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Äspö Hard Rock Laboratory

CROP – Cluster Repository Project

Deliverable D6

Comparison of repository concepts & recommendations for design and construction of future safe repositories

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February 2004

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Comparison of repository concepts and recommendations for design and construction of future safe repositories

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Foreword

This document is the summary report from the Cluster Repository Project (CROP). It presents a basis for evaluating and developing concepts for safe deep geological disposal (repository) of long-lived radioactive waste, and the design and conduct of related tests in underground research laboratories (URLs). The classification of radioactive waste differs among the countries participating in CROP and the term "long-lived radioactive waste", as used in this report and other CROP documents, covers spent nuclear fuel (SF) and other high-level radioactive waste (HLW) as well as long-lived transuranic waste (TRUW), intermediate-level waste (ILW) and low-level radioactive/reactor waste (LLRW).

Nine different leading national waste management organizations participated in CROP and each Participant provided information from its respective organization and country on the project topics, which has been summarized in this document under three major rock types: salt rock, crystalline rock and clay rock, by Roland Pusch (Geodevelopment AB) and Christer Svemar (SKB). These summaries as well as the conclusions in common for all rock types presented in this report were discussed and agreed upon in seven topical project meetings with all Participants taking part. Each meeting addressed the information prepared by the Participants in draft topical reports, which were subsequently refined and included in Country Annexes (CAs) under one of four topical Work Packages.

This report is based on the information presented in the CAs, as synthesized by Tilmann Rothfuchs (GRS), Wilhelm Bollingerfehr (DBE), Mark Matthews (USDOE CBFO) and Leif Eriksson (GRAM Inc.) on salt rock, Peter Bluemling (Nagra), Fernando Huertas (Enresa), Gary Simmons (G.R. Simmons & Associates Consulting Services Ltd.), Christer Svemar (SKB) and Jukka-Pekka Salo (Posiva) on crystalline rock, and Peter Bluemling (Nagra), Fernando Huertas (Enresa), Jan Verstricht (SCK-CEN) and Fredric Plas (Andra) on clay rock. In the final stage, the text was refined by a working group consisting of: Peter Bluemling (Nagra), Leif Eriksson (GRAM Inc), Roland Pusch (Geodevelopment AB) and Christer Svemar (SKB). Gary Simmons (G.R. Simmons & Associates Consulting Services Ltd.), Mark Matthews (USDOE CBFO) and Leif Eriksson (GRAM Inc) have provided extensive review of contents as well as comments on linguistic matters. Agneta Lindgren and Marina Lindén (SKB) have provided the final touch to the format in order to make the text comply with the SKB report standards.

The project was funded by the European Commission and performed as part of the 5th Framework Programme, key action Nuclear Fission (1998-2002). The DBE (Germany) as well as the non-EU participants Nagra (Switzerland), USDOE CFBO (USA) and OPG (Canada) funded their own participation in the project.

AEspoe in March 2004

Christer Svemar

Project coordinator

Abbreviations

^{o}C	Degree Celsius
2-D	Two dimensional
3-D	Three dimensional
AECL	Atomic Energy of Canada Limited
AGP	Almacenamiento Geológico Profundo (Spanish for crystalline geological formation)
AIC	Active Institutional Control
AIS	Air Intake Shaft
Aitemin	Asociación para la Investigacion y Desarrollo Industrial de los Recursos Naturales
ALI	Annual limit on intake
ANSI	American National Standards Institute
ARCHIMEDE	Acquisition and regulation of water chemistry in an argillaceous medium (Hades)
AWID	Absolut Widerstandssprung Druckmesskissen
B	Biological/bacterial/microbial process
BACCUS	Backfill control experiment with hydration for the underground storage of radioactive waste (Hades)
BAMBUS	Backfill and Material Behavior in Underground Repositories in Salt (Asse)
BCE	Buffer/container experiment (AECL´s URL)
BGR	Bundesanstalt fuer Geowissenschaften und Rohstoffe
BMT	Buffer Mass Test
BWR	Boiling water reactor
C	Chemical process
CA	Country Annex
CCA	Compliance certification application for the Waste Isolation Pilot Plant
CCDF	Complementary cumulative distribution function

CEC	Cation exchange capacity
CERBERUS	Control experiment with radiation for the Belgian repository for underground storage (Hades)
CHLW	Civilian-generated high-level radioactive waste
CH-TRUW	Contact-handled transuranic radioactive waste
CoC	Agreement for Consultation and Cooperation between the U.S. Department of Energy and the State of New Mexico on the Waste Isolation Pilot Plant
CIEMAT	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (Research Centre for Energy, Environment and Technology)
CIMNE	Centro Internacional de Métodos Numéricos en Ingeniería
Clay Tech	Clay Technology AB
CLIPEX	Clay instrumentation programme for the extension for an underground research laboratory (Hades)
CORALUS	Corrosion of active glass in underground (Hades)
CPR	Celluloses, plastics and rubbers
CRT	Canister Retrieval Test (AEspoe)
D&D	Decontamination and decommissioning
DAC	Derived air concentration
DAS	Data acquisition system
DEBORA	Development of borehole seals for radioactive waste disposal (Asse)
DHLW	Defense-generated HLW
DI	Diffusion experiment (Mont Terri)
DIN	Deutsche Industrie Normen
DM	Deformation mechanism exxperiment (Mont Terri)
DOE	United States Department of Energy, also referred to as USDOE
EB	Engineered Barrier experiment (Mont Terri)
EBS	Engineered barrier system
EC	European Commission
EDZ	Excavation disturbed zone (here both damaged by excavation and disturbed by stress redistribution)

EH	EDZ self-healing (Mont Terri)
EPA	United States Environmental Protection Agency, also referred to as USEPA
ESDRED	Engineering Studies and Demonstration of Repository Designs
ESS	Excavation Stability Study (AECL´s URL)
Febex	Full-scale engineered barriers experiment in crystalline host rock (Grimsel)
FEM	Finite element method
FEP	Features, events and processes
GFS	Gesellschaft fuer Strahlenforschung
GP	Gas permeability test
GTA	Groupe Travail Architecture
H	Hydrological process
Hades	High Activity Disposal Experimental Site
HE	Heater experiment (Mont Terri)
HFT	Heated Failure Tests (AECL´s URL)
HLW	High-level radioactive waste
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
IEC	International Electrotechnical Commission
ILW	Intermediate-level radioactive waste
IP	Intergranular pore space
IPC	Inorganic Phosphate cement
ITT	Isothermal Buffer/Rock Concrete Plug Interaction Test (AECL´s URL)
JNC	Japan Nuclear Cycle Development Institute
KBS-3	Kaernbraenslesaekerhet #3 (Swedish for “ nuclear fuel safety 3”)
LANL	Los Alamos National Laboratory
LHS	Latin Hypercube Sampling
LLRW	Low-level radioactive/reactor waste
LOT	Long-term Test of Buffer Material (AEspoe)

LWR	Light water reactor
M	Mechanical process
MA	C and B experiment (Mont Terri)
MEGAS	Modeling and experiment on gas migration in repository host rocks (Hades)
MII	Materials Interface Interaction tests (WIPP)
MOX	Mixed oxide fuel
MPC	Maximum permissible concentration. Refers to maximum levels of radioactivity in drinking water or in air as established by national authorities. (See also annual limit on intake [ALI] and derived air concentration [DAG] in Appendix 2)
MS	Micro-seismics
NBS	Natural barrier system
NET.EXCEL	Network of excellence in nuclear waste management and disposal
NIST	United States National Institute for Standards and Technology
NRC	United States Nuclear Regulatory Commission, also referred to as USNRC
OC	Over-consolidation
OCR	Over-consolidation ratio
OCRWM	United States Department of Energy Office of Civilian Radioactive Waste Management (responsible for deep geological disposal of spent nuclear fuel and other high-level radioactive waste in the USA)
OECD/NEA	Organisation for Economic Co-operation and Development/Nuclear Energy Agency
OPC	Ordinary Portland cement
OPHELIE	On surface preliminary heating simulation experimenting later instruments and equipments (Hades)
P&S	Plugging and sealing tests (WIPP)
PA	Performance assessment
PAVT	Performance Assessment Verification Test (WIPP)
PC	Pore water chemistry experiment
PHEBUS	Hydraulic transfer between host rock and (ventilated) underground structures (Hades)

PI	Principal investigator
PIC	Passive institutional controls
ppm	Parts per million (unit)
PRACLAY	Preliminary concept in clay (Hades)
PS	Principal scientist
PWR	Pressurized water reactor
QA	Quality assurance
QC	Quality control
Rem	A radiation dose unit equivalent to one hundredth of a Sievert
RCRA	The Resource Conservation and Recovery Act of 1976 (Public Law 94-580 in the USA)
RESEAL	Repository sealing in argillaceous rock (Hades)
RH	Relative humidity
RH-TRUW	Remote handled transuranic radioactive waste
RN	Radionuclide
RRC	Reference repository configuration
RTD	Research, technical development and demonstration. Or Resistance Temperature Detector
RWMC	Radioactive Waste Management Funding and Research Center (Japan)
SA	Safety assessment
SAFIR	Safety assessment and feasibility interim report (Hades)
SAM	Systemanalyse Mischkonzept
SELFRAC	Fractures and self-healing within the excavation disturbed zone in clay (Mont Terri)
SF	Spent nuclear fuel
SFR	Slutfoervar foer reaktoravfall. Swedish for “final repository for reactor waste”
SHS	Salt handling shaft
SI	International Standards Units
Sievert	A radiation dose unit equivalent

SNL	Sandia National Laboratories
SSS	Shaft-seal-system
SWB	Standard waste box
T	Temperature/thermal process
TBM	Tunnel boring machine
TDS	Total dissolved solids
THE	Thermal-Hydraulic Experiment (AECL´s URL)
THMCB	Coupled thermal, hydrological, mechanical, chemical, biological processes
THS	Thermal-Hydraulic Studies (AECL´s URL)
TMSS	Thermal Mechanical Stability Studies (AECL´s URL)
TRUW	Transuranic radioactive waste
TSDE	Thermal Simulation of Drift Emplacement (Asse)
TSI	Thermal/structural interaction tests (WIPP)
TSX	Tunnel Sealing Experiment (AECL´s URL)
UPC	Universitat Politècnica de Catalunya
URL	Underground research laboratory
USEPA	United States Environmental Protection Agency, also referred to as EPA
USNRC	United States Nuclear Regulatory Commission, also referred to as NRC
UWC	University of Wales Cardiff
VE	Ventilation Experiment (Mont Terri)
WIPP	Waste Isolation Pilot Plant
VLJ	Voima Laitos Jaete. Finnish for “power plant waste”
VOC	Volatile Organic Compound
WP	Work Package
WPP	Waste package performance
WS	Pore water chemistry experiment (Mont Terri)

SYMBOLS AND PARAMETERS	**DEFINITIONS**
Mathematical	
E+ or E-	Exponential functions expressed as E+ or E- (e.g., E-6 = 10^{-6}).
Geometrical	
d	Grain diameter (µm, mm).
H	Height (m, km).
L	Length (nm=E-9, Å=E-7 mm, m, km).
Soil physical/ chemical	
e	Void ratio (ratio of pore volume and volume of solids).
g	Gravity (m/s^2).
i	Hydraulic gradient (m/m).
k	Permeability (m^2).
n	Porosity (ratio of pore volume and total volume), (%).
m	Mass (kg).
t	Time (s).
w	Water content (ratio of mass and solids), (%).
w_L	Atterberg Liquid Limit (%).
w_P	Atterberg Plastic Limit (%).
CEC	Cation exchange capacity mE/100 g solids).
D	Diffusivity (m^2/s), Diameter (m).
D_a	Apparent diffusivity (m^2/s).
D_e	Effective diffusivity (m^2/s).
D_p	Pore diffusivity (m^2/s).
K	Hydraulic conductivity (m/s).
K_d	Sorption factor (m^3/kg).
Sv	Sievert, radiation dose.
S_r	Degree of fluid saturation (ratio of volume of saturation and total volume) (%).
T	Temperature (^{0}C, K).
η	Viscosity (Ns/m^2).
ρ	Density at actual degree of fluids saturation (kg/m^3).
ρ_d	Dry density (kg/m^3). Mass of solids divided by total volume.
ρ_{sat}	Density at fluid-saturation (kg/m^3).
Grain size	
Clay	Particle size smaller than 2µm, with at least 20 weight% particles of this size.
Silt	Particle size ranging from 2 to 60 µm, with at least 20 weight% particles of this size.
Sand	Particle size ranging from 60 to 200 µm, with at least 40 weight% particles of this size.
Gravel	Particle size from 2 to 20 mm, with at least 40 weight% particles of this size.

Cobble	Particle size ranging from 60 to 600mm, with more than 40 weight% cobbles.
Boulder	Particle size exceeding 600 mm, with more than 40 weight% boulders and cobbles.
Soil and rock mechanics	
c	Cohesion (kPa, MPa). Shear strength for zero effective normal stress.
p	Pressure (kPa, MPa).
p_s	Swelling pressure (kPa, MPa).
q	Load intensity (N/m^2).
u	Porewater pressure (kPa, MPa).
E	Modulus of elasticity (kPa, MPa, GPa).
G	Shear modulus (kPa, MPa, GPa).
M	Odeometer modulus.
K	Compression modulus (N/m^2).
P	Force (N, kN, MN, tons).
ε	Strain (m/m).
Φ	Angle of international friction.
σ	Stress (kPa, MPa).
σ'	Effective stress (kPa, MPa).
$(\sigma_1 - \sigma_3)_o$	Reference deviator stress (kPa, MPa).
$(\sigma_1 - \sigma_3)_f$	Deviator stress of failure.
τ	Shear stress (kPa, MPa).
υ	Poisson's ratio.
Thermal	
C	Heat capacity (Ws/kg, K).
λ	Heat conductivity (W/m, K).
α	Coefficient of linear thermal expansion (1/^oC) or (1/K).
α_L	Theoretical lower bound of linear thermal expansion (1/^oC) or (1/K).
α_U	Theoretical upper bound of linear thermal expansion (1/^oC) or (1/K).
β	Coefficient of volume expansion (1/^oC) or (1/K).
γ	Grueneisen parameter.
γ_{th}	Grueneisen parameter: thermodynamic gamma.
δ_r	Anderson-Grueneisen parameter.
ε	Strain.
Θ_D	Debye temperature (K).
ρ	Resistivity (Ωm).
ρ	Specific mass (kg/m^3).
σ	Stress (Pa).
A	Area (m^2).
c	Stiffness tensor.
C_P	Specific heat constant pressure (J kg^{-1} K^{-1}).

C_V	Specific heat in constant volume (J kg^{-1} K^{-1}).
D	Diameter (m).
E	Modulus of elasticity (Young's modulus) (MPa, MN/m^2).
E	Energy of lattice vibrations (J).
GF	Gauge factor.
K	Bulk modulus (compressibility).
K_T	Isothermal bulk modulus (Pa).
L	Length (m).
n	Number of atoms in chemical formula (mol).
N	Axial force (N).
P	Pressure (Pa).
R	Residence (Ω).
R	Gas constant, 8.314*(J mol^{-1} K^{-1}).
S	Entropy (J mol^{-1} K^{-1}).
T	Temperature (^oC) or (K).
U	Internal energy (J).
V	Volume (m^3).

*Only major and frequently used abbreviations are listed

Abstract

In January 2001, the European Commission (EC) signed a contract with nine organizations with leading national responsibility for radioactive waste management for funding the development of a basis for evaluating and developing concepts for safe final repositories for long-lived radioactive waste by January 2004. The project is called the “Cluster Repository Project” and referred to in this document as either “CROP” or “the project”. The nine Participants are in alphabetical order:

1. Agence Nationale pour la gestion des Déchets Radioactifs (Andra), France.
2. Empresa Nacional de Residuos Radiactivos S.A. (Enresa), Spain.
3. Gesellschaft fuer Anlagen- und Reaktorsicherheit mbH (GRS), Germany.
4. Nationale Genossenschaft fuer die Lagerung Radioaktiver Abfaelle (Nagra), Switzerland.
5. Ontario Power Generation Inc (OPG), Canada, supported by G.R. Simmons & Associates Consulting Services Ltd.
6. Posiva Oy, (Posiva), Finland.
7. Svensk Kaernbraenslehantering AB (SKB), Sweden, supported by Geodevelopment AB
8. Studiecentrum voor Kernenergie-Centre d′étude de l′Energie Nucléaire (SCK-CEN), Belgium.
9. United States Department of Energy Carlsbad Field Office (USDOE CBFO), USA, supported by GRAM, Inc. and Sandia National Laboratories (SNL).

Nagra, OPG and USDOE CBFO were self-funded Participants. Deutsche Gesellschaft zum Bau und Betrieb von Endlagern fuer Abfallstoffe mbH (DBE) joined CROP as a self-funded observer in 2002. SKB served as the project coordinator.

The project focused on design, construction and modeling of engineered barrier systems (EBSs) as well as on experimental procedures, and the cluster of Participants constituted a forum for exchange of information on these topics through correspondence and through seven meetings in different countries. Each meeting was combined with a visit to the URL in the host country. The improved knowledge gained in this manner and documented in the CROP reports will be valuable in resolving issues in selecting repository designs, including engineered barrier components, systems to monitor *in-situ* test and repository system performance, and accurate theoretical models and numerical codes and for engineering designs and performance/safety assessment, and in describing the function of repositories to the scientific society and the public. It should be noted that the classification of radioactive waste differs among the countries participating in CROP and the term “long-lived radioactive waste”, as used in this report and other CROP documents, covers spent nuclear fuel (SF) and other high-level radioactive wastes (HLW) as well as long-lived transuranic waste (TRUW), intermediate-level (ILW) and low-level radioactive/reactor waste (LLRW).

Several national underground research laboratories (URLs) for studying the possibility of safe deep geological disposal of long-lived radioactive waste have been operated by the Participants for different periods of time in different geological media, such as bedded or domal salt rock in the United States of America (WIPP) and Germany (Asse), crystalline rock in Sweden (Stripa and AEspoe), Finland (Olkiluoto), Switzerland (Grimsel), and Canada (URL, Pinawa), and clay rock in Belgium (Mol), France (Bure) and Switzerland (Mont Terri). The different site-specific geological conditions have led to different design and instrumentation of the aforementioned URLs. However, the engineered barriers tested and analyzed in the URLs have a similar function and, despite some obvious differences, many of the solutions and techniques summarized in the CROP documents are believed to be applicable to disposal concepts in a variety of different rock types. The results from tests conducted by the Participants in the many different geological media and involving a large number of EBS components are expected to be valuable to all organizations involved in repository development.

The report notes that all the repository concepts studied by the Participants fulfill very high demands of long-term safety, and summarizes lessons learned, remaining issues and areas of high potential for technical improvements of repository concepts and the testing of them. The conclusion is that improved technical solutions will evolve from the joint analyses conducted and documented by the Participants.

Sammanfattning

I januari 2001 tecknade Europeiska Unionen ett avtal med nio organisationer med ledande, nationellt ansvar för hantering av långlivat, radioaktivt avfall. Innebörden av avtalet var att Europeiska Unionen finansierade framtagandet av en bas för utvärdering och utveckling av koncept för säker slutförvaring av långlivat, radioaktivt avfall till januari 2004. Projektet benämndes ”Cluster Repository Project” och förkortades “CROP”. De nio deltagarna är i alfabetisk ordning:

1. Agence Nationale pour la gestion des Déchets Radioactifs (Andra), Frankrike.
2. Empresa Nacional de Residuos Radiactivos S.A. (Enresa), Spanien.
3. Gesellschaft für Anlagen- und Reaktorsicherheit mbH (GRS), Tyskland.
4. Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle (Nagra), Schweiz.
5. Ontario Power Generation Inc (OPG), Kanada, understött av G.R. Simmons & Associates Consulting Services Ltd.
6. Posiva Oy, (Posiva), Finland.
7. Svensk Kärnbränslehantering AB (SKB), Sverige, understött av Geodevelopment AB
8. Studiecentrum voor Kernenergie-Centre d′étude de l′Energie Nucléaire (SCK-CEN), Belgien.
9. United States Department of Energy Carlsbad Field Office (USDOE CBFO), USA, understött av GRAM, Inc. och Sandia National Laboratories (SNL).

Nagra, OPG och USDOE CBFO finansierade sitt deltagande själva. Deutsche Gesellschaft zum Bau und Betrieb von Endlagern für Abfallstoffe mbH (DBE) gick med i CROP 2002 som självfinansierad observatör. SKB var projektkoordinator.

Arbetet fokuserades på design, konstruktion och modellering av ingenjörsbarriärer för slutförvar av använt kärnbränsle och annat långlivat radioaktivt avfall liksom på experimentella tillvägagångssätt, och gruppen av deltagare har utväxlat information i dessa frågor i korrespondens och sju möten i olika länder med tillgång till ett besök till värdlandets berglaboratorium. Den förbättrade kunskapen kommer att bli värdefull vid val av förvarsdesign inklusive komponenter i ingenjörsbarriärerna, system för att registrera och övervaka fältförsök och förvarsfunktioner, noggranna, teoretiska modeller för ingenjörsutformning och säkerhetsfunktioner, och beskrivning av förvarsfunktioner till samhälle och allmänhet.

Olika nationella berglaboratorier för studier av möjligheten till säker geologisk deponering av radioaktivt avfall har varit i drift under olika lång tid. De representerar i projektet olika geologiska medier såsom kristallint berg i Sverige (Stripa och Äspö), Finland (Olkiluoto), Schweiz (Grimsel) och Kanada (URL i Pinawa), bergsalt i USA (WIPP) och Tyskland (Asse) samt lera och lerberg i Belgien (Mol), Frankrike (Bure) och Schweiz (Mont Terri). De olika geologiska förhållandena har lett till olika utformningar och olika instrumenteringar i de nämnda berglaboratorierna. Men, ingenjörsbarriärerna har likartad funktion, och trots vissa uppenbara olikheter, bedöms många av lösningarna och metoderna vara applicerbara på deponeringskoncept i många, olika typer av bergmedier. Resultaten från tester i många olika geologiska medier, inkluderande ett stort antal olika komponenter i ingenjörsbarriärerna, förutskickas bli värdefulla för alla organisationer som är engagerade i utveckling av säkra geologiska slutförvarsmetoder för använt kärnbränsle och annat långlivat radioaktivt avfall. Det skall noteras att klassificeringen av radioaktiva material inte är enhetlig i alla länder och termen ”långlivat, radioaktivt avfall” i den här och i de andra CROP-rapporterna avser att täcka alla långlivade radioaktiva material såsom använt kärnbränsle (SF), högaktivt, radioaktivt avfall (HLW), medelaktivt, radioaktivt avfall (ILW), lågaktivt, radioaktivt avfall/lågaktivt reaktoravfall (LLRW), och transuraniskt, radioaktive avfall (TRUW).

Rapporten drar slutsatsen att alla studerade geologiska förvarskoncept uppfyller mycket högt ställda nationella säkerhetskrav. Den rapporterar om lärda läxor, återstående frågor att studera och indikerar områden med hög potential till tekniska förbättringar av förvarskoncept och tester av dem. Slutsatsen är att förbättrade tekniska lösningar kommer att utvecklas med hjälp av resultaten från arbetet i CROP.

Executive summary

In January 2001, the European Commission (EC) signed a contract with nine organizations with leading national responsibility for radioactive waste management for funding the development of a basis for evaluating and developing concepts for safe final repositories for long-lived radioactive waste by January 2004. It should be noted that the classification of radioactive waste differs among the countries participating in CROP and the term “long-lived radioactive waste”, as used in this report and in the other CROP documents, covers spent nuclear fuel (SF) and other high-level radioactive wastes (HLWs) as well as long-lived transuranic waste (TRUW), intermediate-level waste (ILW) and low-level radioactive/reactor waste (LLRW). The project is called “Cluster Repository Project” (CROP) and is henceforth referred to as “CROP” or “project”. The nine Participants in the project are in alphabetical order:

1. Agence Nationale pour la gestion des Déchets Radioactifs (Andra), France.
2. Empresa Nacional de Residuos Radiactivos S.A. (Enresa), Spain.
3. Gesellschaft fuer Anlagen- und Reaktorsicherheit mbH (GRS), Germany.
4. Nationale Genossenschaft fuer die Lagerung Radioaktiver Abfaelle (Nagra), Switzerland.
5. Ontario Power Generation Inc (OPG), Canada, supported by G.R. Simmons & Associates Consulting Services Ltd.
6. Posiva Oy, (Posiva), Finland.
7. Svensk Kaernbraenslehantering AB (SKB), Sweden, supported by Geodevelopment AB
8. Studiecentrum voor Kernenergie-Centre d′étude de l′Energie Nucléaire (SCK-CEN), Belgium.
9. United States Department of Energy Carlsbad Field Office (USDOE CBFO), USA, supported by GRAM, Inc. and Sandia National Laboratories (SNL).

Nagra, OPG and USDOE CBFO are self-funded Participants. Deutsche Gesellschaft zum Bau und Betrieb von Endlagern fuer Abfallstoffe mbH (DBE) joined CROP as a self-funded observer in 2002. SKB has served as the project coordinator.

The project focused on design, construction and modeling of engineered barrier systems (EBSs) as well as on experimental procedures, and the cluster of Participants has constituted a forum for exchange of information on these topics. The improved knowledge gained in this manner and documented in the CROP reports will be valuable in resolving issues on selecting adequate and robust models and codes for performance/safety assessment and in describing the function of repositories for long-lived radioactive waste to the scientific society and the public.

Several national underground research laboratories (URLs) for studying the possibility of safe deep geological disposal of radioactive waste have been in operation for different periods of time. They represent in the project different geological media, such as salt rock (bedded and domal) in the United States of America (WIPP) and Germany (Asse), crystalline rock in Sweden (Stripa and AEspoe), Finland (Olkiluoto), Switzerland (Grimsel), and Canada (URL, Pinawa), and clay rock (soft/plastic and hard/indurated) in Belgium (Mol), France (Bure) and Switzerland (Mont Terri). The different geological situations have led to different design and instrumentation of the aforementioned URLs. However, the engineered barriers have a similar function and, despite some obvious differences, many of the solutions and techniques reported by the Participants are believed to be applicable to disposal concepts in other rock types. The results from tests conducted in the many different geological media by the Participants and involving a large number of EBS components are expected to be valuable to all organizations involved in repository and URL development.

It is concluded that all the repository concepts studied by the Participants fulfill very high demands of long-term safety requirements relevant to respective country. The study reports on areas of lessons learned and remaining issues. The study also indicates areas of high potential for technical improvements of repository concepts and the testing of them. The conclusion is that improved technical solutions will evolve from the joint analyses conducted and documented by the Participants.

Objectives and strategic aspects

The main objective of the project was to collect and document information on how deep geological disposal of long-lived radioactive waste is planned and developed in countries involved in the project, for the purpose of identifying the current status, similarities and differences among the Participants. The purpose was to establish a common basis for the development of repositories for long-lived radioactive waste and to identify areas with a high potential for improvement. Three different groups of geological environment were evaluated by the Participants: salt rock (both bedded and domal salt rock), crystalline rock, and clay rock (both soft plastic clay and hard indurated clay).

The resulting CROP reports can serve as an aid for future repository and URL design and construction in all countries utilizing nuclear power and hence be of value to national and international experts engaged in the handling and disposal of long-lived radioactive waste.

Research performed and methods/approach adopted

The work was performed in a series of seven workshop sessions at different places (AEspoe in Sweden, Braunschweig in Germany, Mol in Belgium, Murten in Switzerland, Winnipeg in Canada, Carlsbad in USA and Olkiluoto in Finland), where the Participants met and discussed pre-determined issues and exchanged information on the topics. Each meeting was combined with a visit to the URL in the host country. The workshops have stepwise addressed Work Packages (WP) dealing with the following issues:

WP1:	Design and construction of engineered barrier systems (EBS).
WP2:	Instruments and experimental procedures.

WP3: Assessment of the function of EBS and the understanding of and capability to model the important processes.

WP4: System improvement and development.

The start of the project was the compilation of the Project Plan [1] and the main results are compiled in this report, and summarized in the Final Technical Report, which has been submitted to the EC in compliance with the Contract.

Main achievements

WP1 - Design and construction of engineered barrier system (EBS)

For each of the geological media considered by the Participants the principles for repository design have been described with special emphasis on the EBS performance. The URL/repository locations are in the interval between 200 to 1 200 m below the ground surface. All Participants consider one-level repository, and some also consider multi-level repository concepts. Access to the repositories is through shafts for salt rock, while both ramps and shafts are planned for crystalline rock and clay rock.

The major repository design principle is to use a system of natural and engineered barrier components to control the containment and isolation of radionuclides so that any potential release of radionuclides to levels acceptable in the biosphere is kept as low as reasonably achievable (ALARA) and well below the respective/applicable national requirements. The accomplishment of this principle requires prediction of the evolution and performance of the repository system over unprecedented spatial and temporal scales, which to a large extent may be governed by the degradation of the EBS, which appears to have been modeled very conservatively by the Participants. The temperature in the near-field during the heat pulse, generated by the disposed radioactive waste, is shown to be an important factor since it could strongly affect the chemical processes in and longevity of the EBS components as well as the structural stability of the underground openings and the magnitude and direction of groundwater flow.

According to the different features of the geological media the EBS of the various concepts are different. As to the waste canisters, SKB, Posiva and OPG are designing very corrosion-resistant canisters for the spent fuel, while less durable canisters represent a feasible and safe option for several of the other Participants. For long-lived transuranic radioactive waste (TRUW)), which is being routinely disposed of in the Waste Isolation Pilot Plant (WIPP) bedded salt rock repository since 1999, no post-closure barrier function is ascribed to the steel waste containers, and a canister lifetime of only up to a thousand years is assumed for several other repository concepts.

Buffers and backfills considered by the Participants are of different types. For the two concepts in salt rock, a combination of magnesium oxide (MgO) and/or crushed salt will be used. For those in crystalline rock and clay rock, smectitic clay is relied upon as buffer and backfill, either alone or mixed with other materials. Cementitious seals and concrete are options for Andra's concept intended for either crystalline rock or hard clay rock and for SCK-CEN's repository concept in soft clay rock.

All Participants recognize the importance of structurally sound, low permeability plugs and seals. The isolation provided by a plug or seal is closely related to the extent and properties of the excavation disturbed zone (EDZ) in all the geological media evaluated by the Participants, and the capability of the plug to seal or cut off flow in the EDZ in a long-term perspective.

WP2 - Instruments and experimental procedures

The Participants´ work on instrumentation and experimental procedures has been very successful, and both the background for selection and the evaluation of performance in the field are summarized below. An important finding is that the instruments themselves and the tubing and cables that transfer signals to the monitoring units may have a significant adverse effect on the performance of the buffer and backfills in URL demonstrations. The experiments with complete systems of heat-producing canisters, clay buffer and surrounding rock have provided extensive data on the various short-term processes that would affect the maturation of the EBS in real repositories. These data are being used for comparison with numerical model predictions.

The selection, application and performance of the various instruments in the Participants´ URLs are described in detail in the CAs supporting WP 2. The major findings are described below:

Temperature evolution in buffers, backfills and near-field rock

Temperature data are required for confirming repository design and for validating theoretical models and numerical codes. High accuracy (e.g., +/- 0.1°C) may be needed to correct for thermal expansion and thermal sensitivity of instruments, and to use the temperature evolution as a basis of predicting the hydration rates of clay-based EBS components. The sensitivity of the sensors to chemical attack by the pore water may cause quick breakdown of the sensors, and their design should thus include inert coatings, such as titanium, in demanding chemical environments.

Stress and strain measurements in the EBS and the near-field rock

Stress/strain data are needed for validating theoretical models and numerical codes for predicting hydration of buffers and backfills, impact on rock and displacement of canisters. However, there are difficulties in obtaining accurate data, one of the major problems being water leakage along tubing and cables.

A general conclusion is that stress and strain gauges are relatively big and that the data they record only represent average conditions in a rather large volume of the rock or the soil. The risk of *in-situ* chemical degradation requires that inert metals are used to shield the sensor elements.

Hydration measurements

Moisture gauges, such as psychrometers, are used for recording the rate of wetting and drying in buffers and backfills. Each type of sensor serves accurately only up to a certain degree of fluid saturation and combination of two different types of sensors to cover the full range of expected fluid saturations is thus recommended. The number of gauges that can be applied in a large-scale demonstration test is limited by the space they require and the need to avoid physical interactions between adjacent sensors.

A general conclusion is that sensors for recording the degree of fluid saturation are the least reliable of all instruments and the first to fail according to the experience gained in several URLs. Hence, new types of more durable/robust sensors would be beneficial to future experiments.

Gas percolation, mineral changes, ion migration and microbial activities

Filters in buffers have been successfully used for recording gas flow. For evaluation of ion migration and determination of microbial activities, cups can be installed for sampling at the termination of the test. Mineral changes and microbial populations can only be evaluated using samples taken after the experiments have been terminated.

WP3 - Assessment of the function of EBS and the understanding of and capability to model the important processes

The development of conceptual and theoretical models for describing and predicting maturation of clay and salt buffers under varying thermal conditions has been extensive among the Participants. However, more needs to be known about the conditions for hydration of clay buffers and the role of the rock structure, including the EDZ, in providing water to support buffer maturation. For example the detailed movement of water associated with condensation/evaporation and film transport needs more attention. A further question that also deals with inflow of water is how one can stop excessive water inflow into deposition holes or drifts during the construction and waste placement phases, and in particularly during the placement of clay buffers and backfills.

Maturation of salt buffer in salt rock and of clay buffer in clay rock is intimately connected to the rheology of the surrounding host medium and, with the exception of the already certified and operating WIPP repository, the development of the rate of convergence in the final codes and models the rate of convergence will need further site-specific study. The understanding of creep processes in salt buffer and salt rock as well as in stiff and plastic clay rock should benefit from additional study of the mechanisms on the micro-structural scale.

Gas release from canisters and gas migration through the buffer requires more attention in HLW repositories although the conceptual understanding of processes involved has been developed.

Modeling of chemical processes in clay buffer is an issue that requires more work, especially in the areas of complexation and cementation. A remaining task is to develop more accurate theoretical models and numerical codes for cementation by mineral precipitation, and conversion of smectite to non-expandable minerals.

WP4 - Discussion, conclusions and lessons learned

The multi-media comparison is a new issue brought up in this project and lengthy discussions were conducted throughout the project. Some general conclusions derived from these discussions follow.

Salt rock

- Crushed salt rock makes a good backfill as stress and creep-induced room closure (convergence) ultimately leads to consolidation of crushed-salt backfill and ultimately the complete encapsulation of the waste canisters.
- With the given weight and size of waste packages, the repository design is a country- and site-specific issue, of which the WIPP repository in bedded salt rock is an operating/functioning proof-of-principle example. The designs of seals and plugs, which are the main engineered barriers in salt rock, are also site-specific.

- For the German domal salt repository, work remains to be conducted for verification/optimization of design details.
- Good capability exists of modeling excavation-induced effects, e.g., the rate and extent of EDZ generation, but adequate prediction of EDZ healing needs further research.
- Final confirmation of the technical emplacement system for Cogéma canisters, as well as the testing of the feasibility of the emplacement of alternative canisters for spent nuclear fuel (SF) into 300 m deep boreholes, is pending.
- *In-situ* testing of the suggested drift seal design under representative conditions is pending.
- The THM behavior of crushed salt rock backfill is largely understood. With the exception of the MgO used at WIPP, the effectiveness of including geochemical additives in the EBS to increase sorption of special radionuclides in the near-field has not been tested adequately.

Crystalline rock

- Crystalline rock has brittle characteristics and contains fractures, which may form patterns of groundwater transport pathways from a repository to the ground surface. The existence of fracture systems and their transport characteristics are the major factors that influence both the construction conditions and the long-term safety case.
- Canister design and manufacturing, as well as the performance of different materials, have been investigated in detail.
- The most important single parameter for the design of the repository is the maximum temperature allowed in the near-field.
- The selection of excavation method needs consideration with respect to the repository design and operation and the consequences of the presence and extent of the EDZ.
- Grouting as a means for sealing drift walls against inflowing water needs to be developed as current experience shows limited success in grouting unsupported rock surfaces, and low-alkali (low pH) cements should be used because ordinary cementitious materials (high pH) are potentially detrimental to the properties of the clay-based EBS.
- Swelling clay alone or mixed with other materials is an outstanding material for use in buffer, backfill and plugs and has been thoroughly investigated for more than 20 years. Manufacturing of highly compacted blocks of various sizes has been verified.
- Emplacement and deposition methods have been tested on a full scale for vertical in-hole emplacement, but other emplacement configurations must be demonstrated at full scale.
- Backfilling of deposition drifts in the KBS-3V vertical in-hole emplacement method has been tested on a full scale for low-electrolyte-water but is not verified for salt water.

Clay rock

- The disposal concepts in both soft/plastic and hard/indurated clay rocks (clay shale, clay stone or argillite) are governed by the fact that the clay layers exhibit limited thickness and homogeneity. This favors in-room emplacement of canisters rather than in-hole emplacement in vertical holes. The alternative is several tens of meter long horizontal large diameter boreholes or micro-drifts.
- Excavation is typically more complex in clay rock than in salt rock or crystalline rock, but proven technology can be applied. Major verification of optimum techniques has been made in soft clay in the Mol URL, where the rock promptly needs permanent support of liners to prevent/alleviate the inherent plastic deformation/closure of the excavated openings.
- The clay rock is the main barrier in the multi-barrier system, but the near-field of the repository has to be designed and constructed in a way that man-made damage or disturbance due to the construction of the repository does not jeopardize long-term safety.
- Drift convergence, EDZ creation and de-saturation of clay rock may be minimized by concurrent excavation and operation (waste emplacement) of underground openings because it would keep the emplacement cells open for a minimum of time.
- Repository components such as large waste packages, buffer, backfill, seals and plugs are being investigated and the work exhibits many similarities with the work going on in crystalline rock.

General

- The application of the “observational method” that is based on design with probabilistic techniques (First Order Reliability Method) as identified by the Eurocode 7 [2] would be advantageous in order to plan for flexibility that allows for necessary changes caused by new information from site characterization or under ground excavation work on the existence of unexpected structural elements/discontinuities in the rock. Such discontinuities can occur especially in crystalline rock and stiff clay rock and could result in e.g., local drift instabilities.

Concluding remarks

From the successful development and 1999 opening of the WIPP repository and from all other programs advancing towards the licensing of deep geological repositories for long-lived radioactive waste, it is clear that authorities issuing future permits for repository development will recognize the importance of a sound safety case, good science and engineering, and public acceptance.

The CROP project has further clarified that there exist geological disposal concepts for SF, HLW, TRUW, ILW and LLRW that have been verified to perform in accordance with the respective nation’s safety requirements as well as international standards and that have been checked and found safe by international peer review teams.

The basis for the performance/safety analysis has been existing data bases built up, with among other things, full-scale testing in URLs of the combined and complex processes that are expected to take place in geological repositories.

As the objective is to identify, verify and develop methods for simulating processes, important for the design and the safety case, i.e., that is operative in a repository for long-lived radioactive waste, the Participants concluded that some full-scale verification tests, with extensive process coupling, remain to be done. These tests would be different for different geological media and in each country depending among other things upon the country's state of progress.

The existing URLs have performed according to plans and the ones in operation and under planning/construction represent a large enough variety of geological conditions in order to have the capability to provide credible generic information on repository concepts in all geological media of consideration in the world today (except tuff). However, they are neither capable of providing the site-specific information that every disposal program requires for final verification and fine-tuning of the safety case nor the detailed construction/operation parameters.

The different geological situations have led to different design and instrumentation of the respective Participant's URL. However, the EBSs have a similar function and, despite some obvious differences, many of the solutions and techniques documented by the Participants are believed to be applicable to disposal concepts in several other rock types. The results from tests conducted in the many different geological media and involving a large number of EBS components are expected to be valuable to all organizations involved in repository development, and it is thus expected that improved technical solutions and repository and URL designs will evolve from the joint analyses conducted and documented in the CROP reports by the Participants.

References

[1] **Pusch R., Svemar C., 2001:** AEspoe Hard Rock Laboratory. Project Description, SKB International Progress report IPR-01-23

[2] **Eurocode 7, 2004:** Geotechnical design – Part 1: General rules. EN 1997-1:2004.

