LANL Contributions to Technical Support for Underground Research Laboratory Activities

Spent Fuel and Waste Disposition

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Appendix E
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☐ Technical Review	☐ Peer Review
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List of Acronyms

AOI	Area of interest
ANDRA	French National Radioactive Waste Management Agency
COX	Callavo-Oxfordian argillites (geologic repository medium at Bure)
DOE	Department of Energy
DOE-EM	DOE Office of Environmental Management
DOE-NE	DOE Office of Nuclear Energy
DRZ	Disturbed Rock Zone
EBS	Engineered barrier systems
EDZ	Excavation damaged zone
FEPs	Features, events and processes
FY	fiscal year (October-September)
GDSA	geologic disposal safety assessment
GPAM	Generic performance assessment model
HLW	High level nuclear waste
IAEA	International Atomic Energy Agency
ILW-LL	Intermediate level long-lived nuclear waste
LANL	Los Alamos National Laboratory
Ma	Millions of years ago
PA	performance assessment
R&D	research and development
RD&D	research, development and demonstration
SDI	Salt Disposal Initiative
SFWD	Spent Fuel & Waste Disposition (DOE-NE program)
SNF	Spent nuclear fuel
SNL	Sandia National Laboratories
THCMBR	Thermal-hydrologic-chemical-mechanical-biological-radiological processes
TRL	Technology readiness levels
URF	Underground Research Facilities
URL	Underground Research Laboratory
US	United States
ZIRA	Zone of interest (30 km^2) where Bure waste repository will be located.
ZT	Transposition zone (250 km^2 area within Bure designated for detailed study)

1 Introduction

The Office of Spent Fuel and Waste Science and Technology (SFWST) of the U.S. Department of Energy (DOE) Office of Nuclear Energy (NE), a part of the Office of Spent Fuel and Waste Disposition (SFWD), is tasked with conducting research and development (R&D) related to the geological disposal of spent nuclear fuel (SNF) and high level nuclear waste (HLW). As part of this work, planning for generic Underground Research Laboratories (URLs) is being undertaken. To begin the URL task, the project is initiating a review of existing URLs and co-located repositories around the US and the world.

Various activities will be conducted at the site for a deep geologic repository prior to repository construction and waste emplacement. Some of these activities may have the potential to adversely impact site characterization testing and waste isolation capabilities of the site. Construction of a site-specific URL and the conduct of testing and maintenance activities in the URL are examples of such activities. The objective of this work package is to review existing evaluations of impacts to site waste isolation capabilities that have been assessed at existing URLs, both nationally and internationally. In addition to the primary objective, we also include brief discussions of possible URL impacts that were not analyzed in existing documents.

Figure 1-1 shows a list of world-wide URLs and the years of construction. From this list, four URLs (Figure 1-2) with co-located repositories were chosen to analyze in the current DOE reporting period (FY2019). This work is being split between LANL and LBNL, with each laboratory responsible for analysis of two of the four URL/repository pairs. Thus, in this document, LANL is reviewing Bure (France), and WIPP (USA), while LBNL in a separate deliverable (Dobson, 2019) is analyzing Onkalo (Finland) and Yucca Mountain (USA).

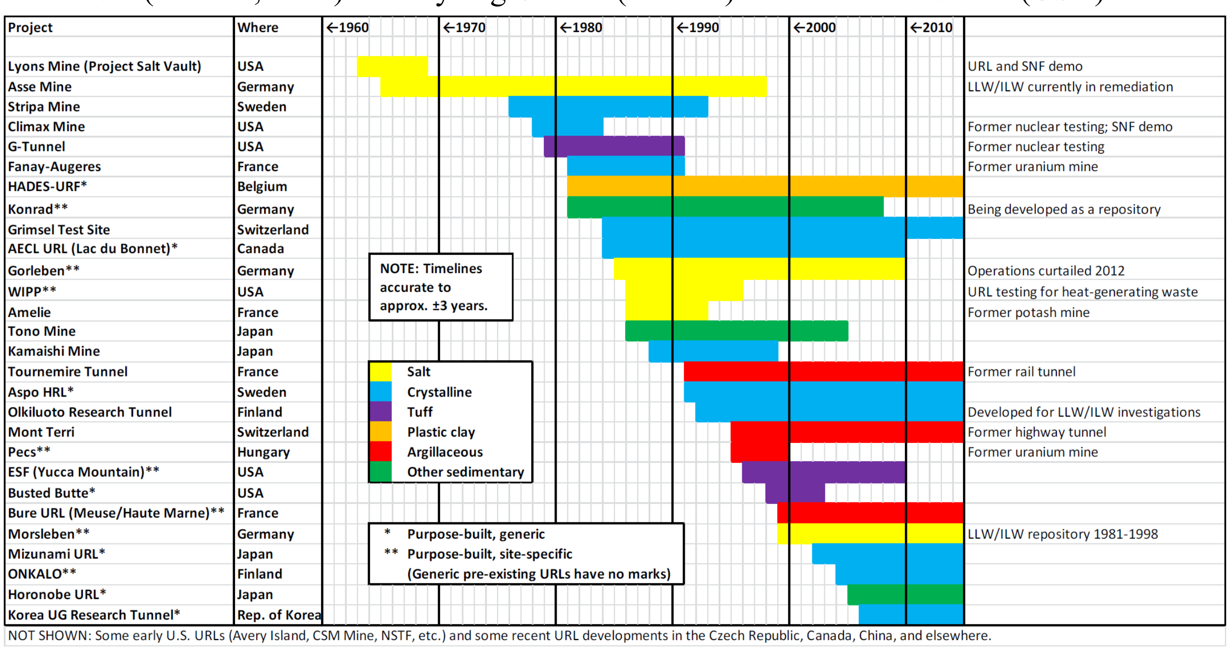

Figure 1-1 List of world-wide underground research labs (URLs) by country, geologic medium and date of construction. From MacKinnon et al., 2015.

This deliverable fulfills the Spent Fuel and Waste Disposition LANL Salt R&D Work Package Level 4 Milestone – LANL Contributions to Technical Support for Underground Research Laboratory Activities (M4SF-19LA010310012)

URL/Repository/rock type	Issues Evaluated
ONKALO/Olkiluoto (Finland)/crystalline	Groundwater inflow via tunnels and boreholes, changes in shallow hydrogeology (mixing of shallow oxidized groundwater with deeper reduced brines), effects of introduced materials (cement, steel), microbial impacts on water chemistry, impacts of accidents at URL affecting future operations
Bure (France)/argillite	Impact of URL on hydrology around underlying repository
Yucca Mountain (USA)/tuff	Impact of infiltration of construction and testing water on repository performance, impact of URL construction methods on fracture creation and opening
WIPP (USA)/salt	Impacts from excavations (spalling and brine release) and thermal perturbation from heater tests

Figure 1-2 Initial four URL/repository pairs reviewed for FY2019.

1.1 Background on repository design and possible URL impacts on performance

Here we review the primary components of nuclear waste repositories and discuss general ways in which construction and operation of a URL could impact performance of a co-located repository. Figure 1-3 shows a schematic of generic disposal system components and processes. Transport can occur from the waste form, on the left side of the figure, through the engineered barrier system to the host rock and eventually to the accessible environment of the biosphere.

Performance of the system relies on both man-made features (e.g., EBS) and the properties of the geosphere. Although termed co-located, URLs associated with a given repository are often built with some off-set from the locations of future waste packages. Thus, URL operation and maintenance are unlikely to directly affect waste forms, waste packages, or localized waste package buffers. However, for components of the engineered barrier system lying farther from the waste, URL activities have the possibility to modify subsurface conditions and impact the long-term repository performance.

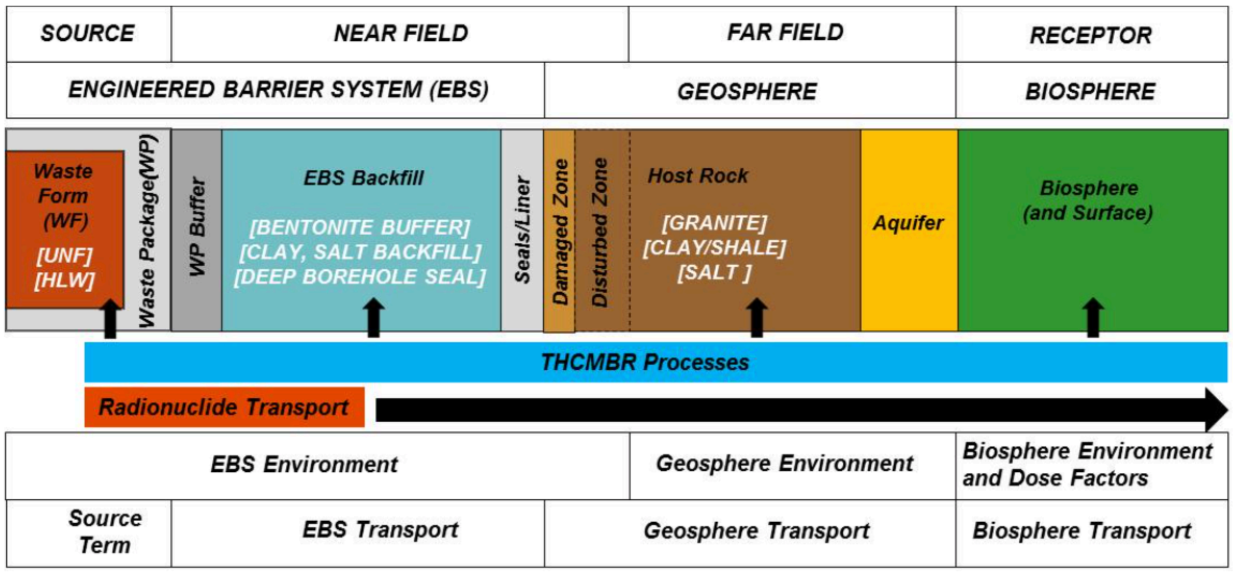

Figure 1-3 Generic Disposal System Components and Phenomena. From Freeze and Vaughn, 2012.

2 Bure (Meuse/Haute-Marne)

2.1 Background and Geologic Setting

The Bure (Meuse/Haute-Marne) underground research laboratory (URL) is located at the edge of the Paris Basin in eastern France, approximately 300 km east of Paris near the village of Bure (Figure 2-1). The site straddles the political border between the Meuse and Haute-Marne districts (Figure 2-1B). The rocks exposed at the surface and down to a depth of ~1 km are Jurassic in age (205–140 Ma) and consist primarily of limestones, marls and argillites (Andra, 2005). The strata are sub-horizontal (dipping from 1° to 1.5 to the west toward the basin center), having experienced only mild tectonic deformation (Andra, 2005)(Figure 2-2). As a consequence, the French radioactive waste agency (ANDRA) was able to site both the URL and the future waste repository in rocks devoid of major fault zones as determined through drilling, excavations and seismic surveys (Andra, 2005). This is in marked contrast to the argillite-hosted Mont Terri URL in Switzerland, which is situated in a complexly deformed and faulted thrust sheet within the contractional Alpine tectonic province (Jaeggi et al, 2017).

The geological host rock for the URL and the waste repository is the Callovo-Oxfordian argillite (COx), a clay-rich shale found at depths between 400 and 600 m in the study area (Figure 2-3). The overall thickness of the COx argillite is ~130 m, with a mineralogical composition consisting primarily of clays, carbonates and quartz with minor components of feldspar, pyrite, and organic matter (Lerouge et al., 2011). The physical, chemical and hydrologic properties of the COx argillite make it well suited for hosting the URL and ultimately for consideration as a nuclear waste repository (Table 2-1). The clay minerals exhibit good retention properties, the carbonates regulate pH and promote chemical stability, and the quartz provides mechanical strength to the formation that enables excavation and construction. The 130 m thickness of the

COx formation allows for a 50 m thick buffer with respect to the overlying and underlying rock formations, placing the URL facilities within a 30 m thick band in the middle of the formation.

Hydraulic conductivities of the undisturbed argillites within the COx argillite range from 10^{-12} to 10^{-14} m/s (Table 2-1), owing to the platey structure of the clay minerals and the very small radius (less than 0.1 micron) of the rock pores (Andra, 2005). Experiments conducted in boreholes drilled in the lower drift floor yield an effective porosity of 18% and an intrinsic permeability of 10^{-19} to 10^{-20} m^2 for intact COx argillite (Enssle et al., 2011). The overlying (Oxfordian) and underlying (Dogger) carbonates have hydraulic conductivities of 10^{-7} – 10^{-10} m/s, and display similar hydraulic heads at the sector scale. Thus the vertical water flow velocity (Darcian) within the COx formation is on the order of several cm per 100,000 years (Andra, 2005). Contour maps of hydraulic head for Oxfordian (argillite) strata prior to URL construction show a northwesterly groundwater flow direction with a 0.3% gradient in the vicinity of the URL and future repository (Figure 2-4 ; Kerrou et al, 2017).

The exploration phase for the Bure (Meuse/Haute-Marne) underground research laboratory began in earnest in the mid-1990's with the drilling and testing of deep boreholes and the collection of high-resolution seismic surveys. In all, 27 deep boreholes were drilled between 1994 and 2005, yielding a total of 4200 m of cored rock, of which 2300 m consist of Callovo-Oxfordian argillite.

Construction of the URL began in the year 2000 with the sinking of two vertical shafts. Both shafts were cased and cemented down to 20 m depth. The main shaft (509 m total depth) has a diameter of 5 m and provides for the transport of personnel and equipment, ventilation and material extraction (Delay et al, 2008). The auxiliary shaft (505 m total depth), located 100 m distant from the main shaft, has a diameter of 4 m and was built to enhance mine safety and to provide ventilation. Construction of experimental drifts commenced in 2004, with the upper drift excavated from the main shaft at 445 m depth and the lower drift excavated from the auxiliary shaft at a depth of 490 m (Figure 2-5).

Based on regional exploration and experimental results from the URL, areas of focus were identified for further characterization, feasibility studies and siting of the repository. The 200 km^2 "transposition zone" (ZT) was delineated in 2005 (Figure 2-6; Kerrou et al., 2017). It is defined as the area in which the physical, chemical and hydrologic properties of the Callovo-Oxfordian argillite and surrounding formations are similar to those determined at the URL (Andra, 2005). In 2008 a 30 km^2 zone of interest (ZIRA) was defined within the transposition zone for designing the waste repository. ANDRA released the master plan for proposed operations of the argillite-hosted Cigeo waste repository in 2016 (Andra, 2016).

The Cigeo repository at Bure is being designed to accommodate an inventory of up to 73,000 m^3 of intermediate-level long-lived waste and 10,100 m^3 of high level waste (Andra, 2016). As is the case for the URL, the repository will be constructed in the middle of the Callovo-Oxfordian argillite at an approximate depth of 500 m below the surface (Figure 2-7). Five vertical shafts each having a diameter of 5 m will provide ventilation and access for personnel and equipment during the excavation phase. Two access tunnels (ramps) inclined at a 12° slope from the SW will extend over 5 km in length to intersect the host formation at the repository depth of 500 m

(Figure 2-8). Although the storage cells for the waste packages will be > 3 km to the north-northeast of the URL, the entrance to the access ramps designed to lower the waste packages into the repository will be within ~750 m of the URL. A proposed time table for the Cigeo repository, from construction to final closure, may be found in Table 2-2.

