Ensuring safe Long-Term Operation: Research challenges for ageing of critical concrete structures

Workshop on LTO Beyond 60 Years, NRG, Petten-NL, 27-28.2.2024

Miguel Ferreira, ACES Project Coordinator
VTT Technical Research Centre of Finland Ltd.

ACES Towards improved Assessment of Safety Performance for LTO of nuclear Civil Engineering Structures

This project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 900012

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   - Achievements
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Olkiluoto 3, biggest NPP in Finland (TVO)

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ACES

Towards improved Assessment of safety performance for long-term operation of nuclear Civil Engineering Structures

Advance the assessment of safety performance of civil engineering structures by addressing scientific and technology gaps for the safe and LTO of NPP safety-critical concrete infrastructure

- **Duration:** 57 months (September 2020 – May 2025), EC extension approved 1.2024.
- **Budget:** 5.4 M€ total, of which EC contribution of 3.99 M€
- **Call:** Euratom NFRP 1 (2019): Ageing phenomena of components and structures and operational issues (RIA)
- SNETP/NUGENIA awarded ACES the “NUGENIA Label” (2019NUG0070)

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ACES Partners

VTT (Finland) – Miguel Ferreira, Project Coordinator
CEA (France) – Véronique Dewynter-Marty
CV ŘEŽ (Czech Republic) – Zbyněk Hlaváč
CTU (Czech Republic) – Petr Štemberk
ENERGORISK (Ukraine) – Stanislav Sholomitsky
ENGIE Laborelec (Belgium) – Sokratis Iliopoulos
EDF (France) – Jean-Luc Adia
IRSN (France) – Christophe Marquie
SCK CEN (Belgium) – Diederik Jacques
ZAG (Slovenia) – Andraž Legat
ORNL (USA) – Yann Le Pape

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ACES – Work packages

- **WP1 – State-of-the-art of quantitative assessment of ageing of concrete SSC**

  SCK•CEN, **Diederik Jacques** (diederik.jacques@sckcen.be)
- **WP2 – Corrosion assessment of embedded liners in concrete**

  ZAG, **Andraž Legat** (andraz.legat@zag.si)
- **WP3 – Characterization, prediction and monitoring of ISR in concrete**

  IRSN, Christophe Marquie (christophe.marquie@irsn.fr)
- **WP4 – Delayed strains of containment in operational & accidental conditions**

  EDF, **Jean-Luc Adia** (jean-luc.adia@edf.fr)
- **WP5 – Assessing the performance of irradiated concrete.**

  CTU, **Petr Štemberk** (stemberk@fsv.cvut.cz) & ORNL, **Yann Le Pape** (lepapeym@ornl.gov)
- **WP6 – Dissemination, communication and training**

  CVR, **Zbyněk Hlaváč** (zbynek.hlavac@cvrez.cz)
- **WP7 – Project management –** VTT, **Miguel Ferreira** (miguel.ferreira@vtt.fi)

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Governance and structure

Decision Making

General Assembly
Chair (PC) & Representative from each partner

Steering Committee
Chair (PC) & WP leaders

Advise

Advisory Board
and
End-User Group

Execution

Project Coordinator (VTT)

WP7 – Project management (VTT)

WP1 – State of the art of quantitative assessment of ageing of concrete SSC (SCKCEN)

WP2 – Corrosion assessment of embedded liners in concrete (ZAG)

WP3 –Characterization, prediction and monitoring of internal swelling reactions in concrete (IRSN)

WP4 – Delayed strains of containment buildings in operational and accidental conditions (EDF)

WP5 – Assessing the performance of irradiated concrete (CTU)

WP6 – Dissemination, communication and training (CVR)

European Commission

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Achievements

- Improved engineering methods to assess components under LTO taking into account specific operational demands (all technical WPs)
- Advanced simulation tools and combined empirical and mathematical material models addressing coupling effect of various loadings on concrete performance (all technical WPs)
- Critical review of ageing management practices across EU NPPs focusing on deterioration and ageing mechanisms of reinforced concrete (WP1)
- Integrated probabilistic assessment methods to account for uncertainties and improve inspection capabilities (WP2)
- Innovative quantitative methodologies to transfer laboratory material properties to assess the structural integrity of large concrete components (WP3)

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Achievements

- Improved understanding of corrosion phenomena focusing on embedded liners, predicting the occurrence of corrosion and developing an innovative inspection tool for early detection of corrosion (WP2)
- Improved understanding of internal swelling reactions and temperature/moisture effects on the delayed strains of containment buildings (WP3/WP4)
- Improved prediction of the evolution of moisture, strain and stress of prestressed concrete containment buildings, during operational and accidental phases (WP4)
- Improved assessment of the effects of prolonged irradiation of the concrete biological shield using a holistic approach combining operating conditions, materials degradation and structural significance (WP5)

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End Users Group

1) TVO (Finland, NPP)
2) EDF DI (France, NPP)
3) Ringhals (Sweden, NPP)
4) Oskarshamn (Sweden, NPP)
5) EPRI (USA, TSO)
6) STUK (Finland, Regulator)
7) Kajima Corporation (Japan, TSO)
8) Tecnatom/Westinghouse (Spain, TSO)
9) IETcc-CSIC (Spain, TSO)
10) NNEGC Energoatom (Ukraine, NPP)
11) US NRC (USA, Regulator)
12) SVTI (Switzerland, TSO)
13) GRS (Germany, TSO)
14) SWECO (Finland, Consultant)
15) ČEZ, a.s. (Czechia, NPP)
16) FORTUM (Finland, NPP)
17) SÚJB (Czechia, Regulator)
18) CSNC (Canada, Regulator)

4th EUG Seminar – 14.3.2024

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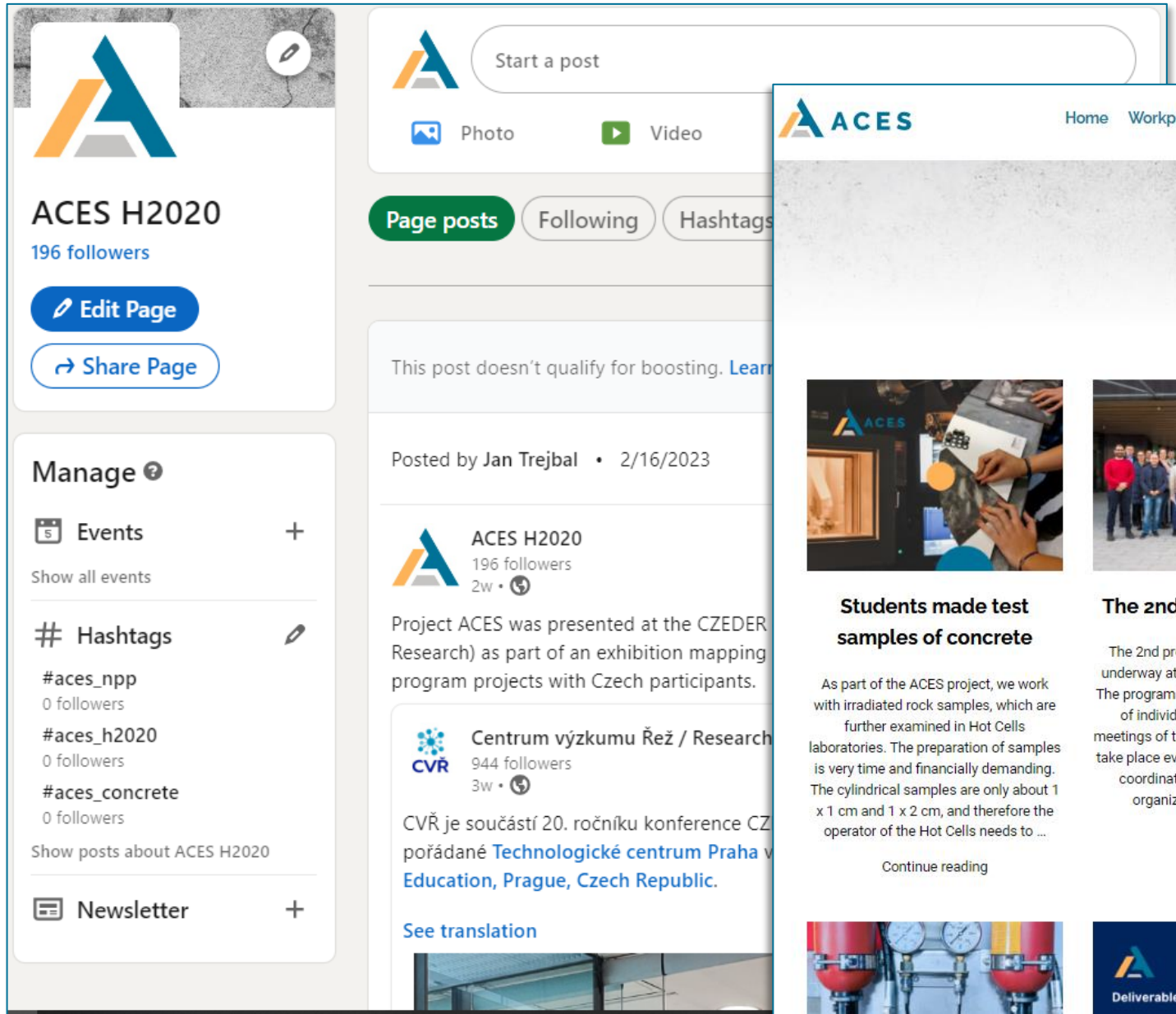
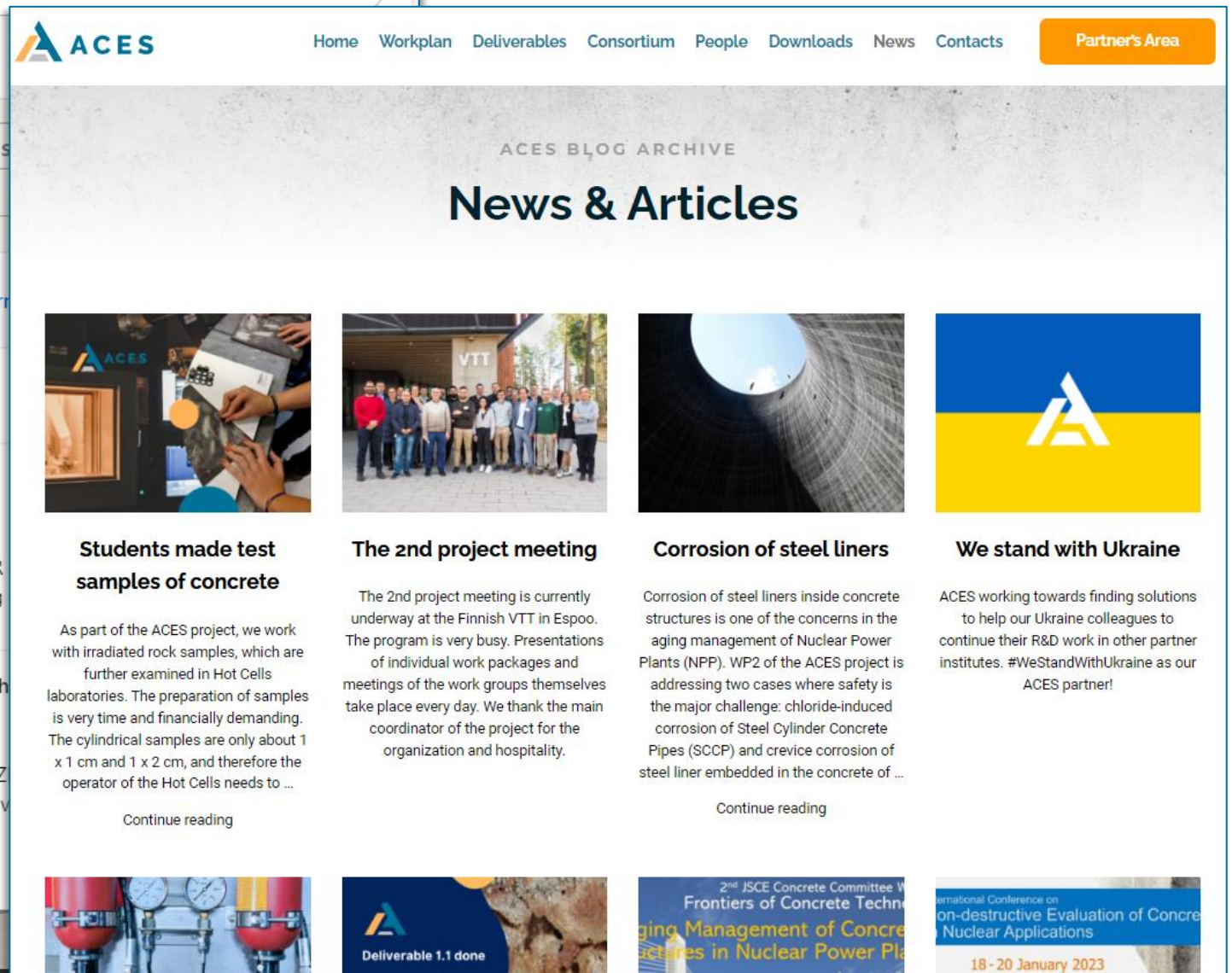
ACES on social media