Contents

1 Introduction

Several leading national organizations active in research, technical development and demonstration (RTD) projects underground, which deal with disposal of long-lived radioactive waste in salt rock, crystalline rock and clay rock have with the funding support of the European Commission (EC), joined forces and formed a cluster for evaluation of the results and experiences gained to date among the Participants and for using discussions to summarize and document the findings in a report that may serve as an aid for future underground research laboratory (URL) and long-lived radioactive waste repository designs and constructions in countries facing the task to isolate long-lived radioactive waste from man during an unprecedented long time period. This objective was met by the publication of this report. (The classification of radioactive materials differ among the Participants' nations and the term long-lived radioactive waste is used in this report and in other CROP documents for covering spent nuclear fuel (SF) and other high-level radioactive wastes (HLWs) as well as long-lived transuranic (TRUW), intermediate-level waste (ILW), and low-level radioactive/reactor waste (LLRW)).

The resulting collaboration is called the "Cluster Repository Project (CROP)", and nine end-user organizations, hereinafter referred to as the Participants, took part in the cluster representing Europe as well as North America. The Participants were in alphabetical order:

1. Agence Nationale pour la gestion des Déchets Radioactifs (Andra), France.
2. Empresa Nacional de Residuos Radiactivos SA (Enresa), Spain.
3. Gesellschaft für Anlagen- und Reaktorsicherheit mbH (GRS), Germany.
4. Nationale Genossenschaft fuer die Lagerung Radioaktiver Abfaelle (Nagra), Switzerland.
5. Ontario Power Generation Inc (OPG), Canada, supported by G.R. Simmons & Associates Consulting Services Ltd.
6. Posiva Oy, (Posiva), Finland.
7. Svensk Kaernbraenslehantering AB (SKB), Sweden, supported by Geodevelopment AB.
8. Studiecentrum voor Kernenergie-Centre d Etude de l`energie Nucleare (SCK-CEN), Belgium.
9. United States Department of Energy Carlsbad Field Office (USDOE CBFO), USA, supported by GRAM, Inc. and Sandia National Laboratories (SNL).

Nagra, OPG and USDOE CBFO were self-funded Participants. Deutsche Gesellschaft zum Bau und Betrieb von Endlagern fuer Abfallstoffe mbH (DBE) has participated as a self-funded observer since 2002. SKB served as the project coordinator, i.e., project manager.

The aforementioned CROP Participants represent URLs in several different geological media, such as salt rock (bedded and domal) in the United States of America (WIPP) and Germany (Asse), crystalline rock in Sweden (Stripa and AEspoe), Finland (Olkiluoto), Switzerland (Grimsel), and Canada (URL, Pinawa), and clay rock (soft/plastic and hard/indurated) in Belgium (Mol), France (Bure) and Switzerland (Mont Terri).

2 Scope of work and structure of report

2.1 Scope of work

The aim of CROP was to provide a forum for exchange of information among the Participants on repository design, construction and operation with the purpose of optimizing scientific networking among key experts in the involved countries. This was achieved by conducting a number of progress meetings at which pre-selected important issues were discussed, and by subsequently preparing individual Country Annexes (CA) providing detailed technical information on the issues from each of the CROP Participants. As summarized in this report, each of the participating organizations has extensive experience in the siting, design, development, and operation of URLs supporting the design and development of deep geological repositories for safe disposal of long-lived radioactive waste in the following geological media:

- *Salt rock*, including both domal and bedded salt (CBFO, GRS, and DBE).
- *Crystalline rock* (Andra, Enresa, Nagra, OPG, Posiva, and SKB).
- *Clay rock*, including both soft/plastic and hard/indurated clay (Andra, Enresa, Nagra and SCK-CEN).

In addition, USDOE CBFO brought to the project the unique experience of having successfully developed, certified, and, since March 1999, safely operated a deep geological repository for safe disposal of long-lived TRUW in bedded salt rock.

A large number of issues of fundamental importance for designing, constructing, operating, monitoring and assessing the safe performance of repositories for long-lived radioactive waste and for designing, constructing and operating URLs have been addressed and described for each of these geological media by the CROP Participants to assist in future planning of such facilities. The focus was on the following matters:

- Principles of siting, designing and constructing repositories and URLs.
- Objectives of activities in URLs with special respect to the relevance of experiments related to engineered barrier systems (EBS).
- Principles of designing, manufacturing and placing EBS.
- Selection of instruments and recording systems for measuring changes in temperature, groundwater and stress conditions in the far- and near-fields, and for monitoring the function and conditions of the EBS.
- Collection of data and description of the performance of the rock and EBS in URLs and repositories.
- Development and application of conceptual and theoretical models for predicting the performance of repositories and URLs with special respect to the EBS and its interaction with the near-field rock.

- Comparison of predicted and actual performance of URL and repositories.
- Overall assessment of the repository concepts with respect to lessons learned, problems and potential solutions.
- Possible improvement of the repository concepts.

2.2 Work plan

The work has progressed step-by-step by addressing four Work Packages (WPs) in the following order:

WP1

Description and function of repositories of different design and located in different types of geological media. Design, construction, application and predicted performance of the near-field rock mass in general and EBS in particular.

WP2

Description of the background for selecting experimental procedures, instrumentation, recording and documentation of data for the respective URLs. Evaluation of the performance and comparison of the experience from the URL tests.

WP3

Modeling of the function of EBS based on the tests conducted in URLs and accessory bench- and laboratory-scale experiments. Specification of conceptual and theoretical models and assessment of the capability to accurately predict major thermal, hydrological, mechanical, chemical and biological (THMCB) processes.

WP4

Development/improvement of design of the near-field including the EBS (i.e., canister, buffer, backfill and plugs), selection and conceptual adaptation of most suitable techniques for repository construction, application of waste packages, and sealing drifts and shafts.

At the start of WP1, WP2 and WP3 each Participant compiled a CA with details on the topic in focus, and all together each Participant produced four CAs per host rock media it addressed in the project. USDOE CBFO in addition compiled one CA with its experience of performance of the WIPP; see the Reference list in Section 9.1.

The CAs prepared in each WP were used as the basis for compiling the periodical progress reports to the EC.

The CAs prepared by the Participants are summarized in this report as well as the network discussions that provided the additional conclusions and proposals for future development and improvements. The CAs have not been filed in public report series, but the information is available from the respective originator as outlined in the Reference list.

2.3 Structure of report

The report is structured such that the Participants´ current repository concepts are summarized in Chapter 3. Thereafter follow summaries for each of the three geological media considered in the CROP, as one conclusion from the project is that specific discussion of technical details needs to be focused on one media at the time. Chapter 4 presents “Salt rock”, Chapter 5 “Crystalline rock”, and Chapter 6 “Clay rock”. Each of these three chapters addresses: a) National repository concepts, b) Engineered barrier system (EBS), c) URLs and experimental procedures, and finally d) Conceptual and theoretical modeling.

Chapter 7 summarizes “lessons learned”, and “potential areas for improvement”, which are expected to be of particular use for future designers and modelers. Each Participant’s organization is responsible for the accuracy of the results that they have presented, and it is important to realize that the local conditions under which the various experiments were conducted governed the reported results, their validity and, consequently, limit the applicability of the experiment design and use of the results to other conditions/sites.

Abbreviations and scientific symbols used in this report are explained in the beginning of the report.

A detailed presentation of the major experiments carried out in the different URLs is shown in Appendix 1.

Appendix 2 is a glossary with definitions of the most common terms used in the report. As to “clay rock”, this term is used for all sorts of clayey rock or soils hence avoiding debatable terms such as “argillaceous” rock, etc. The text will clarify the type of clay being referred to.

3 Repository concepts

At the end of the year 2003, many nations faced the challenge of finding an acceptable solution for safe disposal of long-lived radioactive waste. By far, a carefully sited, designed, constructed, operated, and closed deep geological disposal system, hereinafter referred to as a repository, is the most favored solution. This section provides a ”generic” overview of the fundamental objectives and components of a repository for long-lived radioactive waste, their interdependency, and some current trends. Retrievability, reversibility and similar concepts are not addressed below.

The fundamental objective of a repository is to contain and isolate the disposed radioactive constituents until such time as they are rendered harmless to life and the environment. To accomplish this objective, repositories utilize a combination of (1) natural (geologic setting) and (2) man-made (engineered) barrier systems, hereinafter referred to as the NBS and EBS, respectively. Furthermore, since some of the radionuclides involved have to be contained and isolated for very long time periods (hundred thousand to million year scale) and the volume of rock that needs to be evaluated is very large, neither real-time nor full-scale testing is an option. Hence, due to the large temporal and spatial scales involved in assessing the risks associated with a repository for long-lived radioactive waste, the performance and long-term safety of such a repository are based on a closely integrated sequence of information gathering and predictive modeling. The major components of these activities are (1) tests conducted on a variety of scales to establish important parameters and their respective representative value/range, (2) natural analogues (not discussed further in this chapter), and (3) numerical and mathematical projections, where the mathematical projections serve as the main basis for assessing the risk. The mathematical projections are commonly referred to as safety and/or performance assessments (SA/PA).

During the past 45 years, several geological media have been investigated around the world for long-lived radioactive waste repository developments. At the end of the year 2003, the world’s most advanced national radioactive waste management programs focus on the following four groups of geological media. The first three are addressed in this report.

- Salt rock (Germany and USA[1]).
- Crystalline rock (Canada, Finland and Sweden).
- Clay rock (Belgium, France, and Switzerland).
- Tuff (USA).

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[1] The Waste Isolation Pilot Plant (WIPP) repository in the State of New Mexico, USA (Figure 1), opened for safe disposal of long-lived, transuranic radioactive waste (TRUW) on 26 March 1999. Near the end of the year 2003, WIPP had safely received and disposed of more than 2 200 shipments of TRUW. When filled to its current legal capacity, the WIPP repository will contain 175 584 m^3 of TRUW that may include up to 17 Mg of plutonium isotopes with a half-life in excess of 24 000 years and TRUW canisters with surface dose rates of up to 10 Sv/h.

The depths of currently planned and operating repositories for long-lived radioactive waste vary between 200 m and 1 200 m below the ground surface Most repositories for long-lived radioactive waste are, however, situated at more than 400 m but less than 700 m below the ground surface. As follows, the acquisition of the geological information required for the safe design and construction (and SA/PA) of a repository for long-lived radioactive waste is both time-consuming and costly. For example, the sequence employed by the most advanced repository programs for identifying and/or selecting current candidate and operating repository sites included the following key phases:

1. The development of baseline site selection and repository performance criteria, typically comprising a combination of operational-safety and long-term-performance requirements, including requirements defined by the regulators, and a baseline set of data needs and objectives, including a baseline repository design concept. These criteria need to be refined throughout the repository-siting and site-characterization processes based on the information obtained, the refinement of the models involved, and changes in the legal or regulatory frameworks and/or the repository design.
2. National screening to identify potentially suitable repository regions and/or areas (sites are seldom identified during this stage other than in terms of political and local acceptability).
3. Surface-based investigations of potential repository regions and areas, including laboratory tests on samples of varying sizes smaller than "room" scale, leading to the identification and selection of candidate areas and/or potential sites and the refinement of the repository design and/or process and system models.
4. Continued surface-based investigations of potential areas and sites, including laboratory tests on samples of varying sizes smaller than ”room” scale, leading to the selection of one or more candidate sites and the refinement of the repository design and/or process and system models. Phase 4 continues in conjunction with phase 5 throughout the repository construction phase to ensure that the SAs/PAs are based on “best-available” information and data.
5. The development of a URL in the potential host rock at the candidate site(s). The primary data objectives of the URL (and phase 4) are to obtain the *in-situ* information and detailed process understanding required for the development of (a) the final repository design, (b) safe construction procedures, and (c) final process and system models, including the credible up-scaling of all site data to repository scale in SA/PA supporting the license application(s). Simply stated, the main objectives for phases 4 and 5 are to obtain the information required to ensure (a) workers safety during the construction phase and (b) public safety during the time period of concern, which may also be expressed as reducing the uncertainty in SA/PA. Hence, phases 4 and 5 typically continue until such time as when they are no longer needed for supplementary information gathering or environmental monitoring, which may include a post-closure repository performance period.
6. The preparation of the documentation required for the licensing of the repository. It should be noted that phase 6 does not commence upon conclusion of phases 4 or 5. Phase 6 commences during phase 1.

Typically, a very large volume of rock is involved in the SA/PA for a long-lived radioactive waste repository. For example, although the waste-induced effects may be restricted to the immediate surroundings of the waste-disposal location, also referred to as the near-field, groundwater flow and radionuclide transport characteristics are needed from a large volume of the rock, also referred to as the far-field. It should be noted that the terms ”near-field” and ”far-field” are imprecise and neither depicts an exact distance from the repository opening (or waste container) nor a given volume of rock.

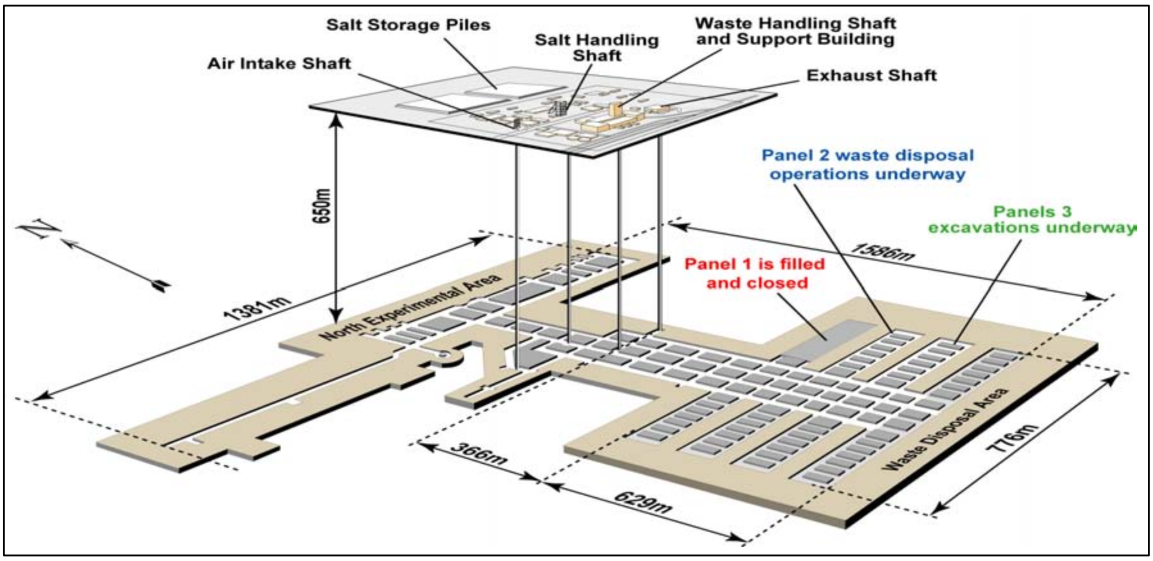

Figure 3-1. *The WIPP Repository. (Courtesy of USDOE CBFO)*

The site-specific information required for the design, licensing, construction, operation, and closing of a safe repository for long-lived radioactive waste includes the thermal (T), hydrological (H),) mechanical (M), chemical (C) and biological/bacterial (B) characteristics of the rock(s) and groundwater systems affecting the safety and long-term performance of the repository. It also includes the effects caused by (1) the construction of the repository and (2) the emplacement of foreign materials (such as waste, backfill, buffer and seals, but also all materials used and contaminants left in the repository by construction for grouting, rock support, preventing water inflow, conditioning roads, etc.) in the excavated underground openings. Particularly important construction-induced parameters include the extent and characteristics of the excavation damaged zone (EDZ) around the underground openings. Particularly important ”emplacement” parameters include (1) the thermal loading of the repository, (2) the radionuclide inventory, (3) the characteristics and response to the human-induced effects and (4) the emplacement environment of any foreign material(s) placed or lost in the underground openings.

However, the relative importance of any given parameter is typically a function of (1) the stage of repository development, e.g., the construction, operations, closure, or post-closure phase, (2) the depth of the repository, and (3) the period of time to be evaluated in SAs/PAs. For example, near-field rock mass characteristics, such as the compressive strength, state-of-stress, and presence of discontinuities, including their groundwater-flow characteristics, of the repository host rock, i.e., the M and H characteristics, are of particular importance to the design (shape, size, and ground support) and construction of underground openings, and the operational safety. However, in order to credibly predict the long-term performance, i.e., post-closure safety/risks, of the repository, the disturbances caused to the NBS by human actions become increasingly more important. Particularly important human-induced post-closure parameters/disturbances include (1) the construction of the repository, i.e., EDZ, (2) the emplacement of the waste, i.e., the related thermal pulse and the transient T, H, M, C and B processes induced and sustained by the emplaced waste, and (3) the emplacement of the EBS. In other words, in addition to being site specific, the relative importance of a parameter may be both space- and time-dependent.

In simple terms, current long-lived radioactive waste emplacement configurations essentially entail either a single or multiple canisters in vertical or horizontal boreholes and/or in drifts. The classical and widely employed KBS-3V concept (see Chapter 5) is an example of the emplacement of a single canister in a vertical borehole. The more recently explored KBS-3H concept (see Chapter 5) is an example of the emplacement of several canisters in long horizontal boreholes. The Swiss conceptual design and one Canadian conceptual design (see Chapter 6 and Chapter 5 respectively) are examples based on emplacement of the canisters in the drift, commonly referred to as “in-room” placement. In addition to these repository-based concepts, deep vertical boreholes from the surface are also a possible long-lived radioactive waste disposal concept, although not addressed in this report.

Clearly, it is more economical to place as many canisters as possible in each borehole. However, the closer together canisters are placed, the more energy they will generate per unit volume. This energy will induce a thermal flux that may adversely affect the radionuclide containment and isolation capacity of the buffer, backfill and host rock(s) as the characteristics of the host rock, the buffer, and the backfill are typically temperature sensitive. Furthermore, modeling of radionuclide transport at high temperatures where both gas and liquid flows are involved is considerably more difficult than at lower temperatures where typically only liquid flow needs to be considered. Hence, for most rock types, backfills and buffers considered or used today in long-lived radioactive waste repositories, there is a threshold waste-induced-energy/temperature value that should not be exceeded to avoid unfavorable chemical reactions that may be induced and/or the need to develop new/unproven conceptual, numerical, and mathematical models. In many national programs, the ambient boiling point of water is regarded as a threshold value that should not be exceeded unless the processes and consequences induced at higher temperatures can be predicted with a high degree of confidence/certainty.

Again, SA/PA provides the tool for evaluating the long-term/post-closure performance, safety, and consequences/risks of a long-lived radioactive waste repository on the spatial and temporal scales involved.

A trend that should be noted is that prior to the availability of and testing in an URL at the candidate site (i.e., an on-site URL), several CROP Participants have or are using an off-site URL to obtain generic rock type data on the potential and/or candidate host rocks and to test portions of their conceptual repository design in representative geological conditions. The main benefits of these off-site URLs are the early, cost-effective, and time-saving (1) establishment of the functionality of candidate instruments, preliminary test designs, and proposed excavation techniques in the potential host rock environment, (2) training of staff, and (3) development of preliminary process and system models. Beginning in 1973 with the Stripa project, international radioactive waste management organizations have and continue to encourage their members to cost-effectively develop knowledge and advance domestic repository-siting by participation in joint international research, technical development and demonstration (RTD) projects in off-site URLs. This approach is also endorsed and subscribed to by many national radioactive waste management organizations. For example, the CROP Participants are currently conducting a variety of joint international RTD in clay, crystalline, and salt rock URLs. These URLs are also available for ”off-site” RTD by others.

Another general trend among current repository designs is the current higher reliance upon containment by the EBS in brittle fractured repository host rocks, such as crystalline and tuffaceous rocks, than in more ductile rocks, such as clay rock and salt rock. This trend should not be interpreted as an indication that clay and salt rocks are significantly more suitable for hosting a safe repository for long-lived radioactive waste than crystalline or tuffaceous rocks. One reason for this trend is that it is generally recognized that, on the repository-scale, high-compressive-strength rocks typically contain discontinuities and anomalies that are more difficult to simulate in SA/PA models than those in clay and salt rocks. Other reasons for the greater focus on containment capabilities of the EBS in high-compressive-strength rocks are (1) national laws and regulations, and (2) domestic availability of rock types. In other words, the reliance upon the EBS may be elective rather than an indication of the radionuclide containment and isolation characteristics of the repository host rock(s). It may also embody cost savings due to simpler process and system models required for analyzing a repository giving greater emphasis to the EBS, i.e., the near-field, for radionuclide containment and isolation relative to one relying essentially upon the NBS, i.e., the far-field. However, these cost savings may be countered by the cost of the EBS. A more appropriate interpretation may thus be that some of the inherent radionuclide containment and isolation capability of the high-compressive-strength rocks mentioned above may not be fully characterized and therefore not used in the PA/SA. This may provide an unquantified safety factor (i.e., conservatism) in the analyses.

Lastly, although it is not a repository-design-concept component, as history has shown in Finland, France, Sweden, Switzerland and the USA, early local acceptance is a very important repository-viability concept. Simply stated, early local acceptance is virtually imperative because, unless the local residents and their elected representatives are favorably inclined to the proposed or selected location of a repository for long-lived radioactive waste, the development of the repository will suffer from time-consuming and costly opposition resulting in schedule delays and cost-increases that ultimately may result in the exclusion of the location from further consideration. Lack of or very late (fait accompli) information or lack of attention to local concerns can turn local residents and politicians against any project. Off-site as well as on-site URLs have played and may play an important role with respect to informing the public and building confidence in the proposed technical solutions. Nevertheless, a sound PA/SA demonstrating the safety of the proposed concept is mandatory for all potential sites and host rocks and helps to obtain public acceptance.

4 Salt rock

Intact salt rock normally exhibits the following six material characteristics making it very suitable for containment and isolation of long-lived radioactive waste:

- High thermal conductivity.
- Very low porosity.
- Very low permeability.
- Adequate structural strength for the safe construction and use of large, unsupported, underground openings.
- Deforms (creeps) under very low deviatoric (differentiating) stresses.
- Very low water content.

The deformational (rheological) characteristics of salt rock are particularly beneficial to the long-term safety and performance of a repository in that they gradually close fractures and underground openings with time as a function of the prevailing material characteristics, the magnitude of the waste-induced thermal load/pulse, and the magnitude of the deviatoric stresses. This process, which is very strongly governed by the prevailing thermal load, is often referred to as “self-healing” because it results in the encapsulation of the emplaced waste/materials into a virtually impermeable monolith within less than a few hundred years. For example, the thermo-mechanical consequences of various disposal concepts were analyzed by Wallner and Stuehrenberg [4-1] in the framework of the project “Systemanalyse Mischkonzept (SAM)” [4-2] for a simplified model of the Gorleben salt dome. Assuming an amount of 700 Mg of spent nuclear fuel (SF) being discharged from Light Water Reactors (LWRs) annually and a ratio of 500 to 200 for non-reprocessed and reprocessed HLW as well as interim storage times for both types of waste of 30 years and 40 years, respectively, maximum temperatures between 134°C and 150°C were calculated in the emplacement zones. However, due to the high thermal conductivity of salt rock, 1 000 years after waste emplacement, the waste-induced temperature increase in the salt would not exceed 5°C and the stresses were similar for all concepts. Tensile stresses exceeding the tensile strength of the salt rock (1 MPa) only occurred if low creep capacity and a large panel width of 300 m were assumed. In all other cases they remain below the “1 MPa-limit” [4-3].

4.1 National repository concepts

The German and U.S. repository concepts for safe deep geological disposal of long-lived radioactive waste in salt rock described below are the most advanced in the world. However, whereas the main focus in Germany during the past 30+ years has been on domal salt rock, the main focus in the U.S. during the past 15+ years has been on bedded salt rock. Furthermore, the German and U.S. disposal concepts differ. They are, therefore, described below under separate subtitles, where domal salt rock denotes the repository concepts investigated in Germany and bedded salt rock denotes the repository concept investigated since 1975 and used since 1999 at the WIPP site in the U.S. (Figure 4-1) for safe disposal of TRUW[2]. Although other salt rock repository concepts than the WIPP disposal concept also have been carefully studied in the U.S., they are not reported in this document because (a) they have not been studied since 1987 and (b) are essentially covered by the data and issues reported for safe disposal of SF and HLW in domal salt rock, and the design described above in Chapter 3 for the KBS-3V concept.

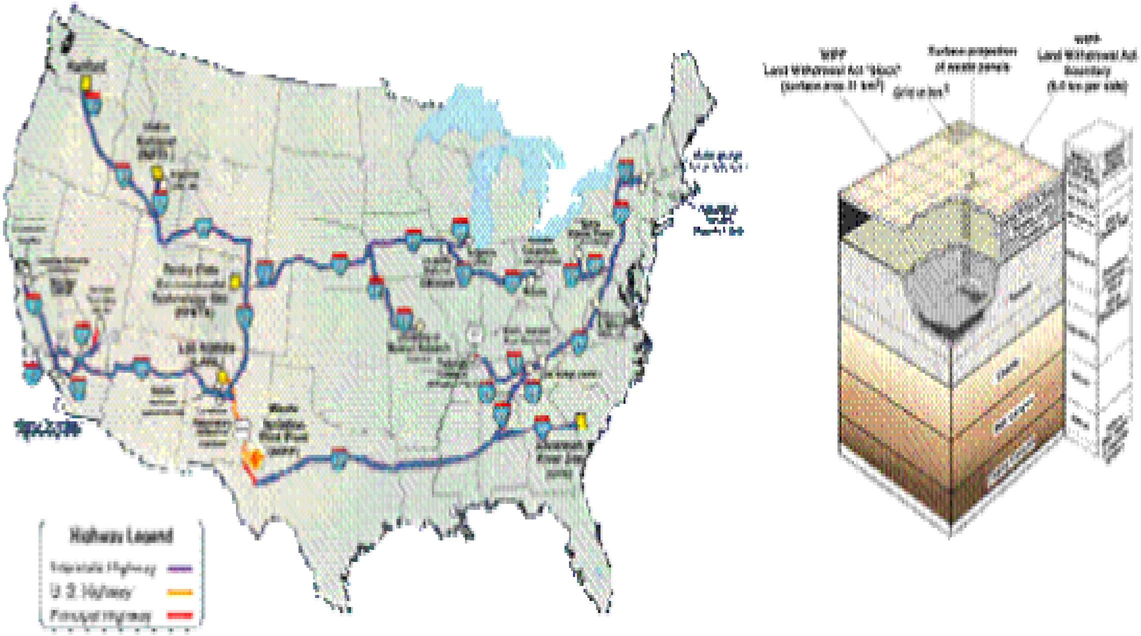

Figure 4-1. *To the left: The locations of the WIPP site, 23 TRUW generator/storage sites, and related transportation routes. To the right: A schematic illustration of the ~76 km^3 WIPP disposal system and the related stratigraphic column.*

4.1.1 Description of disposal concepts

Domal salt rock

Several disposal concepts have been investigated and developed in Germany as a combination of technical variants and waste type ratios, with the technical variants being:

- Borehole emplacement of vitrified HLW.
- Drift emplacement of SF in Pollux casks.
- Combined drift and borehole emplacement of Pollux casks and HLW.

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[2] Only TRUW from defense-related activities containing at least 3,700 becquerels of alpha-emitting, transuranic (atomic weight/number greater than ^{92}uranium) isotopes with half-lives greater than 20 years, per gram of waste, and not exceeding 10 Sv/h in canister surface dose rate may be disposed at the WIPP site. There are two categories of TRUW: (1) contact handled (CH), which may have a maximum canister surface dose rate of 0.002 Sv/h, (2) remote-handled (RH), which may have a canister surface dose rate between 0.002 Sv/h and 10 Sv/h.

According to the concepts considered in Germany, the HLW remaining from reprocessing of SF will be vitrified in steel canisters. The steel canisters will then be disposed in between 300 m to 600 m deep, 0.6 m wide, vertical boreholes [4-4] extending down from a disposal drift located at a depth of some 880 m below the ground surface (Figure 4-2). About 200 canisters will be lowered into each borehole. The annulus between the canisters and the borehole wall will be backfilled with crushed salt to transfer the load of the canister stack to the surrounding rock mass. As shown in Figure 4-2, a seal of crushed salt will also be placed at the top of each borehole. The inherent rheological characteristics of the salt rock surrounding the boreholes will then gradually compact the crushed salt and, thereby, completely encapsulate the HLW canisters within a very short period of time.

Another repository concept has been developed for direct disposal of SF [4-5]. In this concept large self-shielding Pollux casks containing LWR SF elements will be emplaced in horizontal drifts about 200 m long, 4.5-m wide, and 3.5 m high. Following the emplacement of a Pollux cask, the remaining voids in the drift will be backfilled with crushed salt (Figure 4-3). Similar to the borehole emplacement concept for HLW canisters, the creep of the surrounding rock mass will compact the initially loose, crushed salt backfill and, thereby, effectively seal the emplaced Pollux casks from the biosphere.

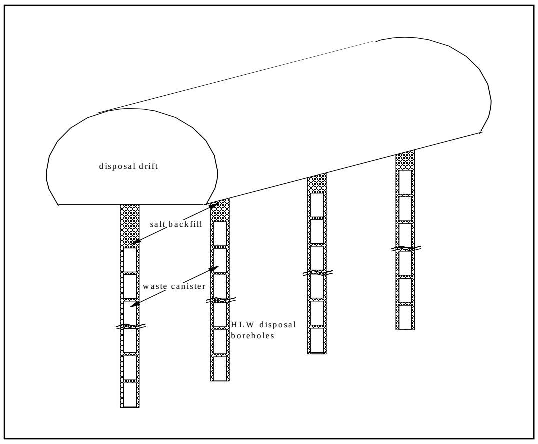


Figure 4-2.*Disposal drift with HLW boreholes.*

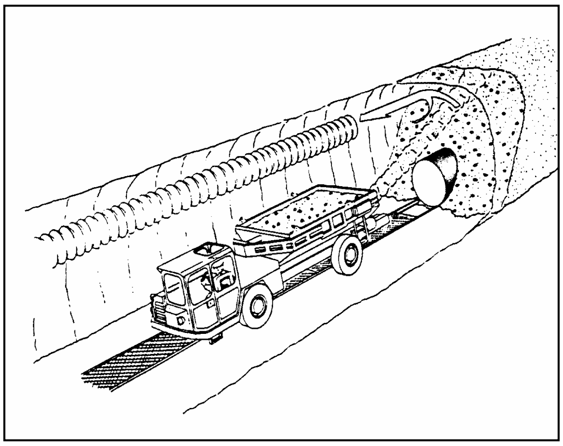


Figure 4-3. *Drift disposal with Pollux casks.*

Different research teams have analyzed these concepts and the results are reported in SAM [4-2]. The most promising disposal concept appears to be the combined drift and borehole emplacement of Pollux casks and HLW-canisters shown in Figures 4-2 and 4-3.

The permeability of the backfill material is of special importance to the long-term safety of a repository in the event of a brine influx to the repository from the overburden or from an undetected brine pocket in the rock mass. In addition to the natural compaction of the backfill material caused by the creeping rock mass, the heat released from the emplaced waste will increase the temperature in both the backfill and the surrounding rock mass, which, in turn, will accelerate both drift-closure and backfill-compaction rates. However, notwithstanding the aforementioned beneficial effects of waste-induced temperature increases/fluxes, the maximum salt temperature is kept at or below 200°C at all times as a safety precaution because, due to its relatively high emplacement porosity, the backfill will exhibit low heat conductivity that results in high temperatures at the interface between the cask/container and the backfill. As the backfill becomes gradually more compacted with time, its porosity decreases and heat conductivity/dissipation increases, which serve to reduce the cask/container and backfill interface temperature.

No other backfill material than crushed salt is considered necessary in any of the above repository concepts for domal salt rock.

Bedded salt rock

Pursuant to the applicable U.S. law [4-6] and the related regulations [4-7,4-8] the post-closure safety of the WIPP repository is based on the radionuclide containment and isolation provided by a combination of NBS and EBS. The fundamental premise of the certified WIPP disposal system [4-9] is that virtually all the radionuclide containment and isolation required to meet the applicable regulatory safety and performance criteria during the post-closure period is provided by the NBS. However, the post-closure safety and performance of the WIPP repository is also governed by five man-made barriers, of which the regulator, the U.S. Environmental Protection Agency (USEPA), presently only considers the magnesium oxide (MgO) buffer/backfill emplaced in portions of the disposal rooms an EBS. No other buffer or backfill is placed in the disposal rooms.

Similar to the domal salt rock repository concepts, a particularly important component of the WIPP repository concept is the inherent rheological (creep) characteristics of the salt rock hosting the WIPP repository. Specifically, the vertical and horizontal disposal-room-closure rates during the first five years after closure are ~100 millimeters per year (mm/a) and ~70 mm/a, respectively, and beyond the first five years, they are ~65 mm/a and ~35 mm/a, respectively [4-10]. These closure rates will gradually encapsulate the emplaced waste, as well as any other material placed in the WIPP repository, into a virtually impermeable monolith within 300 years after repository closure. They also largely govern the present phased development of the disposal panels/rooms, which minimizes maintenance and ground support needs (extensive ground support impedes the closure rates of the underground openings and may compromise the containment and isolation function of the repository).

4.1.2 Required function of the repository

Domal salt rock

According to paragraph 45 of the German Radiation Protection Ordinance, the individual dose to humans caused by radionuclides released from a repository must remain below 0.3 mSv/a [4-11]. To achieve this objective, the required long-term containment and isolation of all kinds of radioactive waste emplaced in a repository have to be provided by the NBS and the EBS.

In all the domal salt rock repository concepts for SF and HLW, the host rock represents the main barrier to radionuclide migration. However, as described further below, EBSs are also required to ensure adequate containment and isolation of the disposed SF and HLW.

Retrievability is not foreseen in any of the present domal salt rock repository concepts. Measures to maintain access to the disposal areas are considered contradictory to the long-term safety of a repository in salt rock.

Bedded salt rock

Pursuant to the applicable U.S. law [4-6] and the related regulations [4-7, 4-8], the ~76 km^3 WIPP disposal system (Figure 4-1), must contain and isolate up to 175 584 m^3 of TRUW for at least 10 000 years, also referred to as the regulatory period, in the following manner:

- In the event the repository is only affected by likely natural events, also referred to as the "undisturbed case", the maximum annual effective dose to a member of the general public living at the WIPP site boundary may not exceed 0.15 mSv/a.
- In the event the repository is affected by inadvertent human intrusions with a probability of occurrence equal to or greater than E-8 (and likely natural events), also referred to as the "disturbed case", the amount of cumulative releases of radionuclides to the accessible environment, i.e., anywhere outside the boundaries of the WIPP disposal system, may not exceed two very stringent, waste-inventory-related limits, i.e., there is not a set radionuclide release limit value for all repository inventories.

As illustrated by the mean and overall complementary cumulative distribution functions (CCDFs) shown in Figure 4-4, even in the event of multiple borehole intrusions and all other natural and human-induced events with a probability of occurrence equal to or greater than E-8, based on the 300 analyses supporting the 1996 WIPP Compliance Certification Application (CCA) [4-10] and the related 300 Performance Assessment Verification Tests (PAVTs) conducted at the direction of the USEPA, the predicted mean and overall mean cumulative releases of radionuclides from the WIPP repository during the 10 000 years regulatory period are less than 10% of the very strict limits defined by the USEPA in the applicable regulation [4-7].

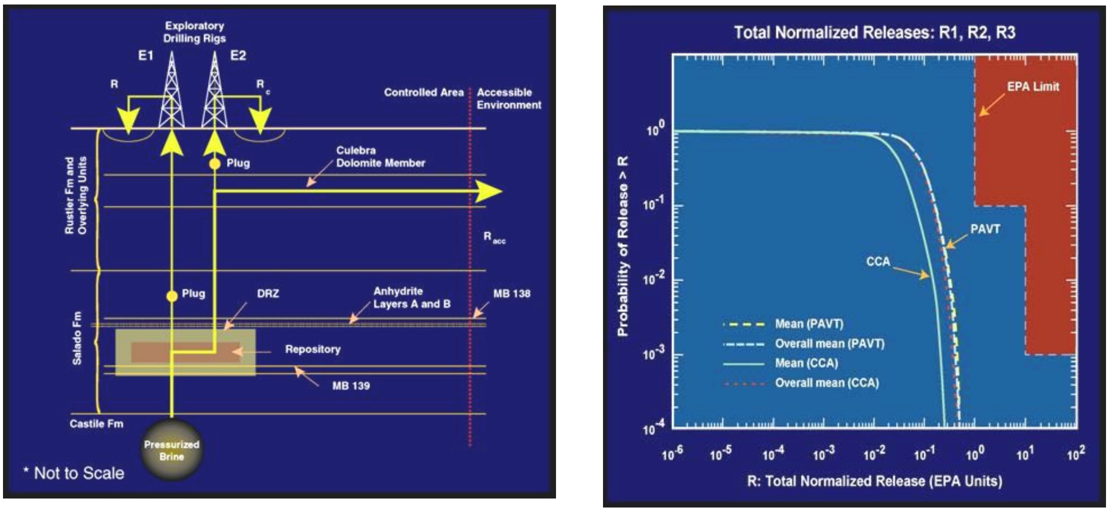


Figure 4-4. *To the left: Schematic illustration of multiple borehole intrusions, also referred to as the E1, E2 scenario. To the right: The predicted cumulative releases of radionuclides from all applicable (600) disturbed and undisturbed cases.*

There is neither a legal nor a regulatory requirement for waste/TRUW retrieval at WIPP. However, the CCA [4-10] contained a feasibility study on retrievability based in large part on a full-scale, waste retrievability demonstration conducted in the WIPP URL. This study concluded that the disposed TRUW could be safely retrieved with existing technologies for a considerable portion of the post-closure period, if needed.

The environmental conditions of the WIPP site have been monitored since 1974 and the performance of the WIPP repository will be monitored throughout the 25-to 35-year operational, the 10-year closure, and the first 100 years of the post-closure periods, also referred to as the 100-year active institutional controls (AIC) period. The WIPP environmental monitoring program, which includes several deep boreholes, is continually reviewed and updated, as needed, and will continue throughout the AIC period. During the 9 900 year passive institutional controls (PIC) period following the AIC, records stored on and adjacent to the WIPP site and in national archives, and monuments erected at and around the WIPP site are the regulatory-required means for advising future generations about the existence and potential dangers of the WIPP repository [4-7, 4-8, 4-9, 4-10].

4.1.3 Current repository design principles

Domal salt rock

Criteria used in the conceptual studies for designing a HLW repository in a salt dome in Germany were reported in EUR 11778 EN [4-12]. They include the following:

- Retrievability is not to be considered.
- Two shafts are sufficient for constructing/developing and operating the repository, including all kinds of transport and the ventilation system.
- Different waste forms with respect to waste type and container are to be placed in different disposal areas.
- The mine/underground workings shall have a lateral safety distance to the flanks of the salt dome of at least 200 m and a vertical safety zone beneath the top of the salt dome and the cap rock of at least 300 m. Additionally, a safety area (pillar) of 300 m, which should not be used for disposal purposes, shall remain around each shaft.
- All disposal areas are located at the same level.
- Salt and waste are transported in different drifts, preferably in a one-way system. However, the number of drifts and other excavations should be kept as low as possible to minimize the required number of drift seals (plugs).

A typical layout of a HLW repository in domal salt rock is shown in Figure 4-5. As indicated in Figure 4-5, Shaft 1 will serve as the air intake and personnel transportation shaft and shaft 2 will serve as the exhaust air and waste transportation shaft. The final layout of the disposal areas and the drifts will mainly be determined by the geology at the disposal level, i.e., the distance of the disposal areas from carnallite or anhydrite seams, and a maximum allowable temperature of 200°C at the interface between the waste cask/canister and the backfill. Table 4-1 summarizes possible geometrical data of a site-specific repository concept for the Gorleben salt dome [4-13] governed by the aforementioned design criteria.