It should be noted that the waste repository does not share any underground facilities with the URL; the mandate provided by the French government to ANDRA (2005) stipulated that (a) the URL shall not serve as a repository, and (b) radioactive waste shall not enter the URL. This is a wise decision as it reduces any impact URL activities may have on the waste repository.

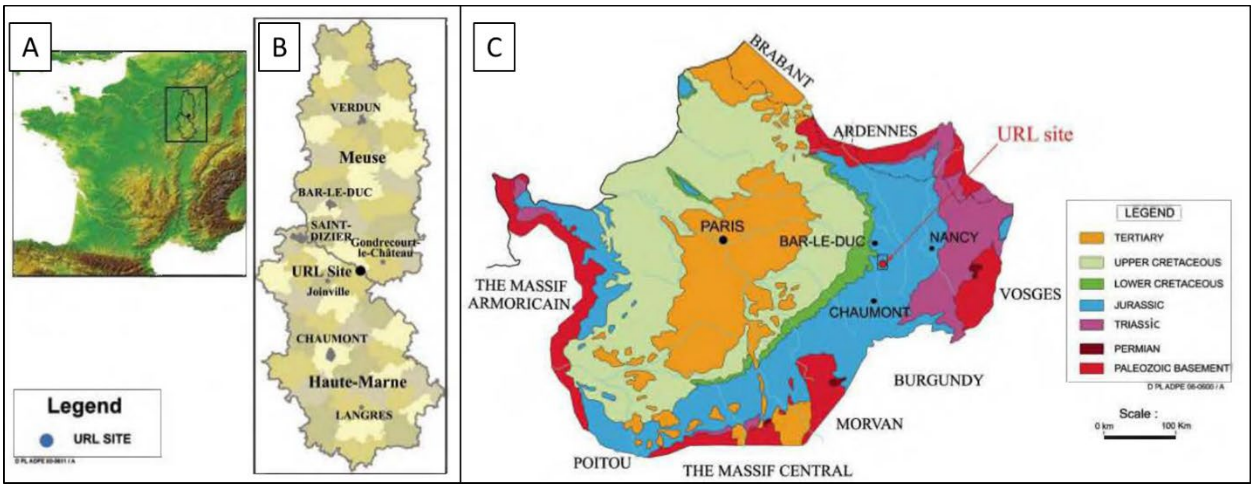

Figure 2-1 Location and geologic setting of the Bure (Meuse/Haute-Marne) underground research laboratory (URL). (A) Index map of France showing regional site location, (B) URL site with respect to Meuse and Haute-Marne political districts, (C) Geologic map of the Paris Basin showing location of URL within sedimentary rocks of Jurassic age. From Delay et al, 2008.

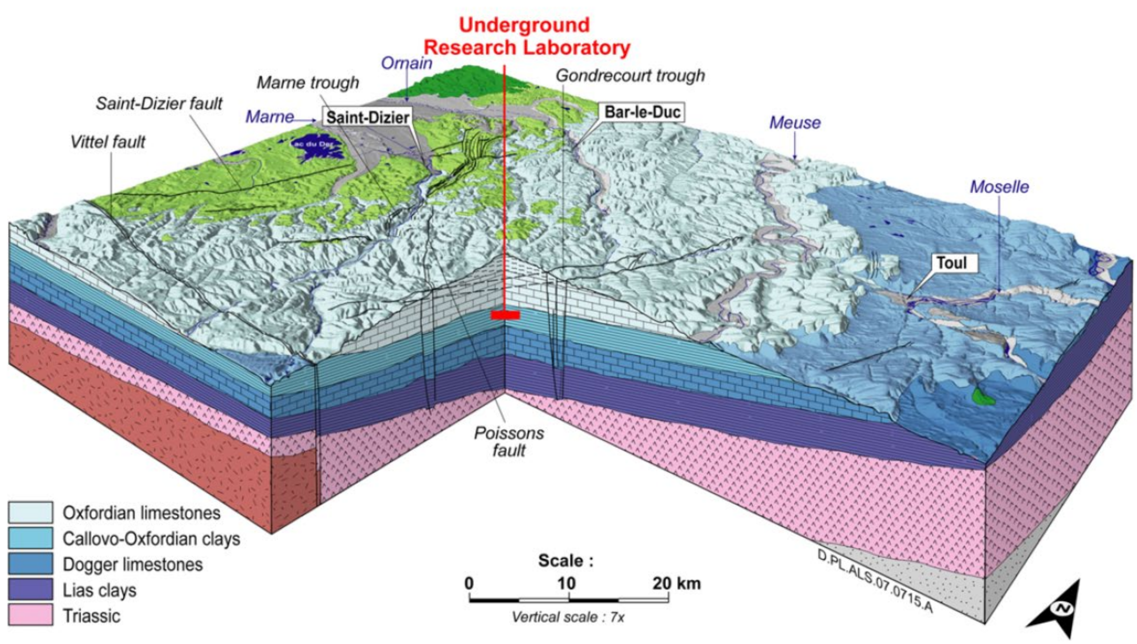

Figure 2-2 Three-dimensional geologic block diagram showing the location, depth and geologic units encountered at the Bure (Meuse-Haute Marne) URL site in France. From ANDRA, 2005.

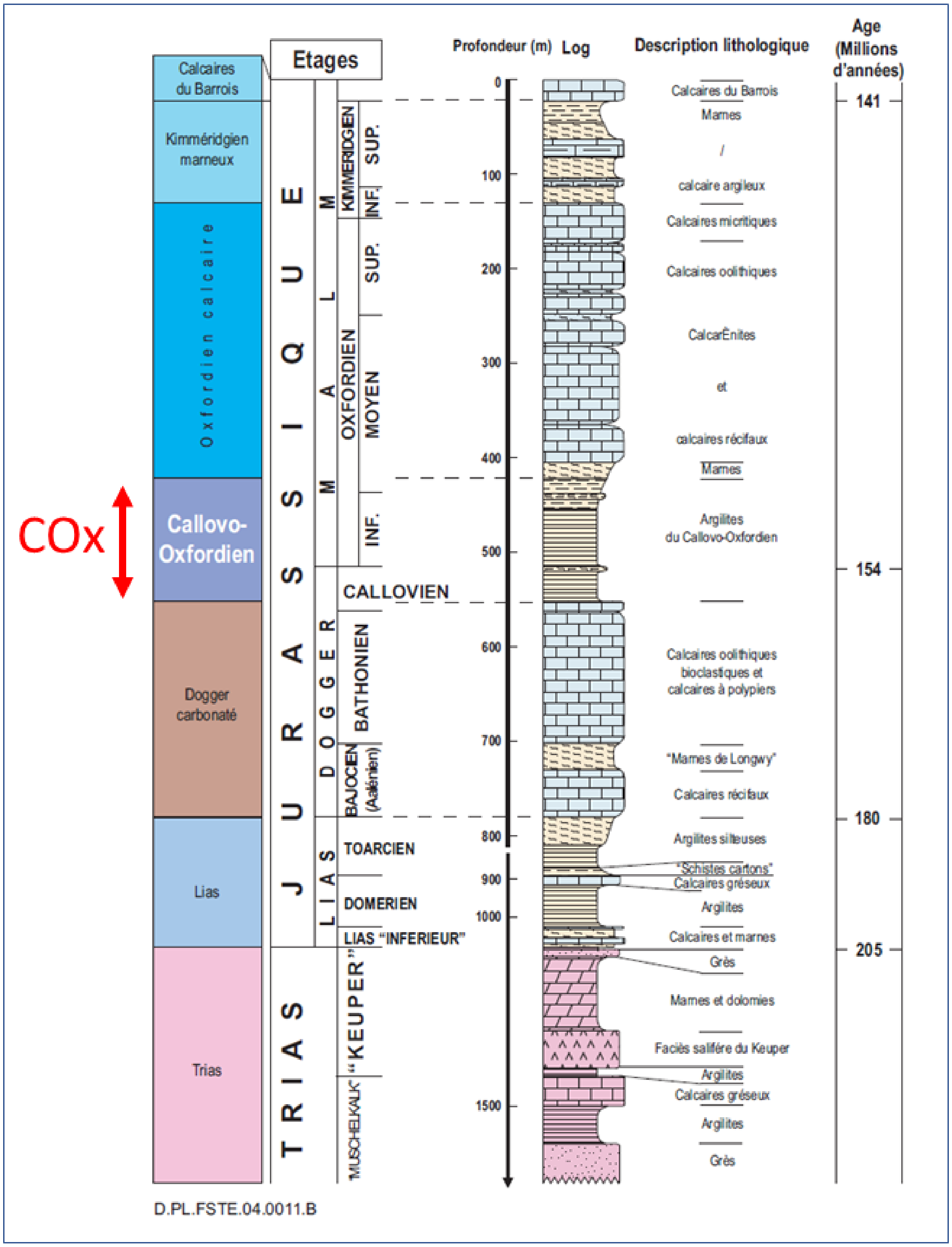

Figure 2-3 Stratigraphic section for the URL site and surrounding area, showing formations, ages and lithologies of the sedimentary rock units. The URL is located within the COx argillite. From ANDRA, 2005.

Table 2-1 Physical, chemical and hydrologic properties of the Callovian-Oxfordian formation at the Bure URL site. From Delay et al (2014).

Property/parameter	Callovian–Oxfordian at Bure
Age	Middle Callovian–Lower Oxfordian, 158–152 Ma
Thickness (m) (at the URL location)	130 m
Clay minerals (weight-%)	40 ± 12
Clay-mineral species (in order of decreasing abundance)	Mixed illite/smectite layers, illite (chlorite, kaolinite)
Other mineral species ordered by decreasing abundance	Calcite, dolomite and other minor carbonates, quartz, feldspars
Pyrite (weight-%)	1
Organic carbon (weight-%)	1
Pore-water type	Na–Cl–SO_4
Mineralization ($g\ l^{-1}$)	4–6
Eh (mV SHE); SHE = Standard Hydrogen Electrode	Eh: < -150
Bulk wet density ($g\ cm^{-3}$)	2.46 ± 0.05
Water content (weight-% relative to dry weight)	6–8
Physical porosity (—)	0.16 ± 0.04
Anion accessible porosity (—)	0.06–0.09
Effective diffusion coefficient De (HTO) ($m^2\ s^{-1}$)	$2 \times 10^{-11} \pm 0.1 \times 10^{-11}$
Hydraulic conductivity K normal to bedding ($m\ s^{-1}$), anisotropy factor	1×10^{-14} to 2×10^{-12}, low anisotropy (within the range of variation)
Thermal conductivity normal to bedding ($W\ m^{-1}\ K^{-1}$)	1.5 ± 0.3 (⊥)
Thermal conductivity parallel to bedding ($W\ m^{-1}\ K^{-1}$)	2.0 ± 0.1 (//)
Uniaxial compressive strength normal to bedding (MPa)	21–29

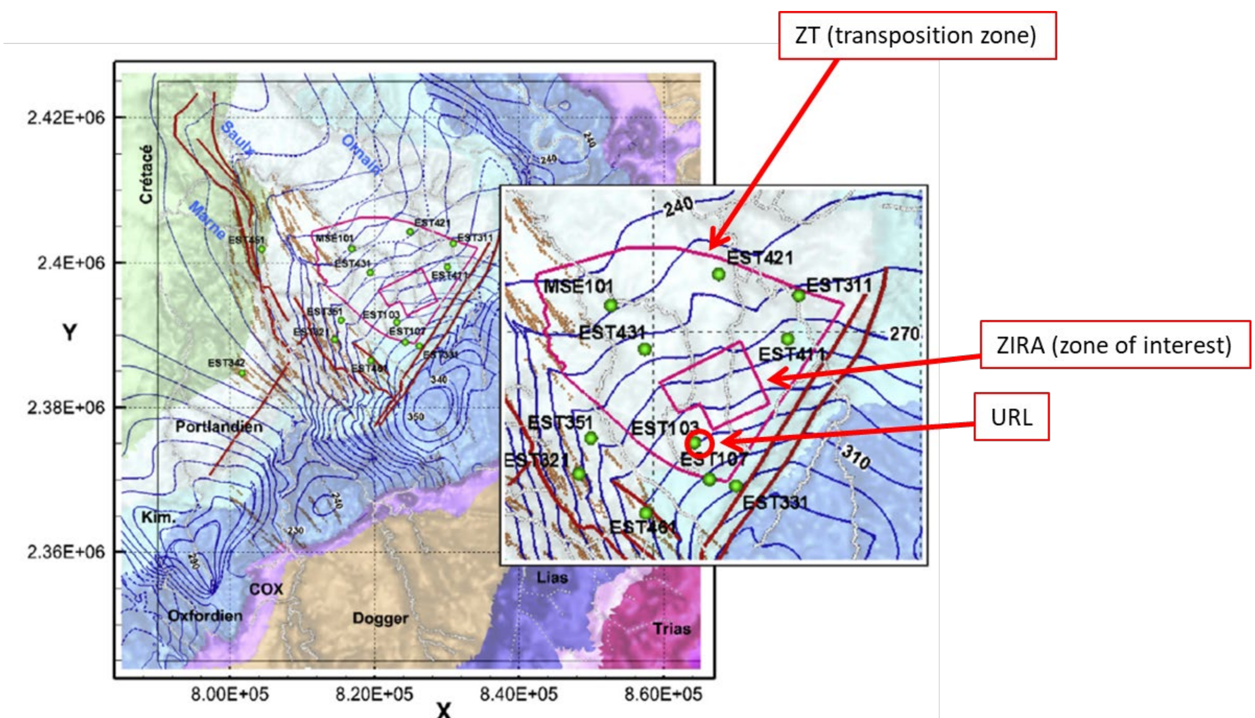

Figure 2-4 Regional and local contours of hydraulic head at Oxfordian (argillite) level prior to construction of the URL, indicating a NW flow direction for groundwater at the URL and ZIRA (future repository) localities. Green dots are observation wells. From Kerrou et al. (2017).

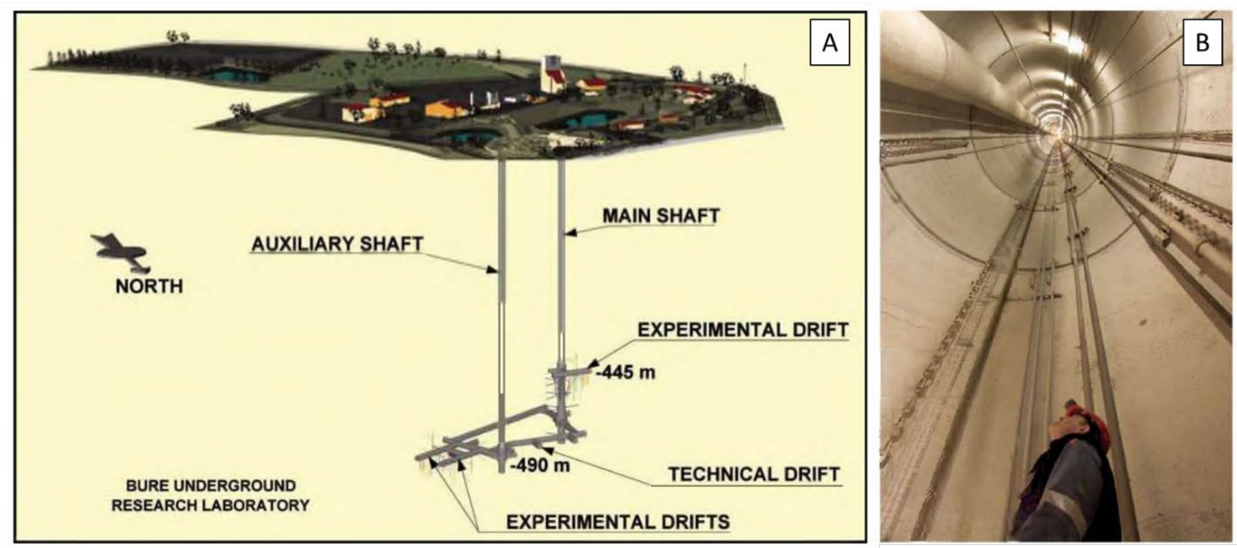

Figure 2-5 (A) Configuration of the vertical shafts and experimental drifts at the Bure URL circa 2006; (B) View of concrete lining in vertical shaft. From Delay et al., 2008.