http://aces-h2020.eu/



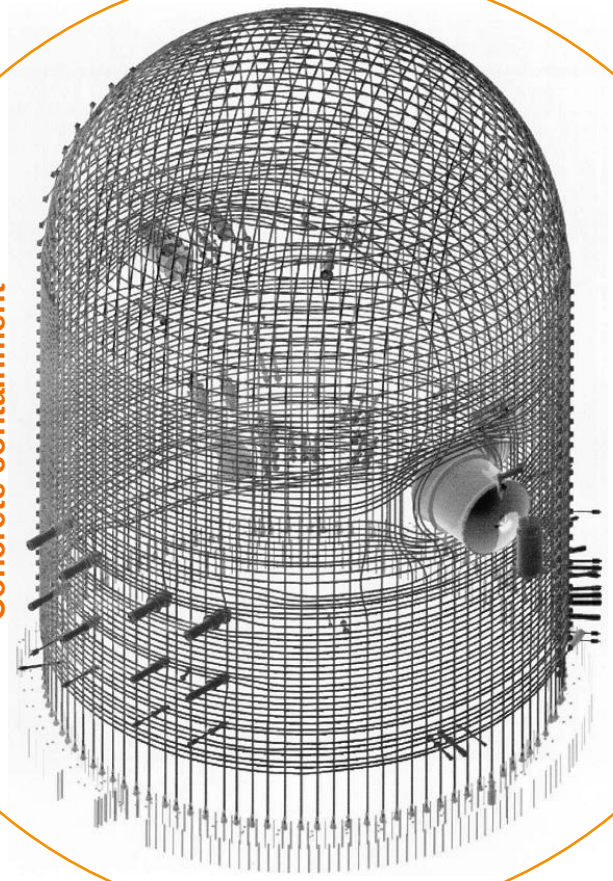


What are the limitations of our knowledge regarding concrete ageing?

What GAPs?

nγ-rad
Neutron and gamma radiation effects

ISR
Internal swelling reactions (ASR & DEF)



Cor.
Embedded liner corrosion

NDE
Non-destructive evaluation

AM
Ageing management

C&S
Creep and shrinkage

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ACES
WP structure

WP1 – State-of-the-art of quantitative assessment of ageing of concrete SSCs in NPPS (SCK•CEN)

Experimental & Numerical work packages

WP2 – Corrosion assessment of embedded liners in concrete (ZAG)
- 2.1. Mechanisms and models of steel corrosion in NPP
- 2.2. Probabilistic analysis
- 2.3. Corrosion inspection of steel cylinder concrete pipes
- 2.4. Robotics – diagnosis tools
- 2.5. Recommendations on methodology for ageing management of NPP

WP3 – Characterization, prediction and monitoring of ISR in concrete (IRSN)
- 3.1. Characterization of ISR reactions
- 3.2. Multiscale assessment of ISR evolution and its effect to long term expansion
- 3.3. Monitoring of IRS evolution in structures
- 3.4. Recommendations for End-Users

WP4 – Delayed strains of containment building (EDF)
- 4.1. VERCORS Benchmark 3 – structural computation codes for prediction of strains during service life of a containment building
- 4.2. Effects of temperature on drying and delayed strains
- 4.3. Prediction of creep & shrinkage from mix at ambient temperature

WP5 – Assessing the performance of irradiated concrete (CTU)
- 5.1. Characterization of neutron and gamma irradiated concrete constituents
- 5.2. Modelling of irradiated concrete physical and mechanical properties.
- 5.3. Assessment of the structural significance of irradiation in CBS
- 5.4 End User guidelines: methodology to assess the LTO of structures exposed to prolonged irradiation

WP6 – Dissemination, communication and training (CVR)

Implementation in coordination with stakeholders

Engagement with the **End User Group** (stakeholders, regulators, TSO, civil society, etc.)

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WP1 Quantitative assessment of ageing/degradation of concrete in NPPs

- Ageing management NPP
- General methodology
- Specificities for reinforced concrete SSCs
- Degradation processes (19)

- Target audience: infrastructure management, engineers, scientists, non experts

Chapter 1	-	D. Jacques, L. Yu, M. Ferreira, T. Oey
Chapter 2	-	D. Jacques, L. Yu, M. Ferreira, T. Oey
Chapter 3	-	D. Jacques, L. Yu, M. Ferreira, T. Oey
Chapter 4.1	Acid Attack	O. Tandre, VTT
Chapter 4.2	Leaching	L. Charpin, P. Desgrée, EDF
Chapter 4.3	External sulphate attack	T. Oey, VTT
Chapter 4.4	Carbonation	D. Jacques, Q.T. Phung, SCK CEN
Chapter 4.5	Alkali-aggregate reactions	J. Jabbour, IRSN
Chapter 4.6	Delayed ettringite formation	J. Jabbour, IRSN
Chapter 4.7	Bacterial processes	D. Jacques, SCK CEN
Chapter 4.8	Freeze-thaw	M. Ferreira, VTT
Chapter 4.9	Elevated and high temperatures	H. De Crits, Engie Laborelec
Chapter 4.10	Irradiation	Y. Le Pape, ORNL
Chapter 4.11	Abrasion, erosion, cavitation	Z. Hlaváč, CV REZ
Chapter 4.12	Creep and relaxation	L. Charpin, EDF
Chapter 4.13	Settlements and movements	P. Štemberk, CTU
Chapter 4.14	Vibration	P. Štemberk, CTU
Chapter 4.15	Thermal stresses	V. Kritsky, K. Pushkareva, Energorisk
Chapter 4.16	Pitting corrosion	M. Hren, A. Legat, ZAG
Chapter 4.17	General corrosion	V. Dewynter-Marty, CEA
Chapter 4.18	Crack corrosion	V. Dewynter-Marty, CEA
Chapter 4.19	Crevice corrosion	V. Dewynter-Marty, CEA
Chapter 5	Challenges	Input from all contributing authors

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WP1 Quantitative assessment of ageing/degradation of concrete in NPPs

- Management of ageing in IAEA-SSG-48 for Reinforced Concrete Structures
- Screening of safety-related NPP RCSs → mapping of relevant loading conditions → likely degradation processes

- E1: High/low temperature (environments where temperature is constantly at high /low values in relation to ambient temperature, or where high temperature gradients can occur)
- E2: High humidity (environments where humidity levels are constantly high, i.e. > 90 %)
- E3: Atmospheric conditions (environmental exposure to all elements of weather, such as rain, wind, freeze/thaw, solar radiation, etc.)
- E4: Submerged or in contact with sea/fresh water
- E5: Underground (structural elements that are in contact with the ground, typically foundation structures, tunnels, etc.)
- E6: Radiation (environments where concrete is subject to a source of radiation)
- E7: Internal building conditions (environments occurring in office type buildings), or low humidity conditions
- E8: Mechanical/Structural loading (dead weight, service load, pressure, vibration, and other types of mechanical loads that are present)

Concrete structure	Environments
Primary containment	
Containment dome/roof	E1, (E3), E7
Containment foundation/basemat	E5
Slabs and walls	E1, E7
Containment internal structures	
Slabs and walls	E1, E7
Reactor vessel support structure (or pedestal)	E1, E6, E7
Crane support structures	E1, E7
Reactor shield wall (biological)	E1, E6, E7
Ice condenser dividing wall (ice condenser plants)	E1, (E6) , E7
NSSS equipment supports/vault structures	E1, (E6), E7
Weir and vent walls	E1, E7
Pool structures (Reactor, fuel, condensation)	E1, E4, E7
Diaphragm floor	E1, E7

WP1 Quantitative assessment of ageing/degradation of concrete in NPPs

- **Description of degradation process:**
  - Process Definition
  - Influential factors
  - Influence of other ageing processes
  - Rates of deterioration
  - Impact on concrete properties
  - Assessment methods
  - Performance indicators & acceptance criteria
  - Model approaches
- **Knowledge gaps:**
  - Process understanding
  - Measuring -> NDT
  - Modelling -> coupling, parameters, confidence
  - Assessment -> database
- **Serve as input for strategic research agendas**