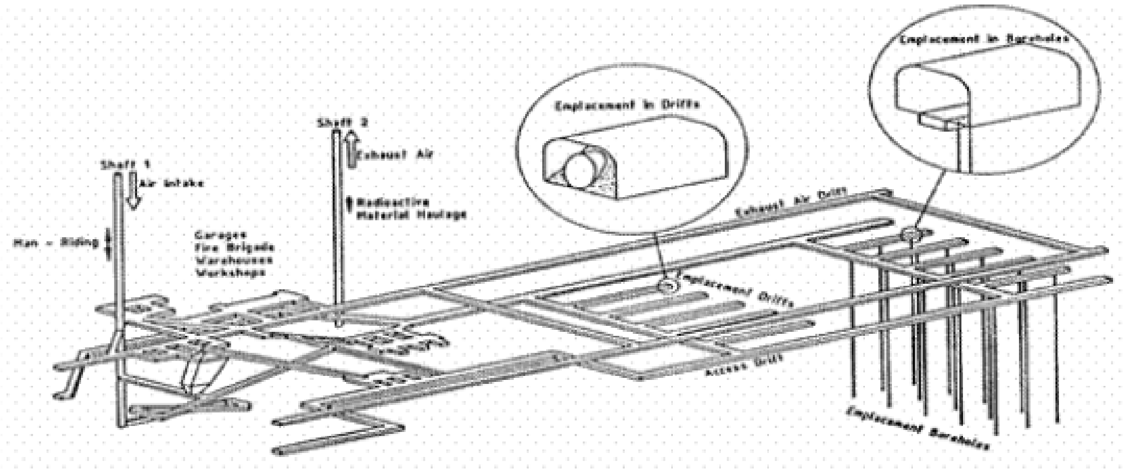


Figure 4-5. *Typical layout of a HLW repository in a domal salt rock formation in Germany. (Courtesy of DBE)*

In the case of borehole disposal of HLW, a drift cross-section of about 5 m by 6 m is required for the operation of the waste/container-disposal machine and the borehole diameter is about 0.6 m. As mentioned in Section 4.1.1, the narrow (85 mm) annulus between the canister and the rock mass is backfilled with crushed salt.

In the case of drift disposal of SF/Pollux casks, a drift cross-section of about 4.5 m by 3.5 m is considered sufficient for the horizontal emplacement of the 1.6-m wide Pollux cask. As illustrated in Figure 4-3, the void between the cask and the rock mass is also backfilled with crushed salt.

Table 4-1. Possible geometrical data of the Gorleben repository concept [4-13]

Drift disposal of Pollux casks	Interim storage period (years)	Cask spacing (m)	Drift spacing (m)
	15	6	28
	30	1	36
Borehole disposal of HLW canisters	**Interim storage period (years)**	**Borehole spacing (m)**	**Drift spacing (m)**
	10	24.50	21.22
	15	21.00	20.00
	30	17.25	14.94

Bedded salt rock

The fundamental WIPP-repository design principle is compliance with applicable laws [e.g., 4-6, 4-14] regulations [e.g., 4-7, 4-8, 4-15, 4-16, 4-17] permits [e.g., 4-18] and certifications [4-9] which entails a safe working environment during the construction, operations, and closure periods followed by safe containment and isolation of up to 175 584 m^3 of TRUW for at least another 10 000 years of the post-closure period. The USDOE CBFO used a combination of laboratory-, surface-, and subsurface-based experiments/tests to develop the codes and models required to design the WIPP repository and the WIPP URL shown in Figure 4-6. Key underground experiments/tests are summarized in Section 4.3.3. Key codes and models used to certify the WIPP disposal system are summarized in Section 4.3.4 Additional information on both experiments/tests and codes/models is available in the CCA [4-10].

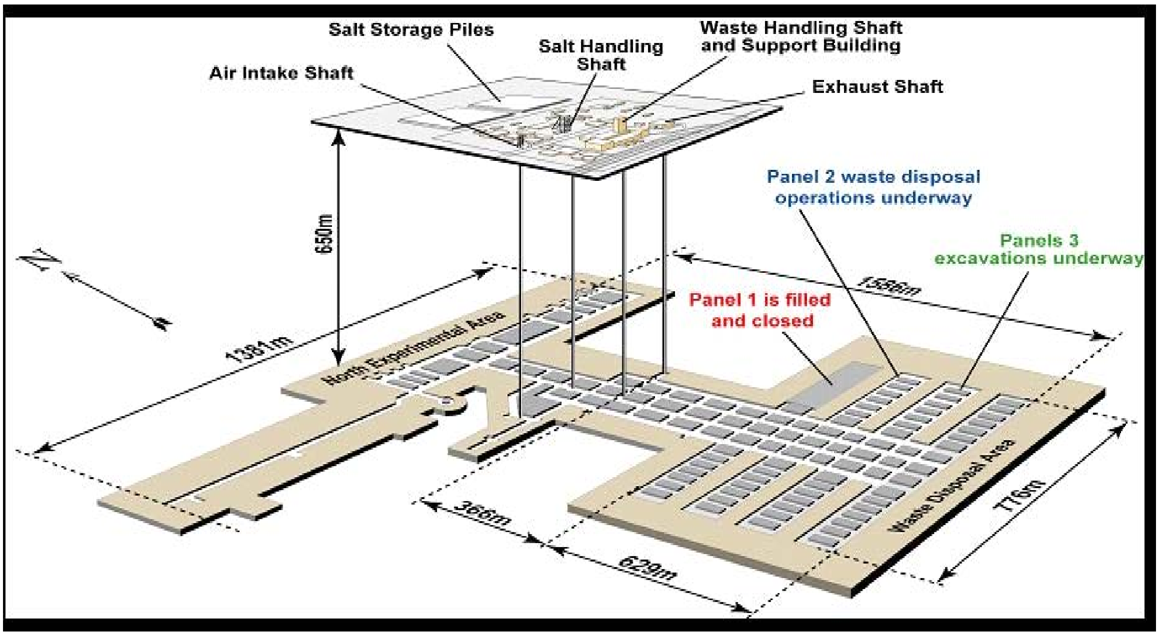


Figure 4-6*. Schematic illustration of surface and subsurface facilities at the WIPP site. (Courtesy of USDOE CBFO)*

As indicated in Figure 4-6, an ~400-m wide shaft pillar that hosts four shafts: two with and two without lifts, separates the WIPP repository and the WIPP URL. The two shafts without lifts are mainly used for ventilation purposes. One of the shafts with lift is mainly used for personnel, equipment/machinery, and non-radioactive material (e.g., salt and MgO) transportation and the other is mainly used for TRUW transportation, however, it can also be used for personnel, equipment/machinery, and non-radioactive material transportation.

As also illustrated in Figure 4-6, the baseline room-and-pillar repository design of the WIPP repository comprises eight panels, four on each side of the central underground transportation and ventilation system. Each panel contains seven disposal rooms and is separated laterally from the adjacent panel(s) by a 61 m wide salt rock pillar. Each disposal room measures 4 m in height, 10 m in width, and 91 m in length and is separated laterally from the adjacent disposal room(s) by a 30 m wide salt rock pillar.

Essentially all underground openings either have or will be excavated by means of mechanical mining methods to minimize the extent of the damaged part of the EDZ. Furthermore, a baseline design assumption is that only underground openings with a considerable performance-life or exhibiting local instability will be supported because, as described in Section 4.1.1, the WIPP disposal concept relies upon the inherent creep of the repository host rock for long-term containment and isolation of the disposed TRUW.

The respective disposal concept for CH-TRUW and RH-TRUW is described below.

As illustrated in Figure 4-7, the RH-TRUW containers will be emplaced/disposed in 0.75 m diameter, 4 m deep, horizontal boreholes located 1.2 m above the invert/floor and spaced   2.4 m apart in the walls of the disposal rooms. However, only some rooms will contain RH-TRUW because the projected amount of RH-TRUW will not require the use of all rooms but, when RH-TRUW is disposed, it precedes the disposal of CH-TRUW in the same portion of the disposal room.

Figure 4-7. *Simulated disposal of RH-TRUW containers. (Courtesy of USDOE CBFO)*

As illustrated in Figure 4-8, CH-TRUW is emplaced in the disposal rooms. Granulated MgO buffer/backfill is emplaced in portions of the disposal rooms in step with the gradual disposal of CH-TRUW. As described further in Section 4.3, although the WIPP repository has five man-made barriers, including the sophisticated 13-component shaft seal design illustrated in Figure 4-9, the MgO buffer/backfill is the only man-made barrier considered an EBS by the USEPA [4-9].

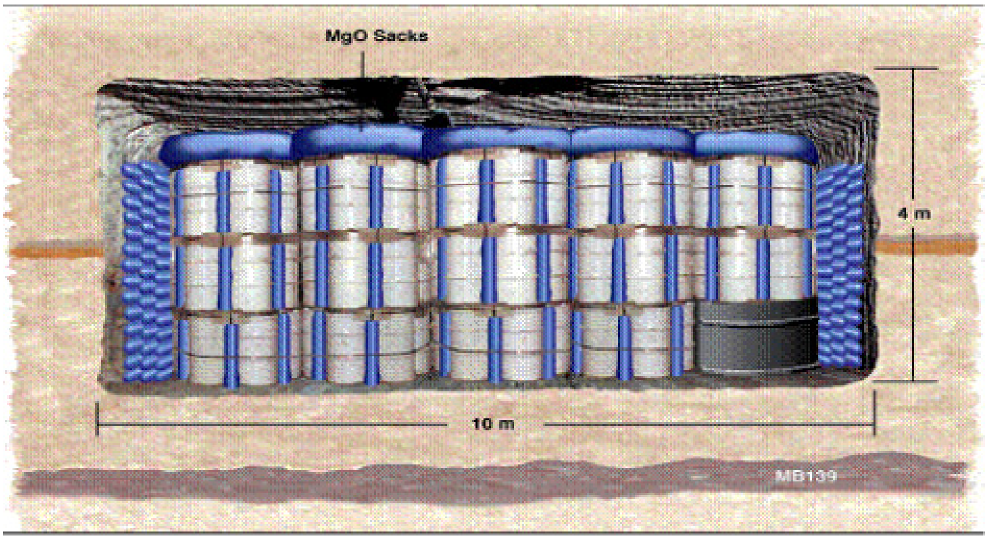


Figure 4-8. *Schematic illustration of the emplacement configuration for CH-TRUW containers and MgO sacks in the WIPP repository.*

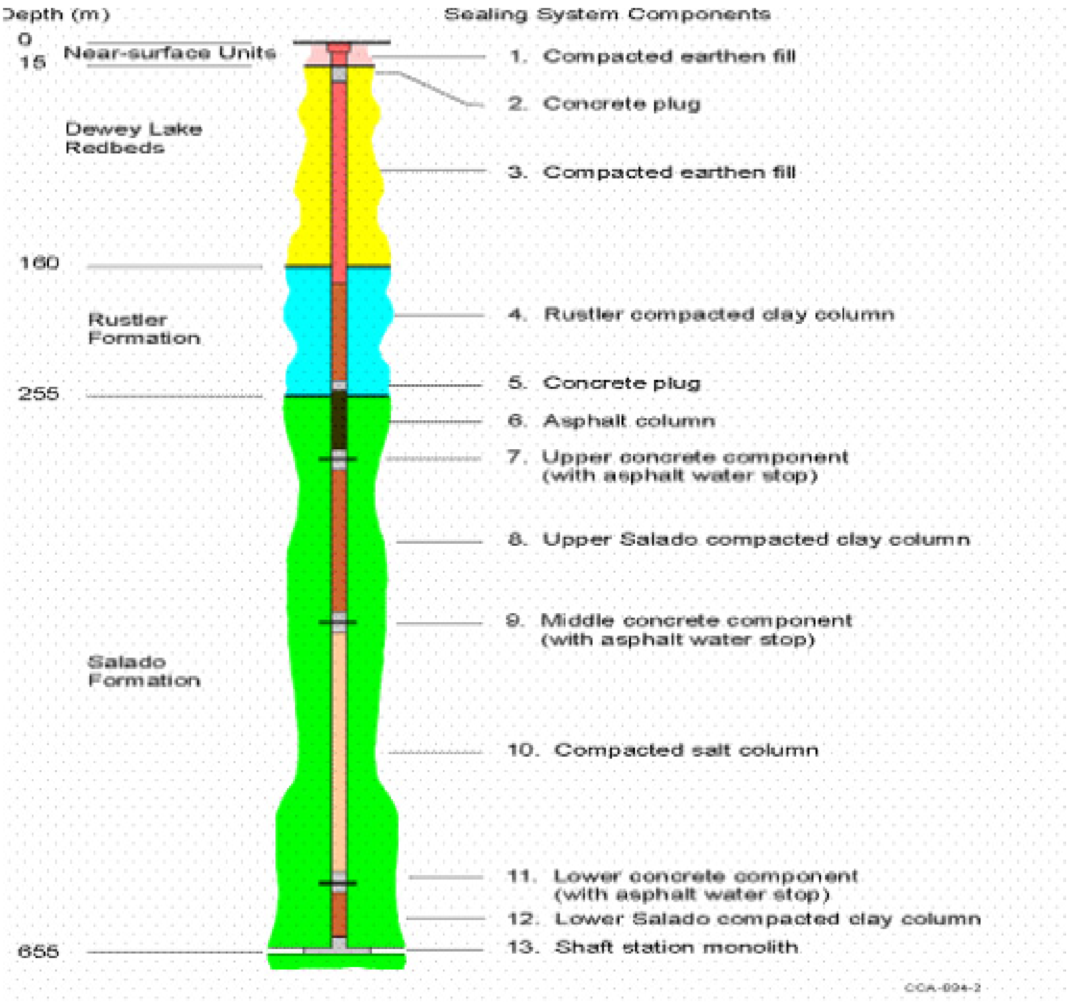


Figure 4-9. *Schematic illustration of the 13-component shaft seals at WIPP.*

4.2 National URLs

4.2.1 Description

Domal salt rock

No special URL has been designed or constructed in salt rock to support the characterization and the understanding of the safety and performance of a specific repository site. Instead, the German government has owned and used the Asse mine (Figure 4-10) since 1965 as a URL to perform *in-situ* testing of repository concepts in domal salt rock. In the framework of these research activities, about 130 000 two-hundred liter drums containing long-lived radioactive waste from research and industry activities (Figure 4-11) and about 1itre 300 two-hundred l drums containing non-heat-producing ILW were disposed in the Asse mine/URL. The main objective of these tests was the development of optimized transport, unloading, emplacement, and backfilling techniques.

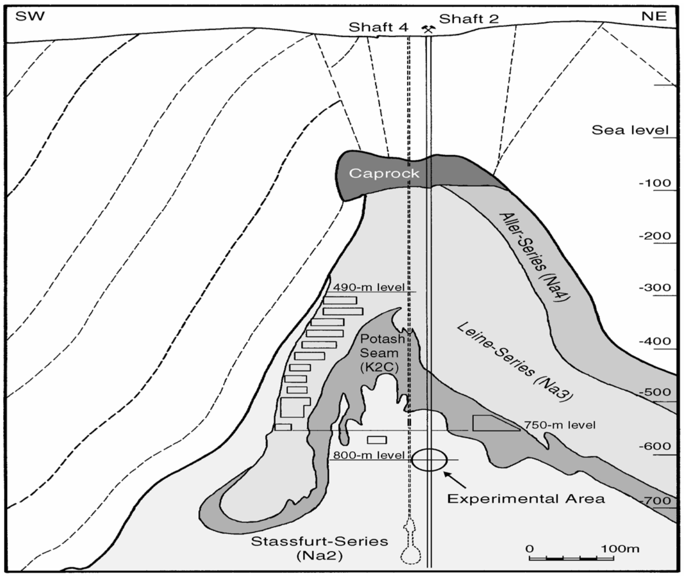


Figure 4-10. *Cross section of the Asse salt dome and mine/URL. (Courtesy of GRS)*

Figure 4-11. *LLRW-storage room in the Asse mine/URL.*

In Germany, the research supporting the safe disposal of heat-producing HLW from reprocessing of SF started in the mid-sixties and focused on the investigation of thermal and coupled thermo-mechanical as well as hydraulic and radiolytic effects in the near-field of the disposed HLW-canisters until the mid-eighties. Later on, several full-scale simulation tests were performed in the Asse mine/URL 800 m below the ground surface, which corresponds to 600 m below sea level, in the centre of the Asse anticline (Figure 4-12). These full-scale tests included the Thermal Simulation of Drift Emplacement (TSDE) experiment (Figure 4-12a) in support of the drift disposal concept and the High Active Waste (HAW) project (Figure 4-12b) in support of the borehole disposal concept. An overview of the most important large-scale tests conducted in the Asse mine/URL is provided in Appendix 1.

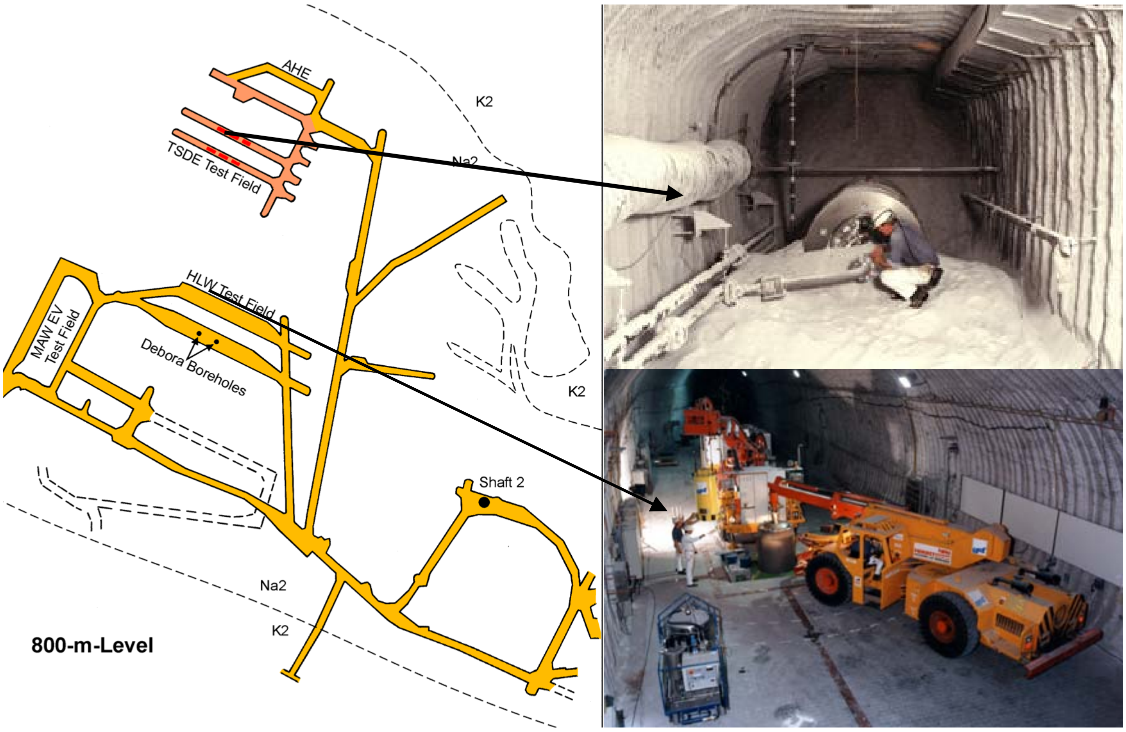


Figure 4-12. *Test areas on the 800-m level of the Asse mine/URL. a) Right upper figure shows the Thermal Simulation of Drift Emplacement (TSDE) experiment. b) Right bottom figure shows the High Active Waste (HAW) project. (Courtesy of GRS)*

Bedded salt rock

The U.S. program for siting and development of deep geological repositories in salt rock has used both on-site and off-site URLs since the early seventies to obtain the large-scale rock mass information required to support the design, construction, and operation of deep geological repositories for safe disposal of long-lived radioactive waste. However, since 1987, only the WIPP URL has been used to support the development of repositories in salt rocks. Hence, only the WIPP URL is described below. Figure 4-13 shows the regional geological setting at the WIPP site, Figure 4-6 shows the main spatial relationships of the WIPP repository, the WIPP URL, and the four shafts, Figure 4-14 provides a plan view of their layouts and locations, and Appendix 1 provides an overview of large-scale, *in-situ* tests conducted in the WIPP URL between 1983 and 1995.

The primary initial objective of the WIPP URL was to facilitate the acquisition of the large-scale, *in-situ* data required for:

- Corroborating and upscaling the data obtained by laboratory- and surface-based tests.
- Refining underground experiments, testing and excavation techniques, the repository design, and process and system models.
- Credibly predicting the long-term safety of the proposed WIPP TRUW repository.

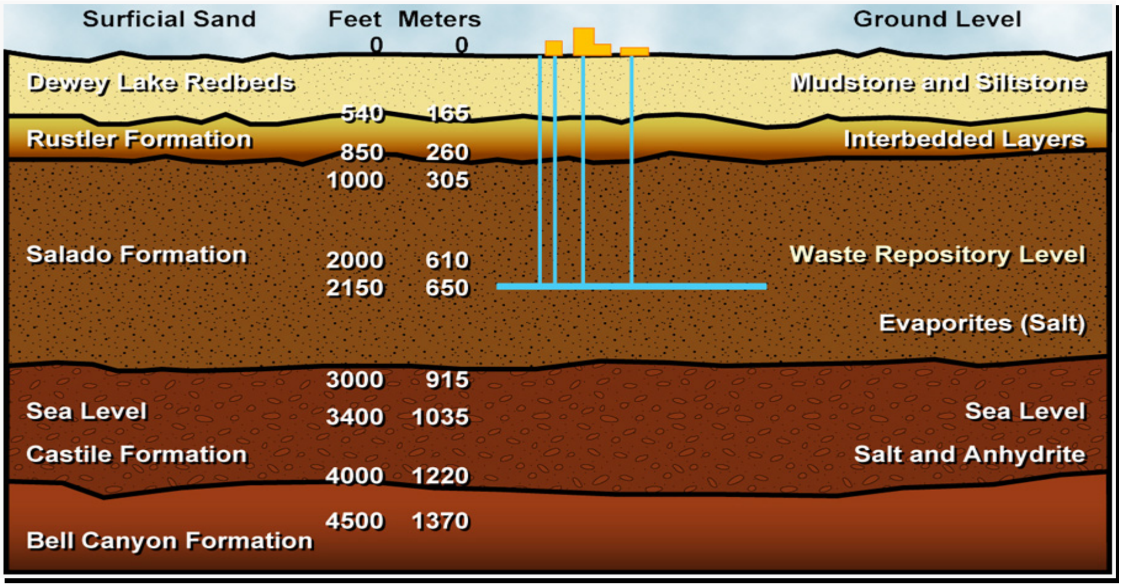


Figure 4-13. *North (left) - South (right) cross section of the regional geological setting at the WIPP site.*

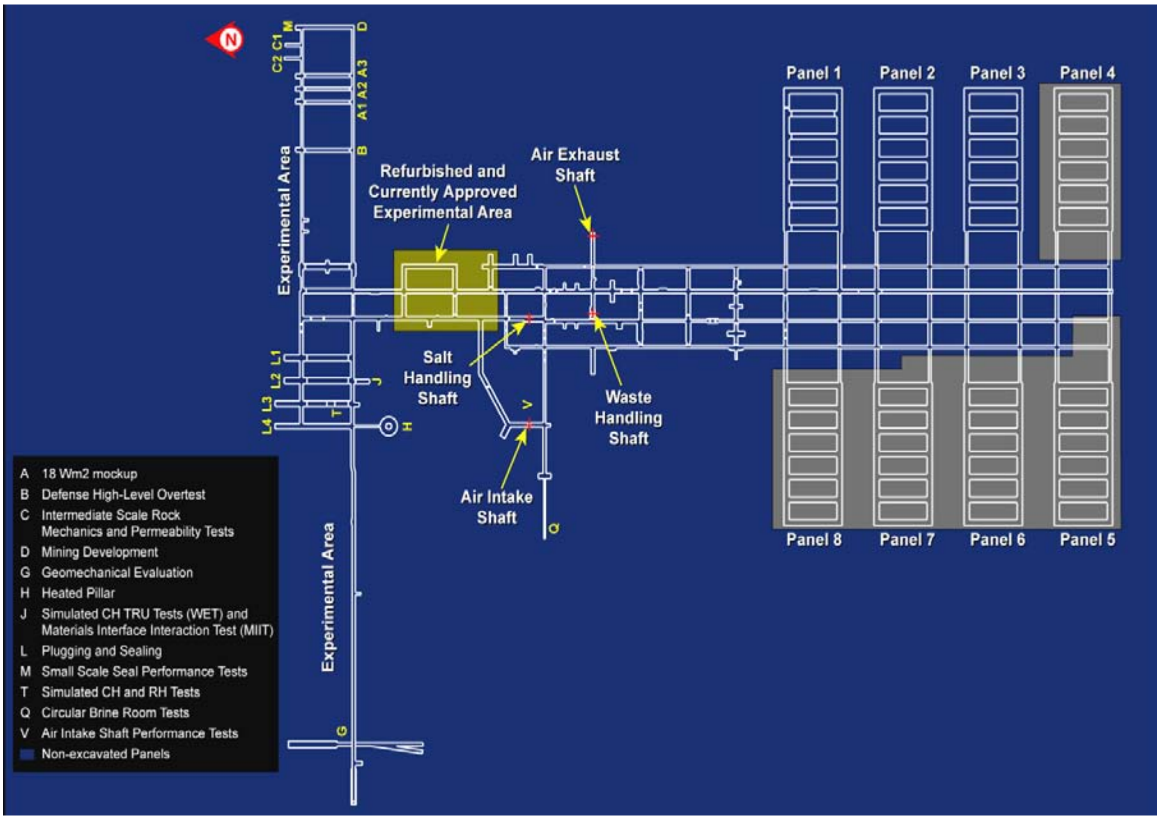


Figure 4-14. *Layout of the WIPP URL (to the left), repository (to the right), and shafts (between the URL and the repository), and a listing and the locations of some of the major large-scale, in-situ tests conducted in the URL. (Courtesy of USDOE CBFO).*

A secondary objective was to acquire similar information on HLW disposal in salt rock. However, in 1987, salt rock was deferred until at least the year 2007 [4-19] as a potential geological medium for disposal of HLW. Notwithstanding deferral, the WIPP URL hosted a comprehensive suite of large-scale *in-situ* tests between 1983 and 1995 addressing the ability of salt rock to safely contain and isolate both TRUW and HLW. These tests are summarized in Appendix 1 and described further in the CCA [4-10] and therein referenced sources [e.g., 4-20, 4-21]. Suffice it to here emphasize the fact that the suite of large-scale *in-situ* tests/experiments conducted in the WIPP URL was key to the related refinements of testing and excavation techniques, repository design, and process and system models that contributed to the successful 1998 certification of the WIPP repository.

4.2.2 Design and construction of URLs

Domal salt rock

In Germany, no specific criterion has been developed for the design and construction of URLs because of the availability of the abandoned Asse salt mine. The old mine contained a number of 130 empty excavations in the southern flank of the Asse salt anticline (Figure 4-10) remaining from the rock salt production that occurred between 1908 and 1964.

After Asse became a research mine in 1965, the first experiments were conducted in boreholes in the existing non-backfilled rooms on the 490 m and the 750 m levels. Later on, test rooms were excavated in areas with specific geological features, e. g., mineral and moisture content, to enable the investigation of special effects and processes. One such example is the Temperature Test 5, which was conducted in the Polyhalitbaenkchensalz (Na_2P) with higher polyhalite ($K_2Ca_2Mg[SO_4]_4 \times 2H_2O$) concentration and, thus, higher water (H_2O) content. A heater test was conducted here to investigate the heat-induced decomposition of polyhalite and the accompanying release of the crystalline water into HLW disposal boreholes. The location of this and other experiments in the mine was planned from the beginning in a way that it was possible to take samples from the heated area after termination of the experiment either by core drilling or by excavating special access drifts.

For example Figure 4-15 right shows the uncovered heater liner of the DEBORA-2 experiment covered by compacted crushed salt backfill and technicians removing the remaining backfill from the liner for the retrieval of corrosion specimens and measuring instruments. A special access drift (Figure 4-15/left) was excavated below the 800 m level to enable these extremely important and useful post-test activities.

Furthermore, whenever possible, newly mined test rooms were located far away from old excavations to avoid influences of the disturbed stress field. For example, Figure 4-15/right shows the uncovered heater liner of the DEBORA-2 experiment covered by compacted crushed salt backfill and technicians removing the remaining backfill from the liner for the retrieval of corrosion specimens and measuring instruments. A special access drift was mined below the 800-m level to enable these extremely important and useful post-test activities.

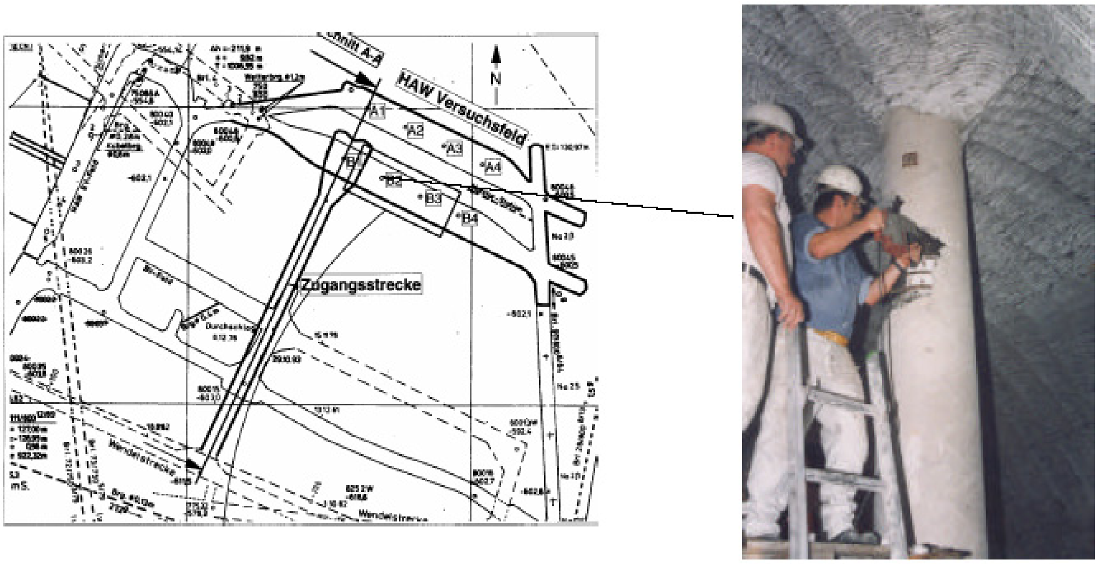


Figure 4-15. *Undermining of the DEBORA experiment.*

Left: Asse mine: HAW test field with underlying access drift to the DEBORA experiment.

Right: Uncovering and retrieval of corrosion specimens in the DEBORA 2 experiment.

Bedded salt rock

The location of the WIPP URL was selected in 1974 based upon the information obtained through surface-based investigations at and adjacent to the WIPP site. One basic siting criterion was that the URL and the potential repository would be located reasonably close together to fully draw upon the information obtained and experiences gained during the construction and testing of the URL. However, neither the URL nor the shafts could be located so close to the repository that they compromised the containment and isolation capability of the repository.

The design of the WIPP URL, as well as the repository, was based on practices and experiences gained from decades of salt rock mining in the area, in other salt-mining areas, and the then tentative cross-sections considered for TRUW and HLW disposal. One of the basic design criteria was (and is) that ground support should be minimized to optimize the inherent "self-healing" characteristic of rock salt. In most cases, with the circular Q Room (Figure 4-14) being the most apparent exception, the opening size/cross section of the "rooms" dedicated to the large-scale, TRUW-related tests were based on the preliminary baseline TRUW-repository design and measured 4 m in width and 10 m in height. Likewise, even if TRUW tests also were involved the opening size/cross section of the "rooms" dedicated to large-scale, HLW-related tests was based on the Reference Repository Configuration (RRC) for a potential HLW repository for defense-generated HLW (DHLW), the rooms measuring 5.5 m in both height and width and 93 m in length. This repository was then considered for the Umtra-Cowden horizon situated approximately 150 m below the candidate TRUW repository horizon at the bottom of the Salado Formation, The Axisymmetric Heated Pillar Test in Room H is the most apparent exception to these dimensions.

Based on the promising information obtained through a combination of environmental monitoring and extensive literature-, laboratory-, and surface-based investigations since 1974, the USDOE constructed the WIPP URL in the candidate TRUW repository horizon at the WIPP site in the early 1980s. The construction of the first of four shafts and the WIPP URL (Figures 4-6 and 4-14) commenced in 1982, and was essentially completed in 1986. As mentioned above, indicated in Figure 4-14, summarized in Appendix 1, and described further in Section 4.3, a suite of large-scale, *in-situ* tests were conducted in the URL between 1983 and 1995. Since then, portions of the WIPP URL have been closed in stages. The three main governing conditions for the phased closing of portions of the URL were (1) the intentional driving of several rooms to failure, (2) acquisition of the data needed to certify the WIPP repository, and (3) maintenance costs. However, as indicated in Figure 4-14, a portion of the WIPP URL was recently refurbished and remains available for potential additional underground tests in salt rock.

4.3 Engineered Barrier Systems (EBS)

As mentioned in Section 4.1, the host rock represents the most important barrier within the multiple-barrier concept of a salt rock repository employed in both Germany and the U.S. However, as concisely described below, notwithstanding this very advantageous inherent characteristic of salt rocks, both the German domal salt rock and the U.S. bedded salt rock programs also benefit from EBS that vary in design and performance requirements as a function of the types of waste involved. Appendix 1 summarizes the main experiments conducted in support of the German and U.S. EBS.

4.3.1 Description of EBS

Domal salt rock

According to the German disposal concept for SF and HLW [4-11], as illustrated in Figure 4-16, the main EBSs to be implemented in addition to the geological barrier, consist of (a) borehole seals, (b) drift seals (dams), and (c) shaft seals. In addition, access and transport drifts will be backfilled with crushed salt to minimize remaining voids in the repository and to assure rock stability as soon as possible after the completion of waste disposal operations.

The main EBSs shown in Figure 4-16 comprise the following main components:

- Approximately 30 m long seal consisting of crushed salt rock will be placed at the top of each HLW-disposal borehole (Figure 4-2).
- Drifts for direct disposal of SF in Pollux casks will be backfilled with crushed salt rock concurrent with the cask emplacement (Figure 4-3).
- Drift seals (dams) will be installed between the shaft area and the disposal areas after the repository-operations period is over.
- Shaft seals will be installed to seal the repository against water bearing overlying strata.

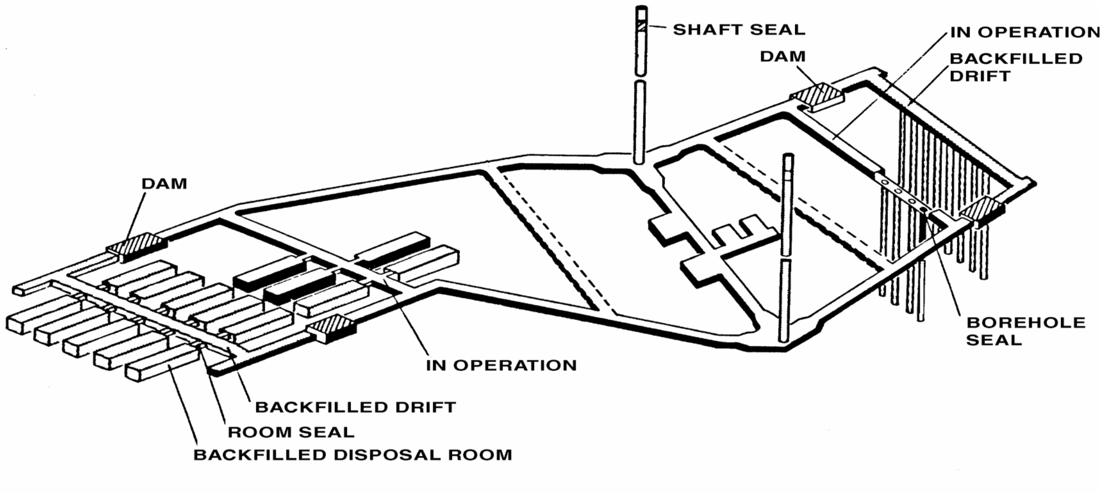


Figure 4-16. *Layout of a domal salt rock repository, including principal seals. (Courtesy of DBE)*

The crushed salt in the HLW boreholes will be adequately compacted by the creep of the surrounding host rock within about 10 years [4-22]. No additional sealing of the waste emplaced in the borehole is required.

The SAM-project [4-2] showed that a radionuclide release into the overburden rock strata and the biosphere is not to be expected if the HLW disposal areas, i.e., the heat-producing areas, are located closer to the central shaft than the non-heat-producing disposal areas. The main reason for this condition is that the heat-producing waste causes a significant temperature increase in the adjacent rock mass, which, in turn, causes higher opening-convergence/closure rates and faster compaction rates of the salt backfill in the borehole seals and drifts located in the heated rock mass than those located in the non-heated rock mass, and, thereby, accelerates the closing of any potential pathway for radionuclide migration. The convergence-induced transport of contaminated brine from the disposal drifts or the boreholes to the shafts is prevented because the backfill porosity in the drifts connecting the disposal areas with the central area will reach its final compaction, permeability, and hydraulic conductivity values in a relatively short period of time after waste and backfill emplacement. In the SAM-example [4-2] the flank drift connecting the central area and the HLW-area will be closed after 155 years, whereas the brine coming from the shaft will reach this drift only after 233 years. The drifts above the HLW-disposal boreholes, into which a limited amount of brine from undetected brine inclusions is supposed to be released, will be closed after 70 years to 80 years, ensuring that the brine coming from the shaft will not reach the disposal areas.

Bedded salt rock

The WIPP disposal system includes the following five main man-made barriers:

- Borehole plugs.
- Panel closures.
- Shaft seals.
- MgO buffer/backfill material in portions of the disposal rooms.
- Waste containers.

The reference to “man-made” barriers is used above because the USEPA considers the MgO buffer/backfill the only EBS in the WIPP design. Notwithstanding USEPA’s definition, for the purpose of this document, the aforementioned five man-made barriers are henceforth referred to as EBSs. Since only the main components of the five EBSs are described below, the reader is directed to the CCA [4-10] for additional information.

Borehole plugs limit the migration of (a) liquids into and out of the repository and (b) gases out of the repository. Thus, all boreholes reaching into or below the repository horizon within the WIPP site have been sealed based on very strict State regulations. These seals must have at least the radionuclide isolation characteristics of the surrounding rocks. Hence, the rock properties were and are used in the post-closure SAs/PAs and the borehole plugs are not addressed further in this document. Additional information on the borehole plugs is available in Appendix DEL of the CCA [4-10].

Panel closures (a) limit the migration of liquid and gas between the panels and (b) enhance the containment and isolation of the radionuclides emplaced in the repository. At WIPP, the current (concrete) panel closures are designed for a maximum permeability of E-15 m^2. However, they were not relied upon in the CCA because they were neither designed, intended, nor needed to support the long-term repository performance. The main objective of the panel closures is to protect workers against potentially unacceptable levels of volatile organic compounds (VOCs) during the operational period. They do, however, comprise a solid structure at the end of each panel that decreases the permeability in the EDZ in the portion around the panel closures faster than around the unsupported portions of the underground openings. Furthermore, the 1998 USEPA Certification Decision [4-9] stipulated implementation of a robust panel closure and excavation of the damaged rock. Hence, the current panel closure system will likely be evaluated further and addressed in the pending recertification(s). Additional information on the currently approved panel closures is available in Appendix MASS, Attachments 1-7, and Appendix PCS of the CCA [4-10] and in the USEPA Certification Decision [4-9].

Pursuant to the applicable regulations [4-7, 4-8] the four shafts connecting the repository (and the URL) with the surface facilities at the WIPP site (Figure 4-6) must be sealed upon completion of the disposal operations. The primary objectives of the current, multi-component, baseline WIPP shaft-seal-system (SSS) design shown in Figure 4-9 are to:

- Limit the amount of waste constituents reaching the accessible environment.
- Restrict formation-water flow through the seal.
- Use materials possessing mechanical and chemical compatibility.
- Protect against structural failure of system components.
- Limit subsidence and prevent accidental entry.
- Utilize available construction methods and materials.

As shown in Figure 4-9, the current WIPP baseline SSS design comprises 13 discrete seal components that completely fill the shaft with engineered materials possessing high density and low permeability. Only minor differences exist in the lengths of the components among the four shafts, whereas shaft diameters range between 3.5 m and 6.1 m.