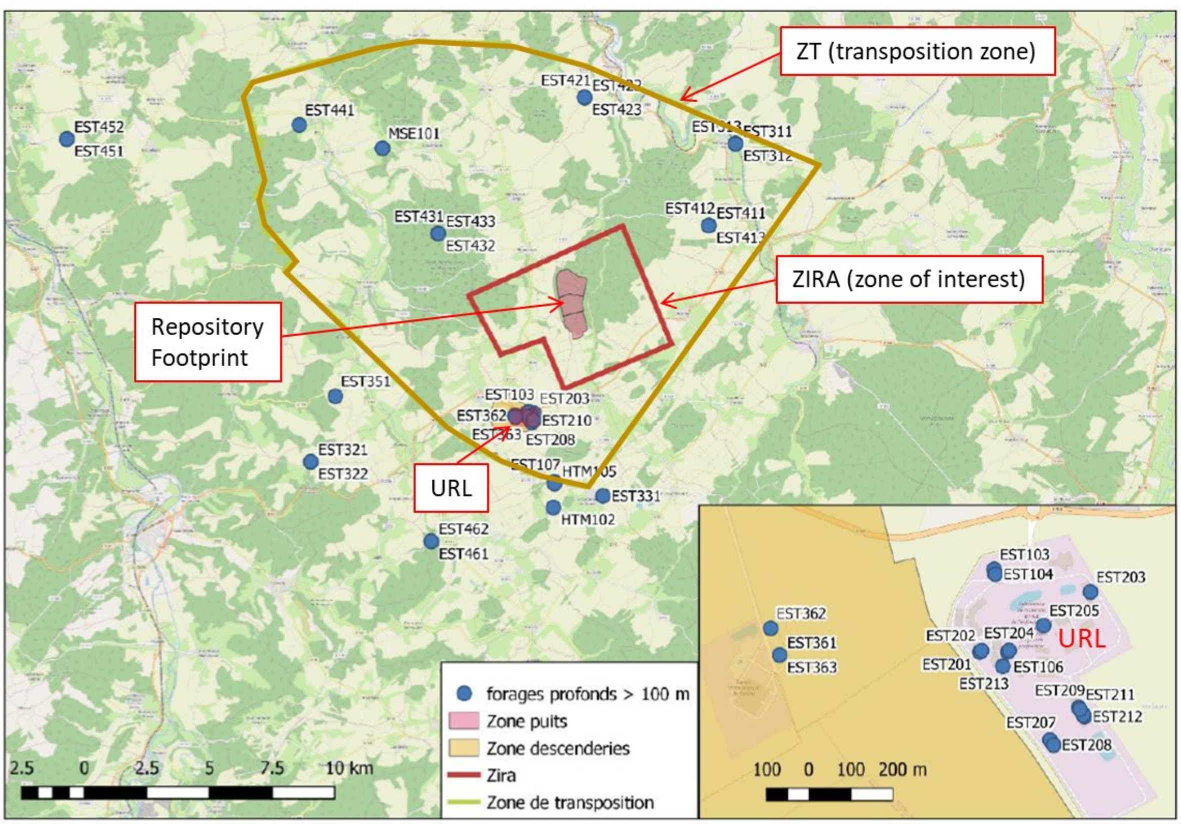

Figure 2-6 Map showing the location of the underground research lab (URL) with respect to the transposition zone (ZT), zone of interest (ZIRA) and footprint of the proposed repository. Labeled blue dots are deep boreholes drilled to investigate the Callovo-Oxfordian argillite. Note the inset map of the URL at bottom right. From ANDRA, 2019.

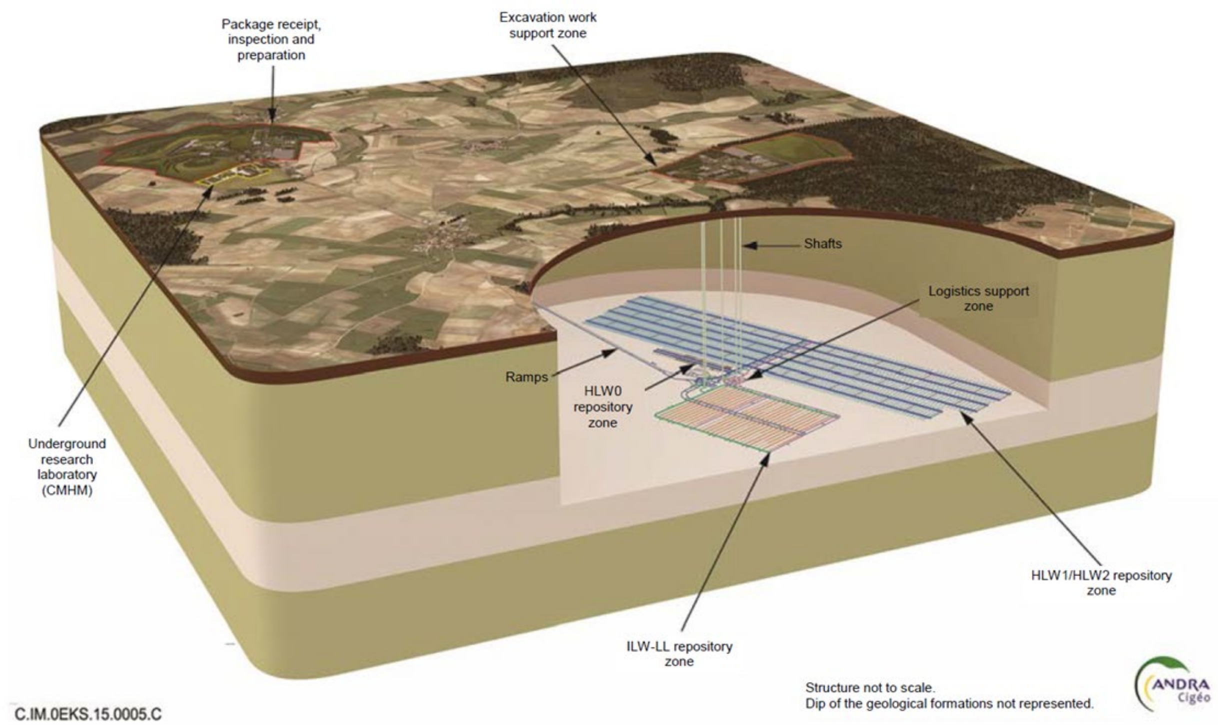

Figure 2-7 Three dimensional view of the Cigeo waste repository with surface and underground facilities. Note the proximity of the ramp entrance to the underground research laboratory. From Andra, 2016.

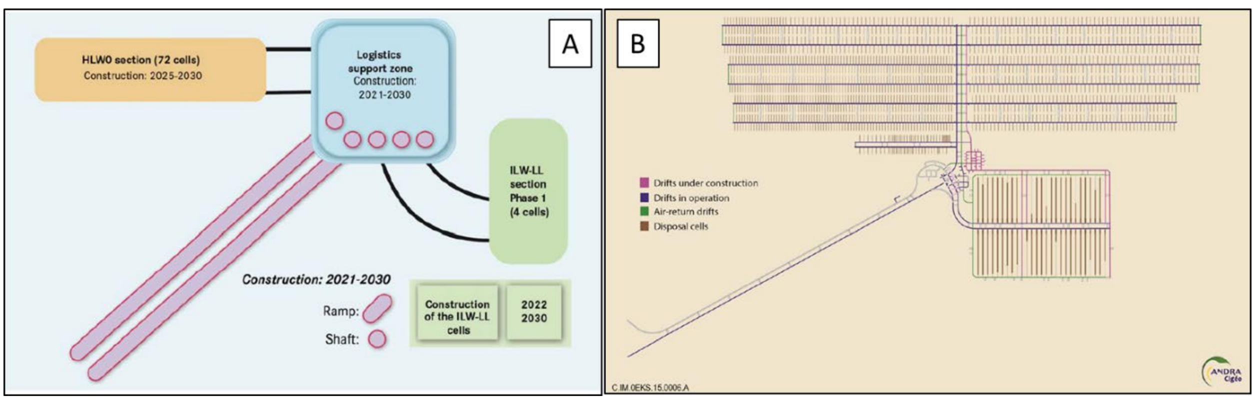

Figure 2-8 (A) Schematic diagram of the underground structures and facilities for the Cigeo waste repository at Bure with timeline for construction. Note the positions of the vertical shafts and inclined ramps; (B) Engineering design of underground structures at Cigeo built up to completion. From Andra, 2016.

Table 2-2 Timetable proposed for the Cigeo waste repository to be hosted at 500 m depth in the Callovo-Oxfordian argillites at Bure (from ANDRA, 2016).

Subject to obtaining the necessary licences, Andra has proposed the following provisional timetable:

- **Between 2015 and until 2020** – Initial local work (rescue archaeology, building of substations, changes to some roads, preparation of the site's rail sidings, preparation of the electrical and water supplies, etc.).
- **In 2018** – Filing of the construction licence application (DAC);
- **Around 2020** – Start of preparation work on building the repository (general earthwork, testing of excavation equipment, etc.) at the end of the public inquiry.
- **Around 2021** – Granting of Cigéo construction licence and start of work on building of the repository (excavation of the ramps, shafts, and surface buildings).
- **Around 2025** – Start of the industrial pilot phase (start of the first tests of the facility).
- **Around 2030** – Granting of the industrial operations licence. The industrial pilot phase will continue with active tests followed by emplacement of the first waste packages. The facility will ramp up to full operation and the second phase of underground structures will be built.
- **Throughout Cigeo's operating life**, the repository zones will be extended during consecutive periods lasting around 10 years each.
- **Around 2035** – Routine operation.
- **Around 2070** – Construction of surface facilities and repository structures for HA1 and HA2 packages;
- Partial closure of Cigeo is scheduled to occur around:
  - ✓ **2070** for the HLW0 repository zone.
  - ✓ **2100** for the ILW-LL repository zone.
  - ✓ **2145** for the HA1/HA2 repository zone.
- Final closure of Cigeo is scheduled to occur by **2150**.

2.2 Activities and perturbations in the Bure URL that could impact the waste repository

The main threat to waste containment in the Bure-argillite repository as identified by Andra's research team is enhanced water and fluid circulation through the engineered barrier system (EBS) and geosphere, which could lead to the release of radionuclides into the biosphere (Figure 1-3). Thus two main areas of research focus for the Bure URL are (1) characterizing the hydrologic and physical properties of the host geological medium (e.g., hydraulic conductivity, permeability, diffusivity) under variable conditions (e.g., temperature, pressure, strain rate), and (2) identifying potential features, events and processes (FEPs) that might create high-permeability pathways. Insofar as the matrix permeability is extremely low (10^{-19} to 10^{-20} m^2) and the Callovo-Oxfordian clay is largely unfractured by tectonic processes, considerable effort has been devoted to investigating man-made fractures in the excavated damage zone (EDZ). These studies include mapping the geometry and extent of the disturbed zone, developing experiments to measure permeability across the disturbed zone and into the intact host rock, evaluating the state of stress and deformation around underground structures, and devising strategies to mitigate fracture-enhanced flow parallel to drift and tunnel axes (Wileveau et al., 2007; Armand et al., 2013, 2014; Yildizdag et al., 2014; de L Vaissiere et al., 2015; Souley et al., 2017; Andra, 2019).

Activities at site-specific URLs that could impact an adjacent repository fall into three broad categories:

1. Drilling, Excavation and Construction
2. Conducting Experiments
3. Introduction of New (Exogenic) Materials

The consequence of these activities are "perturbations", or changes in the host rock properties and processes from its original, undisturbed state. For example, the network of tunnels, shafts and boreholes provide enhanced connectivity and high-permeability pathways in the subsurface that did not exist prior to excavating the URL. If connected to the repository (perhaps via an unmapped fault zone or EDZ) these pathways could facilitate radionuclide transport through the geosphere. Another example is the perturbation of local stress fields around engineered structures that could lead to brittle failure in the form of borehole breakouts, stress-relief fractures, and pillar and roof collapse (Wileveau et al., 2007; Delay et al., 2008; Armand et al., 2014; de la Vaissiere et al., 2015). A third example is the dewatering of underground facilities which can lead to severe drops in hydraulic head and influx of water, thereby enhancing fluid circulation and potentially reversing groundwater gradients (Hakim et al., 2014; Kerrou et al., 2017). Concrete, metallic bolts, atmospheric air and bacteria are examples of external materials that could perturb the underground system through chemical reactions with the host rock, EBS and waste package containers (Delay et al., 2008; Meleshyn, 2014; Vinsot et al., 2014).

Numerous experiments have been conducted in the Bure URL since its construction to the present (Table 2-3). However, they are restricted to a small footprint around the underground facilities (Figure 2-9) and are isolated from the future waste repository (Figure 2-6). During the course of our investigation of activities and experiments at the Bure URL, we did not encounter any publications or reports that specifically evaluated the potential impact of URL activities on the waste repository. This could be because the waste repository is only in the planning and design phase, and/or the repository will not be physically connected to the URL. We therefore focus our attention on the two primary perturbations resulting from activities at the Bure URL: (1) changes in hydraulic head and gradient due to desaturation, and (2) excavated damage zones in the host rock created by the construction of underground facilities.

2.2.1 Dewatering of the Underground Facilities – Impact on Hydraulic Head

Hakim et al. (2014) and Kerrou et al. (2017) modeled the impact of the Bure URL and future waste repository on the hydraulic regimes of the surrounding COx argillite and overlying carbonate aquifers. They incorporated daily measurements of hydraulic head in four boreholes (EST-104, EST-107, EST-201, EST-203) and flow rates in the two vertical shafts (PPA and PAX) over the course of an eleven year period of URL construction and operation. The drawdown of hydraulic head measured at different stratigraphic horizons in the Oxfordian limestone ranges from 50 to 150 m (Figure 2-10). Flow rates of water into the vertical shafts stabilize at around 7-8 m^3 per day (Figure 2-11), with high porosity zones 1-4 accounting for 90% of the water. Kerrou et al. (2017) used results of the transient flow calibration to define values of hydraulic conductivity and storativity for hydrogeological units in the Oxfordian limestone, which in turn were used to estimate discharge rates of groundwater into the ramp and vertical shafts of the repository (Figure 2-12A). At one hundred years after repository construction, the model predicts a flow perturbation extending over 10 km around the site, with up to 100 m of localized drawdown of hydraulic head in the Upper Oxfordian (Figure 2-12B) and up to 200 m of drawdown in the Middle Oxfordian (Figure 2-12C). Note in both cases the perturbed flow is directed toward the waste repository. Therefore, the desaturated URL at Bure does not pose a threat as a pathway for the escape of radionuclides from the waste repository.

