PREDIS

WP7 Innovations in cemented waste handling and pre-disposal storage

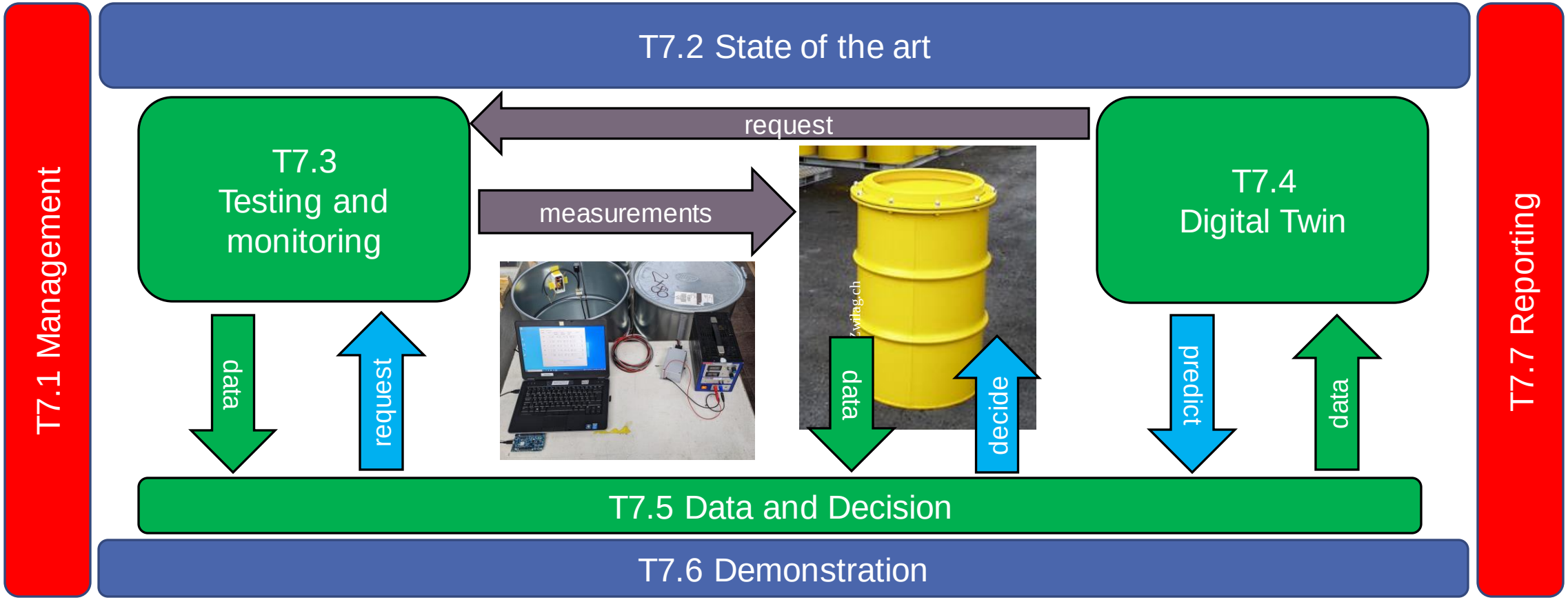
Ernst Niederleithinger and the WP7 team

Mechelen, Thursday Session,

25.05.2023

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 945098.

Overview



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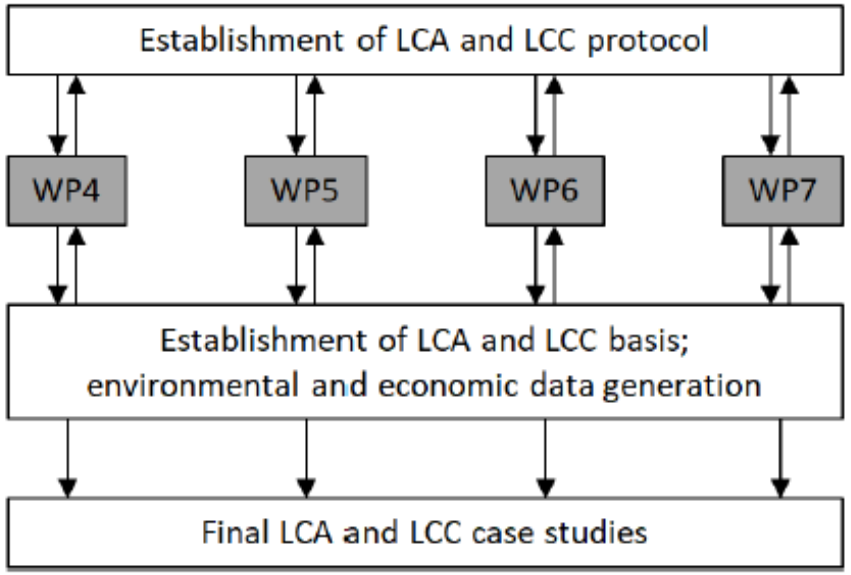
T7.2 State of the Art (SoTA), Reference package

Criteria	Single Skin
Wasteform grout formulation	>3:1 wt/wt BFS: OPC blended mix, 0.35-0.5 w/s, no additives, sand, aggregate or superplasticisers
Waste type	Magnox metal (or Mg). Large discrete pieces or small bits evenly distributed throughout the grout matrix. Recommended use 62kg of Magnox (or Mg).
Storage Environment	0-20 ºC, RH < 50%, controlled air change and controlled chloride content (< 100 $\mu g_{Cl^-} cm^{-2}$)

Criteria	Single Skin
Geometry	Cylindrical
Size	200 L (60 cm Ø, 90 cm height)
Construction material	Austenitic Stainless Steel (300 grade, 1.2 ± 0.2 mm thickness)
No. of skins	One
Closing system	Concrete layer between wasteform and lid. Stainless steel (300 grade) lids. Suggested this be vented. Closing system can be screw, clamp or bolted.



Reference cemented package

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T7.3 Integrity Testing and Monitoring Techniques

- Investigation of the relevant conventional and innovative NDE/monitoring techniques
- Adaptation for using under typical storage conditions, and implementation into individual waste packages, for wireless data transmission and wireless energy supply
- Integrity testing by means of relevant technologies using full-size package mock-ups is the aim
- Provide guidance for technology selection, deployment and automation

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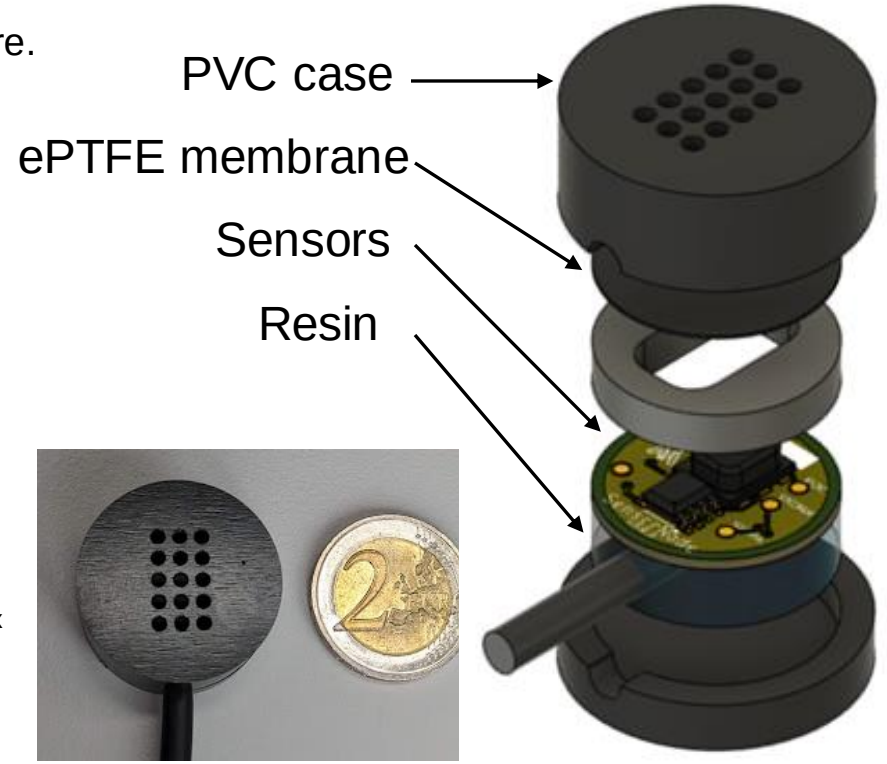
Waste Drum Embedded Sensors (BAM)

- **SensorNode**

  A device that can measure relative humidity, temperature and pressure. The membrane's pores allow water and gas particles to pass through and let the enclosed air equilibrate with the external environment. It's possible to connect multiple units in order to create a distributed matrix of uniquely identifiable measurement points.

  - **Onboard sensors:**
    - Honeywell ABP2LNNT400KA2A3XX
      - Absolute pressure range: 0-400kPa
    - Honeywell HIH8131-021
      - Relative Humidity range: 0%RH – 100%RH
      - Temperature range: -40 °C to 125 °C
  - **Power consumption:**

    The energy consumption of one measurement cycle for each node is about 0.4mAs (20mW x 60ms).
  - **Limitations**
    - Max 64 nodes on the same bus (Unique ID limit)
    - Max 6m water depth (Membrane limit)
    - Max 10m cable length (Communication protocol limit)



Dimensions: Ø 3cm x 1.5cm

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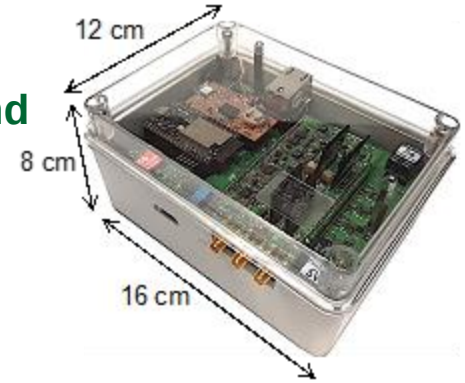
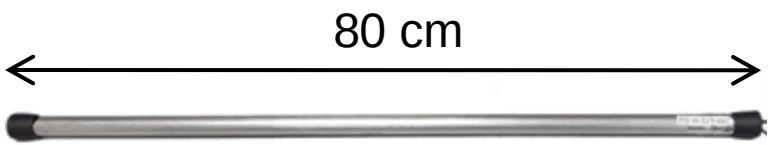
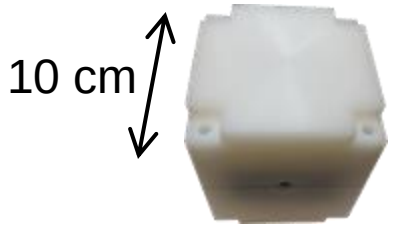
SciFi and SiLiF detectors for external monitoring

WiFi front-end and data acquisition electronics

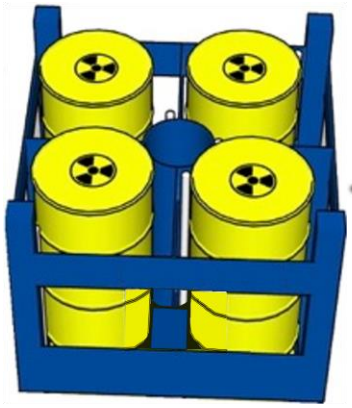




SciFi (Scintillating Fiber) gamma ray detector

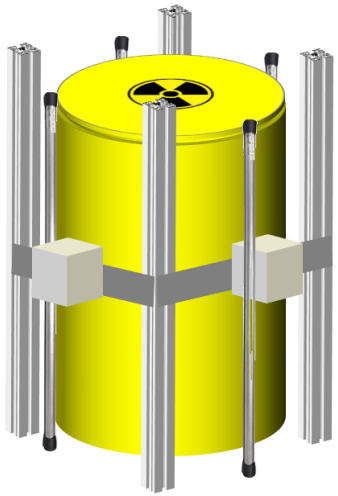


SiLiF (Silicon Lithium Fluoride) neutron detector



installed on stillage

installed on standalone drums



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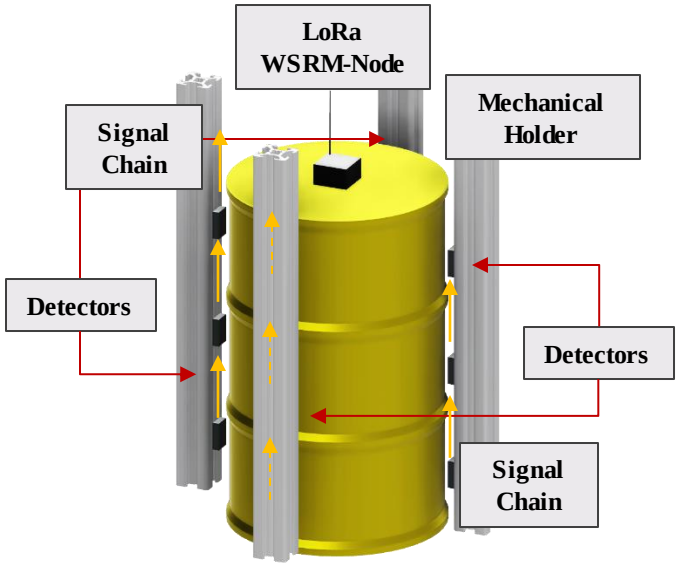
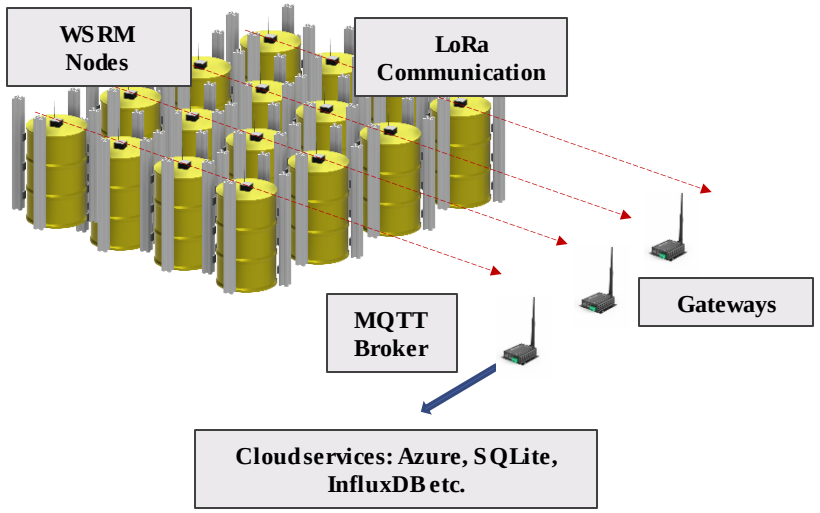
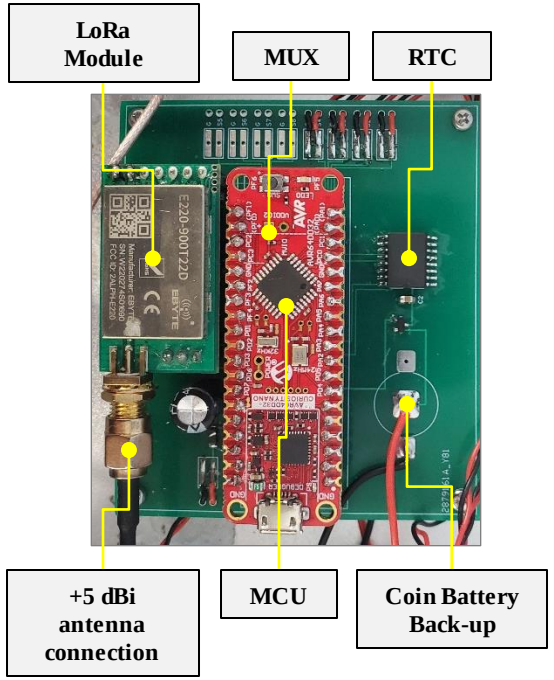
Wireless Radiation Monitoring Network Architecture

UniPi Approach: technology implemented as distributed Wireless Sensor Radiation Monitoring Network (WSRMN) of sensorised micropower end-nodes to be installed on waste drums and communicating through Long Range Radio technology (LoRa)







Goal: develop a flexible and autonomous monitoring system for the identification and monitoring of the structural integrity of RWDs, improving the safety and security, while minimizing errors due to human intervention and maximizing the storage capability.

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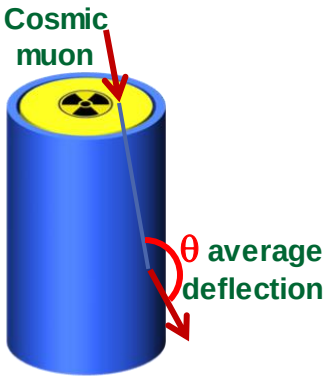
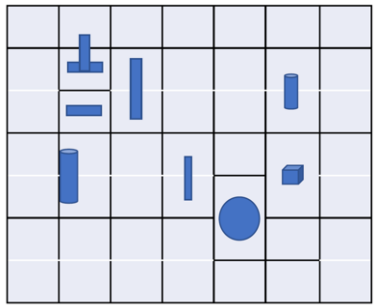
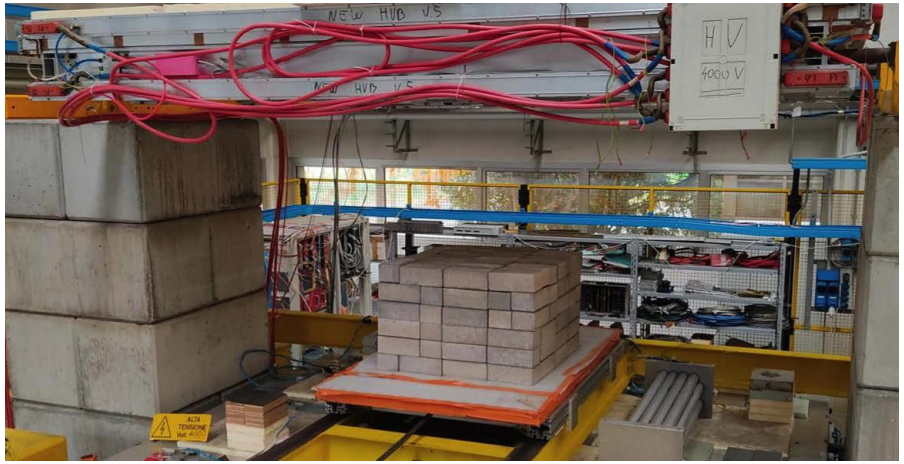
Looking inside thick objects: Muon Tomography

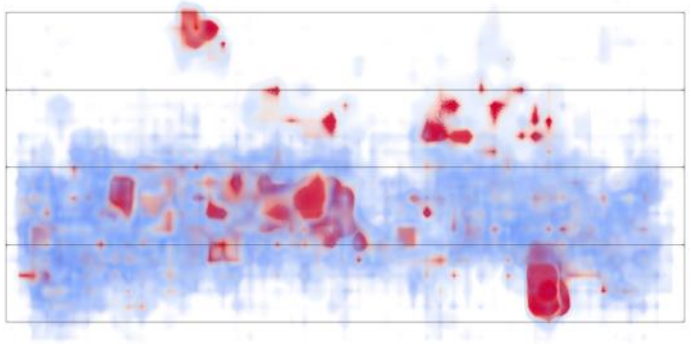


- Muons are highly penetrating
- Can be deflected by high density materials
- Average deflection informs on the density profile
- Test with samples of various metals in cement

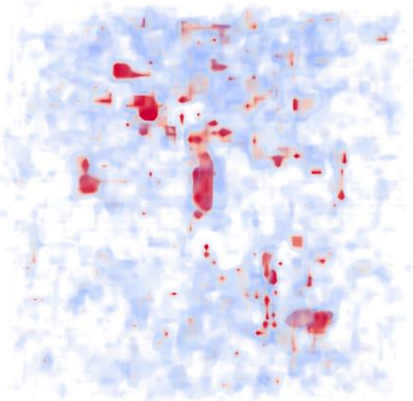
Top view (sketch)







Side view (real data)



Top view (real data)

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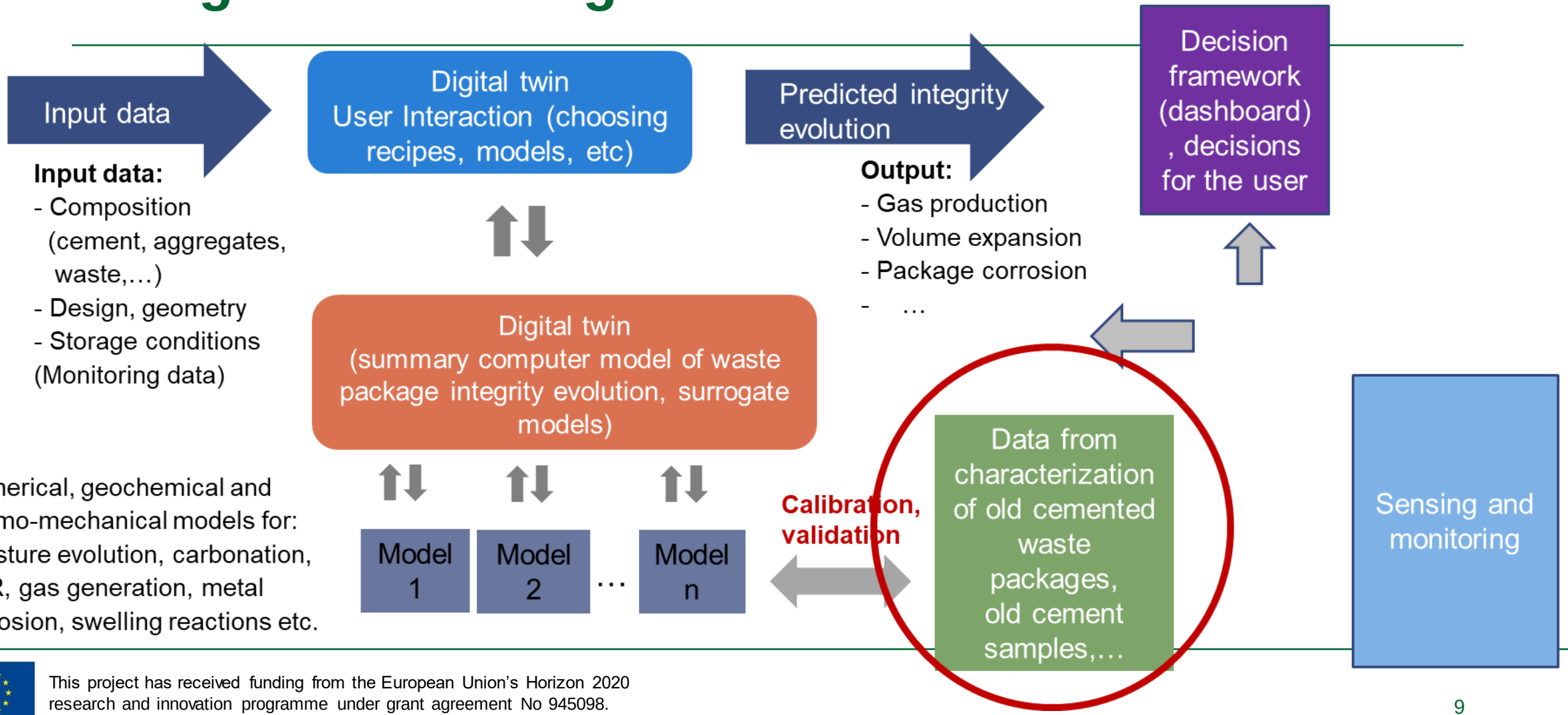
Background T7.4 Digital Twin



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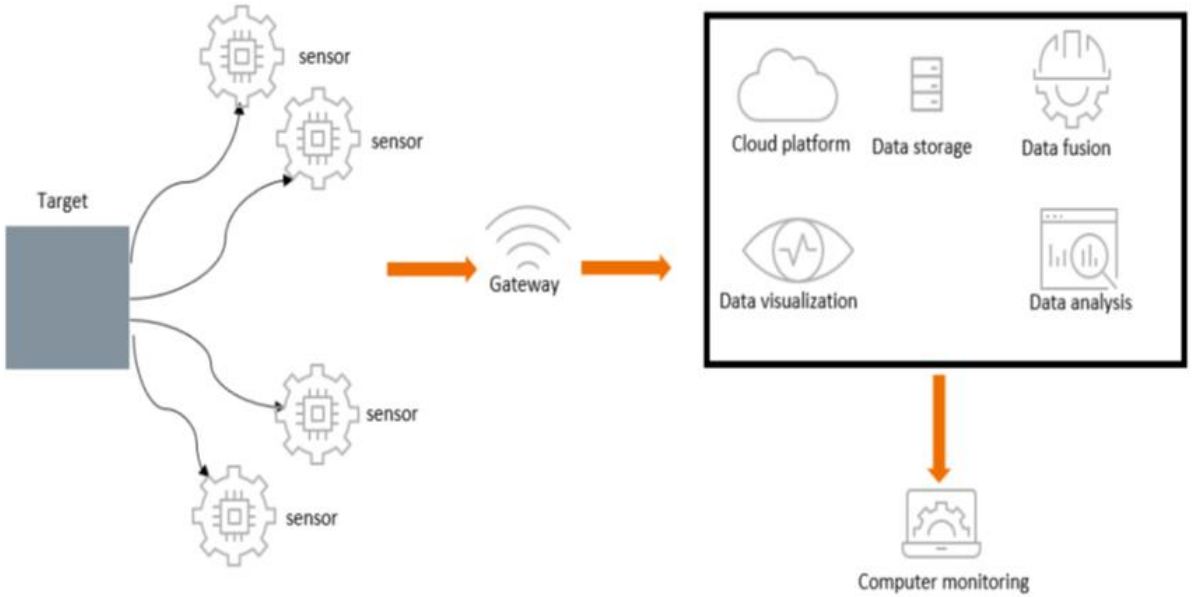
T7.5 Data handling, processing and fusion

Aim: building the condition monitoring system of predisposal storage.

