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soluciones ambientales

El Cabril Low and Intermediate Level Radioactive Waste Disposal Facility

Long-term performance assessment

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Introduction. General description

- **ENRESA is the Spanish organization responsible for long term management of spent fuel and radioactive waste and for nuclear installations decommissioning as well**
- **El Cabril is the Spanish low and intermediate level radioactive waste disposal facility, in operation since 1992. It has 28 vaults with a total internal volume of 100,000 m^3**

Introduction. El Cabril Disposal facilities for LLW and VLLW

El Cabril LILW Disposal facility. General objectives

- **El Cabril facility objectives:**
  - Disposal of LLW
  - Disposal of VLLW
  - Treatment of some waste streams from NPP
  - Treatment of Institutional producers waste
  - Verification and support to acceptance of waste packages
  - Fabrication of overpacks
  - Laboratories, workshops and ancillary installations

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PA strategies 1

- **Preliminary phase (site licensing)**
  - 2D hydrogeology and migration model
    - *Envelop assumptions derived to feed Safety Assessment model*
  - Optimization of barriers durability
    - *Design objectives*
    - *Justification of assumptions*
  - 1D simplified model for Safety Assessment
    - *Sensitivity analysis*
- **Licensing phase (operations license)**
  - Revision of 2D hydrogeological model and revision of assumptions for PA
  - Service life modeling of structures
  - 1D and 2D simple model for PA based on data and assumptions from the more detailed models

PA strategies 2

- **Safety Periodic Review requires enhancement of Safety Assessment Models**
  - 3D hydrogeological and migration model
  - Detailed model for structures behavior
  - Safety Assessment adapted to IAEA trends (ISAM)
    - *Scenario selection presentation*
    - *Enhancement of tools or more detailed models*
  - Attention paid to and specific models on specific issues
    - *Water table rise*
    - *Potential water tub effects*
    - *Influence of Capillarity phenomena observed*
      - Behavior of the system
      - Radionuclide potential migration new pathways

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PA and related research work

- **PA development and research work are linked**
- **Two support research and development lines:**
  - Hydro-geo-chemical
    - *3D detailed Hydrogeological model*
    - *Kd determination*
    - *Geochemical surveillance of underground water: help to system understanding*
  - Cementitious barriers behavior
    - *Kd determination*
    - *THM characterization*
    - *Durability studies and tests*
      - Characterization tests
      - Phenomenological tests and analysis
      - Large size experiments
    - *Behavior, THM and geochemical modeling*
- **Integration and licensing support line**
  - Surveillance of parameters important for long-term safety
  - Safety assessment enhancement
    - *Models improvement*
    - *Data improvement*

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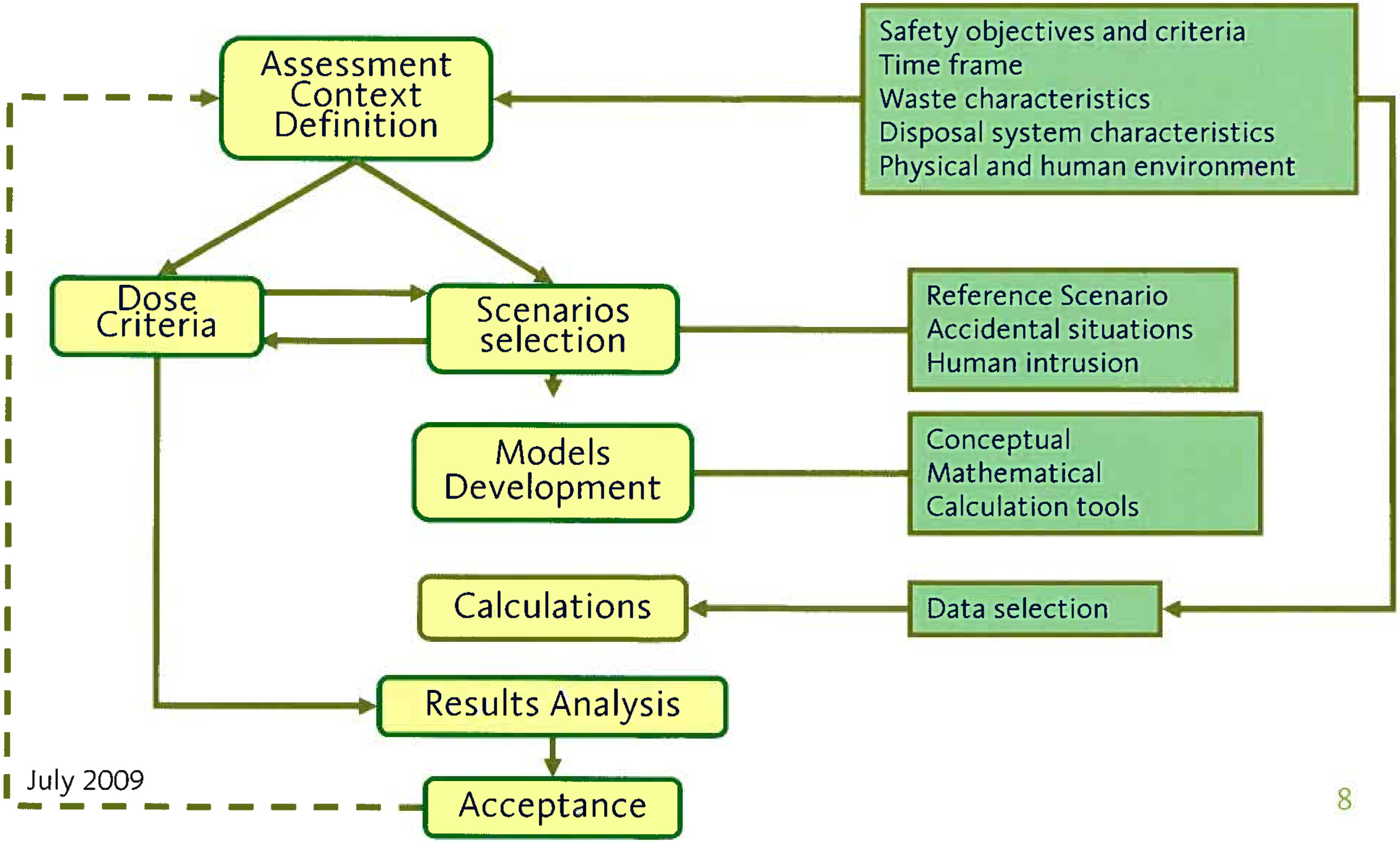
GENERAL OUTLINE OF THE ASSESSMENT PROCESS



ASSESSMENT CONTEXT SAFETY OBJECTIVES AND CRITERIA

SAFETY OBJECTIVES

- **Immediate and post-closure protection**
  - *Workers*
  - *Public*
  - *Environment*

- **Inadvertent intrusion at post-surveillance phase**

- **Retrievability in case of necessity**

→

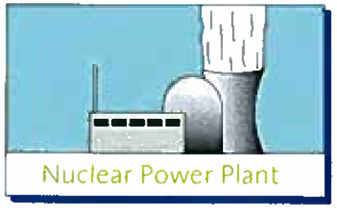
DESIGN CRITERIA

- **Waste Isolation through a multi-barrier system)**
  - Waste forms, vaults, cap
  - Natural barriers limiting the consequences of failures.

- **Surveillance period no longer than 300 y**
- **Activity Limitation**
  (Total Activity / Activity Concentration per vault or package)

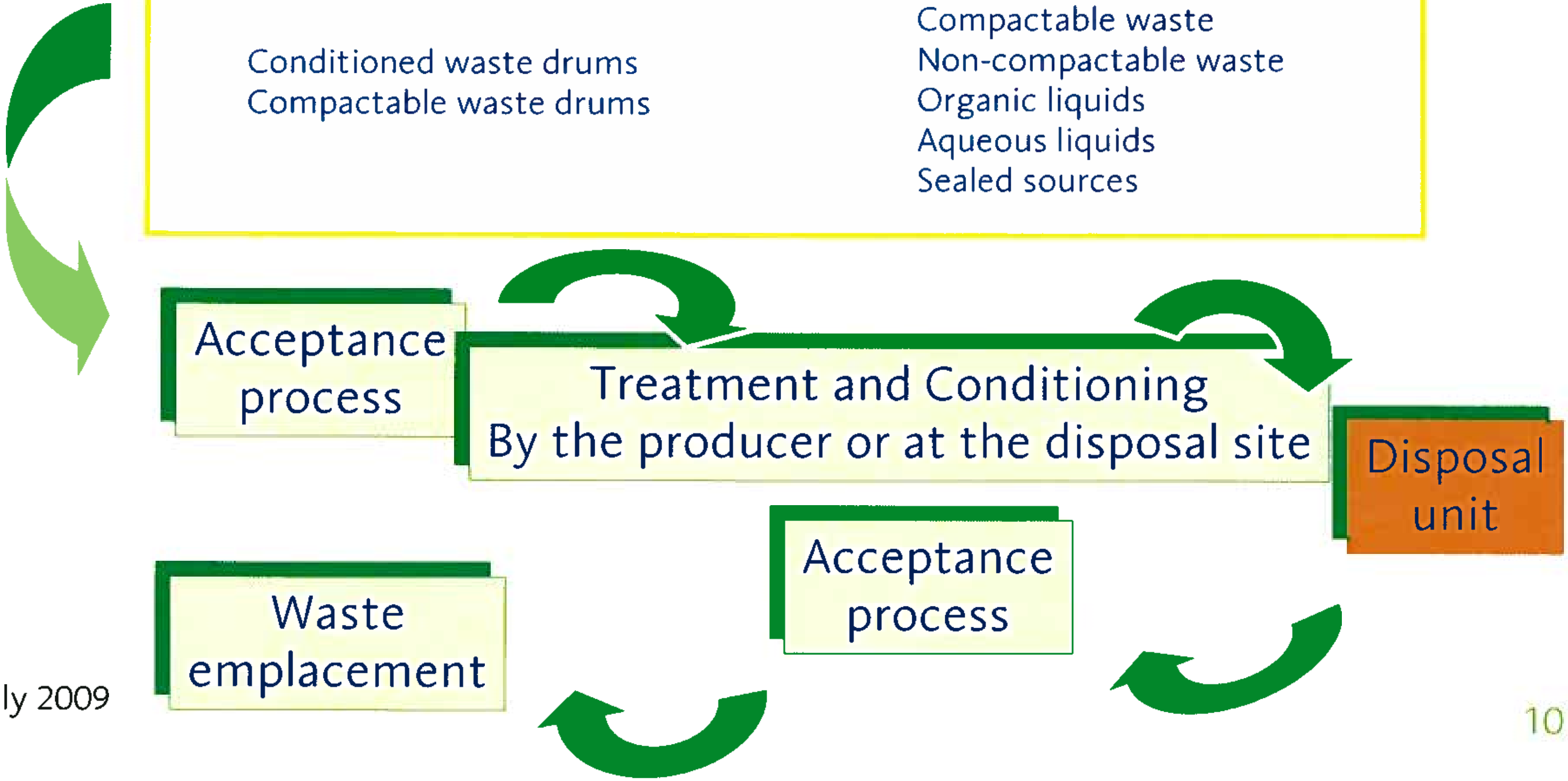
- **Use of "durable" containers**

ASSESSMENT CONTEXT WASTE CHARACTERISTICS (1/2)



Conditioned waste drums
Compactable waste drums

Organic solids
Compactable waste
Non-compactable waste
Organic liquids
Aqueous liquids
Sealed sources



Assessment context. Waste characteristics

- **Solid (including solidified waste)**
- **Activity limits**
  - Two levels with different conditioning and acharacterisation requirements
    - *Level 1*
    - *Level 2*
  - Activity limit per vault
  - Activity limit for the whole facility (reference inventory)

