The research programme on argillaceous rock in France
Current status, future research needs

ESK-Workshop on German radioactive waste disposal research
20/01/2015
Andra’s Disposal Projects

R&D Programme
2 disposal projects in clay

Cigéo Project (HLW/ILW-LL)
- Centre industriel de stockage réversible profond de déchets radioactifs en Meuse/Haute-Marne
  - Underground Research Laboratory
  - Long-lasting observatory of the environment (since 2009) + Ecothèque (since 2012)

Investigation on near surface disposal of « FAVL » waste (LLW-LL)
- Soulaine community
  - Geological survey under going

- Geological formation: argiles du Gault and argile à Plicathules

- Geological formation: Callovo-Oxfordian ~ 500 m depth and ~ 130 à 160 m thickness
Geological disposal of HLW-ILW-LL: Major milestones

The 1991 Waste Act

- 3 research areas for High Level Long-lived Waste

1996: Licence application for 3 URLs (clay; granite)
1998: Government decision to licence the Meuse/Haute-Marne URL,
2001: Intermediate Clay report, first NEA peer review...

The 2006 Programme Act: Reduce/avoid the burden on future generations

- Reference option for final waste: geological repository with respect to reversibility (100 y at least)
- Continue research on P/T (CEA) and interim storage (Andra) on a complementary basis.

2009: Safety, reversibility and design options, reviewed 2010
2010-2012: Launch of the industrial design phase
2013: Public debate
   Law defining reversibility conditions

2015-2017: Phased licence application
2020-2025: Construction
2025-2028: Pilot industrial operation phase without real waste
2029-2035...Pilot industrial operation phase with real waste

- Consultation mission led by Member of Parliament Christian Bataille
- Site selection on the basis of voluntary sites
  - 2 types of rocks, 4 areas preselected:
    - Granite: Vienne
    - Clay: Gard, Meuse, Haute-Marne

1994-1996: Above/ground geological survey in the 4 preselected areas, with regard to safety criteria

- 1996: Licence application for 3 URLs, reviewed by the National review board (CNE) and the French regulator (ASN)

1998: URL licenced in Meuse/Haute-Marne
The Meuse/Haute-Marne URL: 1991-2005 period

1998-2005: The construction and the operation of the URL made it possible to collect all basic data necessary for the feasibility and safety assessment provided in 2005.
A project combining scientific acquisition, design and safety


Functional analysis → Conceptual design → Process & evolution modelling → Safety analysis, Performance assessment → Review

Knowledge acquisition → Architecture and design

Understanding of the system Modelling and simulation

Safety studies

Feedback on:
- uncertainties,
- design,
- robustness,
- feasibility

Research priorities → Design guidelines

new iteration

new iteration
Major milestones

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French HLW-ILW management scheme

2006 Act

UOX fuel reprocessing, Pu+U recycling (MOX, URe)

Heat decrease storage of final HLW

Interim storage of final ILW

Interim storage of reusable matter (MOX SF)

Areva La Hague

Areva La Hague

CEA Cadarache

Areva La Hague

Areva La Hague
French HLW-ILW management scheme

2006 Act

UOX fuel reprocessing, Pu+U recycling (MOX, URe)

Heat decrease storage of final HLW

- Early disposal of older HLW
- Disposal after 60-90 y. for currently produced HLW

Interim storage of final ILW

Disposal of ILW with a view to making the best use of storage capacities

Interim storage of reusable matter (MOX SF)

Reuse in GenIV reactors?
P-T of minor actinides?

Heat decrease storage + disposal?

Prospective studies of GenIV waste disposal

As a precaution, direct disposal of spent fuel has been explored.