→ Ample data! Good data handling helps to minimize potential errors and reduce the risks related to data processing. A need for a versatile data platform!

PREDIS WP7: develop and research tools for monitoring cemented waste packages to better understand and utilize the available data, with the possibility to detect and even predict important features from the measured data:

(1) How long will the concrete last?
(2) Which measurements are truly relevant?
(3) What is the current condition?



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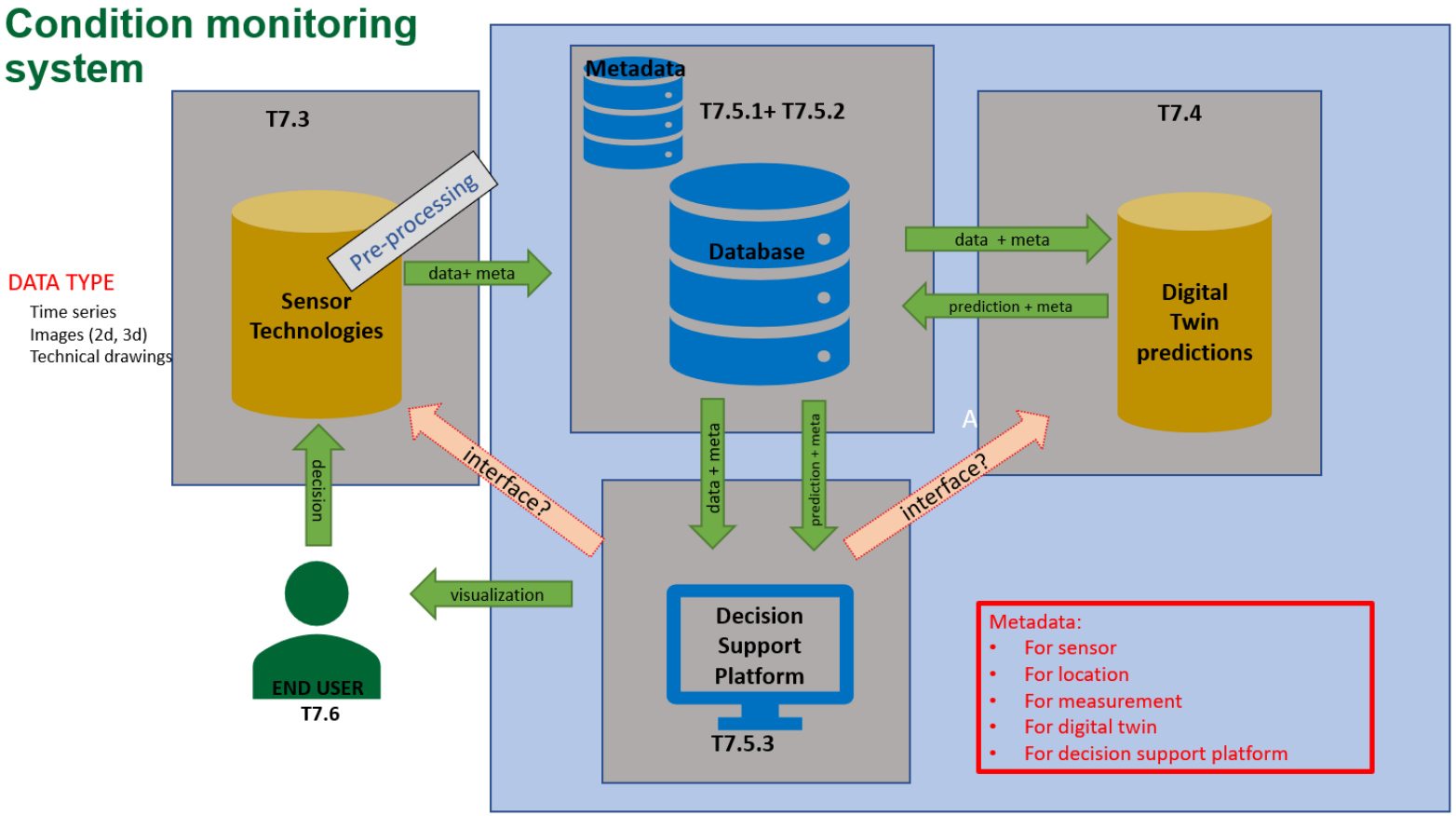
Condition Monitoring System Overview



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Decision Platform

A decision platform can be considered a holistic solution for enabling **centralized decision management** that incorporates **data driven insights** & **analytics**, along with **human expertise**.

- **business intelligence (BI) process** (gather/organize data; query the data/visualize.
  - use the information for decision making
- **information for decision making & strategic planning**
  - **Online Analytical Processing (OLAP)**
    - data is aggregated on metrics pH, temp., pressure, …
    - data is associated with multiple dimensions time, place, categories, ...
    - data can be ”sliced” / ”diced” / …. by filtering & segmenting !slow to write, fast to query!

→ visualization using DASHBOARD (ALARMs/STATUS ...)
→ interactive ANALYSES
→ generating REPORTS

⇒ **increase safety, reduce uncertainty, decision making for intervention**
⇒ ⇒ **designing of a waste route modelling system utilizing LCA/LCC data**

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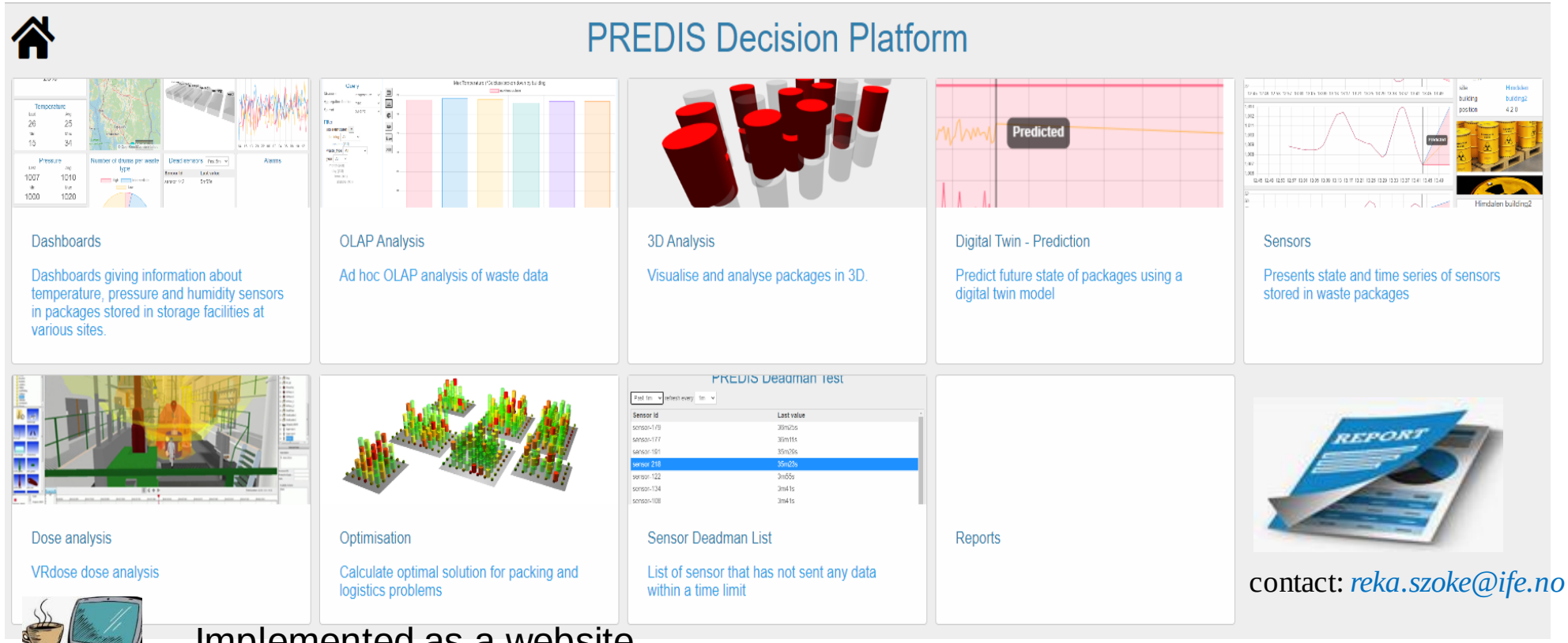
PREDIS Decision Platform



contact: *reka.szoke@ife.no*

Implemented as a website

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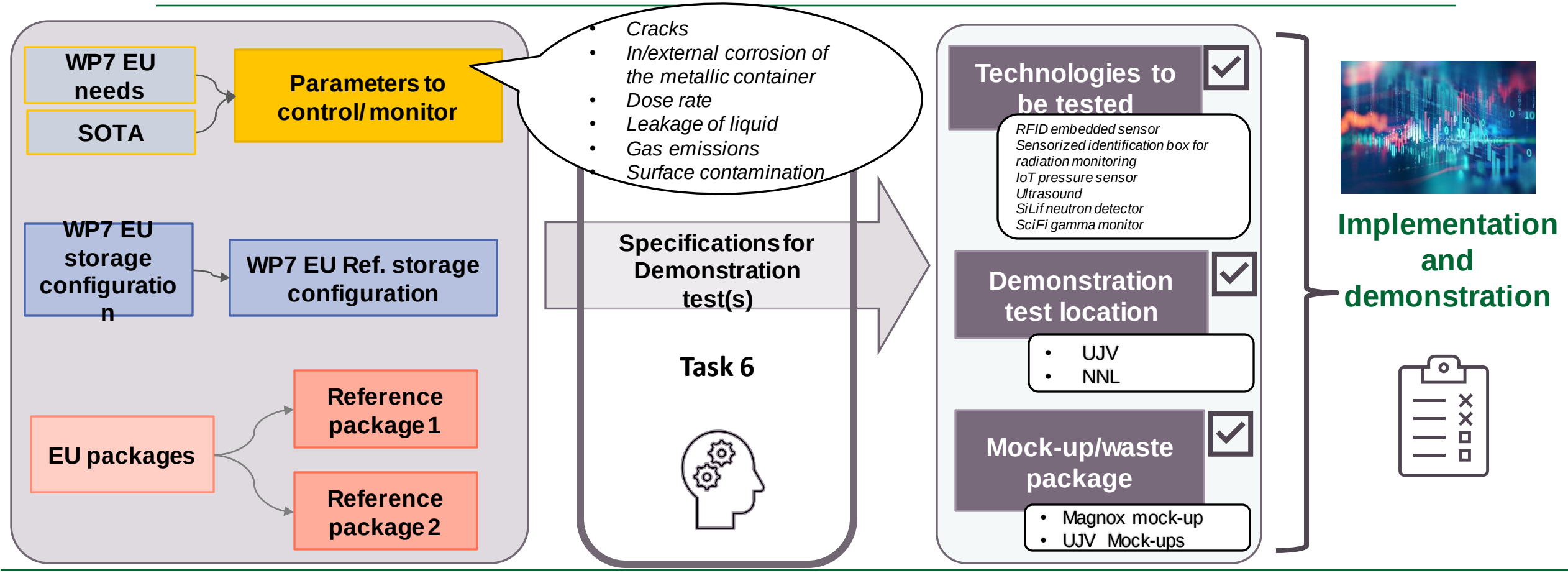
Evaluation & demonstration of technologies and systems



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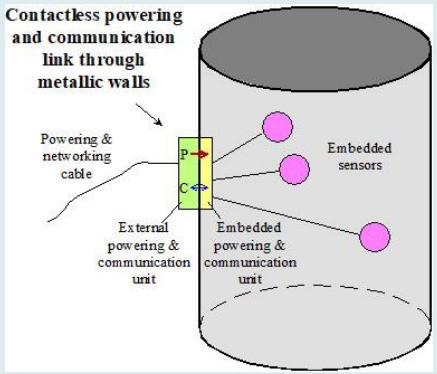
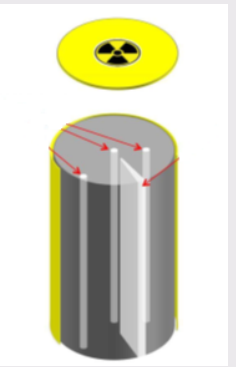
Mock-ups used for demo tests

	Non active mock ups		Active mock-up
	NNL legacy inactive package	**Mock-up 1.2**	**Mock-up 2**
Technology	**Air-coupled US**	**RFID embedded sensor with Iot pressure sensor**	**SciFi + SciLiF & Sensorized RF identification box**
Developper	**NNL**	**BAM/VTT & Magics**	**INFN & UniPi**
Matrix	BFS:OPC (>75 % BFS) + Magnox inactive waste	Belgian formulation – reactive cement IAW BAM	Concrete mixture based on OPC with sand filler (UJV recipe)
Dimensions	Cylindrical; 500 L (D = 800 mm, H = 1200 mm)	216 L drum (D = 620 mm, H = 876 mm)	216 L drum (D = 620 mm, H = 876 mm)
External container	single skin	single skin	Single skin
Phenonema expected	/	Volumetric expansion, Cracks in the matrix	Cracks (through wedges)
Parameter followed	swelling, external corrosion, leakage	Humidity, temperature, pressure	Dose rate
Package producer	NNL	UJV	UJV
Test location	NNL	UJV	UJV
Additionnal	Vented	Non vented	Hole in the matrix for insertion of ^{137}Cs (180MBq) source





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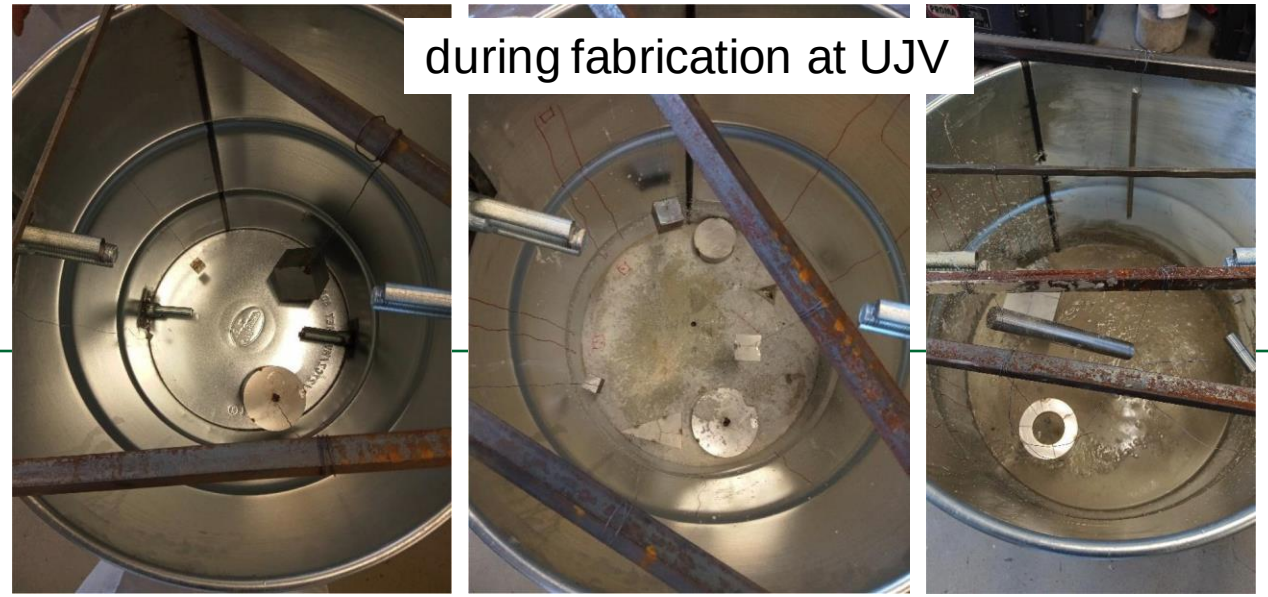
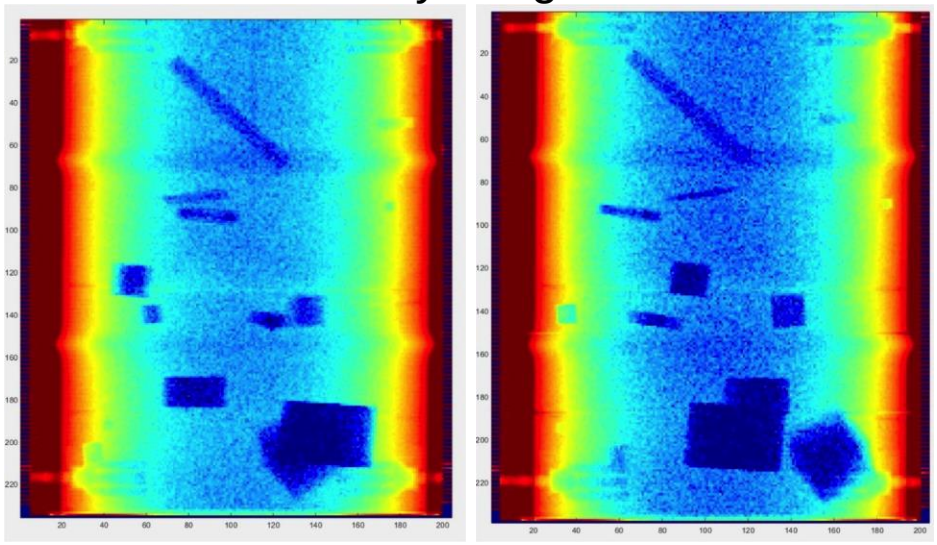
Mockup drum for tomography



	material	shape	size [cm]
1	stainless steel	cube	3x3x3
2	stainless steel	cube	5x5x5
3	stainless steel	cube	10x10x10
4	stainless steel	cylinder	diam=10; H=5
5	stainless steel	cylinder	diam=15; H=10
6	stainless steel	bar	diam=2; L=6
7	stainless steel	bar	diam=3; L=25
8	stainless steel	sphere	D=10
9	stainless steel	toroid	D=10; d=5.5; h=1.5
10	stainless steel	triangle	thickness 2; b=7; h=12
11	lead	cube	1.5x1.5x1.5
12	lead	cube	3x3x3
13	lead	cube	5x5x5
14	stainless steel	cube	1.5x1.5x1.5
15	stainless steel	bar	diam=1; L=30

Stainless steel 1.4301 Concrete C16/20

X-ray images



the horizontal support

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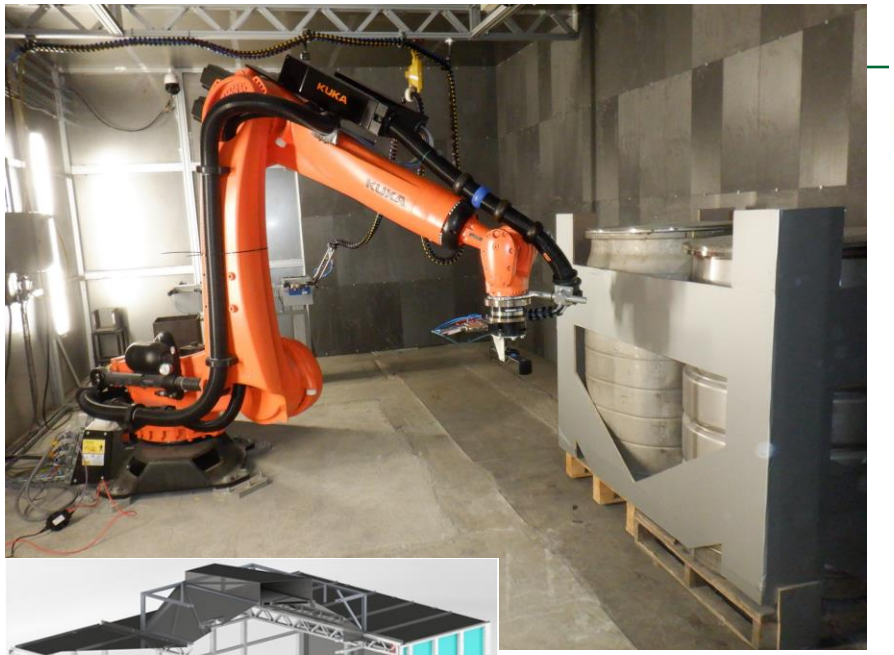
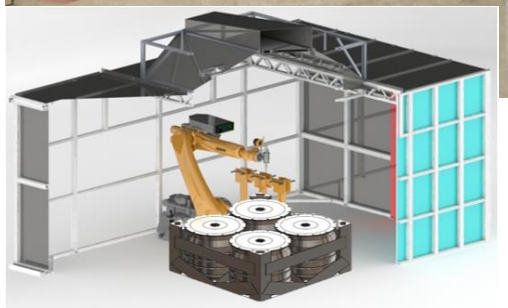
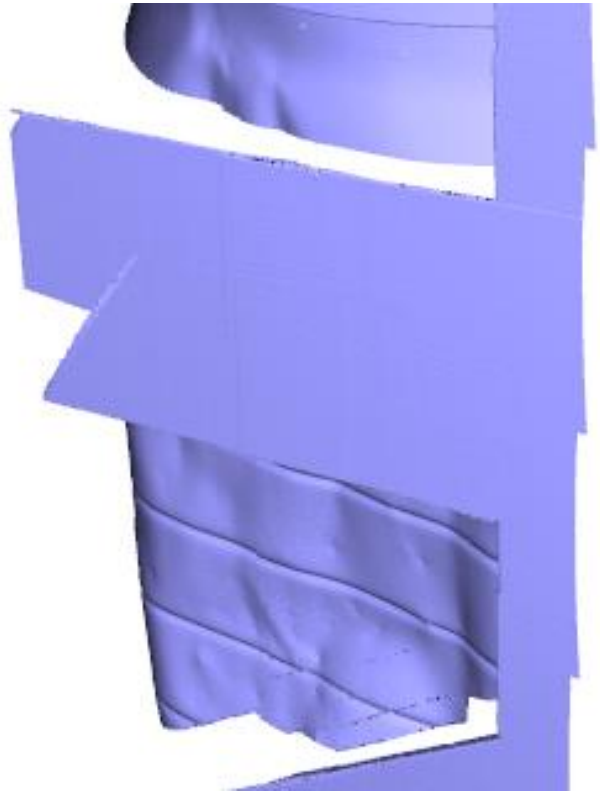
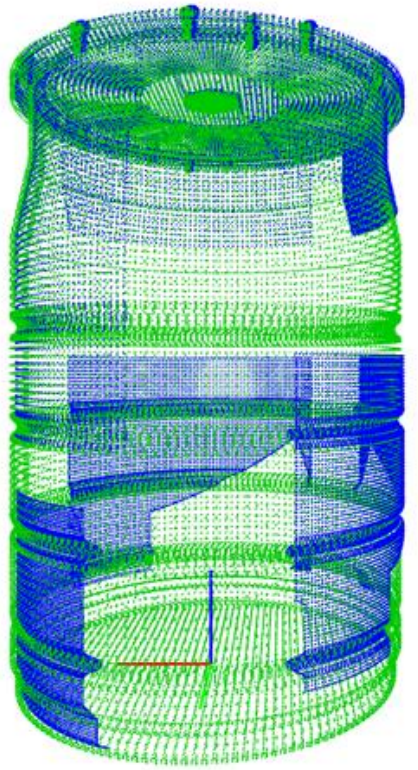
Demonstration test at NNL with Magnox package









3D point cloud - stitched from a combination of 3D scans collected using a Phoxi camera mounted onto a kuka manipulator end effector

Sensor Fusion
To build a full picture of the drum - Multiple scanning methods will be required - complementing each other with the missing information from each type of sensor.