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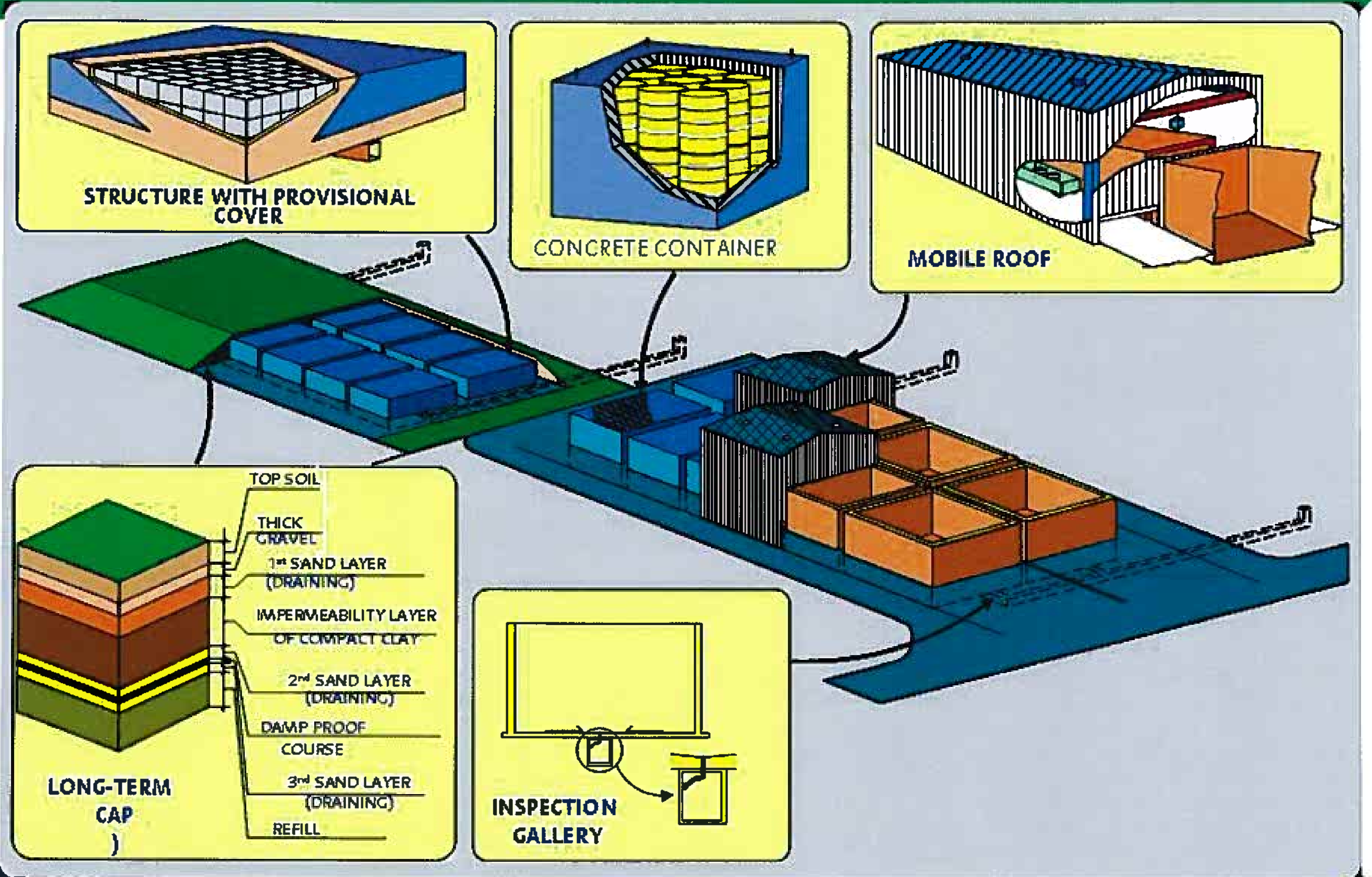
ASSESSMENT CONTEXT DISPOSAL SYSTEM

- Packages disposed of (disposal units)
  - Generally: 11 meters cube concrete containers
    - With 18 220-L solidified waste drums
    - Up to 40 super-compaction pellets
    - Backfilled with cement grout (or conditioned waste)
  - Specific cases
    - 480-L drums with concrete sleeve
- Disposal vaults
  - 24 x 20 x 10 outside dimensions; 0.5 m thick walls
  - 28 vaults built
  - Separated seepage system by gravity
- Final engineered cap

- Disposal area lay out

El Cabril Disposal facility. Long-term performance assessment

ASSESSMENT CONTEXT: DISPOSAL SYSTEM



Disposal system. Relevant features

- **Waste package is a 11 m^3 concrete container with 18 0.22 m^3 drums.**
- **OPC reinforced concrete 60 MPa**
- **Stacked touching each other, but…**
  - 2 cm gap with vault walls
  - Temperature differences
- **External surfaces of vaults painted for imperviousness. Internal surfaces and containers unpainted**
- **Closing slab built when a vault is completed, before moving the metallic shelter**

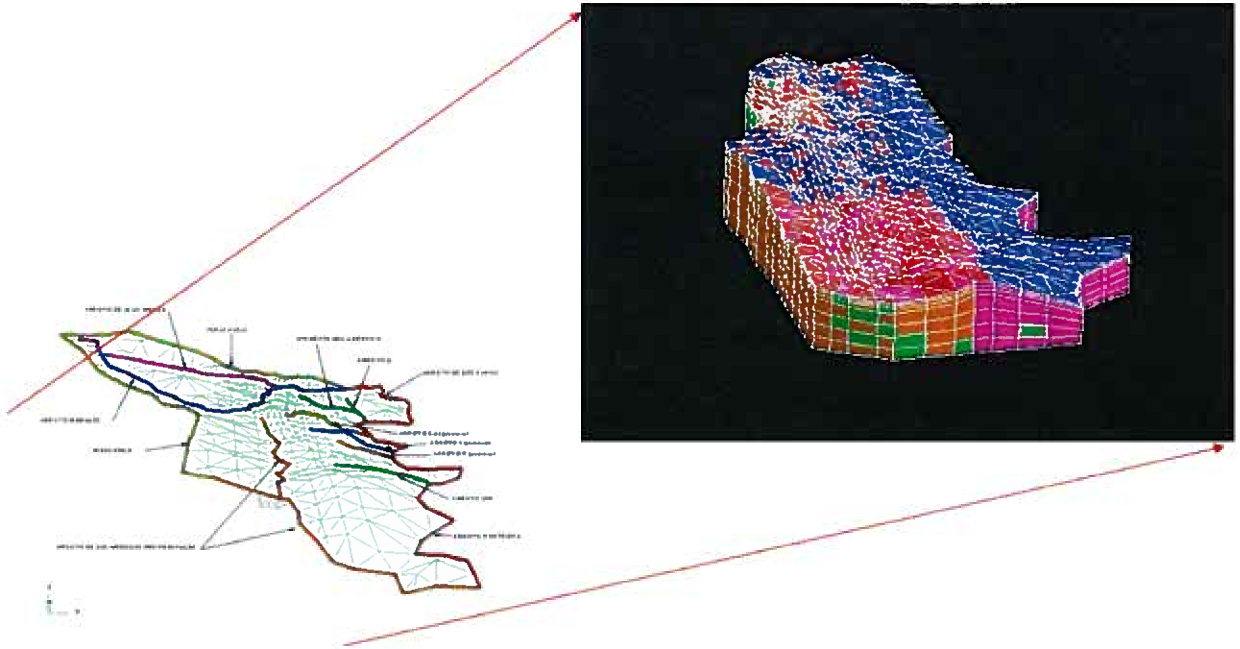
ASSESSMENT CONTEXT. Site characteristics

Physical characteristics ➜ Meteorology and climatology, Geology, Seismology, Hidrology, Hidrogeology, Geochemistry ➜ Precipitation, Evapotranspiration, Water table, Preferential flow paths, Surface water

Physical characteristics	Meteorology and climatology Geology, Seismology Hidrology Hidrogeology Geochemistry	Precipitation Evapotranspiration Water table Preferential flow paths Surface water
Human environment	Land use Water resources Agriculture	Critical individual Land and water use Diet

ASSESSMENT CONTEXT. Site characteristics 2

- Geology and seismology
- Climate
- Surface hydrology and hydrogeology
- Human environment



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DOSE CRITERIA

- **Normal situation** → Water ≤ 10^{-1} mSv/y
- **Accidental Situations** → Air ≤ 5 mSv; Water ≤ 10^{-1} mSv/y
- **Human intrusion** → ≤ 1 mSv/y

The dose is used as the safety indicator to evaluate the acceptability of the disposal facility

As part of the results analysis the activity flux form relevant interfaces is taken into account

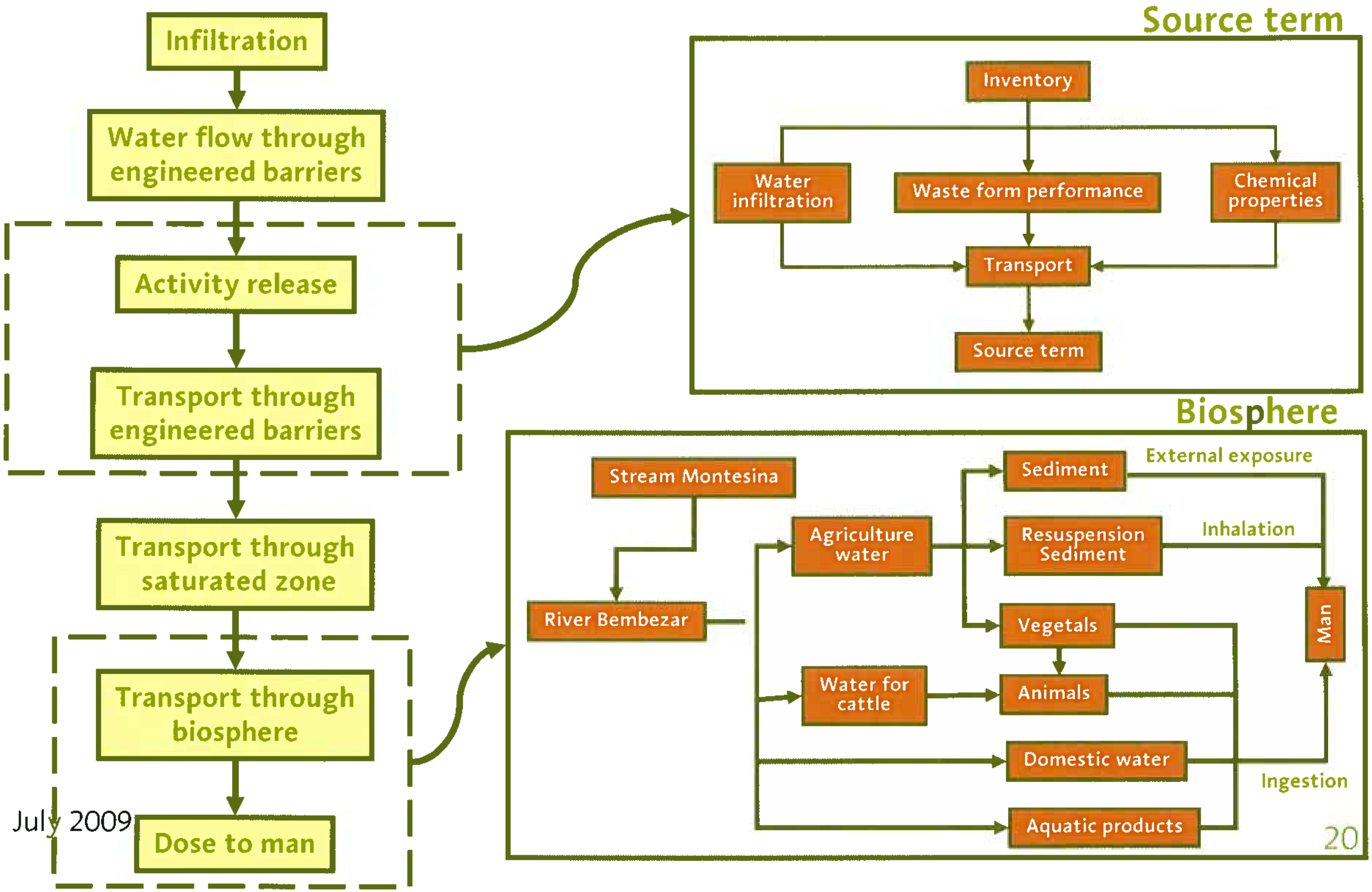
EXPOSURE SCENARIOS SELECTION

- **Normal Evolution**
  - Water → Migration ground water pathway
- **Accidental Situations**
  - Water
    - → Migration ground water pathway with cap failure
    - → Rise of water table
  - Air → Aircraft crash
- **Inadvertent Intrusion Human**
  - Air, External exposure
    - → Construction Scenarios
    - → Residential Scenarios
  - Air, External exposure, Soil contamination → Residential Agriculture Scenario

