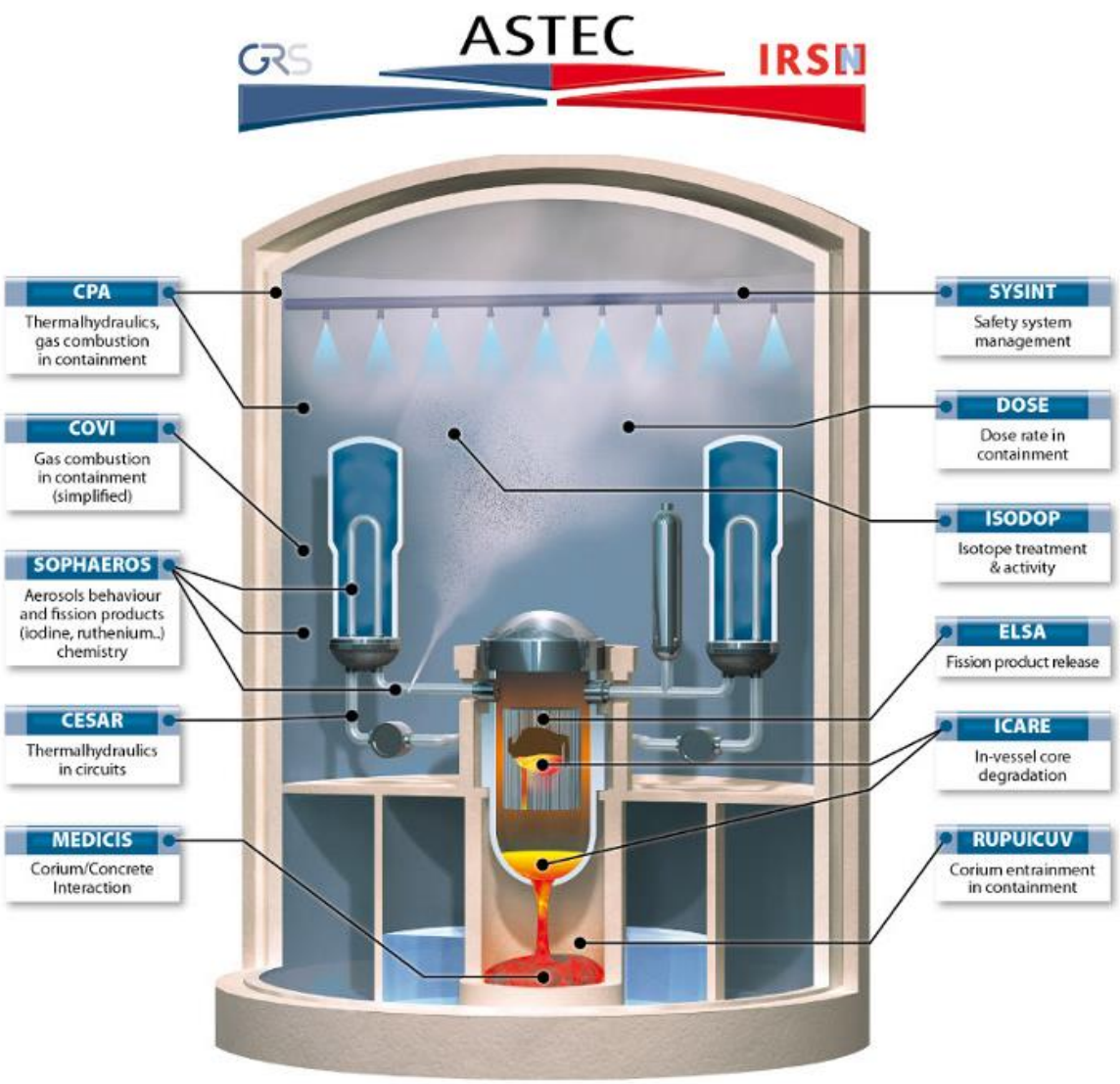
Calandria vault floor failed because of concrete ablation