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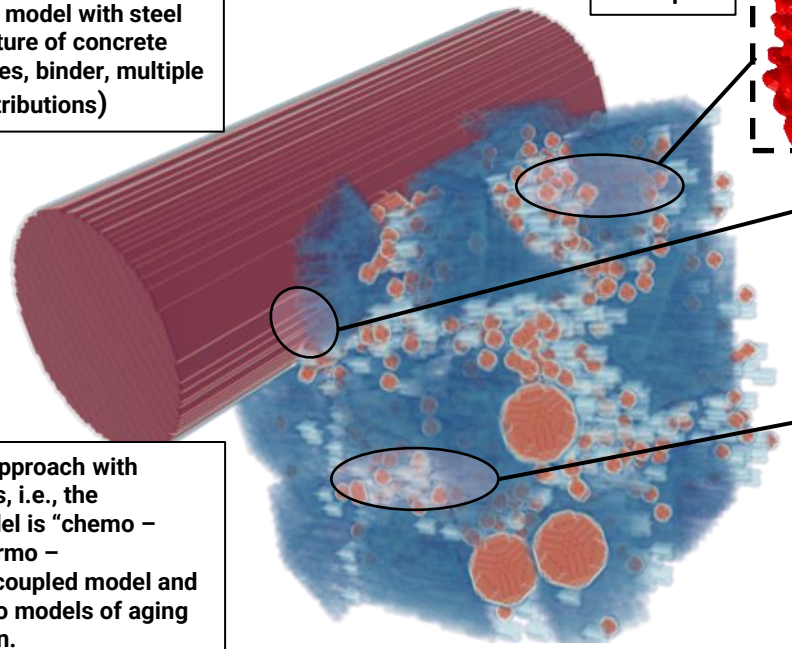
WP2 Corrosion assessment of embedded liners in concrete

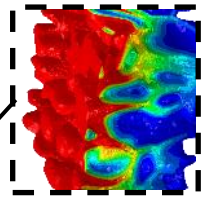
- Mechanisms and models of steel corrosion

→ Chloride-induced corrosion of SCCP; Crevice corrosion mechanisms of steel liner in containment; Phenomenological modelling of steel corrosion

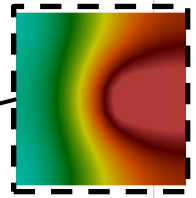
Section of a simplistic 3D microstructural model with steel and microstructure of concrete (aggregate, pores, binder, multiple spatial size distributions)

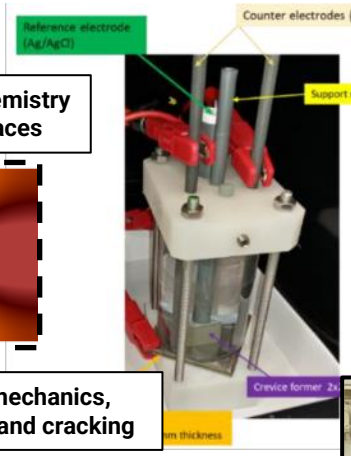


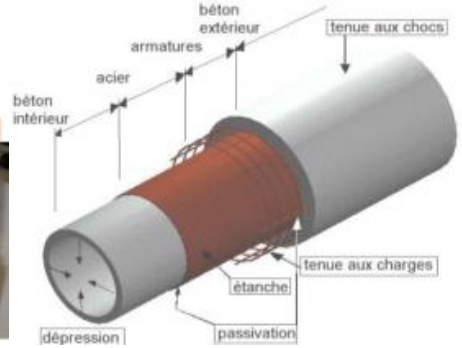
Transport



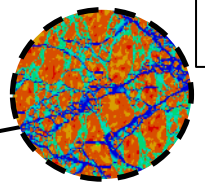
Electrochemistry and interfaces





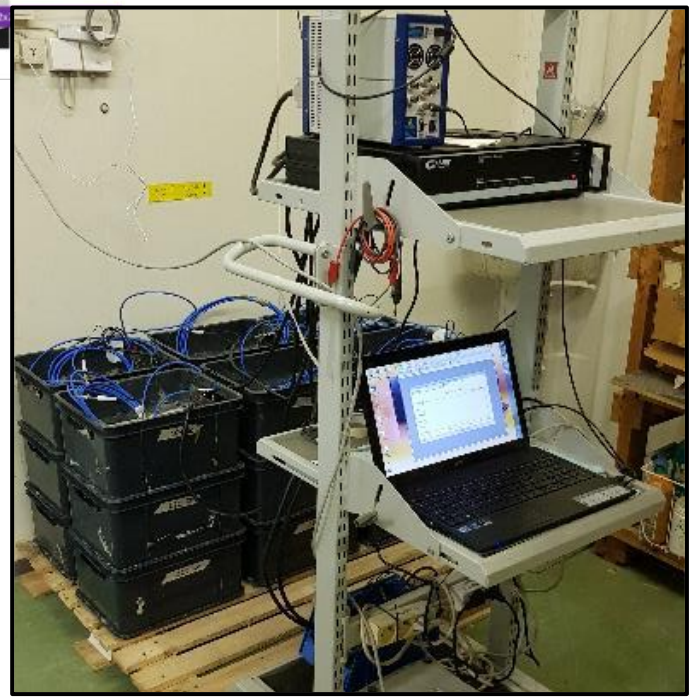


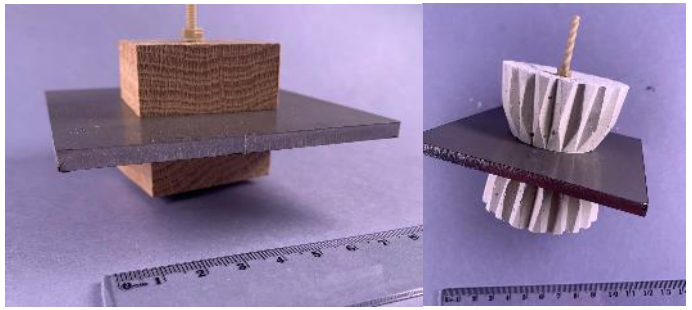
Thermomechanics, damage and cracking

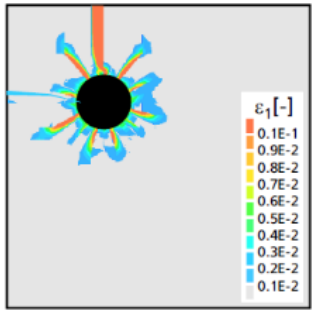


Multiphysical approach with microstructures, i.e., the underlying model is "chemo – transport – thermo – mechanically" coupled model and will be linked to models of aging and degradation.

FULL coupling between the respective mechanisms (adaptive model reconstruction during solution)