Several fluid-flow and structural codes and models were used to design and demonstrate the projected performance of the shaft seals. Shaft seal elements were modeled discretely in the BRAGFLO numerical grid used for the CCA (see Section 4.3.4). Properties and distribution functions for the shaft seal elements comprised almost a third of all the parameters used in the CCA [4-10]. The SSS design and performance evaluations, which are documented in the WIPP SSS design [4-23] and parameters [4-24] reports, include:

- Seal material specifications.
- Construction methods.
- Rock mechanics analyses.
- Fluid flow valuations.

Two different categories of waste containers and related disposal concepts are used at WIPP. As illustrated in Figure 4-8, the CH-TRUW is contained in mild-steel drums and standard waste boxes (SWBs) that are stacked three layers high in the disposal rooms. As illustrated in Figure 4-7, the RH-TRUW, which may comprise up to 7 080 m^3 (= max. 4 vol.% of the total legal TRUW volume), is contained in thick-walled steel canisters that will be emplaced in horizontal holes in the ribs/walls of the disposal rooms. Neither the CH-TRUW nor the RH-TRUW containers were assigned any performance credit or assessed for post-closure radionuclide containment and isolation in the CCA because their main purpose is to ensure workers protection during handling, transportation, and emplacement of the TRUW. The 208 l steel drums and the SWBs containing the CH-TRUW (Figure 4-8) will be breached early by room closure because, in only 50 years after closure, the inherent creep characteristics of the repository host rock will have reduced the height of the unsupported disposal rooms from 4 m to 2 m. The steel canisters containing the RH-TRUW (Figure 4-7) may survive the closure pressure somewhat better, but they are also assumed to be breached relatively early in repository history by corrosion.

As illustrated in Figure 4-8, crushed MgO in bags is placed on top of the stacks of the CH-TRUW drums/SWBs and in a portion of the void between the drums/SWBs and the walls of the disposal room. The primary functions of the MgO buffer/backfill are to:

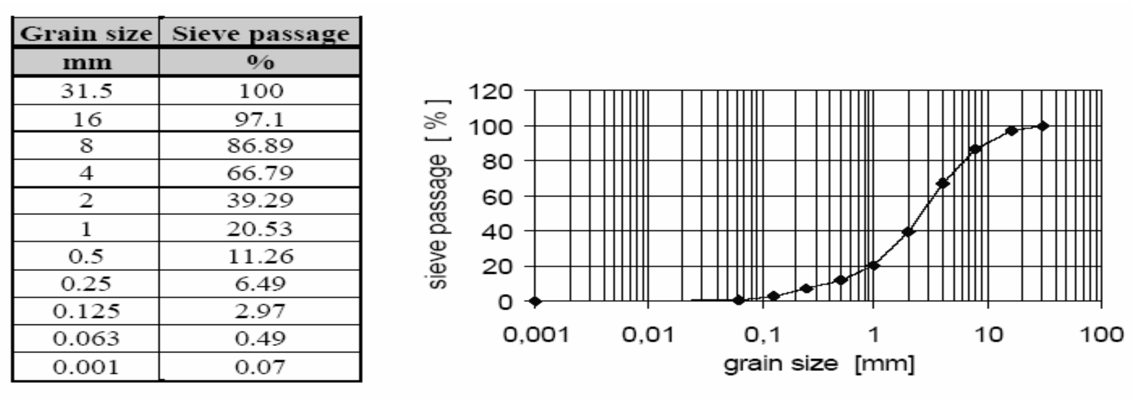
- Consume essentially all carbon dioxide (CO_2) produced in the WIPP repository.
- Control the disposal room CO_2 fugacity/partial pressure (f_{CO2}) and brine pH within ranges that result in lower actinide solubility than at the ambient pH.

In addition, the MgO is able to consume significant quantities of water in any brine that may seep into the disposal room. However, the MgO mainly contributes chemically rather than physically to the long-term containment and isolation of radionuclides at WIPP by driving the repository pH to about 9, giving a basic chemistry in which the actinides are much less soluble than at the ambient pH. Although the MgO is only placed in a portion of the disposal rooms, sufficient amount of MgO is emplaced to react with all the CO_2 possible in the respective waste disposal room, combining with water to form magnesium carbonate/ magnesite ($MgCO_3$), which is an insoluble mineral.

4.3.2 Design and construction of EBS

Domal salt rock

No specific design or construction criterion is needed for the crushed salt rock backfill used as sealing material in the HLW disposal boreholes and drifts. However, the grain distribution of the crushed salt rock backfill needs to be controlled to avoid emplacement problems, especially in the narrow (85 mm) annulus between the waste canister and the host rock in the deep HLW-disposal boreholes. Typical data on the drift backfill produced during the continuous, mechanical mining of the TSDE drifts in the Asse mine/URL are shown in Figure 4-17, with the maximum grain size being 31.5 mm. However, in the DEBORA borehole annulus experiment, the largest grain size of the crushed salt rock emplaced without problem in the narrow annulus between the canister and the borehole wall was 10 mm. Further details on experiments conducted to investigate and demonstrate the sealing function of compacting crushed salt are provided in section 4.3.4



Grain size	Sieve passage
mm	%
31.5	100
16	97.1
8	86.89
4	66.79
2	39.29
1	20.53
0.5	11.26
0.25	6.49
0.125	2.97
0.063	0.49
0.001	0.07

Figure 4-17. *Grain size distribution of crushed salt rock produced by continuous mining in the Asse mine.*

Drift seals (dams) between the shaft area and the disposal areas will be installed after the completion of the disposal operations. A preliminary drift-seal design (Figure 4-18) has been developed by Stockmann et al [4-25]. This design includes:

- Short-term seal of sand-asphalt, which is required in the early stage after the installation of the main seal (dam) to prevent inflow of liquid solutions.
- Long-term seal, consisting of pre-compacted salt bricks, and an abutment of salt concrete providing stability against brine pressure in the unlikely case of a complete flooding of the repository. The sealing function of the long-term seal increases with time by its compaction due to drift convergence.

Upon completion/termination of the repository operation period, the infrastructure in the repository will be dismantled and the shaft seals will be installed to close the repository. A concept for a shaft seal (Figure 4-19) has been developed by Schmidt et al [4-26]. An *in-situ* experiment on the effectiveness and stability of a shaft seal consisting of bentonite pellets was recently conducted successfully at the Salzdetfurth mine in Germany [4-27].

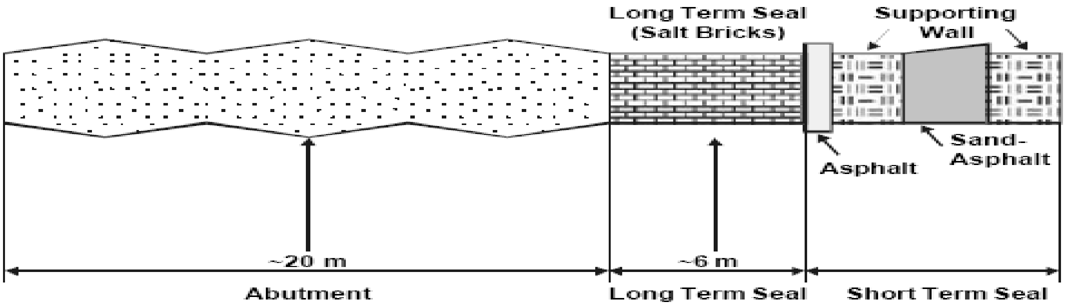


Figure 4-18. *Principal design of a drift seal (dam).*

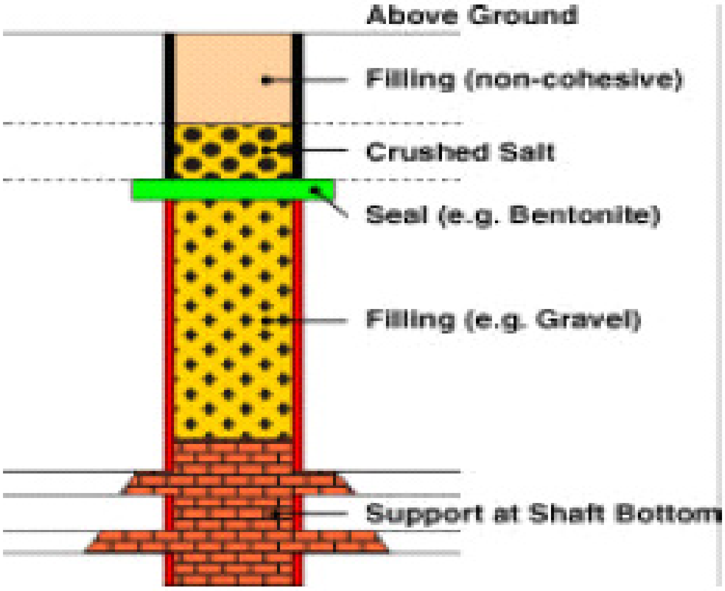


Figure 4-19. *Principal design of a shaft seal.*

Bedded salt rock

Following are three conditions governing the design and analyses of the WIPP tests:

- The large strains and displacements encountered in the salt rock in combination with the elevated temperatures used and the corrosive environments hosting the tests were all conducive to instrument failure over the time span of the experiment, which could be as long as ten years or more. Furthermore, salt creep and lack of access to high temperature rooms prevented the replacement of many instruments/gauges. Hence, the test designs at WIPP included redundancy of instruments and heaters to assure adequate measurements even if instrument- and/or heater-failures occurred. The data from each of the major test rooms were sent to an adjacent underground instrument shed, which was air-conditioned and humidity controlled. The data were multiplexed and sent to the surface recording trailer through a single cable. Each shed was capable of processing 1 500 channels of data. Several of the experiments, where the test geometry allowed, were instrumented before excavation and were monitored while the subsequent excavation for the experiment took place. This was particularly important to capture the very early time transient creep.

- The WIPP *in-situ* experiments were frequently preceded by laboratory experiments and always by numerical modeling. Pre-test modeling predicted the strain and displacements and temperatures to be expected in the WIPP experiments. This information was used to acquire and place the instruments, and to guide the experiments. Redundancy was built into the plan. As experimental data were acquired, they were used to adjust the model concept as required. This iteration was repeated until there was satisfactory agreement between experimental observation and model prediction.

- The cognizant SNL Principal Investigator (PI) and/or Principal Scientist (PS) for each experiment was responsible for interpreting and analyzing the data from the experiment. Data were presented in tabular or graphical form to allow for easy examination. When spurious data points were removed or the data were smoothed, a record of that had to be entered into the record by the PI/PS so that others could reproduce the results. The conclusions derived from the data for each experiment were always published in an SNL report and, usually, in professional peer-reviewed journals at a later date.

The geometries and main components of the five EBSs at the WIPP site are summarized in Sections 4.1, 4.2, 4.3.1, and 4.3.3, and illustrated for the RH-TRUW, the CH-TRUW, MgO buffer/backfill, and the shaft seals in Figures 4-7, 4-8, and 4-9, respectively. As illustrated in Figures 4-7 and 4-8, the placement of waste and the related EBSs at WIPP vary as a function of waste type. Notwithstanding this variability, the two common design principles/criteria for the three aforementioned EBSs are to:

- Provide a man-made barrier that exhibits radionuclide containment and isolation characteristics equal to or superior to those of the surrounding rock.

- Use proven materials, preferably earthen materials.

Emplacement evaluations and fluid flow studies provided guidance on the design of the WIPP seal system. Characterization of the EDZ, which surrounds the excavations and any emplaced plug, was accomplished by gas-flow testing. The long-term sealing strategy utilized the reconsolidation of crushed salt, eventually resulting in a seal that approaches the density, permeability, and strength of the intact host salt rock. To ensure isolation and prevent fluid intrusion in the period before crushed salt reconsolidation is completed, as illustrated in Figure 4-9, bentonite clay, concrete, and asphalt plugs supplement the primary salt plug in the shaft seals. Testing involved both laboratory studies and intermediate-scale (m-diameter holes) *in-situ* testing of these materials.

The basic construction principle/criterion for the EBSs, as well as the URL and the repository, is to inflict as little damage to the host rock as possible. Hence, virtually all underground openings at the WIPP site were, are, and will be constructed by means of mechanical mining methods and/or rotary drilling techniques. However, drill-and-blast techniques were used for establishing/developing the initial bailout and equipment-assemblage/storage/staging space adjacent to the shafts at the URL and repository level.

EBS test locations were chosen that required no ground support by the careful selection of the URL and repository horizon that achieved one of the principal test objectives, the simulation of real repository conditions, which includes the deformational characteristics of the host rock. However, due to the inherent deformational characteristics of the salt rock in combination with either expected or unexpected long-stand-up times, the ceilings/backs of several disposal rooms and transportation drifts were supported and are currently being monitored. Subsequent to the opening and during the continued phased/staged development of the WIPP repository (Figures 4-6 and 4-14), panels and disposal rooms were, are, and will not be supported to ensure rapid encapsulation of the emplaced waste.

4.3.3 Instruments and experimental procedures

Domal salt rock

Based on more than 30 years of German experience, the most important processes to be measured in URLs and repositories dedicated to the safe disposal of HLW in salt rock formations are the following:

- Initial ambient rock mass conditions, i.e., baseline conditions, including temperature (T).
- Strength and deformational characteristics (M).
- Chemical conditions and characteristics (C).
- State of stress.
- Discontinuities/impurities.
- Permeability and flow characteristics/patterns (H).

Changes in the initial ambient rock mass conditions will occur due to man-made actions, such as mining (e.g., EDZ) and waste disposal (simulated or real). (Due to the inherent characteristics of salt rock, convergence and displacement are two particularly important, highly temperature-dependent parameters that need to be established.)

Initial EBS conditions.

Changes in EBS conditions will occur due to waste disposal (simulated or real), including changes in T, M, C, H, state of stress, compaction and pressure developments, and gas generation due to e.g., heat up, radiolysis, bacterial/microbial activity (B), and material corrosion, as applicable.

Due to the broad range and potential variability of the main parameters of importance to the design, construction, operation, and closure of a safe repository for long-lived radioactive waste in salt rock, special development and application of measuring instruments of adequate resolution is required for their measuring and monitoring.. Furthermore, a robust design is necessary to ensure the proper functioning of the measuring equipment under the harsh environmental conditions expected in a salt rock URL or repository that, typically, include significant temperature changes/fluxes, large rock mass deformations, and traces of corrosive fluids . A robust design is particularly important for long-term monitoring because most URL and repository sites will not be accessible after being backfilled and sealed/closed. The most important measuring methods and devices used, and experiences gained in the German salt rock URLs are described below.

Temperatures were recorded by thermocouples and resistance temperature detectors (RTDs). The accuracy of the thermocouples was determined by Deutsche Industrie Norm (DIN) 43710. For temperatures up to 400°C, the DIN-permitted deviation is 3°C. Thermocouples with an accuracy of 1/2 or 1/4 of the permissible DIN deviation (e.g., a maximum deviation of 1.5°C or 0.75°C, respectively) were commonly used. The RTDs consisted of an encapsulated metallic wire (usually platinum) with two to four connector wires. As the four-wire configuration allows for the compensation of the wire resistance, this configuration was preferred and is highly recommended. The measuring accuracy, as regulated by the International Electrotechnical Commission (IEC) 751, is ±0.3K at 0°C, ±0.8K at 100°C, and ±1.55K at 250°C. The platinum-type RTD was more accurate than the thermocouple, especially at moderate temperature.

The closure of underground openings was determined by convergence measurements. The convergence meters were and should always be installed immediately after excavation to ensure that data on the high deformations caused by the initial primary creep are obtained. For drift closure measurements in backfilled rooms or at and in EBS locations, stationary devices were designed consisting of a measuring rod and an electric displacement transducer between opposite points of a drift. Both the displacement transducers and the measuring rods were inserted into telescopic steel tubes and thereby protected against external mechanical impact. The maximum measuring range was up to 400 mm at temperatures of up to 180°C.

Rock deformations were recorded by extensometers and inclinometers measuring axial and radial borehole displacements, respectively. Axial borehole displacements were monitored by multiple point glass-fiber rod extensometers sliding inside protecting PVC tubes. Advantages of this extensometer type are its flexibility to be installed in one operation and its low coefficient of linear thermal expansion (0.6E-6/°C instead of 13E-6/°C for steel), which makes a temperature correction unnecessary. The anchors were fixed by wedging or by grouting. After the installation of the extensometers, all boreholes were filled with a supporting cementation. At the instrument head at the borehole collar, the displacements of the anchor points were registered by displacement transducers. For high temperature applications, a reverse gauge design was chosen with the instrument head being installed in the deepest part of the borehole where the temperatures were lower than at the borehole collar. It was found that the accuracy of the measuring system depended upon the length of the extensometer and it ranged between 0.02 mm (for lengths up to 20 m) and 0.3 mm (for lengths up to 100 m).

Stress monitoring probes were emplaced in boreholes and subsequently grouted to observe long-term stress changes in the host rock. The probes consisted of Gloetzl-type hydraulic pressure cells orientated in different directions. Generally, stress measurements in salt rocks are difficult because of the inherent stress release due to creep. After installation, pressure cells take up stress only gradually. According to Heusermann [4-28], the prevailing stress is approached only after a very long time period in the range of E8 days. Consequently, absolute stress measurements with these probes are only reasonable under some ideal conditions, e.g., in areas where high stresses lead to a very fast loading of the cells. However, the hydraulic pressure cells proved to be very suitable for measurements of stress changes (e.g., due to temperature changes). Additionally, large flat jacks and the overcoring method were successfully used [4-29] to determine the absolute rock stress.

Pressure development in the EBS was monitored by electropneumatically operated, hydraulic Gloetzl pressure cells and Absolut Widerstandssprung Druckmesskissen (AWID) cells. The AWID cells [4-30] can be operated at high temperatures because their accuracy and performance are not dependent upon material properties. To avoid damages during installation, the AWID cells were grouted into casings before placement. Laboratory tests revealed an accuracy of 0.3% for the AWID measurements.

Geoelectric survey, combined with laboratory calibration, was the non-destructive method used for measuring the water content in the rock mass and backfilled underground openings. The resistivity changes in surveyed areas, typically caused by water accumulations or dry-out effects, were successfully determined by special electrode arrays and repeated measurements. This method was also successfully used in the rock salt for the characterization and measuring of temporal changes in the EDZ [4-31]. All measuring systems were remotely computer-controlled and designed for multipurpose use.

A typical data collection system was operated in the TSDE experiment using local front-end processors, which were operated independently. The measuring sensors were scanned regularly. The data from all front-end processors were received by a local computer, and transferred via modem to an aboveground, archiving and evaluating computer. Different precautions were taken to safeguard against loss of data and unauthorized access. Additionally, an alarm system was recording different fault messages in the test field. The coded fault messages were transmitted to the aboveground service facilities.

Bedded salt rock

As illustrated in Figure 4-20, a large number of different types of instruments were used in connection with the different types of experiments conducted in the WIPP URL (Figure 4-14) to acquire the data required for the design, construction, certification, operation, closure, and post-closure performance of the WIPP repository. As summarized below and as described to a greater level of detail in Appendix 1, many of the tests conducted in the URL involved high temperatures that simulated HLW disposal [4-32].

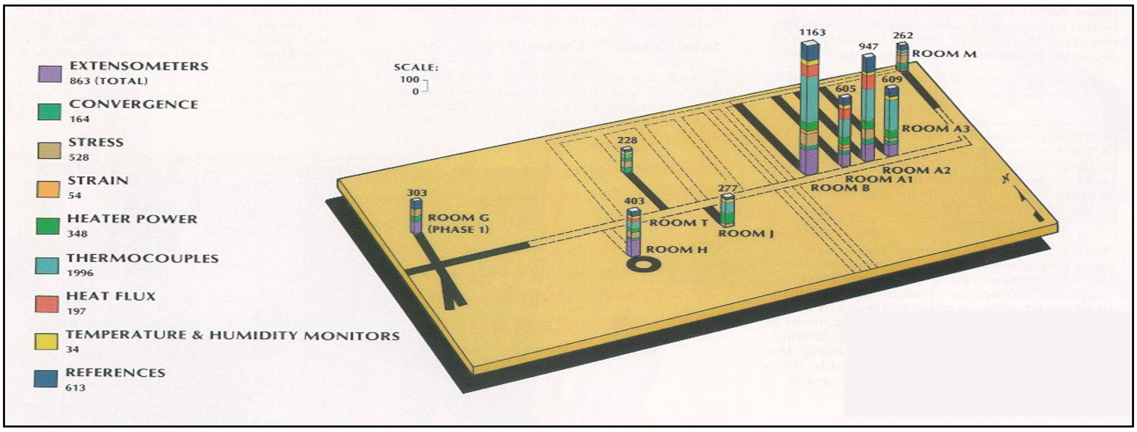


Figure 4-20. *Instrument distribution in the WIPP URL (see Figure 4-14 for test locations).*

Due to the large number of experiments/tests conducted at the WIPP site during the past 30 years, this Section focuses on the following four major groups of large-scale, field tests:

1. The Thermal/Structural Interaction (TSI) Tests.
2. The Plugging and Sealing (P&S) Tests.
3. The Waste Package Performance (WPP) Tests.
4. Hydrologic testing.

Whereas the first three groups of tests were conducted in the URL, the fourth group includes both URL- and surface-based tests. Furthermore, due to the extensive design and parameter databases associated with the URL-based tests, their primary objectives and main benefits are summarized in Appendix 1 and the emphasis below is on:

- Primary purpose of the WIPP experimental program.
- Processes and parameters measured.
- Location, purpose, and design of the experiments/tests, including the main instruments used and their accuracy and reliability.

Additional information on the objectives and designs of all four groups of tests is available in the CCA [4-10]. (and in the USDOE CBFO CAs) including detailed descriptions of the rationale for selecting the more than 4 200 instruments and gauges shown in Figure 4-20 (comprising ~3 500 remote-handled and ~700 manually-monitored instruments and gauges) and observations and findings resulting from the testing, calibration, and use of these gauges in the harsh WIPP URL environment.

Initially, the primary purpose/criterion of the WIPP experimental/test/RTD program was to develop an adequate understanding of the physical processes and parameters needed for designing, constructing, operating, and decommissioning a deep geological repository for safe disposal of TRUW and DHLW in salt rock. [4-10, 4-20, 4-21] With time, the construct and use of the codes and models described in Section 4.3.4 that supported the adequate prediction of post-closure behavior and safety for the EBS and the WIPP repository for at least the 10 000-year regulatory period became increasingly important.

The five main processes and parameters studied and characterized at the WIPP site were:

- T, H, M and C characteristics of the candidate repository host rock, the Salado Formation, including structural discontinuities and anomalies.
- H, M and C characteristics of the Rustler Formation, which includes the site's highest hydraulic conductivity unit, the 11 m thick Culebra Dolomite Unit.
- H, M and C characteristics of the shaft seals (Figure 4-9).
- T, H, M and C characteristics of the EDZ.
- H, M and C characteristics of the MgO buffer/backfill (Figure 4-8).

However, restrictions at the WIPP site prior to its operation required that experiments involving radioactive isotopes and radioactive waste be conducted off site. Consequently, studies with the actinide isotopes were conducted at several off site laboratory locations, such as SNL and Los Alamos National Laboratory (LANL).

The TSI Tests include the following seven major, large-scale, *in-situ* tests (see Figure 4-14 for locations): (1) The 18 Watt per square meter (W/m^2) DHLW Mockup Tests, which were conducted in Rooms A1, A2, and A3, (2) The DHLW Overtest, which was conducted in Room B, (3 &4) The Geomechanical Evaluation Tests, including the *In-Situ* Stress Determination by Hydraulic Fracturing in the Room G Entry test, which were conducted in and adjacent to Room G, (5) The Heated Axisymmetric Pillar Test, which was conducted in Room H, (6) The Ambient Room Temperature Test, which was conducted in Room D, and (7) The Scale-Effect Tests, which were conducted at two locations, one being a 30m long, 1m diameter borehole constructed between Rooms C1 and C2, and the other being conducted in conjunction with the construction of the 100-m long, 3-m diameter Room Q. As summarized in Appendix 1 and further described in the CCA [4-10] and therein referenced sources [e.g., 4-20, 4-21], in a variety of approaches and designs, the TSI Tests essentially addressed the mechanical behavior of rock salt as influenced by excavation effects, stress, and thermal loading, and interactions induced by waste emplacement. They were instrumental to the development and validation of the codes, predictive models, and calculation techniques used for the design and SAs/PAs supporting the 1998 certification of the WIPP disposal system.

Extensometers proved to be the most useful instrument for measuring the creep of the salt. Because of the large strains, wire-extensometers were the principal type used. Rod-extensometers were used in a few instances where precise measurement of small strains was desired. Most extensometers were multi-point with four additional anchors between the collar of the installation hole and the deepest anchor at 15.24 m. Teflon sleeves covered the wires of the extensometers where they were subject to salt accumulation due to the brine seepage. Convergence measurements provided direct information on the changing dimensions of the excavated openings. Because the dimensions of the excavations were a critical parameter in the modeling, the experimental rooms were excavated to tight tolerances to compare to later observations. A high precision laser survey was brought underground from a benchmark on the surface to put all these relative movements on an absolute basis. Extensometers and convergence gauges proved to be more useful than the large number of stress gauges used due to the creep of the salt around the stress gauges, which compromised the recorded stress value. Interpretation of the stress-gauge readings required de-convolution through numerical modeling techniques. Thermocouples were used in large numbers to acquire good spatial information on the thermal field for the heated rooms because the salt creep rate is highly temperature dependent. The design, instrumentation, and results of the TSI Tests are described further in the CCA [4-10].

The P&S Tests include the following two groups of tests: (1) Salado Formation Characterization, including permeability (underground areas), gas flow (underground areas), moisture transport and release (conducted in Rooms A1, B, and Q in Figure 4-14), and Air Intake Shaft (AIS) Performance, and (2) Developing and Evaluating Seals, including Plug Test Matrix (conducted in Rooms L1 and L2 in Figure 4-14), Borehole Plug (underground and surface), Small-Scale Seal Performance (conducted in Room M in Figure 4-14), and Backfill Design and Emplacement (conducted a several locations in the WIPP URL) Tests. The P&S Tests provided the technical basis for an adequate and defensible design for sealing the WIPP repository after decontamination and decommissioning (D&D) [4-23, 4-24].

In addition to the type of instrumentation described above for the TSI Tests, the Small-Scale Seal Tests employed fluid pressure testing to determine the leak rates around and through the various seals. Gas pressure changes in a known volume behind the seal were used to determine the leak rate and tracers in pressurized liquid were used to determine the path of leakage. Periodic measurements evaluated the effectiveness of the progressive creep closure around the seal in healing the interface between the seal and the rock, and the EDZ. At termination of the active phase of the experiment, cores taken through the salt-seal interface were examined in the laboratory for chemical interactions and bond strength.

As summarized in Appendix 1, several WPP Tests were conducted to evaluate the short-term (5 to 50 years) integrity of waste packages for CH-TRUW, RH-TRUW, and HLW. A secondary objective was to develop an understanding of the conditions that might be faced during the operational period of WIPP in the event that retrieval would be required. Because bedded salt rock was also being considered for disposal of civilian-generated HLW (CHLW) in the mid-1980s, *in-situ* tests were conducted in the following areas to evaluate possible HLW canister materials and to examine leaching of candidate glass waste forms of several nations: (a) Simulated CH- and RH-TRUW Technology Tests, (b) Simulated DHLW Technology Experiments, and (c) Materials Interface Interaction (MII) Tests. Despite their TRUW and DHLW classifications, no radioactive material or constituent was used in any of the field tests.

The Simulated CH- and RH-TRUW Technology Tests were conducted in Rooms J and T (Figure 4-14). A total of 174 208-l standard oil drums filled with simulated CH-TRUW were emplaced in Room J: some were immersed in the purposely filled brine pool, others were covered by one or two types of backfill (salt and salt/bentonite), and some were subjected to humid air only. In the Room J “overtest”, the drums were immersed in the brine pool, which was heated to about 40°C. Other drums were emplaced in a salt and in a salt/bentonite backfill into which some brine was wicked. The purpose was to examine corrosion under “worst-case” conditions. Tests to study radionuclide migration, using non-radioactive chemical tracers, were also conducted in Room J, both in the surrounding salt rock and in the marker bed located about 0.3 m below the floor/invert of Room J. Eight full-size, simulated RH-TRUW canisters were emplaced into boreholes in the side of a design validation test Room T. These canisters were heated with 120 W heaters to impart about twice the maximum heating expected from the RH-TRUW. Four of the holes were backfilled with a mixture of 70% bentonite and 30% silica sand. The other four holes were not backfilled. Tests were monitored with borehole closure, temperature, and pressure gauges. The stresses and strains on the drums in Rooms J and T were measured, as was room closure, by remotely-read instruments. The initial plan was to recover the drums after about five years to determine the condition of the drums at a time when recovery might be performed. However, these plans were changed and a “post-closure” drum-removal (retrievability) test was conducted in another portion of the WIPP URL in April 1992.

The Simulated DHLW Technology Experiments were conducted in Rooms A1 and B (Figure 4-14). Eighteen full-size (0.6 m to 0.79 m in diameter and 3.0 m long) simulated DHLW packages were installed vertically into the floors/inverts of Rooms A1 and B, six in Room A1 and 12 in Room B. Eight of the 12 DHLW packages in Room B contained 1 000 W heaters. The remaining 10 DHLW packages in Rooms A1 and B contained 470 W heaters. The primary purpose of these tests was to evaluate alternative canister materials and backfill materials in a heated, corrosive salt environment under normal and overtest conditions. The tested backfill materials comprised crushed salt, low-density bentonite/sand mixture, and entrapped air. Canister surface temperatures ranged between 90°C and 200°C. The only aspect not simulated in these tests was the radiation field. Only a few canisters from the most severe environment were recovered before policy changes and funding constraints terminated the DHLW studies.

The MII Tests were also conducted in Room J (Figure 4-14). Fifty boreholes, each about 100 mm in diameter and between 1.2 m and 2.1 m deep, were used to test domestic and foreign waste-package materials that included 980 waste form samples of 15 different compositions, 16 different glasses, and 11 different metals. In addition, 278 canister or overpack metals and 587 geologic, salt, and backfill specimens were involved. Intermediate sampling and analysis occurred at one-half, one, two and five years. The MII Tests, which added brine to the experiment, had brine-proofed connections to the immersed thermocouples. For the Q-Room brine experiment (Figure 4-14), which required that the room environment be well isolated from the rest of the underground, data and power cables accessed the room through gas tight bulkhead feed-through connectors. The primary cable routing from the underground to the surface recording station was through the Salt Handling Shaft (SHS) (Figure 4-14). The activity in this shaft led to a concern for cable damage and a back up cable plant was emplaced in the AIS, which had no routine access activities.

In addition to the standard rock mechanics instrumentation described for the TSI Tests above, selected waste packages were instrumented with strain gauges to record the deformation of the package as creep of the salt imposed increasing stress on the surface of the package. Waste package experiments involving elevated temperature used a large number of thermocouples and thermistors to detail the thermal environment (Figure 4-20). The DHLW Technology Experiments also employed stress and strain gauges to record the conditions to which the waste packages were subjected. The canisters in the DHLW Overtest were recovered by overcoring and retained for corrosion analysis in the laboratory. The MII Tests also used extensive periodic sampling of the brine in which the samples were immersed to determine the chemistry of the test environment. Periodic removal of duplicate test specimens allowed for determination of the corrosion and leaching as function of time.

The suite of *in-situ* tests conducted in different locations of the WIPP URL (Figure 4-14) involved the selection, installation, calibration, maintenance, recording, and, in some cases, removal and replacement of gauges of various types in several large underground test rooms to measure the mechanical and thermal response of the rock mass surrounding the test rooms, and to measure the environmental conditions in the test rooms. Gauges were selected that could accommodate the range of responses predicted by pre-test calculations and that could operate in the harsh underground environment of the WIPP site. For each main category of gauges, gauges were evaluated prior to test construction and, when deemed appropriate, design modifications were made prior to gauge manufacturing that would improve gauge operation and longevity at the WIPP site. Gauges were also modified as the testing progressed based on the knowledge gained from test operation and maintenance programs. The mechanical response gauges included room-closure gauges, borehole extensometers, stress gauges, inclinometers, survey references, and borehole strain gauges. The thermal-response gauges included thermocouples, thermal flux meters, and heater-power gauges. The environmental gauges comprised a small number of air velocity gauges and air temperature thermocouples that were installed to evaluate heat loss from the test rooms.

To ensure measurement accuracy, gauges were calibrated either by SNL or the manufacturer. The results of the calibrations were fit to equations that were used by the data acquisition system (DAS) to convert gauge voltages to engineering units. The mechanical displacement gauges were calibrated by SNL personnel and contractors on fixtures that were traceable to National Institute for Standards and Technology (NIST) standards. The stress meters were calibrated by SNL with a two-step process that calibrated gauge output to formation stress. Thermal flux meters were calibrated by gauge factors and temperature corrections supplied by the manufacturer. The air velocity gauges were calibrated by the manufacturer and, later at the WIPP site, with a portable wind drift. The thermocouples were an exception as the DAS used NIST Thermocouple Reference Tables to convert voltages to temperatures. Later in the experimental program, however, NIST polynomials were used. Gauge output was reviewed on a regular schedule and gauges were maintained on a routine basis to ensure long-term success of the experiments. Simple problems were corrected in the field while malfunctioning gauges were replaced with new or refurbished units. Gauges that could not be repaired or replaced were deactivated and data acquisition was discontinued, however, most gauges performed well throughout the life of the tests. Indeed, some gauges reliably monitored room closures after 12 years of service.

The measurement accuracy of the various types of closure gauges, extensometers, and thermocouples was evaluated and it was found that these gauges all had an uncertainty less than +1 % of the gauges' full-scale range [4-10]. Because the maximum uncertainties of the various components were used to derive the combined accuracy, the derived uncertainties will, in general, be larger than the actual uncertainties. As a result, the derived uncertainties, because they are within 1%, provide a large degree of confidence in the data obtained at WIPP. While the derived uncertainties can be taken as a measure of the actual uncertainty, other factors may modify the conclusions drawn from these derived values. Specifically, the calibration data, when represented by a least-squares fit to the linear equation for remote closure gauges and extensometers, typically showed deviations well within 1%. However, on rare occasions, the maximum deviations were slightly greater than 1% due to uncertainty in the calibration data measurements and the intentionally limited (linear) degree of fit.

As mentioned above, natural processes are not expected to breach the integrity of the WIPP disposal system [4-10]. For example, water inflow during shaft construction did not pose a significant problem. Free flow into the shafts, before lining, amounted to less than 5 l/min. Shaft lining and pressure grouting reduced this in-flow to insignificantly low levels. However, human intrusion could introduce radioactive isotopes into boreholes and into the Culebra and Magenta aquifers of the Rustler Formation located above the repository host rock. It is thus necessary to understand the WIPP hydrologic system and the transport processes in that system, in order to predict the movement and concentration of radioactivity with adequate assurance to satisfy the regulatory requirements [4-7, 4-8]. As studies of the aforementioned aquifers progressed, it became clear that the aquifer and the transport mechanisms were more complex than first anticipated. Extensive, surface-based pumping tests and large-scale, chemical-tracer tests were thus conducted to clarify the hydrologic transport mechanisms involved [4-10]. These tests permitted determination of the transmissivity field over the site region and identified the physical transport mechanisms that occurred in the aquifers. All holes were subjected to slug tests and draw down tests to obtain local estimates of Culebra transmissivities. In regions that could sustain long-term pumping, long-term pumping tests were used to interrogate much larger intervals, frequently for a distance out to as much as 1 000 m. These locations were usually also the location of non-radioactive, chemical tracer studies in which tracers were injected into three or more satellite holes and periodically sampled from the pumping hole. One such location used six injection holes at different distances and azimuths with injections occurring at different horizons within the Culebra.

Overall, more than 50 deep boreholes have been drilled from the surface and more than 50 boreholes have been drilled from the URL and the AIS and tested to assess and evaluate the hydrologic system at the WIPP site/disposal system. The very low permeability of the Salado Formation salt rock could not be accurately assessed from the surface due to the special techniques and precision required. Hence, hydrologic studies were also conducted in the repository horizon even though salt rocks have a very low permeability. Twenty-two hydraulic tests have been performed in impure halite, and two in pure halite. Interpreted permeabilities, using a Darcy flow model, vary from E-23 m^2 to 4E-18 m^2 for impure halite intervals. Interpreted formation pore pressures vary from 0.3 MPa to 9.7 MPa, with the lower pressures believed to show effects of the EDZ. Tests in pure halite show no observable response, indicating either extremely low permeability (<E-23 m^2), or no flow whatsoever, even though appreciable pressures are applied to the test interval [4-10]. Fourteen hydraulic tests have been performed in anhydrite beds above and below the repository horizon. Interpreted permeabilities, using a Darcy-flow model, vary between 2E-20 m^2 and 7E-18 m^2 for anhydrite intervals. Interpreted formation pore pressures vary from atmospheric to 12.5 MPa for anhydrite intervals [4-10]. Lower values are caused by depressurization near the excavation. These tests were performed in order to understand and quantify the issue of brine seepage into repository rooms. This seepage is one possible source of water that could interact with the waste and lead to the generation of significant amounts of gas, an important aspect of long-term performance. The tests also provided permeability values for modeling the movement of gas and brine outward from the waste rooms.

Pressure decay testing proved to be the most appropriate method to arrive at the salt permeability. The extremely low flows involved required careful attention to tubing and fittings to be sure leakage did not compromise the test. Likewise, specially designed packer configurations utilizing guard packers provided confidence that leaks around the primary packers were not compromising the test result. Pure halite had permeability of less than E-22 m^2, about the limit of the testing capability to measure. Some clay-rich salt had permeability as high as E-18 m^2. Tests were conducted in boreholes at depths ranging between 5 m and 50 m. Inclined boreholes were used to test the anhydrite interbeds above and below the waste emplacement horizon.

Hydrologic testing in the Culebra unit utilized conventional electronic instrumentation to record water levels and pressure fluctuations. Measurements were conducted in boreholes that were between 10-m and 30-m long/deep. These measurements, which were obtained over long periods, in a very saline environment, put a premium on gauge longevity. Drill stem tests and slug tests were used to determine aquifer characteristics close to the borehole. Some drill-stem tests utilized a multiple packer configuration to assure the test interval was adequately isolated from the open portions of the borehole. Long-term (30 days to 60 days) pumping test were used to interrogate the aquifer over much greater distances, often 1 000 m or more. Brine density and chemistry varied significantly over the site area. These parameters were established by borehole sampling with subsequent laboratory analysis. Non-sorbing tracer tests were used to provide better definition of the hydrologic system and of the transport mechanisms. Multiple tracers injected in up to six satellite holes were detected through frequent sampling of the pumping well and analysis of samples in the laboratory. Radioactive tracers were not employed due to the prohibition of using radioactive material at the WIPP site during the site characterization period.

As mentioned above, hydraulic testing in the Salado presented unique problems due to the very low permeabilities that exist in the salt rock. Guarded packer systems were designed and used to assure a tight borehole seal and provide the ability to determine how much packer leakage, if any, was occurring. Measurements were conducted in both the halite and the anhydrite interbeds. Both pressure build-up and pressure decay measurements were used to calculate the permeability. The pressures used in the testing were quite high, often approaching 15 MPa, and the change in pressure could be quite small. This required pressure transducers that could resolve a small fraction of the peak range. Because the volumes of fluid flow were so small, even miniscule leaks in the tubing and coupling could confuse the measurements and had to be eliminated. For studies in conjunction with brine seepage in the Q-Room (Figure 4-14), permanently emplaced resistivity grids tracked the movement of the brine through the EDZ, from the walls into the floor of the experimental drift, and pore pressure gauges measured the changes in inter-crystalline brine pressure as the drift was excavated and the EDZ formed.

Remote, electronic measurement was the principal data recording technique but, wherever possible, these data were substantiated by strategically located manual measurements. Documentation of gauges, their specifications and calibrations, their location and other experiment related information was a high priority because this information would ultimately be subjected to critical QA examination by the USEPA and others. Commercial instrument power, which frequently failed in the initial years of the *in-situ* studies, was backed up by standby diesel generator power to avoid loss of data and upset of experiments with critical thermal requirements. Redundancy was also applied to the main cable plant, carrying the multiplexed data to the surface, by a totally independent cable plant in a different shaft. Most of the gauges used in the WIPP URL were electronic that could be remotely monitored by an automated DAS. Automated data collection was necessary because of the large number of gauges used and the frequency of measurement required. All remotely-read gauges (3 500+) were connected to the DAS and scanned at regular intervals, typically every four hours, although scan periods as short as 15 seconds were used for a limited number of gauges. The WIPP *In-Situ* Data Acquisition and Management (WISDAAM) system was capable of handling 65 534 measurands, where a measurand is a single measured value or a calculated engineering value.