2.2.2 Excavation and Construction of the Bure URL – Excavated Damage Zones

Excavation and tunneling activity during the construction of underground facilities invariably leads to brittle deformation within the host rock adjacent to the newly-formed openings. This “disturbed” or “damage” zone consists of a network of fractures aligned parallel to the tunnel axis, with a cross-sectional dimension proportional in size to the radius (or diameter) of the tunnel opening (Figure 2-13A). Excavation-induced fractures form by a combination of elevated pressures applied by the excavating equipment and the perturbed stress field created by the cylindrical-shaped opening. The disturbed zone is often divided into an inner zone where induced fractures are more intensely developed and interconnected, and an outer zone where the induced fractures are sparsely distributed and not connected (Figure 2-13A). The prospect of enhanced permeability within the inner disturbed zone suggests that EDZ could serve as continuous pathways for radionuclide migration, and thus should be incorporated into the performance assessment (PA) of any bedrock-hosted waste repository. Experiments in the argillite URL at Mont Terri (Switzerland) show a 2 to 5 order of magnitude increase in permeability within a 20-40 cm distance from the tunnel wall (Figure 2-13B), illustrating the potentially significant impact of EDZ on the hydro-mechanical behavior of the repository host rock.

Armond et al. (2014) performed a comprehensive study of excavation induced fractures at the Bure URL by analyzing forty-two 3D scans of the drift walls and describing core from nearly 400 boreholes drilled into the URL drifts. All totaled they measured 1200 fractures from the drift wall surveys and over 4000 fractures from the cores. They did not observe any natural fractures (joints) or faults, indicating the COx formation at the URL experienced only mild tectonic deformation. Armond et al. (2014) classified the induced fractures according to their brittle mode of failure, i.e., shear fractures (~75%) and tensile fractures (~25%)(Figure 2-14). They noted that the two fracture types formed by different mechanisms, with shear fractures forming under compression ahead of the excavation front, and tensile fractures resulting from stress relief parallel to drift walls (Armond et al., 2014).

The overall shape of the EDZ at Bure is elliptical owing to the geometry (dip direction and magnitude) of two sets of shear fractures (Figure 2-15), in contrast to the circular shape for the EDZ at Mont Terri which is comprised entirely of tensile fractures (Figure 2-13A). The EDZ at Bure can be divided into two domains, with the zone nearest to the drift consisting of both tensile and shear fractures (Zone A in Figure 2-15) and an outer zone consisting only of shear fractures (Zone B in Figure 2-15). It should be noted that the induced fractures in Zone A (tensile and shear) are of variable orientations and interconnected, whereas the induced fractures in Zone B (shear only) are homogeneously oriented and poorly connected (Armand et al., 2014). On average, the lateral extent of the tensile fracture zone is ~ 1m (0.2 times the drift diameter) whereas the lateral extent of the induced shear fracture zone is ~ 4.3 m (0.8 times the drift diameter).

The hydraulic perturbation created by the EDZ at the Bure URL was measured by a series of experiments in boreholes drilled into drift GCS, whose axis is oriented parallel to the maximum horizontal principal stress (σ_H). The hydraulic conductivity of intact (unfractured) COx argillite is $1x10^{-12}$ m/s at this locality (Armand et al, 2014). The hydraulic conductivity in Zone B (shear fractures only) is only slightly elevated from the intact values (between $1x10^{-11}$ and $1x10^{-12}$ m/s). However, within the zone of tensile fracturing (Zone A) hydraulic conductivities between approximately $1x10^{-9}$ and $1x10^{-11}$ m/s were observed (Figure 2-16A), corresponding to greater than 3 orders of magnitude above background levels (Armand et al., 2014). This suggests that fractures within 1 m of the drift walls are hydraulically connected and may accommodate accelerated fluid migration parallel to drift axes.

The elevated hydraulic conductivities within induced tensile fracture zones of the EDZ suggest the potential for high permeability pathways within an envelope of about 1 meter surrounding the drifts and tunnels of the Bure URL and any future underground facilities belonging to a waste repository. Because the hydraulic conductivities return to background levels at distances greater than 1 m away from the tunnel walls of the URL, any impact on the waste repository will be highly unlikely. The biggest risk would be the presence of an unmapped fault zone in the subsurface which would provide connectivity between the EDZ of the URL drifts and the inclined ramp to the proposed waste repository, whose entrance is ~0.75 km from the URL shafts (Figure 2-7).

Any risks for radionuclide migration posed by EDZ can be mitigated by intrinsic properties of the host rock and engineering intervention. For example, induced fractures of the EDZ undergo a self-sealing process due to expansion of the argillite with time (Andra, 2019). Baechler et al. (2011) report a more than 2 order of magnitude decrease in hydraulic conductivity within the EDZ over a span of three years (Figure 2-16B), which they attribute to the natural healing processes of clay-rich host rock. A mechanism to suppress drift-parallel flow within the EDZ was tested by Andra with the KEY experiment (Table 2-3), whereby grooves were cut into the zone of excavation-induced fractures and filled with swelling clay (Figure 2-17A). Results of the experiment indicate the clay-filled grooves severely limit flow parallel to drift axes, and they are being incorporated into the design of the waste repository (Figure 2-17B).

Table 2-3 List of experiments conducted at the Bure URL from 1999 to present.

	Experiment	Objectives	Start	Location
ACC	Seismic waves experiment	Assessment of attenuation of seismic movements in depth by setting up accelerometers in shafts and drifts	2008	surface, shaft, drift at 445m and 490m
AHA	HLW disposal cell/liner behaviour	Demonstrate the technological feasibility of HLW construction in accordance with 2015 concept Obtain data on liner mechanical behaviour Test long term monitoring devices	2016	GAN
ALC	HLW disposal cell construction phase 1	HLW constructability (microtunelling pilot hole) HLW cell liner mechanical behaviour without and with thermal load Assessment of THM rock behaviour around HLW cell Assessment of gas exchanges between HLW cell and the rock mass	2009	GRM
	HLW disposal cell construction phase 1 bis		2010	GAN
	HLW disposal cell construction phase 2		2010	GAN
	HLW disposal cell construction Phase 3.1 (Heater test) (HAC)		2012	GAN
	HLW disposal cell construction ALC3004 (Gas) (HAC)		2012	GRM
	HLW disposal cell construction ALC3002 (Gas) (HAC)		2012	GRM
	Pilot holes for HLW cell		2013	GCR
BAC	Microbiological disturbances	Characterize impact of bacterial activity created by human activity and drift ventilation. Characterize the microorganism embedded in the rock mass	2009	GED
BBP	Low pH concrete test	Test of various type of low pH concrete formula - Assessment of their industrial feasibility Assessment of the durability and chemical stability at the rock contact Assessment of the THM characteristics	2014	GAN
BHN	Hydrated bentonite behaviour	Follow up natural watering of a bentonite plug directly in contact with HL cell wall	2014	GAN
BPE	Shotcrete layers as support	Assessment of the technical feasibility and performance of a thick (40 cm) shotcrete support	2012	GRD
CAC	HLW cells and sleeves behaviour	Assessment of the watering velocity of a HLW cell rock /liner annulus - assessment of the influence of the liner mechanical behaviour ; Test of an optical fibre in order to follow up THM liner behaviour Provide additional data on THM liner behaviour Assessment of 40m liner behaviour under mechanical loading	2010	GMR/GED/GEX/GAN/GCS
CCC	Compressible blocks behaviour at galleries crossing	Follow up complex structures behaviour lined with compressible blocks and supported by shotcrete	2015	Carrefour GVA/GCR
CDZ	EDZ compression behaviour	Test effect of confining pressure on drift wall mimicking bentonite clay swelling Test effect of deconfining after support breakdown	2011	GET

Table 2-3 (continued Part 2)

	Experiment	Objectives	Start	Location
DCN	Steel rib removal test	Removal of the steel rib and follow up of drift wall behaviour and fracturing	2014	Niche -445m
DIR	RN diffusion test n°1	Assessment of diffusion and retention parameter through in situ injection of tracers	2005	Niche -445m / GEX
DPC	Two phases construction test	Drift construction in two phases (two diameters) in order to check if EDZ extension could be reduced	2013	GRM
DRN	RN diffusion test n°2	Assessment of diffusion and retention parameter through in situ injection of tracers Assessment of vertical diffusion (anisotropy) Use of actinides as tracers	2011	NED
EPT	Pore water chemistry with temperature	Assessment of pore water composition evolution under a thermal load of 85°C	2012	NED
ERA	Filling liner/rock annulus of an HLW cell	Technical feasibility of annulus filling - assessment of mechanical performance	2013	GAN
FRO	Effect of oxidized rock on pore water composition	Study pore water composition evolution at the contact with drift wall subject to oxidizing due to ventilation	2014	GEX
FSS	Full Scale Sealing	Technical feasibility of a bentonite pellet plug at real scale with low pH concrete formulas	2013	Saint Dizier
GGD	Large diameter drift test	Assessment of the mechanical behaviour or an IL-LLW disposal cell	2012	GRD/GVA
GIS	In situ geotechnical measurements	Geo mechanical properties measurement in boreholes	2005	URL
KEY	EDZ cut-off experiment (180°) test n°1	Technical feasibility of slots - Technical feasibility of slot filling with bentonite	2005	GKE
MAG	Chemical interaction between rock an filling material	Assessment of the HLW cell annulus filling material	2018	URL
MCC	Metal corrosion in contact with concrete materials	Study metal corrosion under stress. Evolution of the stress field around metal ribs cast in a concrete block.	2016	GCS
MCO	Metal corrosion	Corrosion kinetics in various thermal conditions	2009	GMR/GED/GET /GCS/GRM
MHS	Surface hydrogeological survey	Long term head measurement monitoring of all aquifer formations below and under the Callovo-Oxfordian layer	2011	Surface
MLH	Chemical interaction between rock and concrete	Assessment of · chemical interaction clay rock/ lining concrete; · effect of environmental conditions (temperature hygrometry) on lining concrete evolution and concrete waste packages for IL-LLW.	2009	GED

Table 2-3 (continued Part 3)

	Experiment	Objectives	Start	Location
MVE	Vitrified waste behaviour	Dissolution kinetics in various thermal conditions	2009	GED
NSC	Real scale sealing plug	Performance assessment of a sealing plug at a scale close to real	2012	GCS/GES
NIH	Slanted bentonite sealing plug	Improve knowledge of sealing plugs behaviour in slanted boreholes	2016	Niche -445m
OHZ	EDZ survey	Follow up EDZ inception and long term evolution along drifts and cells	2008	all URL
ORS	Lining and support observations	Lining and support survey and in particular: follow-up mechanical load, fracture inception and evolution ; follow up of lining and support behaviour Develop monitoring and survey devices for IL-LLW cells	2010	GCR/GER/GCS/GRD
PAC	Pore water chemistry	Pore water composition in clay rock - effects of disposal disturbances on pore water composition - pore water CO2 equilibrium	2005	GMR/GKE
PEP	Permeability measurements	Assessment of pressure head at distance of drift walls. Permeability tests in natural and disturbed conditions. Assessment of factors influencing the permeability.	2005	all URL
PGZ	HM disturbances created by gas	Assessment of gas pressure threshold - assessment of gas transfer in geological media and through plugs and seals	2009	GMR/GED/GEX
POX	Oxygen disturbance	Assessment of oxygen disturbances at the drift wall and potential consequences on pore water composition and retention properties	2009	GED
REM	Bentonite block watering	Bentonite block watering at large (1 cubic meter) scale	2014	Technological Centre
REP	Shaft mine by test	Follow up hydro mechanical response of clay rock during and after shaft excavation	2004	Niche 445m
RES	Regional seismic survey	Running and operation of a regional seismic network to assess natural conditions	2008	Surface
SDZ	EDZ under saturation and dewatering	Assessment of EDZ evolution under controlled hygrometry	2008	GED
SUG	Drift geological survey	Geological survey including EDZ inception and development under all excavation conditions	2004	all URL
TEC	Lining plastic deformation	Assessment of condition for liner deformation under thermal and mechanical stress	2010	GED
TED	Heater experiment 2	Heater experiment ; Assessment of THM properties of the rock under controlled thermal stress created by three thermal elements	2008	GEX
TER	Heater experiment 1	Assessment of thermal intrinsic properties of the rock	2005	GKE/GEX
TPV	Tunnel boring machine	Technical feasibility of tunnel boring machine with segment erector. Segments are compressible – **(GVA)**	2012	GRD/GVA
TSF	Wireless transmission	Wireless transmission (electromagnetic waves) between two boreholes	2007	GEX
TSS	Slot tests	Technical feasibility of a slot 360°- follow up of its behaviour for 2 years	2010	GET

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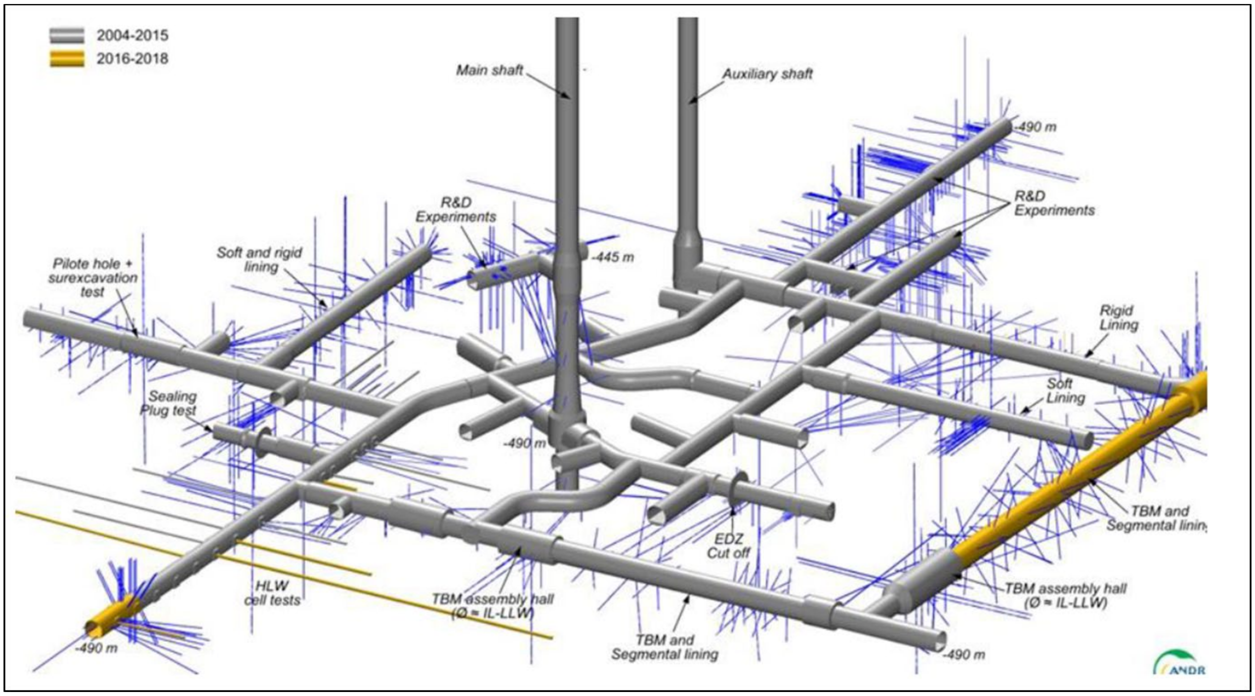

Figure 2-9 Underground facilities and experimental zones in the Bure URL from 2004 to 2019. From Andra, 2019.