- Vitrified fission products and minor actinides
- Fuel tubes, nozzels...
- Maintenance/dismantling waste
- Waste from liquid effluent treatment
Planned Waste Inventory

- By law only end waste can be disposed of (no recyclable material)
- Cigeo is designed for the waste generated by existing nuclear facilities, under operation (50 years for PWR) or licensed

**Cigéo Inventory**

<table>
<thead>
<tr>
<th></th>
<th>Total volume to be disposed of (m³)</th>
<th>Volume already produced in 2010 (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HLW</td>
<td>10 000</td>
<td>2 700</td>
</tr>
<tr>
<td>ILW</td>
<td>73 000</td>
<td>40 000</td>
</tr>
</tbody>
</table>

**MAVL**

- Vitrified HLW
- Clads, ends
- Solidified effluents
- Maintenance waste
- Activated waste and ITER
Area defined after local consultation (2009) for location of repository U/G facilities and detailed geological survey from the surface.

Location of repository surface facilities.

Transposition zone of URL results (proposed 2005).

Siting Cigéo

Transposition zone
≈ 250 km²

ZIRA
≈ 30 km²
Post closure safety is mainly based on the host clay layer:

- Provisions for siting, geological survey and URL;
- Repository designed to limit induced disturbances;
- High confidence in long term safety demonstration.

Low permeability;
Depth and thickness;
Favourable geochemistry;
Geodynamic stability.

View of the repository after 100 years in operation

2012 Preliminary design
The Cigéo project – layout

Surface Facilities

- Waste preparation facility

U/G facilities

- Waste transfer ramp and service ramp
  - HLW disposal 2025-2040

Construction support facility

Ventilation and service shafts

- HLW disposal 2075-2140

ILW disposal 2025-2085

View of the repository after 100 years in operation

2012 Preliminary design

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ILW disposal cells are horizontal tunnels located at the median of the host clay layer:

- Thick concrete lining to limit long term deformations;
- Ventilation of ILW repository cells as long as they are not closed.
HLW will be placed in 65mm steel overpacks to prevent glass leaching during the thermal phase:

Ceramic skids for easy handling

To explore the direct disposal option, steel containers have also been studied and prototyped for Spent Fuel.
HLW will be disposed of in lined horizontal micro-tunnels:

- Heat conduction in clay
  - Max. temp in clay rock: 90 °C
  - Limitation of large scale THM effects
- Steel liner
- Cell length to be optimized with regard to technological limits and cost
2010-2012: Launch of the industrial design phase

2011: the results of 20 years of R&D have made it possible to issue detailed project technical requirements:

- Postclosure Safety,
- Nuclear safety and security in operation
- Waste emplacement and retrievability
- Control, monitor, observe
- Sustainable development, corporate and social responsibility
- Project governance

2012-2013: contracting agreements with engineering companies (overall system; conventional surface facilities; nuclear surface facilities; nuclear process; underground facility).

2013-2017: industrial detailed design
Surface and U/G larger scale tests make it possible to:
- develop construction / operation techniques,
- investigate scale effects and interactions

Developments on repository construction techniques
Developments on repository sealing techniques
Industrial Design and Technological Development

Excavation Techniques, Rock Support

TBM Test in the URL

Drift Rock Support Tests in the URL

HLW Microtunnel Construction Test in the URL

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In situ Tests

Sealing Technology and Demonstration Tests

Full Scale Test
DOPAS* European Project
(Demonstration of plugs and seals)

In situ Tests
Waste Package Handling

WDP Emplacement and Retrieval Tests

ILW ←

HLW →
### Major milestones

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Disposal Projects

Andra's R&D Programme: Overview
Supports the Agency's disposal projects:

- The Cigeo geological disposal project for HLW and ILW-LL waste
- The investigation on LLW-LL disposal

And the operation of existing disposal facilities *(Periodic Safety Reports)*:

- Surface disposal facilities for LILW-SL waste (CSM and CSA)
- The VLLW waste disposal facility (Cires)
5 priorities:

- Preserve the “rare resources” of disposal facilities
- Define requirements of disposal facilities and update them to reflect the current state of knowledge, optimize the design
- Support construction and operation of disposal facilities
- Collect and use data, monitoring systems and techniques
- Optimise the disposal materials
The programme relies on the Agency's R&D partnerships and on groups of laboratories to ensure (i) multi-disciplinary scientific representation (ii) involvement of the best scientific teams in research projects (iii) synergy of methods and skills (iv) long-term collaboration and (v) a tool guaranteeing transparency, performance and responsibility in governance and research at Andra.
Andra’s R&D Programme is periodically updated