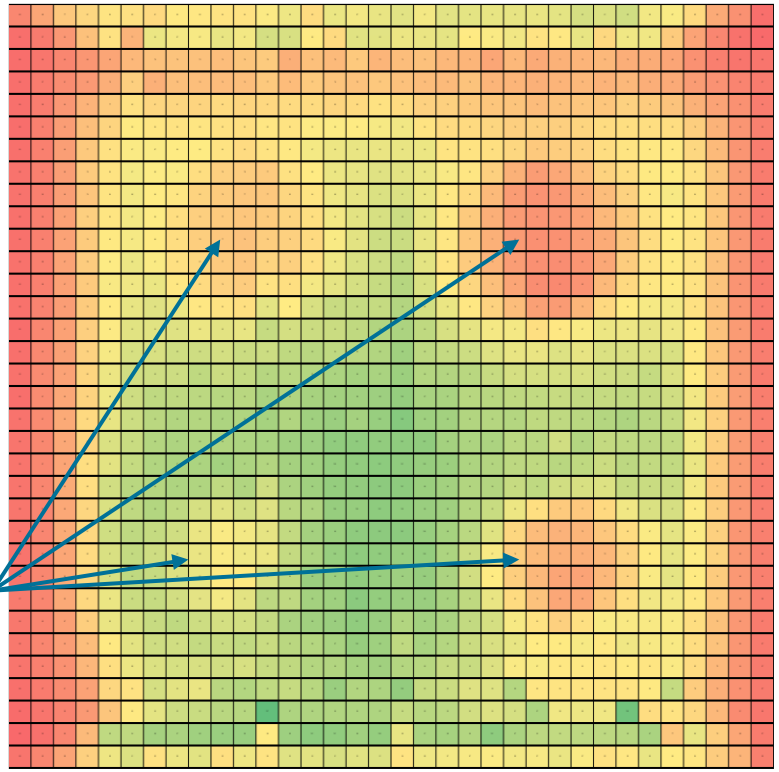


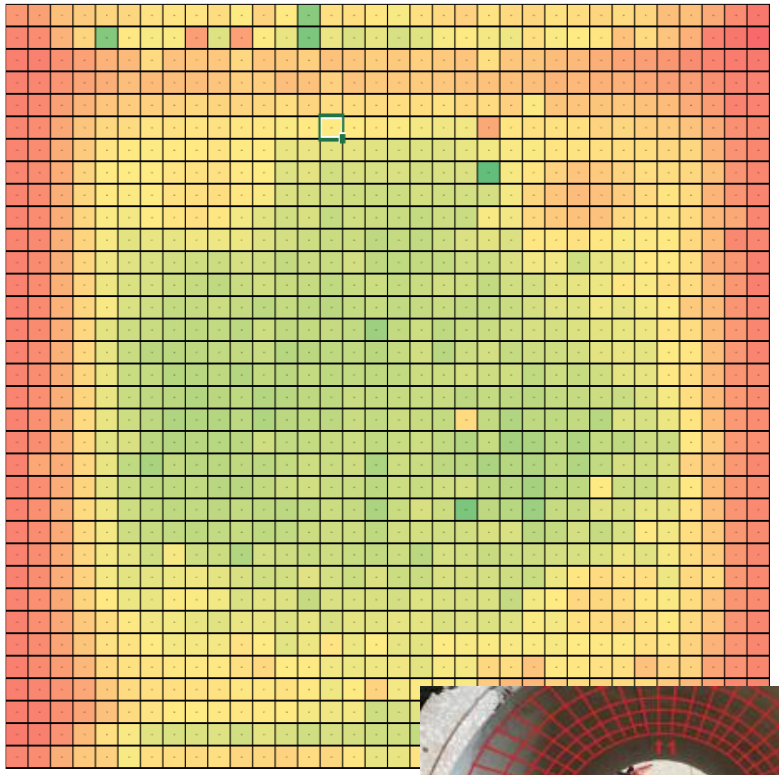


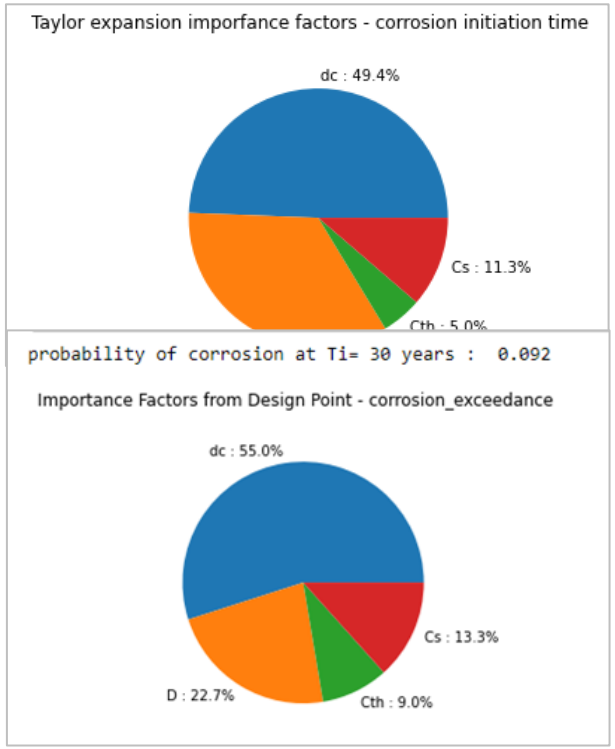


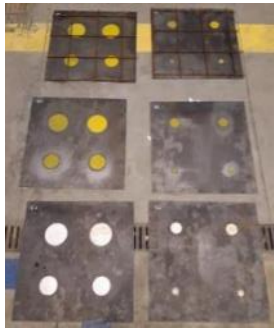
WP2 Corrosion assessment of embedded liners in concrete

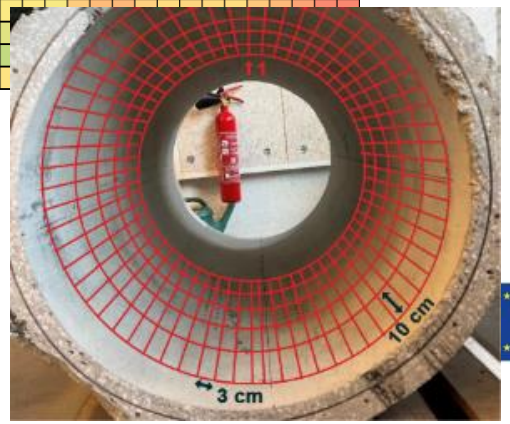
- Probabilistic assessment of corrosion; Corrosion inspection











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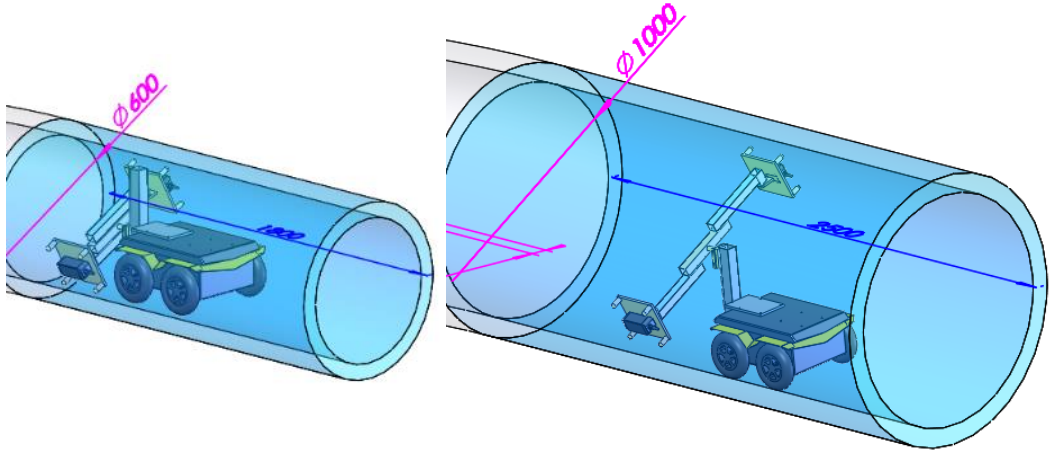
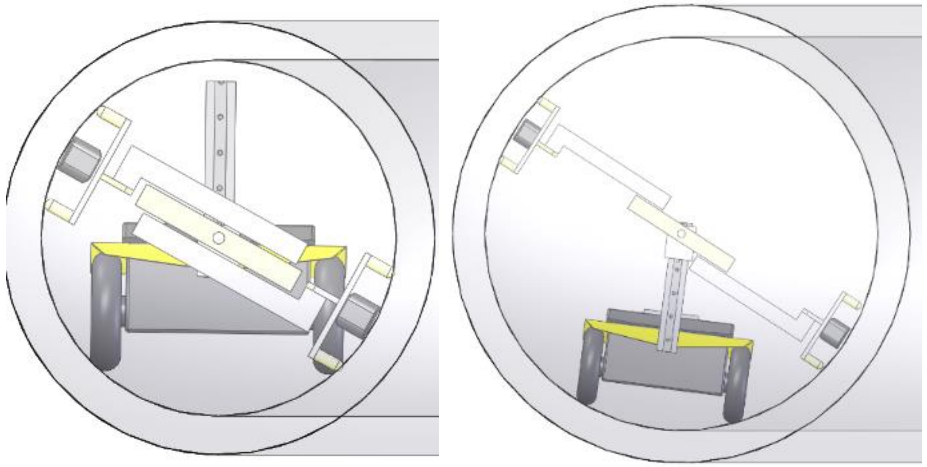
WP2 Corrosion assessment of embedded liners in concrete

- Robotics diagnosis

World Nuclear Exhibition 2023





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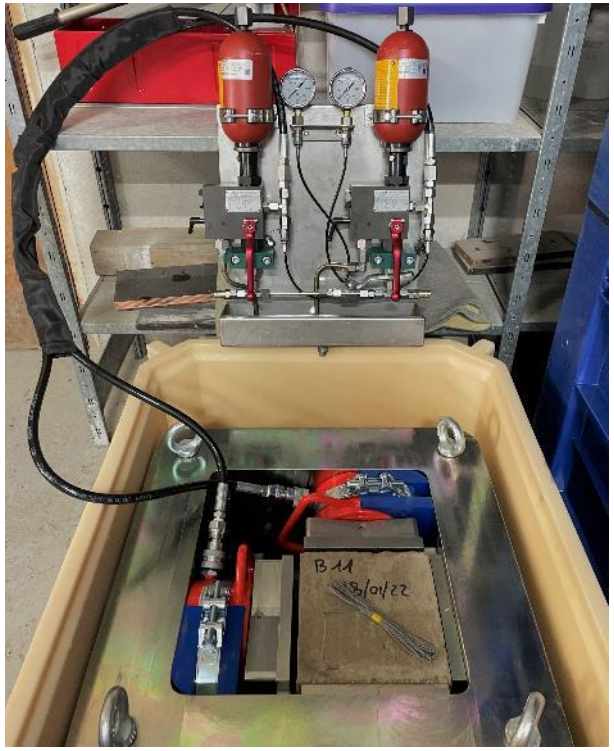
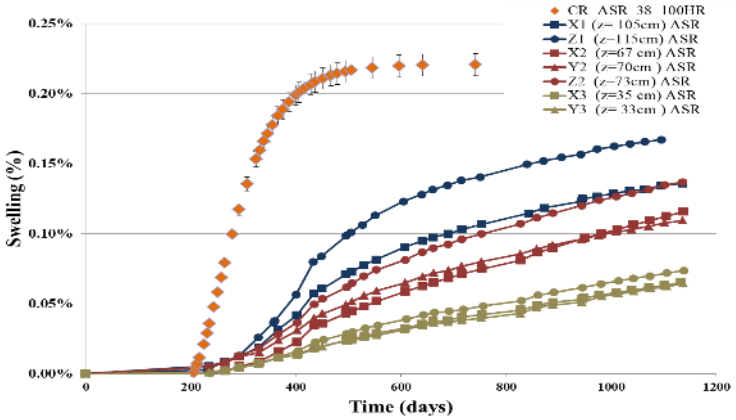
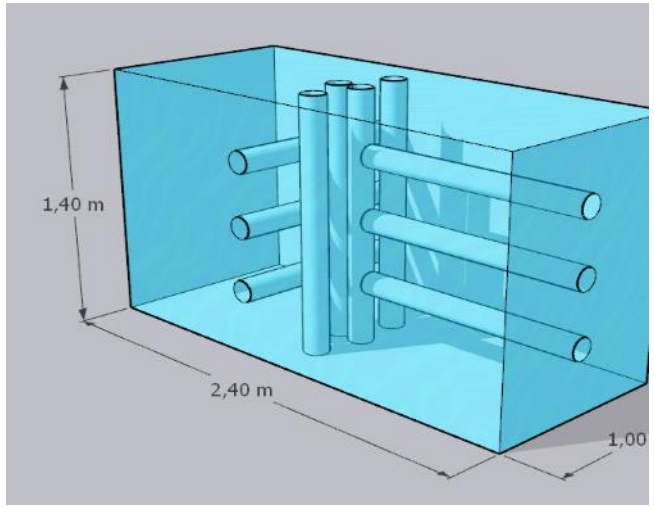
WP3 Characterization, prediction and monitoring of ISR