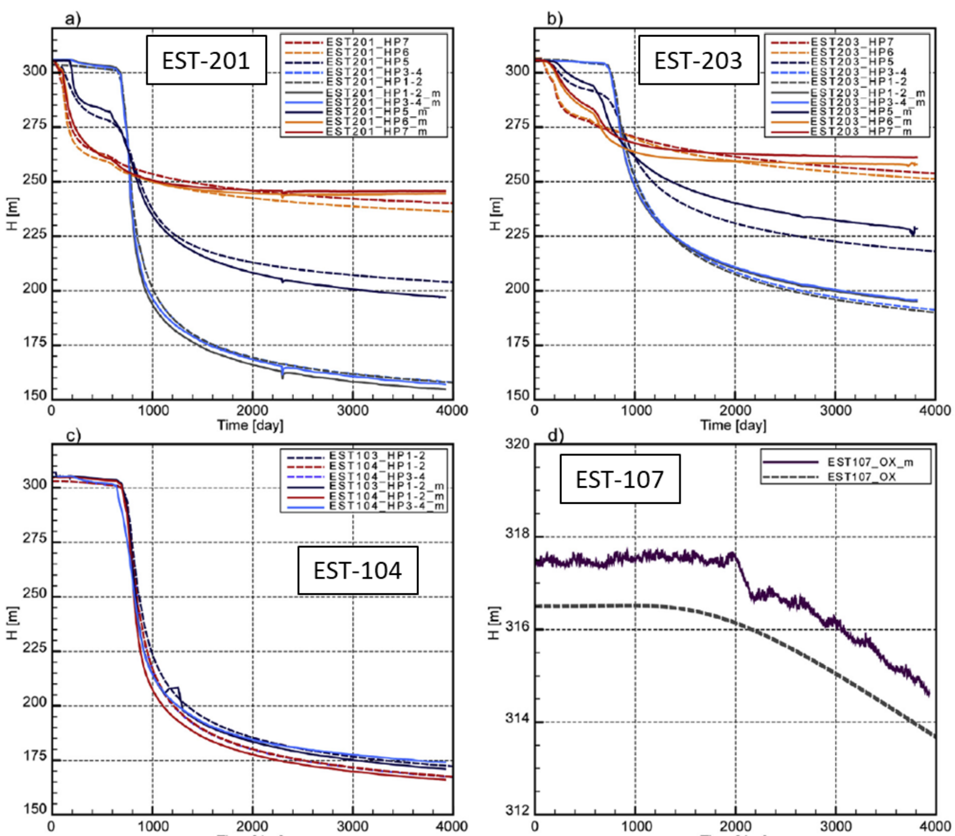

Figure 2-10 Measured (solid lines) and computed (dash lines) hydraulic head time series for four boreholes within and adjacent to the Bure URL. The data span ~11 years of daily observations at different stratigraphic levels. From Kerrou et al, 2017.

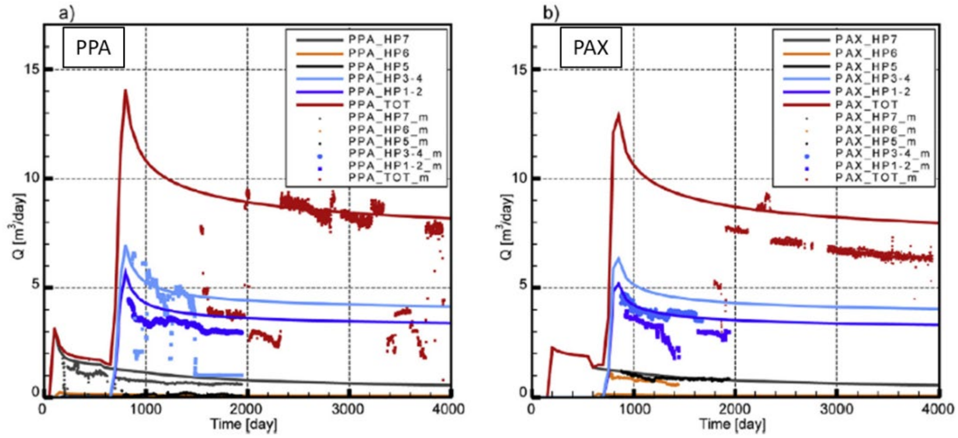

Figure 2-11 Measured (symbols) and computed (solid lines) flow rate time series for the two vertical shafts at the Bure URL. The data span ~11 years of daily observations at different stratigraphic levels. From Kerrou et al, 2017.

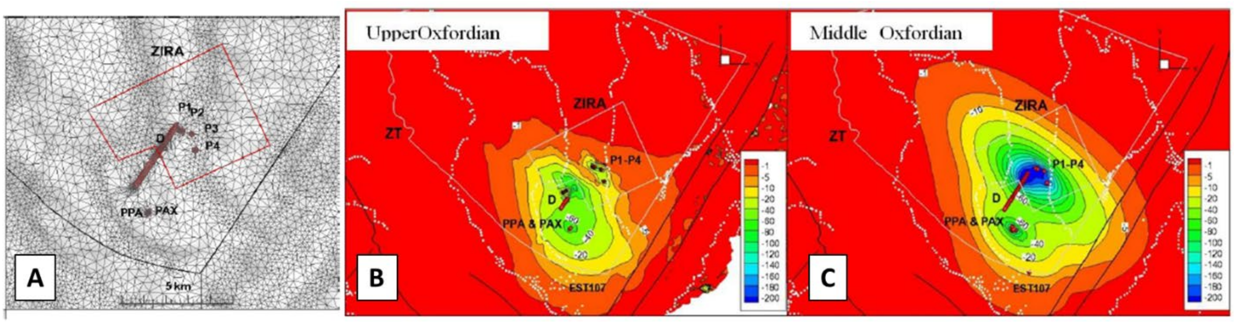

Figure 2-12 (A) Meshing and layout of shafts and tunnels for finite element modeling; (B) Hydraulic impact in the Upper Oxfordian at 100 years after repository construction; (C) Hydraulic impact in the Middle Oxfordian at 100 years after repository construction. From Hakim et al., 2014.

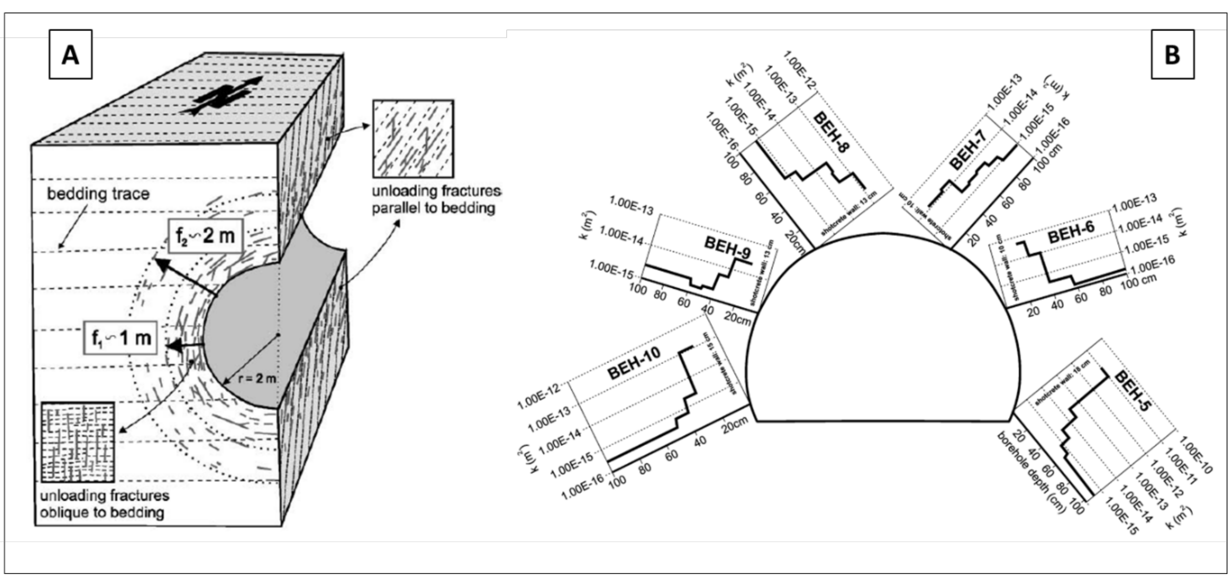

Figure 2-13 (A) Conceptual model of the excavated damage zone in the Mont Terri argillite URL. (B) Permeability distribution as a function of distance into the host rock as measured in a tunnel at Mont Terri. From Bossart et al., 2002.

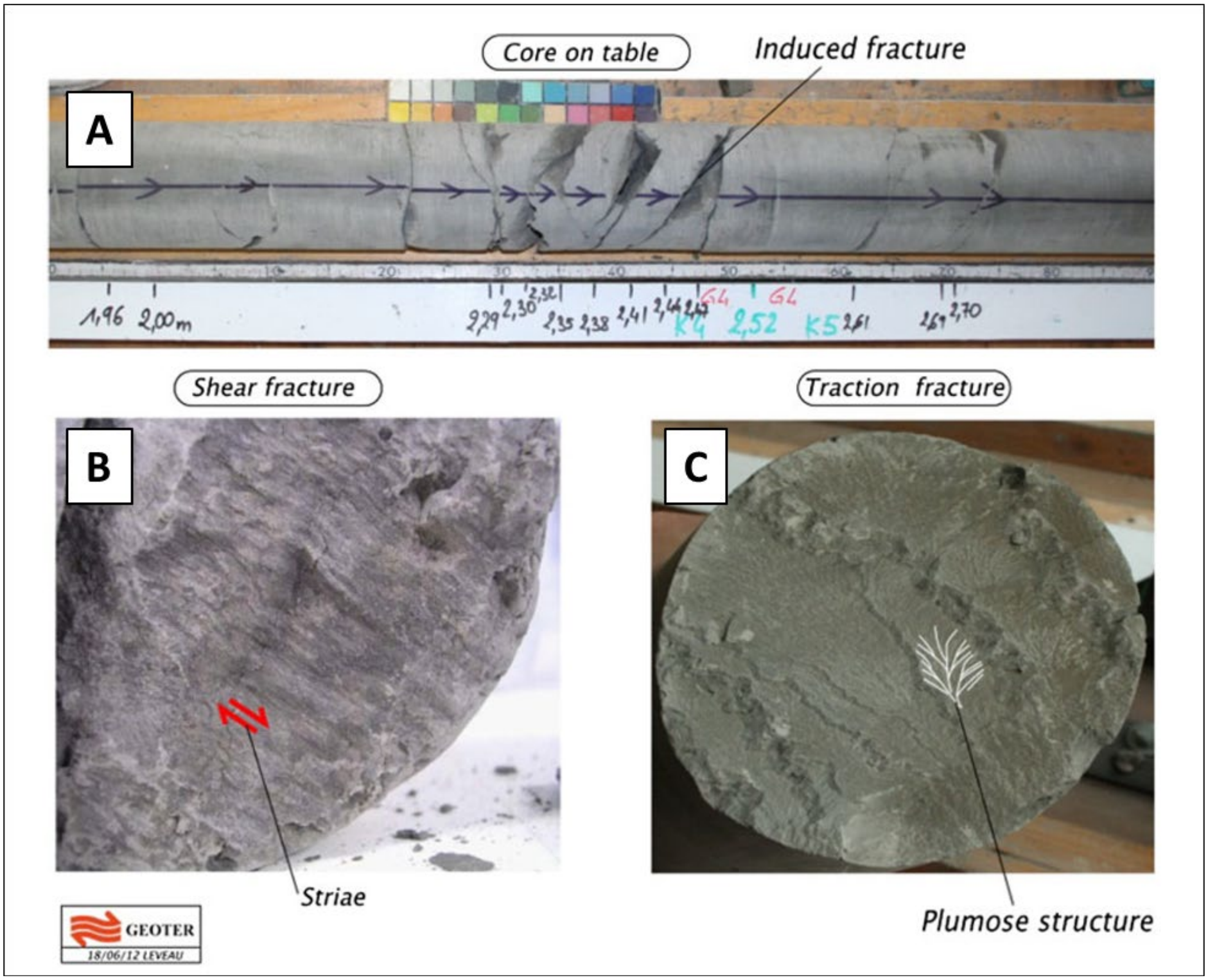

Figure 2-14 Induced fractures observed from core taken in the Bure URL. (A) Whole core cut by induced fractures; (B) Surface of induced shear fracture showing slickenside lineations (striae) indicative of shear displacement; (C) Surface of induced tensile fracture showing plumose structure indicative of opening-mode displacement.

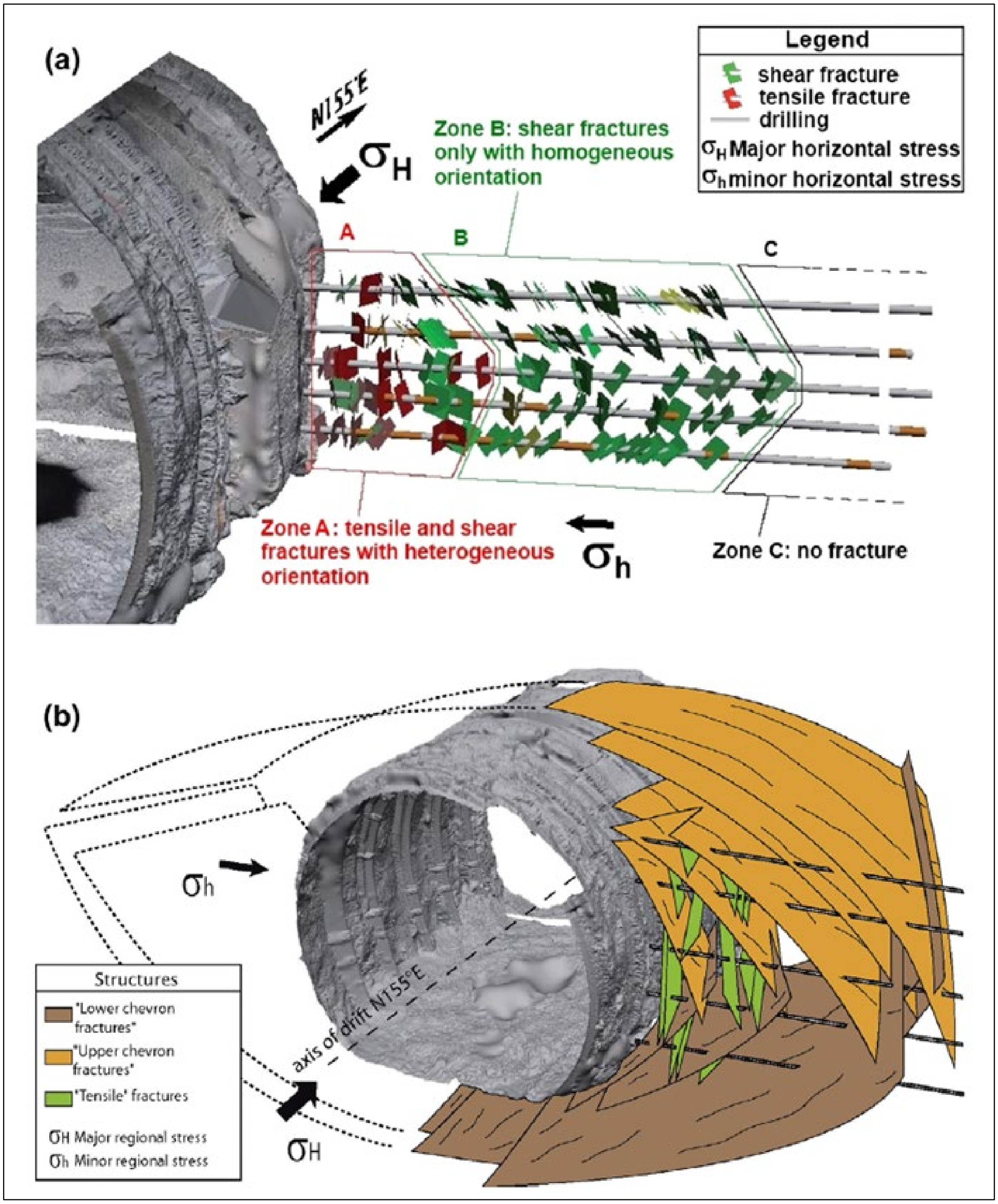

Figure 2-15 Excavation induced fracture nework in the GET drift at the Bure URL. (A) Vertical cross section showing fracture zones as a function of distance from drift wall; (B) Conceptual model showing shear fractures (lower and upper) and tensile fractures. Note drift axis is parallel to maximum horizontal stress (σ_H). From de la Vaissiere et al., 2015.