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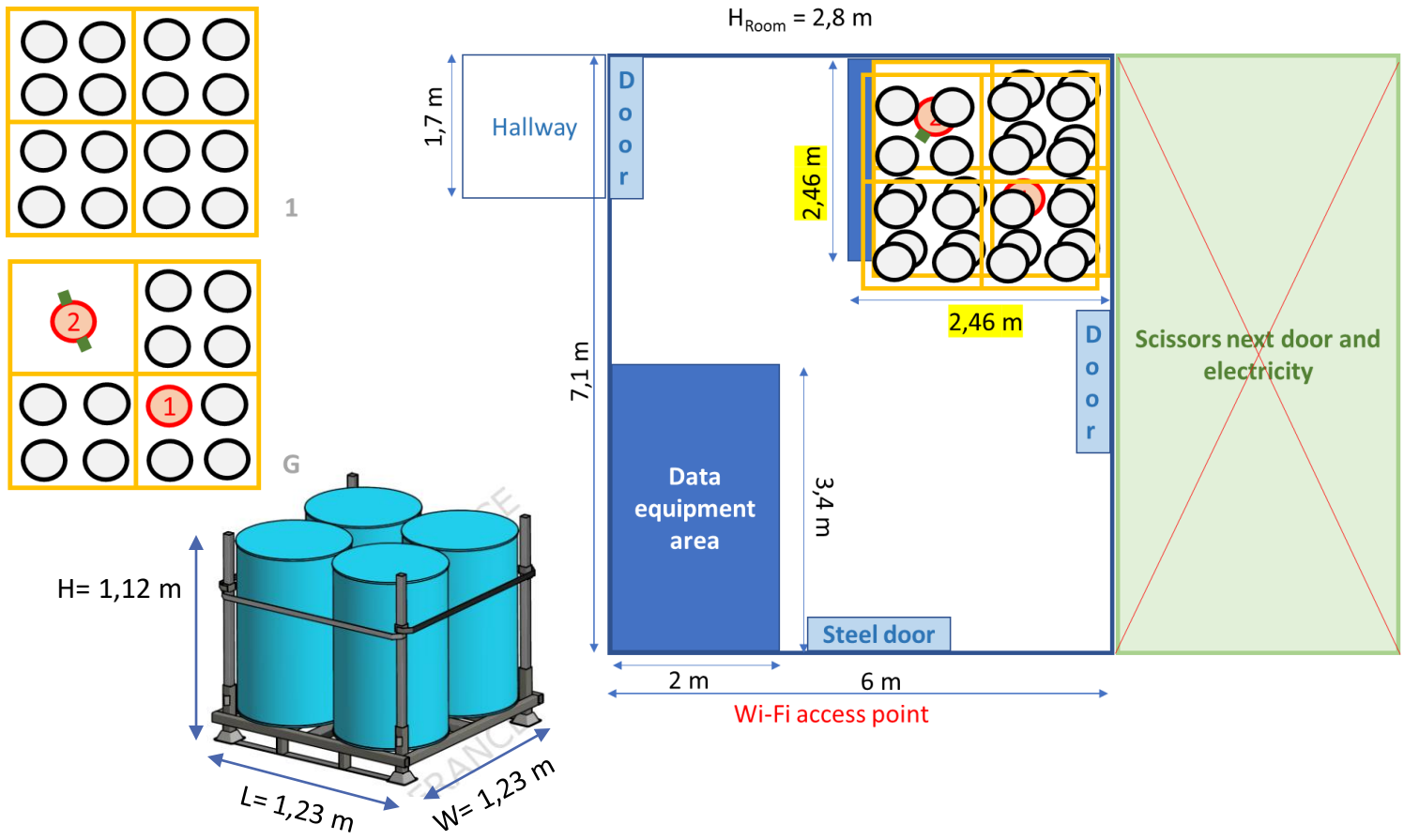
Specifications for demo test at UJV

- Optimized storage configuration for the demo test is:
  - 27 cemented packages
  - 8 stillages
  - 2 mock-ups
    1. Mock-up 1.2: Non-active mock-up (RFID + IoT)
    2. Mock-up 2: Active mock-up (RF + SciFi + SciLif)
- Timeline: Q4 2023/Q1 2024
- Duration of UJV test: 3 months



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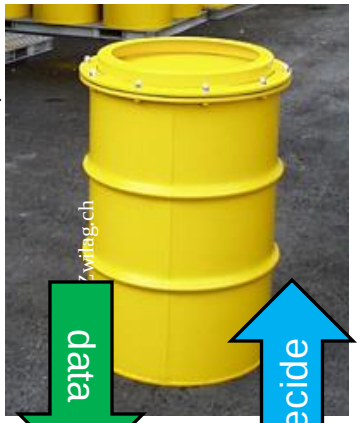
T7.1 Management

T7.2 State of the art

T7.3
Testing and
monitoring

request

measurements



T7.4
Digital Twin

data

request

data

decide

predict

data

T7.5 Data and Decision

T7.6 Demonstration

T7.7 Reporting

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PREDIS

WP7 Innovations in cemented waste handling and pre-disposal storage

Update of Task 7.3 – Embedded Monitoring

LEONE PASQUATO (BAM) & ESKO STRÖMMER (VTT)

WP7 Workshop, 25th of May 2023

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 945098.

Introduction

- The aim is to long-term monitor by embedded batteryless sensors the process of hardening and the evolution of the concrete itself over time, to indirectly identify potential defects such as corrosion or cracking of metallic waste drums.
- It is necessary to develop a technology able to transmit power and communicate through the metal layer of the sealed drum, as well as develop low-power sensors able to work embedded in concrete.
  These two main tasks have been carried out by BAM and VTT:

  - BAM: development of a net of custom low-power measurement units (*SensorNode*) that allow the onboard sensors to measure the state of the concrete without being in direct contact with it.
  - VTT: development of a customized RFID solution to power sensors and transfer data through solid metal structures.

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Sensor instrumentation in the waste drum (BAM)

- **SensorNode**

  - The membrane's pores allow water and gas particles to pass through and let the enclosed air equilibrate with the external environment.
  - One measurement cycle for each node requires about 0.4mAs (20mW x 60ms).
  - Onboard sensors:
    - Absolute Pressure (0 to 400kPa)
    - Relative Humidity (0%RH to 100%RH)
    - Temperature (-40 °C to 125 °C)
  - Limitations:
    - Max 64 nodes on the same bus (Unique ID limit)
    - Max 6m water depth (Membrane's permeability limit)
    - Max 10m cable length (Communication protocol limit)

Dimensions: Ø 3cm x 1.5cm

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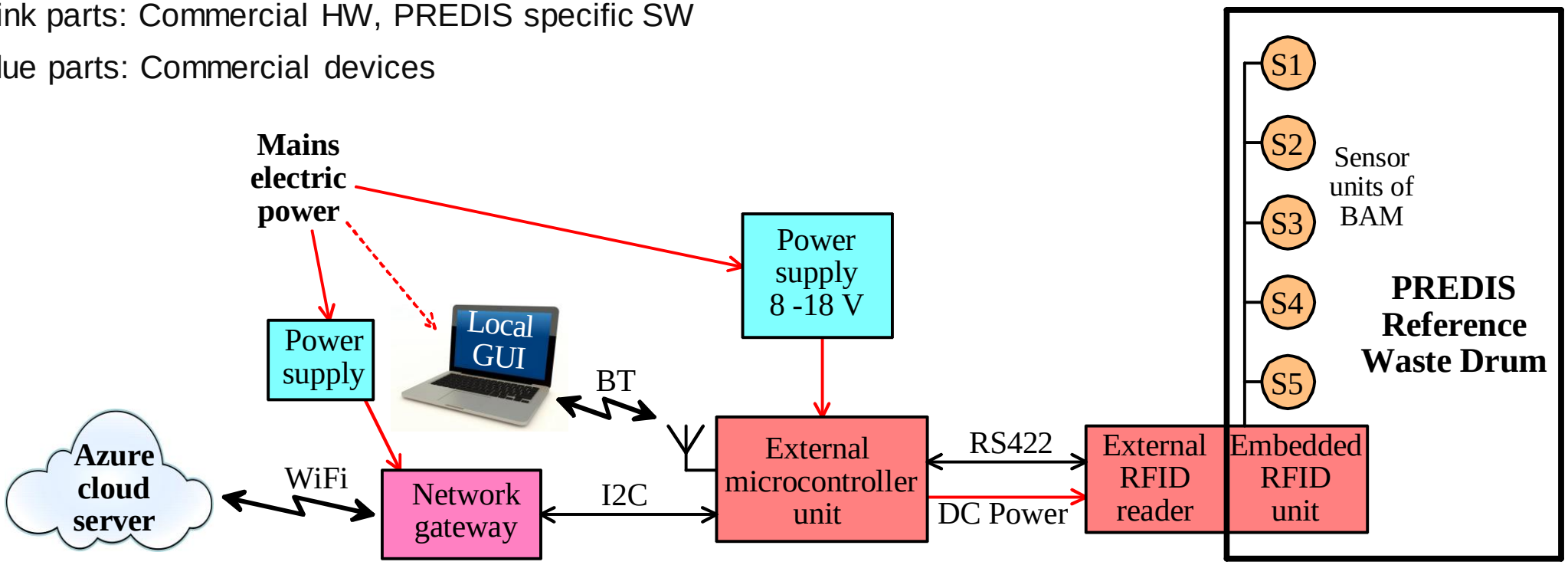
Sensor data acquisition system (VTT)

- Red parts: PREDIS specific HW and SW
- Pink parts: Commercial HW, PREDIS specific SW
- Blue parts: Commercial devices



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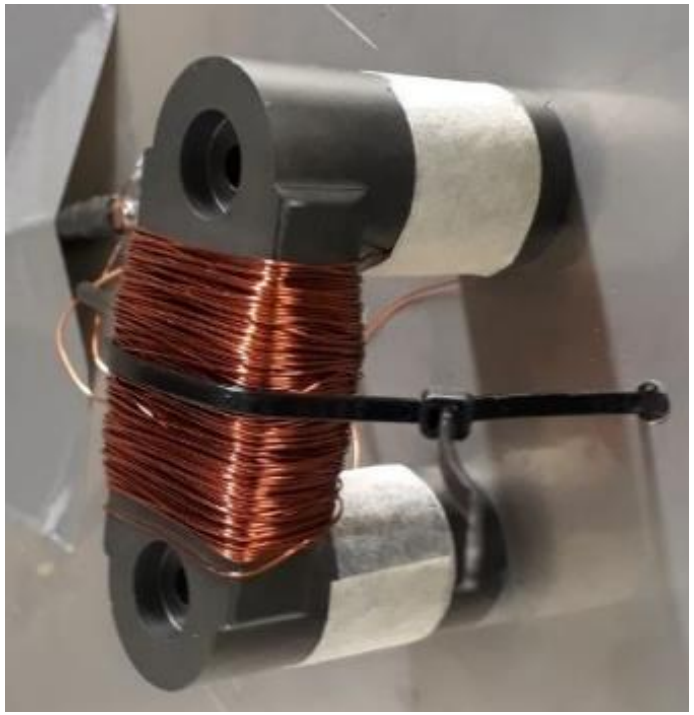
Customized RFID (VTT)

- The contactless powering and data uplink of the sensors in the drum is based on a couple of UR ferrite core antennas, symmetrically placed on the inner and outer surface of the drum.
- The PREDIS mock-up is a 1.4 mm thick steel drum, with a total gap between the antenna cores of about 2 mm. The maximum power transfer (about 1%) is achieved by superlow frequency carrier (100 Hz). With a similar non-magnetic stainless steel drum, the power efficiency would be much higher.
- The required time to transmit enough energy to control up to 5 *SensorNodes* is about 30sec.



View of a UR ferrite core with wrapped coil

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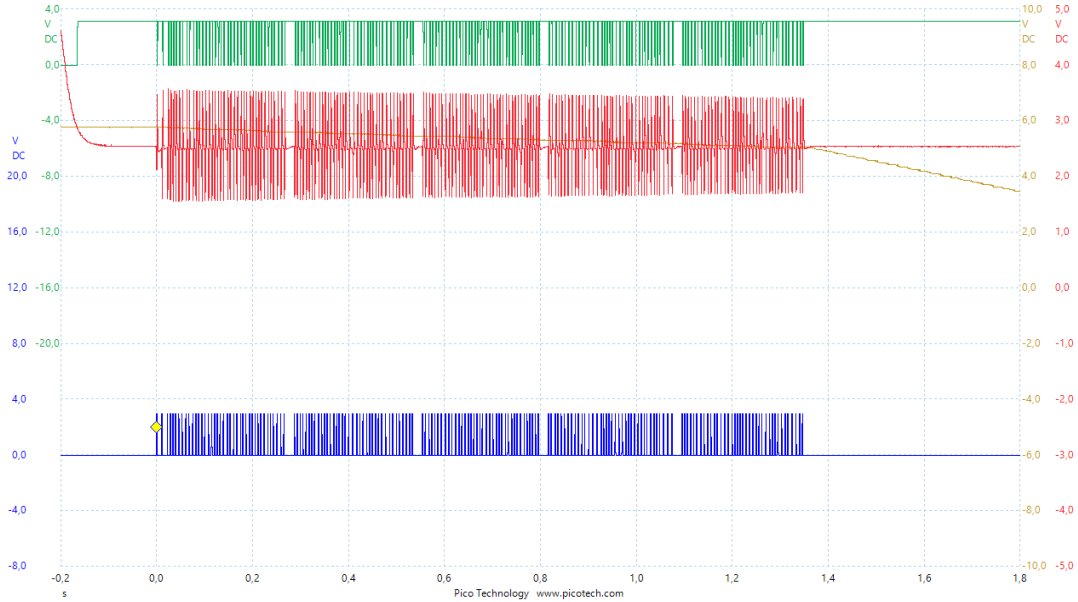
First drum integration at BAM 9-12/05/2023

Drum Instrumentation



Measured data uplink signals of five sensors:

- Blue: *Embedded RFID* unit transmitted data
- Red: *External RFID unit* received data
- Green: Regenerated data in the *External µC unit*
- Yellow: Embedded RFID energy storage voltage

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Further activities in PREDIS Task 7.3

- June 2023: Start experiment with Mockup 1.1 @BAM
- Autumn 2023: PREDIS demonstration of Mockup 1.2 @UJV (same setup as Mockup 1.1 with cloud database integration)
- Autumn 2023: Demonstration by VTT @TVO

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 945098.

PREDIS

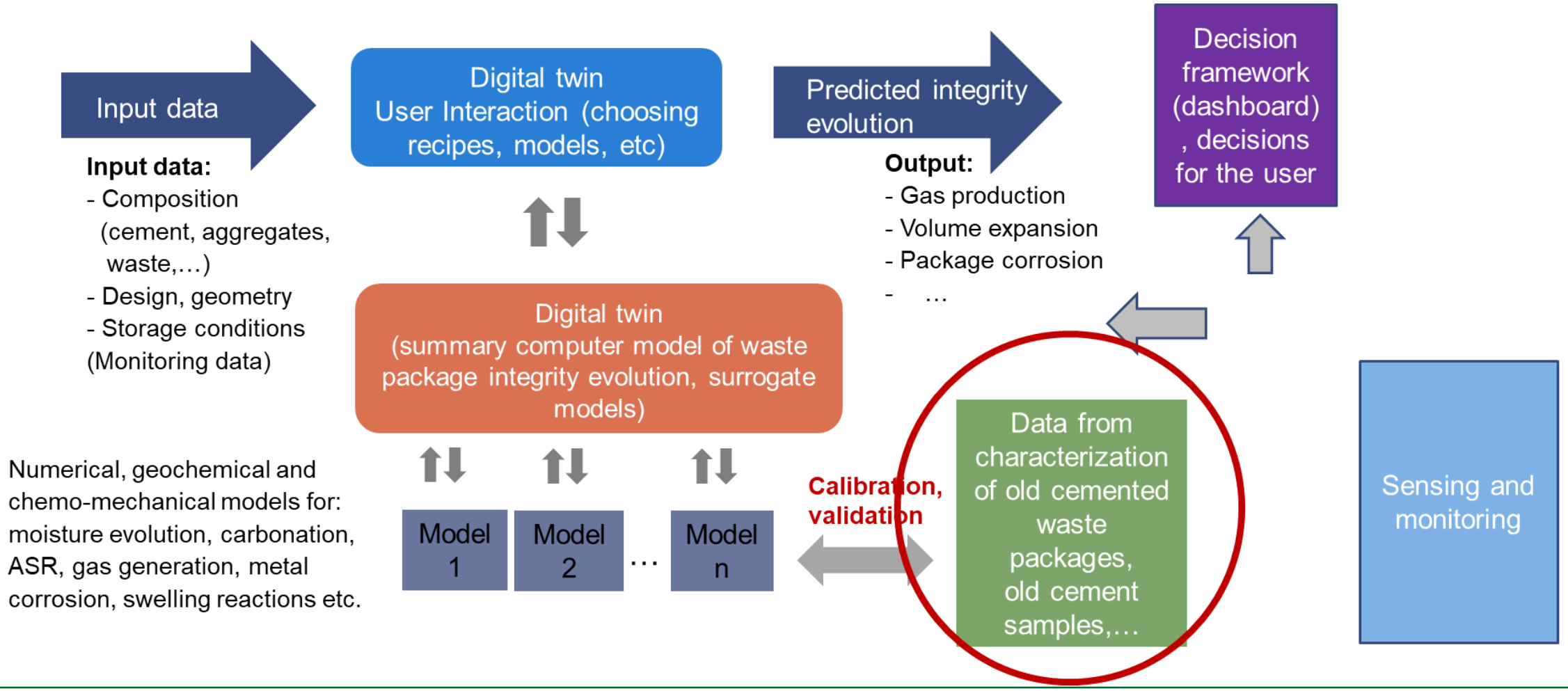
WP7.4. Step towards Digital Twins

RAINER DÄHN, DAN MIRON (PSI)

25th of May 2023

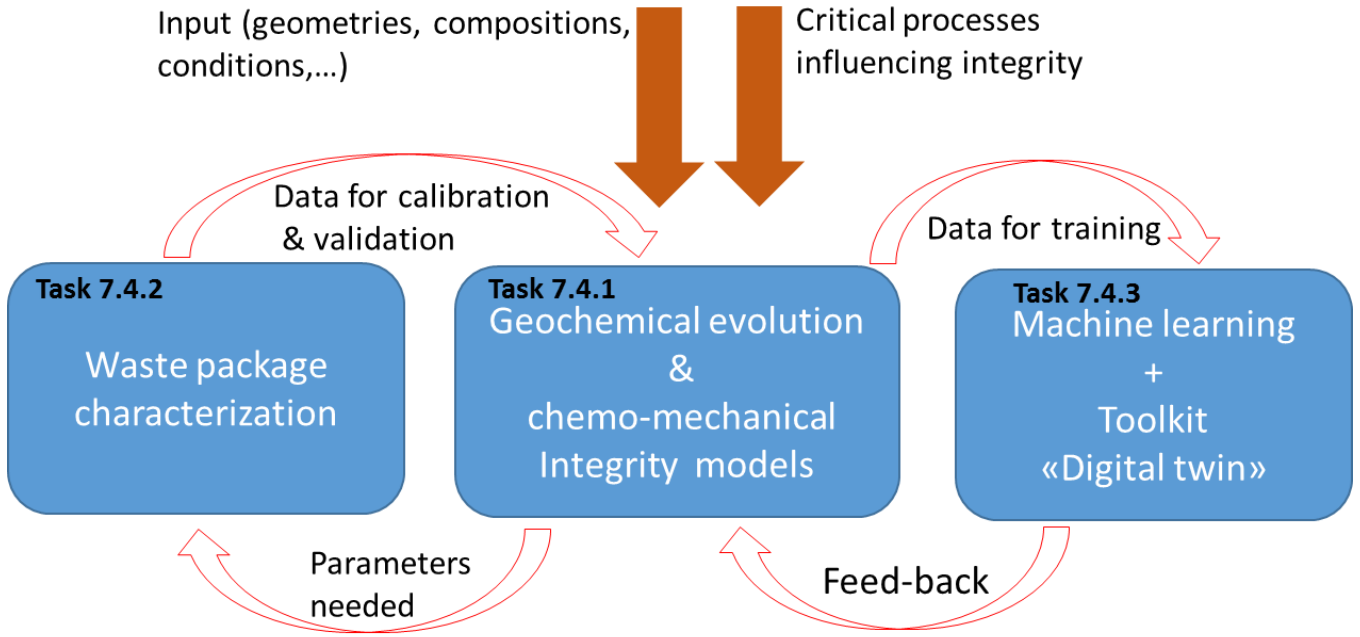
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 945098.

Background T7.4 Digital Twin



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 945098.