4.3.4 Conceptual and mathematical models

Domal salt rock

In the German *in-situ* research program on radioactive waste disposal in salt rock formations, the main emphasis was placed on:

- Analysis of the integrity and stability of the host rock, because it was considered the most important barrier.

- Potential backfill materials envisaged to be used as sealing materials in repository boreholes, drifts, and chambers.

Borehole and drift disposal are the main generic conceptual models used for analyzing and assessing the performance of HLW repository systems in German salt rocks. These conceptual models were used and are further described in the SAM [4-2] and the Backfill and Material Behavior in Underground Repositories in Salt (BAMBUS) [4-33] reports.

The conceptual model for borehole disposal (Figure 4-2) comprises (1) a 6 m wide and 6 m high disposal drift, (2) a 0.6-m diameter and 300-m deep, vertical, waste-emplacement borehole below the disposal drift, and (3) a stack of 0.43 m diameter HLW canisters of Cogema type 7/86 in the borehole. The disposal drift, the seal area at the top of the emplacement borehole, and the 85 mm wide annulus between the canisters and the host rock in the borehole are backfilled with crushed salt. The maximum grain size of the crushed salt is 30 mm in the disposal drift and the seal area, and 10 mm in the borehole annulus. The drifts and boreholes are initially surrounded by an EDZ with higher porosity and permeability than the undisturbed salt rock.

The conceptual model for drift disposal comprises direct disposal of SF in 4.5 m wide and 3.5 m high disposal drifts, in which 1.54 m diameter and 5.46 m long waste canisters of the POLLUX type are placed at least 1m apart (Figure 4-3). The minimum pillar width between the disposal drifts is 10 m. The drifts include a seal area at the entrance and a free space surrounding and separating the canisters, which are backfilled with crushed salt. Similar to the borehole disposal concept, the drifts are initially surrounded by an EDZ with higher porosity and permeability than the undisturbed salt rock.

In both of the aforementioned conceptual models, the inherent creep of the salt will gradually close the underground openings. During this process, grain displacement and finally grain deformation takes place in the crushed salt, which thereby is consolidated into a gradually denser mass with gradually decreasing permeability that, eventually, is equal to or very close to that of the intact salt rock. The gradual compaction of the crushed salt also results in a gradual stress build-up in the backfill, which stabilizes the underground openings and, ultimately, leads to an almost homogeneous (isotropic) stress distribution around drifts and boreholes. The compaction process is temperature dependent and faster at high temperatures. Potential flow paths for gases and liquids will be sealed under the impact of lithostatic pressure.

An additional sealing of the waste by buffer materials is not considered necessary in a salt rock repository. Thus, the modeling of the coupled T-H-M behavior of the heat releasing waste packages, the host rock, and the backfill in the drifts and boreholes is most important.

The individual processes considered in numerical simulations of the described conceptual models are:

- Excavation of disposal rooms and resulting change of stress state and resulting host rock deformation.
- Development of EDZ around disposal rooms.
- Waste emplacement and backfilling/sealing of disposal rooms.
- Heat generation of the waste containers and heat dissipation in backfill and host rock in space and time.
- Thermally induced stress and deformation fields in EBS and host rock.
- Backfill compaction and healing of EDZ.

- Thermally induced pore water release into disposal boreholes.
- Gas generation by corrosion of waste packages.
- Gas pressure build-up in disposal boreholes.
- Intrusion of brine from undetected reservoirs - two-phase flow in backfilled disposal room. This scenario being only considered in safety analysis is not considered relevant in a repository in a well-explored salt formation.

The empirical models used for describing the creep behavior of the elasto-visco-plastic salt rock and the crushed salt were published within the BAMBUS project [4-33].

Creep of the rock salt is dependent on stress and temperature. The steady state creep rate is

$$\dot{\varepsilon}_s = A \cdot exp\left(\frac{-Q}{RT}\right) \cdot \left(\frac{\sigma}{\sigma^*}\right)^n \qquad \text{4-1}$$

$\dot{\varepsilon}_s$ = strain rate (1/s)

A = constant factor (MPa/s)

Q = activation energy (J/mol)

R = universal gas constant: 8.314 (J/(mol · K))

T = absolute temperature (K)

σ = stress (MPa)

σ^* = 1 (MPa)

n = stress exponent = 5 (-)

For predicting the compaction behavior of the crushed salt the constitutive law given by Hein (1991) was applied.

$$\dot{\varepsilon}_{ij} = \frac{A}{2} \cdot \left[\exp\left(- \frac{Q}{RT} \right) \right] \cdot \left(h_1 \cdot p^2 + h_2 \cdot q^2 \right)^2 \cdot \left(\frac{1}{3} h_1 \cdot p \cdot \delta_{ij} + h_2 \cdot S_{ij} \right) \qquad \text{4-2}$$

$\dot{\varepsilon}_{ij}$ = strain rate tensor (1/s)

A = constant factor (MPa/s)

p = hydrostatic pressure (MPa)

q = invariant of stress tensor (MPa): $q = \sqrt{S_{ij} \cdot S_{ji}}$

δ_{ij} = Kronecker-Symbol (-): δ_{ij} = 1 if i = j, otherwise 0

S_{ij} = deviator of stress tensor (MPa)

h_1, h_2 = material parameter (dependent on porosity) (1/MPa^2)

The parameters h_1 and h_2 are dependent on the porosity ϕ as follows:

$$h_1(\phi) = \frac{1 - d(\phi) \cdot c_3^2}{\left(\frac{c_4}{c_5} \left(\left(\frac{1-\phi}{1-\phi_0} \right)^{c_5} - 1 \right) \right)^2} \ , \qquad h_2(\phi) = c_6 + c_7 \cdot h_1(\phi) \qquad \text{4-3}$$

$d(\phi)$ = porosity dependent material parameter (-): $d(\phi) = c_1 \cdot exp(c_2 \cdot \phi)$

c_i = material constants (c_3 = coefficient of internal friction (-): $c_3 = \tan \varphi$

φ = angle of internal friction(-)

ϕ_0 = initial porosity of the crushed salt (-)

Data and parameter values of the models used in the numerical calculations were determined by laboratory investigations and are described in the aforementioned reference [4-33].

The codes MAUS/TAUS were used by the DBE in the numerical simulation of the TSDE experiment in the BAMBUS-I project The code SUPERMAUS [4-34] was used by the Gesellschaft fuer Anlagen- und Reaktorsicherheit mbH (GRS) for modeling the DEBORA experiments. The code FLAC 3-D [4-35] was applied in BAMBUS-II. MAUS and TAUS are two-dimensional (2-D) finite element codes for M and T analyses, respectively. Temperature data calculated with TAUS are used as input data for MAUS and considered in each time increment. SUPERMAUS provides the coupling between the T and M calculations in the sense that not only the thermal influence on the mechanical parameters and quantities but also the influence of mechanics on the thermal behavior is taken into account. This is of special importance for the "soft" backfill, which undergoes great changes in its thermal parameters during the compaction process. Therefore, all material parameters for salt rock and crushed salt are given as a function of temperature and porosity, but they are kept constant within a time increment. Generally, SUPERMAUS is a structural code used to analyze/predict the coupled temperature, stress and strain/deformation fields in the elasto-visco-plastic salt rock and crushed salt backfill.

Besides the standard constitutive laws for heat transfer and elastic deformation behavior, SUPERMAUS implements the above given creep law for rock salt and the thermal and mechanical material behavior of crushed salt.

The differential equations solved by the code for each volume element Ω are the balance equations for mass, momentum, energy, and entropy:

$$\dot{m} = \int_{\Omega} \left(\frac{\partial \rho}{\partial t} + \nabla_i (\rho \cdot v_i) \right) d\Omega = 0 \tag{4-4}$$

$$I_j = \int_{\Omega} \left(\frac{\partial(\rho \cdot v_j)}{\partial t} + \nabla_i (\rho \cdot v_j \cdot v_i) \right) d\Omega = \int_{\Gamma} \sigma_{ij} \cdot n_i \; d\Gamma + \int_{\Omega} \rho \cdot f_j \; d\Omega \tag{4-5}$$

$$\dot{U} = \int_{\Omega} \left(\frac{\partial(\rho \cdot u)}{\partial t} + \nabla_i (\rho \cdot u \cdot v_i) \right) d\Omega = -\int_{\Gamma} J_{T\,i} \cdot n_i \; d\Gamma + \int_{\Omega} \sigma_{ij} \cdot \nabla_j (v_i) \; d\Omega + \int_{\Omega} \rho \cdot \dot{e} \; d\Omega \tag{4-6}$$

$$\dot{S} = \int_{\Omega} \left(\frac{\partial(\rho \cdot s)}{\partial t} + \nabla_i (\rho \cdot s \cdot v_i) \right) d\Omega = -\int_{\Gamma} J_{T\,i} / T \cdot n_i \; d\Gamma + \int_{\Omega} \rho \cdot \dot{s} \; d\Omega + \int_{\Omega} \rho \cdot \dot{e} / T \; d\Omega \tag{4-7}$$

Ω = volume element (m^3)

Γ = surface of volume element (m^2)

m = mass (kg)

ρ = density (kg/m^3)
v_i = velocity vector (m/s)
I_i = momentum vector (N·s)
σ_{ij} = Cauchy's stress tensor (Pa)
f_i = specific force (N/kg)
U = internal energy (J)
u = specific internal energy (J/kg)
$J_{T\,i}$ = heat flow vector (W/m^2)
$\dot{e}$ = specific heat generation rate (W/kg)
S = entropy (J/K)
s = specific entropy (J/(kg·K))
T = Temperature (K)
$\dot{s}$ = specific entropy production (W/(kg · K))
t = time [s]

The balance equation of moment of momentum is not mentioned, as it only yields the symmetry of the stress tensor.

The above equations are solved to give the temperature and the displacement fields. The displacements are calculated as sum of the results of elastic, visco-plastic, and thermal strains.

Instead of calculating the thermal and mechanical quantities with their mutual interaction simultaneously, the relatively slow processes investigated make a stepwise solution possible. The method applied is to calculate the temperature field of a time step with the mechanical conditions at the beginning of the time step kept constant through this step, and then perform the mechanical calculation for this time step with the temperature change during this time step taken into account.

This is iterated until the calculation is completed.

FLAC 3-D is a three-dimensional (3-D) finite difference code that includes an M and a T module and couples T-M within a time increment.

MUFTE (MUltiphase Flow, Transport, and Energy) and TRAVAL are two codes used by the GRS for the simulation of two-phase flow and water (vapor) transport in the surroundings of heated boreholes in several studies. MUFTE is a development of the University of Stuttgart [4-36] and it aims at the simulation of groundwater flow of two immiscible fluids in porous, fractured, and fractured-porous media. MUFTE exists in different versions that allow the study of different problems and different stages of development. The one-dimensional (1-D) code TRAVAL is a special development of the Technical University of Aachen for the numerical simulation of water (vapor) flow in low permeable salt rocks around heated HLW boreholes.

The most important experiments conducted to assess the T-M processes related to the interaction between heat generating waste containers, crushed salt backfill in disposal drifts and boreholes, and the surrounding host rock were the TSDE and the DEBORA experiments. The TSDE-experiment (Figure 4-21), which was based on the above described conceptual model for the drift disposal of SF, was performed in two parallel drifts at the 800 m level of the Asse mine/URL to measure drift convergence/backfill compaction. Each drift was 70 m long, 3.5 m high, 4.5 m wide, and separated by a 10 m wide intact salt rock pillar. Three electrically heated casks, each with a nominal power of 6.4 kW, were placed in each drift. Crushed salt with an initial porosity of 0.35 was used as backfill material. Backfill and host-rock temperatures, drift closures, and backfill pressures were measured at several cross sections. Additional parameters of interest were gas release and metal corrosion. The initial host-rock (salt) temperature was about 36°C and the initial stress at the test level was estimated to be 12 MPa. The heating phase started on 25 September 1990 and terminated on 1 February 1999. The codes MAUS/TAUS were used by the DBE in the numerical simulation of the TSDE experiment in the BAMBUS-I project [4-33].

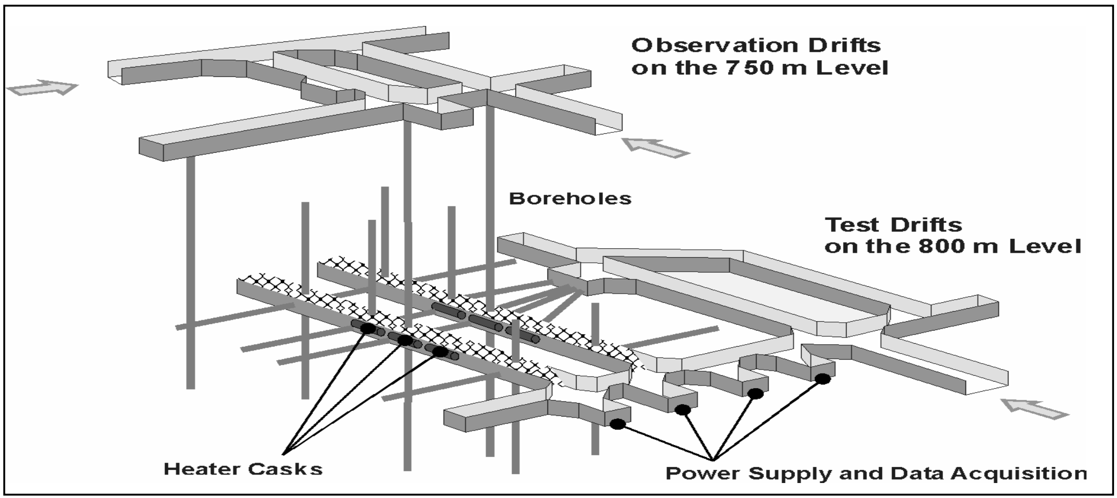


Figure 4-21. *The TSDE test area at the 800 m level of the Asse mine/URL.*

Results of measured and predicted data for the convergence (wall-to-wall closure of an underground opening) and the temperature evolution are shown in Figures 4-22 and 4-23. A related 3-D calculation performed during the BAMBUS-II project shows a much better agreement between measured data and calculated convergence values. This improvement can be seen in the temperature plot shown in Figure 4-23, suggesting that at least the T prediction must be 3-D to allow the T-M behavior at the mid-plane of the test field to be estimated adequately. The 3-D model appears to be well suited for predicting the compaction behavior of crushed salt qualitatively. However, observed quantitative deviations and inconsistencies regarding the prediction of stresses indicate shortcomings in the material models that need to be reconciled.

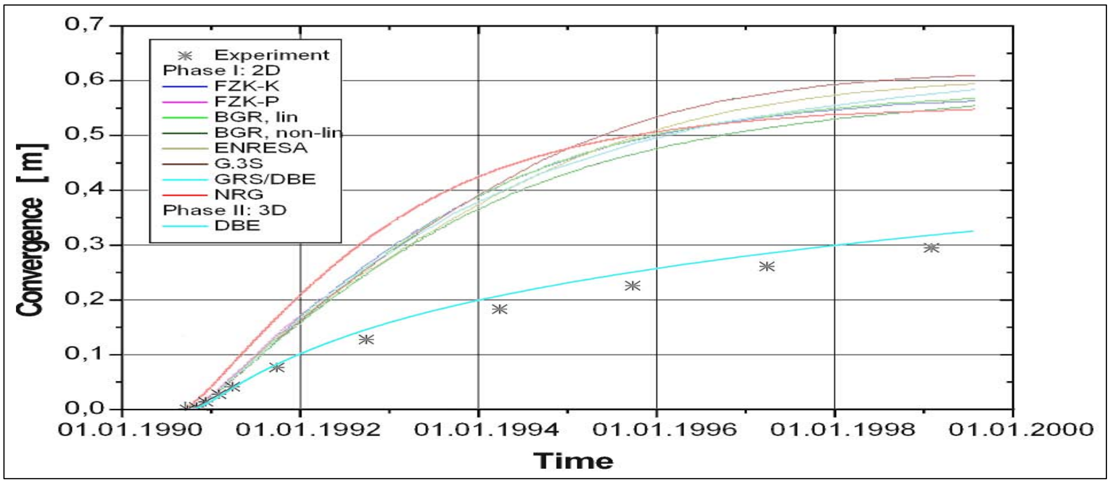


Figure 4-22. *Convergence in the central cross section of TSDE from 2-D (BAMBUS I) and 3-D calculations (BAMBUS II).*

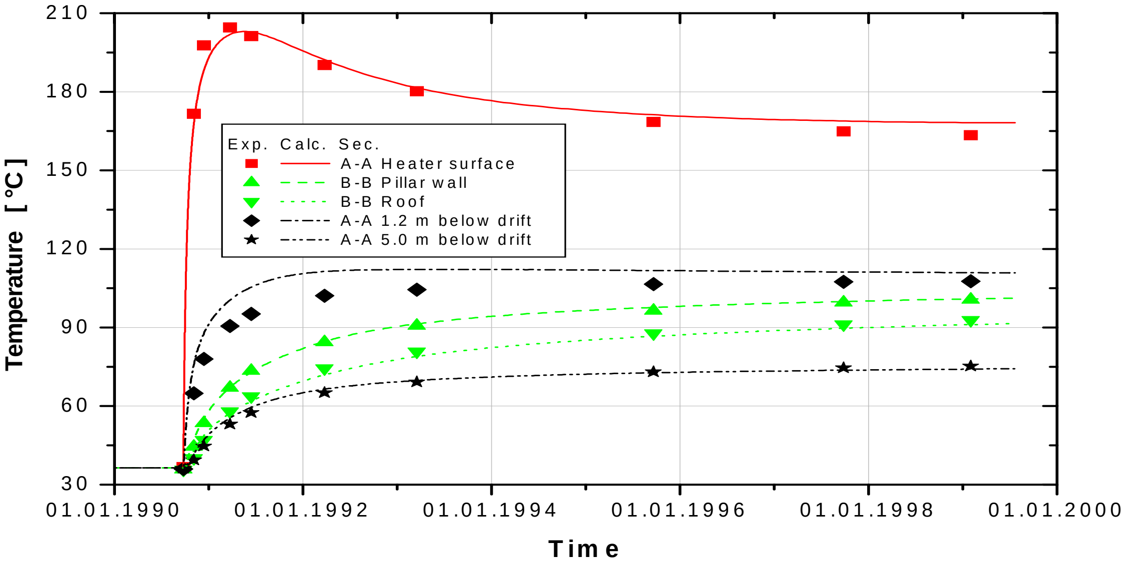


Figure 4-23. *Temperature at selected points of two central cross sections from 3-D calculations.*

The DEBORA-2 experiment (Figure 4-24) simulated the borehole seal between the drift and the top of the canister stack. It was performed in a 0.6-m diameter, 15-m deep, unlined borehole located at the 800 m level of the Asse mine/URL to measure borehole convergence/backfill compaction. The heat production of the waste canisters was simulated by four equally spaced, peripheral heaters surrounding the borehole at a distance of 1.1 m. However, only the lower third of the borehole representing the borehole seal was backfilled with crushed salt. Backfill temperatures, borehole closures, and backfill pressures were then measured at three levels in the backfilled section. The test was conducted over a period of 14 months. The experiment was modeled with the same material model used in the TSDE experiment, but with an axisymmetric, finite element method (FEM) representing a quasi 3-D model. The agreement between predictions and measured results was remarkably better than in the TSDE experiment, corroborating the necessity of 3-D modeling concluded from the TSDE experiment.

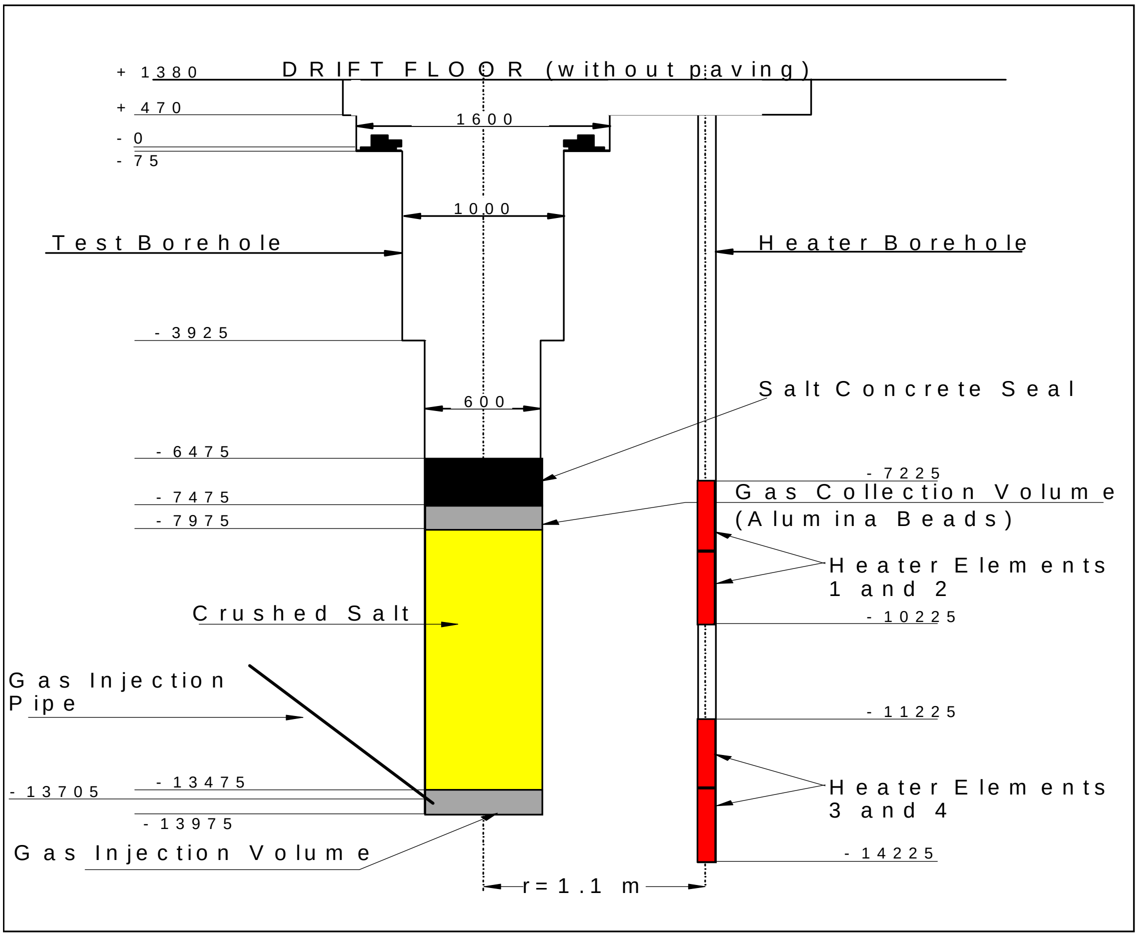


Figure 4-24a. *Layout of the DEBORA 2 experiment.*

In addition to the TDSE and the DEBORA experiments, brine or vapor flow from the host rock into the disposal boreholes was addressed in some of the experiments conducted in the Asse mine/URL. This phenomenon is of importance in the event the host rock contains significant amounts of small brine inclusions or adsorbed water on the crystal boundaries [4-37]. In the temperature field around HLW disposal boreholes, these water forms may be mobilized by evaporation and reach the waste canisters, thereby accelerating their corrosion. Models to assess the amount of liquid that can reach the heat-producing, HLW canisters were developed and numerically tested by Schlich [4-38].

Best results in predicting/modeling the migration of water traces in the rock salt have been obtained by using an evaporation front model (Figure 4-25).

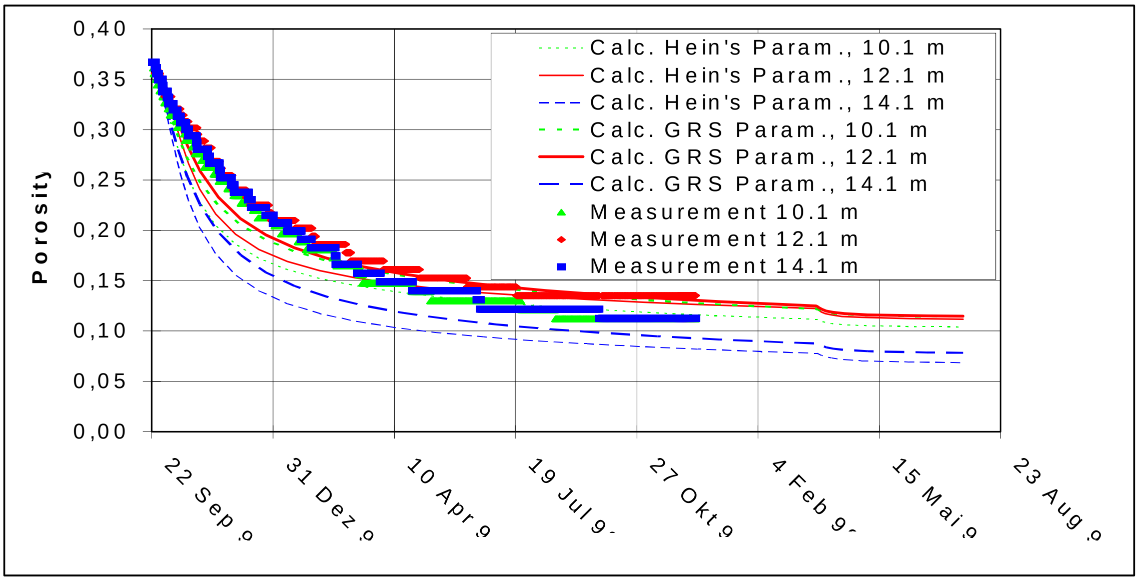


Figure 4-24b. *Porosity decrease in the DEBORA borehole backfill.*

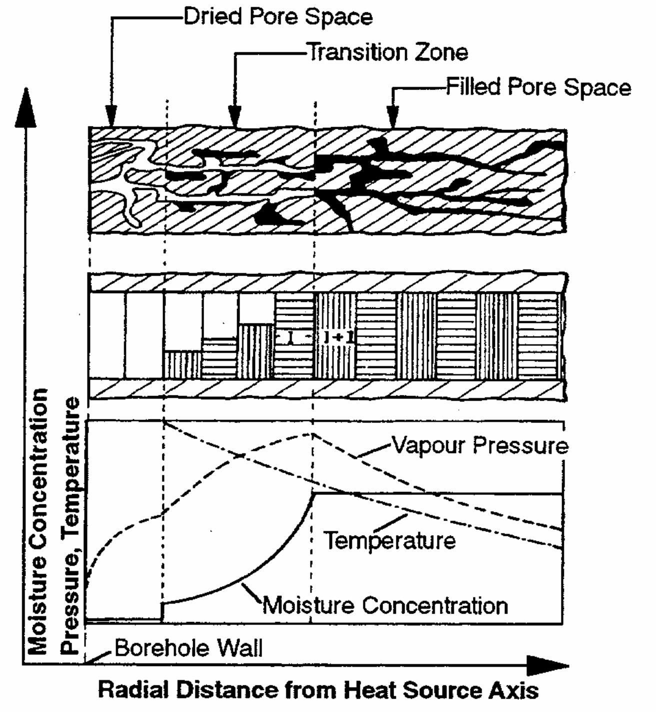


Figure 4-25. *Evaporation front model.*

In this model it is assumed that the complete intergranular pore space (IP) is filled with brine. In the borehole the concentration and the pressure of water vapor is low in contrast to the area of the IP filled with brine. In the evaporation front model, the brine front moves from the heated borehole into the rock salt and transfers all of the liquid phase into vapor. Behind the front, the released vapor will be transported in the direction of the borehole because of the strong gradient of partial pressure. The velocity of the migrating front, u, is given by

$$u = -\frac{\rho_v}{\rho_w \cdot \phi}\; v \qquad 4\text{-}8$$

u = velocity of the migrating front (m/s)

ρ_v = vapor density in the IP (kg/m^3)

ρ_w = density of water in the IP (kg/m^3)

ϕ = porosity (-)

v = filter velocity of vapor (m/s): defined as volume flow divided by the area perpendicular to the flow

Using velocity u the rate of vapor production at the evaporation front can be calculated from a mass balance of evaporated water and released vapor. The balance of mass (continuity equation) for a volume element behind the evaporation front is expressed as

$$\phi \frac{\delta \rho_v}{\delta t} = -\frac{\delta}{\delta r}\,(r \rho_v\; v) \qquad 4\text{-}9$$

r = radial distance from the axis of symmetry (m): flow in one dimension.

The relation to partial pressure p_v of the vapor which is chosen as the variable to be solved for is given by the equation of state

$$p_v = R_w\;\rho\;T \qquad 4\text{-}10$$

p_v = partial pressure of the vapor (Pa)

R_w = special gas constant of water vapor: 461.7 (J/(kg · K))

T = temperature (K).

The equations for the filter velocity v and the mass flow depend on the mechanism of transport.

According to [4-38] the general filter velocity, v, is given by:

$$v = \frac{k}{\eta}\, grad\ p + c_K \frac{\sqrt{T}}{p_v} \cdot \phi\, grad\ p_v \qquad 4\text{-}11$$

v = filter velocity of the water vapor (m/s)

k = permeability of the rock salt (m^2)

η = dynamic viscosity of the water (Pa · s)

c_K = Knudsen factor (m^2/(K$^{0.5}$ · s))

Whether the first part (Darcy term) or the second part (Knudsen term) governs equation 4-11 depends on the relationship of the radius of the salt pores to the average free path length of the water molecules. If the radius of the salt pores is smaller than the average free path length of the water molecules then the Darcy term becomes zero and the Knudsen term becomes dominant.

In case of Knudsen-flow (in very low porous media) it holds (special form of Fick's first law)

$$v = \phi \frac{D_k}{p} \frac{\partial p}{\partial r} \qquad \text{4-12}$$

$$\dot{m} = \rho \, v = -\phi \frac{D_k}{R_w T} \frac{\partial p}{\partial r} \qquad \text{4-13}$$

$\dot{m}$ = mass flux (kg/(m^2 · s))

D_k = Knudsen-migration constant (m^2/s).

According to Schlich the Knudsen-factor c_k can be defined in m^2/s/K$^{0.5}$

$$c_k = \phi \frac{D_k}{T^{0.5}} \qquad \text{4-14}$$

As a minor effect on the release of water, the thermal expansion of brine in the IP has been included, see [4-38].

After specification of boundary and initial conditions, the equation of continuity can be solved to obtain the distribution of partial pressure in the IP. The mass flow into the borehole is calculated at the location of the borehole wall to estimate the input rate and the accumulated amount of vapor in the borehole as well as the increase in pressure in case the borehole is considered to be sealed.

Comparison of predictions and measurement results were made in the Asse Temperature Test 5. A major result was that both Darcy flow and Knudsen diffusion models proved to be adequate for modeling vapor transport through the low permeable rock salt.

The code TRAVAL, which was developed to numerically simulate the fluid flow in the temperature field of HLW-disposal boreholes, is only a 1-D code. It was not developed further because the brine-release data observed in the domal salt rock at the Asse mine/URL were considered acceptable with regard to repository safety.

Two-phase flow in the backfill of HLW disposal boreholes is of interest for the investigation of altered evolution scenarios. Because of its importance to the long-term performance of a repository, the modeling exercise involved is described here even if no related *in-situ* experiment has been performed yet. The considered disposal system/concept consists of a short horizontal drift and a vertical borehole containing the waste canister stack and a seal. Each part is assumed to be filled with crushed salt in a different state of compaction. The cross-section areas were 10.50 m^2 for the drift, 0.2827 m^2 for the seal and 0.1385 m^2 for the annulus around the canister stack. The following three altered evolution scenarios were investigated:

- Brine inflow into the drift from an instantaneously flooded 500-m high shaft.
- Hydrogen production in a flooded borehole due to corrosion of the HLW steel canisters.
- Spontaneous connection of an unexplored brine pocket with the bottom of the borehole.

The main objective of this modeling exercise was to investigate the two-phase flow processes in view of the high material parameter contrasts at discontinuities such as, for instance, the shaft-drift interface or the seal-drift interface. In order to improve the understanding of the principal mechanisms and the significance of two-phase flow in a sealed, HLW-disposal borehole, the dynamics of the processes were analyzed. The calculations, which were done with the finite element code MUFTE, showed that (a) complex displacement processes of one phase by the other are to be expected in the boreholes and (b) these processes are controlled by the principal mechanisms of the two-phase flow and cannot be captured by single-phase flow models.

The crushed salt is typically rather tight and shows comparatively high capillary pressures and low permeabilities. The contrast of the material properties between different sections in the repository, for example borehole seal and drift – can easily exceed the contrast between layers of natural soil formations. Modeling of altered evolution scenarios implies therefore demanding conditions for the numerical simulator and the results are sensitive to almost all model parameters. This is particularly the case with the material parameters, the equations of state, the model geometry, and the initial and boundary conditions for the considered scenarios.

Due to the strong non-linearity of the differential equations, it is not possible to anticipate the reaction of a two-phase-flow system to changes of the input parameters. This implies that it is very important to know the uncertainties of the quantities mentioned above, as well as the data themselves. Actual predictions need therefore a profound understanding of the material laws of compacting crushed salt and an adequate description of the repository layout.

Bedded salt rock

The present WIPP PA requires more than 1 800 parameters for execution of a single calculation. Prior to the conduct of the final CCA calculations, numerous sensitivity studies reduced the number of parameters requiring uncertainty treatment to less than 100. Recognition by both the USEPA and the USDOE CBFO that uncertainty exists within the geologic system, physico-chemical processes within the host rock and disposed waste has led to a probabilistic approach at WIPP to assess overall disposal/repository system safety, as well as scenarios for long-term performance. Stochastic uncertainty respecting various processes has also contributed to this decision. This approach required evaluation of several different scenarios (Figure 4-26) and included the variation of more than 50 near-field parameters (Figure 4-27), all implemented within the context of the system model for WIPP disposal system (Figure 4-28). The scenarios selected for inclusion in the calculations were exposed to significant public and peer review before being finalized in the CCA [4-10]. This exposure provided CBFO with a robust argument that all relevant features, events and processes (FEPs) had been included in the CCA.

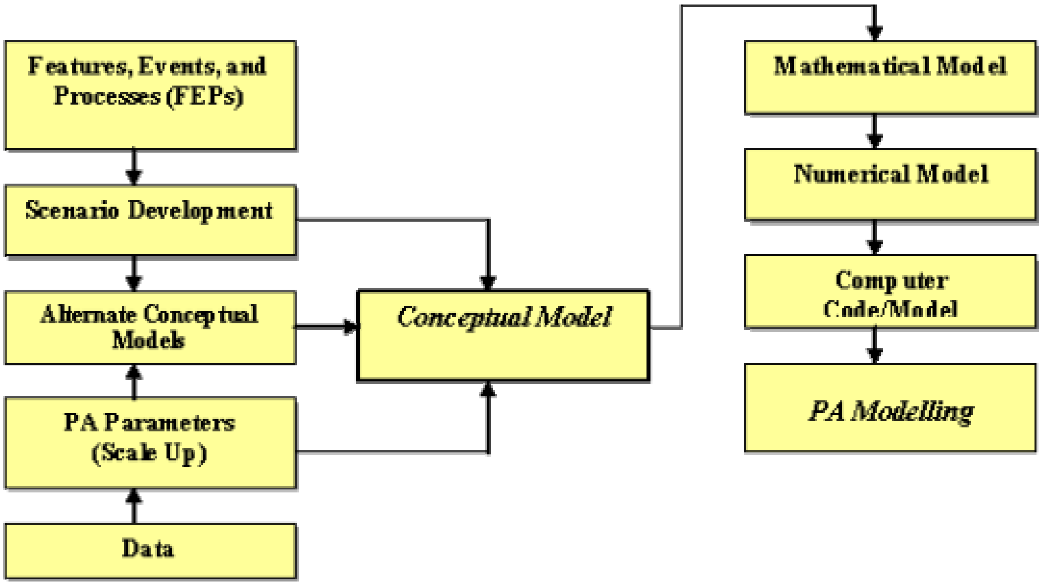


Figure 4-26. *Logic for the progression of code/model development and modeling at WIPP.*

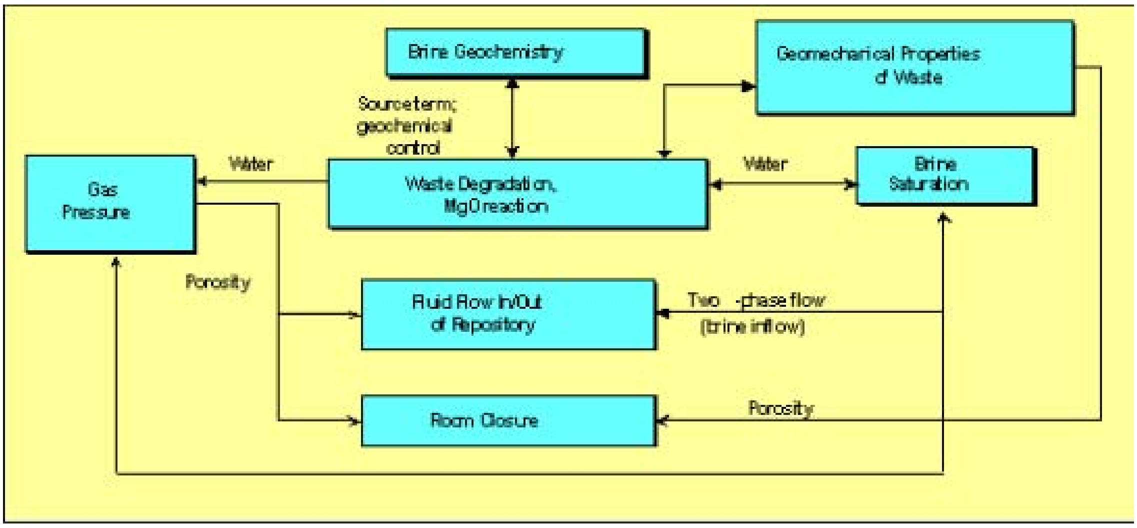


Figure 4-27. *Near-field processes relevant to the WIPP system model.*

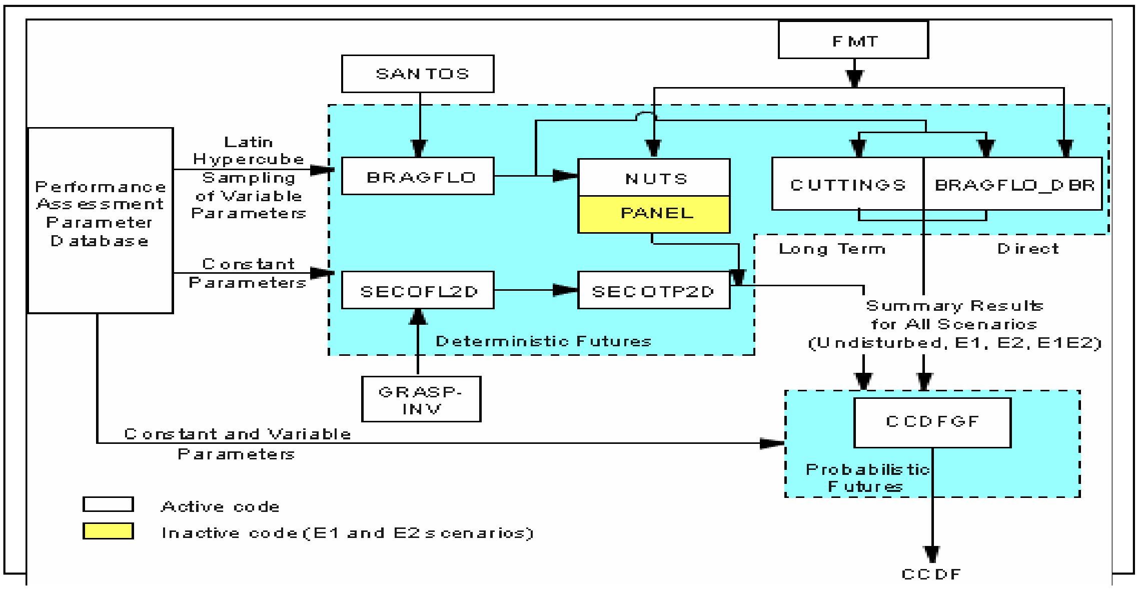


Figure 4-28. *Schematic illustration of major codes, code linkages, and flow of numerical information used in the WIPP PA.*

As illustrated in Figure 4-1, the WIPP disposal system comprises a ~41.5 km^2 (6.44 km by 6.44 km) "controlled (surface) area" set aside from public use by law [4-6] and the underlying portion of the geosphere down to a depth of 1.83 km. Scenarios that impact long-term repository behaviors require consideration of transient physical/chemical properties, flow, and discrete events. As described further below, the WIPP conceptual model comprises a system model, linking both near-field and far-field processes directly through time-dependent processes.