Main assessment scenarios

- **Post-closure scenarios**
- **Water pathway (normal evolution)**
  - Radionuclide migration through groundwater
- **Water pathway (accidental situation)**
  - Radionuclide migration through groundwater – Cover failure
  - Rise of water table
- **Atmospheric pathway (accidental situation)**
  - Aircraft crash (inhalation exposure)
- **Inadvertent human intrusion**
  - Road construction (inhalation and external exposure)
  - Residence construction (inhalation and external exposure)
  - Residence use (inhalation and external exposure)
  - Residence and playground use (inhalation and external exposure)
  - Residence and agricultural use (inhalation, ingestion and external exposure)

Models development . Ground water pathway (2/2)



MODEL DEVELOPMENT. Conceptual model for Groundwater pathway

- Calculation methodology is based on three areas

  - SOURCE TERM ANALYSIS
    Water flow
    Activity release
    Transport through engineered barriers

  - RADIONUCLIDE MIGRATION THROUGH GEOSPHERE

  - BIOSPHERE TRANSFERENCE (including doses to man)

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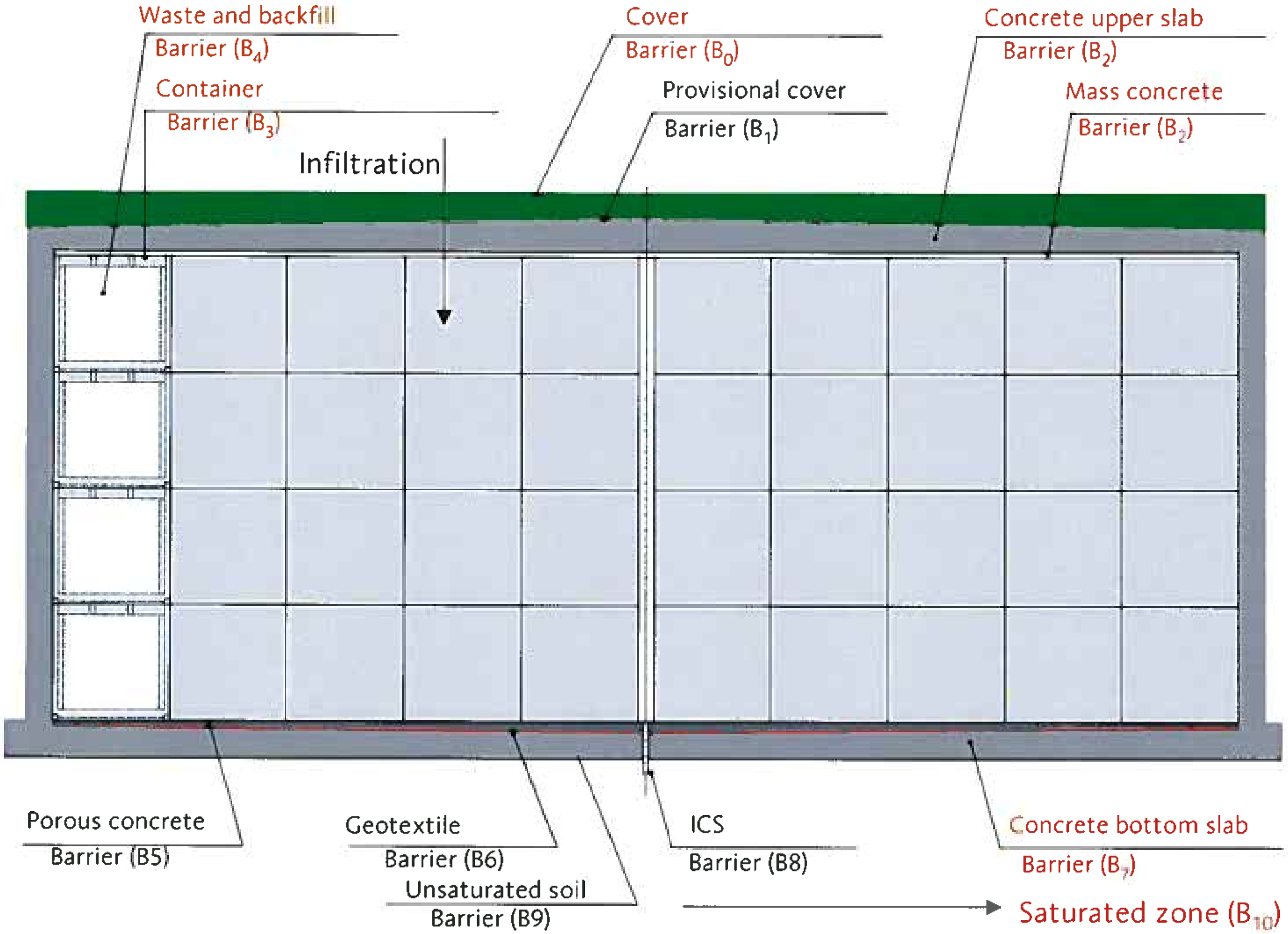
MODEL DEVELOPMENT. Conceptual model for Groundwater pathway

- Deterministic evaluation
- Perform two successive time intervals (0-300 years, > 300 years) to consider degradation of materials
- Properties of materials are constant in each interval
- Homogeneous activity distribution of wastes in the repository
- The geosphere is conservatively considered as a saturated area by preferential ways
- Geosphere / biosphere interface is a stream system
- Equilibrium between biosphere compartments

Models development. Ground water pathway



Credit to Barriers in red

Normal evolution (reference) scenario: Engineered barriers

- The whole facility is formed by 2240 columns, consisting of 4 concrete containers vertically piled. Wastes are grouted inside the disposal units
- The radioactive inventory is uniformly distributed in the 4 disposal units of the column
- All engineered barriers, except the cover, are cemenititious barriers
- The cap is modelled by means of an infiltration rate
- After 300 years: Engineered barriers are fully degraded (initial concrete or grout transformed into sand like granular material

Normal evolution (reference) scenario. Flow

- In each column, the water flux is vertical and constant (steady state).
- The moisture content of materials of the column are taken from structure models. In most cases the moisture content in saturation is considered
- The Darcy's velocity and the moisture content for the ground are derived from hydro-geological site specific developed studies

Normal evolution (reference) scenario. Release mechanisms

- The main release mechanisms considered in the simulation are Dissolution (surface rinse) and Diffusion.
  - Dissolution is assumed for all stages of the facility lifetime
  - Release by diffusion is considered only during the institutional control period
- Release occurs instantaneously, when the water is in contact with the waste form
- No dissolution limits considered (although a specific study was developed)
- Chemical equilibrium in solution is controlled by the distribution coefficients (K_D).

Normal evolution (reference) scenario. Transport

- During the transport of contaminants, both in the column and in the terrain, the following processes are taken into account:
  - advection,
  - diffusion,
  - radioactive decay
  - and sorption reactions
- Regarding sorption reactions during the transport, the K_D coefficient plays a role similar to the before explained for the release
- The ground is considered as saturated zone.
- Preferential ways of transport have been considered

Model development. Calculation codes

- **DUSTM-MS**
  - D isposal U nit S ource T erm (M odified) – M ultiple S pecies
  - Basic Reference: NUREG/CR-6041
  - Main objective: Estimation of the rate at which radionuclides migrate out of the facility (i.e., the source term)
  - Source term is influenced by:
    - ***Radionuclide inventory***
    - ***Waste form and containers used to dispose of the inventory***
    - ***Physical processes that control the release from the facility***
  - Physical processes:
    - ***Fluid flow***
    - ***Container degradation***
    - ***Radionuclide release from waste form***
    - ***Radionuclide transport***
  - **Influence of the design of the facility**

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Model development. Calculation codes

- **DUSTM-MS (cont)**
  - DUSTM-MS calculates transport of radionuclides through the facility solving the transport equation by the one-dimensional (1D) finite difference (FD) method
  - The FD model solves the transport equation with the processes of advection, dispersion, retardation (sorption), radioactive decay and generation (radioactive chains), waste form sources, and external sources and sinks

$$\frac{\partial}{\partial t}(R_i\theta C_i)=\frac{\partial}{\partial x}\left(\theta D_i\frac{\partial C_i}{\partial x}\right)-\frac{\partial}{\partial x}(V_D C_i)-\lambda_i\theta R_i C_i+\sum_{j=1-N}^{j-i} f_{ij}\lambda_j R_j C_j+S_i$$

$$D=\frac{\alpha_L V_D}{\theta}+D_m$$

$$R=1+\left(\frac{\rho K_{D.i}}{\theta}\right)$$

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Model development. Calculation codes

- DUST MS (Cont) develops mathematical models for the physical processes (above cited):
  - Fluid flow is modelled by the code through tabular input of the flow velocity versus time
  - Container degradation is modelled through a unique container failure time. The localized failure container is allowed. If it is requested, a fraction of the container becomes breached prior to total failure
  - Waste form release is modelled through three release mechanisms:
    - *A surface rinse process in which radionuclides are released upon contact with the solution. Partitioning between the waste form and solution can be modelled*
    - *Diffusion controlled release from the waste form*
    - *Uniform release in which a fixed fraction of the inventory is released every year*

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Model development. Calculation codes

- BIOAQUA
  - Specifically developed by INITEC for ENRESA, based on French code
  - BIOAQUA calculates individual dose, as a function of time, as results of a radioactive release to the biosphere via water.
    - *Sources of water considered: River, tributary stream and water table*
  - Doses are evaluated through different exposition pathways
    - *Exposition pathways: Inhalation, direct external, ingestion of aquatic foods, vegetables, water and animal foods (milk, meat, etc.)*
  - The ingestion pathway relates different intermediate compartments where a equilibrium, between the input and the output of activity at the compartment, is established (steady state)

Incidental scenarios. Cap failure

- It is modelled as a perturbation of normal evolution scenario assuming an increase of water infiltration rate into a limited surface of the disposal for a given period in the institutional control phase

- Other hypotheses and conditions of the Scenario of Reference were maintained in the assessment of this scenario

- The calculation method is also the same used for analysis of the reference scenario