T7.4 Digital Twin

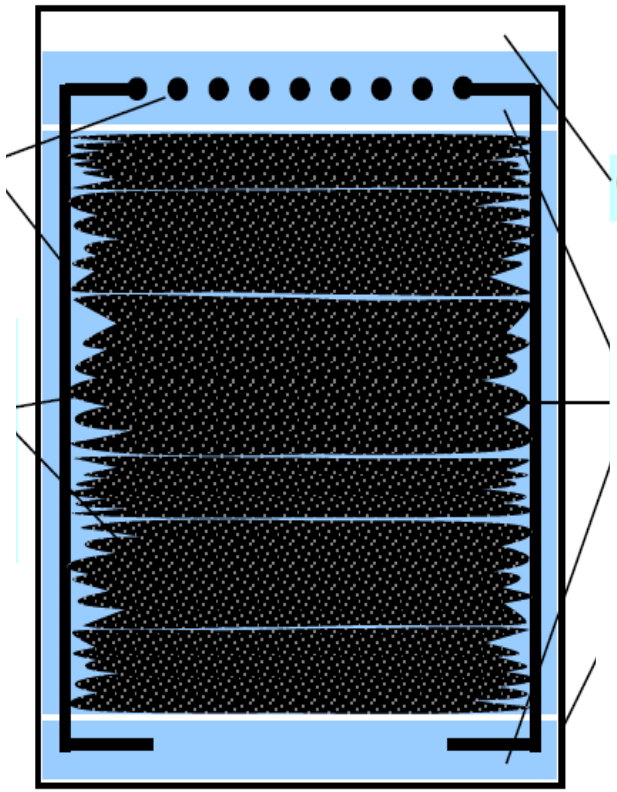


Subtasks :

- T7.4.1 Geochemical evolution and mechanical integrity monitoring (Responsible: NRG, Hans Meeussen)
- **T7.4.2 Experimental characterization of cemented waste packages for model validation and calibration (Responsible: PSI, Rainer Dähn)**
- **T7.4.3 Development of a toolkit "Digital twin" (Responsible: PSI, Dan Miron)**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 945098.

Background – 200l drums with waste



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 945098.

Background – Swiss Federal Interim Storage Facility (BZL)

Swiss Federal Interim Storage Facility on the PSI campus was built for the interim storage of all radioactive waste from medicine, industry, and research and began its operation in 1992.. Capacity for interim storage is expected to be needed up to 2065.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 945098.

Material inventory

Drum Nr.	Date kondi-tioning	Bulk mass						Al	ORGANICA	PVC	Steel	Na-22
		Tara	Mortar	Reinforcement steel	Raw waste	Pressed waste	Total					
		kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	Bq
1303	24.06.1994	25	159.9	4.5	101.1	38.5	329			101.1	38.5	2.21E+01
1312	18.07.1994	25	159.9	4.5	125.1	38.5	353	25	100.1		38.5	3.95E+01

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 945098.

Activity inventory according to gamma spectrometry measurements in January 2022 (initial nuclide Na-22)

Nr.	Date conditioning	Mass of the raw waste	K-40		Cs-137		Pb-214		
		kg	Bq	Bq/kg	Bq	Bq/kg	Bq	Bq/kg	
				1000		**100**		**1E+05**	**LL-Wert**
1303	24.06.1994	101.1	7E+04	692					
1312	18.07.1994	125.1	3E+04	240	5E+04	400	5E+05	3997	

Inventory data together with the sampling concept were submitted to the Swiss Federal Nuclear Safety Inspectorate ENSI

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 945098.

Some paperwork

05.04.2022

PAUL SCHERRER INSTITUT

PSI

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5232 Villigen PSI
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Eidgenössisches Nuklearsicherheitsinspektorat
z.H. Herrn Dr. Olivier Beffort
Industriestrasse 19
5201 Brugg

Ihr Zeichen:
Unser Zeichen: 20220405_PREDIS_NL96

Klassifizierung: keine

Villigen PSI, 5. April 2022

Konzept zur Untersuchung alter Abfallfässer aus dem BZL im Rahmen des EU-Projekts PREDIS

Sehr geehrte Damen und Herren

Wie bereits im AERA-Jahresbericht 2021 (AN-96-21-724) beschrieben, ist es vorgesehen, alte Abfallgebinde aus dem BZL im Rahmen des EU-Projekts PREDIS zu untersuchen. Das geplante Vorgehen bei den Untersuchungen und der weiteren Behandlung der Gebinde ist in der beigefügten AN-96-22-823 «Konzept zur Untersuchung alter Abfallfässer aus dem Bundeszwischenlager (BZL) im Rahmen des EU-Projekts PREDIS» vom 23.03.2022 dargestellt.

Das PSI bittet das ENSI um Zustimmung für die im beigefügten Probenahmekonzept dargestellte Vorgehensweise und um eine zeitnahe Antwort.

Freundliche Grüsse

Paul Scherrer Institut

Dr. Werner Roser
Sicherheitsdelegierter

Dr. Latina Nedyalkova
Gruppe Dokumentation und Genehmigungen

Beilage:
AN-96-22-823 «Konzept zur Untersuchung alter Abfallfässer aus dem Bundeszwischenlager (BZL) im Rahmen des EU-Projekts PREDIS» vom 23.03.2022

20.06.2022

ENSI, CH-5201 Brugg

A-Post
Paul Scherrer Institut
Herr Dr. Werner Roser
OVGA / 315
Forschungsstrasse 111
5232 Villigen-PSI

Klassifizierung: **keine**

9623
P. Meuspath
S. Kaya
N. Walthe
A. Karli
L. Rohner
O. Deppeler
K. Hirtzel
L. Pedicatti
J. Tite
R. Dähn

Ihr Zeichen: 20220613_PREDIS_NL96
Unser Zeichen: BMA/NEP - 22KFS
Sachbearbeiter: Brunell Magnus: +41 56 460 86 89
Brugg, 20. Juni 2022

Stellungnahme zur Antwort des PSI betreffend Auflage 1 beim Projekt PREDIS

Sehr geehrte Damen und Herren

Mit Schreiben vom 13 Juni 2022 /1/ geht das PSI auf die vom ENSI im Brief vom 3. Juni 2022 /2/ formulierte Auflage 1 für das Projekt PREDIS ein. Die Auflage 1 lautet:

Die persönliche Schutzausrüstung beim Durchtrennen des Fassmantels und beim Durchsägen der Abfallpresslinge hat sowohl radiologische Risiken als auch die konventionelle Gefahr durch gesundheitsgefährdenden Staub vorzubeugen. Die konkrete Schutzausrüstung ist 10 Tage vor Beginn der Arbeiten dem ENSI mitzuteilen.

Das PSI teilt mit, dass die PREDIS-Arbeiten im Abfalllabor (OALA) und in einem Zonentyp III mit der entsprechenden persönlichen Schutzausrüstung mit Vollschutzmasken und Filtern der Klasse FFP3 durchgeführt werden sollen. Diese Schutzausrüstung deckt auch konventionelle Gefahren (Staub) ab. Zusätzlich und bei Bedarf werden Schutzbrille, schwerentflammbare Kleidung und Arbeitsschürzen getragen. Sollten Arbeiten in einem Zonentyp IV notwendig sein, kommen fremdbelüftete Schutzanzüge zur Anwendung.

Die Durchführung der Arbeiten ist vom 20. Juni bis 24. Juni 2022 bzw. vom 27. Juni bis 1. Juli 2022 geplant.

Zum Thema Oberflächendosisleistungen (Kontakt) an den drei zu beprobenden Abfallfässer zeigten am 9. Juni 2022 vom AERA-Personal durchgeführte Messungen lediglich Werte kleiner als 1 mikroSv/h.

Das ENSI nimmt diese termingerecht mitgeteilte Information zur Kenntnis und betrachtet die Auflage 1 aus /2/ als erfüllt.

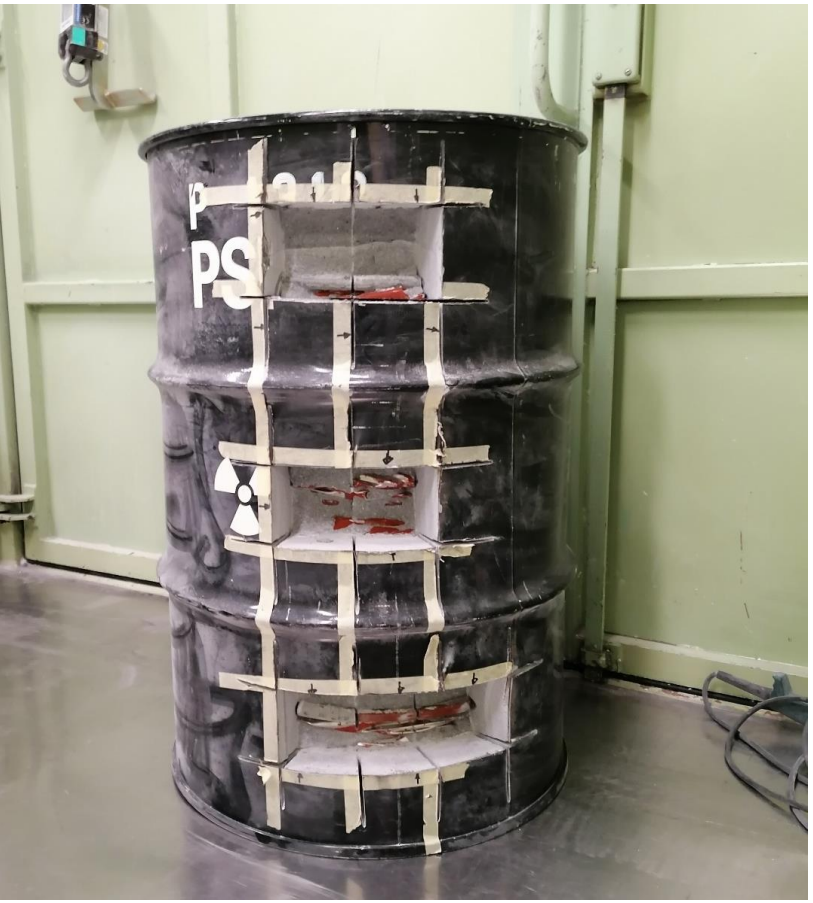
Eidgenössisches Nuklearsicherheitsinspektorat
Industriestrasse 19, 5201 Brugg
Tel. +4156 460 8400, Fax +4156 460 8499
www.ensi.ch

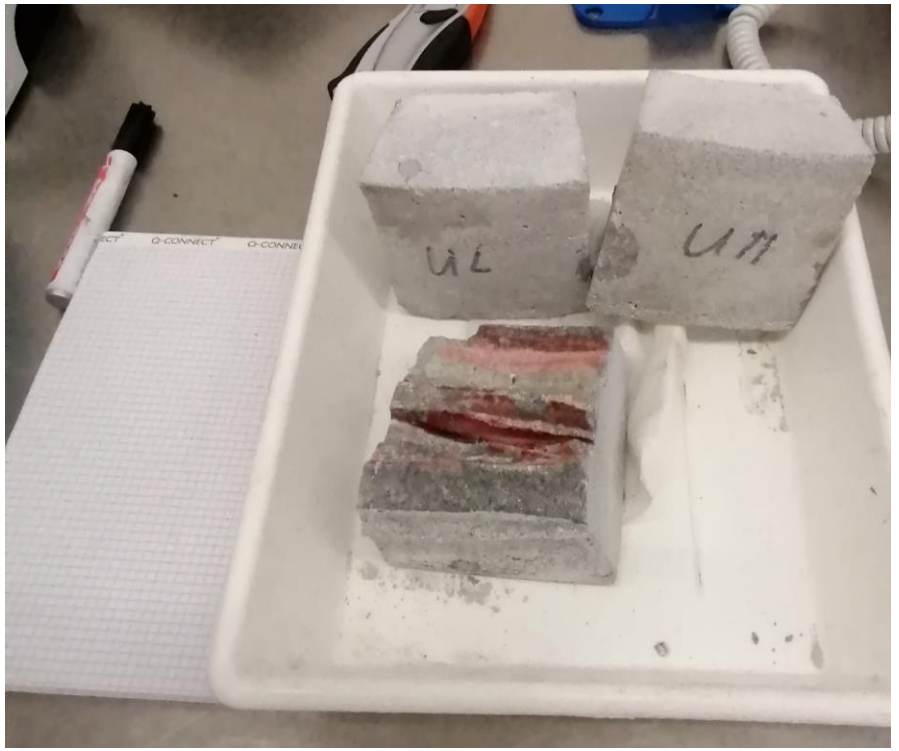
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 945098.

Sampling of two cement drums created in 1994

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 945098.

Sampling of cement drums created in 1994





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Reconditioning

Content of the drums			
Number of the drum	Material	Mass [kg]	Date of the clearance measurement
P-1303, P-1312	Stell 200-l-drums	57	26.08.2022
P-1312	Steel of the waste drums	42	25.10.2022
P-1303, P-1312	Inaktive mortar	406.5	16.11.2022
P-1303	Steel of the waste drums	48.5	24.11.2022
P-1303	Rubber, paper/wood, plastic, PVC	62.1	Condinioned as burnable waste
P-1312	Aluminium, paper/wood, plastic, PVC	54.5	

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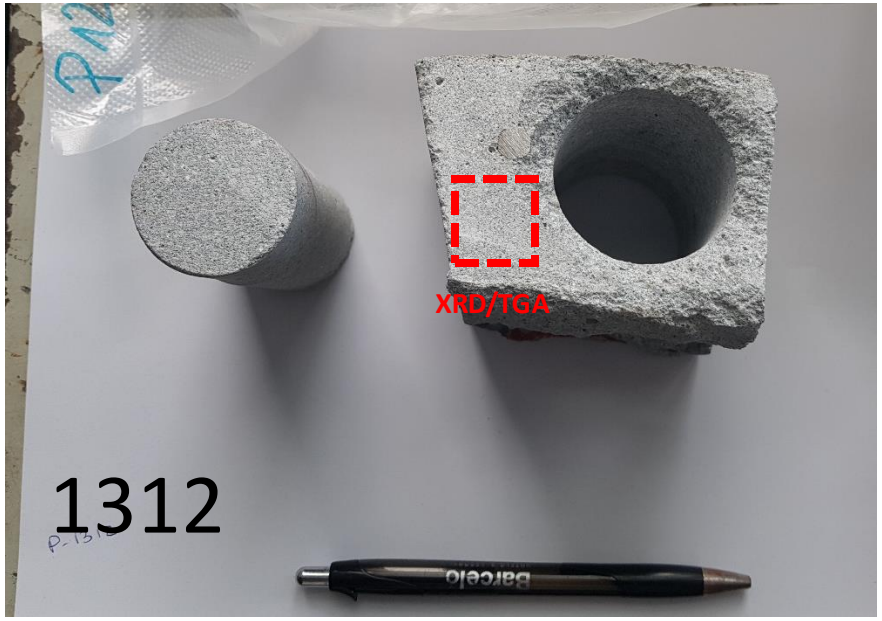
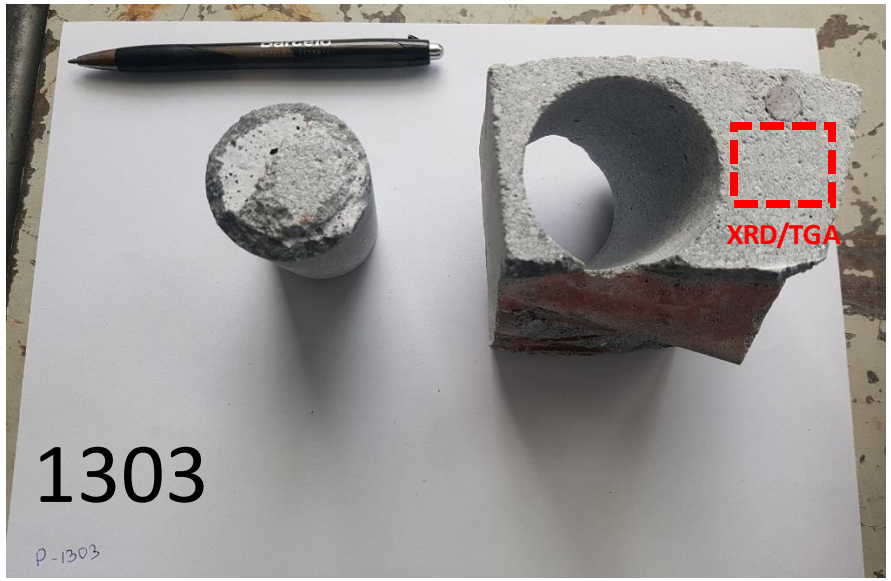
Compression strength





Compression strength: 74.9 MPa

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 945098.

Young Modul

1312

Nominal-Festigkeit: 74.9 MPa

Name	d [mm]	h [mm]	m [g]	p [kg/m³]	$f_{c,no}$ [MPa]	$E_{c,0}$ [GPa]	s_b [MPa]	s_a [MPa]	e_b [%]	e_a [%]	e_d [%]	F_{br} [kN]	f_c [MPa]
1	40.2	81.7	206.8	1990.6	74.9	24.715	0.51	17.49	0.001	0.070	0.00	...	...
Mittelwert				1990.6		24.715							0.0
Std. Abw.				0.00		0.00							0.00

d = Durchmesser; h = Höhe; m = Masse; p = Rohdichte; $f_{c,no}$ = Nominal-Festigkeit; $E_{c,0}$ = stabilisierter E-Modul; s_b = untere Spannung (stab.); s_a = obere Spannung (stab.); e_b = untere Dehnung (stab.); e_a = obere Dehnung (stab.); e_d = Dehnungsdifferenz; F_{br} = Bruchlast; f_c = Festigkeit

E-modulus 24.7 GPa

1303

Nominal-Festigkeit: 74.9 MPa

Name	d [mm]	h [mm]	m [g]	p [kg/m³]	$f_{c,no}$ [MPa]	$E_{c,0}$ [GPa]	s_b [MPa]	s_a [MPa]	e_b [%]	e_a [%]	e_d [%]	F_{br} [kN]	f_c [MPa]
P1303 UL	40.2	82.0	215.3	2064.6	74.9	29.549	0.50	17.47	0.001	0.058	0.00	...	...
Mittelwert				2064.6		29.549							0.0
Std. Abw.				0.00		0.00							0.00

d = Durchmesser; h = Höhe; m = Masse; p = Rohdichte; $f_{c,no}$ = Nominal-Festigkeit; $E_{c,0}$ = stabilisierter E-Modul; s_b = untere Spannung (stab.); s_a = obere Spannung (stab.); e_b = untere Dehnung (stab.); e_a = obere Dehnung (stab.); e_d = Dehnungsdifferenz; F_{br} = Bruchlast; f_c = Festigkeit

E-modulus 29.5 GPa

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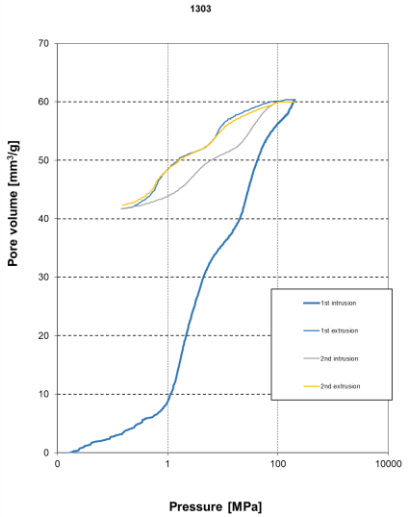
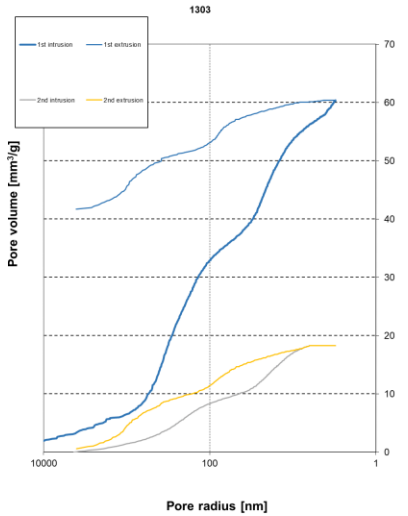
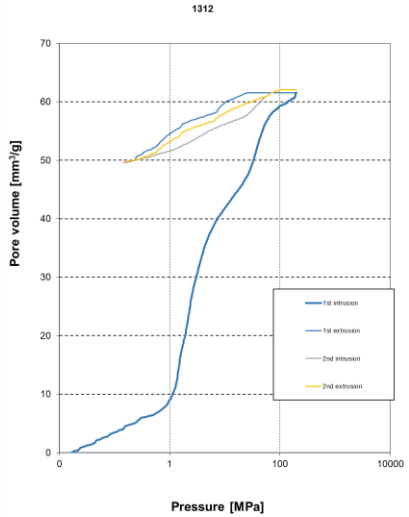
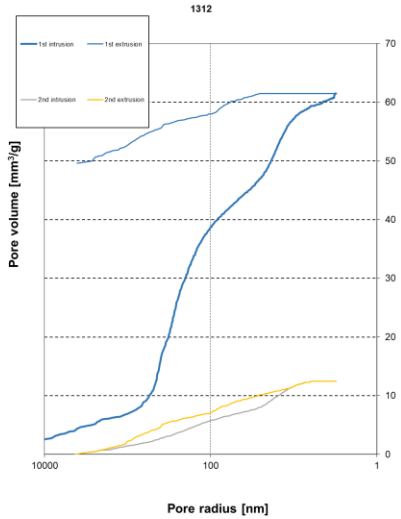
Mercury porosimetry

Porosity:
41.7 mm^3/g for 1303
49.6 mm^3/g for 1312









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XRF

Parameter		1303	1312
SiO2	MA-%	65.9	62.17
Al2O3	MA-%	1.56	1.76
Fe2O3	MA-%	0.75	0.83
Cr2O3	MA-%	< 0.003	< 0.003
MnO	MA-%	0.016	0.019
TiO2	MA-%	0.069	0.074
P2O5	MA-%	0.029	0.032
CaO	MA-%	17.96	19.87
MgO	MA-%	0.27	0.31
K2O	MA-%	0.35	0.39
Na2O	MA-%	<0.06	<0.06
SO3	MA-%	0.41	0.36
LOI	MA-%	12.59	14.06
Summe	MA-%	99.9	99.88
TC	MA-%	0.63	0.69