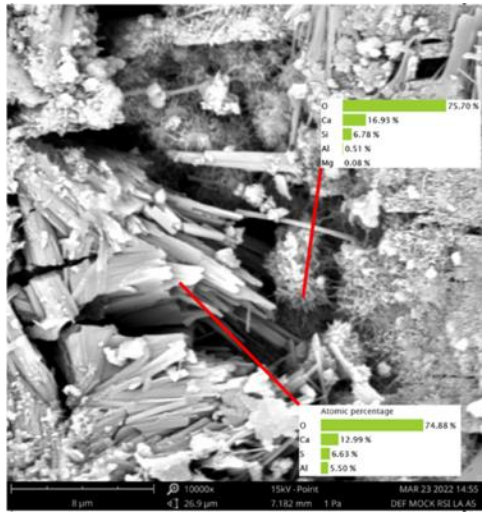
- Characterization of ISR reactions

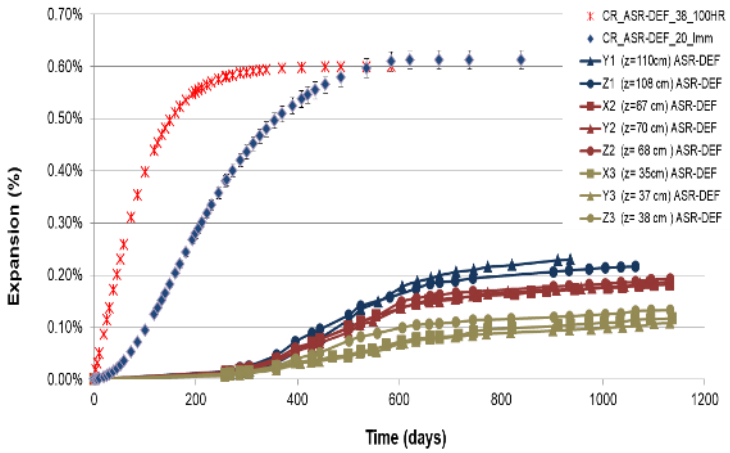
→ Laboratory to large-scale correlation of ISR; Interaction if ISR with biaxial loading; ISR characterization for modelling

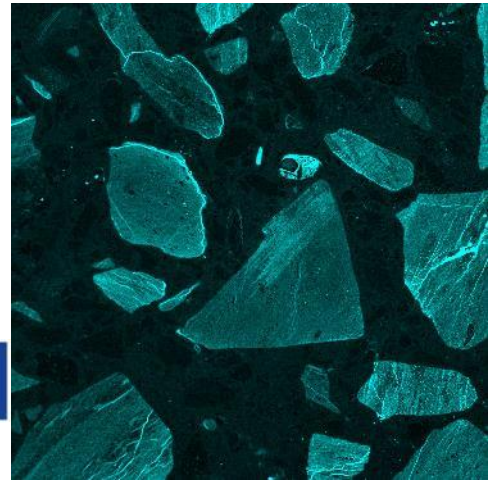












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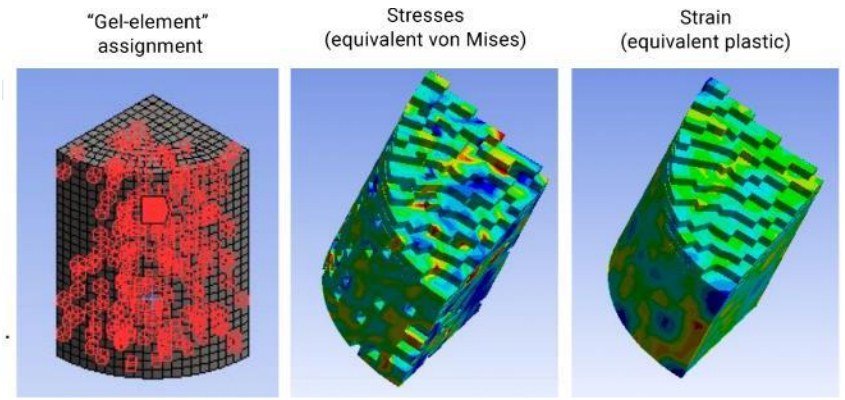
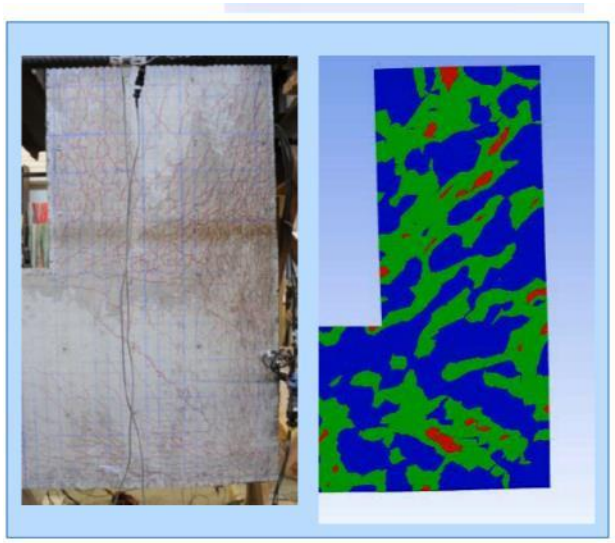
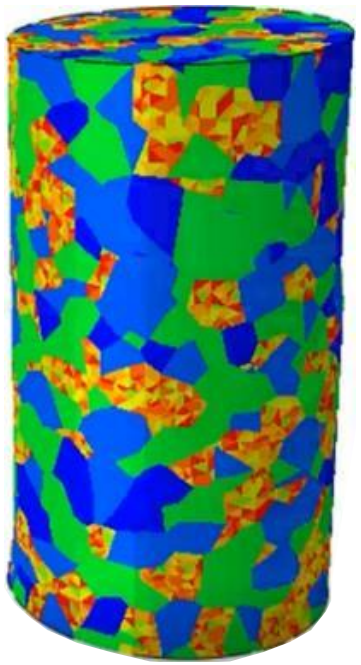
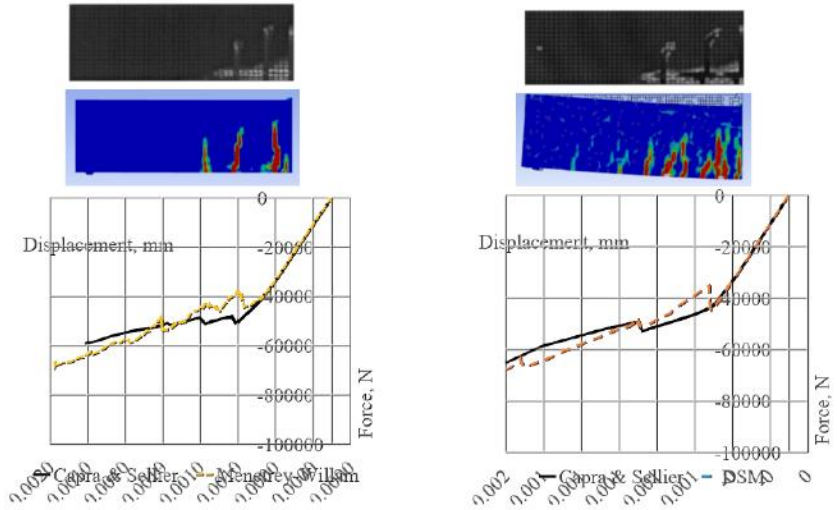
WP3 Characterization, prediction and monitoring of ISR

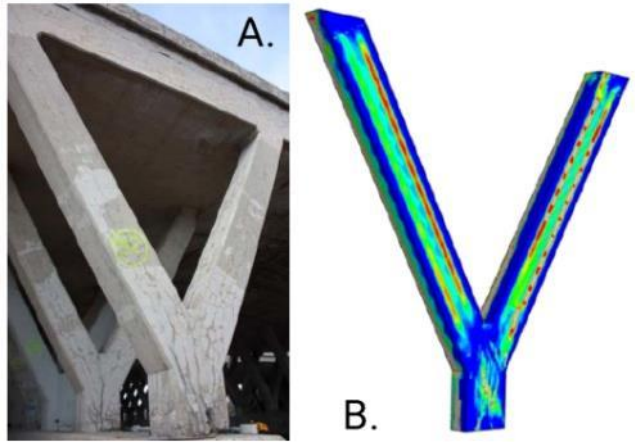
- Multi scale modelling (Macroscale models, Structure scale models)











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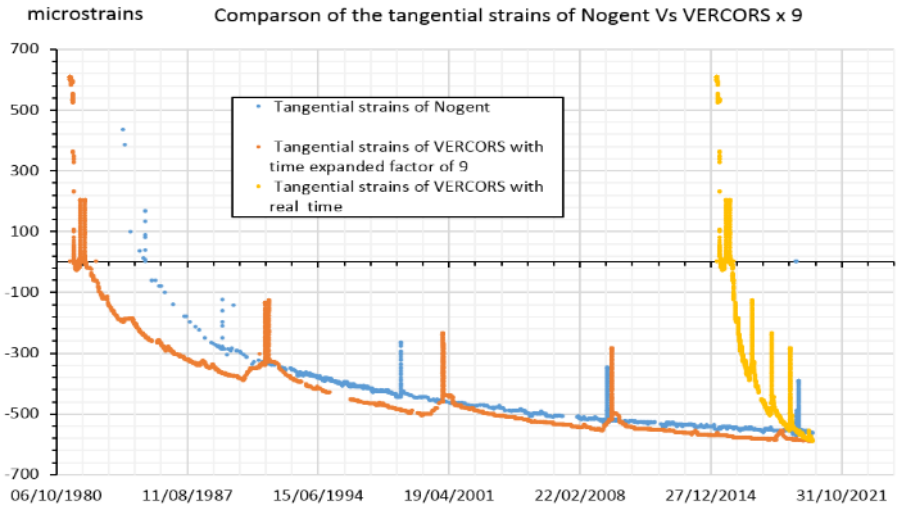
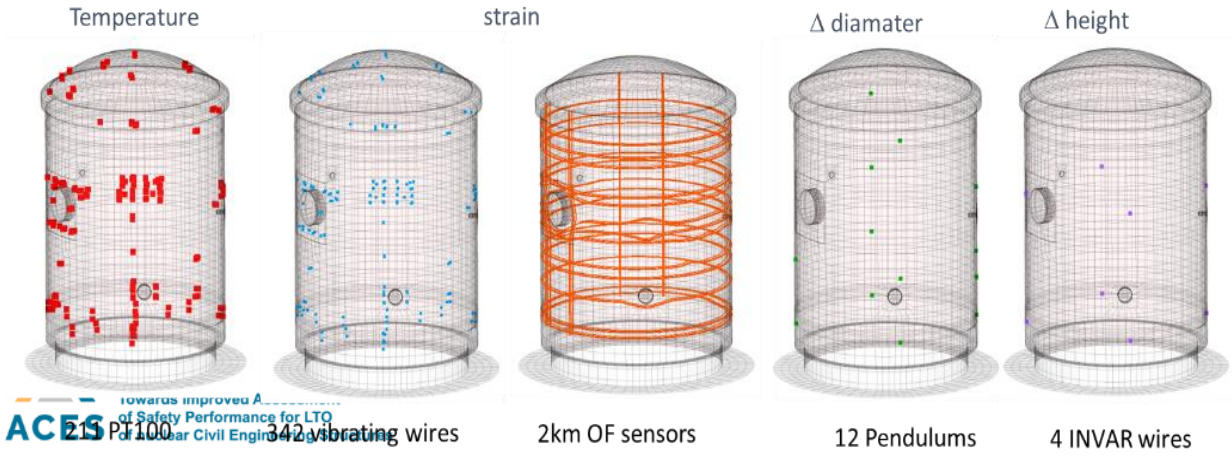
WP4 Delayed strains of containment building