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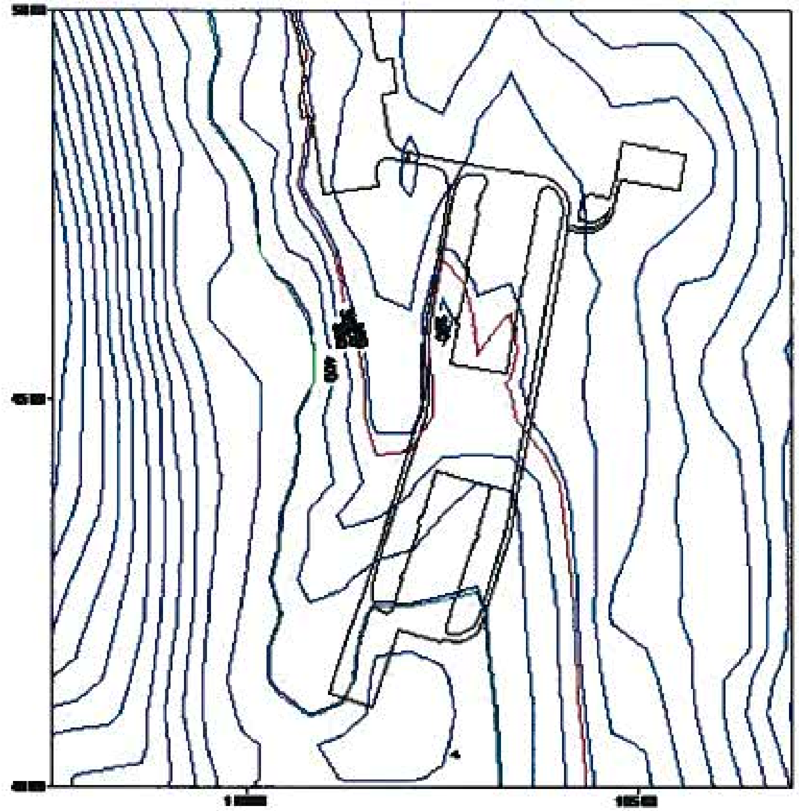
Incidental scenarios. Rise of water table 1

- It is modelled as a perturbation of the Scenario of Reference assuming an increase of the water table that could affect some disposal vaults
- Specific hydrological studies have been developed to characterize this incidental scenario. Main conclusions from these studies were as follows (scenario definition):
  - The rise of water table scenario is supposed to occur after the institutional control phase
    - After that time, the degradation of engineered barriers and the potential failure of drainages could lead to the rise of water table.
    - An increase of recharge is simultaneously postulated
    - 6 disposal vaults at Northern Disposal Area, and 3 disposal vaults at Southern Disposal Area are analysed to have 0.5-2.5 m affected by a rise of the water table

Incidental scenarios. Rise of water table 2

- In the 9 (out of 28) potentially affected vaults, vertical and horizontal components of the water flow must be considered
- General hypotheses and conditions of the Reference Scenario (those not directly derived from the previous definition of the rise of water table scenario) were maintained.
- 2D Model with use of BLTM Code was needed



BLTM-MS

- B reach L each T transport (M odified) – M ultiple S pecies
- Basic Reference: NUREG/CR-6492
- BLTM-MS has the same main objective, considers the same physical processes involved, applies the same models and equations used by DUSTM-MS
- BLTM-MS is a two-dimensional code (2D). This is the most relevant difference with DUSTM-MS.
- There are certain improvements, already developed for DUSTM-MS, incorporated to BLTM-MS
- The 2D character of BLTM-MS permits appropriate assessment in scenarios in with no symmetry (e.g., the rise water table scenario)

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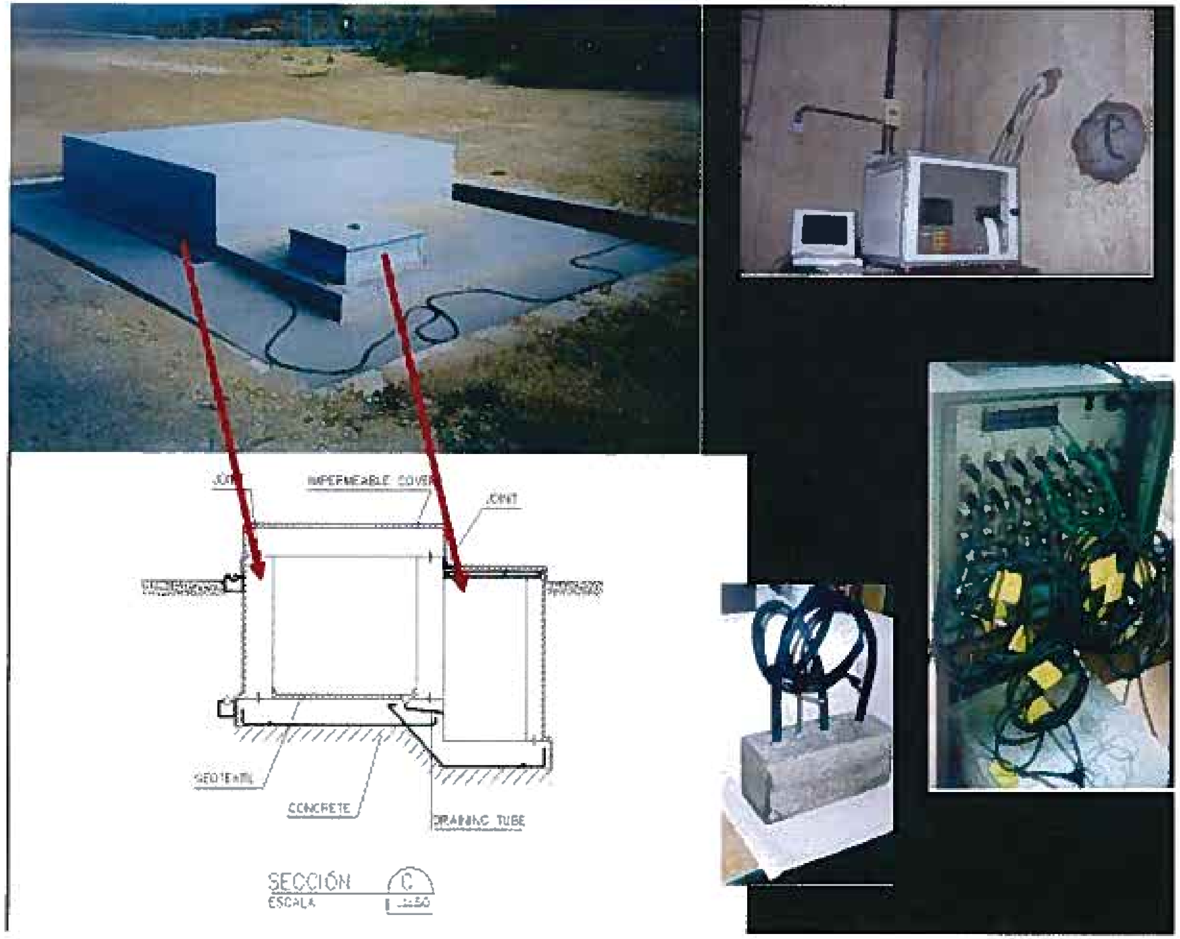
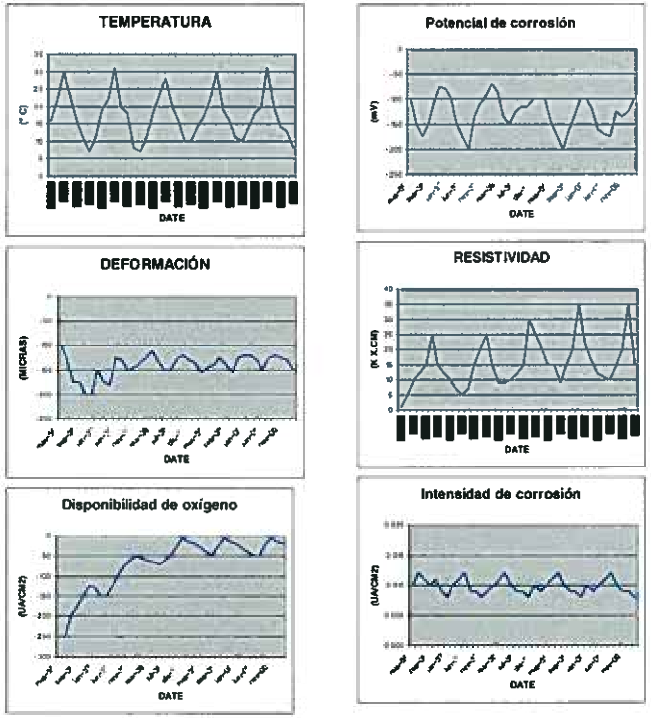
R&D supporting PA improvement. Instrumented waste container





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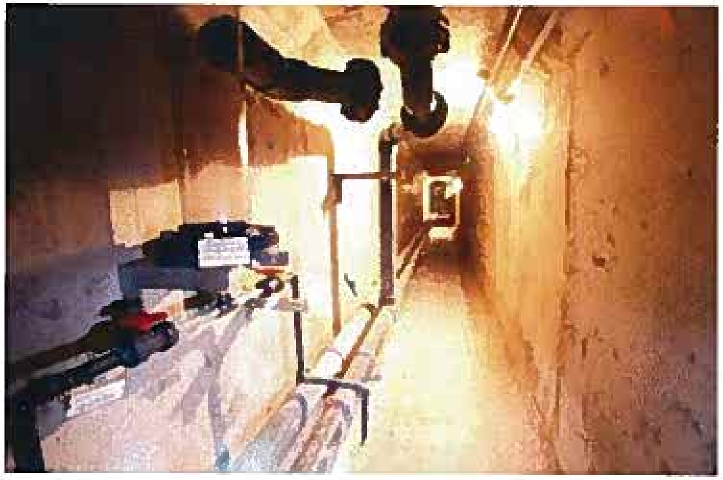
Specific case: capillary phenomena

- The facility has an Inspection gallery, with the seepage system, beneath each row of disposal vaults.
- After 10 years operation, we begun to collect small amounts of water in the individual control tank of vault number 16 (the first vault constructed, filled up and sealed), in winter time
- Years after we also collected small amounts of water in some other vaults, and also in summer
- An investigation was launched to verify potential water ingress pathways.
- Evaporation-condensation-capillary absorption cycles determined as the origin of the process



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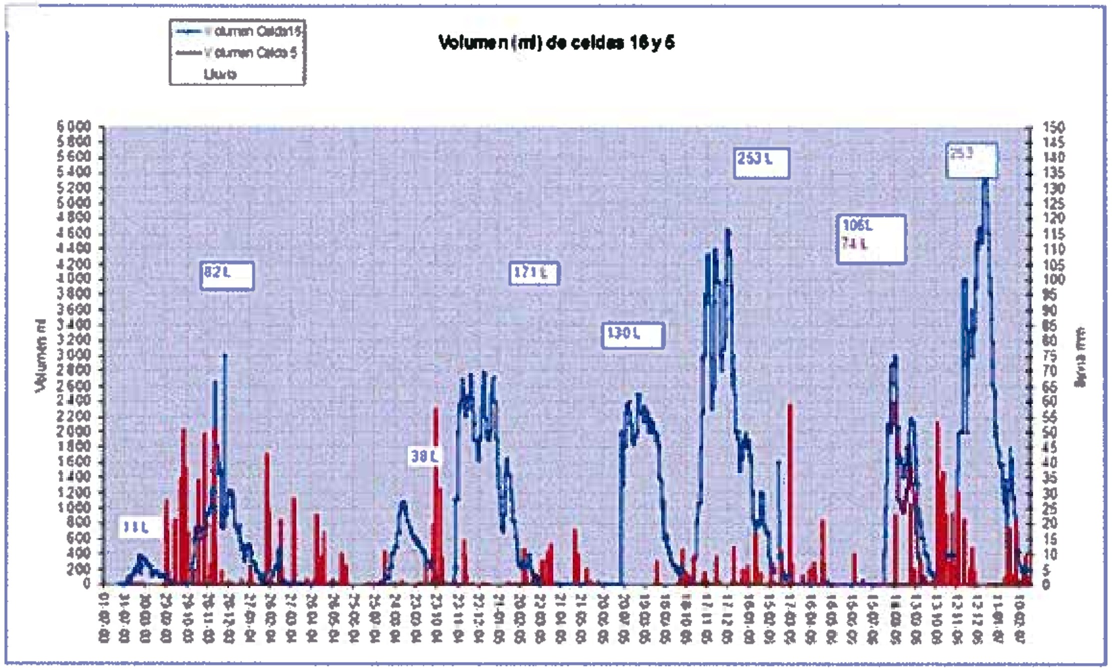