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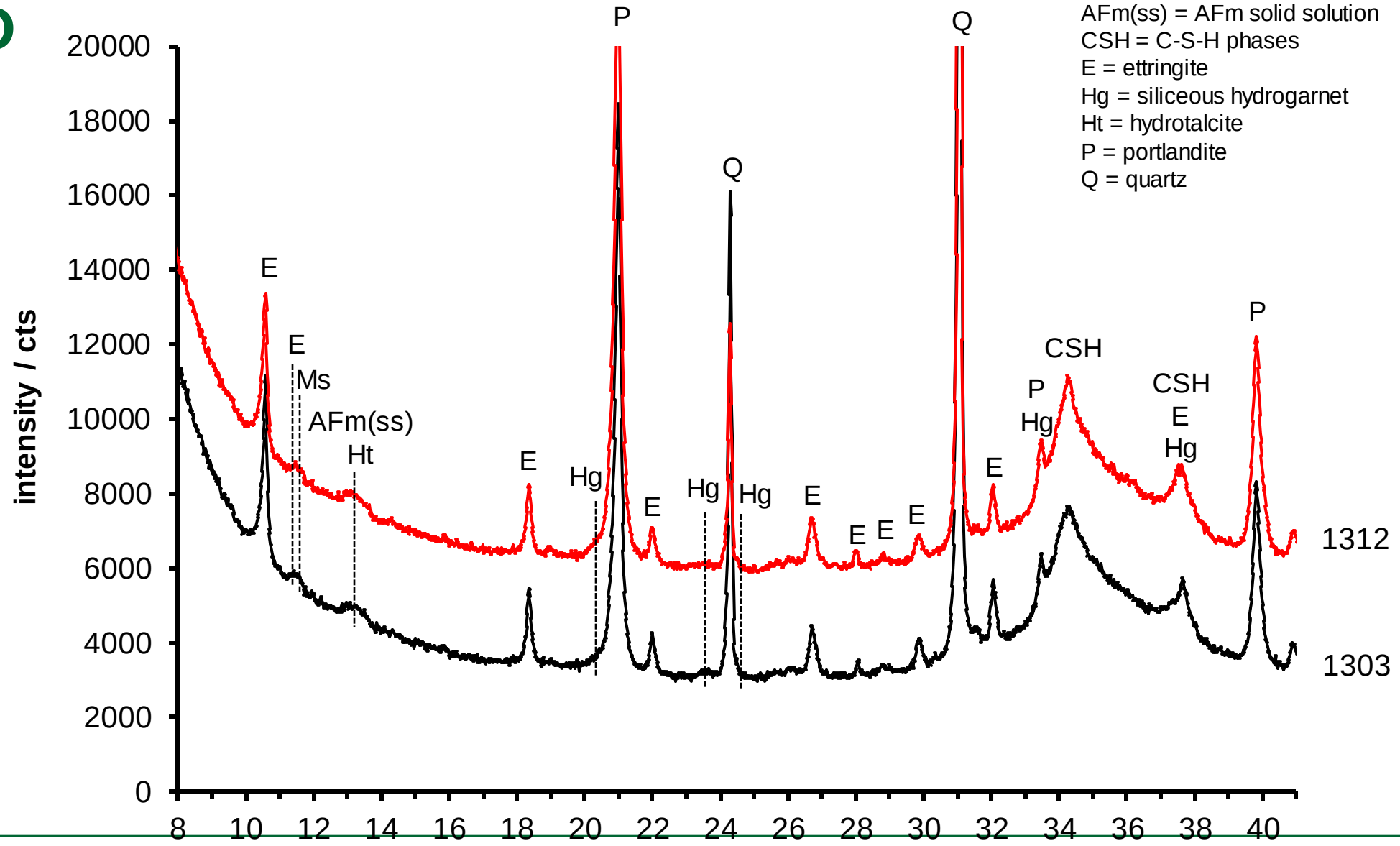
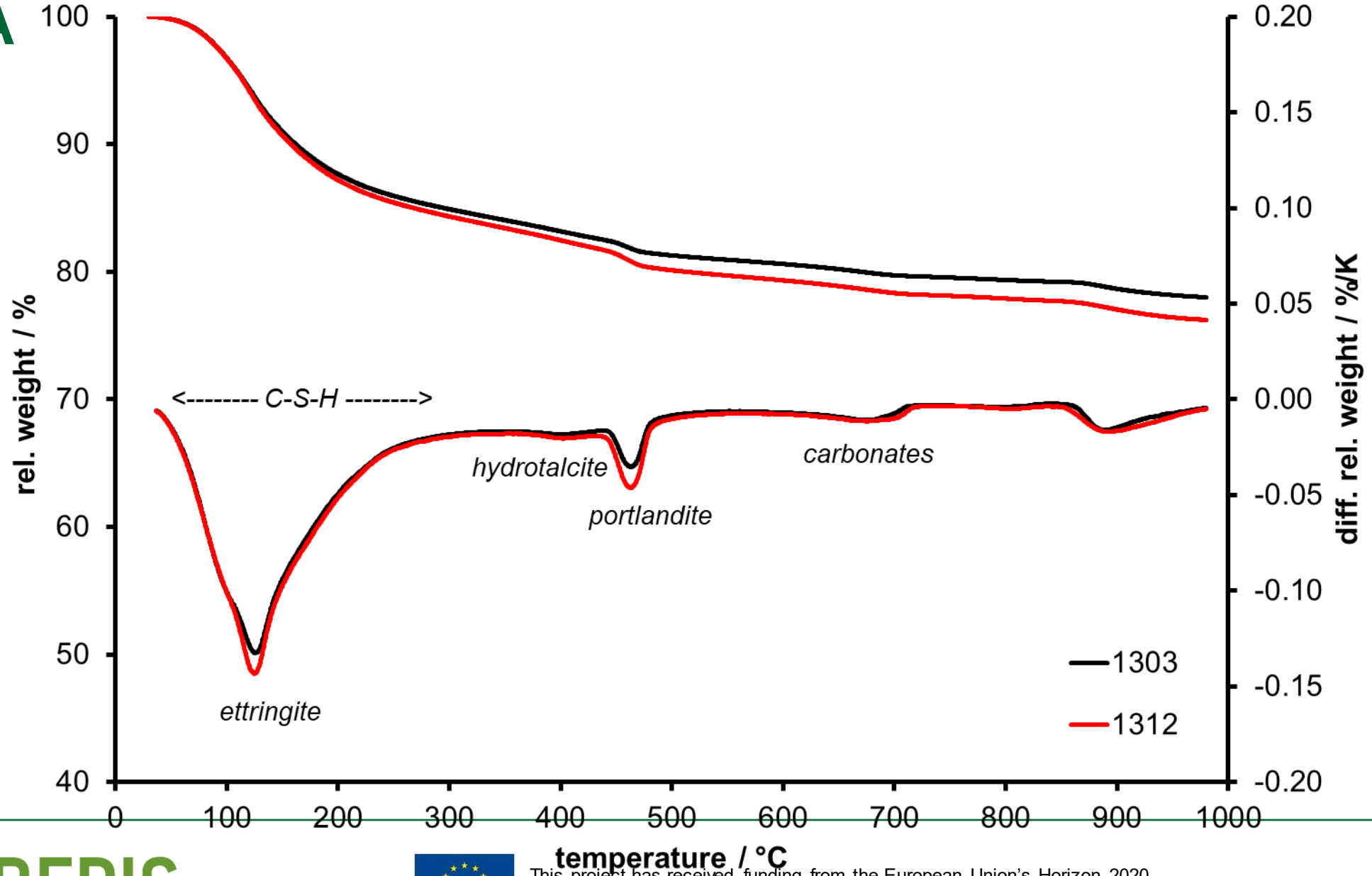
XRD



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 945098.

TGA



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Digital TWIN 1.0 a toolkit of models

- A **collection of models** (simplified) that predict the evolution.
- Ability to **run processes on different compositions / input waste package properties.**
- Asses **different waste package compositions** for possible problems in chemical evolution.
- Predict the **normal evolution and identify exceptional cases** using monitoring.

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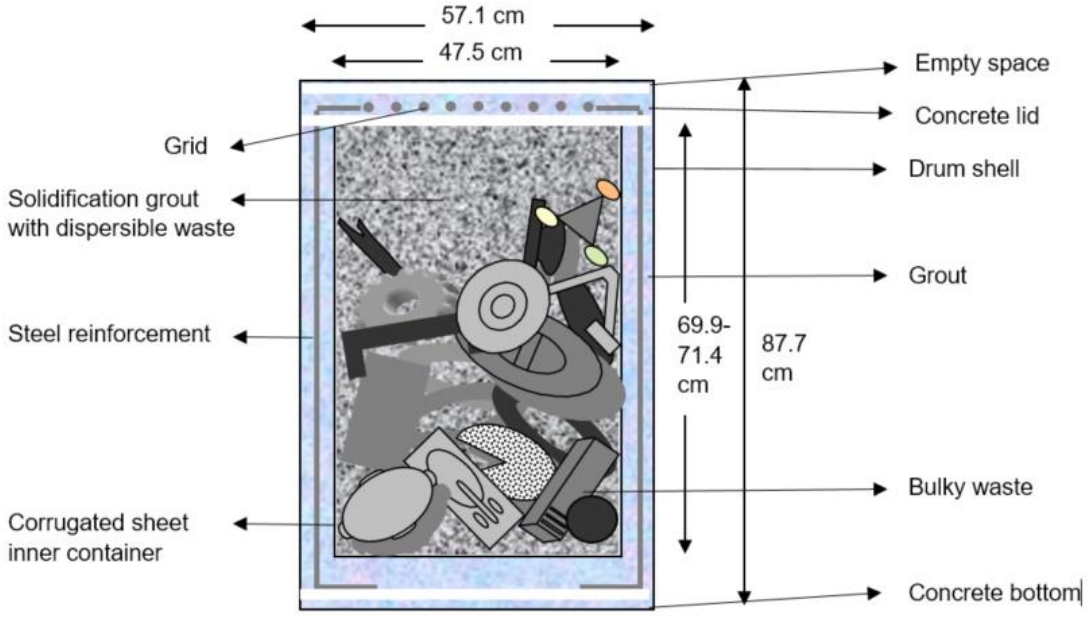
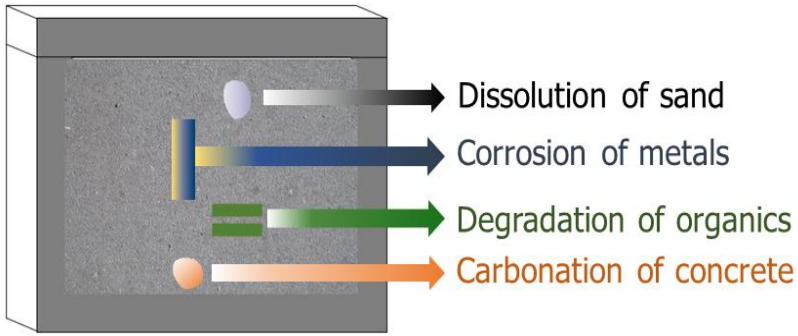
Mixing tank approach + kinetics

Homogenized waste package materials (waste, backfill, container etc.) with reactions in the liquid, gaseous and solid phases and in between the phases via estimated reactive surface areas and specific kinetic rate.



Schematic diagram of a cemented waste package: Cement solidified dispersive and bulky waste in a 200 L steel drum. (Wällisch, A. 2020. Paul Scherrer Institut, Villigen, Switzerland. Pers. Comm.)



Schematic presentation of degradation processes in the waste package (Wieland 2019)

Simplified reaction stoichiometry

$SiO_2(s) + 2\ H_2O = H_4SiO_4(aq)$

$x\ Me + y\ H_2O = Me_xO_y + y\ H_2$

$2\ \{CH_2O\} = CH_4 + CO_2$

$Ca(OH)_2 + CO_2 = CaCO_3 + H_2O$

$$R_{dis}(t) = \frac{dm}{dt} = A\left(k_1(1-\Omega) + k_2 a_{H^+}^{-0.5}(1-\Omega)\right) \quad (\text{mol s}^{-1})$$

A: Reactive surface area (m^2)
k: Rate constants in neutral (k_1) and alkaline (k_2) conditions (mol s^{-1} m^{-2})log $k_1 = -13.99$; log $k_2 = -16.29$
a_H^+: Activity of protons
Ω: Saturation index

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Technical implementation / user interaction

- Use **of Jupyter notebook** development environment to run the models based on user input
- Can call GEMS/Orchestra/other codes/ for doing geochemical calculations
- Different models can be added, input/output can be developed
- Can be run on an online platform (e.g., GeoML.eu, google colab, binder, setup on Azure) or installed and run on a local machine (use of sensitive data)

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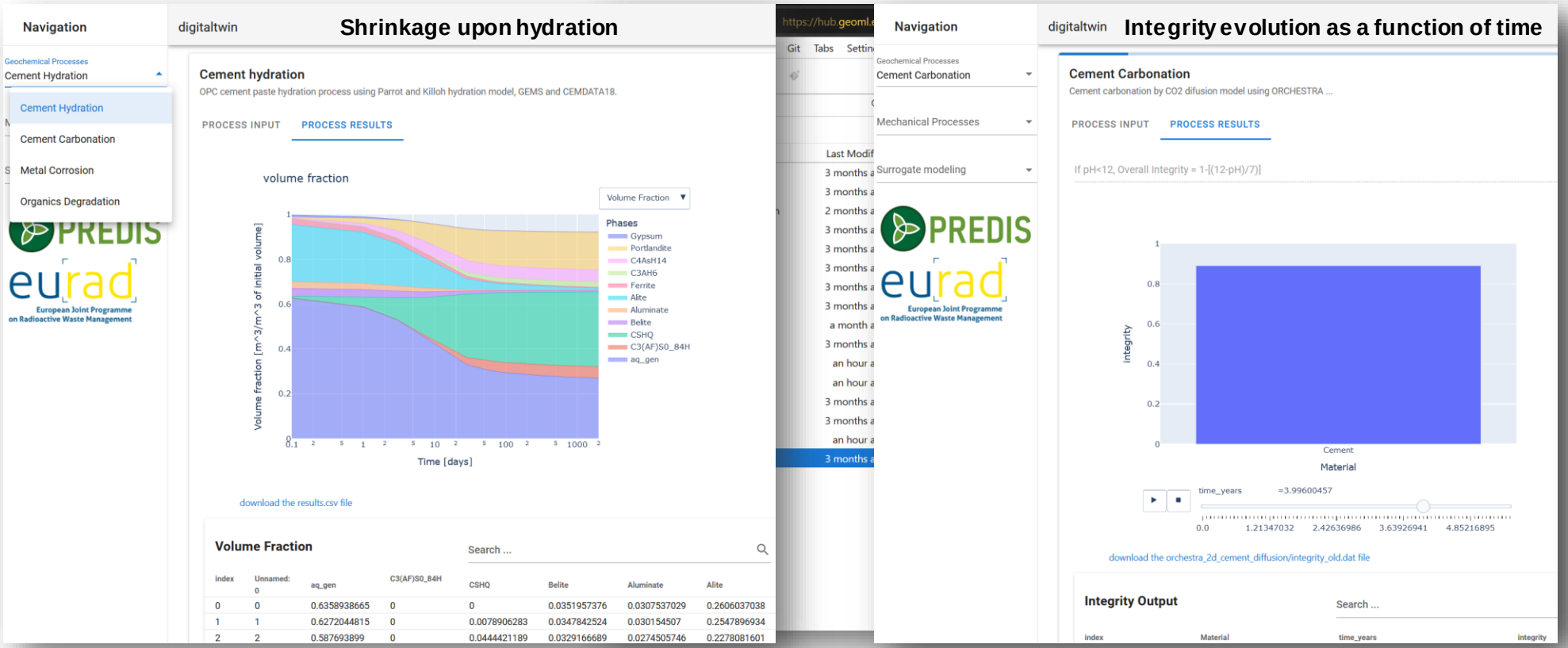
https://digitaltwin.geoml.eu/ - demo hydration/carb.

For users:
User interface, process modeling

For developers:
Scripting, running models



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Ongoing work

- Implement additional models
- Refine the input and output – user interaction
- Would need access to a database of waste composition (to provide relevant input for users)

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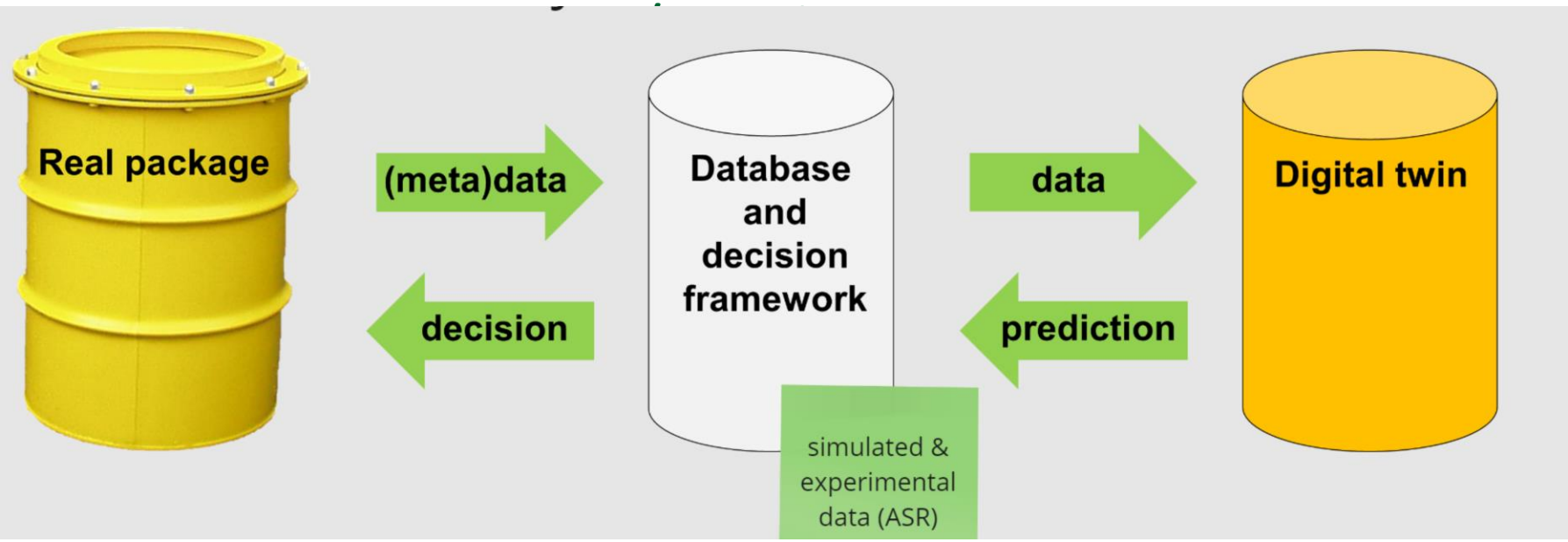
Digital TWIN 2.0 – real time



- Data cycle between package – sensors and database
- Data cycle between the Digital Twin and the database
- data formats / interfaces to connect and queries to retrieve data

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 945098.

Work on ASR example

- Laboratory experiments – accelerated alkali-silica-reaction
- Analytical model for expansion and strain evolution
- Monitoring at the waste package level – used to actively optimize a model that then can make predictions
- Simple geochemical / kinetic model for aggregate dissolution and ASR product formation could also be tested
- In principle the model can also be used in DT 1.0

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Github (actions) and metadata

- https://github.com/predis-h2020 (public) - everybody is welcomed – can be also transferred to other solutions
- Develop a consistent solution from the minimal example – works / tested / can be referred by everyone
- github actions a “free” solution that can be used in the demonstrator to trigger the DT workflow.
- Can run on Azure or locally (private data)

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 945098.

Spare slides

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 945098.

Characterization at PSI of bottom/top part

- Optical microscopy
- Pore water press – tried but no water was coming out
- Total digestion
- Thermogravimetry
- Mercury porosimetry
- XRD/XRF (lab or synchrotron based)
- ICP-OES/MS
- REM/EDX
- Raman spectroscopy
- Soft X-ray absorption spectroscopy, Ca-edge (synchrotron based, 1300 – 4040 eV)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 945098.

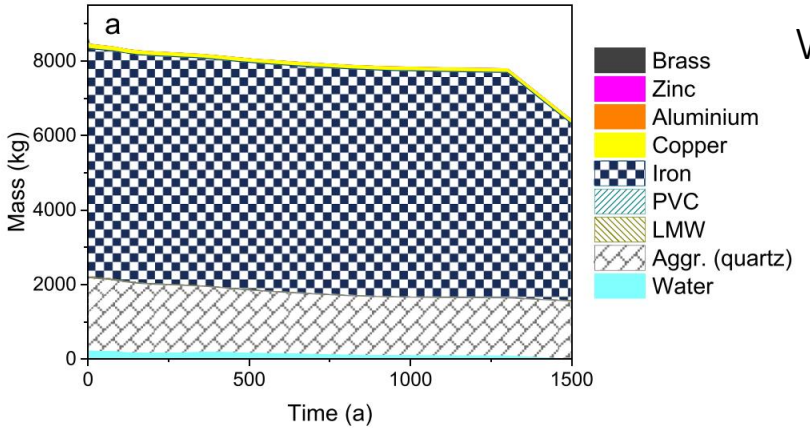
Characterization at PSI/EMPA of bottom part

- Pore water press – tried but no water was coming out
- Compression strength and young modul
- Thermogravimetry
- Mercury porosimetry
- XRD
- XRF
- Concrete of the lid: Soft X-ray absorption spectroscopy, Ca-edge (synchrotron based, 1300 – 4040 eV)

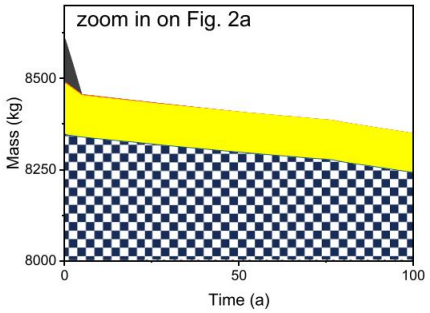
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 945098.

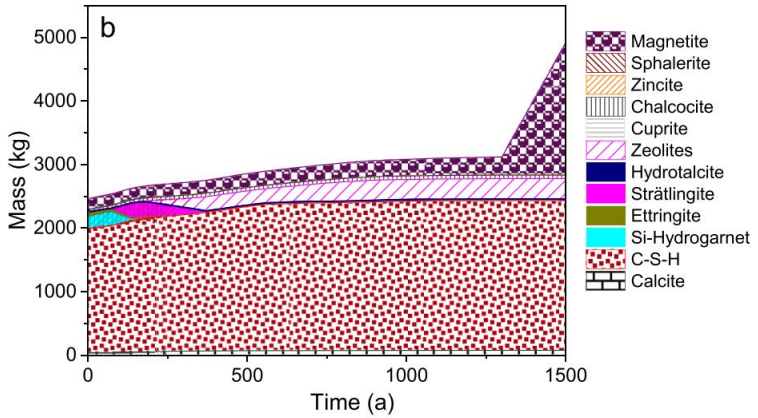
Limited/Unlimited water

- Only free water entrapped in the waste package was available for reaction
- The reactivity ceased already at ~1500 years for silicious and 8000 for calcareous aggregate

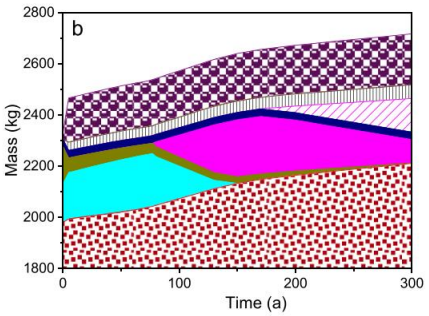


Waste materials





Cement materials / minerals



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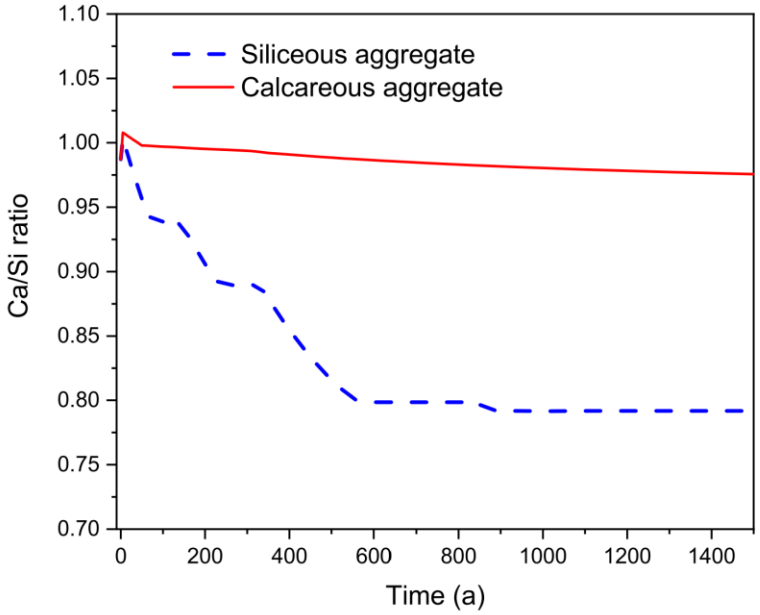
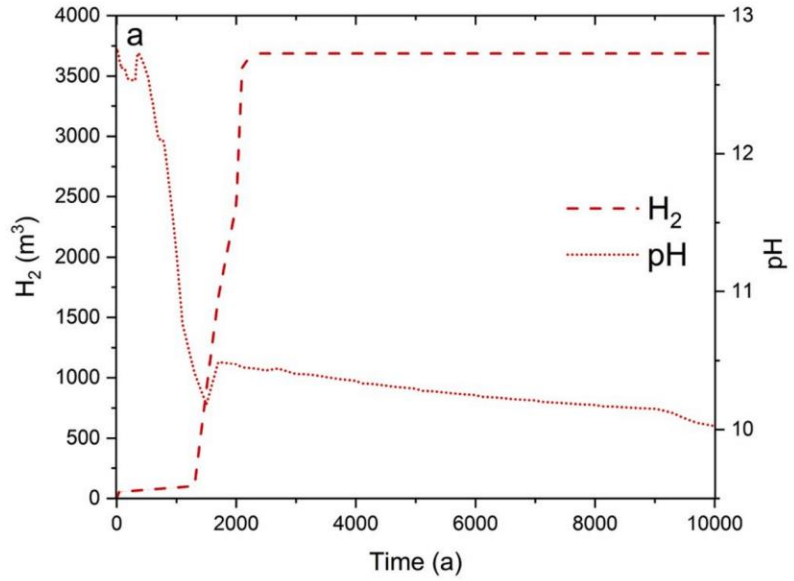
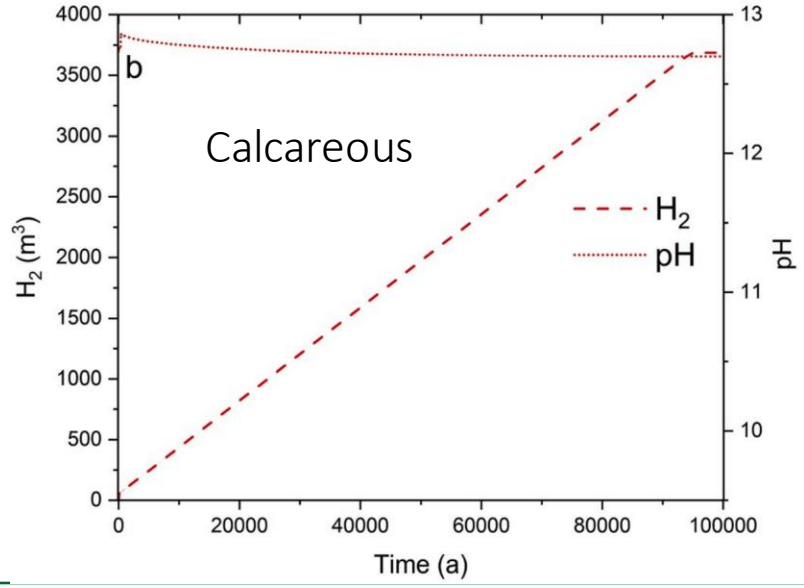
Silicious/Limestone aggregates

- Unlimited water
- pH, Ca/Si of CSH



Silicious





This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 945098.