- VERCORS Benchmark 3 - monitoring and material characterization

Measured variable	Sensor type	VeRCoRs mock-up	EDF fleet
temperature	PT100 probes	>200	30
strain	vibrating wires	>300	50
diameter variation	plumb-lines	4	4
length variation	invar wires	4	4
rebar strain	strain gages	80	-
water content	TDR	20	-
water content	Pulse	20	-
strain+temperature	optic fiber (OF)	2km	-



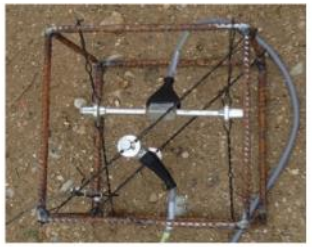


12 Pendulums

6 Dynamometers for instrumented tendons (VW6 + GLOTZL)

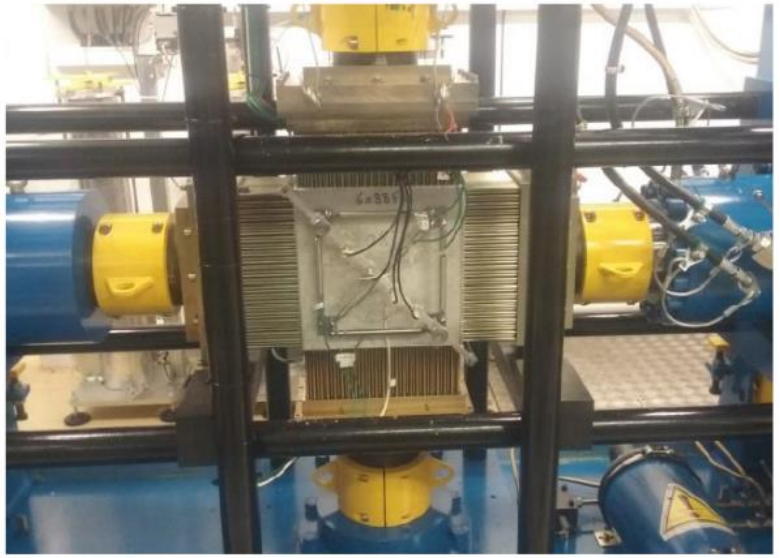
Temperature PT100 (211)

- 1 meteorological station
- For the ambient air measure : 10 thermometers, 10 relative humidity sensors,
- 1 atmospheric pressure gage,
- 1 flow meter
- 2 km of optic fiber
- 31 TDR (Time Domain Reflectometry) sensors
- 30 « pulse » sensors (permeability measurement)
- 160 strain gauges on rebars


Embedded strain sensors (326)

WP4 Delayed strain of containment building

- Effect of temperature on drying and strains - Behaviour of VERCORS concrete at temperatures 20-150°C



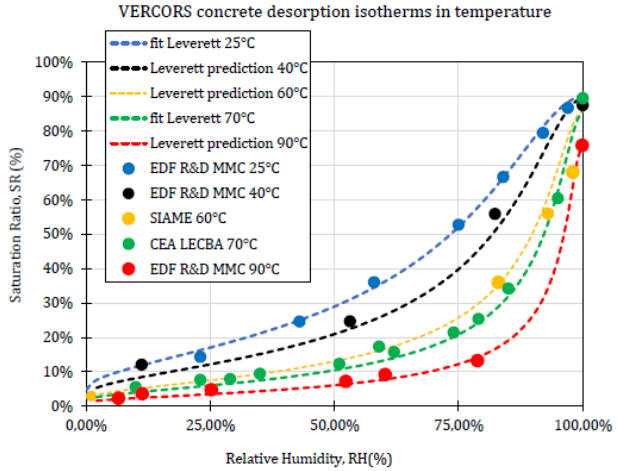
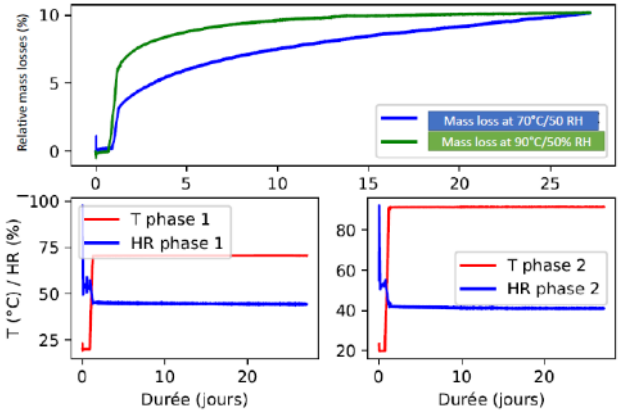


Fig9: First desorption isotherms of VeRCoRs concrete



Accidental situation

Intrados :
T = 150 °C ; RH = 100%, P =5,2 bar

Extrados :
T = 25 °C↑ ; HR = 55%↓, ,P = 1 bar

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WP4 Delayed strain of containment building

- Effect of temperature on drying and strains - Behaviour of concrete at temperatures 20-150°C

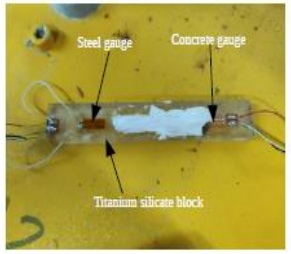
Compression creep test on cylinder specimen at 70°C and 90°C

Four points creep bending setup

Uniaxiale compressive creep setup

Free strain measurement setup

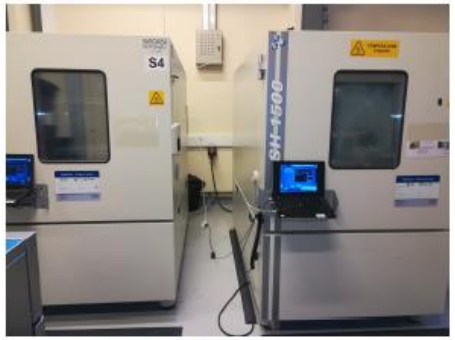
Gauge bridge setup for acquisition



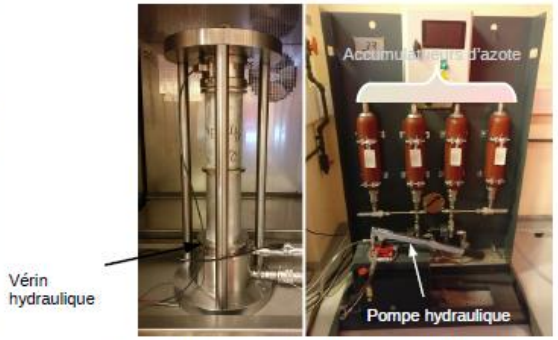
Non-expandable titanium silicate block for measuring the specific deformations of concrete and steel gauges

Climatic room monitorable in temperature and relative humidity

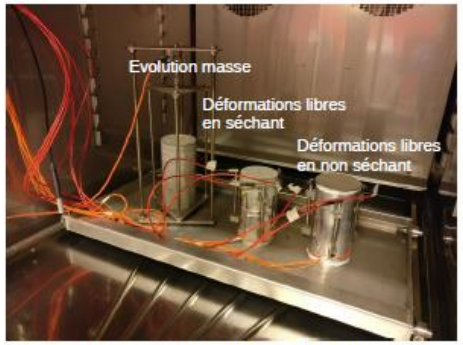
- LMDC Toulouse device



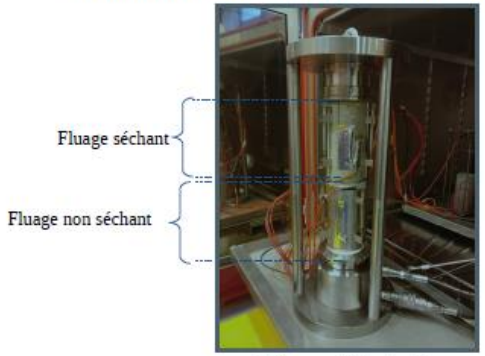
Enceintes climatiques



Banc de fluage relié aux accumulateurs d'azote



Mésure des déformations libres et de la cinétique d'évolution de la masse



Dispositif de fluage

- EDF Toulouse device

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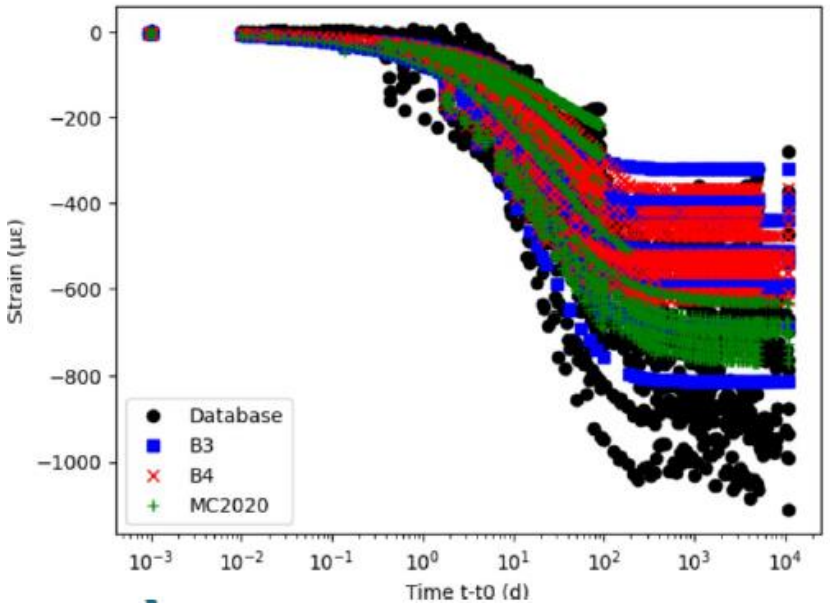
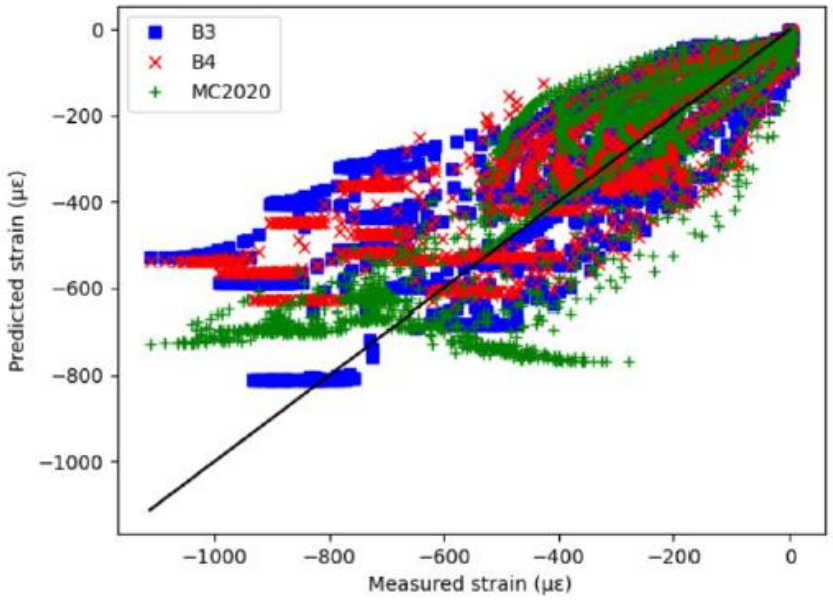
WP4 Delayed strain of containment building