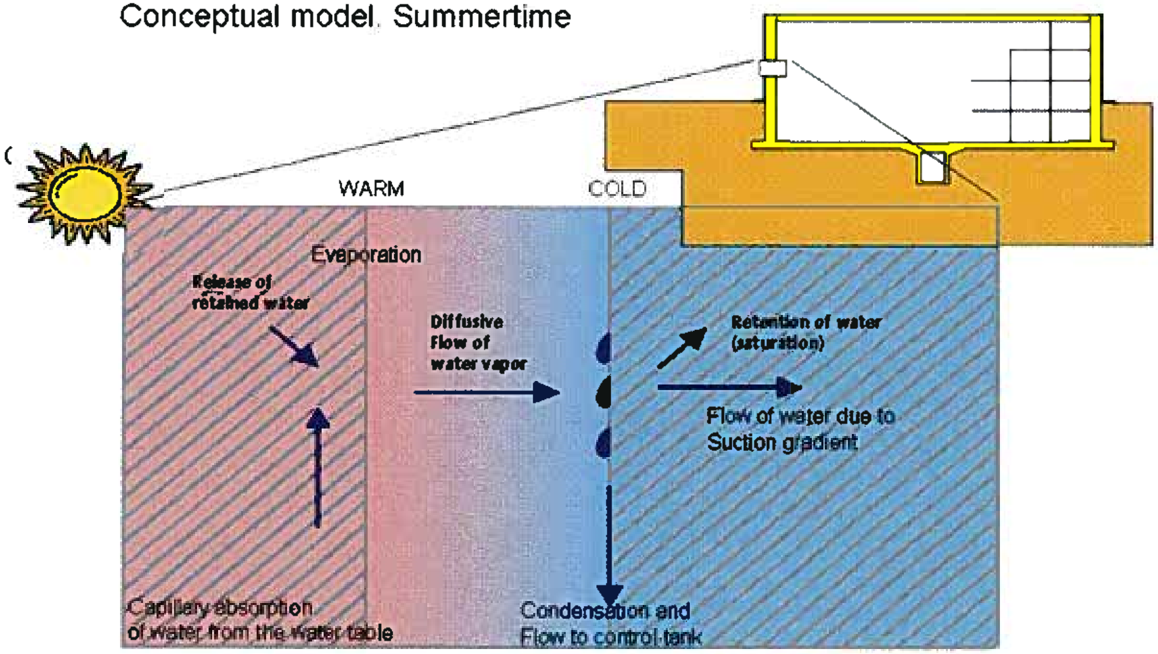
Inspection and Surveillance

- **Tests performed to verify absence of in-leakage, among others:**
  - Excavation of lateral areas
  - Flooding of closing slab
  - Water tightness of construction joints with tracers

- **Specific surveillance program established**
  - Additional control boreholes
  - Additional sampling
  - Chemical, radiological and isotopic analysis of collected liquid
  - Materials' characterization and research on barriers behavior
  - Reporting to the safety authority

Thermo-hydraulic model: Conceptual model

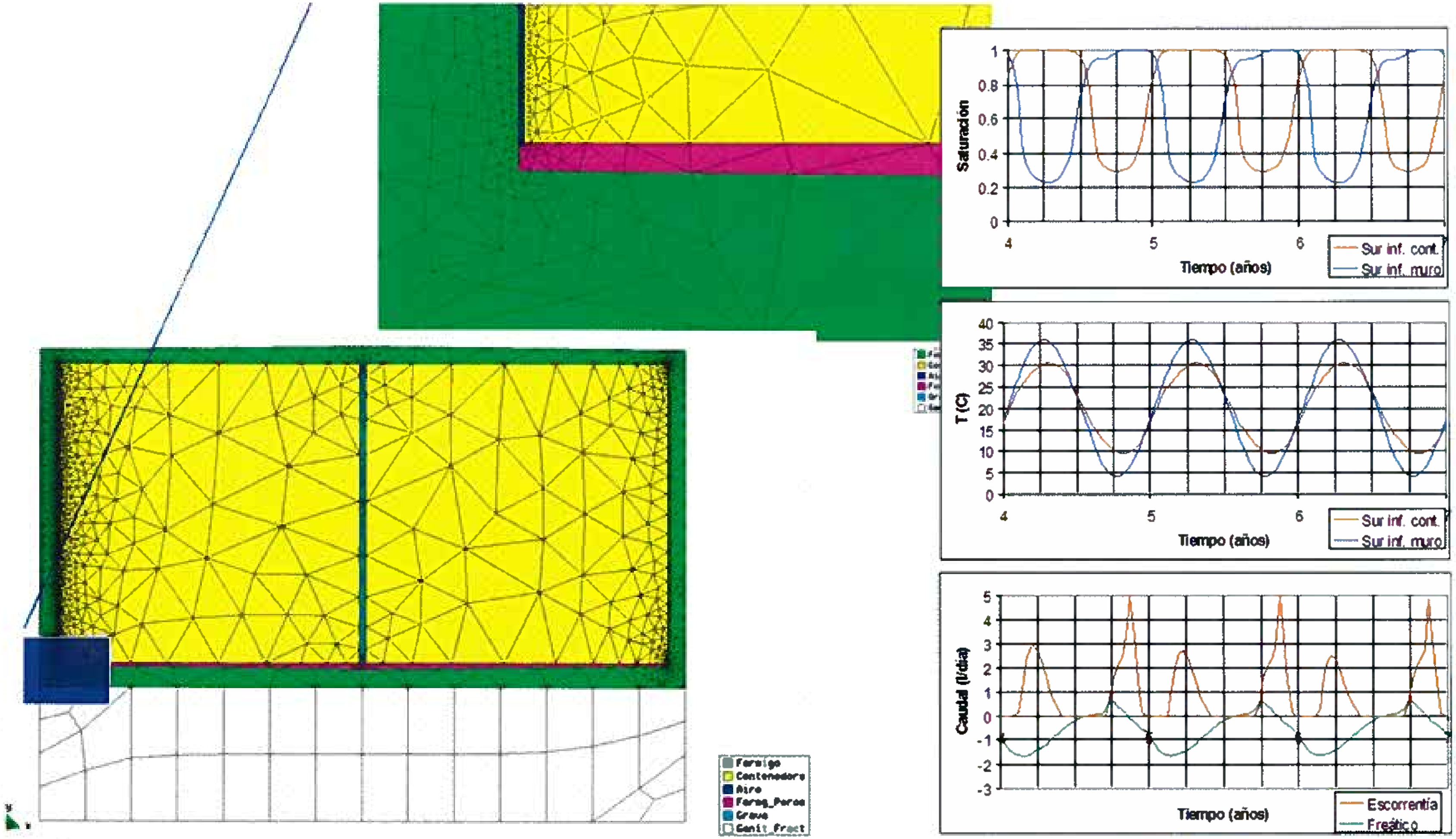
- **In summer**
  - Walls heat up. External surface is isolated. Evaporated water diffuses to the colder containers' surface.
  - Capillary condensation in pores, until 100% saturation is reached.
  - Then, condensation at the surface c waste containers.
- **In winter**
  - Walls are colder. Evaporation in containers' pores produces water vapor diffusion to the colder wall surface.
  - Capillary condensation in walls' pores until saturation. Then, condensation on the surface and seepage to the drain and control tank



Thermo-hydraulic model: Numerical Model

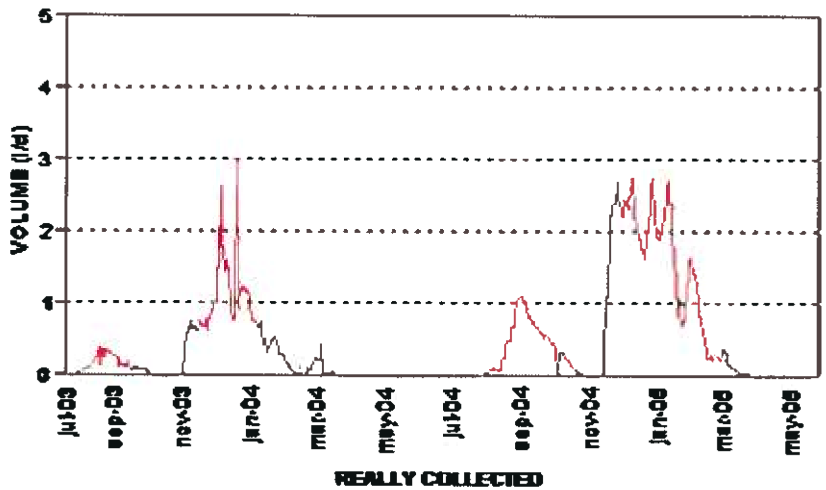
- **UPC Barcelona (Sanchez-Vila, Saaltink, Carrera)**
- **Uses CODE_BRIGHT Code (UPC). Finite element**
  - Previously developed for ENRESA's HLW program
- **Balance of mass and heat at each node**
- **Two states: liquid and gas (or vapor)**
- **Two components: Water and dry air**
- **Constitutive laws:**
  - Among them: Laplace, Kelvin-Laplace (Psychrometric), Darcy, retention curves, relative permeability, Fourier, Fick, Gases,

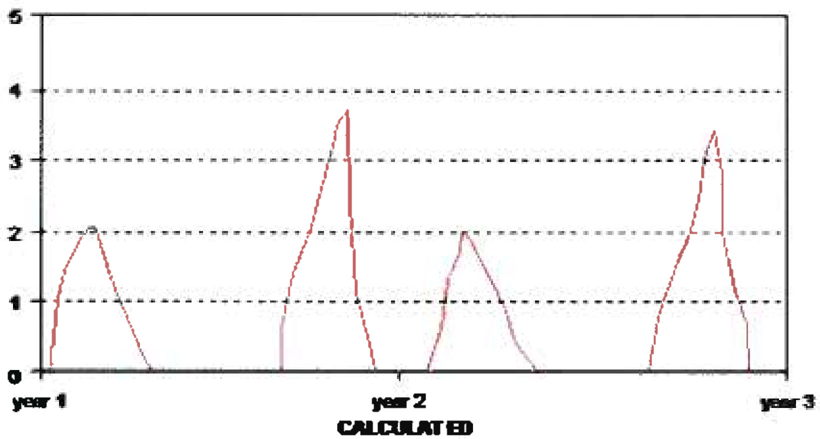
Thermo-hydraulic model: base case



Water volume collected

- **The water flow model represents the real liquid volumes collected**
  - The model represents the pattern of water collection volumes
  - It predicted the appearance of liquid in summer episode before occurrence
  - There is a clear dependence of the time of the year when collection begins with temperature. No correlation to rainfall conditions





Sensitivity analysis and variation of the conditions

- **The model is sensible to:**
  - Hydraulic and retention parameters
    - *Few experimental data*
- **Less sensible to:**
  - Temperature variations (after initiation) and water table depth