(Source: T. Nitheanandan and M.J. Brown - Backup and ultimate heat sinks in CANDU reactors for prolonged SBO accidents , Nuclear Engineering And Technology", Vol.45 No.5 October 2013)*

Accident Source Term Evaluation Code

- ASTEC code (IRSN-GRS)
- Integral code for SA in Water Cooled Reactors
- Able to simulate an entire SA sequence from the IE through to release of radioactive elements out of the containment
- Applications:
  - Source term determination studies;
  - PSA level 2;
  - Accident management;
  - Physical analyses of experiments to improve the understanding of the phenomenology
- ASTEC is now considered as the European reference severe accident code by the continuous capitalization of international knowledge through new or improved physical modelling
- The high priority is to continue to capitalize existing knowledge in the code to ensure a rapid feedback of the accidents interpretation. Attention is paid in particular on models of BWR core degradation and other NPPs (including CANDU), and to their validation.

Accident Source Term Evaluation Code (cont.)

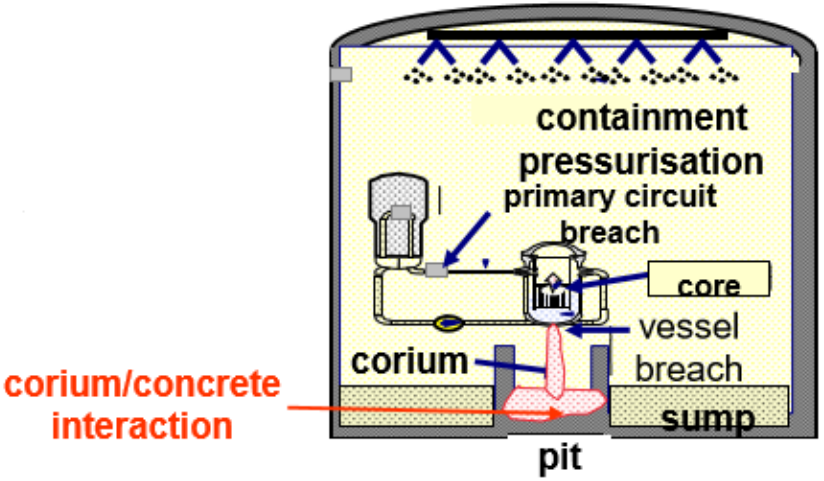


Model of **E**rosion **D**ue to **I**nteraction of **C**or**I**um with basement **S**ubstance

- ✓ MCCI occurs after vessel failure leading to corium slumping into the reactor pit
  - ❑ Decay power of FPs and heat from oxidation reactions into the corium causes the concrete wall ablation

- ✓ To see if and when, the melt can penetrate the concrete, opening a pathway for FPs getting into soil and water
  - ❑ radiological consequences on people and environment

- ✓ MEDICIS describes:
  - ➢ Concrete ablation
  - ➢ Corium oxidation
  - ➢ Release of incondensable gases (H_2, CO, CO_2) into the containment