- Predicting creep & shrinkage from mix design – predicting mechanical behavior of CCB when no shrinkage/creep tests are available
  - Available tools: Codes (B4, FIB Code model, …), Micromechanics tools (Vi(CA)2T developed at EDF, MOSAIC code developed at ORNL), other custom tools (e.g. at SCK-CEN)
  - Need for improving the validation of these tools and apply them to CCB concrete

- 43 sets (+ ≤901 sets)





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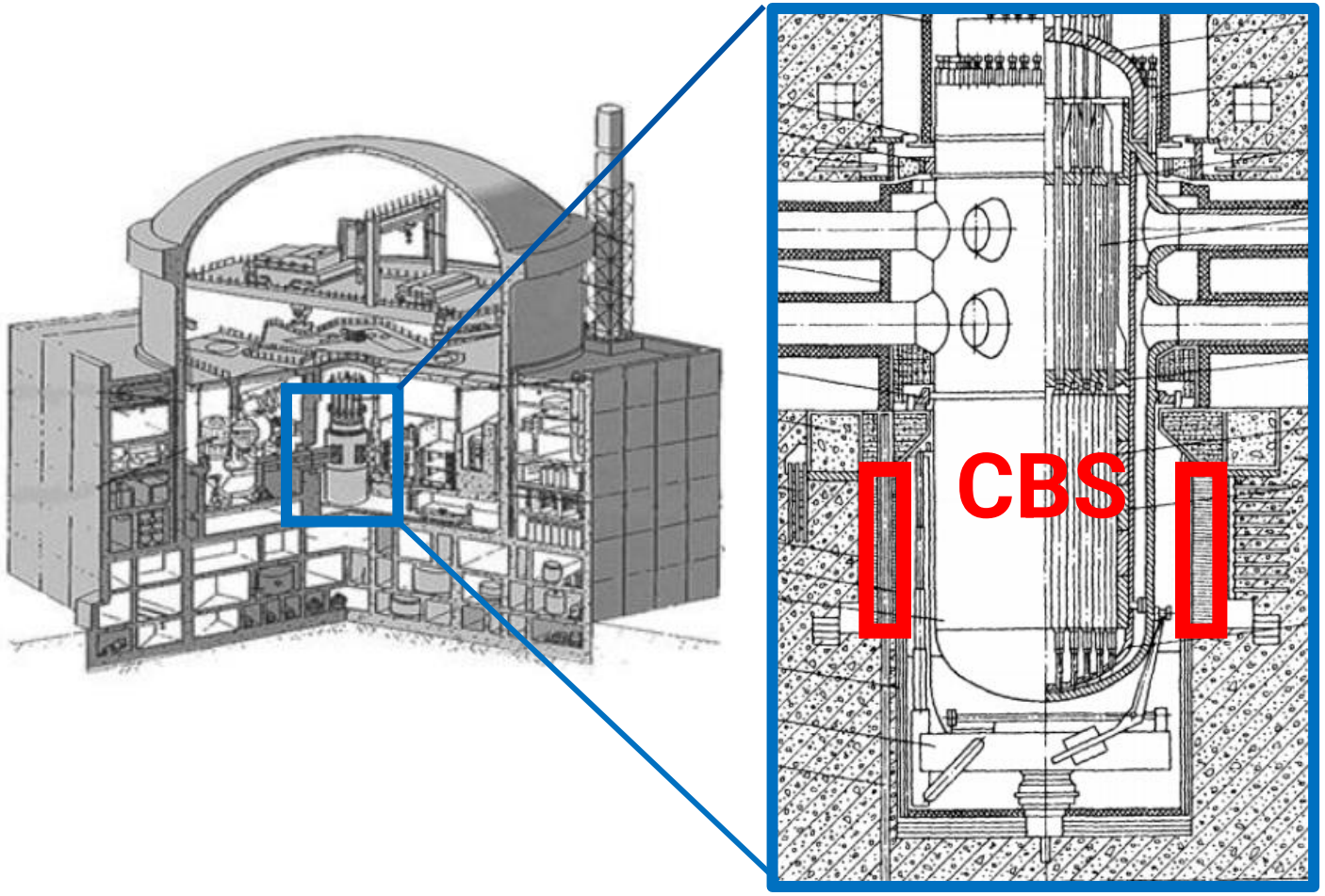
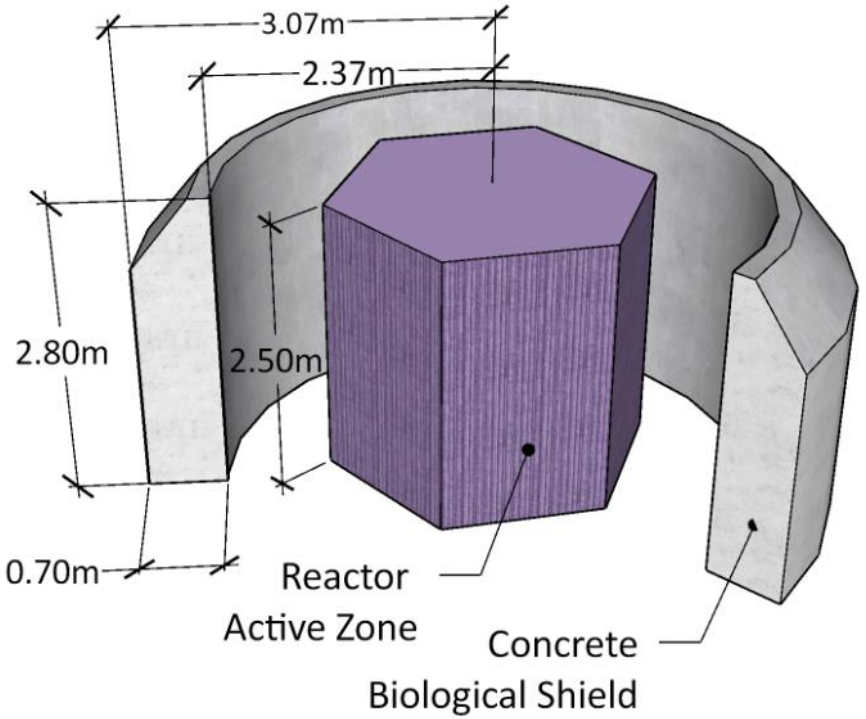
WP5 Assessing performance of irradiated concrete





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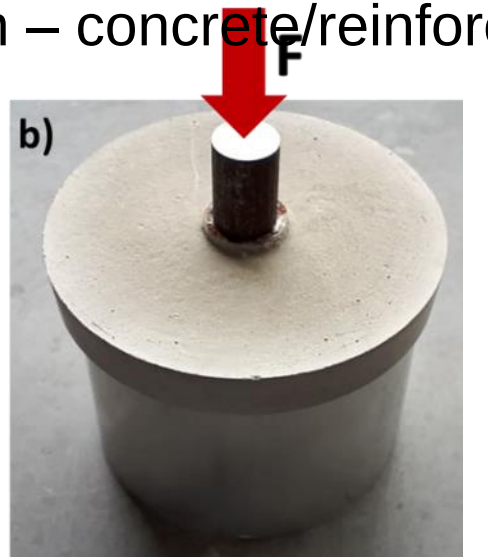
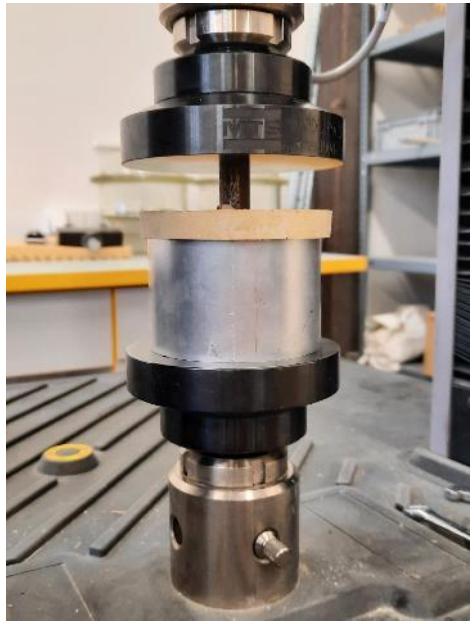
WP5 Assessing performance of irradiated concrete

- Gamma irradiation – concrete/reinforcement and rock



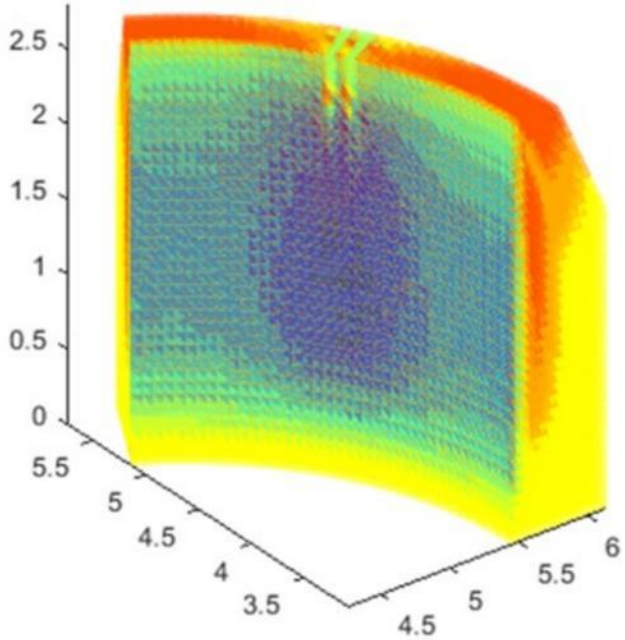


#	Rock
1	Serpentenite CZ
2	Soapstone FL
3	Granite FL
4	Diabase FL
5	Quartz A1 FR
6	Calcite A2 (grey) FR
7	Quartz A2 (black) FR
8	Granite A6 FR
9	Barite (white) SK
10	Barite (dark) SK