R&D Programmes
Geological environment and host rock, engineered materials, waste form

1991-1998
Preliminary phase
Initial data on the geological environment and studies of its long-term behaviour

1998-2005
Feasibility of the disposal facility
Acquisition of data on the geological environment, and initial data on the materials used for the disposal facility and on the waste packages

2005-2009
Definition of the ZIRA (area of installation) and of the safety design options
Consolidation of data on the geological environment, acquisition of data on the materials and on the waste packages, geared towards operation of the disposal

2009-2012
Consolidation of materials and waste packages, R&D supporting the operating phase of Cigéo

2013-2016
Technical and economic optimisation of Cigéo, quantification of margins and reduction of uncertainties

2015-2017
Deliverables for Cigéo application
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» DAIE »
» Dossier 2005 »
» Dossier 2009 »
» Dossier 2009 »

✓ Favourable characteristics of the Meuse Haute-Marne site and a homogeneous clay layer on a large area, with simple and regular geometry

✓ Understanding of major processes (hydraulic evolution of the disposal facility, desaturation/re-saturation, radionuclide transfer…)

✓ Basic knowledge of the long term behaviour of glass, SF and compacted clads

2015 – 2017
Deliverables for Cigéo application

1991-1998
2000-2002
2002-2005
2005-2009
2009-2013
2013-2016

« Dossier 2005 »
« Dossier 2009 »
« Dossier 2009 »

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Andra’s R&D Programme is periodically updated

R&D Programmes
Geological environment and host rock, engineered materials, waste form

- Geological characteristics of the Meuse/Haute-Marne site suited to creation of a disposal facility
- Compliance with site criteria provided by basic safety rule (geological stability, very low water flow, absence of natural resources, high capacity for containment, ability to buffer chemical disturbances, mechanical resistance compatible with creation of U/G structures)
- Minimal disturbances induced by the construction and operation of a disposal facility

1991-1998
- Preliminary phase
- Initial data on the geological environment and studies of its long-term behaviour
- « DAIE »

1998-2005
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- « Deliverables for Cigéo application »

2015 – 2017
- ESK-Workshop on German radioactive waste disposal research 20/01/2015
- DP/15-0026

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R&D Programmes
Geological environment and host rock, engineered materials, waste form

Andra’s R&D programme and its outcomes are reviewed by Andra’s Scientific Advisory Board and submitted to the National review board (CNE)

1991-1998
- Preliminary phase
- Initial data on the geological environment and studies of its long-term behaviour

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2015 – 2017
Deliverables for Cigéo application
2013-2016 Andra’s R&D Programme

- Natural/engineered materials and behaviour of structures
- Processing/treatment of waste
- Monitoring, processing of information, databases
  - Innovative measurement techniques to develop an expert system to support decision-making and transmission of knowledge
- Simulation
- Environment and interfaces
- Social Sciences and Humanities (SSH)
  - Governance of waste and disposal systems
Improving the characterization of the radiological inventory

- Inventory in chlorine 36 and in iodine 129 (vitrified waste, spent fuel, graphite)
- Inventory and speciation of the carbon 14 (hulls, graphite, REI)

Developing processes of treatment and conditioning

- Treatment of TRU maintenance organic waste
- Treatment of graphite waste
- Optimization of the management of dismantling waste

Estimating more precisely gas build-up

- Reactive metals: aluminum, magnesium
- Radiolysis of organic materials (polymers, bituminous waste)
- Radiolysis of cimentitious materials

Quantifying the release of complexing species

- Nature and having complexes power of the species not identified this day
Waste packages

خصوصية الورق والأحذية

_release_of_radionuclides_

- Vitrified waste
- Corrosion of not reactive metals (alloys of zirconium, inconel, stainless and not allied steels)
  - Effect of the organic on corrosion rate
  - Risk and consequences of galvanic coupling
- Waste graphite
  - Release of chlorine 36, carbon 14 and tritium
- IRF of Mox fuel
  - At present between 30 and 50 %
  - Need to demonstrate the stability of U-Pu O₂ matrix containing fissile isotopes