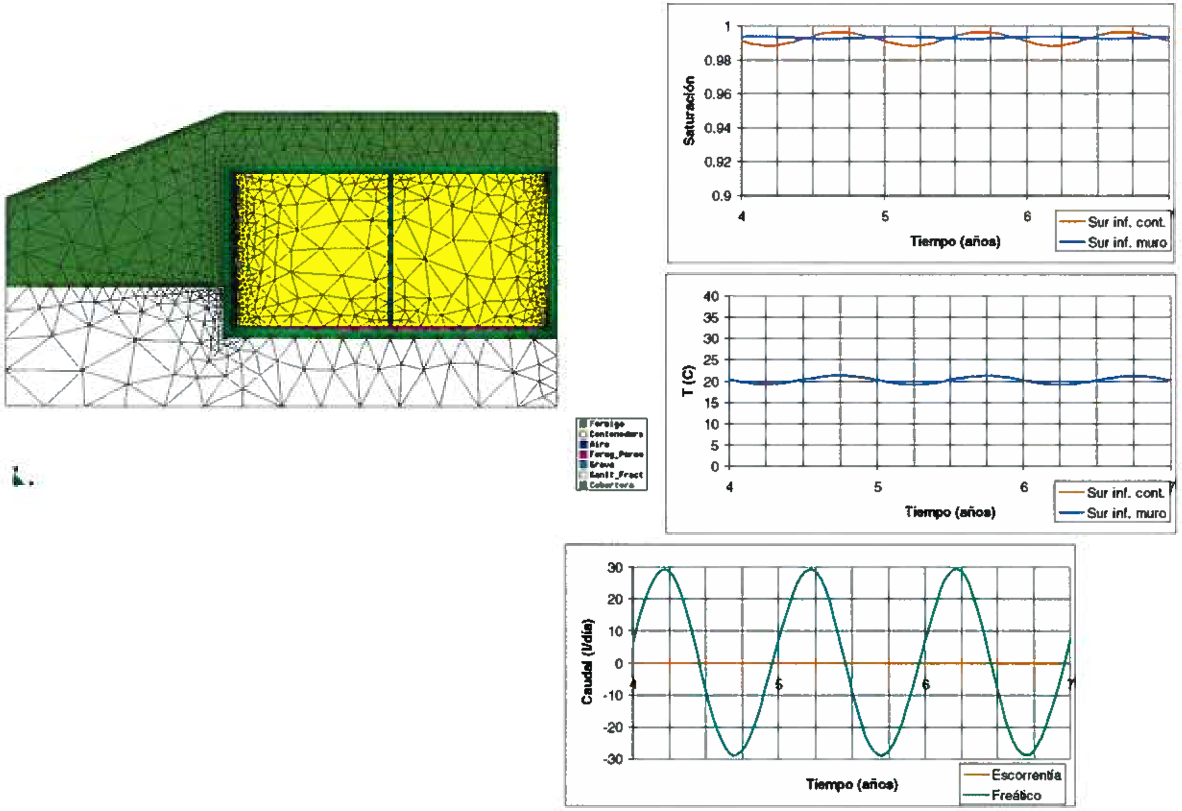
Analysis of water in-take prevention

Analyzed potential changes for prevention of water intake due to capillary raise:

- **Unpainting of walls to allow evaporation into the atmosphere**
  - Water collection interrupted, but increase of water absorption from the water table and, accordingly, of aggressive intake
- **Backfilling with dry fine aggregates (sand)**
  - Seems a cheap a easy solution. Not liked by some experts from the regulator.
- **Thermal insulation**
  - Insufficient. Not feasible
- **Engineered cap construction**
  - Water collection disappears.
  - Test cap built for validation
- **Painting concrete containers and inner surface of walls**
  - Solution proposed (Only for disposal vaults not yet in operation)

Thermo-hydraulic model: After capping case.

- **Water collection will disappear with engineered cap construction, due to**
  - lower temperature variations
  - retention of earthen cap

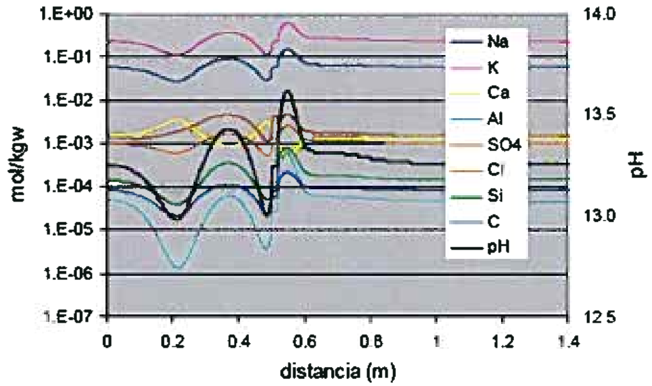


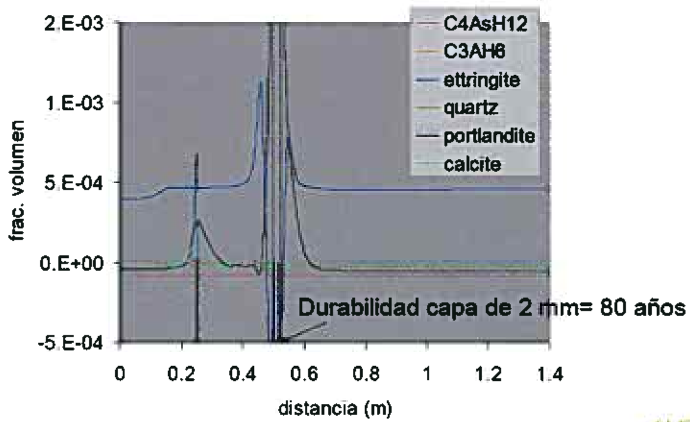
Geochemical model

- **UPC (Saaltink) and CSIC-IJA (Ayora, Soler)**
- **Derived from TH model**
  - Balance of mass at each node
  - Quick reactions: equilibrium
  - Slow reactions: kinetics
- **CODE_BRIGHT RETRASO Code (UPC CSIC)**
  - Derived from CODE_BRIGHT thermo-hydraulic-mechanical code
- **Hydrated Calcium Silicates modeled as solid solution**
- **Figures:**
  - Pore Concentration vs. distance after 3 years
  - Dissolved molar fractions after 20 years
- **Good representation of experimental data**
  - 2 mm depth in 80 y

$$X_i = K_i^{-1}\gamma_i^{-1}\prod_{j=1}^{N_c}\left(\gamma_j C_j\right)^{\nu_{ij}} \qquad (i = 1,2,\ldots,N_x)$$

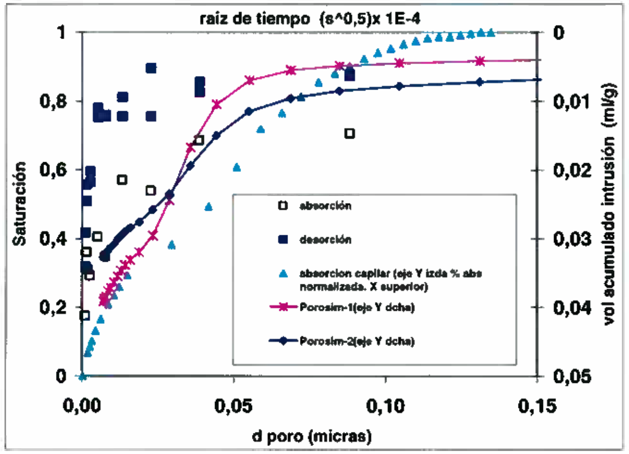
$$R_m = \mathrm{sgn}(\log[Q_m/K_m])A_m k_m f(\Delta G)$$

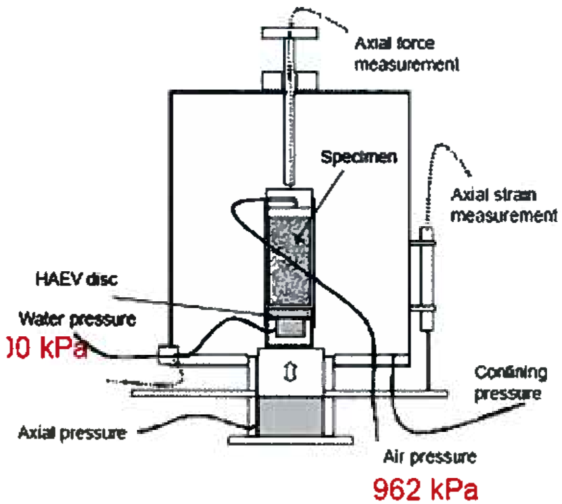




Thermo hydraulic enhanced characterization

- **Many key parameters were taken from literature**
- **Enhanced characterization of thermo-hydraulic properties**
  - Saturated permeability
  - Unsaturated permeability
  - Sorption Isotherms and retention curves
  - Correlation to porosimetry tests
- **Large scale tests**
  - Instrumentation of real vaults
  - Cap and concrete vault upper part
  - Climatic chamber tests

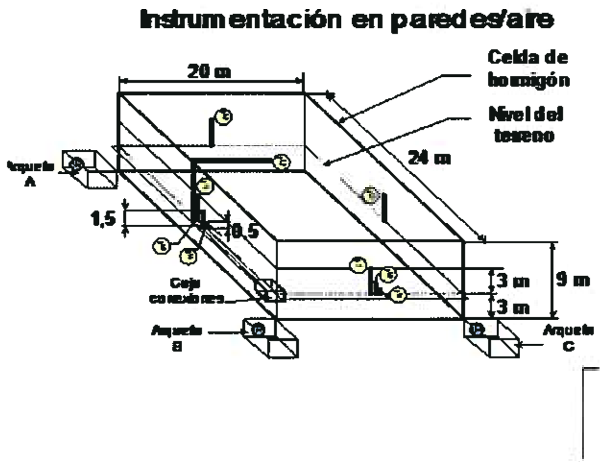


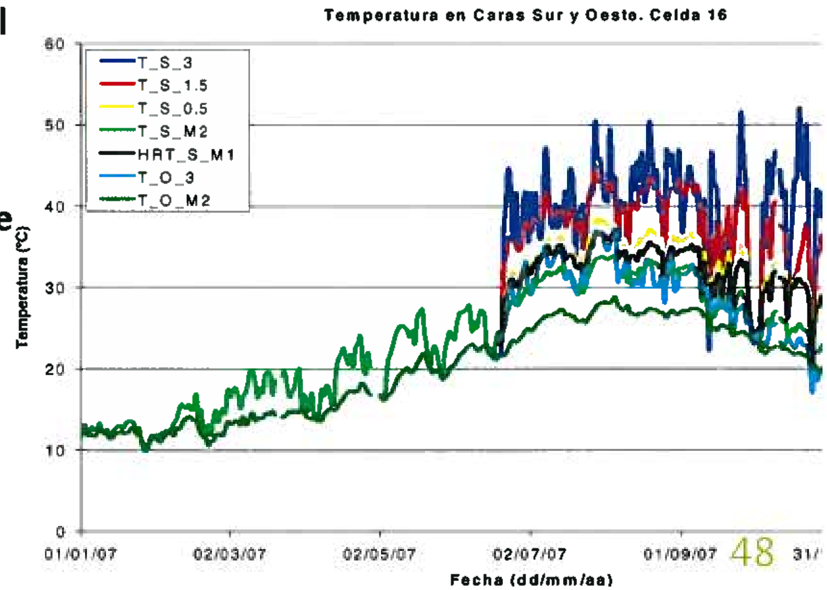


El Cabril Disposal facility. Long-term performance assessment

Instrumentation installed on real vaults

- **Thermocouples, Thermohygrometers and psychrometers installed on real vaults**
  - Nº 16 (**Already sealed**): Outer surfaces (20 Thermocouples, 2 Thermohygrometers, 2 psychrometers)
  - Nº 1 (**Then in operation**, now sealed): Inner surface and bulk of containers (7 Thermo-couples, 4 Thermo-hygrometers)
- **Temperatures follow the pattern estimated by the model**
  - Maximum temperatures in insolated zones of vault nº 16 higher than assumed
- **Only first results from vault nº 1 (sealed in 2008) available**
  - Max. Temperature differences between wall inner surface and concrete containers of 5ºC, as predicted