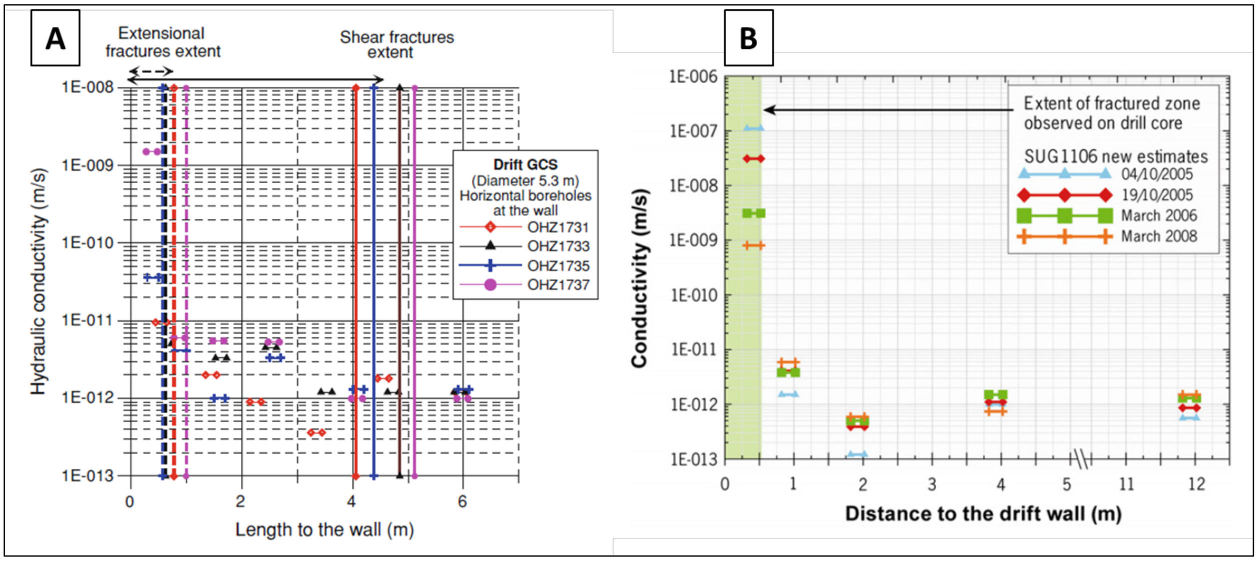

Figure 2-16 (A) Hydraulic conductivity measured as a function of distance from GCS drift wall from four horizontal boreholes. Note up to 3 orders of magnitude greater hydraulic conductivity within extensional fracture extent (Zone "A"). From Armand et al., 2014; (B) Hydraulic conductivity measured as a function of distance from drift wall in a single borehole, at four different times between 2005 and 2008. Note two orders of magnitude decrease in hydraulic conductivity with time within the fractured zone. From Baechler et al., 2011.

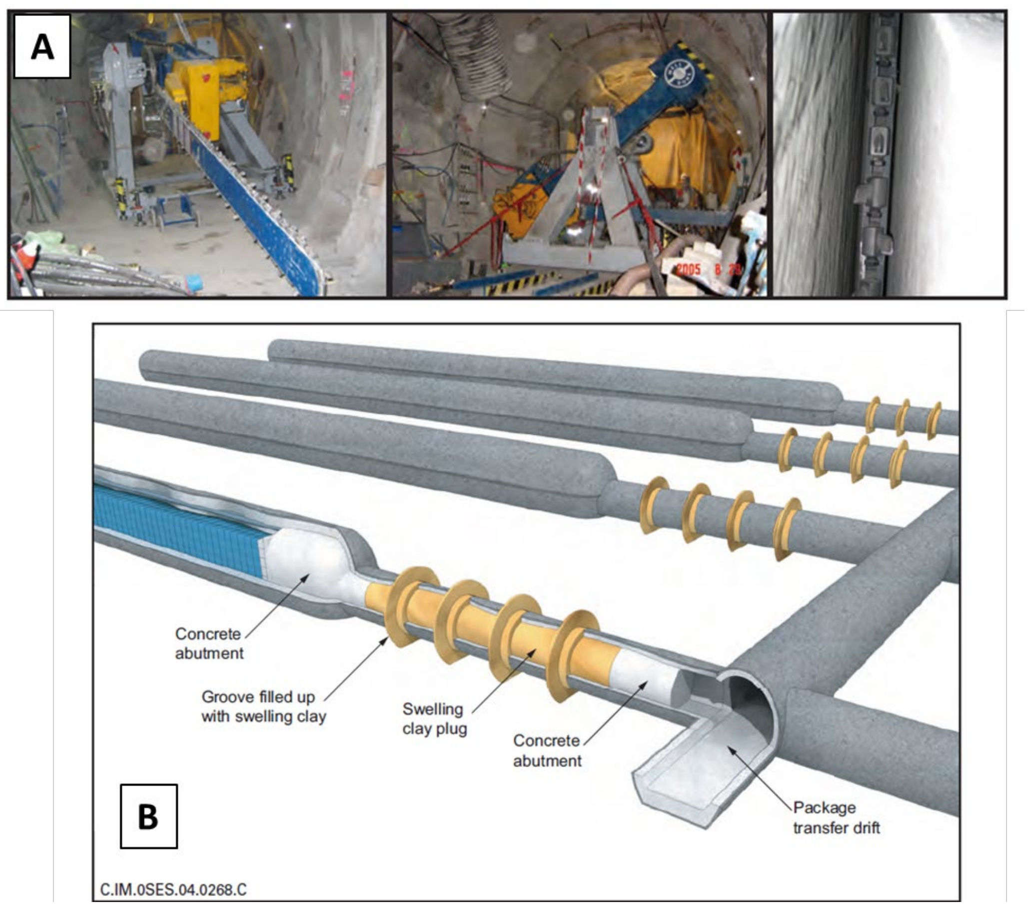

Figure 2-17 (A) The KEY experiment performed at the Bure URL, where grooves are cut through the EDZ and filled with swelling clay in order to prevent fluid flow parallel to drift axes; (B) Depiction of groove-filled barriers in future repository. From Andra, 2005.

3 WIPP

3.1 WIPP Background

The Waste Isolation Pilot Plant (WIPP) is located in southeastern New Mexico in the US (Figure 3-1). This facility is the only deep geological radioactive waste repository operating in the US, and is limited to the disposal of defense generated transuranic (TRU) waste. Authorization to build the facility was granted in 1979, and the first underground testing of the facility began in the late 1980s. The first shaft was completed in 1981 and full construction of the underground facility began in 1983 (Figure 3-2).

Figure 3-1 Location map for WIPP. From WIPP, 2019.

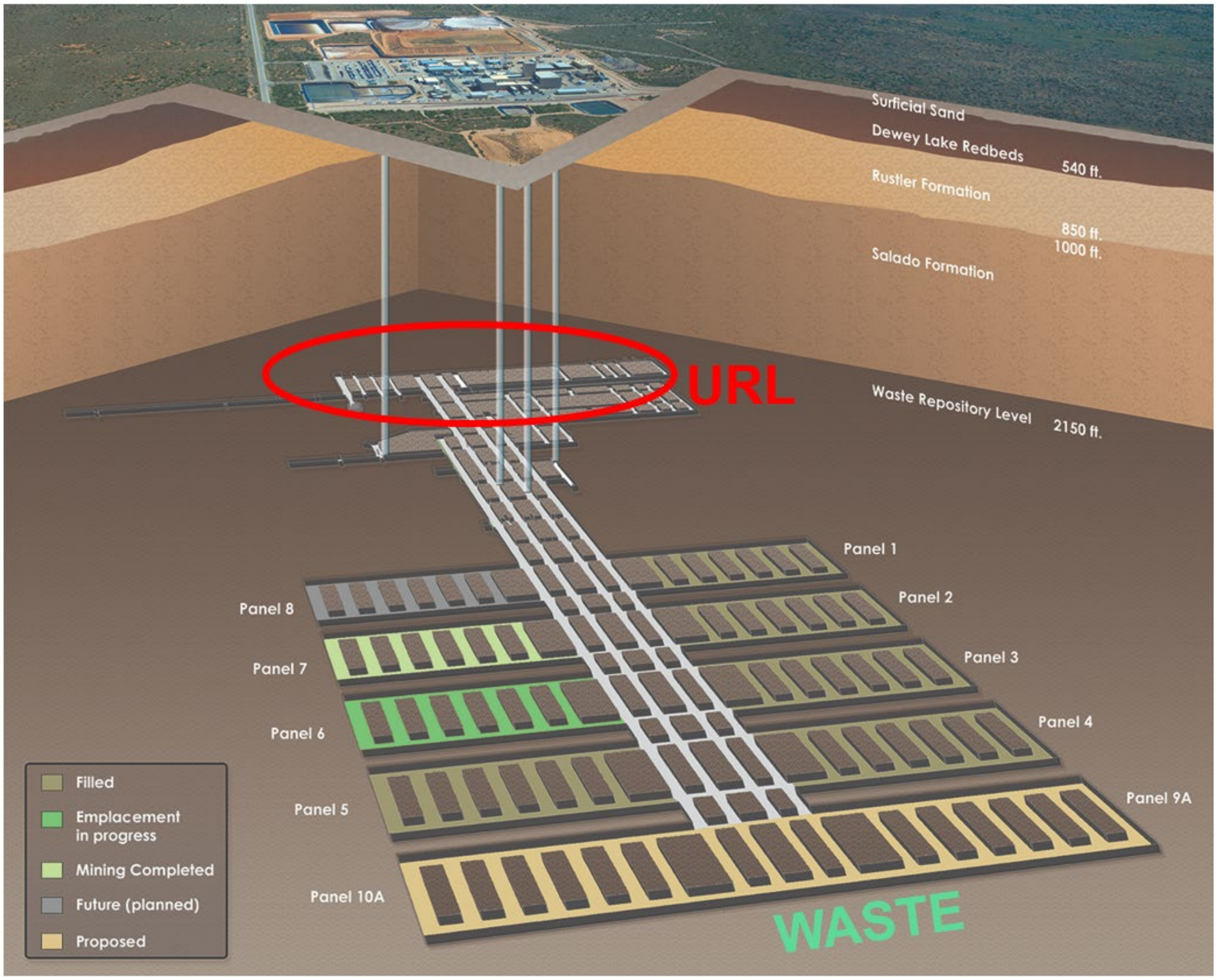

Figure 3-2 Schematic of WIPP including waste panels and the location of the URL activities. Modified from WIPP, 2019.

From 1984-1992, scientists performed large scale underground experiments. These experiments were done in the North end of WIPP, several hundred meters from the closest waste panels (Figure 3-3). These URL activities were divided into two distinct subsets. The first, running from 1984-1990, were focused on the disposal of Defense High-Level Waste (DHLW) and are perhaps the most applicable to the SFWD project (Figure 3-3). The second set of experiments were focused on the WIPP mission, mainly TRU waste emplacement issues without the generation of heat (Kuhlman 2017). Due to regulatory directives, no HLW or TRU were allowed to be used in experiments during this time.

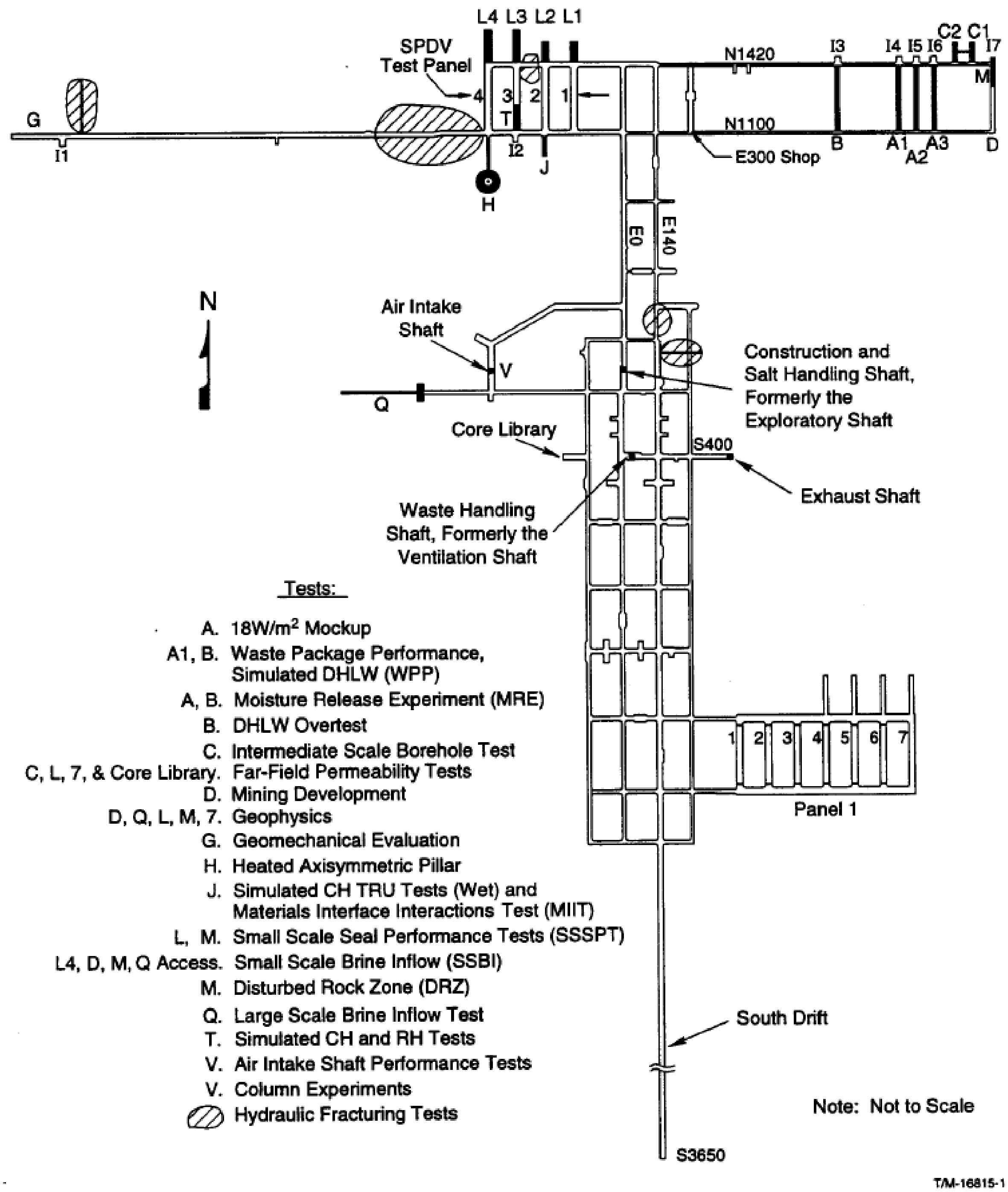

Figure 3-3 As-Built Plan of the WIPP Underground Experimental Area. From Munson et. al., 1997.