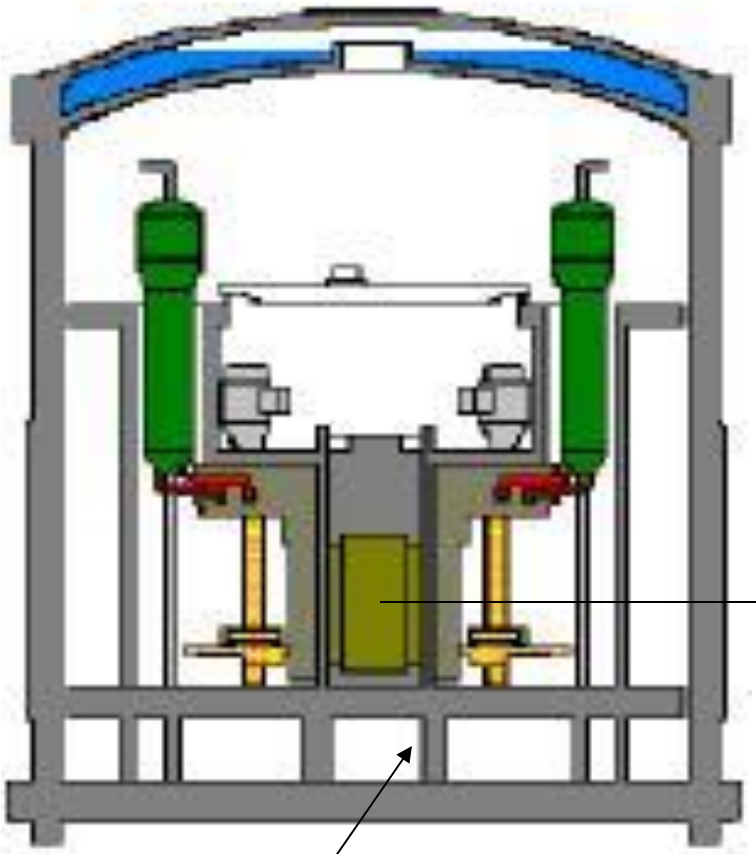
- ✓ MEDICIS
  - ➢ stand alone mode
  - ➢ coupled with CPA

Model of **E**rosion **D**ue to **I**nteraction of **C**or**I**um with basement **S**ubstance (cont.)

✓ MEDICIS contains:

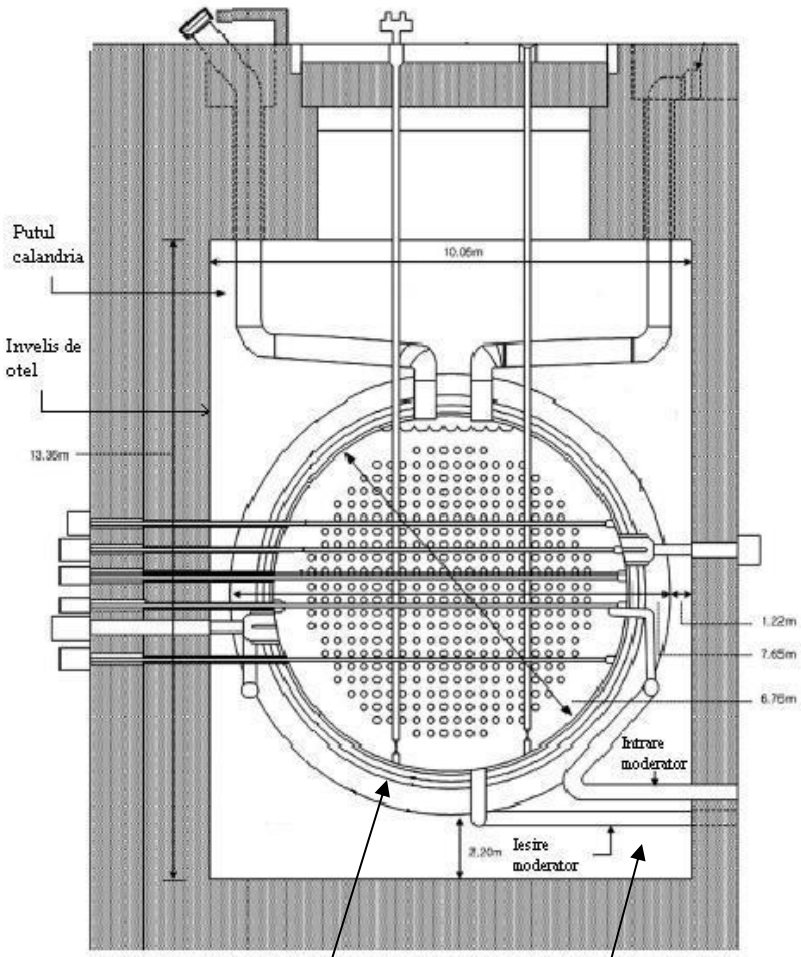
- A model of the structure of the corium concrete interface
- Models of corium coolability in case of water injection upon the corium pool surface
- Models of evolution of corium pool configuration
- Models to evaluate the release from the ex-vessel corium pool of concrete aerosols and the release of fission products during MCCI
- interface with the physico-chemistry MDB package (Material Data Bank), to evaluate the corium layers properties