WP5 Assessing performance of irradiated concrete

- Modelling meso-scale to structural analysis

Minerals → **Aggregates** → **Concrete** → **Structural analysis**



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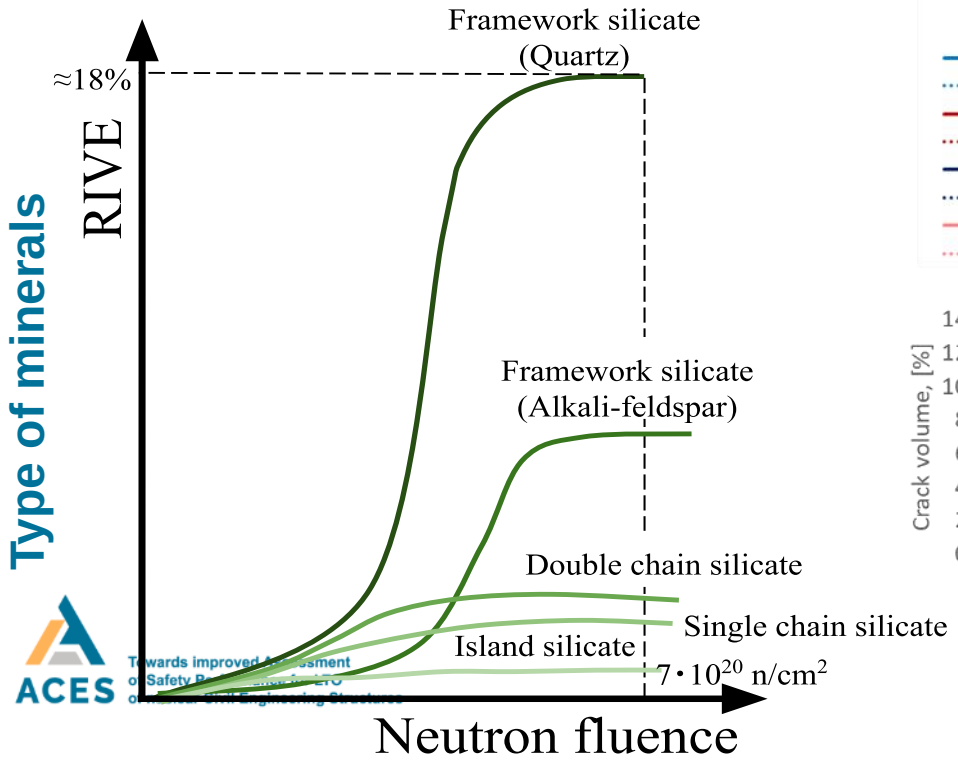
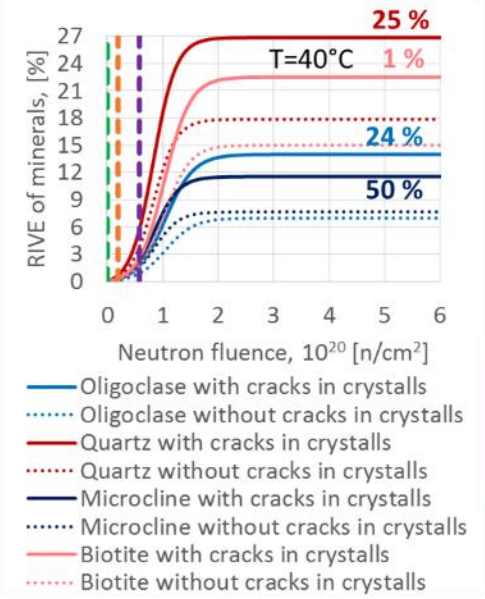
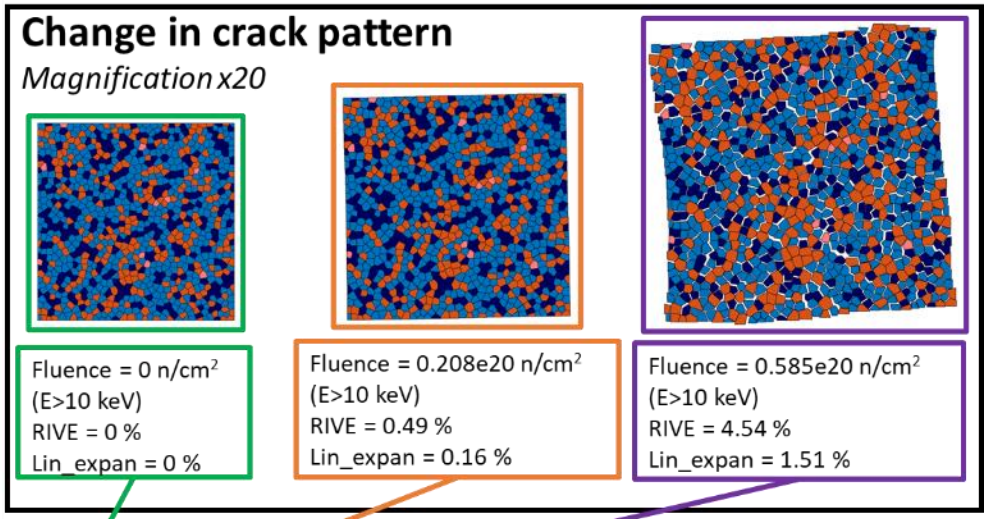
WP5 Assessing performance of irradiated concrete

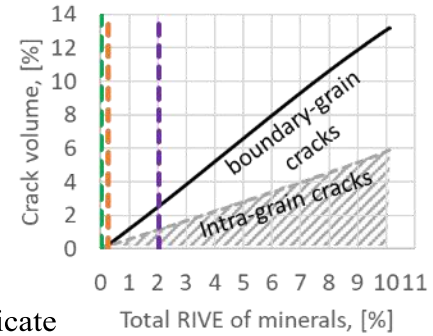
- Modelling meso-scale to structural analysis

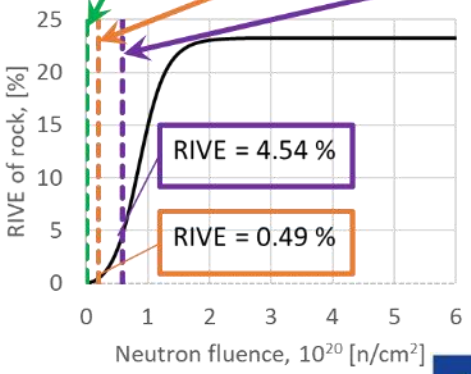
RIVE of aggregates

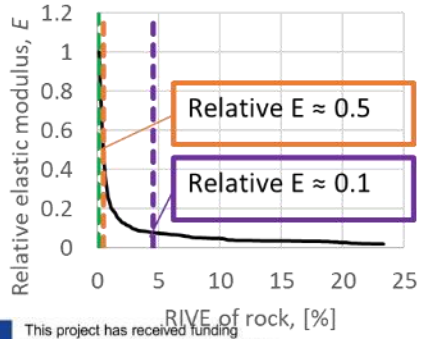












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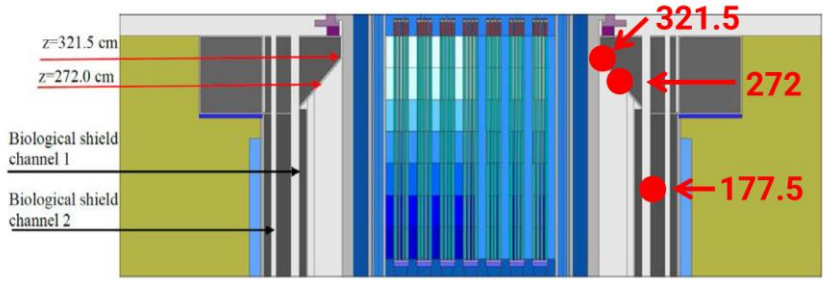
WP5 Assessing performance of irradiated concrete

- Modelling meso-scale to structural analysis

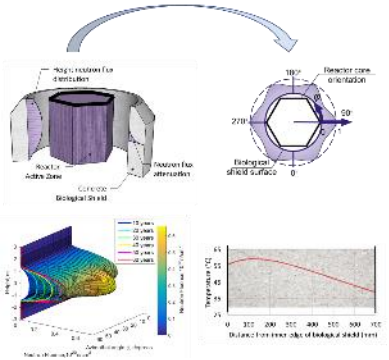
T5.3.1 Radiation, thermal and moisture fields

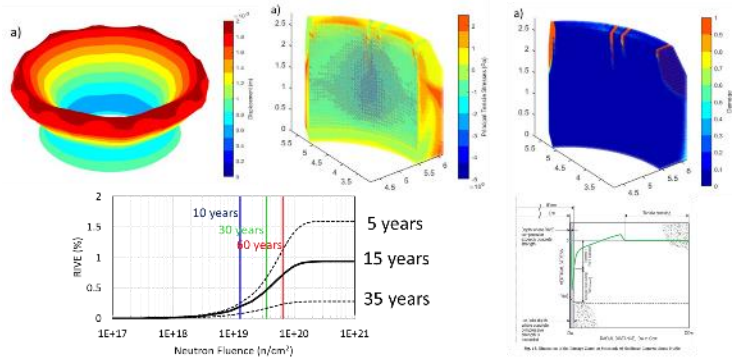


	z= 272 cm	z = 321.5 cm	z = 177.5 cm
Total neutron flux [1/cm2s]	2.974e+10	2.718e+10	4.078e+10
Thermal neutron flux E<0.41eV [1/cm2s]	4.650e+09	2.555e+09	7.154e+09
Fast1 E>0.1 MeV [1/cm2s]	8.911e+09	9.752e+09	1.368e+10
Fast2 E>1 MeV [1/cm2s]	7.772e+08	9.096e+08	1.487e+09
Gamma flux [1/cm2s]	1.148e+10	1.016e+10	1.892e+10

- Data from EUG
- Numerical model for neutron transport for VVER 1000 ready, (VVER 440 to be finalized)

T5.3.2 Structural modeling of irradiated CBS





<u>Benchmark definition</u>
to be discussed

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Thank-you!

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