خصوصية الورق والأحذية

Thermal reactivity of bituminous waste

- Reactivity of waste salts in temperature (fire hazard during operation)

خصوصية الورق والأحذية

Swelling of bituminous waste in contact of water
Mechanical behaviour of claystones (damaged zone)

- Anisotropy, coupled THM behaviour, coupling of damage-swelling-creeping on extended paths and behaviour at crossing of the damaged zone,
- Damaged zone: fractured system vs. "continuous system"
- Self-healing
- Transfer of gases
  - Consolidation of existing data on claystones and claystone/bentonite - concrete interfaces

Main means of study

- Tests in Underground Laboratory
  - testing different techniques of excavation/support/lining
    - Currently ongoing: OHZ, GGD, GCS, GCR, BPE, TPV…
  - Compression / crossing test: ongoing CDZ: "gripper" test to follow
    - To follow: DPC, GVA, GER, GGD(2)
- Tests on different scales in surface laboratories plus theoretical developments
Corrosion of non-alloy or low-alloy steel

- Kinetics of corrosion in anoxic medium
  - Consolidation of low speeds (< 10 μm/year) and of the duration of the raised kinetic transient
- Role of radiation (approx. 10 Gy/h), of micro-organisms or of local conditions (heterogeneity, cathode deposits)
- Risks of cracking under stress
  - Choices and tests of steel grades:
    - Liner API 5L X65MS (thermo-laminated steel, oil industry standard)
    - Overpacks: P285NH (forged and stress-relieved steel)
- Corrosion-mechanical coupling, especially when close to plasticity
  - Definition of macroscopic parameters

Main means of study

- Tests on demonstrators of liners and overpacks (body and welding)
- Tests in above-ground laboratories (especially by electrochemical techniques)
- Tests in URL

- MCO tests ongoing and planned (especially by electrochemical techniques)
Chemical and chemical-mechanical behaviour of "low pH" concretes

**Low pH concretes** > e.g. CEM I cement base, with high proportion of mineral additions: blast furnace slag, silica fumes, fly ash. CEM I: 20 to 40% - Additions 60 to 80%.

- Geochemical models of interactions and associated thermodynamic data, early behaviour
  - Validation of reaction drawings at interfaces
  - Validation of kinetics and extensions of modifications on both sides of concrete/claystone interfaces
- Chemical-mechanical coupling, particularly in relation to concrete/concrete and concrete/claystone friction
  - Definition of mechanical macroscopic parameters

▷ Main means of study

- Tests for technological (+ scientific) purposes
  - On surface > **FSS** (ongoing)
  - At URL > **NSC** (≥2014)

- Tests for scientific purposes at URL
  - **MLH tests** (ongoing)
  - **BBP test** (≥2014)
Hydromechanical-gaseous behaviour of bentonite powder/pellet mixes

- Hydromechanical behaviour
  - Characterisation of the parameters of "double porosity" models (e.g. BBM at UPC – Barcelona)
- Hydromechanical-gaseous behaviour
  - Characterisation of gas input pressures and hydric parameters

Main means of study

- Tests at URL: new PGZ (≥ 2014)
- Metric model test above ground: REM

FSS mix test

PGZ

REM
Complex chemistry of disposal cells for ILW-LL organic and salt waste

- Coupled behaviour in solution/retention of groups of organic solids and salts (thermodynamic and kinetic models and data), in cement-based medium and in claystone
- Associated behaviour of radionuclides (actinides)
  - Acquisition and validation of elementary data

Main means of study

- Acquisition of thermodynamic and kinetic data (thermo-chemical base)
- Experiments in above-ground laboratories (batches, centimetric cells, large diameter cells)

Experiments in URL

Cellule d’essais en acier

Découpage post-mortem

Modélisation interprétative
Karst aquifers of Barrois limestone

Characterization of karst and assessment of the repository hydro-impacts

◆ Karst networks geometry and flow
  ○ Construction of the 3D karst conduits based on geo-hydrological data and stochastic modelling
  ○ Reproduction of observed transient flow behavior

◆ Hydraulic impacts of engineered structures
  ○ Reproduction of the transient flow behaviour with respect to recorded (last 15 years) URL data
  ○ Position of tunnels and shafts with regard to karst distribution
  ○ Water flow prediction
    ▪ During construction and operation;
    ▪ After closure.