From 1992 to 1999, regulatory issues were resolved and the first nuclear waste arrived at WIPP on March 26, 1999. Waste continues to be shipped to WIPP and plans call for TRU disposal through 2050 (DOE, 2019). Beginning in 2011, proposals for continued URL activity were developed. These proposals, the Salt Disposal Investigations (DOE, 2019) and the Salt Defense

Disposal Investigations (DOE, 2013) were not pursued. However, beginning in 2015, plans for a small-diameter borehole heater test and possible further phased testing were proposed (Stauffer et al., 2015). Shakedown testing of the borehole testing plan was initiated in June 2018 (Boukhalfa et al., 2018), and full implementation of the first phase of the borehole testing plan (Figure 3-4) is slated to begin in the fall of 2019 (Mills et al., 2019). In parallel with the borehole testing, an operational test of a full-scale canister heated with 1000W was implemented from 2017-2019 (Figure 3-5).

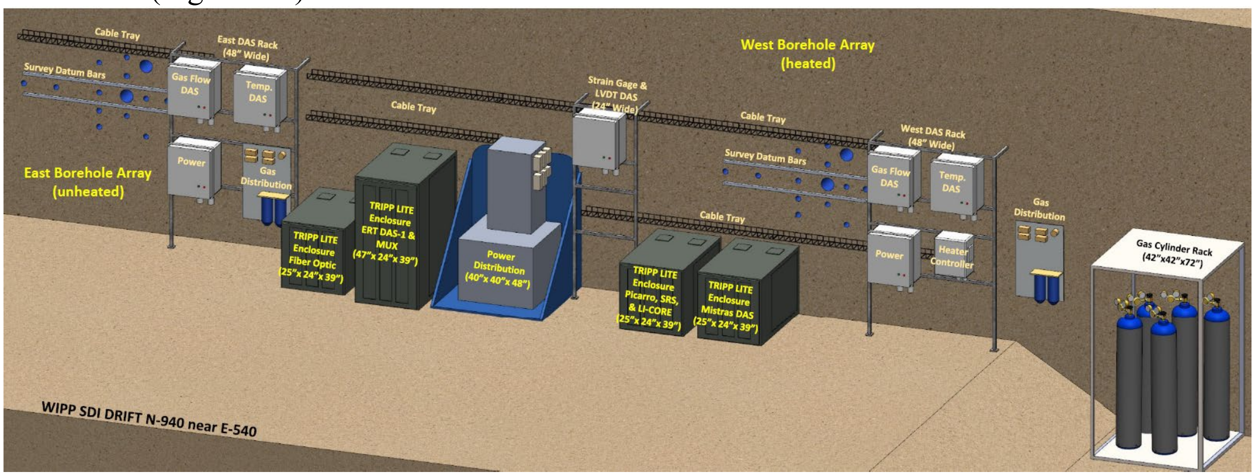

Figure 3-4 Phase I of the small-diameter borehole testing program.

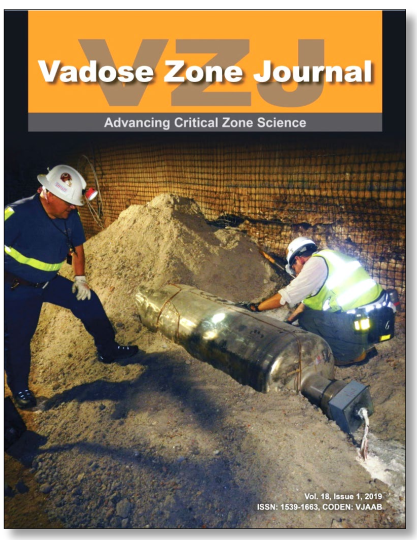

Figure 3-5 Operational testing of a full-scale canister.

During the 8 years of URL activities in the 1984-1992 period, large tests were performed with high thermal loads, including the Room A test shown in Figure 3-6 that generated 64kW using 68 heaters (Kuhlman, 2013). Heated canisters in this test were buried in the floor and heated for 5 years. Compared to these historical tests, the current round of testing is using much more modest heat loads, where the borehole testing uses a maximum of 750W.

Figure 3-6 Room A URL test from the 1980s. From Kuhlman 2011.

3.2 Existing reports discussing URL impacts on the WIPP repository

In a literature review, we have found two examples where in which direct URL impacts on the WIPP repository have been explored. The first, Kuhlman (2011), describes temperature changes from a proposed URL that could impact waste panels. The second study examines the impacts of the SDI excavations on WIPP performance related to the increase in drift volume created during mining of the SDI (Camphouse 2011, 2014).

3.2.1 Temperature impacts from a URL on WIPP waste panels

In this analysis, potential temperature changes from a proposed URL activity were calculated to determine if any temperature rise would be seen at the WIPP waste packages. The proposed URL, the Salt Disposal Investigations (SDI), was slated to run for two years and to use 5 heaters, each with a thermal load of 8500 W (U.S. DOE 2011a, 2011b). The location of the proposed SDI URL was approximately 700 m from Waste Panel 1, the closest waste panel to the URL.

The numerical model used to calculated potential thermal impacts on waste includes several assumptions (Kuhlman, 2011). First, the model uses an analytical solution for heat transfer, with fixed material parameters based on values found in previous experimental work. Superposition of analytical solutions is used to 1) simulate a finite 2 year source, 2) implement marker beds 138 and 139 as perfectly insulating boundaries, and 3) sum the impacts of 5 canisters. The second of these techniques turns what would be a 3-D spherical solution into a 2-D solution with the energy radiating from the canisters forced into a pancake shaped plane. Implicit in the pancake solution is that the energy from each canister is distributed across the entire thickness of the pancake (16.7 m between the two insulating marker beds).

Figure 3-7 shows results from the heat conduction solution. These results are at 22 years from the start of the proposed thermal test, and include a 2 year heated period with 8500 W x 5 = 42,500 W (=J/s) added to the domain. With 3.15e7 seconds per year, this represents 2680 Gigajoules of added energy. After 22 years of simulation time the measurable thermal signal (>1 °C) has reached only approximately 100 m from the URL (Figure 3-8).

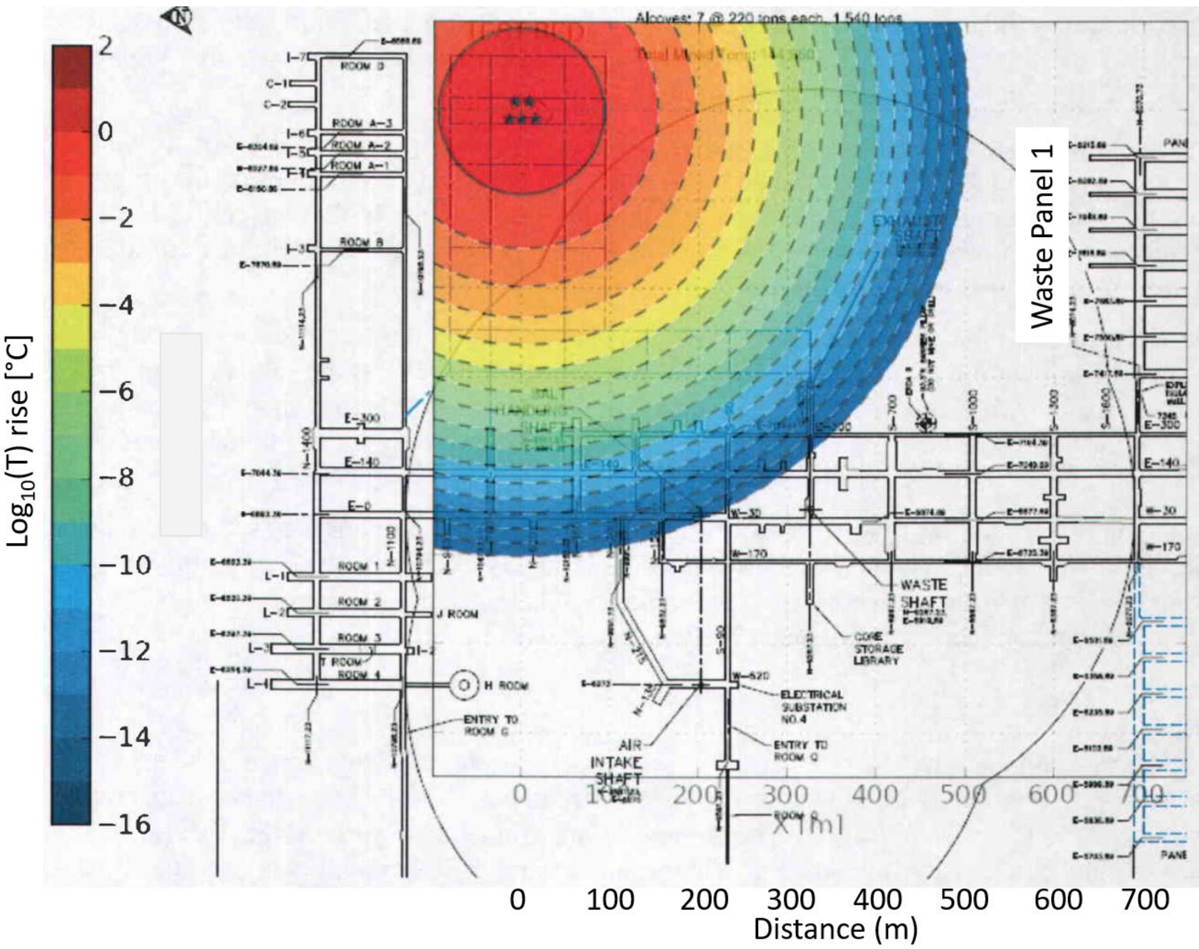

Figure 3-7 Thermal impact of the proposed SDI URL relative to Waste Panel 1 at 22 years of simulation time. From Kuhlman 2011.

To determine the maximum temperature rise at Waste Panel 1 (700 m from the URL), temperature through time at this distance is plotted in Figure 3-8. Included in this figure are temperature rises at other radial distances, showing that peak temperatures from the thermal signal propagate outward from the URL through time. At 700 m, the peak temperature increase occurs after approximately 1000 years and is roughly 0.02 °C.

The conclusion from Kuhlman (2011) is that the URL would have had an insignificant thermal impact on the repository at any time in the future.

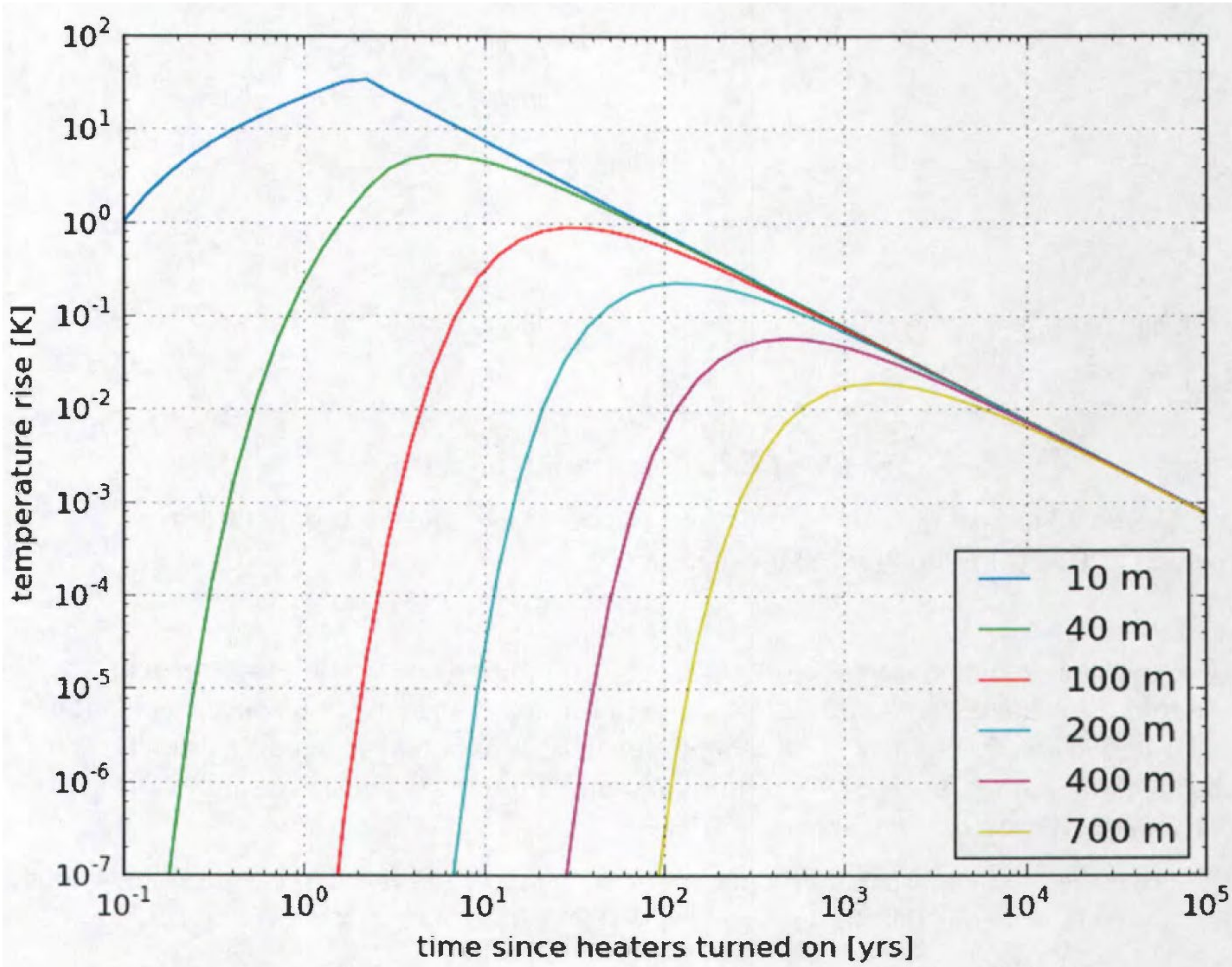

Figure 3-8 Predicted temperature rise through time at six radial distances from the proposed SDI URL experiment. From Kuhlman 2011.

3.2.2 SDI mining impacts on WIPP performance

In November of 2010, DOE submitted a PA baseline (PABC-2009) that was certified by EPA (U.S. EPA 2010). Due to the planned expansion of mining to create the SDI URL, DOE was required to provide analysis that could demonstrate that the additional mining would not impact the overall conclusions of the PA. Sandia National Laboratory (SNL) was tasked with comparing the PA baseline results to new calculations that included the increased mining volume for the SDI (U.S. DOE 2011a, 2011b). Here we summarize findings from the initial 2011 SDI Impact Assessment that were carried into the 2014 Compliance Recertification Application (CRA-2014) study performed by SNL (Camphouse et al., 2011, 2014).