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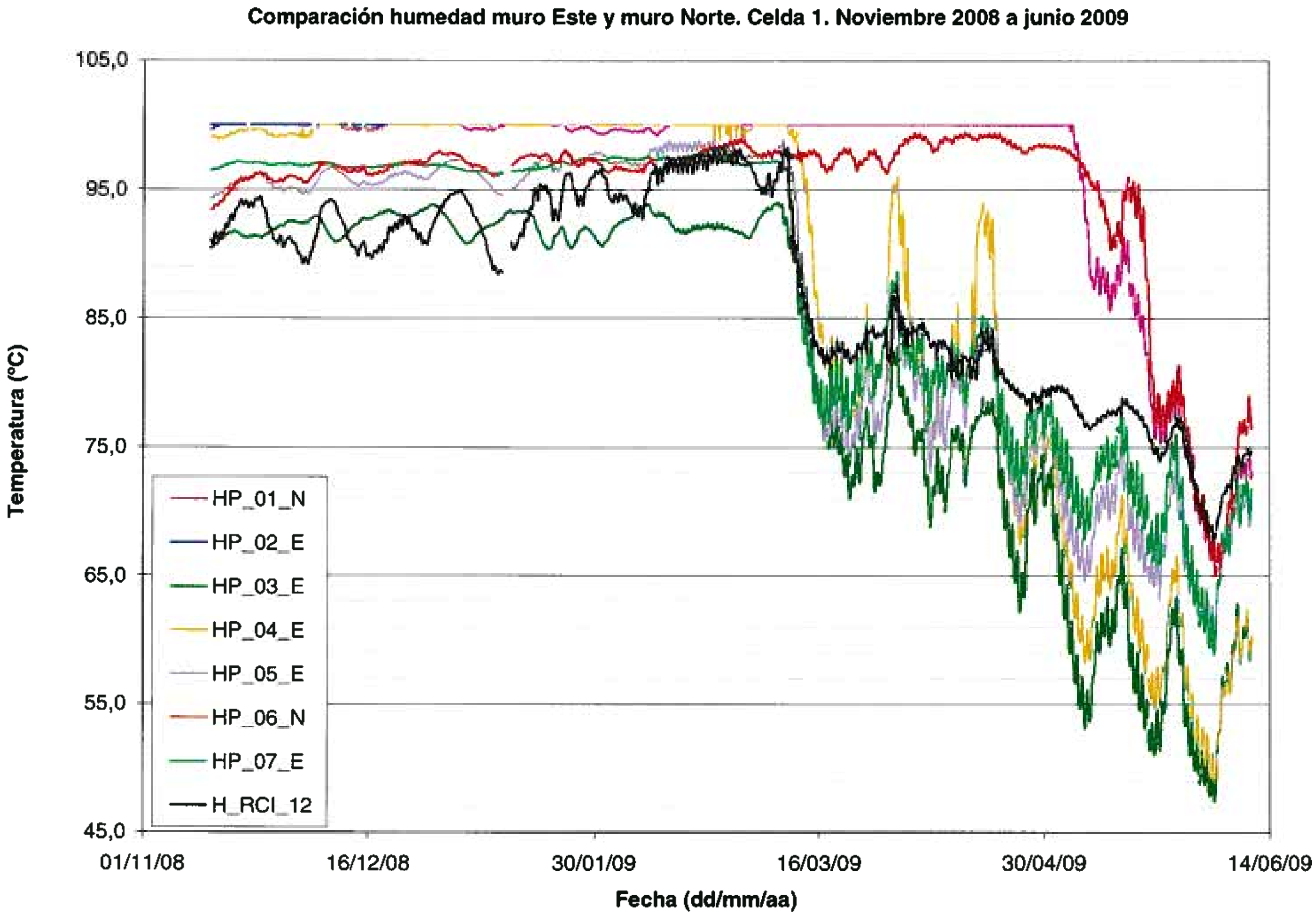
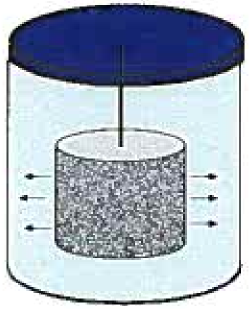
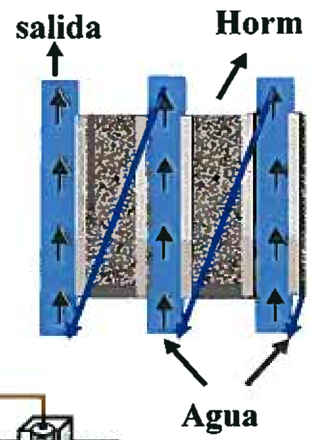
Humidity measured in a real vault (nº 1)

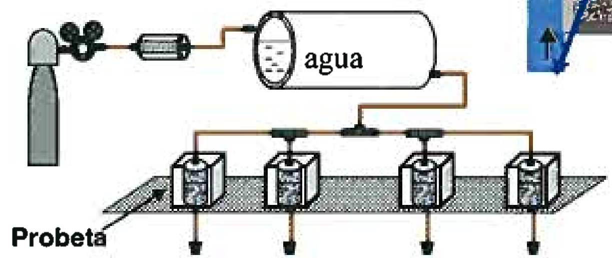


Calcium leaching

- **Four types of leaching tests**
  - Static (Type ANSI/ANS 16.1/1986)
  - External Water flow
  - Water permeation through the sample
  - Migration (Galvanostatic)
- **Four concretes**
  1. OPC El Cabril mix
  2. Flying ashes
  3. Microsilica
  4. Flying ashes + Microsilica





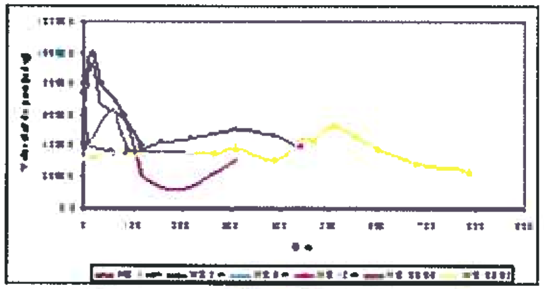


Calcium leaching. Measurements

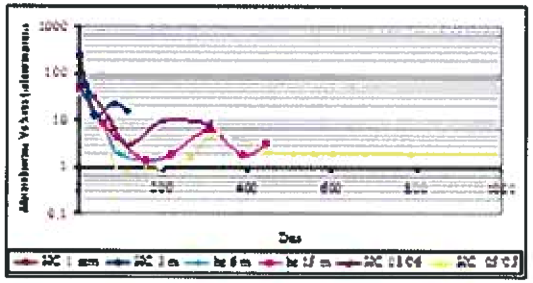
- **Measurements**
  - During test
    - *Chemical analysis of leachate*
    - *Hardness*
    - *Resistivity*
    - *Ultrasonic velocity*
  - After the end of the test
    - *X-Ray diffraction*
    - *Thermogravimetry*
    - *Porosimetry*
    - *Elementary analysis. Particulate induced X Ray emission (PIXE) and RBS*
    - *Microscopy*

Calcium leaching. Some results 1

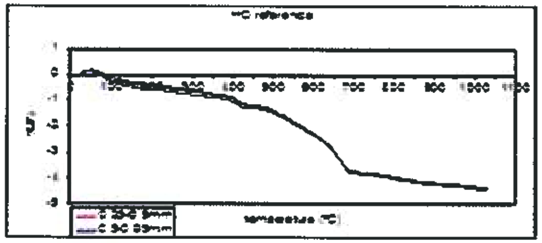
- No relevant conclusions from resistivity and ultrasonic tests

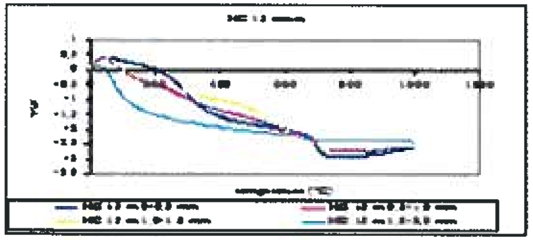


- Micro hardness. Surface deterioration

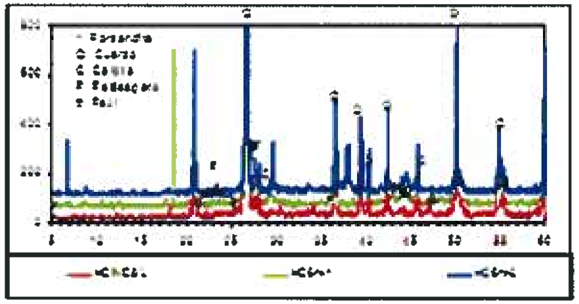


- Differential thermo gravimetric (every 5 mm)

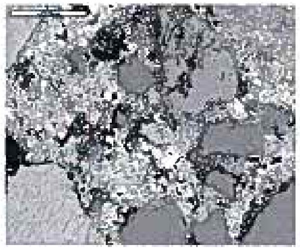




- X Ray diffraction. Total loss of portlandite in the first millimeters. Depending on test duration