MEDICIS Investigation – CANDU specificities



CANDU Geometry Configuration

Room bellow the Calandria vault

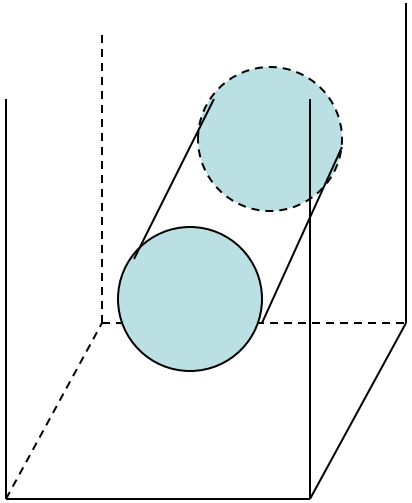


Calandria vessel

Calandria vault (full with water)

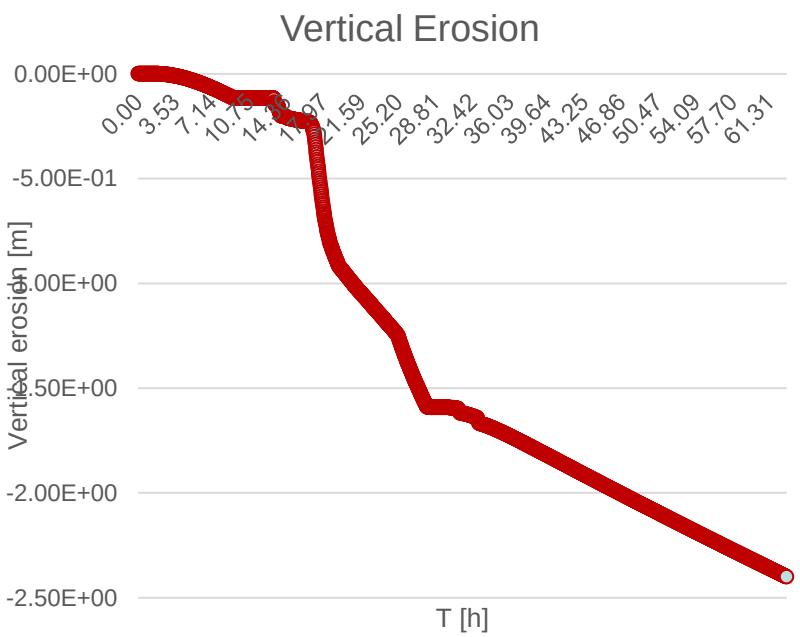
when the floor of calandria vault is passed through by the corium (a very low probability), water may provide an important cooling source for corium on long term

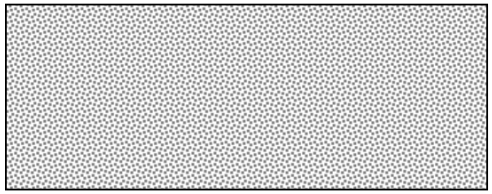
Simulation of MCCI for CANDU accident late phase by MEDICIS module