The system model illustrated in Figure 4-28 consists of a set of models, each of which simulates a principal physical component of the WIPP disposal system. A set of models is used rather than a single, 3-D system model because it would be neither temporally feasible nor financially possible to build such a complete, complex model. In addition, implementing the system model in a set of principal physical models enhances the ability to develop and refine the various models. This flexible approach permits complete separation of near-field and far-field models, while maintaining appropriate interfaces between regions. Figure 4-26 depicts the iterative development approach utilized to evolve the system model for WIPP. The main near-field processes studied at WIPP are summarized in Figure 4-27 and described further below. Table 4-2 summarizes the data used. Additional information on the codes, models, parameters and parameter values successfully used in support of the 1998 certification of the WIPP disposal system is available in the CCA [4-10].

Regulatory-required consideration of post-closure, inadvertent human intrusion events generate the primary radionuclide release mechanisms at the WIPP site. Four CCA PA scenarios included a human intrusion into the disposal regions [4-10]. Capturing the consequences of these intrusion events requires execution of several detailed numerical models, which are analyzed within several near-field model post-processing tools to assess releases for each possible future state associated with a human intrusion.

The principal physical models used at WIPP are known as “process models” and consist of sets of mathematical equations describing the hydrological, mechanical, and chemical behavior of the disposal system embodied within numerical simulators (codes). Many models derive from widely held theories regarding the relevant physical processes, while others were developed for unique processes occurring at the WIPP site. Although the process models contain significant detail relative to the coarse assumptions frequently made during preliminary site assessments, practical considerations still require a degree of abstraction to move from specific physics to repository-scale processes.

Table 4-2. Data used for modeling at WIPP.

Parameters	**Values**
Deposition holes	The RH-TRUW canisters are deposited in horizontal holes in the walls of the disposal rooms (Figure 4-7) but are not modeled in the WIPP system model. The CH-TRUW drums/SWBs are placed in the disposal rooms (Figure 4-8) and are modeled with a volumetric plasticity constitutive model, and a porosity surface is used as a look up for the WIPP PA.
Fractures mapped in drift and deposition holes	Fractures in salt rock are assumed to ”self-heal” with time.
Buffer/backfill (MgO)	The MgO buffer/backfill was included in the WIPP PA through parameter value in the computer codes for gas generation and actinide solubility but not in the mechanical-behavior computer codes.
Rock	The post-closure radionuclide containment and isolation at WIPP is essentially provided by the natural barriers.
Rock-mechanics properties	Creep model for salt.
Rock structure (discontinuities)	Non-tectonic, “horizontally” bedded, mainly vertical mineralogical change. Discontinuities are “self healing”.
Rock hydraulic conductivity, intact rock	E-14 m/s.
Rock hydraulic conductivity, EDZ	E-5 m/s – E-12 m/s.
Rock stress conditions (in the host rock)	Pre-excavation stresses are lithostatic, uniform, and ~15 MPa
Petrology	Bedded salt rock (mainly halite).
Canister	See deposition holes above.

The WIPP abstraction process incorporated the following key assumptions regarding near-field system behavior:

- Over the time and length scales of interest for long-term performance, processes and properties of the waste within the disposal areas are homogeneous, and most (with the exception of porosity) remain constant throughout the simulated period.

- Detailed processes associated with container degradation and failure, mixing of waste constituents with repository fluids, and bio-chemical reactions are not modeled in the determination of the waste transmissivity.

- Chemical equilibrium is a conservative position for all bio-chemical processes.

- Transient effects associated with salt creep and compaction of waste packages are coupled to other near-field processes solely through variation of disposal area porosity.

The WIPP process models were developed during the site characterization and/or experimental phases. Extensive site characterization activities, including laboratory and field experiments, supported the iterative model development and refinement process. Laboratory experiments assessing the potential for corrosion of ferrous (Fe) and non-ferrous metals present within the disposal areas and biodegradation of organic materials under WIPP-specific conditions proved of exceptional value in the treatment of the conceptual model for waste degradation. Similarly, large-scale field experiments, coupled with carefully designed laboratory studies, provided the initial data sets as well as validation results for the WIPP creep-closure model, which considers the influence of variable fluid (brine and gas) pressures within the excavated regions, and represents one of the most robust conceptual models within the WIPP PA system. By contrast, multiple field experiments designed to establish the conceptual model for fluid flow in the host salt rock provided results that remain difficult to interpret within the context of existing theories for multiphase flow and transport. An assumption that Darcy's law for flow through porous media applied to the WIPP repository host rock governed the consequent development of applicable two-phase (brine and gas) parameters for this model. WIPP field data support this assumption as a conservative means to simulate brine inflow from and contaminant transport within the bedded salt rock.

The conceptual models of near-field processes related to actinide solubility and transport are of particular interest at WIPP. The presence of large quantities of Fe metal will induce chemically reducing conditions through most of the WIPP repository. Speciation of the primary actinides in the projected WIPP waste, i.e., plutonium (Pu), americium (Am), neptunium (Np), and uranium (U) in the disposal areas, which may include up to 17 Mg of isotopes with a half-life in excess of 24 000 years, likely, will be limited to the (+III) and (+IV) oxidation states. The WIPP conceptual model for near-field actinide solubility assumes these conditions, but also considers the possible presence of organic ligands and chelating agents within free brines. Kinetic processes, such as sorption of mobilized actinides on backfill or other waste components, while likely to occur under repository conditions, are omitted from the conceptual model as a simplifying, yet conservative, assumption.

To assess long-term regulatory compliance, performance metrics are calculated and evaluated against established regulatory performance criteria. In the WIPP PA, the various principal models are interconnected to form the system or consequence model. The interconnection is realized through a WIPP-specific architecture, a system that provides a common data format optimized for WIPP's problem space, a set of utilities to manage and visualize simulation data and results, and several programming interfaces that allow model developers to integrate modeling codes into the PA infrastructure and manage, view, and visualize modeling code outputs.

The conceptual models for the WIPP EBS rely upon engineering studies of material properties and stress responses for the individual components of each EBS, with particular attention paid to the influence of salt-saturated fluids on the EBS materials. For the panel closures, this applies to any concrete monolith(s) emplaced in the drifts. The WIPP SSS comprises 11 different materials within 13 components (Figure 4-9). Primary SSS barriers include concrete, crushed salt, and compacted clay columns, and an earthen fill to provide stability in the near-surface regions. Effects of the only regulator-certified EBS, the MgO buffer/backfill, are incorporated into the overall conceptual model for chemical conditions in the disposal areas, especially with respect to its effect on actinide solubility and uptake of CO_2.

Initial parameter values, uncertainty ranges, and development information are stored in a parameter database, and a single value is used for the parameter in the modeling codes. Parameter uncertainty is handled probabilistically using the Latin Hypercube Sampling (LHS) technique over a range of values for the parameter. To treat parameter uncertainty, the selected parameters were sampled probabilistically, generating sets of input parameters. For the CCA, 100 sets were generated for each of six scenarios. Each parameter set, or vector, was implemented within a single execution of the near-field models for a simulated period of 10 000 years. Results of this exercise comprise a "probable future state" for the WIPP repository. The objective of the probabilistic PA is to bound all probable future states for the WIPP disposal system. Indeed, inherent within this approach is the assumption that uncertainty in future states precludes any such prediction, and the overall system model is exercised many times over to yield a suite of realizations capturing the full range of possible performance of the system. Average repository fluid pressure represents one key outcome of the near-field simulations. Outcomes for this dependent variable range from hydrostatic conditions (~8 MPa) to lithostatic (~15 MPa). The amount of Fe metal is another important dependent variable in the repository near-field. Of particular interest is the fact that, for conditions in which no future boreholes intersect the WIPP repository (leading to possible influx of additional brines), at least 40% of the initial Fe is still present in the disposal areas at the end of the 10 000-year regulatory period (completion point) due to the low availability of corrosive fluids (brine) within the repository host rock.

As indicated in Figure 4-28, the following eight codes and models were mainly used to design and/or project the long-term performance of both the WIPP EBS and the certified WIPP disposal system: (1) BRAGFLO, (2) NUTS, (3) SECOFL 2-D, (4) SECOTP 2-D, (5) SWIFT II, (6) TOUGH28W, (7) EQ3/EQ6, and (8) FMT. Highlighted below are key components and applications of these codes and models. The extensive testing, validating, and verifying of these eight and all other codes and models used in the CCA, as well as the results, are described further in the CCA [4-10].

BRAGFLO is the numerical code used for estimating brine and gas flow everywhere within the WIPP disposal system (and beyond). It couples the flow of brine and gas to other important repository processes such as creep closure and gas generation. The resulting brine-phase and transient flow fields are used in the NUTS code to simulate radionuclide transport in these flow fields. BRAGFLO calculates two-phase (brine and gas), 3-D isothermal flow in porous media. The physical model is described by material balance equations for brine and gas, Darcy's law, and two-phase fluid properties. The numerical model includes a cell-centered finite difference discretisation, Newton solution of the nonlinear constitutive equations, and linear equation solvers necessary for the Newton iteration. Other WIPP-specific submodels include pressure-induced fracture treatment, creep closure of the repository, and gas generation resulting from corrosion and biodegradation of waste components. Ten test cases were used to verify the BRAGFLO code.

The NUTS code models the migration of radionuclides in the repository and surrounding formations. It models radionuclide transport within all regions for which BRAGFLO computes brine and gas flow, and uses as input for each realization the corresponding BRAGFLO velocity field, pressures, porosities, saturations, and other model parameters including, for example, the geometrical grid, residual saturation, material map, and compressibility. NUTS also models radionuclide transport by advection and disregards sorptive and other retarding effects throughout the entire flow region. Physically, some degree of retardation must occur at some locations within the repository and the geologic media, and the disregard of retardation processes is therefore conservative. NUTS also disregards reaction-rate aspects of dissolution and colloid formation processes, and mobilization is assumed to occur instantaneously. Neither molecular nor mechanical dispersion is modeled in NUTS. These processes are assumed to be insignificant in comparison to advection. NUTS is designed to apply to single-porosity, dual-porosity, and/or dual-permeability porous media. Its principal PA role at WIPP is to estimate the radioactive contaminant load mobilized into the brine phase of the brine/gas mixture that seeps or flows through and around the waste panels. Thirteen test cases were conducted for functional testing and validation of the NUTS code.

The SECOFL 2-D code performs ground water hydrology simulation by solving a partial differential equation of head using a fully implicit formulation. The code then calculates the Darcy velocity using the head solution. The modeling capabilities include heterogeneous materials, steady state or transient solutions and fixed head or fixed gradient (user specifies as either a head gradient or as a flux) boundary conditions on a quasi-horizontal grid. The code is designed so that the computational grids are decoupled from the problem definition grid (defining the material properties). Problems may be run on regional and local grids where the local grid is decoupled from the regional grid in space and time. For WIPP PA, the regional computational grid is identical to the problem definition grid. Also, the local grid is decoupled from the regional grid in space, but not in time. Two test cases were used to verify and validate the SECOFL 2-D code.

The SECOTP 2-D code performs single- or multiple-component radionuclide transport in fractured or granular aquifers. Fractured porous media are represented using a dual porosity model. The code uses total variation diminishing (TVD) schemes to model the advection part of the transport equation. This approach helps to eliminate the guesswork in predicting the amount of upwinding required to control sharp gradients in the solution, as opposed to specifying a number a priori as required by upwind-weighted schemes. The selection of the parameter values required for physical retardation and chemical retardation is performed in LHS. Four test cases were used to verify and validate the SECOTP 2-D code, however, the single porosity, or discrete fracture, transport capability has not been thoroughly verified. In addition, the following 11 functionalities were verified as part of the USEPA’s 1997 PAVT: (1) Two-dimensional advective/dispersive transport in a heterogeneous flow field, (2) Matrix/fracture coupling and mass transfer, (3) Matrix diffusion, (4) Matrix retardation, (5) Radioisotope chain decay, (6) Point source term, (7) Dirichlet boundary conditions, (8) Discharge reporting, (9) Multiple point source terms, (10) Neumann boundary condition, and (11) Setting of initial condition.

SWIFT II is a fully transient, 3-D code that solves the coupled equations for transport in both fractured and porous geologic media. The processes considered are: (1) Fluid flow, (2) Heat transport, (3) Dominant-species (brine) miscible displacement, and (4) Trace species (radionuclides [RNs]) miscible displacement. The first three processes are coupled via fluid density and viscosity and they provide the velocity field required in the third and fourth processes. A dual porosity approach was applied to designated fractured regions. In these regions, two sets of equations were solved, one for processes in the fractures, and the other for processes in the matrix. The fracture-porosity equations describing flow and transport in the fractured regions are identical to the equations in the porous zone, except for sink/source terms representing exchange processes with the matrix. A variable-density formulation is used throughout. Density, viscosity, porosity, and enthalpy are treated as functions of pressure, temperature and brine concentrations, but not RN concentrations. A waste-leach submodel was also used to determine the source rate at which RNs, within a repository are dissolved into solution. More specifically, the model considers each component to be in one of the following three distinct phases: (1) Unleached from the waste matrix, (2) Leached but undissolved, or (3) Dissolved. The first two phases are coupled through the leach rate. The last two phases are coupled by the solubility. A salt dissolution submodel appears as a source term in the brine transport.

TOUGH28W is a numerical simulation program for multi-dimensional coupled fluid and heat flows of multi-phase, multi-component fluid mixtures in porous and fractured media. The TOUGH code has been used extensively in studies of HLW isolation in partially saturated geologic media, and has undergone several modifications to accommodate processes occurring at the WIPP site. The version used at WIPP, TOUGH28W, allows for simulation of the following three phases: (1) Water, (2) Air, and (3) Oil. It includes features that allow specification of: (1) Fluid properties representative of WIPP brine instead of water and hydrogen (H2) instead of air, (2) Permeability as a function of time for specific model regions (this feature was included to simulate the reduction in permeability of the EDZ around the shaft attributable to healing after seal emplacement, and (3) Permeability as a function of depth and pressure. Twenty-seven test problems were exercised to verify that the functional requirements of the code were adequately satisfied. These problems generally tested the code's ability to simulate various processes and the results were compared with hand calculations or results from other codes. In all cases, the numerical differences were found to be small, generally less than 0.1%. TOUGH28W was also compared to results from laboratory experiments and the code's prediction of changes in water content and pressure in the flow domain under artificial recharge was in good agreement with the laboratory measurements.

The commercially available code EQ3/EQ6 was used at WIPP to determine chemical effects [4-10]. The EQ6 (part of the EQ3/EQ6 software package), predicted that brucite ($Mg[OH]_2$) and magnesite ($MgCO_3$), the stable hydration and carbonation products, respectively, of periclase (MgO), would buffer the f_{CO2} at about E-7 atmospheres (atm.) and the pH between 8 and 10 [4-10]. These values of f_{CO2} and pH and the speciation-solubility code in FMT were used to calculate actinide solubilities in WIPP brines. During its evaluation of the CCA, the USEPA carried out the PAVT to verify the results of the CCA PA and asserted that brucite, the stable hydration product of periclase, and hydromagnesite ($Mg_5[CO_3]4[OH]_2 \bullet 4H_2O$ or $Mg_4[CO_3]3[OH]_2 \bullet 3H_2O$), a possible metastable carbonation product, would buffer the f_{CO2} within E-5 atm. and E-6 atm. and the pH within 8 and 10. The USEPA then used the Fracture-Matrix Transport (FMT) code to recalculate actinide solubilities for the PAVT [4-10].

The FMT code is a FORTRAN computer code that was used at WIPP to calculate chemical equilibrium speciation in high ionic-strength geochemical systems through minimization of the Gibbs free energy [4-10]. Dissolved actinide source terms, i.e., the time-dependent concentrations of dissolved thorium (Th), U, Np, Pu, and Am, were required for the CCA PA calculations. The FMT code was used to: (1) Predict mineral solubilities in the $Na\text{-}K\text{-}Mg\text{-}Ca\text{-}H\text{-}Cl\text{-}SO_4\text{-}OH\text{-}HCO_3\text{-}CO_3\text{-}CO_2\text{-}B(OH)_3\text{-}H_2O$ to high ionic strength at 25°C, (2) Predict solubility behavior of Am(+III), Th(+IV), and Np(+V) in brines found in Castile, Rustler, and Salado formations at the WIPP site, (3) Calculate chemical equilibrium for a given set of element abundance in the batch simulation mode, also know as flash problems, (4) Support three titration calculation modes, (a) user-specified increments, (b) linear increments, and (c) logarithmic increments, (5) Fix solution pH or f_{CO2} as specified in an input file, and (6) Disable any chemical species as specified in an input file. Eight test cases were conducted for FMT functional testing that provided complete coverage of all the aforementioned functional requirements. The testing was conducted in accordance with the SNL Verification and Validation Plan, and all acceptance criteria were satisfied. FMT predictions of actinide solubilities were also compared with measured dissolved concentrations of Th, U, Np, Pu, and Am from 39 liter-scale and 15 drum-scale experiments carried out at LANL and supported the hypothesis that the Am(+II - +V) speciation models implemented with FMT are conservative (measured actinide solubilities are less than predicted solubilities).

Codes and models, as well as their respective parameters and parameter values, used in the CCA [4-10] have been subjected to and successfully met very rigorous USEPA [4-9], USDOE CBFO, and SNL QA and quality control (QC) requirements. They have also been subjected to international and domestic peer reviews, and intense scrutiny by a broad range of affected and interested parties. Notwithstanding this scrutiny, many conceptual models and parameter values used at WIPP are based on “conservative” assumptions made by the responsible PS or PI. As follows, many codes, models, and parameter values used at WIPP can be refined. However, in light of (a) their currently regulator-approved status and proven performance, and (b) the high safety factor embodied in the predicted long-term performance of the WIPP disposal system, only a few of these codes and models, and related parameter values, are presently being refined to support pending re-certifications. In other words, potential refinements of most of the codes and models used in support of the CCA serve no practical purpose in terms of the current WIPP mission. They do, however, offer a cost-effective, timesaving, take-off point for others involved in RTD supporting the design and development of a HLW repository and a supporting URL in salt rock. However, implicit in this statement is that all codes, models, parameters, and parameter values are site- and disposal-concept specific, which means that codes, models, and parameter values used at WIPP cannot be directly applied to any other salt rock site or disposal concept.

Boundaries in modeling of the creep behavior of the underground openings had to be extended to greater distances than initially thought in order to reproduce the test observations accurately. A distance equal to five diameters of the excavation generally produced accurate results. The rock parameters of the stratigraphic units occurring within this distance must also be included in the model.

The WIPP experience transcends from 10 years of *in-situ* testing into full deployment and waste disposal. The large assortment of experiments discussed throughout this report measured most of the important performance-related responses of the underground setting. The theoretical predictions and their relationship with field data are summarized below.

Chemistry

Chemical conditions in the WIPP repository are determined to calculate radionuclide solubilities and to estimate gas generation rates by anoxic corrosion of Fe-based metals. The single regulatory-acknowledged EBS at WIPP comprises MgO, which is predicted to consume the CO_2 that could be produced by microbial consumption of the celluloses, plastics, and rubber (CPR) in the waste. Characteristics of the brine chemistry, such as the fugacity of f_{CO2}, the pH, and the concentrations of organic ligands, continue to be evaluated to assure performance of the MgO.

Mechanical Deformation

Site preliminary design validation was evaluated at full scale in the WIPP URL. Room closure constituted one of the primary measurements, which along with many subsequent experiments helped validate the halite constitutive model for the repository. This multi-mechanism deformation model has been used extensively for compliance calculations, and has empirical parameters for both clean and argillaceous salt. The constitutive model can be decomposed into an elastic volumetric part defined by

$$\varepsilon_{kk} = \frac{\sigma_{kk}}{3K} \tag{4-15}$$

where, ε_{ij} = the total strain components,

σ_{ij} = the total stress components,

K = the elastic bulk modulus, and

a deviatoric part defined by

$$\dot{s}_{ij} = 2G\left(\dot{e}_{ij} - F\dot{\varepsilon}_s\left[\frac{\cos 2\theta}{\cos 3\theta\sqrt{J_2}}s_{ij} - \frac{\sqrt{3}\sin\theta}{\cos 3\theta J_2}\left\{s_{ip}s_{pj} - \frac{2J_2}{3}\delta_{ij}\right\}\right]\right) \tag{4-16}$$

where, $s_{ij} = \sigma_{ij} - \frac{\sigma_{kk}}{3}$: the deviatoric stress,

G = the elastic shear modulus,

$e_{ij} = \varepsilon_{ij} - \frac{\varepsilon_{kk}}{3}$: the deviatoric strain,

$\delta_{ij} = \text{Kronecker delta} = 1 \text{ for i = j}; = 0 \text{ for i} \neq \text{j}$

J_2 and θ are the second invariant of the deviator stress and the Lode angle, respectively, and are defined later.

The second term of the above equation represents the creep contribution. In the creep term of Equation 4-16, *F* is a multiplier on the steady-state creep rate to simulate the transient creep response according to the following equation,

$$F = \begin{cases} e^{\Delta[1-\zeta/\varepsilon_t^*]^2,} & \zeta < \varepsilon_t^* \\ 1 & \zeta = \varepsilon_t^* \\ e^{-\delta[1-\zeta/\varepsilon_t^*]^2} & \zeta > \varepsilon_t^* \end{cases} \tag{4-17}$$

where, $\Delta =$ work-hardening parameter

$\delta =$ recovery parameter

$\varepsilon_t^* =$ so-called transient strain limit

Finally, ζ is an internal-state variable whose rate of change is determined by the following evolutionary equation,

$$\dot{\zeta} = (F-1)\dot{\varepsilon}_s \tag{4-18}$$

In Equation 4-17, the work-hardening parameter Δ is defined as,

$$\Delta = \alpha + \beta \log(\bar{\sigma}/G) \tag{4-19}$$

where, α and β are constants and the variable $\bar{\sigma}$ is the equivalent Tresca stress given by

$$\bar{\sigma} = 2\sqrt{J_2}\cos\theta \tag{4-20}$$

where, $\theta = \frac{1}{3}\arcsin\left[\frac{-3\sqrt{3}J_3}{2(J_2)^{3/2}}\right]$ is the Lode angle limited to the range: $(-\frac{\pi}{6} \le \theta \le \frac{\pi}{6})$.

$J_2 = \frac{1}{2}s_{pq}s_{qp}$: second invariant of the stress deviator

$J_3 = \frac{1}{3}s_{pq}s_{qr}s_{rp}$: third invariant of the stress deviator

The recovery parameter, δ , is held constant. The transient strain limit is given by

$$\varepsilon_t^* = K_0 e^{cT}(\bar{\sigma}/G)^M \tag{4-21}$$

where K_0 , *c*, and *M* are constants.

The steady-state, or secondary creep strain rate, $\dot{\varepsilon}_s$, is given by

$$\dot{\varepsilon}_s = A_1 e^{-Q_1/RT}\left(\frac{\bar{\sigma}}{G}\right)^{n_1} + A_2 e^{-Q_2/RT}\left(\frac{\bar{\sigma}}{G}\right)^{n_2} + |H|\left[B_1 e^{-Q_1/RT} + B_2 e^{-Q_2/RT}\right]\sinh\left[\frac{q(\bar{\sigma}-\sigma_{0)}}{G}\right] \tag{4-22}$$

where the A_i s and B_i s are constant

Q_i s are activation energies

T = the absolute temperature

R = the universal gas constant

n_i s are the stress exponents

q = the so-called stress constant

σ_0= the stress limit of the dislocation slip mechanism

$|H| =$ the Heaviside step function with the argument $(\overline{\sigma} - \sigma_0)$

Agreement between the calculations and actual performance of the underground openings has now been satisfactorily demonstrated for twenty years or more.

Excavation Damaged Zone

In contrast to visco-plastic flow, damage-induced flow in salt rock is less well understood and continues to be evaluated in the WIPP URL. EDZ characteristics have been quantified by several geophysical and hydrological tests. Damage only occurs when the deviatoric stresses are relatively high compared to the applied mean stress and is manifested through the time-dependent initiation, growth, and coalescence of microfractures. Calculations show that prediction of the one-way evolution of the EDZ replicates observations in the WIPP URL. The size and shape of the EDZ around an opening based on a stress invariant criterion are similar to the size and shape derived from sonic velocity studies and from microscopy of core damage. The model output does not provide permeability directly, but the trend and magnitude of permeability around WIPP openings are understood in considerable detail.

As illustrated in Figure 4-29, healing of the EDZ is expected under certain conditions. The EDZ evolution will reverse as the creeping salt approaches equilibrium with the disposal room contents, a condition that could arise quickly if a rigid panel closure is promptly constructed.

Thermal Measurements

As noted in previous sub-sections, the WIPP waste inventory originally comprised heat-generating waste forms and several experiments in the URL were thus thermomechanical and were complemented by laboratory experiments over an applicable pressure and temperature domain. The above constitutive model for salt creep accounts for thermally activated deformation mechanisms.

Hydrologic modeling of the Culebra aquifer requires that an extended hydrologic domain be represented. The boundaries of the current model extend approximately 30 km north and south, and 20 km in east and west of the WIPP site. The boundaries were selected to coincide with natural hydrologic features where possible, such as no-flow boundaries. Furthermore, an extensive network of monitoring wells is monitored on a regular basis and the data are used to update the hydrologic flow conceptual model. Some of these wells will be maintained and monitored after the WIPP repository has closed.

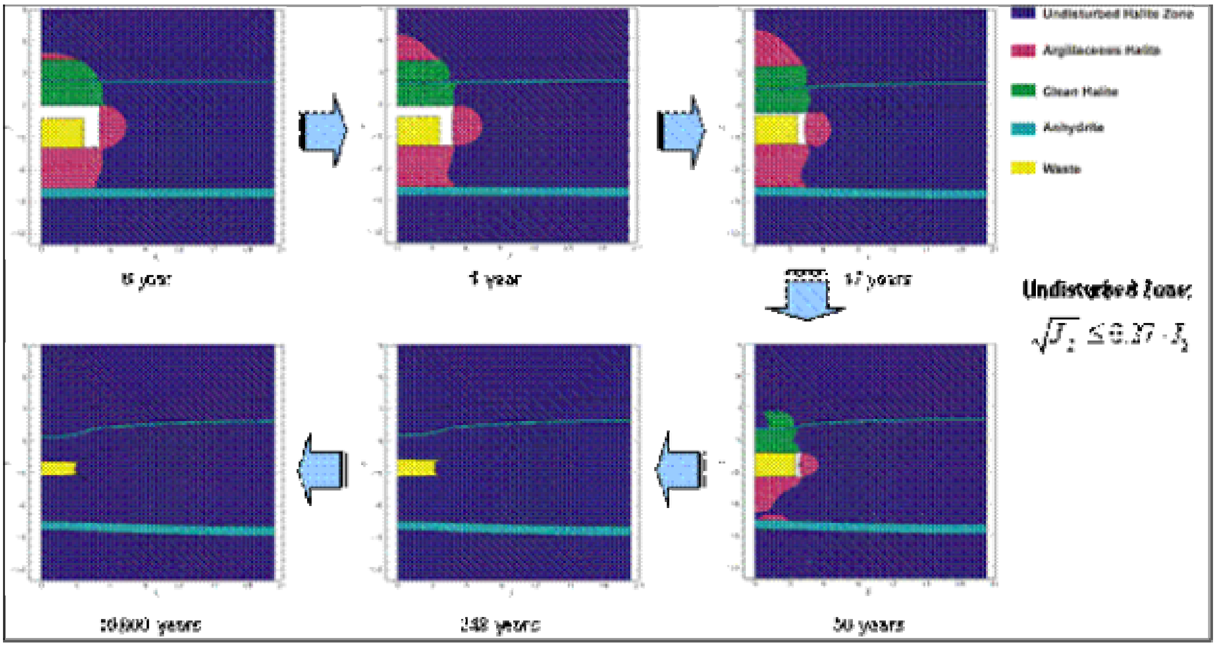


Figure 4-29. *EDZ around a raise bored RH-TRUW disposal hole. In the above illustrations, the EDZ grows until the creeping salt impinges on the waste, at which time the stresses trend back toward equilibrium and the damage zone diminishes.*

As described above, pursuant to current regulations [4-7, 4-8], the assessment of the post-closure performance of the WIPP disposal system and the environmental conditions at the WIPP site extends at least 10 000 years beyond the closure of the WIPP repository. The satisfactory performance of the WIPP codes and models over this period is best illustrated by reference to the large number of internal and external reviews, including the 1998 certification of the WIPP disposal system. It should be noted that the aforementioned 10 000 years post-closure period is not a limiting condition for the use of existing WIPP codes and models, it is simply the minimum period of time for which they have been “validated” by the regulator. In other words, most, if not all, existing WIPP codes and models could be used to assess disposal system performance and environmental conditions for much longer periods than 10 000 years.

In summation, the codes and models used to assess the safety/performance of the WIPP EBS and the WIPP disposal system benefit from a globally unique level of maturity due to the extensive internal and external scrutiny they have experienced, culminating in the 1998 certification of the WIPP disposal system [4-9]. As such, they offer an excellent opportunity for others involved in RTD in support of safe disposal of long-lived and HLWs in salt rocks and excellent opportunity to save time and money by avoiding a major portion of the time-consuming and costly model-development and validation processes. However, as is the case with all codes and models, the mature WIPP codes and models are based on site-specific conceptual, numerical, and mathematical models and formulas that should not be directly applied to another site, environment, or disposal concept without the appropriate modification(s).

4.4 Lessons learned and potential areas for improvements

Summarized below are the main lessons learned:

- In Germany in connection with the siting, design, construction of URLs and repositories for HLW in domal salt rock, including more than 30 years of operation of the Asse mine/URL.
- In the U.S. in connection with the siting, design, construction of URLs and repositories for TRUW and HLW in bedded salt rock, including (a) more than 21 years of operating the WIPP URL and (b) the almost 5 years of operating of the WIPP TRUW repository. Among many important and partially unique elements, this experience includes:
    - Final site characterization and data analyses supporting the CCA [4-10] including the siting, development, and operation of the WIPP URL.
    - Final code and model developments supporting the CCA.
    - Design and partial excavation/construction of the WIPP repository.
    - Preparation and submittal of the draft and final CCA and the TRUW (RCRA) [4-14] Part B Permit (hazardous waste disposal) applications.
    - Intense public interactions with the regulators, oversight groups, and other affected and interested parties during the successful, almost four-year-long, certification and permitting processes.
    - Successful certification and permitting of the WIPP TRUW repository.

However, due to the vast amount of lessons learned at WIPP during the past 28 years and the related evolution in repository sciences (and public opinion), the focus below is on the major lessons learned at the WIPP site during the past 10-15 years [4-39 to 4-45]. Furthermore, in addition to the URL- and EBS-related information presented on bedded salt rock in Sections 4.4.1-4.4.4, following is an introductory overview of a few, particularly important, management-related lessons learned at WIPP that strongly governed the progress and cost of the WIPP project and, likely, would impact other repository projects in a similar manner.

From a management perspective, the two cornerstones to the successful development, certification, and permitting of the WIPP repository were:

- Good science.
- Local acceptance.

Simply stated, it is imperative that any project in support of a URL and/or a repository for long-lived radioactive waste is founded upon good science to achieve the required operating license(s) and/or permit(s). Notwithstanding this fundamental condition/requirement for success, in addition to the excellent characteristics of the chosen site, one of the most favorable conditions for the WIPP success story is the very high local acceptance [4-39 to 4-43]. Indeed, as demonstrated both in the U.S. and abroad, the progress and cost for the siting, development/construction, and opening of a URL and, more so, a repository for long-lived radioactive waste are strongly governed by local acceptance and national politics/policies [4-39 to 4-43].

A public-acceptance-related experience and another very important lesson learned at WIPP is that repository sciences represent the state-of-the-art and span temporal and spatial scales that are very difficult to comprehend by the general public. Recognizing the importance and responsibility of being able to address people's concerns and inform the general public in a timely and understandable manner, beginning in the early 1990s, special emphasis was placed by the USDOE CBFO on the development of:

- A four-year Disposal Decision Plan (DDP) [4-43], which outlined all major decision making points and more than 10 public meetings per year.
- Continuously updated "relational database" that conveyed the evolving, highly specialized, repository-science information in terms, concepts, and metaphors more readily accessible to the general public [4-39 to 4-42].

Furthermore, since 1994, the USDOE CBFO has been very actively involved in international repository-sciences exchanges and projects to ensure that the repository sciences, codes, and models employed at the WIPP site are of highest international standards, including making the WIPP URL available to the International Atomic Energy Agency's (IAEA's) "Network of Centres of Excellence on Training in and Demonstration of Waste Disposal Technologies in Underground Research Facilities" (the IAEA Network initiative) [4-44 to 4-45]. A related important lesson learned is that international collaborations enhance public confidence.

4.4.1 Design and construction of URLs

Domal salt rock

A portion of the abandoned Asse salt mine has served as the only German repository-sciences URL for salt rock since 1967. The Asse salt mine was operated from 1908 until 1964 and about 130 excavations were left from the mining of rock salt in the southern flank of the salt anticline when the Gesellschaft fuer Strahlenforschung (GSF) on behalf of the German government took over the mine in 1965 (Figure 4-10). At the beginning of the underground research work, the experiments were conducted in the old existing excavations in the Leine Halite Na3 salt formation located in the southern flank of the Asse anticline between the 490 m and the 750 m levels (Figures 4-10).

Similar to any other underground opening, with time, the surrounding "undisturbed" stress field and hydrologic regime become disturbed and the data obtained in the "disturbed" rock may not be representative of ambient conditions with regard to THM processes. Hence, to minimize the impact of the old mine workings, all experimental locations/areas in the Asse mine/URL were selected as far as possible based on the transferability of the results to other potential salt rock repository sites with particular attention to the conditions and requirements expected at the Gorleben site.

Thus, from the late seventies and onwards, most of the experiments were conducted at a representative depth of between 750 m and 900 m below the ground surface in the center of the salt anticline, where, similar to the conditions at the Gorleben site, the formation of the Stassfurth Halite Na2ß exists.

This and the detailed characterization of the THMC properties of the host rock in and around the test locations/areas, including the determination of initial and boundary conditions, allowed the adequate verification of surface laboratory-based material and advanced computer models by the comparison of predicted and measured data.

However, on-site confirmation of the Asse results would be useful in an undisturbed salt rock formation, preferably at the candidate Gorleben site.

Furthermore, the experiments at Asse were designed, as far as possible, at full scale to avoid scale effects and to test handling and disposal systems for HLW in a representative way.

Hence, testing of the following technical components was successfully accomplished.

- Components used to operate a repository, e.g., systems for handling waste containers (Figure 4-30), borehole drilling equipment, and dust protection and ventilation equipment.
- Appropriate techniques for the construction of shafts, drifts and other openings.
- Areas with judged significant potential for improvement are summarized in Section 4.4.4.

Figure 4-30. *Testing of a HLW disposal system/concept in the Asse mine/URL.*

Bedded salt rock

The safe, successful design and construction of underground openings at the WIPP site is essentially based on the extensive experience gained in the many potash mines located in the WIPP region, augmented by salt-rock-mine analogues. Whereas the bedded salt rock horizon chosen for the repository would allow the construction of both significantly larger openings and the entire repository to be constructed in one continuous sequence, due to the inherent rheological characteristics of the repository host rock, i.e., the Salado bedded salt rock Formation (Figure 4-13), following are five main design and construction lessons learned and implemented at the WIPP site:

- The design of a URL and/or a repository should embody flexibility to allow for unexpected/uncharacterized conditions. Even the most detailed surface-based site characterization program will not be able to detect all potentially adverse or favorable conditions (e.g., see 3rd bullet below).

- The URL should be located, if possible, in the same horizon as the repository but at a distance from the potential repository that minimizes, and preferably eliminates, any impairment of the containment and isolation functions of the repository host rock.

- The shape, size, and location of openings should take into account existing inhomogeneities in the URL/repository horizon. For example, the height in portions of the roadways in the WIPP URL/repository have been increased and the elevation of pending panels in the WIPP repository will be adjusted to take advantage of natural structures that enhance opening stability and minimize maintenance and ground-control needs.

- Excavation/construction techniques minimizing the extent of the EDZ should be used whenever possible. Essentially all existing underground openings at the WIPP site have been and pending underground openings will be excavated/constructed by means of mechanical mining methods/techniques.

- The excavation/construction of underground openings should be timed relative to their needs to minimize costly maintenance and ground-support needs, because (a) the longer an unsupported opening remains open, the greater is the risk for rock falls and room failure(s), and (b) both the disposal room dimensions and the access routes need to be maintained, which can be done by either ground support, maintenance, or a combination thereof that, in turn, involve significant costs.

Due to the fact the WIPP repository already has been certified and has operated safely for almost five years, additional design and construction RTD is neither needed nor fiscally justified. However, in the event long-lived radioactive waste with higher thermal output than the WIPP TRUW is considered, areas/issues with judged significant potential for improvement are summarized in Section 4.4.4.

4.4.2 Instruments and experimental procedure

Domal salt rock

Full-scale *in-situ* experiments are indispensable to the understanding of the complex processes that will occur in a final repository and for providing valuable experience for repository design, construction, and operation. During the experiments, most data needs to be obtained remotely because inspection and maintenance are impossible during the test period. Furthermore, instrument accuracy and reliability cannot be checked after installation. Therefore, calibration of the instruments before and after testing is an indispensable requirement with regard to QA. However, in most *in-situ* experiments, the instrumentation is installed in a non-retrievable manner. In such cases, post-test uncovering of parts of the test area and representative retrieving of the used measuring equipment is necessary to enable performance studies regarding sensor drift, measurement errors, and failure reasons.

Based on the experience gained in connection with the *in-situ* experiments conducted in the Asse mine/URL, it can generally be stated that the chosen measuring equipment performed well throughout the duration of the tests. Only a limited number of gauges failed during the tests, proving that the gauge design of the different instruments was successful. Actually, the most frequent failures occurred in the measuring systems and most of these failures were due to damage at the measuring lines. Especially, multicore cables were affected by squeezing due to convergence of cable slots and boreholes or by electrolyte intrusion into the multicores, which lead to the following conclusions/recommendations:

- Multicore cable design should not be used for *in-situ* measurements in heated areas. A single cable design is more appropriate/robust.
- Measuring-line protection and cable-duct design are very important features.

A representative number of gauges were chosen from the recovered measuring equipment in the TSDE experiment (Figure 4-21) for further investigations and re-calibration. Generally, the re-calibration results revealed the high reliability of the used sensors. After nearly 12 years of operation, the deviations of the resistance thermometers from the DIN-values were very low. Indeed, almost all the tested sensors were still within the limits of tolerance.

The different displacement transducer types selected for re-calibration had been in operation between 7 and 14 years. The sensors of the convergence measuring devices, which had been exposed to temperatures of up to 90°C, became slightly non-linear though the linearity was still largely within the manufacturer's limit of tolerance of ±0.2%. Only some sensors deviated from the original calibration values but the measuring rods of these devices were significantly bent due to distinct floor uplifting in the heated area. Contrary to the transducers of the convergence measuring devices, the re-calibration results of the extensometer sensors revealed an almost unchanged linearity. This condition is attributed to the lower temperatures the extensometers had been exposed to and suggests that the reverse-gauge design with the instrument head being installed in the deepest part of the borehole should be used for the heated tests. With their negligible sensor drift, these gauges are very suitable for long-term displacement measurements.