Demonstrator

- Mockup demonstration of the Digital Twin workflow
- Sensors – database – models -> predictions – database
- Working on a reproducible workflow that can be iteratively extended and improved (tests for corresponding features)
- Minimum working example (simple model, no frontend, etc.) of the data flow.

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Automated DT workflow

- Automated script (in a virtual machine)
  - Connects to the database -> data for package xyz for a given time period (dataframe, json)
  - Metadata and schemas are used to process the data as input for DT model
  - Model is reparametrized and used to make future predictions – saved in database (with metadata and model) -> data lake

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PREDIS

Monitoring experiments on ASR affected barrels

TRI PHUNG, **SURESH SEETHARAM**, LANDER FREDERICKX (SCK-CEN)
GERT DEKKERS, DYLAN GYBELS, JENS VERBEECK (MAGICS TECHNOLOGIES)
CARLOT VALGAEREN, THOMAS HUYS, GERT VANLOMMEL, GIEL WILMS (BELGOPROCESS)

PREDIS ANNUAL WORKSHOP, 24 MAY 2023

This project has received funding from the Euratom research and training programme 2019-2020 under grant agreement No 945098.

Cemented waste drum in a pre-disposal storage facility

What's happening inside?

Efficient/safe inspection, early warning, …

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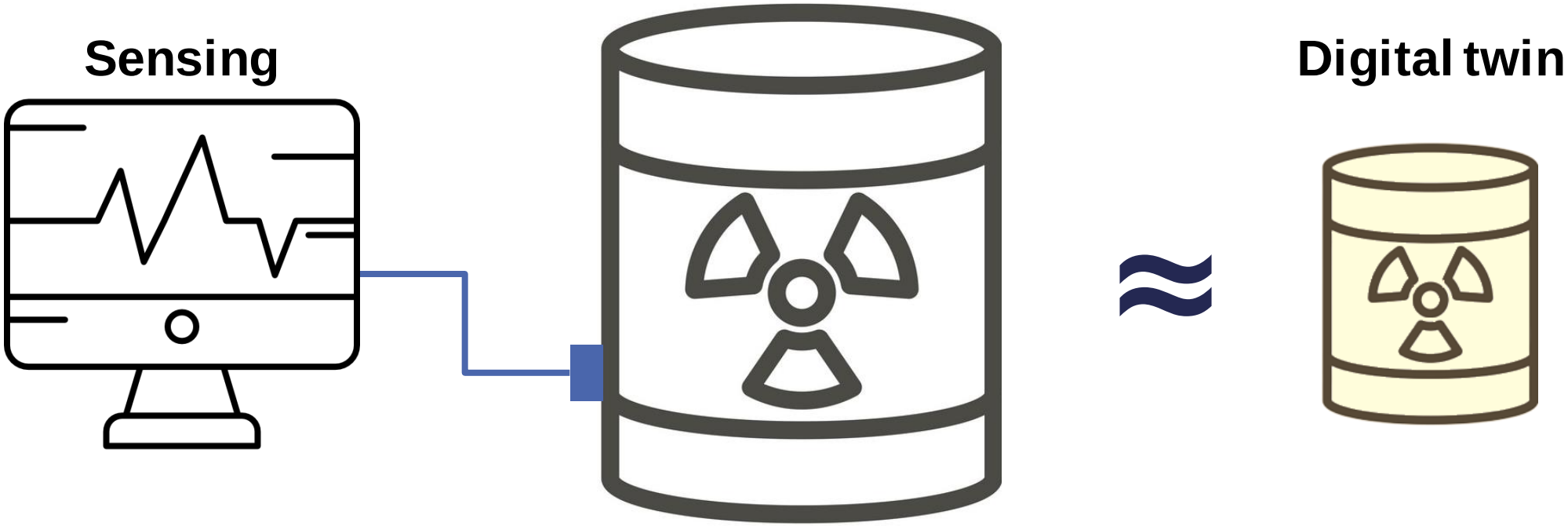

What's happening inside?

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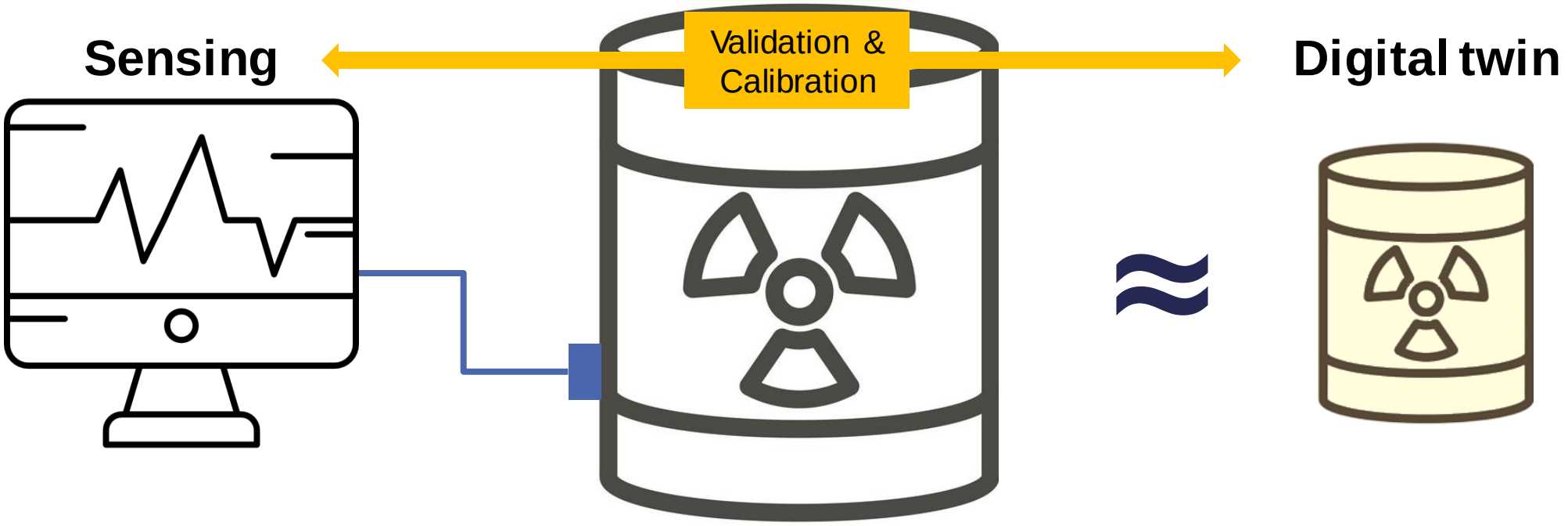

What's happening inside?

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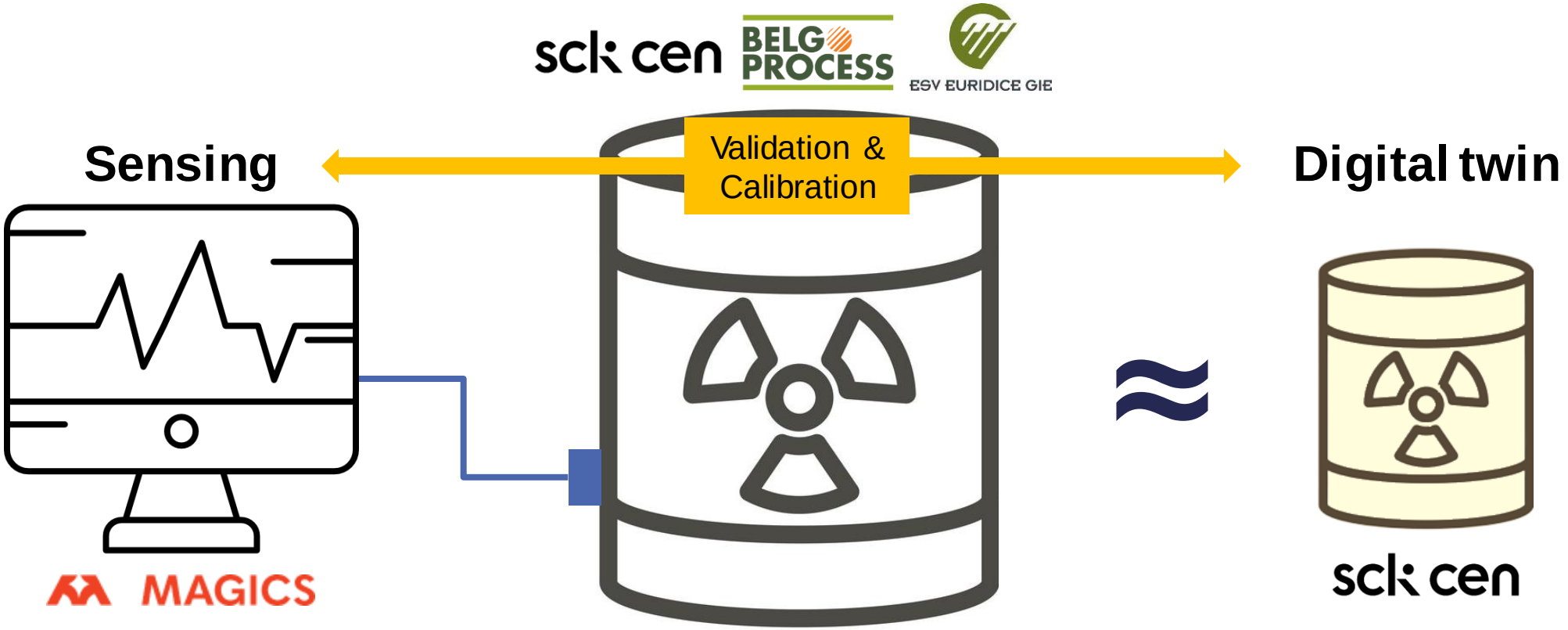

What's happening inside?

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PREDIS

Why do we want to monitor?

- **Cement**-based materials for immobilization of LILW.
- However, long term deterioration of waste packages cannot be ruled out.
- **Alkali-Silica Reaction** (ASR) is a potential deterioration process that can cause de-stabilization of the waste matrix.

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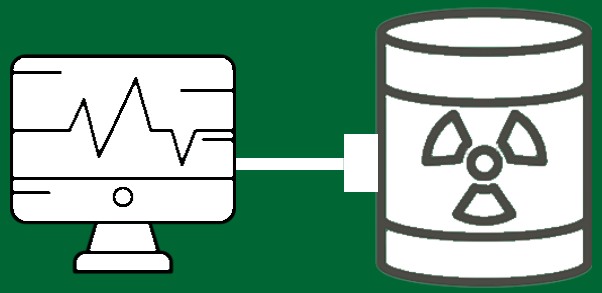
PREDIS

What do we want to monitor?



- ASR produces an **expansive** gel which leads to internal pressure and **cracking** of the concrete

Reference

- Strain
- Temperature
- Humidity
- Pressure

Non-destructive methods

- Stress releases by means of Acoustic Emission

validation

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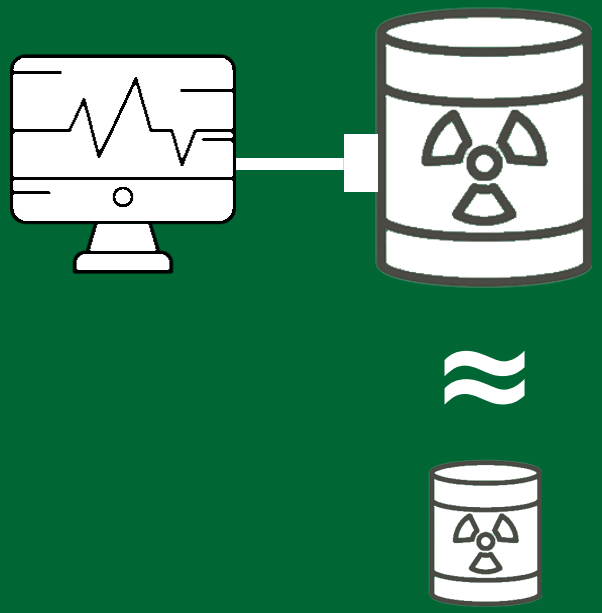
PREDIS

What do we want to monitor?



- ASR produces an **expansive** gel which leads to internal pressure and **cracking** of the concrete

Reference

- Strain
- Temperature
- Humidity
- Pressure

Non-destructive methods

- Stress releases by means of Acoustic Emission
- Digital twin model

validation

validation

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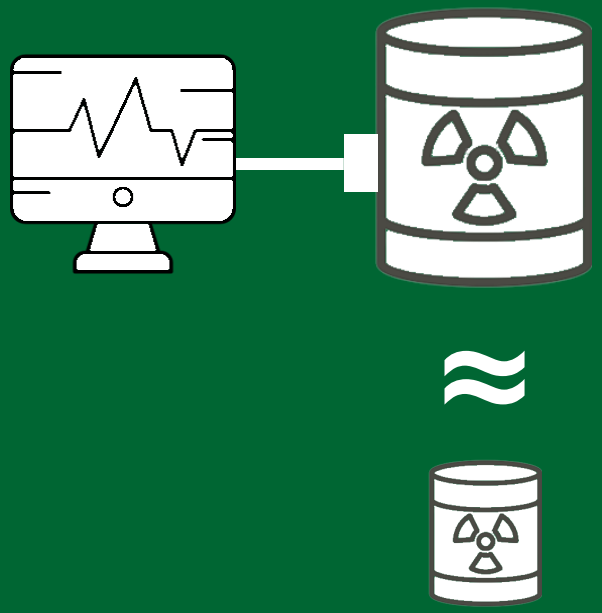
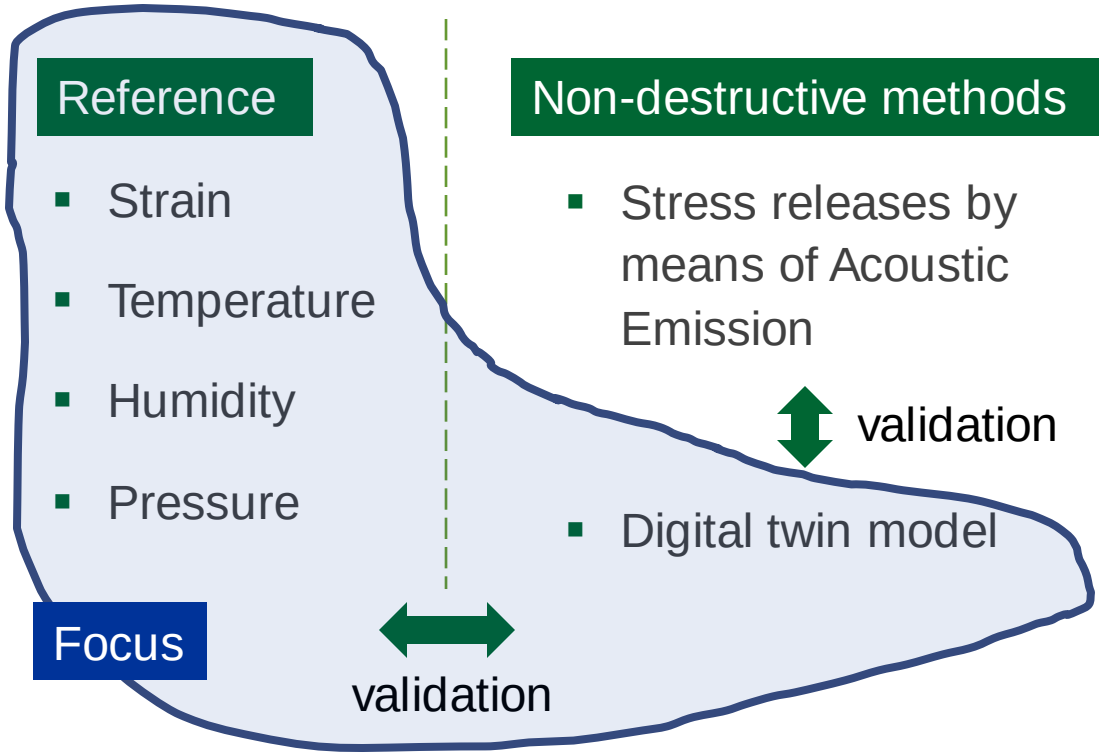
PREDIS

What do we want to monitor?



- ASR produces an **expansive** gel which leads to internal pressure and **cracking** of the concrete



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Data collection setup

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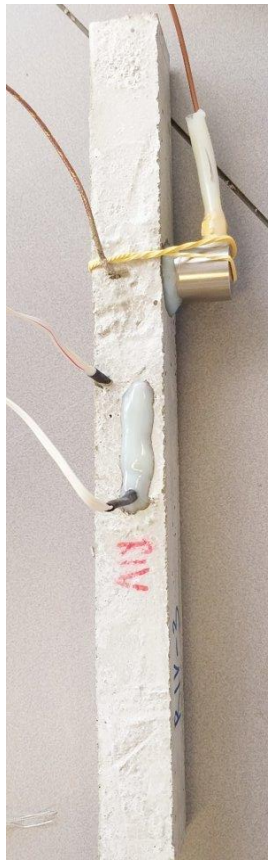

Lab scale

Drum scale

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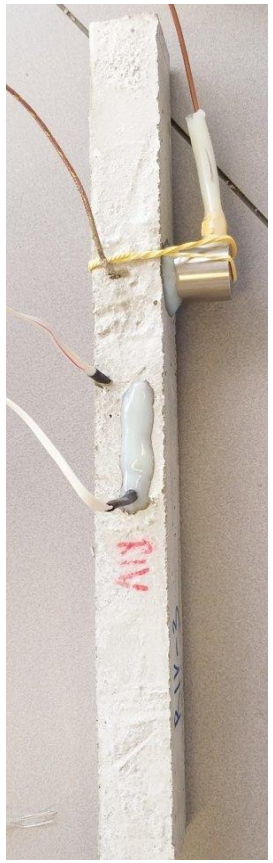

Lab scale

Drum scale

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PREDIS

Sensors and placement

- Inside concrete
  - Vibrating strain gauge (8)
  - Temperature (8)

- Lid of the barrel
  - Pressure

  - ~~Humidity~~
- Ambient
  - Temperature
  - Humidity
- Acoustic Emission

(top of concrete, circumference of the barrel)