Karst networks of Barrois Limestone at Bure site
**Geomorphological Evolution: erosion and changes**
- Develop analyses and 3D / T simulations with fine stitch and small step of time for the near surface LLW-LL disposal concept
- Refine the simulations of the future evolution of valleys on the million years for Cigéo site (possibilities of creation of new outlets)

**Main means of study**
- Studies of ground to reconstitute and quantify the evolution of the past in the relevant scales
  - Dating of superficial environnement
  - Method ESR for alluviums + colluvions
  - Geomorphological analyses
  - 3D modeller (Gocad)

**Digital simulations**
- Climate
  - *Global model LOVECLIM and regionalization ; CEA/LSCE*
- Geomorphologique evolution
  - *Modellings phénoménolgies3D / T (interfluves - reliefs)*
Pursuit of feasibility/pre-feasibility developments concerning innovative monitoring

- Wired monitoring tools
- Mobile and remote methods (non-destructive)
- Wireless transmission
  - Major effort in relation to optical fibres for thermal, mechanical and chemical/gaseous measurements

Main means of study

- Tests in above-ground laboratory
- Tests in URL
  - HLW cell 2016-2017
  - New tests in GER (concrete structures) in 2015
- Partnerships: LNE; Ifsttar; etc.
- Collaborations with EDF and Areva
SAGD Expert (Acquisition & Data Management System)

To optimize the monitoring system:
- For the disposal cell but also for the overall repository
- Determine the optimal number of cell to be monitored

To establish structure health indicators
To provide decision making tools

Parameter tuning
In case of deviation:
« Red flag »
Nominal operating range? or gap?

Computers to process raw data (coefficients, calibration…)
Measurement data comparison
Validated data

To optimize the monitoring system:
- For the disposal cell but also for the overall repository
- Determine the optimal number of cell to be monitored

To establish structure health indicators
To provide decision making tools

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Simulation

Pursuit of effort concerning **High performance calculation and data processing** *(Reactive transport, diphasic water/H$_2$, transport, hydromechanical behaviour)*

- **Digital Resolution Method**
  - Decomposition of fields in space and time and parallel solvers
  - Adapted meshing

- **Data processing methods**
  - Decomposition of order moments > 2, local/global methods, reply surface, etc.
  - Data mining

**Main means of study**

- Partnership with INRIA (theses and post-docorates)
- ANR projects: e.g. H2MNO4 2013-2016 project (digital methods that perform correctly in reactive transport)

*Preparatory work for Cigeo safety calculations, with Porflow & Traces*

*Detailed representation of geological system (physical/geometric)*
*meshing of 3,000,000 elements*
*CPU time = 5 days*
Understand and control the environment

- To prepare for license application and to establish the environmental surveillance plan
- To record and preserve environmental key samples for future use
- To improve dialogue with local communities
- To improve the global understanding of the environmental impact

Main means of study

- Develop and maintain a framework of environmental stations; OPE (Long Term environmental observatory)
  - Atmospheric station
  - Forest (Soil, forest biological cycle and solar flux,)
  - Grassland and crops (Soil, grass and crop cycles and solar flux,)
  - Biodiversity
  - Survey of land use changes through time (environmental and economic impacts)

- Build up and maintain a state of the art sample preservation facility (ECOTHEQUE)
- Maintain a framework of national and international collaborations
- Management of proof
- Economy of long-term routes
- Governance of the disposal process (multiplicity of actors - confidence building)

- Support for current and future debates: reversibility…
Thank you...