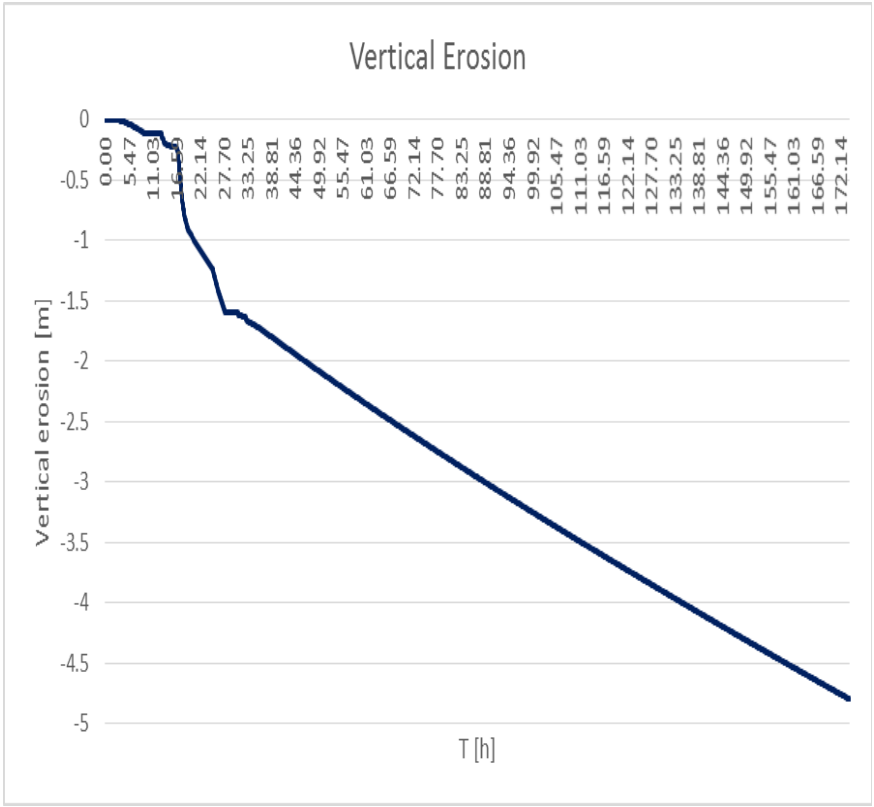
UO_2 total mass [kg]	98,815.00
U mass [kg]	87,103.59
ZrO_2 total mass [kg]	52,203.00 all quantity of Zr is oxidated
Zr total mass [kg]	38,647
Fe total mass [kg] in the core	925
Cr total mass [kg] in the core	382
Ni total mass [kg] in the core	846
Thickness of Calandria vault floor [m]	2.40
Equivalent Radius of Calandria vault [m]	4.37
High of cavity [m]	2.20
Thermal power [MW]	2064
Residual power of the core	$P(t) = P_0 * 0{,}095t^{-0.283}$
Initial temperature of oxide and metal layers [K]	1200
Concrete composition	64% SiO_2, 18% CaO, 10% CO_2 and H_2O
Ablation temperature of concrete [K]	1570

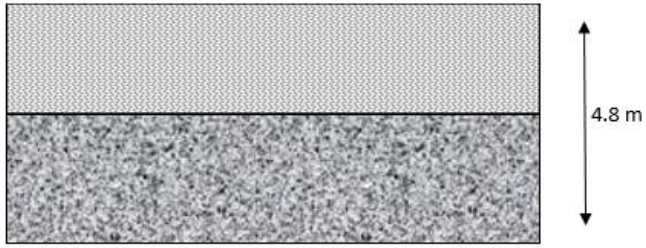
Simulation of MCCI for CANDU accident late phase by MEDICIS module (cont.)