The deviations of the recovered hydraulic Gloetzl pressure cells from their initial pressurization were between 0.01% and 0.08%, which is very tolerable after their long operational time. The *in-situ* measurements are, thus, assessed as very reliable. For verification of their accuracy, the linearity of the gauges was determined in an autoclave. Most values were still within the manufacturer's limit of tolerance of ±0.5%. AWID measurements were less successful. Almost all measuring systems failed early due to damaged pneumatic and/or electric measuring lines. However, even with a better protection of the measuring lines, the application of AWID measuring systems in a repository seems only reasonable for very special cases due to the intricate measuring equipment.

Extensive knowledge of the integrated/coupled behavior of the waste, the EBS, and the host rock is needed to facilitate the adequate prediction of the long-term performance/safety of a radioactive waste disposal system. Many properties of the different sealing components may be determined in the laboratory under simulated repository conditions. However, the very complex nature of large-scale, actual conditions requires *in-situ* testing in representative URLs. One main initial test objective is to verify the predictive capabilities of numerical models used in long-term safety analyses by comparing the quality of predicted and measured results of the integrated waste/EBS/host rock-behavior. Furthermore, URL-based research is required for the development and refinement of site investigation techniques and the confirmation of the data derived from the use of these techniques. The overall outcome of the underground investigations carried out under real conditions in an URL is better knowledge of the physical and chemical parameters governing the behavior of a repository, and thus increased confidence in predicting its safety.

Based on the experience gained at the Asse mine/URL since 1976, the following criteria need to be considered as prerequisites for the adequate design and conduct of URL experiments:

- Intensive site and formation characterization on and below the surface (preferably by means of non-destructive techniques).
- Disposal concept.
- Available modeling tools.
- Technical means for performing the experiments.

Areas with judged significant potential for improvement are summarized in Section 4.4.4.

Bedded salt rock

One of the important lessons learned in terms of how repository-sciences RTD were conducted at the WIPP site involves the selection of processes to be investigated and modeled. Prior to 1995, this process was governed by the information needs defined by the SNL PI and/or PS. However, in 1994, a comprehensive analysis was initiated that evaluated all the then 116 proposed RTD activities in the context of their respective ability to contribute to the certification of the WIPP TRUW repository. This System Prioritization Method (SPM) [4-46] identified eight sets of RTD activities that would provide a 96% probability that the WIPP TRUW repository would meet the very stringent and prescriptive repository-certification criteria [4-7, 4-8], provided the results of the proposed RTD activities were within the boundaries predicted by the responsible SNL PI or PS. The related processes are outlined in Figure 4-27. As evidenced by the successful 1998 certification of the WIPP repository [4-9], the SPM approach achieved its objectives.

The large-scale, *in-situ* data obtained in the WIPP URL, augmented by literature-, laboratory- and surface-based-acquired data, were instrumental to (a) the identification of the physical processes affecting and governing the safe disposal of long-lived and HLW at the WIPP site and (b) the development and refinement of credible conceptual models and the related numerical/mathematical codes and process and system models. Again, as evidenced by the successful 1998 certification of the WIPP repository [4-9], this fully-integrated data-acquisition approach achieved its objectives, i.e., the experiments, instruments, experimental procedures, and DASs used acquired the required information. However, because WIPP has been an operating nuclear facility since 1999, the USDOE CBFO does not consider underground repository sciences as a fundamental part of its present (disposal) mission and has not conducted any large-scale, repository-sciences experiments in the WIPP URL in the few years of the present century. Hence, although the experiments, instruments, and experimental procedures used to certify WIPP adequately acquired the required information, there may be more durable and more accurate instruments and DASs available today than those in the WIPP URL between 1983 and 1995. Notwithstanding the possible existence of more durable and accurate instruments and DASs, the lessons learned at WIPP can be very beneficial to other repository programs [4-39 to 4-47].

Another lesson learned at WIPP is that it is highly likely that preconceived concepts will change during the course of construction, testing, and operations of a URL. It may, therefore, be programmatically beneficial to provide latitude for change. For example, despite the WIPP repository being certified and the related shift in focus and funding from repository sciences to repository operations, the USDOE CBFO continues to maintain a portion of the WIPP URL to ensure prompt, real-time access for addressing future operational and re-certification needs. Although there is no apparent current areas/issue with judged significant potential for improvement at WIPP, areas/issues with judged significant potential for improvement in the event long-lived radioactive waste with higher thermal output than the WIPP TRUW is involved are summarized in Section 4.4.4.

4.4.3 Conceptual and mathematical models

Domal salt rock

The short-term, *in-situ* data obtained from the German URL research are only representative for the repository operation phase and, thus, of limited use for long-term model validation. The confidence in long-term assessments of repository evolution, however, is increased if a sufficient agreement between measured and calculated data can be demonstrated in URL experiments. Following is a summary of the main code- and model-related lessons learned at the Asse mine/URL involving important processes such as heat conduction, backfill compaction, and fluid flow in a HLW repository in domal salt rock.

Drift convergence and backfill compaction

The results of advanced 3-D models show reasonable agreement between predictions and measurements of host rock and backfill behavior. Most of the predictive calculations, however, overestimate the creep deformation of rock salt and the compaction of crushed salt with a corresponding underestimation of stresses. Apparently, the upscaling of material parameters to a model of *in-situ* conditions results in a softer material behavior than in reality. To overcome these shortcomings in the existing material models some further research in this area is recommended.

Heat conduction in salt rock, crushed salt rock, canisters, and other materials in a repository in salt rock

Several temperature experiments were conducted during the past 30 years at the Asse mine. In most of them, the development of the temperature fields was predicted with sufficient accuracy in time and space. In recent years, 3-D modeling yielded a further increase in prediction accuracy so that the current modeling capabilities can be considered sufficient. Special computer programs were developed for modeling the temperature evolution in a HLW repository under consideration of very complex geological conditions in salt rock formations [e.g., 4-47]. Thus, there is no need for significant improvements in this field of research.

Fluid flow (Darcy and Knudsen) in porous backfill and low porous rock salt

The release of volatile components such as water vapor and other gases from the host rock was studied in some of the *in-situ* experiments conducted in the Asse mine/URL. The major finding is that the application of the Darcy flow model seems to be adequate in most considered cases, including flow in both crushed and intact salt rocks. Some experiments, however, showed better agreement between predictions and measurements if the Knudsen diffusion model was applied, but only with minor improvement of the results. Thus, Darcy flow seems to be adequate for most applications. Hence, the development or consideration of further flow models is not deemed necessary.

Areas with judged significant potential for improvement are summarized in Section 4.4.4.

Bedded salt rock

As mentioned in Section 4.3.4, the conceptual and mathematical models used at WIPP have been validated by the USEPA for applications pertaining to the safety and long-term performance of the WIPP TRUW repository. Furthermore, the safety factor embodied in the related repository safety and performance calculations is high and any further refinement of the conceptual and mathematical model used in support of the CCA is neither programmatically nor financially justified based on the current WIPP mission. However, following are three important lessons learned in conjunction with the development and application of the codes and models used at WIPP of potential value to similar, less advanced projects:

- Code and model developments are time consuming, costly, and require very rigorous documentation, testing, and validation.
- The results generated by any code or model are strongly affected by the source term (e.g., the magnitude, duration, and extent of the waste-induced thermal load) and the complexity of prevailing site conditions.
- The use of existing codes and models offers significant opportunities to shorten the duration and reduce the cost of the code and model development period.

Related areas/issues with judged significant potential for improvement if the validated WIPP codes and models were to be successfully used to predict the performance of a repository for long-lived radioactive waste in salt rock experiencing a stronger thermal pulse than that to be experienced at the WIPP site are summarized in Section 4.4.4.

4.4.4 Areas with judged significant potential for improvement

Domal salt rock

Further to the areas described, discussed, and listed for domal salt rock in Sections 4.4.1-4.4.3, following are topical areas deemed to embody significant potential for improvement based on the lessons learned in connection with the RTD program performed in the Asse mine/URL during the past 35 years:

Compaction behavior of crushed salt backfill in case of brine intrusion

In the safety analyses, an intrusion of limited amounts of brine into backfilled disposal boreholes and drifts is being considered possible. Laboratory investigations have shown that adding of 1wt.% of brine leads to a reduction of the compaction resistance by one order of magnitude [4-48]. Further investigations have been conducted in this area but the results have not yet been published. The data published by GRS have been used by the DBE to analyze compaction of moist backfill in large disposal rooms. In the DBE-report [4-49] it is stated that the GRS data [4-48] are the only ones available, so far. Further investigation is, therefore, considered necessary to confirm the GRS data and could be accomplished by using Asse reference backfill material.

EDZ generation and healing

Detailed research on EDZ evolution in salt rock formations started about a decade ago in order to enable the assessment of its importance for the long-term safety analysis of radioactive waste repositories. Constitutive models to predict damage, dilatancy and permeability distribution around excavated drifts have been developed recently. The results of the first numerical simulations of underground experiments/analogues are very promising. However, the extent and degree of healing of the EDZ around the backfilled and over nine years heated TSDE experiment at Asse were significantly underestimated in model calculations. To enable satisfactory simulation of the long-term reduction/healing of the EDZ, adequate model improvement is considered indispensable.

Hydraulic modeling

Hydraulic modeling has so far only been performed with rather simple models or poorly validated material/parameter data. One reason limiting this effort was that the experiments conducted in the Asse mine/URL yielded brine-release data that were considered acceptable with regard to the repository safety issues then at hand. However, at altered repository conditions, fluid flow in a backfilled repository is of high, possibly critical, importance and requires the determination of two-phase flow parameters for both the EDZ and the crushed salt rock backfill. First modeling results for altered evolution scenarios show a very complicated flow behavior, even if only the basic two-phase flow effects are considered. Additional effects such as a non-isothermal temperature distribution or a time-dependent porosity are therefore to be included for more realistic predictions. This leaves a vast open field for the investigation of material behavior as well as for code-development even if it is not clear if a fully coupled THM approach is necessary.

The issue of fracturing of the host rock in case of gas generation in disposal rooms has not yet been addressed in the German research program to a satisfactory degree. Additional RTD-work is thus recommended since high gas pressure may develop due to corrosion and microbial degradation of waste forms if the disposal rooms are sealed gas tight. The corresponding improvement of existing coupled H and M models is also considered very important.

Bedded salt rock

As mentioned above, due to the facts that the WIPP TRUW repository was successfully certified in 1998 and has operated safely since 1999, there is presently no apparent area or issue judged with significant potential for improvement in the context of the current WIPP mission. However, the waste-induced thermal load/pulse at WIPP is very moderate (6°C) and the RTD at WIPP for a HLW repository in salt rock was not completed. Hence, following are examples of areas and issues with judged significant potential for improvement if the WIPP THMCB databases, codes, and models were to be used to design and predict the performance of a deep geological repository for safe disposal of long-lived HLW and/or strongly heat-generating long-lived radioactive waste in salt rock.

- Design and construction.
  - EBS materials and performance.
  - Optional disposal methods.
  - Room and waste emplacement configurations, including canister “mobility”.
- Instruments and experimental procedures.
  - Experiment layout and deployment.
  - Instrument accuracy, reliability, and durability.
  - Performance confirmation.
- Conceptual and mathematical models.
  - Biological, bacterial, and microbial processes.
  - Brine migration.
  - Codes and models that couple T and M response in salt rock because the current SNL codes and models are single purpose, the thermal evolution is determined first, then the mechanical.
  - Colloid and radionuclide transport.
  - Consolidation of crushed salt, the mechanism of particular interest/importance is crystal plasticity and the properties of particular interest/importance are thermal conductivity and permeability.
  - EDZ development, including both the creation and healing of the EDZ, which, probably would require the development and testing of a model that predicts the anisotropic volumetric strain and ascribe to the predicted damage to a permeability and additional benchmarking against field test results and mining analogues.
  - System model.

4.5 Summary and conclusions

Domal salt rock

The domal salt rock sections presented in this report synthesize the information provided by GRS and DBE on the successful design, construction, and operation of the Asse mine/URL. The Asse mine/URL is situated in a Permian salt anticline (dome) with a complex internal structure due to the salt movements and deformations caused by the increasing overburden during Mesozoic and Cenozoic times and the regional stress regime. The experiences and lessons learned at Asse include the design, development, and operation of:

- A test repository for long-lived radioactive waste between 1967 and 1978.
- A URL, primarily located 750 m to 800 m below the ground surface.

The major part of the research program conducted in the Asse mine/URL focused on the disposal of HLW and related issues.

The following two main different disposal concepts have been considered in Germany:

- Disposal of Cogéma-type stainless steel canisters containing vitrified fission products remaining from reprocessing of SF in deep vertical boreholes.
- Disposal of SF in heavy self-shielding Pollux casks in horizontal repository drifts.

In both concepts, the natural geological barrier is considered the main barrier against radionuclide releases to the biosphere but, in addition to that, backfill and EBSs are required to ensure repository stabilization and sealing of repository areas against any potential brine inflow from undetected brine reservoirs in the early post-closure phase. To meet these EBS objectives, crushed salt is used in both concepts to fill the voids in the disposal boreholes and the drifts. With time, stress and creep-induced room closure (convergence) lead to consolidation of the crushed-salt backfill and, ultimately, the complete encapsulation of waste containers, thereby sealing the repository and permanently isolating the emplaced waste from the biosphere. No other near-field buffer material than crushed salt is considered necessary in the aforementioned two domal salt rock repository concepts. However, a special, multi-component seal will be installed in the access drifts to seal off repository areas after the completion of waste emplacement. Finally, upon completion of the disposal operations, a seal system will be installed in the shaft to safeguard the repository in the long-term against any inflow from water bearing strata overlying the repository formation.

Summarized below in random order of importance are the major observations and conclusions provided by the GRS and DBE in support of CROP.

In the initial phase of the Asse RTD program, the *in-situ* investigations focused on host rock characterization in terms of T and M properties. Later on, the main emphasis was on the assessment of the short and long-term evolution of the host rock sealing capability or H properties, respectively, in interaction with the backfill material under the impact of the HLW-induced heat load. During the last decade, the development of coupled THM models has been a major focus area. Good progress has been achieved so far in modeling the excavation induced effects, e.g. EDZ generation and accelerated backfill compaction after heat source emplacement, whereas adequate prediction of EDZ healing needs further RTD.

The THM behavior of crushed salt backfill is largely understood. Adding of geochemical additives to increase sorption of special radionuclides in the near-field is under discussion and has not yet been tested adequately.

In the German CAs, information is presented on drift seals (plugs) between the shaft area and the disposal fields that will be installed after the repository-operations period. However, the possible drift seal design presented by Stockmann et al [4-25] was never tested *in-situ* under representative conditions and is still pending.

The host rock integrity in case of high gas pressure in disposal rooms has not yet been addressed in the German research program to a satisfactory degree. Additional RTD work is thus recommended in combination with the necessary improvement of existing coupled H and M models.

Between 1984 and 1993, preparations were undertaken to conduct a full-scale experiment simulating the disposal of HLW in boreholes at the Asse mine [4-50] This experiment would have involved the retrievable emplacement of 30 highly-radioactive radiation sources in six 15 m deep disposal boreholes on the 800 m level of the Asse mine. During the preparatory phase, a complete transport and emplacement system was developed, successfully tested, and technically approved by the responsible mining authority. In 1993, the project was prematurely terminated because direct disposal of SF became an alternative disposal option in Germany. Thus, the emplacement system was never tested with highly radioactive material. Hence, final confirmation of the technical emplacement system for Cogéma canisters, as well as the testing of the feasibility of the emplacement of alternative canisters for SF into 300 m deep boreholes, is still pending.

In the year 2000, a national expert group - AkEnd - was asked by the German government to develop new, formation-independent, site-selection criteria for the identification of repository sites with favorable geological settings. The final report of this group was published in December 2002 [4-51]. According to this report, the geological formation the repository is built in must meet the following requirements:

- Thickness of the host rock must be at least 100 m.
- Disposal level shall not be closer than 300 m to and not deeper than 1 500 m below the ground surface.
- Potential disposal area at the disposal level must be at least 3 km^2.
- Hydraulic conductivity of the host rock must be lower than E-9 m/s.
- Aforementioned requirements must be assured for 1 million years.

In the light of these requirements, it is necessary to reconsider the conclusions drawn from the RTD work done to date. For instance, the importance of slow migration processes, such as diffusion of carrier fluids such as brines and gases in the whole repository system, including the EBSs, the EDZ in the early as well as in the late (healed) repository stages, in the undisturbed host rock, and in the overburden rock strata, increases significantly.

Since 1995, the Asse mine, which contains 130 000 two-hundred liter drums with long-lived radioactive waste and about 1 300 two-hundred liter drums with ILW, is being backfilled at the request of the government of Federal State of Lower Saxony. Backfilling of most of the underground openings will be completed within the next five years. The research in the Asse mine/URL has thus been significantly reduced during the past nine years and will come to an end in the very near future. Because of the current moratorium of the salt rock option in Germany, an alternative German URL will not be available in the next years. Hence, URL research addressing the aforementioned open issues will shortly only be possible on a case by case basis in Germany.

Bedded salt rock

The bedded salt rock information presented in this report synthesizes the information provided by the USDOE CBFO on the successful siting, design, construction, certification, and operation of the WIPP TRUW repository in the USDOE CBFO CAs (see Section 9.1). The experience and lessons learned at WIPP includes both an operating repository and an on-site URL situated approximately 650 m below the ground surface in a 225-250 million-year-old, 600 m thick bedded salt rock formation. When filled to its current legal capacity [4-6] the WIPP repository will contain 175 584 m^3 of long-lived TRUW. Summarized below, in random order of importance, are the major observations and conclusions provided by the USDOE CBFO in the CAs in support of CROP pertaining to the cost-effective and successful siting, design, certification/licensing, construction, operation and closure of a safe deep geological disposal system (repository) for long-lived radioactive waste:

The three major repository-science-related issues are:

- Site conditions.
- Disposal concept.
- Performance requirements.

Their relative importance and inherent challenges will vary among projects.

The three major social-science- and demographic-related issues are:

- Local acceptance.
- Political will.
- Organizational leadership.

Their relative importance and inherent challenges will vary among projects and organizations, however, credibility and trust are universally important components of all three conditions. In turn, the ability/willingness to (a) interact in an open manner and (b) convey the very advanced and unique repository-science information in “laymen” terms is important to the establishment and maintenance of trust and credibility.

The 1998 certification and 1999 opening of the WIPP repository embodies the following two, first-of-their-kind, global validations:

- Deep geological disposal of long-lived, radioactive waste can be safely done under the right circumstances.
- Salt rock formation possessing the adequate/required dimensional, structural, and material characteristics offers excellent conditions for long-term confinement and isolation of long-lived radioactive waste.

However, the related RTD on strongly heat-generating HLW terminated in 1995 and would likely require additional RTD to address current issues and the above three repository-science-related issues.

Although the WIPP repository already is certified and operating, and the current need for additional RTD is limited, the development of the WIPP repository is phased and, by law [4-9] the safety of the WIPP disposal concept/system has to be recertified at least every five years of development/operation. The USDOE CBFO will therefore maintain a portion of the URL for at least another 25 years to address any potential future operational and/or recertification issue. Furthermore, the USDOE CBFO is a member of the IAEA Network initiative. Hence, although future RTD needs in support of the WIPP project may be limited and the WIPP information is site-, disposal-concept-, and performance-specific, the information vested in the USDOE CBFO and its contractors, and the continued existence of the WIPP URL might offer prompt and cost-effective access for others to the following:

- Experiences and lessons learned during the siting, design, phased/staged development, certification/recertification(s), and operation of the WIPP TRUW repository, including a broad suite of surface- and URL-based investigations, and conceptual and numerical/mathematical codes and models that have been intensely scrutinized and accepted by the IAEA, the two regulators, several domestic oversight groups, and many other affected and interested parties.
- Staff training, design validation, testing, bench marking, and/or validation of EBS components, codes, and models.

Codes, models, and parameters used at WIPP essentially address the performance of the WIPP disposal system rather than any discrete barrier. Also, any code, model, parameter, and parameter value is largely site specific and limited in applicability to the conditions and issues it was designed to address. Hence, although the WIPP codes, models, and databases have passed rigorous QA and QC requirements, domestic and international peer reviews, and regulator scrutiny and acceptance, they should not be used to evaluate other sites or conditions without careful prior evaluation of their applicability to such sites and conditions.

Further to the issues addressed in Sections 4.3 and 4.4, following are examples of scientific/technical areas and issues that could be promptly and cost-effectively addressed at WIPP in support of other long-lived radioactive waste repository projects in salt rocks:

- Design and construction.
  - Waste package materials and performance.
  - EBS materials and performance.
  - Room configurations.
- Experiments, instruments, and experimental procedures.
  - Instrument performance.
  - Experiment layout and deployment.
  - Performance confirmation.
- Conceptual and mathematical models.
  - Code and model performance.
  - Process models.
  - PA.

5 Crystalline rock

In contrast to salt rock and clay rock, crystalline rock has a very high mechanical strength and undergoes very small instantaneous deformation and long-term strain by excavation of underground rooms. However a crystalline rock mass contains a spectrum of fracture zones of varying persistence that are structurally weak and may have a high hydraulic conductivity. Considerable rock movements can take place along the larger fracture zones or faults by tectonically or seismically induced changes in the regional rock stress field. Some scale-dependent shearing, compression and expansion can also occur in the larger fracture zones while the rock matrix with only minor discontinuities remains largely unchanged. It follows from this that crystalline rock, having potentially high permeability along discontinuities, may depend more on the engineered barriers for waste-isolating capacity. The rock structure is of fundamental importance for siting and orienting repositories in crystalline rock and for predicting the performance of the EBSs. The characteristics of the crystalline host rock are also fundamental input data for predicting the evolution and performance of the EBS.

Crystalline rock is being considered as a repository host media by several radioactive waste management programs. In this section, the crystalline rock programs of Sweden, Finland, France, Switzerland, Spain and Canada are summarized.

5.1 National repository concepts

5.1.1 Description of national concepts

SKB and Posiva

The design criteria for disposal of SF primarily refer to the risk of release of radionuclides and hence on the average rate of groundwater percolation of the repository. This requires prediction of the physical/chemical stability of the EBS with some consideration of the long-term performance of the host rock. Major issues are the temperature development and the selection of a site and depth that provides reducing chemical environment. The SF canisters will consist of cast iron forming an inner column with room for the fuel bundles that is surrounded by solid copper with tightly welded lids. The maximum design temperature in the near-field is 100^{o}C. Effective radionuclide isolation must be provided for E5 years.

Access to the repository is through a ramp and/or through main and service shafts (Figure 5-1). The drifts of a KBS-3-type repository will have a length of up to 250 m, drill- and-blasted or bored by TBM, while the deposition holes will have a diameter of 1.8 m and a depth of 8 m and be excavated by use of full-face boring technique applying vacuum technique for removing the muck. The holes will have a spacing which is determined by the thermal properties of the EBS and the rock. The typical center spacing in the deposition drifts vary between 6–10 m except where a larger distance is needed for avoiding water-bearing fractures. A basic requirement in selecting final locations of the deposition holes is to avoid intersection with significantly water-bearing fractures as well as fractures that have a potential to undergo shearing by tectonic events.

The design of the repository for other long-lived radioactive waste than SF may be the same as or similar to that of the Swedish SFR and Finnish VLJ repositories for medium- and low-level reactor waste (partly or fully lined deposition drifts and/or concrete silos. In SFR the silo is surrounded by smectitic backfill).

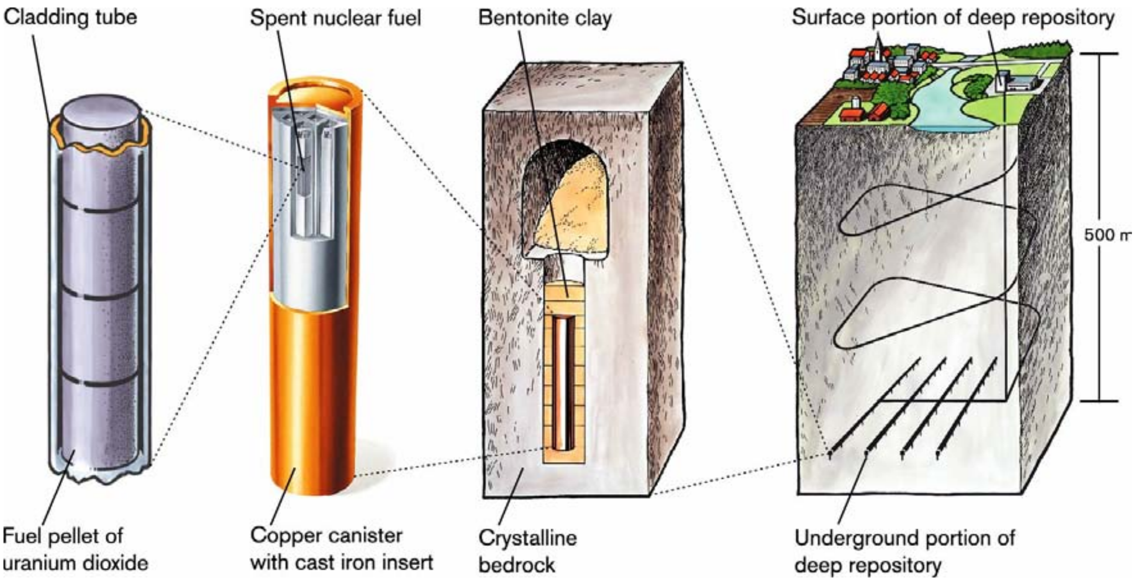


***Figure 5-1**. Conceptual layout of Swedish and Finnish HLW repository. (Courtesy of SKB).*

Enresa

The major design criterion is the average groundwater percolation rate through the repository in a long-term perspective. Particular emphasis is put on the influence of temperature on the groundwater movement and on the longevity of the EBS. This requires prediction of the long-term performance of the EBS and the host rock. The maximum temperature of the buffer clay is set at 100^{o}C.

The canisters, which are of carbon-steel type, are placed horizontally in drifts, each several hundred meters long and having a center-to-center spacing of at least 35 m (Figure 5-2). This part of the repository, the “Regulated Area”, will be excavated by TBM technique with a minimum EDZ, while in other parts, the “Non-regulated area”, conventional mining techniques are acceptable.

The required minimum time for the canisters to remain intact is 1 000 years.

Access to the repository is through a ramp and main service and ventilation shafts. Distribution galleries lead from the central areas to the disposal areas. The 42 disposal drifts will have a length of 500 m and a diameter of 2.4 m. The canisters are placed in a 15 mm thick perforated steel lining with an inner diameter of 920 mm.

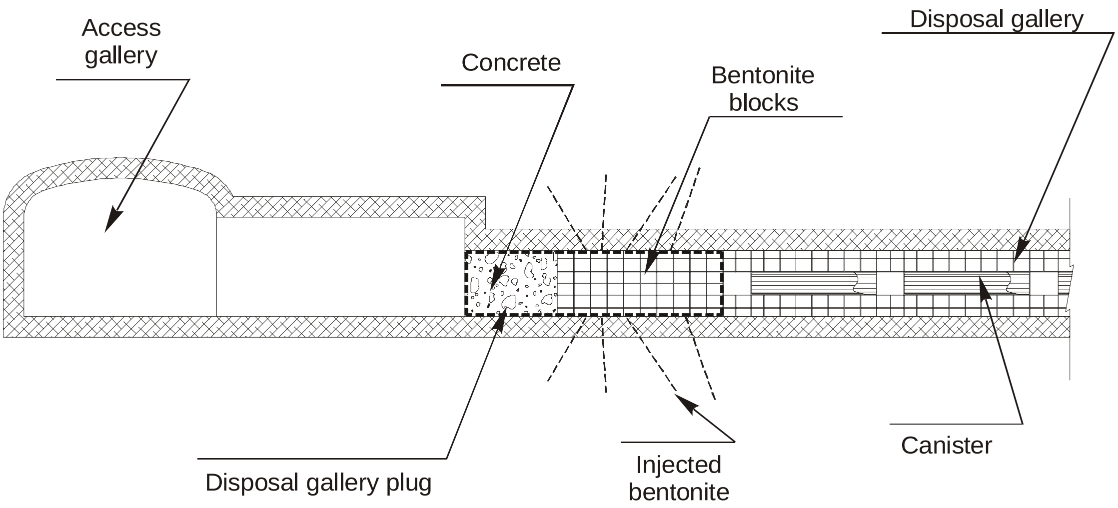


Figure 5-2. *Conceptual layout of Spanish HLW repository. (Courtesy of Enresa).*

Andra

Design criteria

Disposal of exothermic HLW, including SF, will be in vertical boreholes while non-exothermic waste (ILW) will be assembled in packages and placed in a silo-type containment. The maximum temperature is 100-150°C depending on the waste. Effective isolation must be provided for E4 years. Different conceptual layouts are shown in Figures 5-3a to 5-3d.

Access is through a main and a ventilation shaft.

Nagra

Design criteria

The proposed repository consists of three parts, i.e., a test area, a pilot repository, and the main disposal site. The HLW and SF waste will be placed in drifts that will be subsequently backfilled and plugged at the open ends. Non-exothermic ILW will be assembled in packages and placed in concrete silo-type containment.

A major design criterion for the disposal of the radioactive waste is the limitation of the peak annual individual doses according to the Swiss regulatory guidelines of 0.1 mSv/a [6-21]. With the conservative model of geosphere transport appropriate to the current level of uncertainties in the hydro-geological regime and the characteristics of water-conducting features in the crystalline basement, the EBS provides the principal constraint on radionuclide release and transport. The main role of the geological barrier is to provide an environment favoring the longevity and adequate performance of the engineered barriers. This requires prediction of the long-term performance of the EBS with due consideration of the long-term performance of the host rock. The maximum temperature of a significant part of the buffer clay should not exceed 100^{o}C. The canister must provide containment for 1 000 years.

Access to the repository is through a main shaft and through service shafts (Figure 5-4). The waste canisters are centrally placed in horizontally bored (TBM) disposal drifts, 3.5 m in diameter (or smaller). The disposal drifts will be located in blocks of low-permeability domain basement rock, which are geotechnically well suited for construction. These blocks will lie between major water-conducting faults, which are assumed to constrain the layout. If sufficiently large blocks are not found at the potential site, the repository layout could be tailored to the available good rock by defining several emplacement panels. The distribution of such panels is not limited to a single level. The repository could be realized on a single level or, alternatively, a stacked multiple-level emplacement layout could be considered.

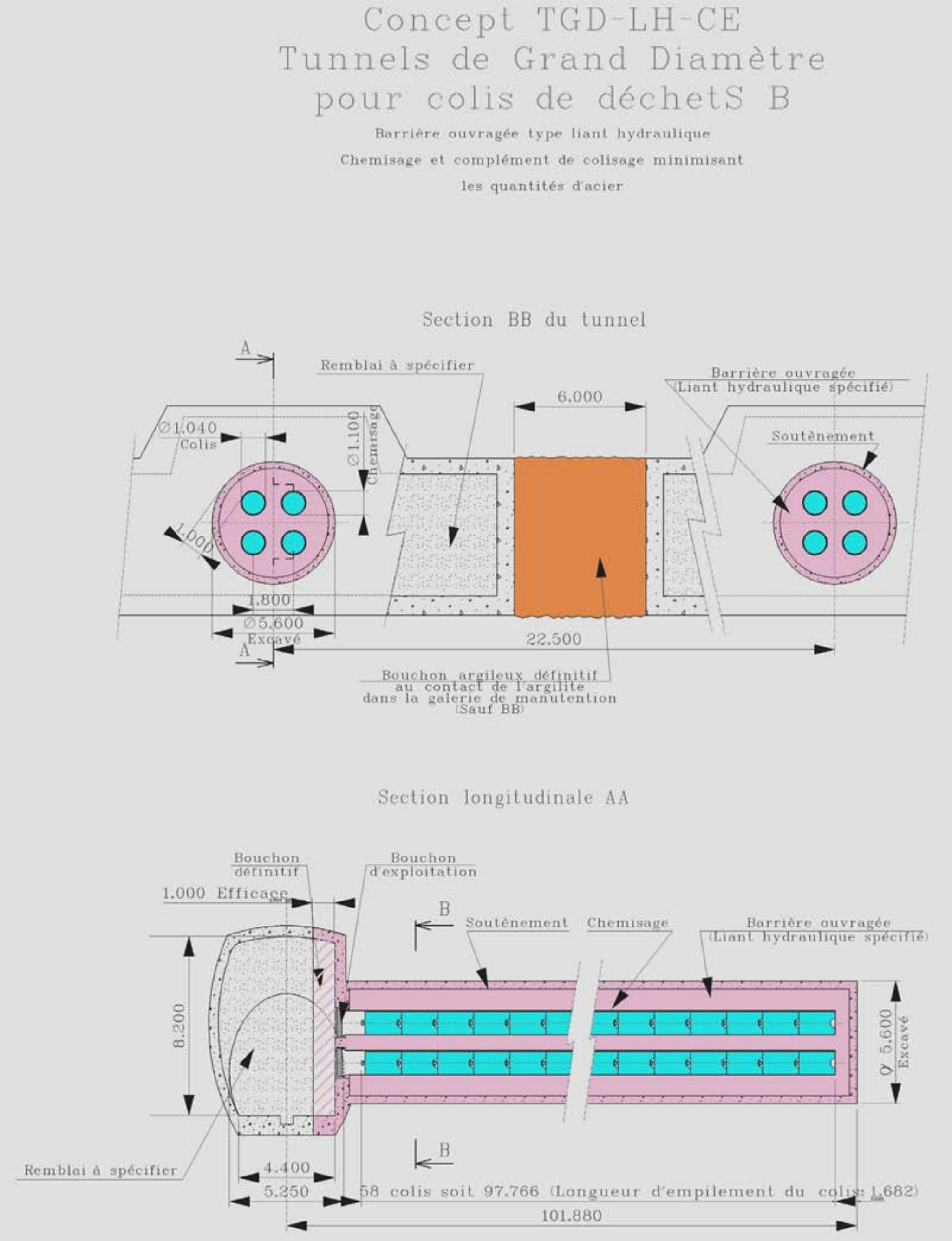


__Figure 5-3a__. Conceptual layout of French TRUW repository. Large drift concept. (Courtesy of Andra).

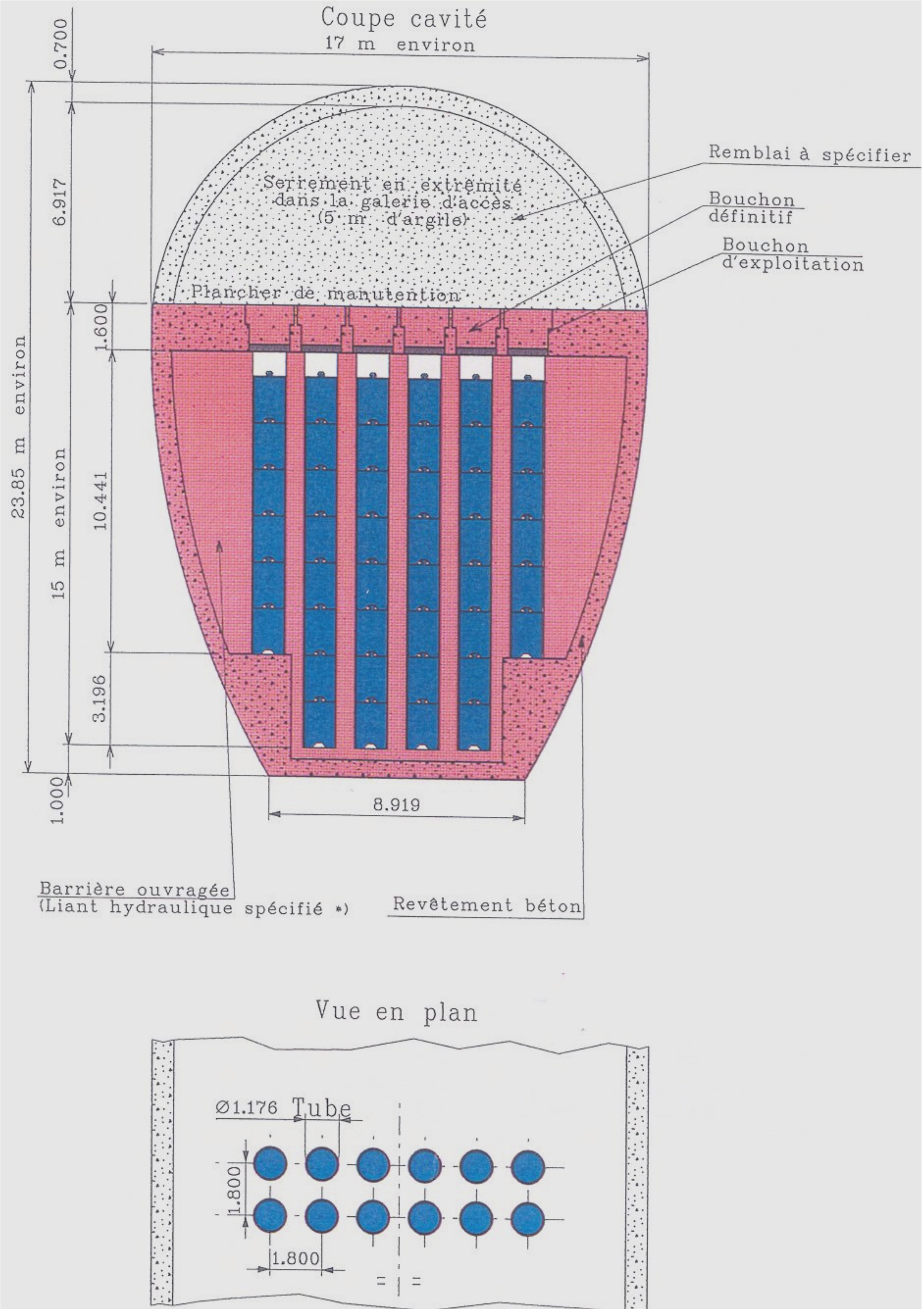


***Figure 5-3b**. Conceptual layout of French TRUW repository. Large cavity concept.(Courtesy of Andra).*

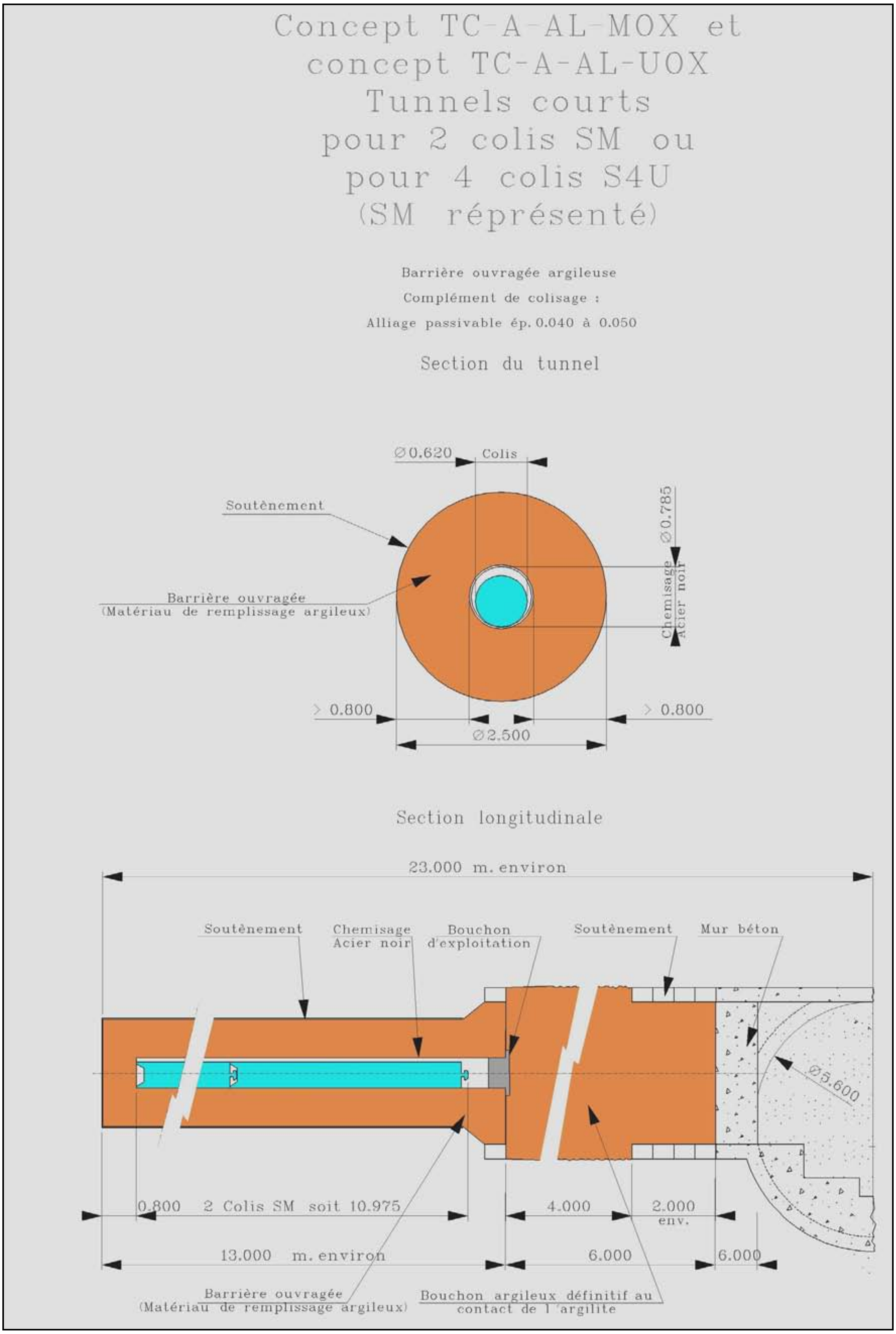


***Figure 5-3c**. Conceptual layout of French vitrified waste repository. Large drift concept. (Courtesy of Andra).*

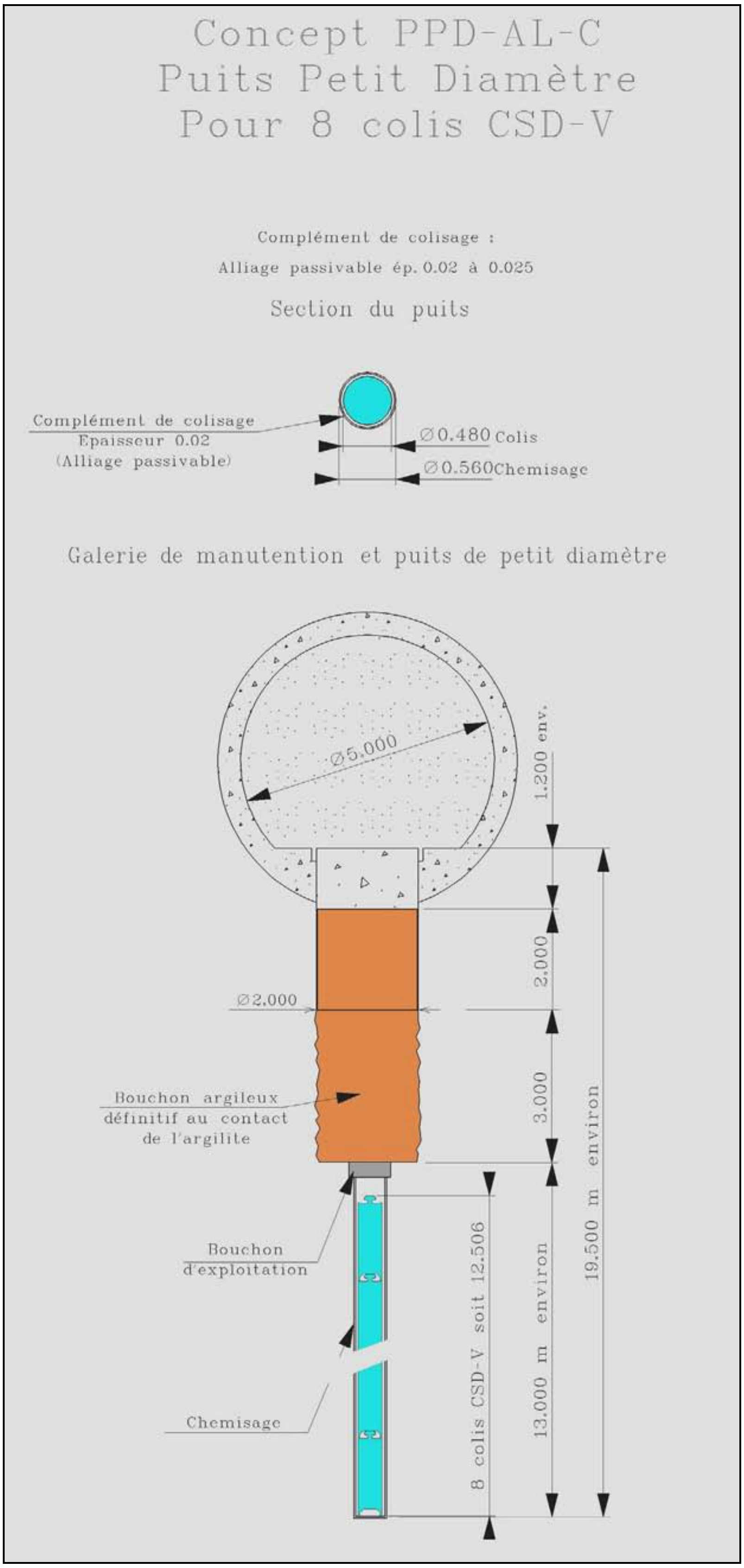


Figure 5-3d. *Conceptual layout of French vitrified waste repository. Large drift concept. (Courtesy of Andra).*