Camphouse et al (2011) report that the additional volume of the expanded URL area (60,355 m^3) can impact the pressure and brine saturation near the waste panels. These changes could impact two release mechanisms 1) spallings and 2) direct brine releases (DBRs, Figure 3-9). The increased volume of void space created by the SDI may lead to a drop in long-term pore pressure. Lower pore pressure in the SDI area in would likely lead to less pore pressure build-up in the waste panels. Pressure changes in the waste panels impact spallings with reductions in pressure yielding reductions in spallings volumes. Lower spallings volumes lead to lower radiological releases during DBRs. However, pressure reductions in waste panels may allow brine in-flow to increases brine saturation in the panels. Increased brine saturation causes higher radiological releases during DBRs. Thus, DBR impacts are a function of pressure and brine saturation at the time of drilling intrusion with competing interactions between released brine volume and the concentration of radionuclides in the material being released.

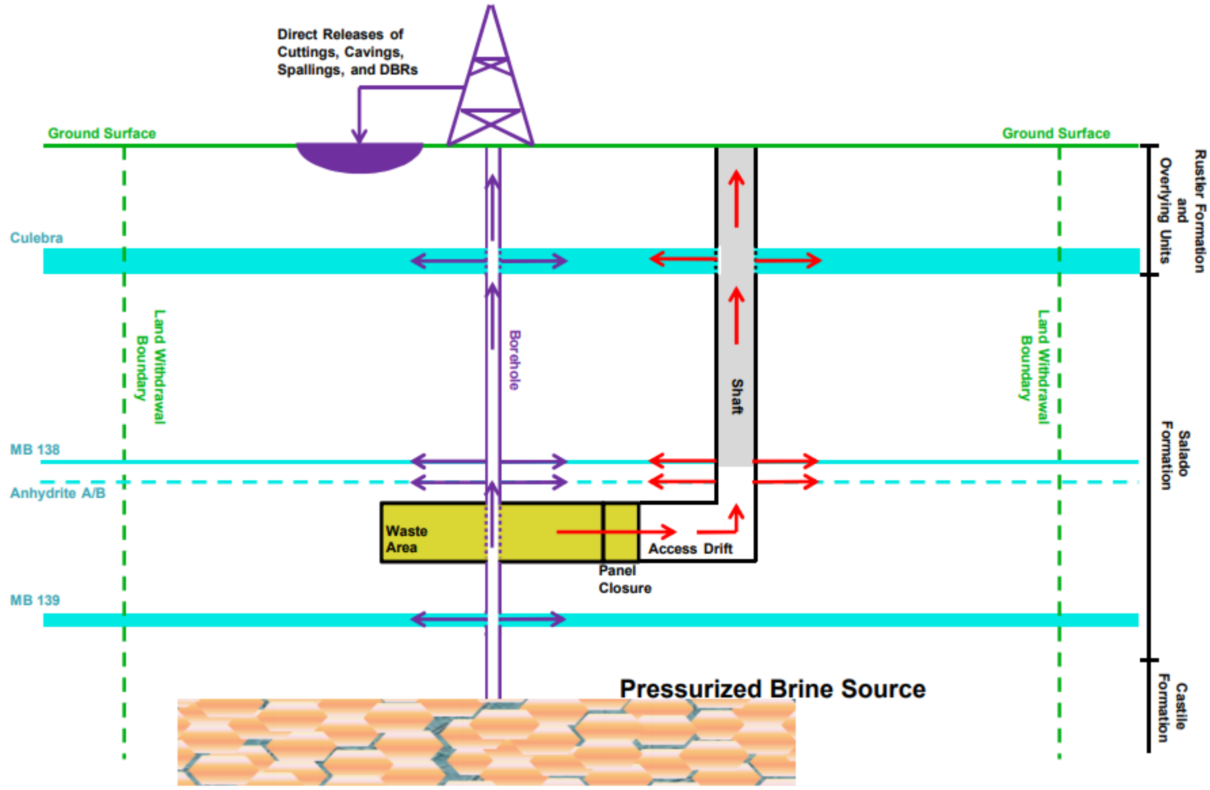

Figure 3-9 WIPP release pathways from the WIPP Performance Assessment. From Zeitler, 2016.

To focus on the changes caused by the increased drift volume from the SDI mining, an SDI impact assessment was performed. In this analysis, the only changes made to the PABC-2009 model were the addition of the SDI drift volume in an extension of the model domain to include this region (Camphouse et al., 2011).

A comparison between radiological releases for the PABC-2009 and the SDI impact assessment is shown in Figure 3-10. The results are virtually identical, showing that the SDI mining has no net impact on the performance of the repository. For both cases, the WIPP releases are well below the EPA release limits.

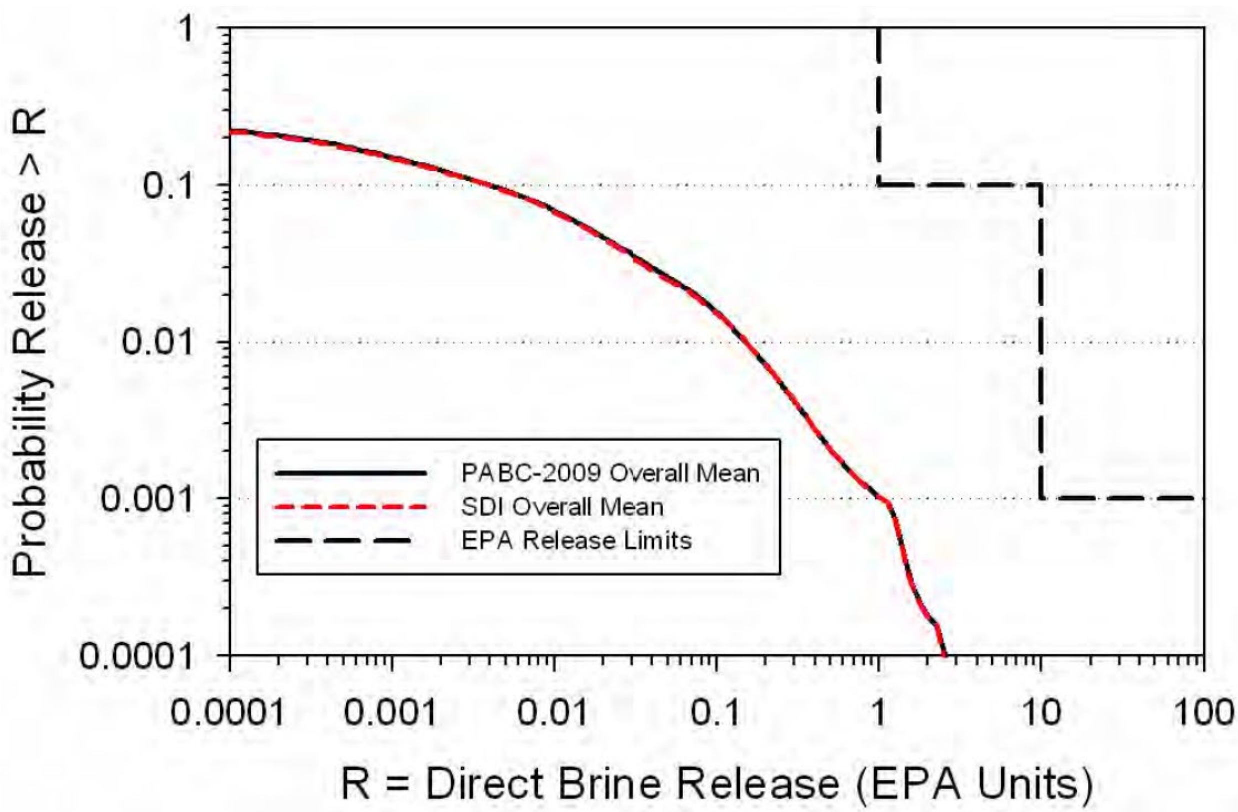

Figure 3-10 Comparison of DBR releases between the 2009 PACB and the SDI impact assessment. From Camphouse et al., 2011.

3.3 Potential impacts from URLs at WIPP

Although both the thermal signal and increased void space from a significant proposed URL was determined to have insignificant impact on radiological releases at WIPP, there are other URL impacts that could be considered as part of the overall Geological Disposal Safety Analysis (GDSA). Here we discuss some ideas that could be of importance for GSDA.

3.3.1 Overall thermal load in the underground

The overall thermal load in the underground at a generic salt repository will be influenced by URL activity. The addition of heat to the underground will impact the long-term rate of salt creep (Hansen and Leigh, 2011). Figure 3-10 shows a strong, non-linear response of creep to temperature. Any increase in the temperature of the salt surrounding a repository, such as from a URL, will lead to an increase in the rate of deformation. Increased deformation rates in the salt surrounding a repository may lead to both short-term and long-term impacts. In the short-term, the impacts could be negative, leading to more frequent required maintenance on drifts to keep them open. In the long-term, increased plasticity at lower effective salt viscosity could be beneficial, allowing the repository to close faster.

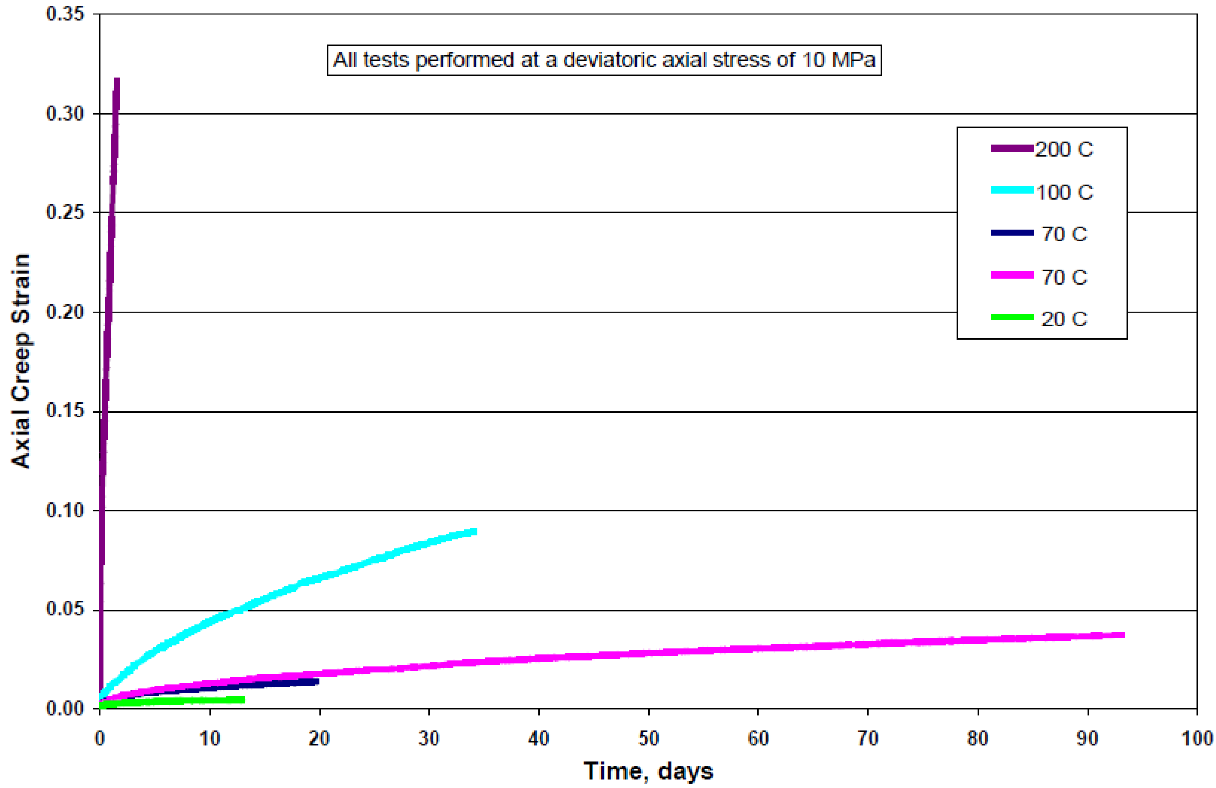

Figure 3-11 Temperature effects on salt creep. From Hansen and Leigh, 2011.

3.3.2 Timing of connected permeability from the URL to the repository

In the current WIPP performance assessment, a potential risk of long-term exposure is through drilling through the waste horizon and encountering high pressure water below the waste that can push contaminated water from the waste horizon to the surface (Figure 3-9). The connected porosity could remain an issue for some time as recent calculations of long-term drift closure (Blanco-Martin et al. 2018) have shown that regions of high permeability can remain in drifts at times of up to 1000 years (Figure 3-11). We posit that if the waste panels are connected through permeable pathways to the URL, the possibility exists for drilling through the URL to allow high pressure brine to flow from beneath the URL into the URL and laterally to the waste panels. This brine would pick up radionuclides and potentially be entrained back into any flow that reaches the surface. The net impact of such a scenario would be to increase the probability that drilling could impact releases, as the footprint of connected permeability would be higher with a URL that is connected to a repository. In the case of WIPP, the extra footprint is significant (Figure 3-2). Thus, the possibility for increased long-term connected permeability between an co-located URL/repository should be explored in GDSA simulations.

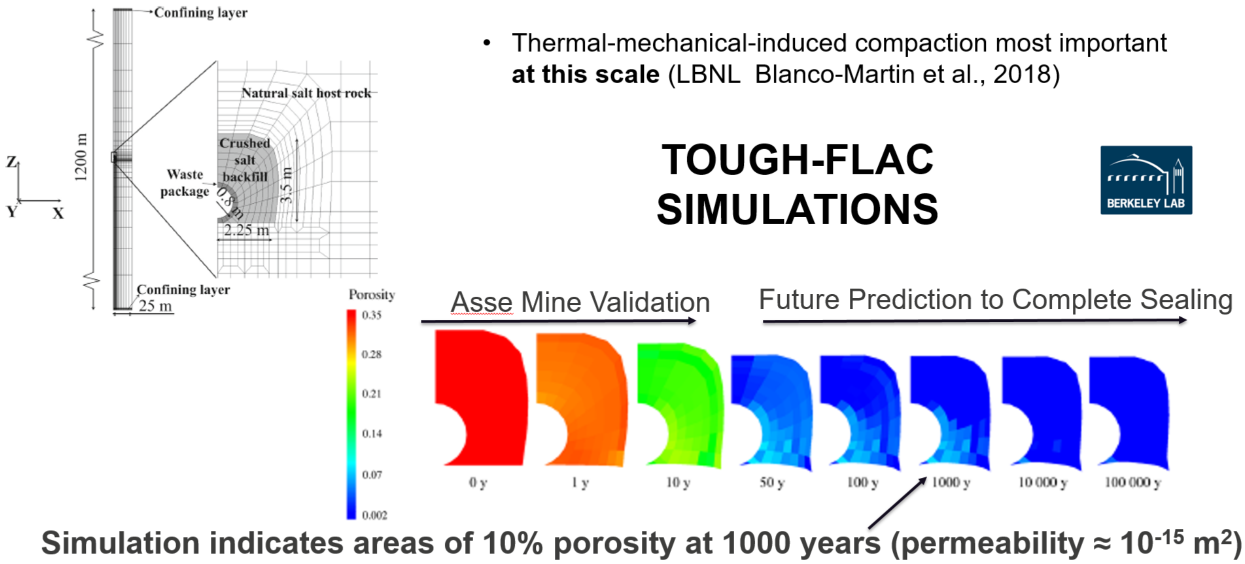

Figure 3-12 Predictions of long-term porosity. Modified from Blanco-Martin et al., 2018.

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