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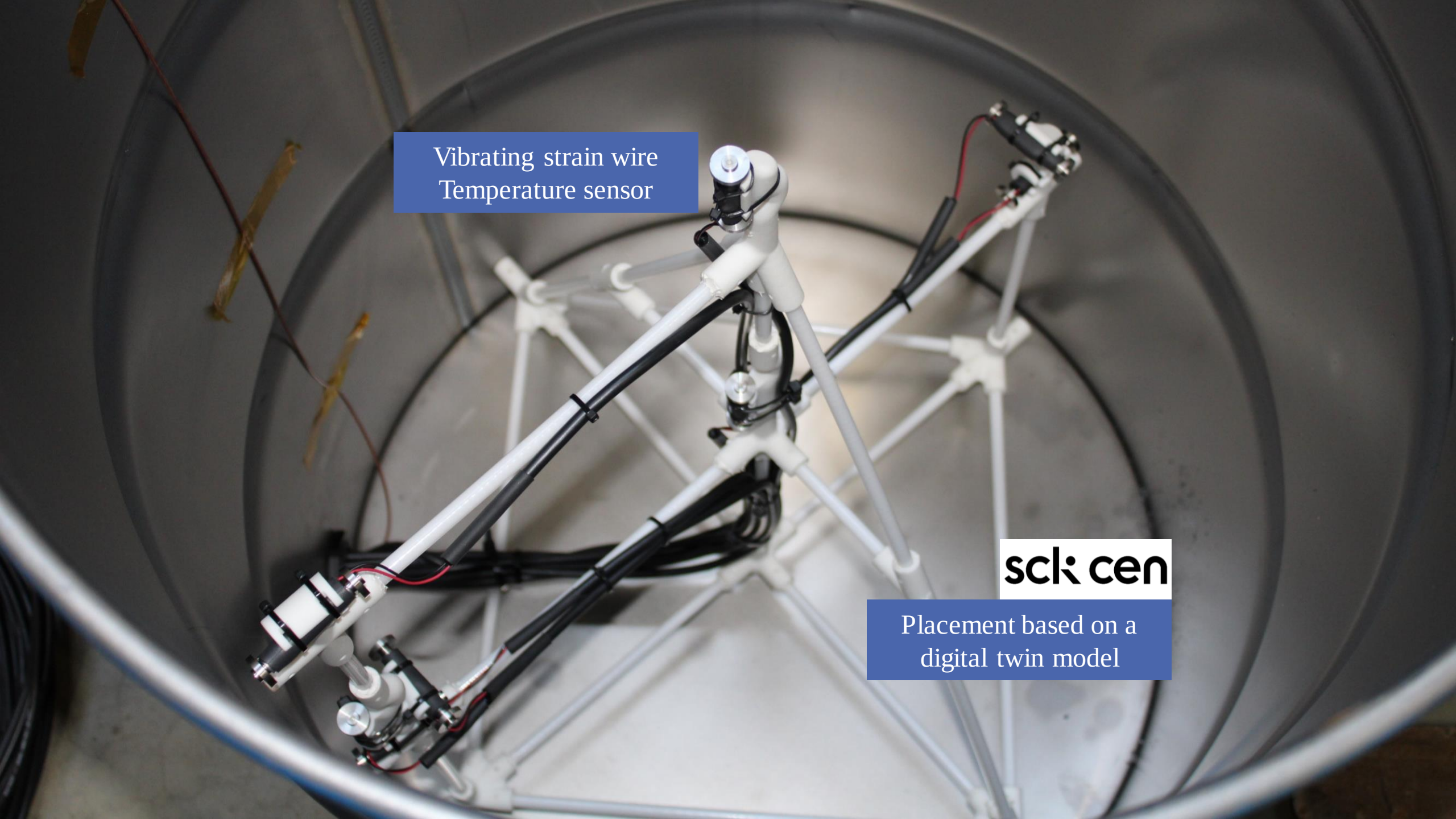
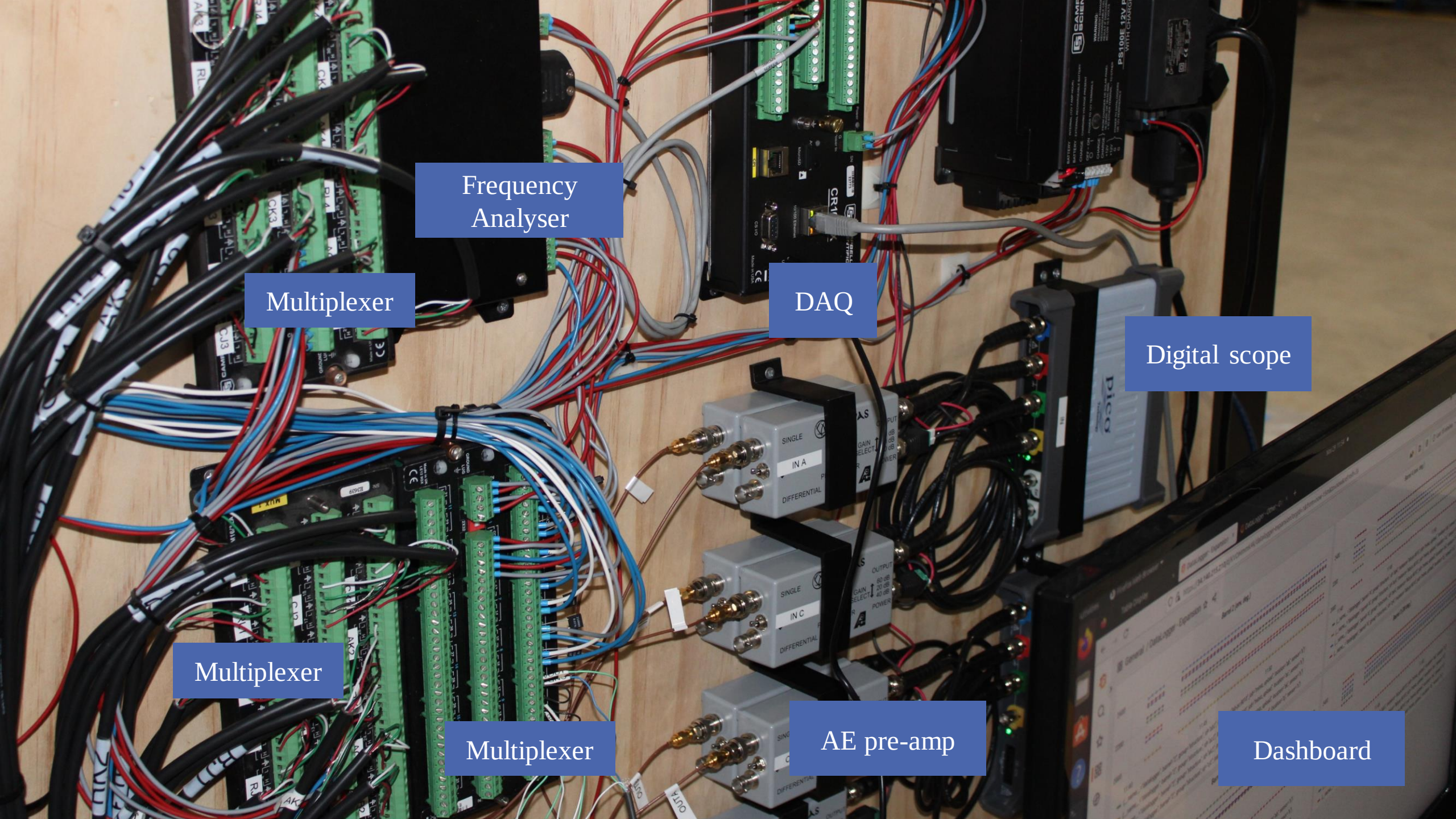
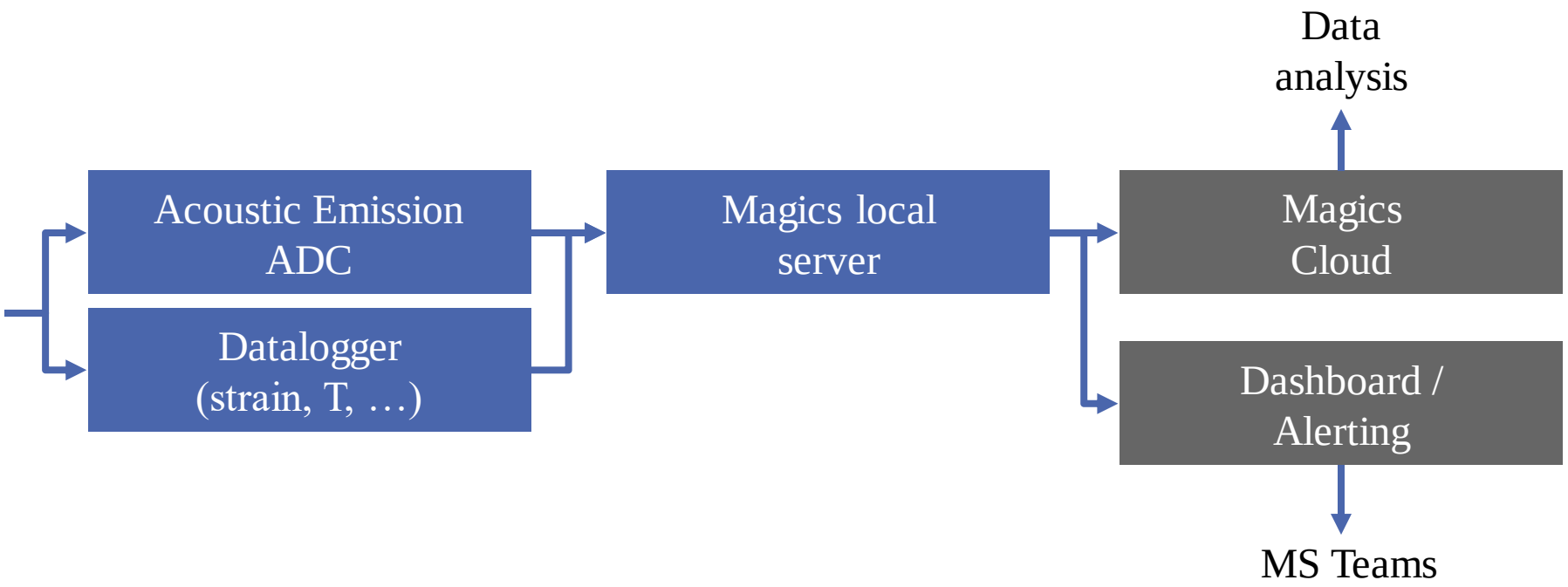

Vibrating strain wire
Temperature sensor
sck cen
Placement based on a
digital twin model


Temperature,
Humidity,
Pressure
Heating belts


Frequency Analyser
Multiplexer
DAQ
Digital scope
Multiplexer
Multiplexer
AE pre-amp
Dashboard

Logging architecture



This project has received funding from the Euratom research and training programme 2019-2020 under grant agreement No 945098.

Logging dashboard

- https://34.140.215.210/dashboards
- User: guest
- Password: magicstech

This project has received funding from the Euratom research and training programme 2019-2020 under grant agreement No 945098.

PREDIS

Experiments

This project has received funding from the Euratom research and training programme 2019-2020 under grant agreement No 945098.

Material

- Mortar samples
- w/c ratio = 0.47
- Sand/cement = 2

Mix	Cement, kg/m^3	Water, kg/m^3	M32 sand, kg/m^3	RCA, kg/m^3	$LiNO_3$, kg/m^3	Note
SIB	635.5	298.7	1270.9	-	-	Non-reactive ((lab + drum tests)
RCA	604.6	284.2	604.6	604.6	-	Reactive (lab + drum tests)
LI	604.6	284.2	604.6	604.6	5.3	Mitigation (lab tests only)

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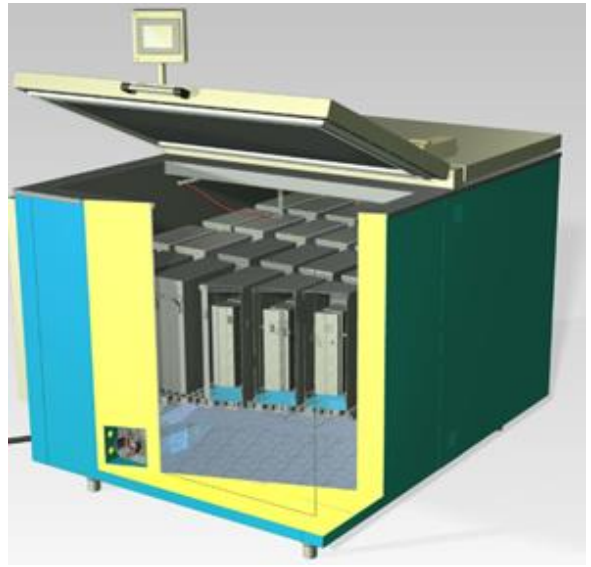
Lab-scale experiment

Mortar bar test instrumentation

Mortar bar emplacement in high T chamber – at 80 °C



Emplacement in a typical industrial ASR chamber at 38 °C

Duration: 1 year

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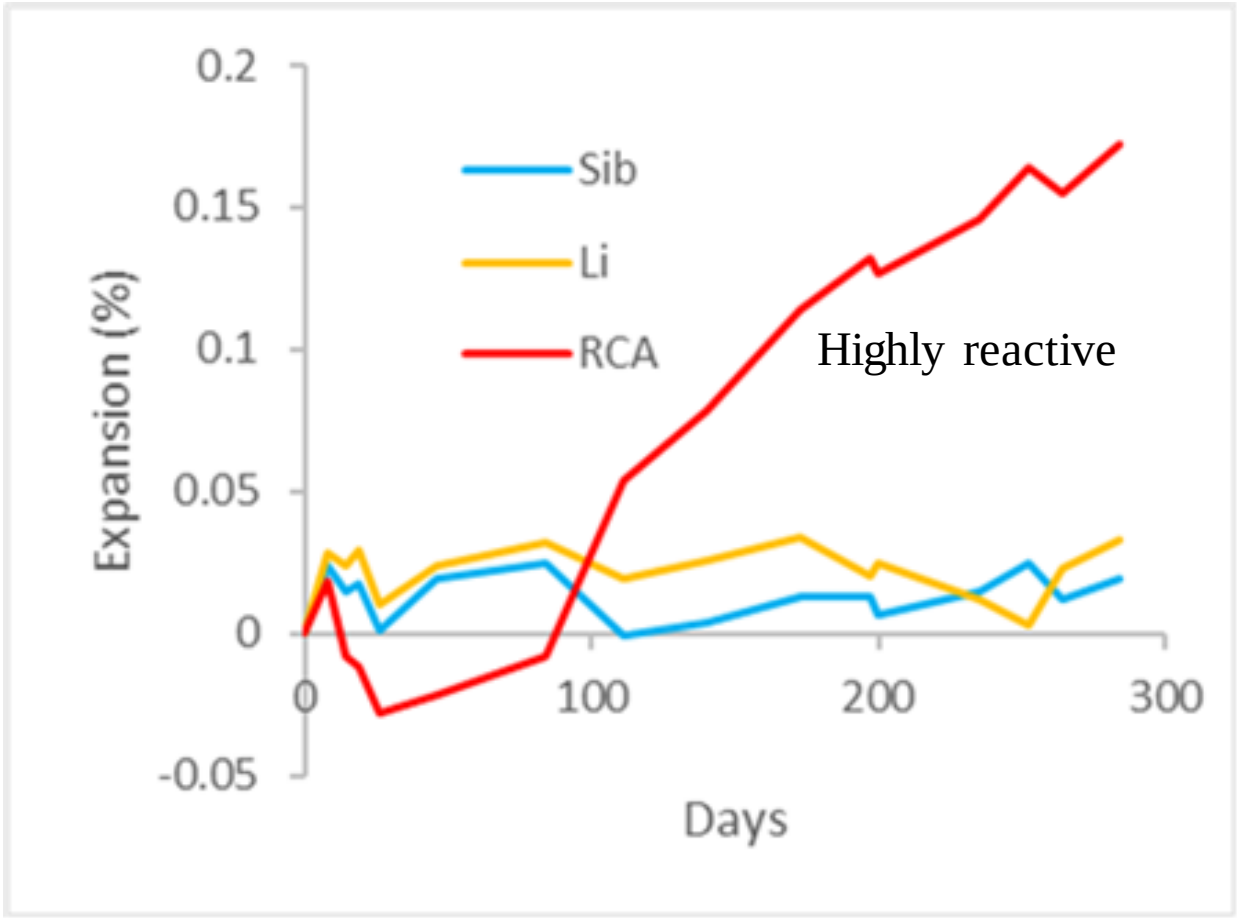
Key data for digital twin – expansion curves



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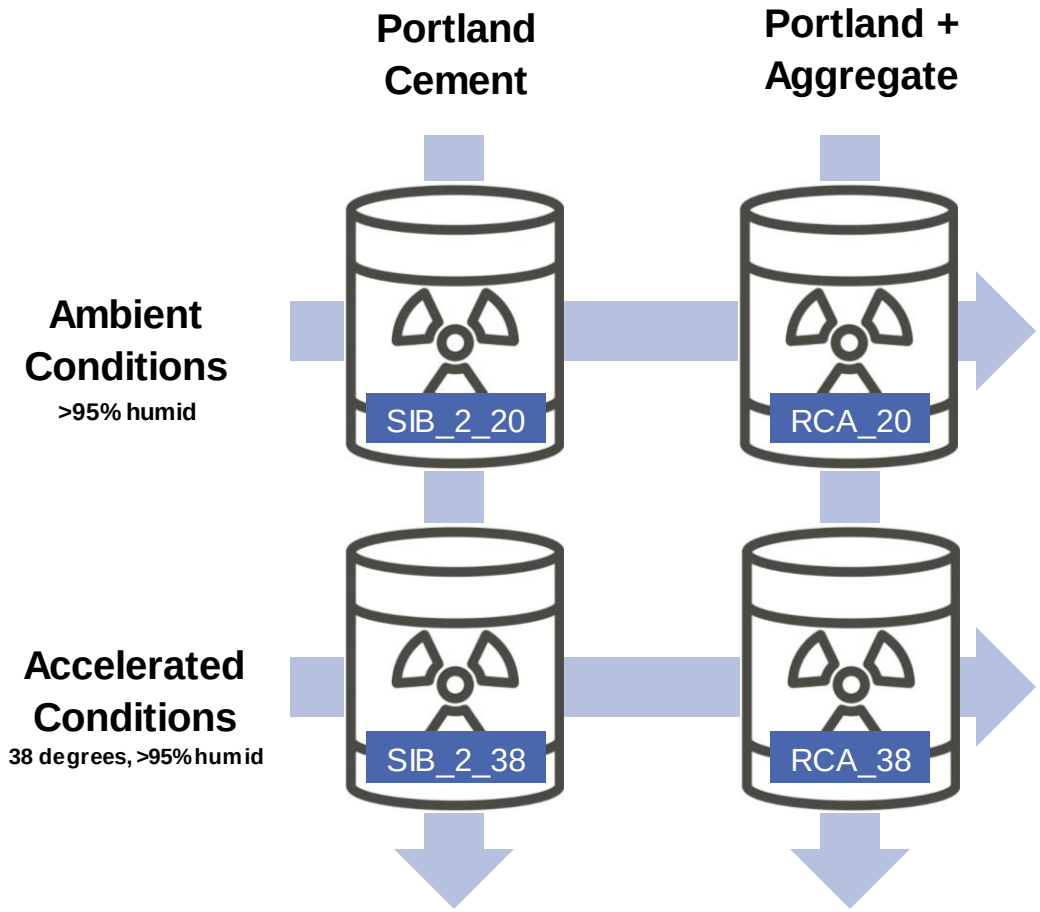
Drum-scale experiment - design

- 2 mixes
  - RCA – recycled aggregate
  - SIB – Sibelco sand
- 2 temperatures
- Duration: 2 years



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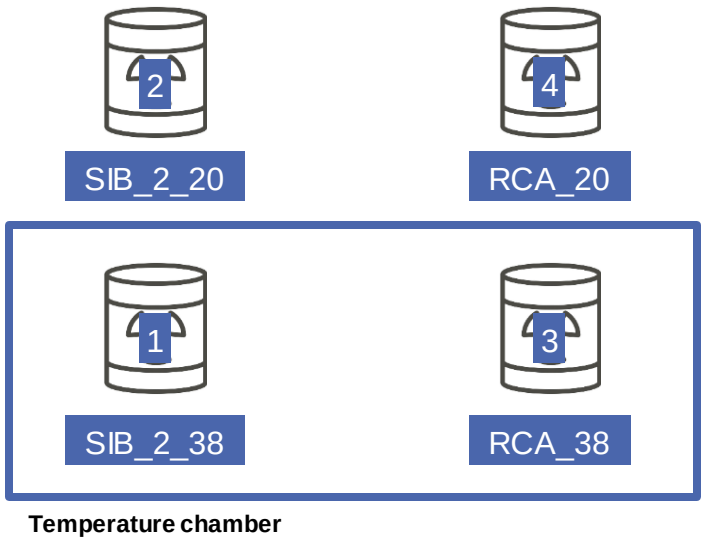
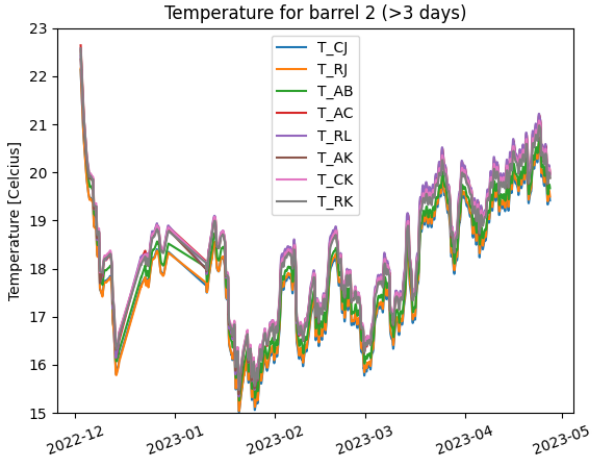
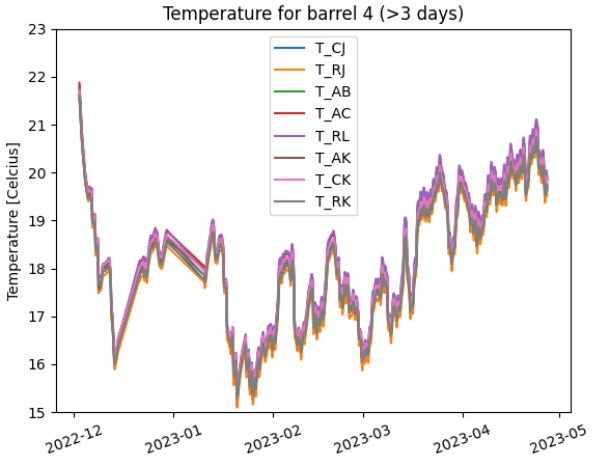
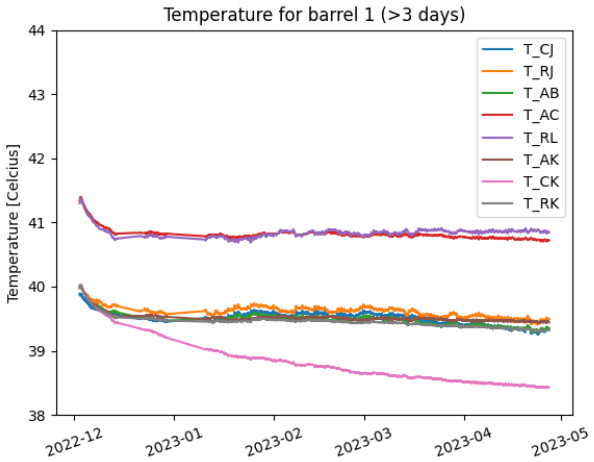
Drum-scale experiment - temperature

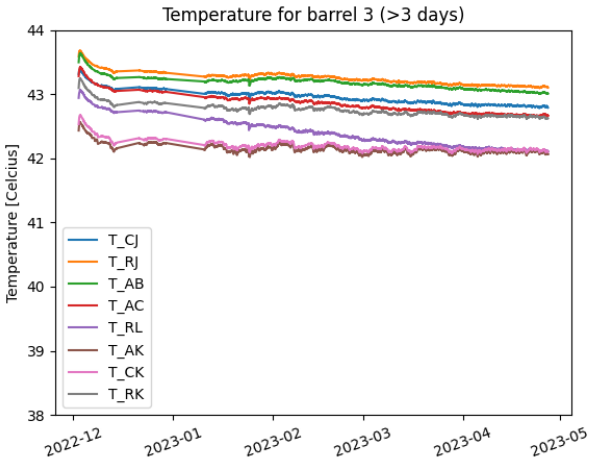


Laboratory expansion is at 38°C, but prevailing temperature at the drum scale is higher. This will have some impact on our predictions