Erosion of floor of the Calandria vault in approx. 63 h

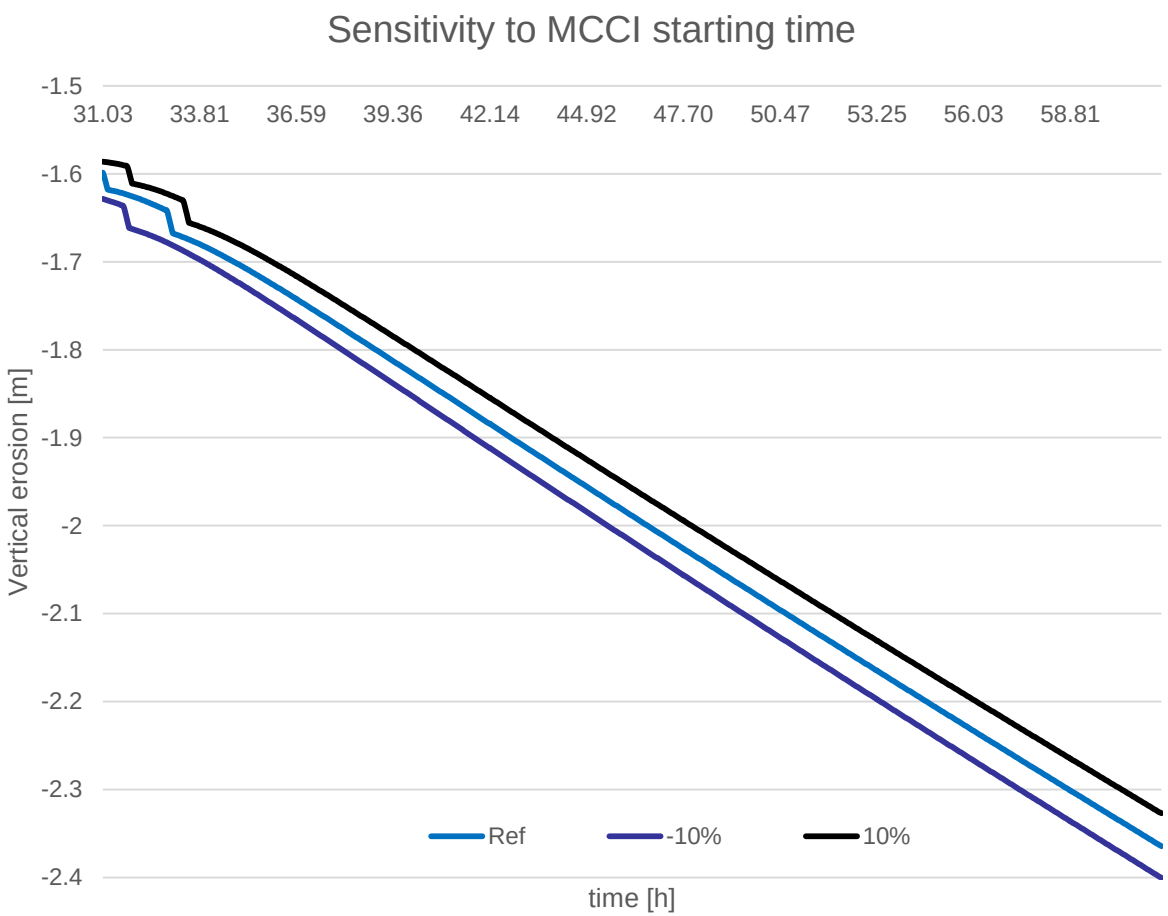




Erosion of CV floor and basement in approx. 174 h

Simulation of MCCI for CANDU accident late phase by MEDICIS module (cont.)

Uncertain parameter: starting time of MCCI



±4 cm

T [h]	Ref	-10%	+10%
61.42	-2.364	-2.400	-2.327

Simulation of MCCI for CANDU accident late phase by MEDICIS module (cont.)