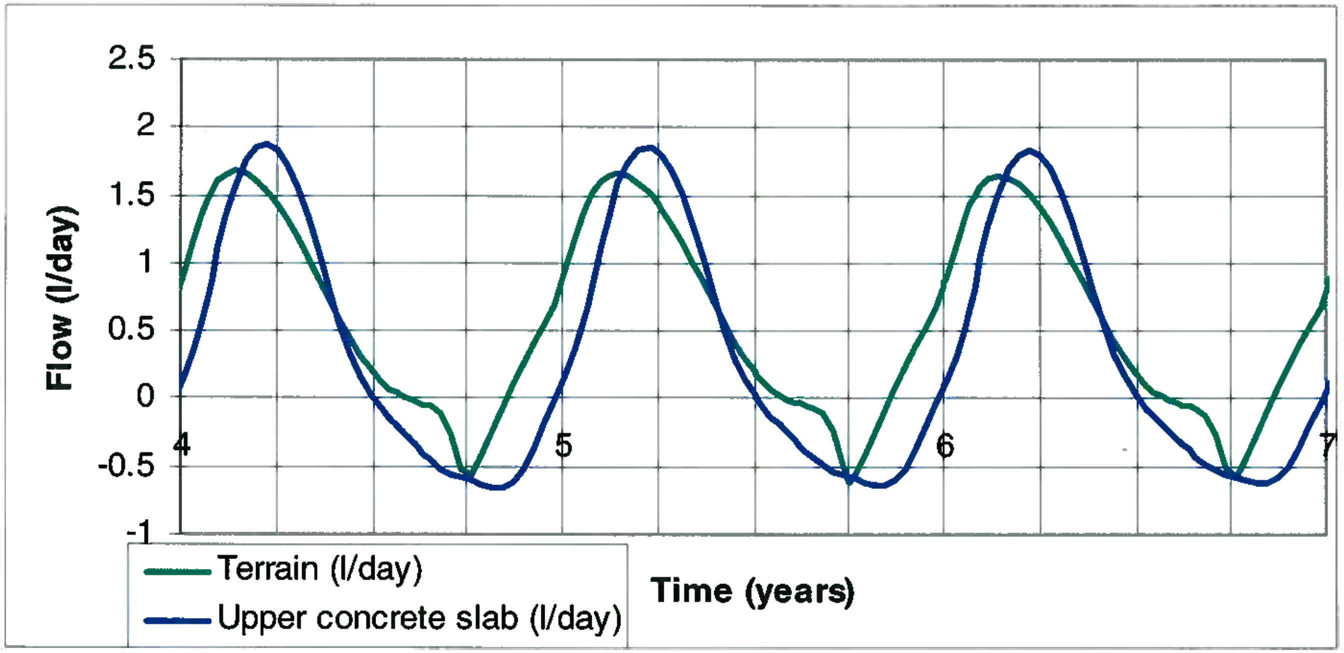


- Electronic microscopy: Surface loss of calcium



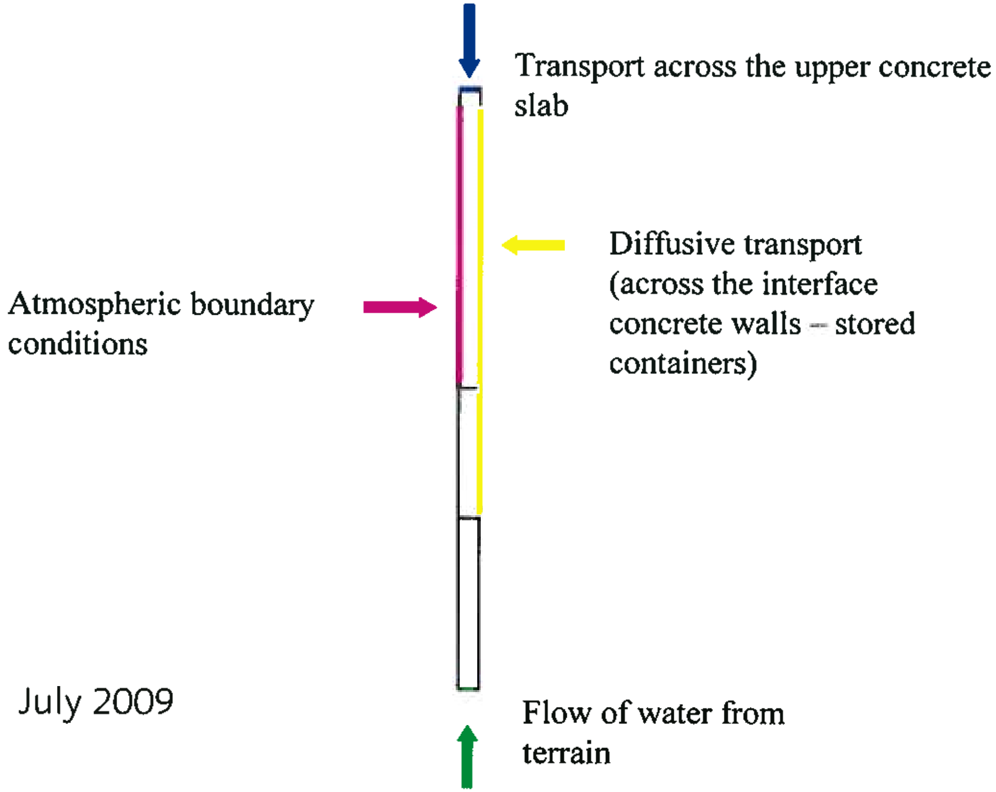
From THM and Geochemical model to radionuclide release and transport through walls

- From the THM model, the flow at two zones involves potential transport of radionuclides to the ground:
  - **Flow of water between the concrete walls of the vault and the terrain.**
  - **Flow of water between the containers disposed of and the walls of the vault, across the upper concrete slab closing the vault.**
  - **Both fluxes follow a seasonal behavior, they enter and/or leave the walls (positive and negative values in figure)**



From THM and Geochemical model to radionuclide release and transport through walls

- Two transport process:
  - **Transport of radionuclides from concrete containers to the walls across, the upper concrete slab. It's possible the transport of solute and volatile elements.**
  - **Diffusive transport of volatile radionuclides between the containers to the walls of the vault, through the air gap.**
  - **1D model derived from 2D THM model, imposing calculated flows at the interfaces**



- **Diffusive transport depends on the evaporation – condensation processes between the concrete walls and the concrete waste containers.**
  - **Radionuclides from waste containers enter the walls during winter and leave them during summer (transport follow a seasonal behavior).**

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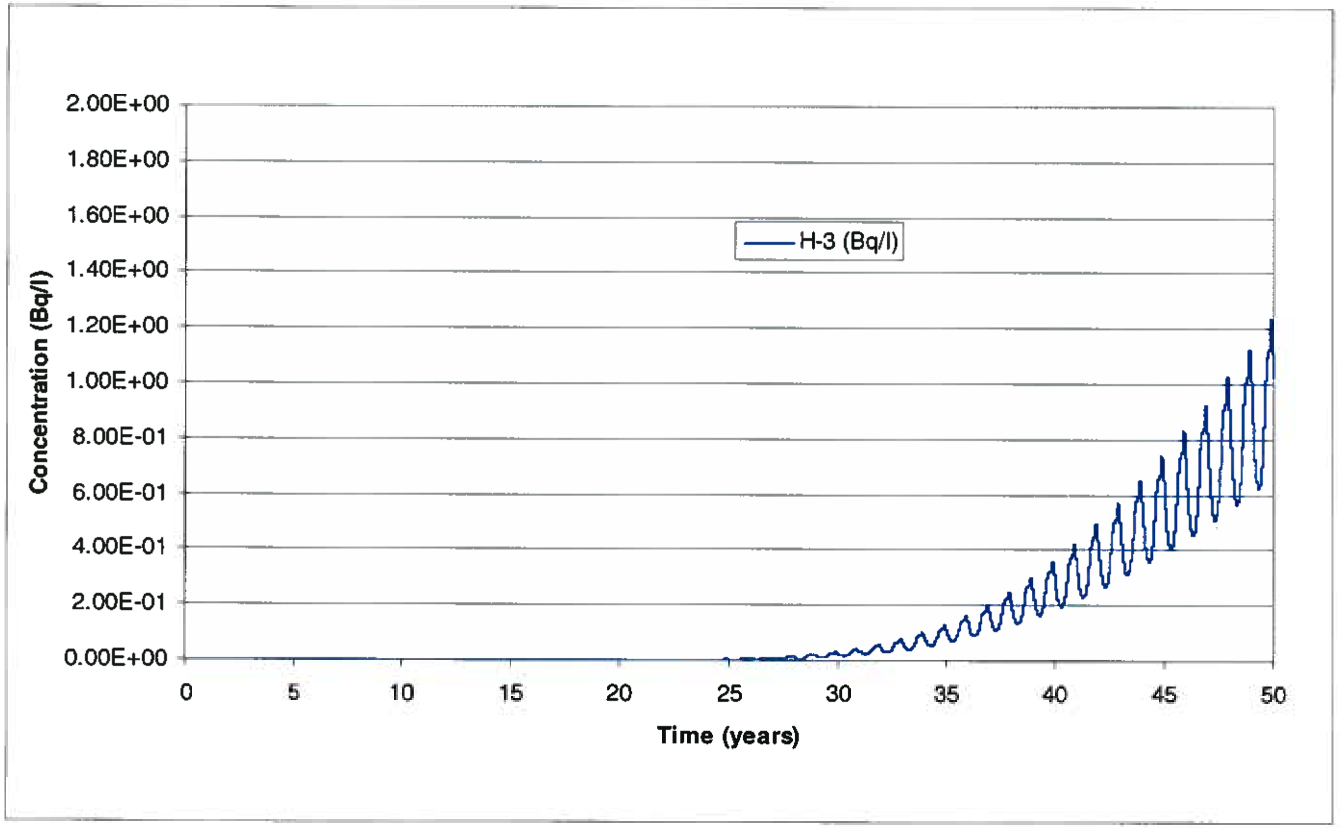
From THM and Geochemical model to radionuclide release and transport through walls

- H-3 concentration evolution, at the wall terrain interface is influenced by the seasonal changes:
  - **A washing off for concentration is produced in the concrete walls during summer (see oscillations in picture).**
  - **Meanwhile, a contamination is produced in the walls of the cell during winter.**



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HUMAN INTRUSION SCENARIOS

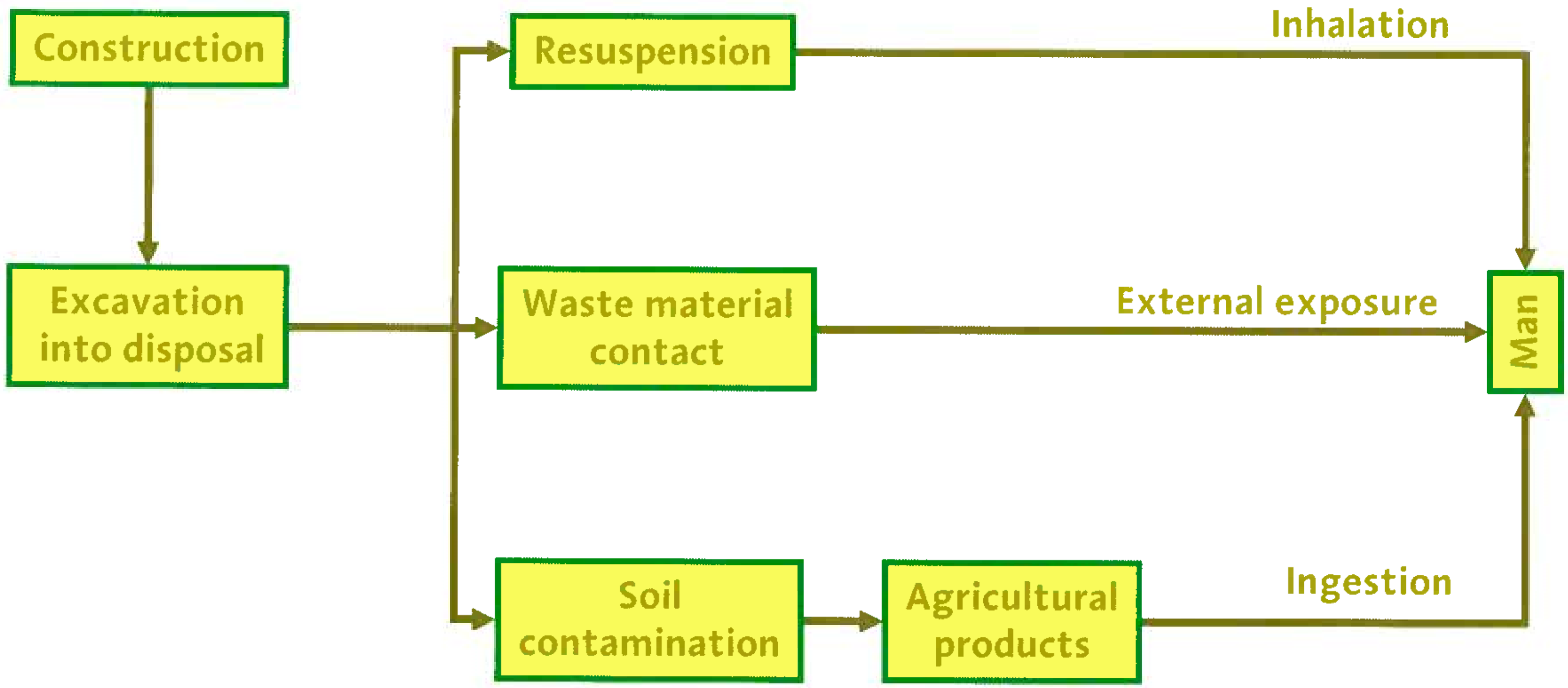
- Construction scenarios:
  - Public construction
  - Residential construction

- Residential scenarios:
  - Residential
  - Residential and play ground
  - Residential and agriculture

- Accidental scenarios
  - Aircraft crash

- Deterministic evaluation: occurrence at 300 years
  - No physical barrier preventing intrusion
  - Historical memory concerning the disposal facility not conserved
- The waste and disposal system are unrecognisable and mixed with soil
- No activity loss due to leaching. Only radioactive decay is considered
- Human activities assumed to be similar to the present ones.

HUMAN INTRUSION SCENARIOS. Model development



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Conclusions and Trends

- **Conclusions**
  - PA models exist and have bee accepted (although with improvements requirements) by the safety authority
  - Focus in details: Generic and very general simplifications may not be sufficient
- **Future work trends**
  - Continuation of the hydrogeological and geochemical surveillance. Ions used as tracers to confirm or better understand the groundwater behavior
  - There is still some concern on long-term calcium leaching, pH change and retention properties after degradation
  - Humidity and temperatures measurement and correlation with THM model
  - Large scale experiments such as pilot cap test or instrumented container buried in a one-container vault
  - PA enhancement is and will remain continuous activity. Next major exam on 2011 safety review

Final

- Thanks to Inmaculada Lopez and manuel Ordoñez, from ENRESA
- Thank you for your kind attention