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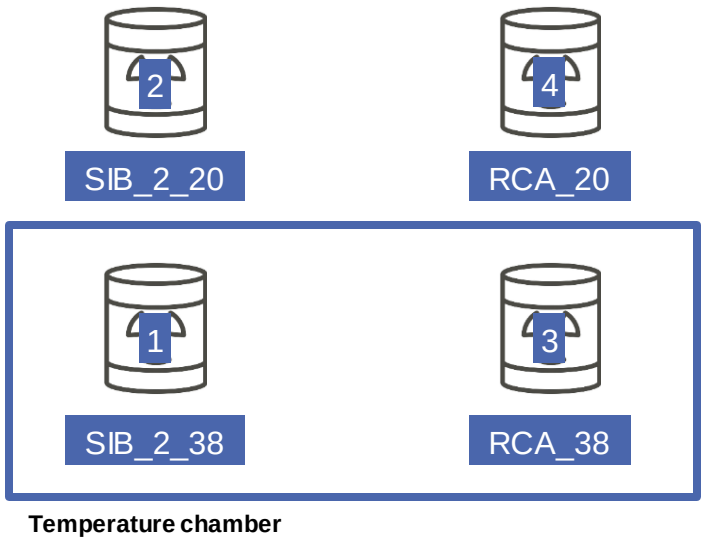
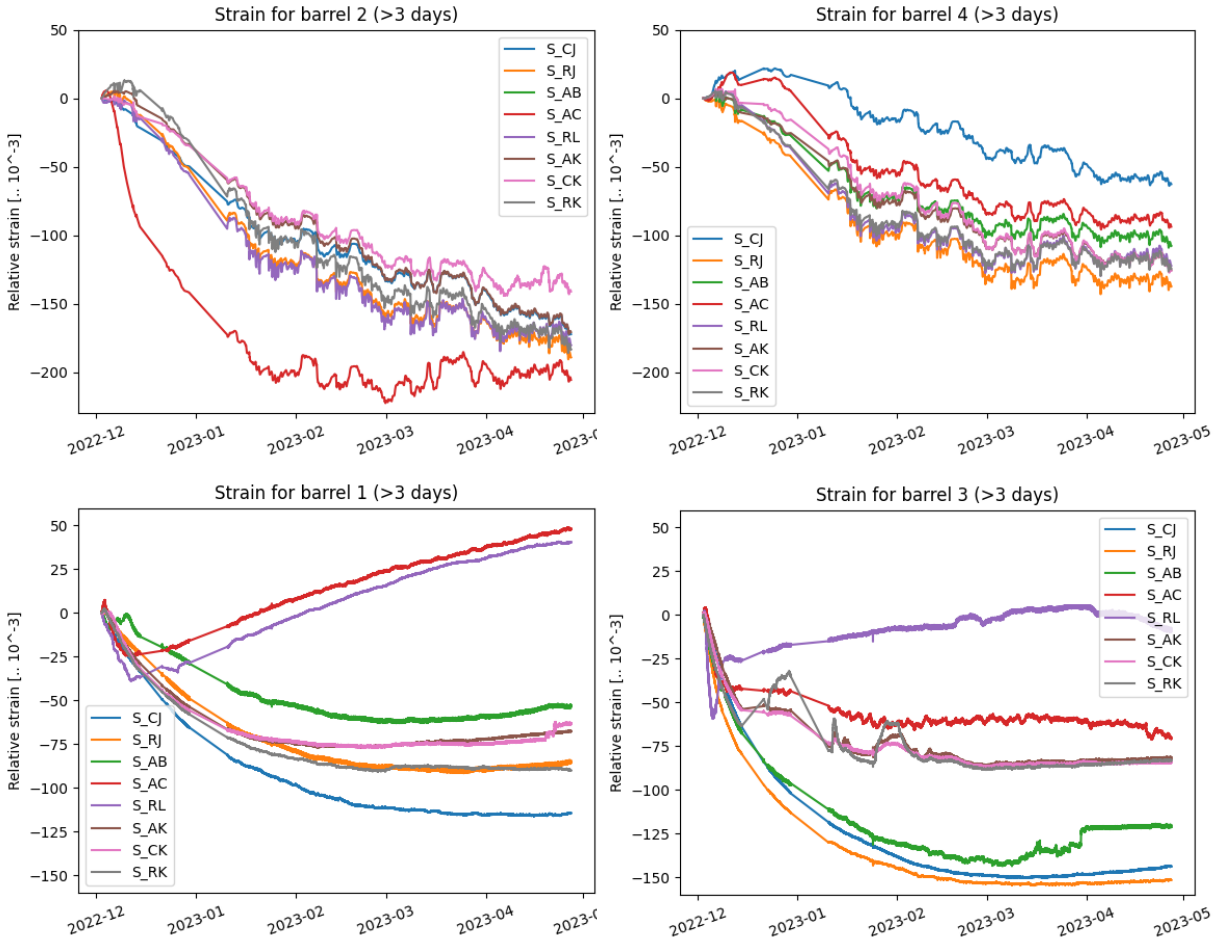
Drum-scale experiment - strains



Laboratory expansion is at 38°C, but prevailing temperature at the drum scale is higher. This will have some impact on our predictions



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Digital twin

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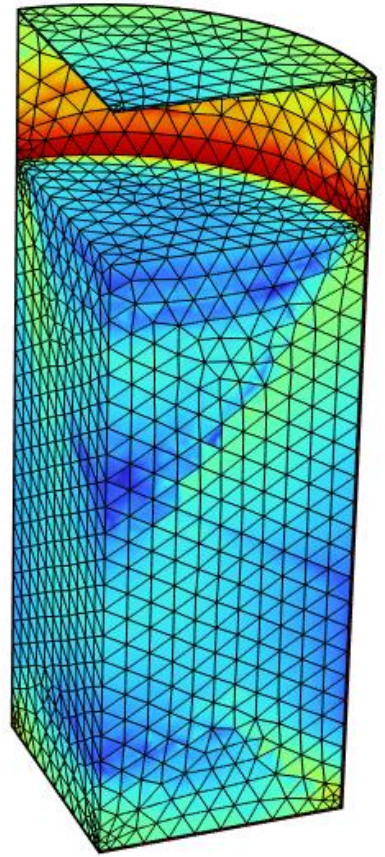
Digital twin workflow

Industrial scale experiments

Sensing

Compare with measurements

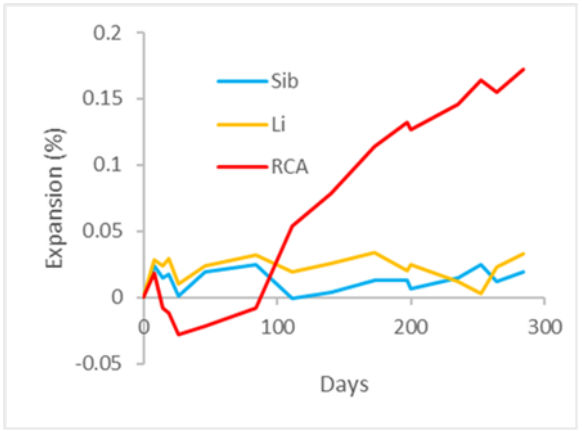
Update the model



Digital twin

Constitutive law

Additional lab data



Laboratory data

Choice of expt. Material

Improved understanding of in situ performance

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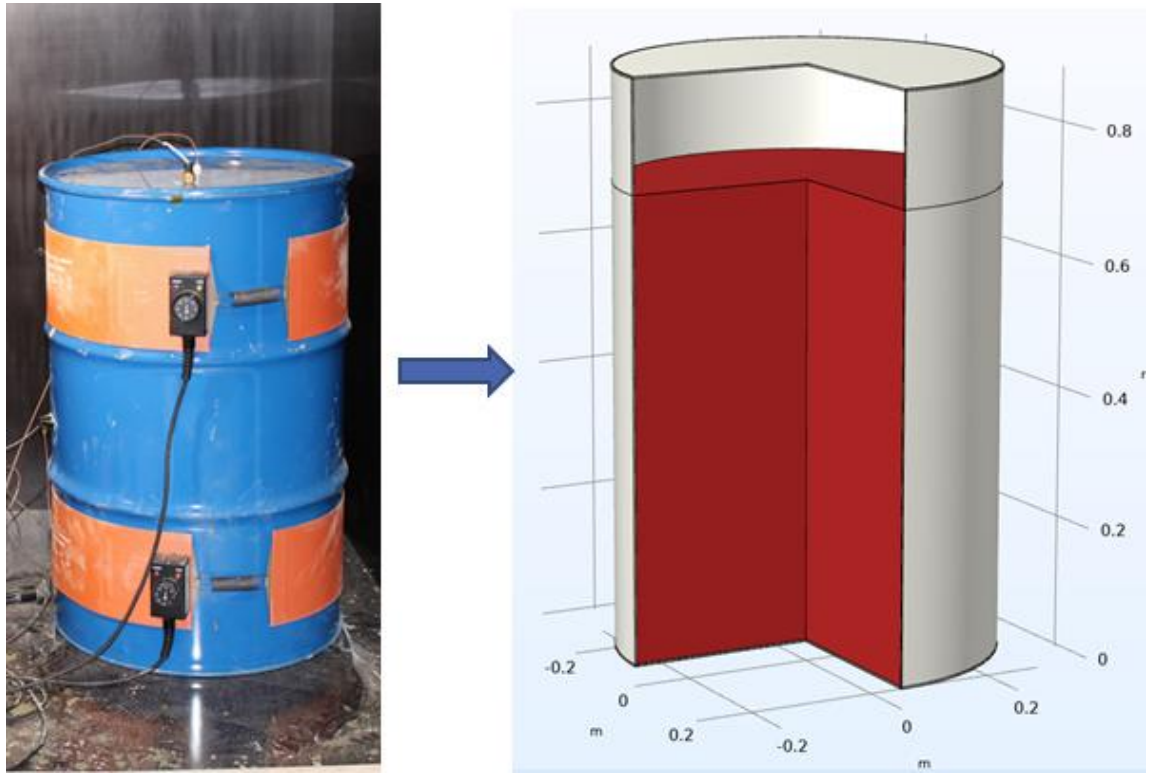
Digital twin

- Predict 2-year evolution of ASR process at the drum scale.
- A simplified chemo-mechanical model to enable prediction.



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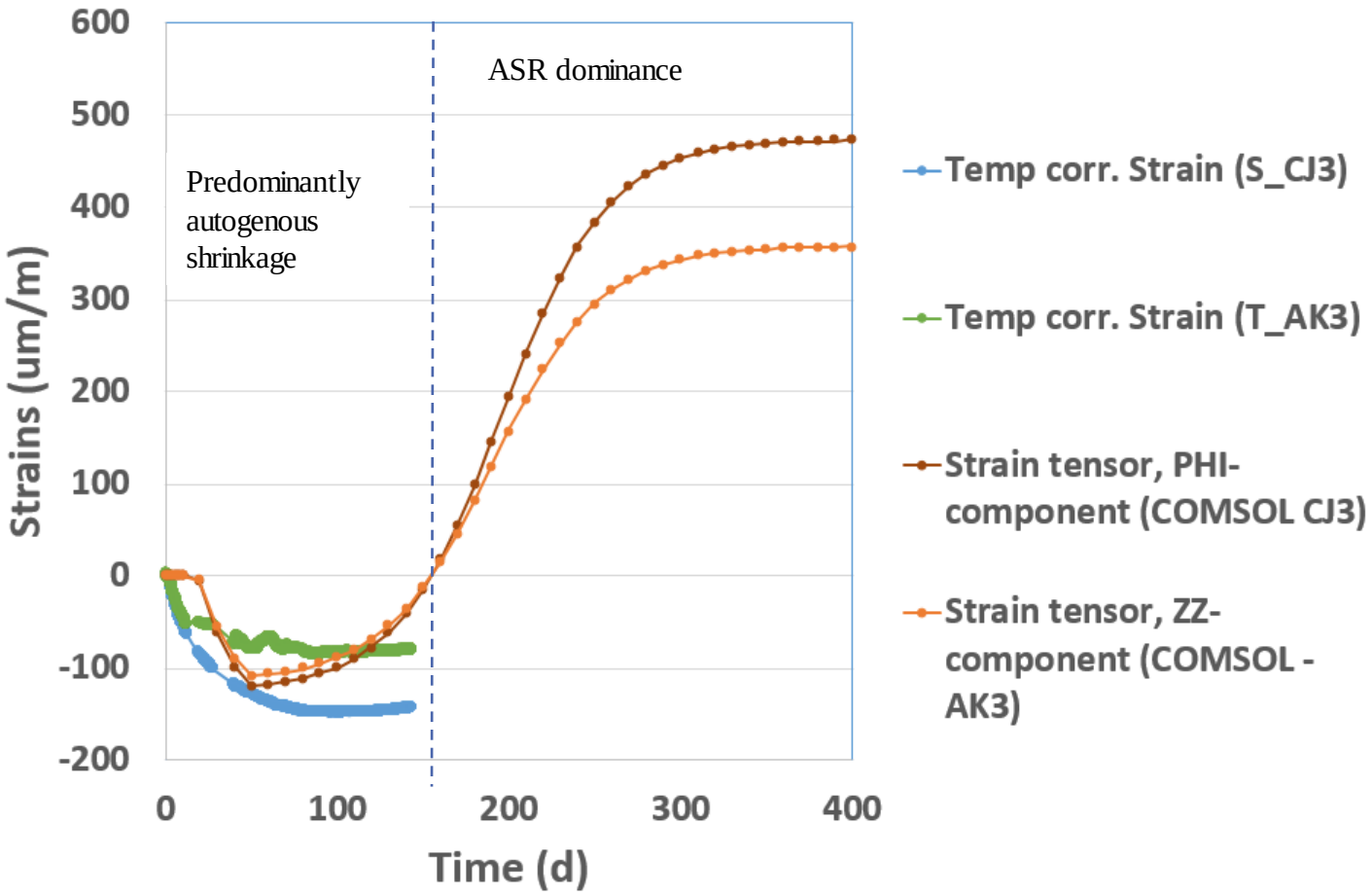
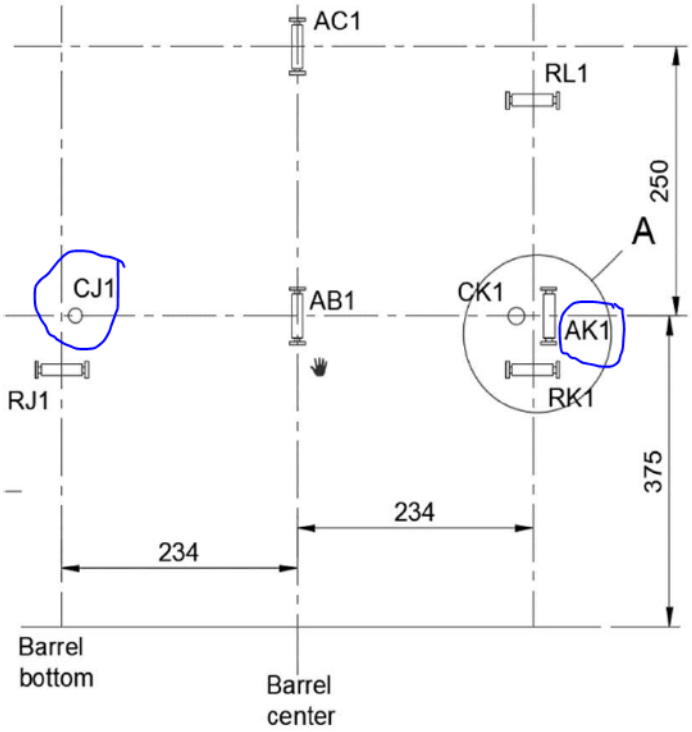
Preliminary results – Blind prediction of strain evolution





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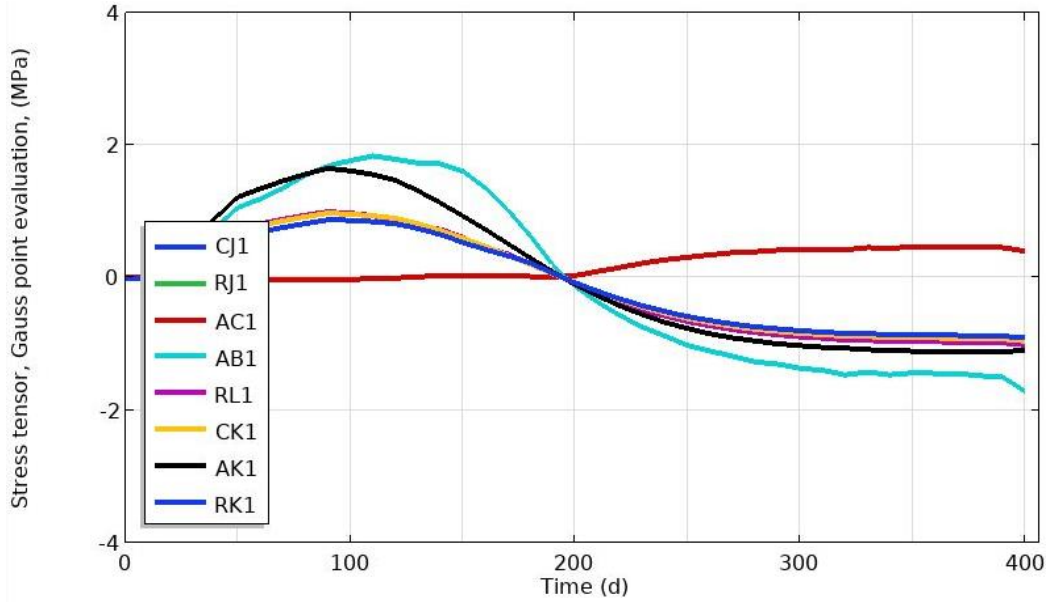
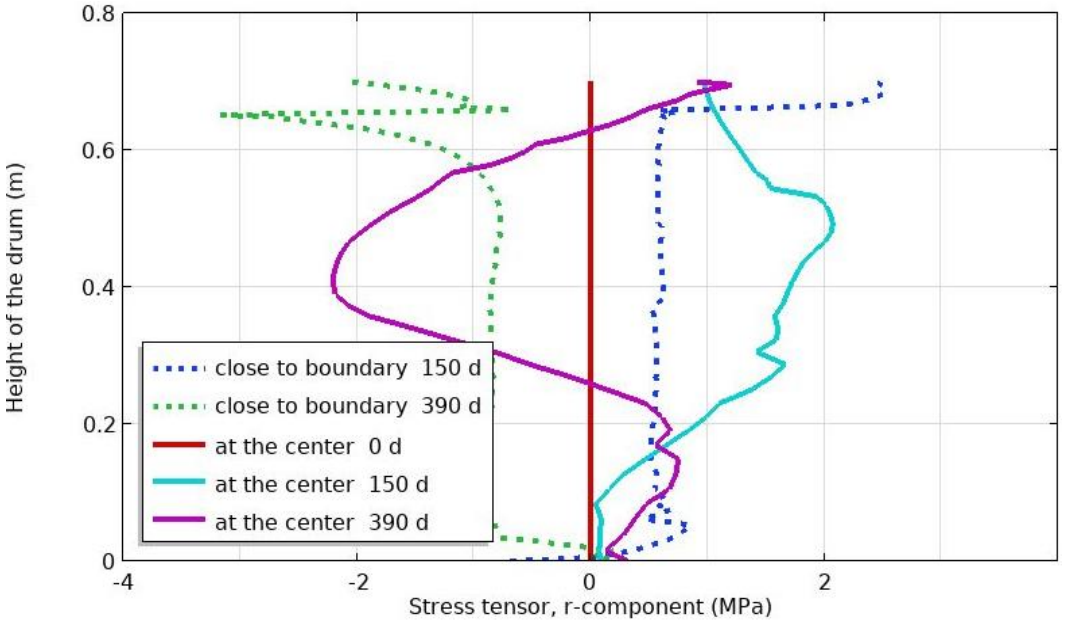
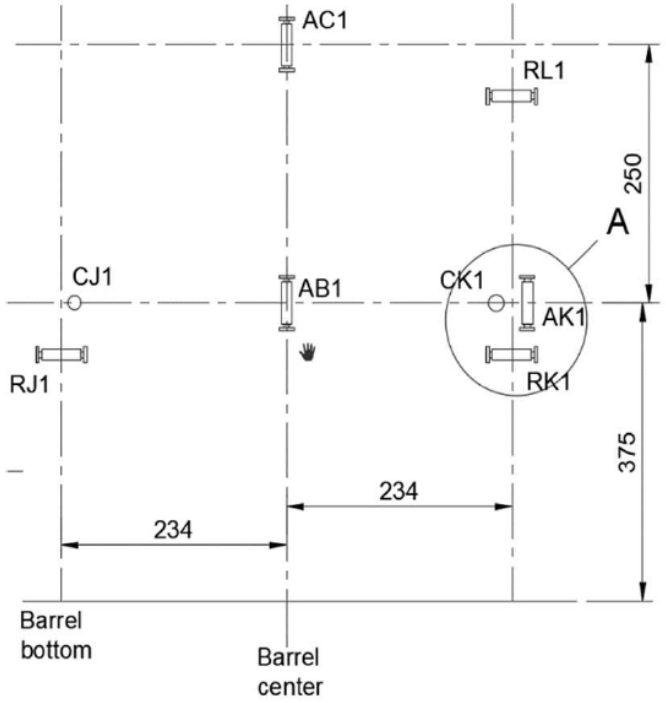
Evaluation of stresses







With preliminary parameter values, the model shows that cracking potential is low. However, it is too premature to make conclusions because only 300 days of data available and ASR can continue long after.

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Future work

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Future work

- Integrating dataset(s) with Predis's dataset standard
- Correlation of Acoustic Emission w/ strain?
- Quality assurance of drum scale experimental data.
- Deploy new experiments to support drum scale simulations, depending on available budget.

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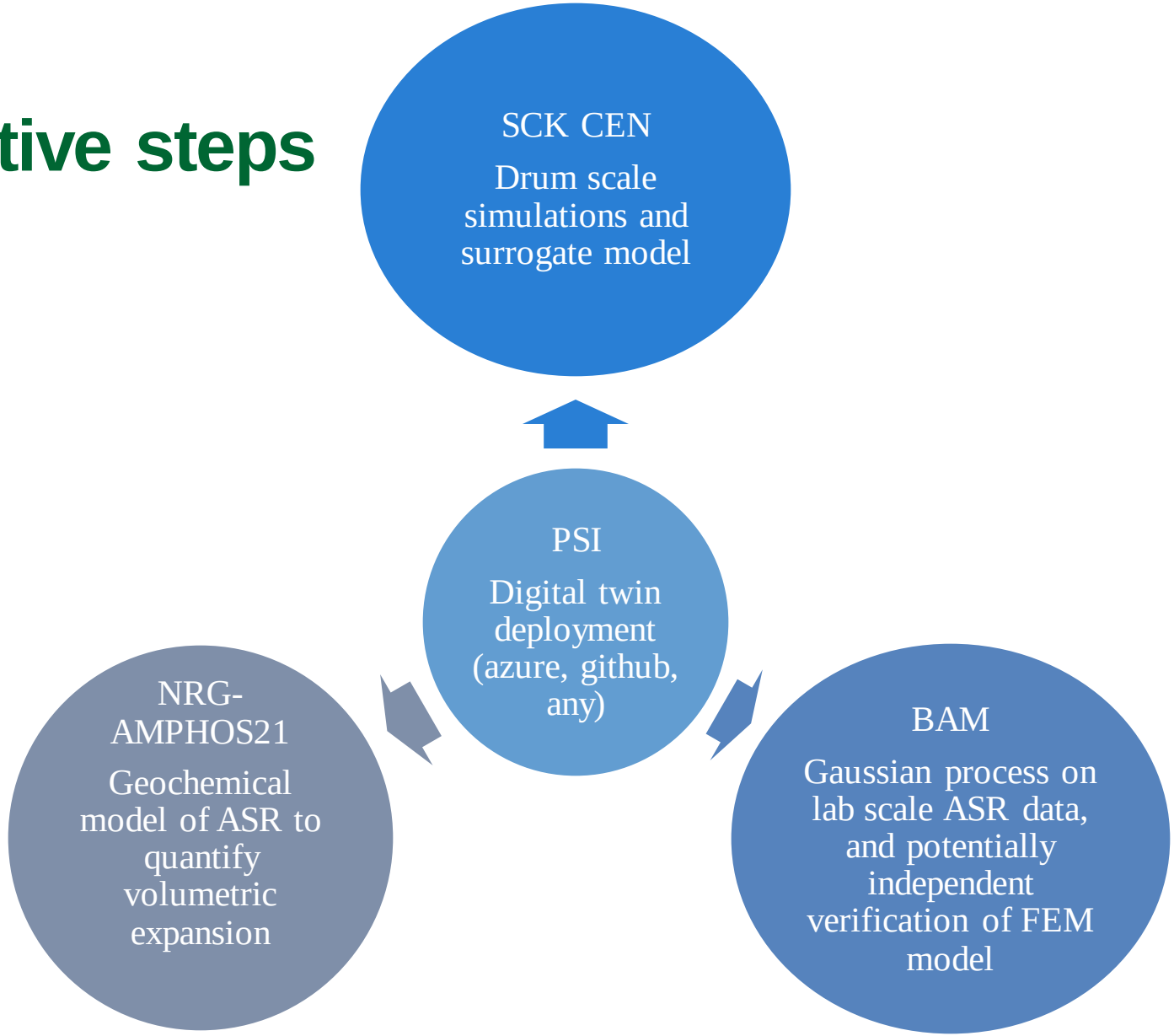
Collaborative steps



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