	-10%	Ref.	+10%
Starting time [h]	52.2	58.0	63.8
Complete erosion of CV floor [h]	61.42 -2.4%	62.91	64.50 +2.5%

T = 0.0
start of
SA

T=58.0 h
Start of MCCI

T=121 h
Complete penetration
of CV floor

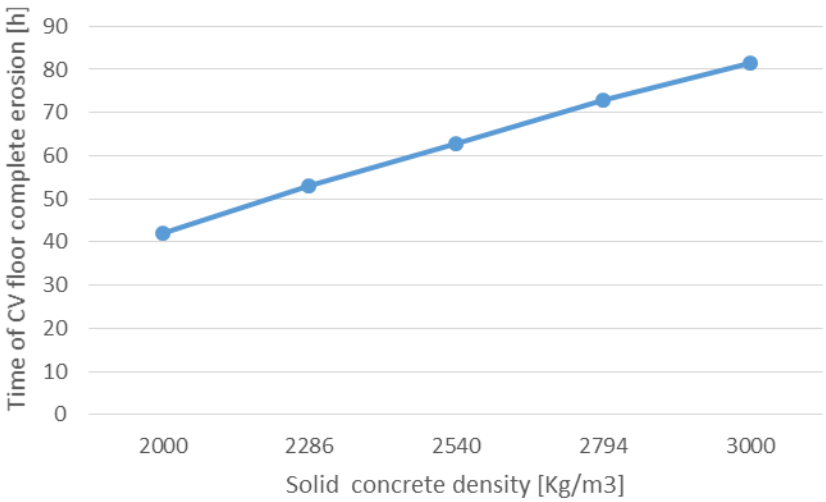
Simulation of MCCI for CANDU accident late phase by MEDICIS module (cont.)

Uncertain parameters: mass of UO_2 and mass of ZrO_2

	Ref	-5%	+5%
UO_2 mass [Kg]	98,815	93,874.25	103,755.8
ZrO_2 mass [Kg]	52,203	49,592.85	54,813.15
MCCI starting time [h]	58.0	58.0	58.0
Complete erosion of CV floor, from the MCCI starting [h]	62.91	66.91	54.55

Uncertain parameter: solid concrete density

	Ref	-10%	+10%
Solid concrete density [Kg/m^3]	2540	2286	2794
MCCI starting time [h]	58.0	58.0	58.0
Complete erosion of CV floor, from the MCCI starting [h]	62.91	53.05	73

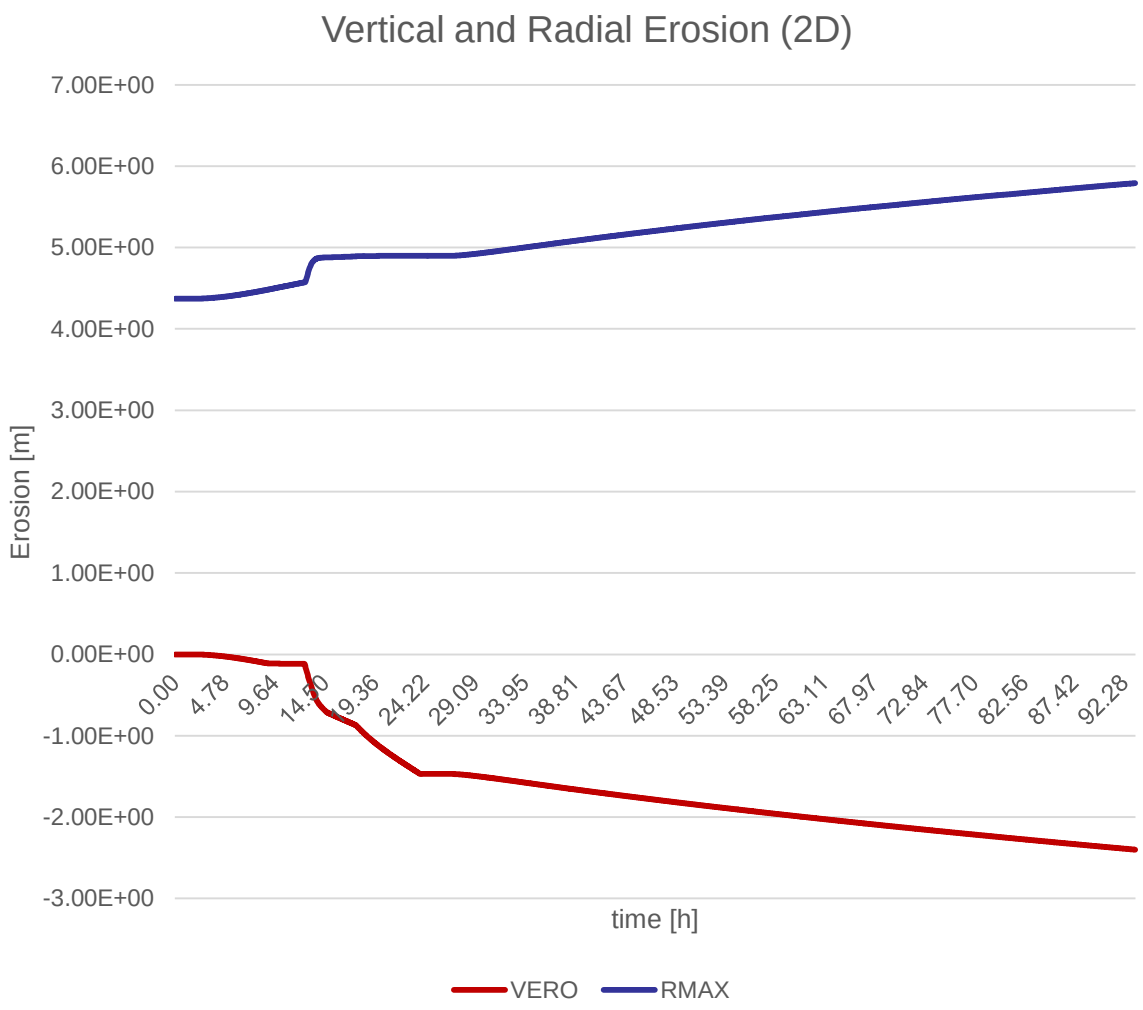


Simulation of MCCI for CANDU accident late phase by MEDICIS module (cont.)

Uncertain parameters: initial temperature of metal layer and oxide layer

	Ref	-10%	+10%
Initial temperature of metal layer [K]	1200	1080	1320
Initial temperature of oxide layer [K]	1200	1080	1320
MCCI starting time [h]	58.0	58.0	58.0
Complete erosion of CV floor, from the MCCI starting [h]	62.91	76.56	53.97

Influence of the radial erosion (2D model)



<u>Maximum vertical erosion:</u>
-2.4 m (penetration of CV floor)

T=93.4 h vs T=62.91 h (1D)

<u>Radial erosion:</u>
delta_R=1.42 m

Recommendations

- ✓ To improve the quality of the input data, sensitivity analysis is compulsory for key parameters
  - ✓ The MCCI starting time seems to be a critical parameter since it aggregate uncertainties from entire in-vessel modeling and data
  - ✓ Corium characteristics have specificities; the quality of experimental data and as-built data are crucial for the quality of the numerical results

- ✓ The MCCI algorithm should be improved to take into consideration multiple cavities. The merging of the cavities into a single one introduces supplementary approximations for the corium behavior.

Conclusions

- The most important SA accidents in CANDU (SBO, LOCA, etc.) has the same late phase after full core collapsing and calandria failure

- CANDU specificity: the large amount of water (calandria vault and moderator) delays the evolution of the accident and allows possible operator interventions

- MEDICIS module of the ASTEC code may be used for late phase modelling of CANDU6

- The results are affected by uncertainties due to the difference between generic and as-built data, scarce of experimental data

- For SA initiated by LOCA approximately 63 h (1D model) and 93 h (2D model), after the MCCI starting, are necessary to penetrate the calandria vault floor

- The radial erosion significantly delays the penetration of CV floor