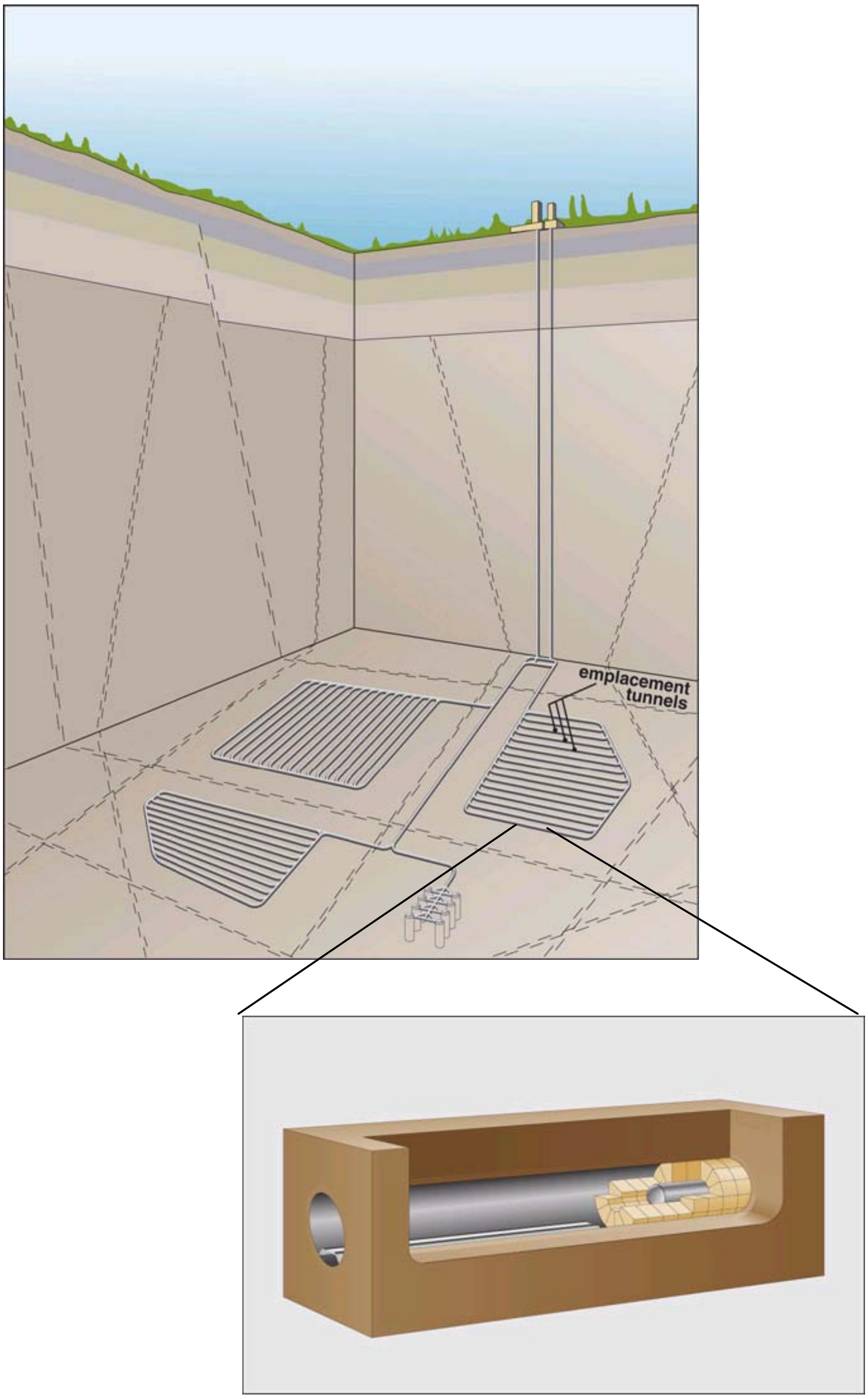


Figure 5-4. *Conceptual layout of Swiss HLW repository. (Courtesy of Nagra).*

OPG

Design criteria

The proposed SF repository design must be structurally stable in the conditions expected in the Canadian Shield under ambient temperature and expected elevated temperature conditions. The SF deposition rooms are to be backfilled and plugged at the open end as they are filled with canisters. The major design criteria for disposal of the SF are basically focused on the risk of release of radionuclides from the canisters to the rock mass and the biosphere, and particular emphasis is therefore on the influence of temperature on the performance and longevity of the EBS and the near-field rock. The maximum temperature of the canister outer surface and the buffer clay is set at 100^{o}C. The canister must provide containment of the SF for E5 years.

Access to the repository is through two sets of shafts: a service shaft complex, and a ventilation shaft complex (Figure 5-5). There are two options with respect to the placement of the waste canisters: 1) in-floor placement of canisters and 2) in-room emplacement of canisters. Minimum thickness of the buffer between canister and the excavation boundary is 0.25 m for option 1 and 0.5 m for option 2.

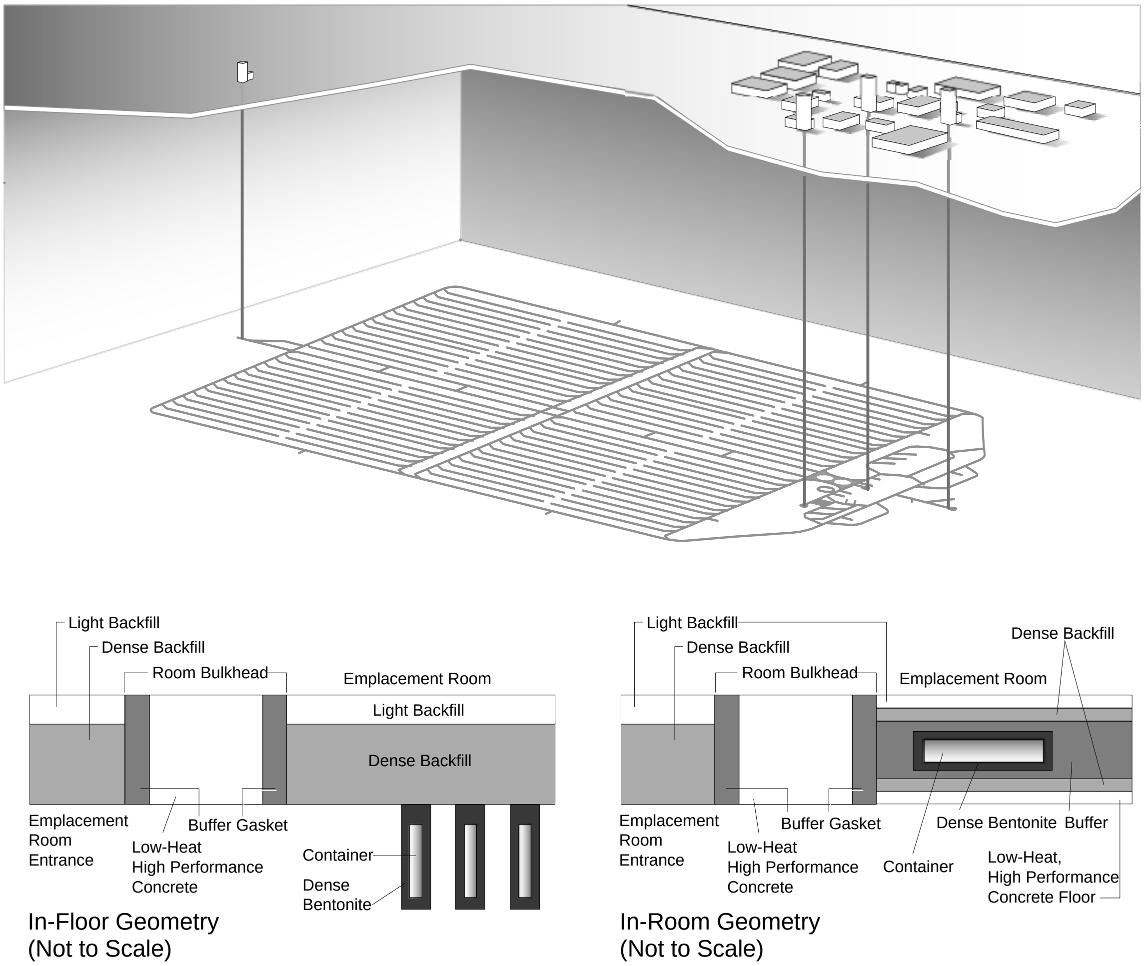


Figure 5-5. *Conceptual layout of Canadian HLW repository. (Courtesy of OPG).*

5.1.2 Required function of repository

SKB and Posiva

Isolation principle

Disposal in a KBS-3 repository would occur at a depth between 400 m and 700 m below ground surface. Isolation is based on the multi-barrier principle, implying use of canisters, buffer, backfill, and bedrock. The host medium can be either granite or gneiss.

Stability

For SKB's crystalline host rock, the stress field at 400-700 m depth is not expected to cause rock bursting or spalling, but orientation of deposition drifts for avoiding critical stability conditions is still an issue of concern. Very minor stabilization will be required because of the high strength of the rock and the insignificant creep that is expected. For the planned host rock of Posiva’s repository, the stress conditions may be a design issue below 500 m depth. The magnitude and frequency of significant tectonic events are moderate in most parts of Sweden and Finland, and particularly low in south-western Sweden according to seismic recordings during the last 200 years, when the magnitude of earthquakes on the Richter scale has not exceeded 3.

Hydrology

The piezometric conditions are hydrostatic in potential crystalline host rock in Sweden and Finland. As an average, the hydraulic conductivity at 300-500 m depth is E-11 to E-9 m/s, while the average conductivity of major fracture zones varies between E-9 and E-6 m/s. EDZ caused by drill-and-blast or boring tend to perform as porous media with a conductivity that can be 10-1 000 times that of the rock matrix, dependent on the excavation method chosen.

Geochemistry

The salt content in groundwater, usually with the Na/Ca ratio being higher than unity down to 500 m depth, can vary between fresh to strongly brackish conditions dependent on the distance from the coast. pH is usually in the interval of 6-8. In Swedish bedrock at repository candidate sites, the salt content expressed as total dissolved solids (TDS) is typically on the order of 5 to 15 g/l at 500 m depth. Similar conditions exist at the proposed site – Olkiluoto - in Finland. Reducing conditions usually prevail at more than 100 m depth.

Enresa

(One of Enresa’s options is disposal in crystalline rock.)

Isolation principle

The repository is situated at a depth of about 500 m below the ground surface. Isolation is based on the multi-barrier principle with EBS - canisters, buffer, backfill and seals (plugs) – as well as the geological host formation.

Stability

Tectonic stability should be provided over the required time period, meaning that the repository may not be intersected by active faults. The seismic and geothermal conditions must be acceptable.

Hydrology

Major water-bearing fracture zones will be identified and avoided. Modeling of these units is deterministic. Minor water-bearing features will be accepted in the repository and they will be modeled stochastically. The EDZ consisting of the mechanically damaged rock and the rock affected by stress changes is taken as an important conductor.

Geochemistry

The generic water is of sodium bicarbonate type with a TDS of 0.4 to 0.5 g/l.

Andra

(One of Andra’s options is disposal in crystalline rock.)

Isolation principle

The repository depth considered is 300 – 1 000 m. The multi-barrier principle is applied, and EBS consists of canisters, buffer clay and clay-based backfill. The rock serves as the surrounding barrier. For SF, the KBS-3 concept (with canisters placed either vertically or horizontally) may serve as an example while for vitrified waste, disposal cells holding several packages may be used.

Hydrology

The repository will be located away from significant water-bearing rock features. EDZ is not considered in the calculation of groundwater flow or estimation of the stability.

Geochemistry

The groundwater chemistry is important in locating the repository but the matter has not yet been considered in detail.

Nagra

(One of Nagra’s options is disposal in crystalline rock.)

Isolation principle

The depth considered for a repository in granite or gneiss is 500 – 1 200 m. A multi-barrier system is selected and for SF and HLW the EBS consists of canisters, buffer clay, and rock. For ILW the waste is solidified in concrete and put in steel packages that are placed in concrete containers, the space between the various components being filled with cementitious mortar. The rock serves as the surrounding barrier.

Stability

The rock stress conditions are not critical to the stability of deep drifts. The magnitude of recorded earthquakes is 3-4 on the Richter scale and the focal depth ranges from very shallow to very deep.

Hydrology

The repository will be located away from significant water-bearing, steep rock faults that are relatively frequent, weak and conductive. The groundwater flow is largely horizontal but may be directed up or down depending on the topography. The average hydraulic conductivity of the lower domain of the siting region is around E-9 m/s.

Geochemistry

The Na-dominated salt content of the groundwater ranges between less than 0.2 to 1.5 g/l, and is occasionally 120 g/l. The groundwater seems to be a mixture of water of meteoric origin and very old water in fractures. In northern Switzerland, four distinct water types can be identified ranging from young "recharge water" to older (70 000 years or more) more saline types.

OPG

Isolation principle

The multi-barrier principle is applied for a SF repository and the EBS barriers are the canister, clay-based buffer, dense and light backfill, and cement-based grouts and seals. The rock serves as the surrounding natural barrier (Figure 5-5). The Canadian program has focused its siting studies on the plutonic rock of the Canadian Shield, which is 75% granitic, 15% gabbroic and 10% all other rock types. The Canadian Shield is widely distributed, occupying about half of the areal extent of Canada. The depth of a repository located in the plutonic rock of the Canadian Shield has not yet been decided but will likely be in the range of about 500 m to 1 000 m.

The canister, consisting of a steel inner load-bearing vessel and a copper outer corrosion-barrier vessel, must provide isolation for at least E5 years. The canister design includes consideration of high glacial pressure (e.g., up to 45 MPa hydrostatic pressure head).

Stability

The rock stress conditions at some locations in the Canadian Shield, below 300 m depth may be a factor in the design of stable deep drifts and may result in some zones of minor yielding and spalling rock in the excavation perimeters (Figure 5-11 shows an example of yielding and spalling around an unfavorably oriented room at AECL´s URL). The magnitude of recorded earthquakes is 3-4 on the Richter scale with a focal depth ranging from very shallow to very deep, primarily located along the Canadian Shield margins, along very large faults or in areas of recent rifting.

Hydrology

The plutonic rock masses in the Canadian Shield likely to be considered for a repository location range from sparsely to moderately fractured, and contain widely spaced sub-horizontal, major fracture zones, from which the repository will be separated by at least one hundred meters. The hydraulic conductivity in the fracture zones is as high as E-4 m/s and in the unaltered, unfractured rock is as low as E-14 m/s.

Geochemistry

The Na-dominated salt content varies between 1 and about 110 g/l, but may reach more than 200 g/l in certain areas. At AECL´s Whiteshell Research Area, which includes AECL's URL near Pinawa, the groundwater from above 300 m depth is Na-dominated and below 400 m to 500 m depth is Ca-dominated.

Acceptable dose rate

Historically, the Canadian regulatory document R-104 provided quantitative criteria for safety assessment of a deep geologic repository (e.g., radiological risk to individuals from a waste disposal facility shall not exceed E-6 fatal cancers and serious genetic defects in a year, calculated without taking advantage of long-term institutional controls as a safety feature). However, Canadian regulations related to nuclear waste disposal are currently being revised. Until new regulations are issued, OPG is, in recent safety assessment studies, comparing the calculated dose rates to the recommendations provided by the International Commission on Radiological Protection in ICRP 81 [5-1], as well as to Canadian natural background dose rates.

The key recommendations made in ICRP 81 are:

- There should be separate assessment of the consequences of natural evolution and of human intrusion scenarios.
- For natural evolution, an upper value for dose rate to an individual member of the public should be 0.3 mSv/a.
- For human intrusion, intervention (e.g., modification of repository design) is not likely to be justifiable if potential doses rates, to a resident living near the site, are below 10 mSv/a, while it is almost always justifiable for potential doses above 100 mSv/a.

With respect to natural background, OPG is using the following indicators:

- The Canadian average background dose rate to humans from natural sources (about 1.7 mSv/a).
- The natural background concentration of radionuclides in Canadian surface waters.
- The natural flux of radionuclides from the geosphere to the surface biosphere.

Retrievability/reversibility of waste

The OPG repository concepts include the capability to retrieve the waste canisters during the period of repository operation and after repository decommissioning and closure. The retrieval of waste containers from a repository has been considered at the conceptual level for both in-floor borehole emplacement configuration and the in-room configuration using the 72-bundle of SF canisters and is considered to be technically feasible. In a current update of the deep geologic repository concept, a conceptual level approach to retrieval of the IV-324-hex canister, which contains 324 bundles of SF, is being developed.

Need and ways of monitoring and documentation

In Canada, the specific requirements associated with long-term monitoring of a geological repository have not been established. Following the filling and sealing of the repository deposition drifts there will be a period of post-operational monitoring to gather data for environmental, safety and engineering PA. These assessments will be one of the factors considered by stakeholders and regulators with respect to repository closure. During this period, the shafts/ramps and underground access drifts would be open and instrumentation systems would be installed from both the surface and underground. During closure of a repository, all systems installed underground that could affect the long-term safety of the repository would be removed and any required monitoring would be installed from the surface. The design of these surface-based long-term monitoring systems should not compromise the passive safety of the closed repository. OPG's technology program is taking a broad approach to addressing the issues related to long-term monitoring of a geologic repository: documenting the state-of-the-art in instrumentation, documenting the needs of a long-term monitoring program, and identifying any gaps in current instrumentation and in the application of these instruments to monitoring. Major challenges in developing a postclosure monitoring capability are the following.

- Longevity of the instrumentation and systems.
- Maintenance, replacement and calibration of the instrumentation *in-situ*.
- Effective monitoring after repository closure without using invasive installations that might affect the passive safety of the repository.

5.2 National URLs

5.2.1 Overall purpose of the national URLs

Crystalline rock URLs are currently used by several CROP Participants to gather experience in the siting, construction and testing of the waste disposal concepts that will the basis for future designs of HLW repositories. Some URLs are operated as pure research facilities that may not become a part of a repository, whereas several others are located in or close to areas where repositories will be sited and they may be included in the repository. A common focus is on the performance of the EBS and on scale-effects. More specifically, the purpose of these URL's can be assigned under one or more of the four categories shown in Table 5-1.

5.2.2 Description of URLs

URLs in crystalline rock have been or are being established in Switzerland (Grimsel), Finland (Onkalo), Canada (Pinawa), and Sweden (Stripa and AEspoe). In the Canadian, Swedish and Swiss URLs international teams have been and are still active as part of the national RTD performed by several of the CROP Participants. The various experiments in the URLs and their respective objectives are listed in Appendix I. A compilation of the most important types of investigations is given below.

Table 5-1. Purpose of underground research laboratories

URL	Organization	Purpose of URL			
		Development of concept	**Confirmation of concept**	**Qualification of design**	**Qualification of Site**
Stripa	SKB	X	X	X	
AEspoe HRL	SKB	X	X	X	
Grimsel, Test Site (GTS)	Nagra	X	X	X	
VLJ Research Tunnel Onkalo	Posiva	X	X X	X	X
URL	AECL	X	X	X	

Stripa URL

The Stripa URL was excavated in granitic rock at a depth of 300-400 m about 200 km NW of Stockholm when mining of adjacent hematite ore ended in 1977. It was initially used for a joint Swedish/American research project that was followed in 1981 by the International Stripa Project. The area was characterized with respect to large-scale structures and hydrology and to rock mechanical conditions during the first phase. Several experiments were performed on various scales in the URL in the second phase that ended in 1992. The main ones related to EBS and near-field rock were:

- Characterization of near-field rock. This work comprised structural identification and hydrological characterization by logging in short and deep boreholes and by cross-hole investigations, and rock mechanical experiments.

- Buffer Mass Test (BMT). This experiment, which represents the KBS-3V concept with canisters embedded in highly compacted bentonite (buffer) clay, took place in a blasted drift. Focus was on THM evolution of the buffer and backfill components of the EBS.

- Borehole, shaft and drift plugging. The experiments comprised sealing of boreholes up to 100 m long and recording the sealing effect, plugging of a 1 m diameter shaft for investigating the effect of excavation damage, and sealing of a 20 m^2 drill-and-blast drift for the same purpose.

- Sealing of fractured rock. This project comprised experiments on different scales for investigating if the EDZ could be sealed by grouting in short holes and if natural fracture zones can be effectively sealed by grouting in medium-long holes drilled in them.

The major results from the experiments are briefly described under the respective headings in this chapter.

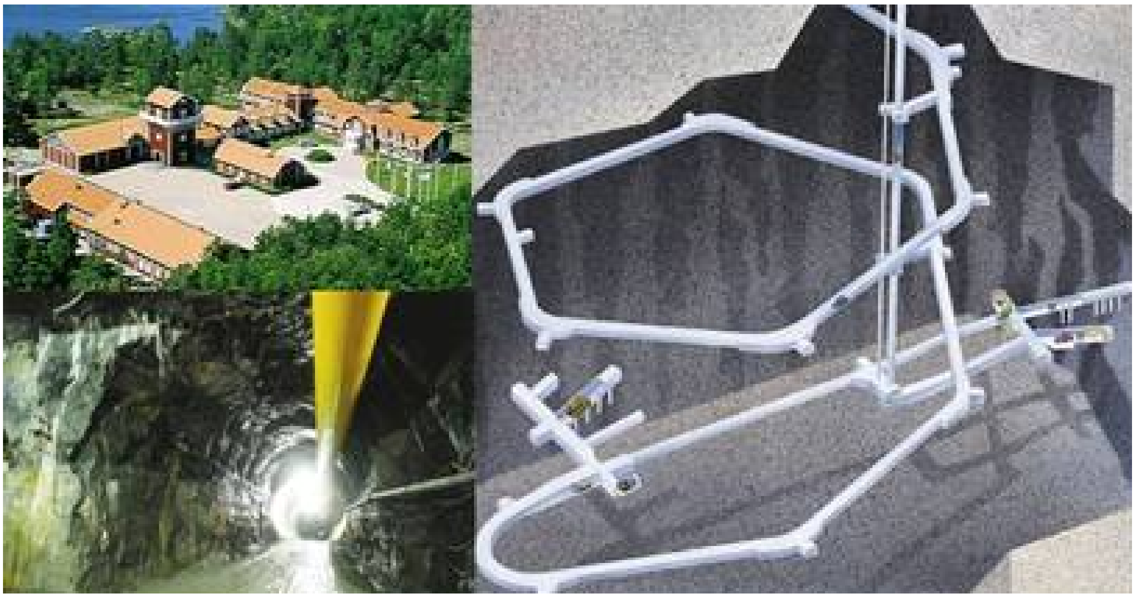


Figure 5-6. *AEspoe URL. (Courtesy of SKB).*

AEspoe URL

The AEspoe URL, see Figure 5-6, was excavated in complex granite-dominated rock about 200 km S of Stockholm for the purpose of demonstrating all the major steps to be taken in constructing and assessing the performance of a repository in virgin crystalline rock Comprehensive structural and hydrological characterization of the repository rock was conducted in conjunction with construction of the ramp down to 465 m depth, and several blasted and TBM-bored drifts in which a number of EBS-related experiments are being conducted. The construction started in 1990.

The main experiments related to EBS are:

- Characterization of near-field rock. This work comprised the identification of rock structures and hydrological characterization by logging in short and long boreholes and by cross-hole investigations, as well as by rock mechanical experiments.

- The Prototype Repository project. This full-scale experiment, which represents the KBS-3V repository concept with full size copper canisters embedded in highly compacted bentonite clay, is conducted in a TBM-bored drift and represents part of a full-scale KBS-3V repository. Focus is on demonstrating construction of buffer and backfill components and to record and evaluate the THMCB evolution of the near-field rock, buffer and backfill.

- The Backfill and Plug Test. The experiment comprised backfilling of a drill-and-blast drift and confining it by construction and measurement of the tightness of a large concrete plug extending into the surrounding rock for sealing off the EDZ.
- The Long-term Test of Buffer Material experiments (LOT) for investigating the chemical stability of the canister-embedding bentonite buffer of the KBS-3V concept.
- Manufacturing and placement of canisters.
- Predictive modeling of the performance of clay buffers and backfills.

The major results from these experiments are briefly described under the respective headings in this chapter.

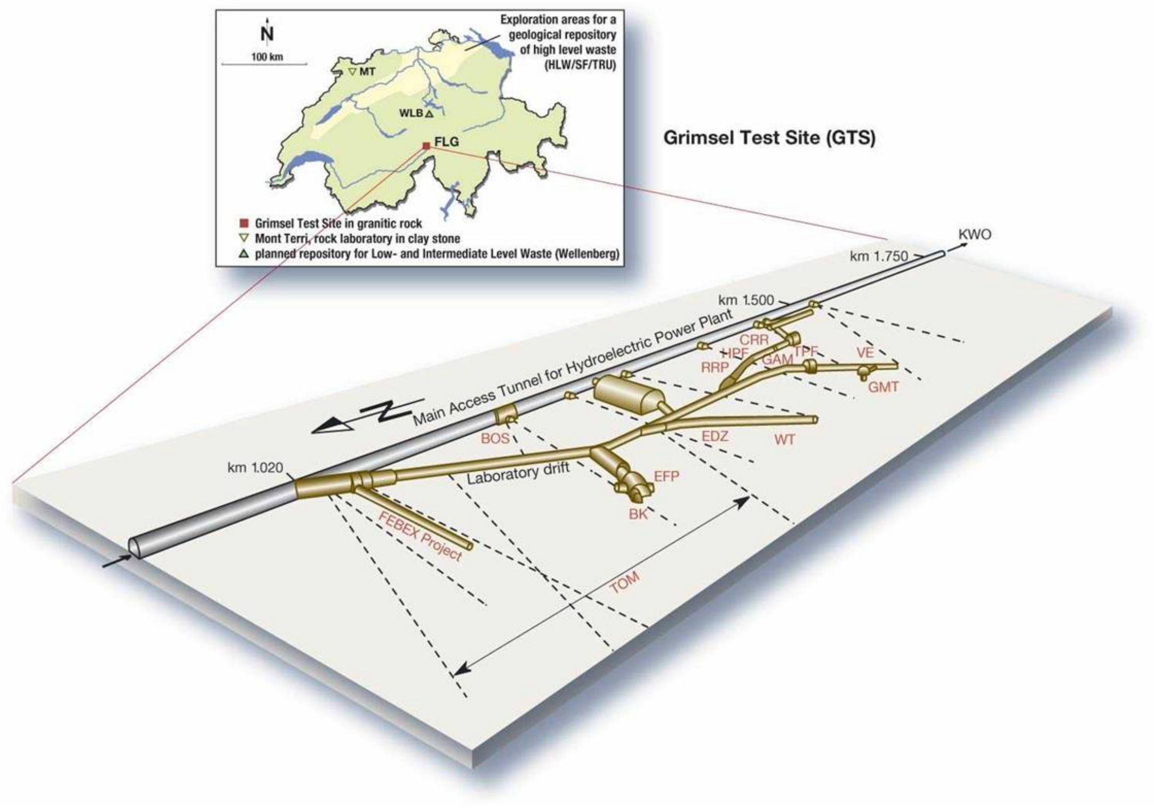


Figure 5-7. *Grimsel URL. Abbreviations for experiments on EBS-related RTD are explained in Appendix 1. (Courtesy of Nagra).*

Grimsel URL (Test Site)

The Grimsel Test Site, see Figure 5-7, is a site-independent or off-site URL. It was excavated at about 400 m depth in rather homogeneous and tight granite by use of TBM technique about 20 years ago. It has since hosted national and multi-national experiments as well as Enresa's comprehensive Febex project. Lamprophyre dykes, widely spaced water-bearing fractures, and relatively few fracture zones of long persistence have been identified. Test activities in the form of experiments performed by Nagra have been preceded by comprehensive structural and hydrological characterization of the rock mass on various scales.

The main experiments related to the EBS carried out by Nagra and its partners (e.g., Andra, BGR, GRS and RWMC (Radioactive Waste Management Funding and Research Centre, Japan)) are:

- Characterization of the drift near-field. This work includes hydrogeological characterization of the EDZ in blasted and bored drift sections.
- Rock mechanical test for determining the rock stress.
- Heater tests to investigate the effect of temperature on the host rock.
- Ventilation test to investigate the "macro"-permeability of the host rock, evaporation processes at the drift surface and the extent and the properties of the unsaturated zone around the drifts.
- Borehole sealing to assess emplacement procedures and the hydraulic performance of plugs made from bentonite pellets and highly compacted granular bentonite.
- Gas Migration Test, which aims at assessing the function of the EBS (in this case a sand/bentonite mixture) and adjacent geosphere with respect to repository-generated gas migration. The experiment, which is led by RWMC, includes a comprehensive field and mock-up test as well as modeling.
- The experiments conducted as part of Enresa's Febex project involved:
- INFLOW tests for hydraulic characterization of the TBM drift that was extended in order to host a test with horizontally oriented canisters embedded in highly compacted clay.
- DESIGN, construction and performance of a full-scale buffer clay experiment representing the Enresa concept with horizontally oriented canisters embedded in highly compacted bentonite clay.
- Plug test. The experiment comprised the construction of large concrete plugs and recording of their tightness with respect to water and gas pressures.
- Predictive modeling of the performance of clay buffers and backfills.

The VLJ Research Tunnel and Onkalo underground rock characterization facility at Olkiluoto.

The Research Drift was excavated at a depth of about 60 m in the VLJ Repository for short-lived low-level radioactive waste and ILW at Olkiluoto about 10 years ago. The repository and the research drift were excavated by drill-and-blast technique. Deposition holes with dimensions corresponding to those of the KBS-3V concept have been bored by using a full-face boring technique with removal of the muck by vacuum. Comprehensive characterization of the deposition holes and the EDZ around them has been carried out, including hydraulic measurements and tracer tests.

In 2004, Posiva will start the construction of an underground rock characterization facility, Onkalo, in the central part of the Olkiluoto island. Onkalo will consist of a system of exploratory drifts accessed by a drift and a ventilation shaft. The main characterization level will be located at a depth of 420 m and the lower characterization level at a depth of 520 m. The total underground volume of Onkalo will be approx. 330 000m^3 with the combined length of drifts and shafts of approx. 8 500 m. The drifts will be excavated using drill-and-blast method. The ventilation shaft will be bored with a raise boring technique and then slashed to final dimensions by drill-and-blast. Onkalo is designed in such a manner that it can later serve as access routes and auxiliary rooms of the repository for SF to be constructed at Olkiluoto. The main EBS-related experiments planned for Onkalo are:

- Rock stress measurements for determining the stability conditions with special respect to possible future heater experiments.
- Correlation of rock structure and water inflow into the deposition holes as a basis of modeling of the hydration rate of clay buffer.
- Sampling of rock in the deposition holes for determination of gas and hydraulic conductivity of the most surficial part, i.e., the boring-disturbed rock.

AECL´s URL

The AECL Underground Research Laboratory (URL) near Pinawa, Canada has been used to develop and demonstrate the methods proposed for underground evaluation of a potential repository site and as the focus of large-scale *in-situ* experiments and demonstrations for the Canadian program (Figure 5-8). The effectiveness of repository sealing system components, such as clay-based buffer and backfill, concrete and clay bulkheads, and cement and clay grouts, are one area of investigation. As conditions in the near-field rock affect the performance of repository sealing systems, the work also includes: developing geomechanics methods and tools for use in the design of stable repository excavations, understanding the processes that cause excavation damage, and developing methods for reducing or eliminating the influence of excavation damage on the movement of water or contaminants.

The AECL´s URL is located in a previously undisturbed and well-characterized portion of the Lac du Bonnet granitic batholith, which is 2 650 million years old (Figure 5-9). It comprises: surface facilities, a vertical shaft to a depth of 443, smaller ventilation raises connecting the 420 level with the 240 level and the ground surface, shaft stations at depths of 130 m and 300 m, and accesses to major experimental levels at 240 m and 420 m depths. Most of the shaft and experimental areas are below the water table and are representative of plutonic rock and hydrogeologic conditions in the Canadian Shield.

The Lac du Bonnet granite batholith is composed of a relatively undifferentiated massive porphyritic granite-granodiorite. Within the first few hundred meters of the surface, the granite contains subvertical joint sets and several major low dipping thrust faults (called Fracture Zones) and has been oxidized to a pink color by secondary alteration processes within approximately 200 m of the surface. The granite transitions back to grey granite below this depth until Fracture Zone 2 is approached at about 275 m depth and the pink alteration halo surrounding the zone is entered. Below Fracture Zone 2 and its splays, the granite is intruded by granodiorite dykes, but is sparsely fractured and grey in color. The hydraulic conductivity of the fracture zones is as high as E-4 m/s, but in the unaltered, unfractured rock, values range is as low as E-14 m/s. The salinity and TDS content of the groundwater and rock pore water increase with depth, reaching TDS concentrations of up to 100 g/l in the sparsely fractured rock at the 400 m to 500 m depth.

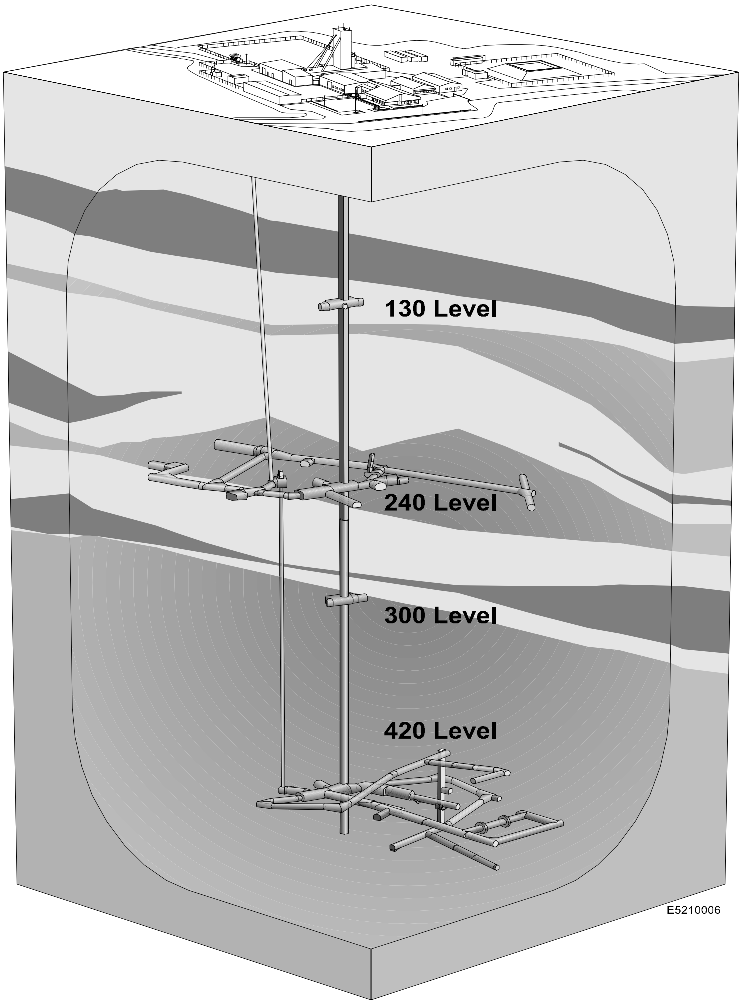


***Figure 5-8**. AECL’s URL at Pinawa. (Courtesy of AECL).*

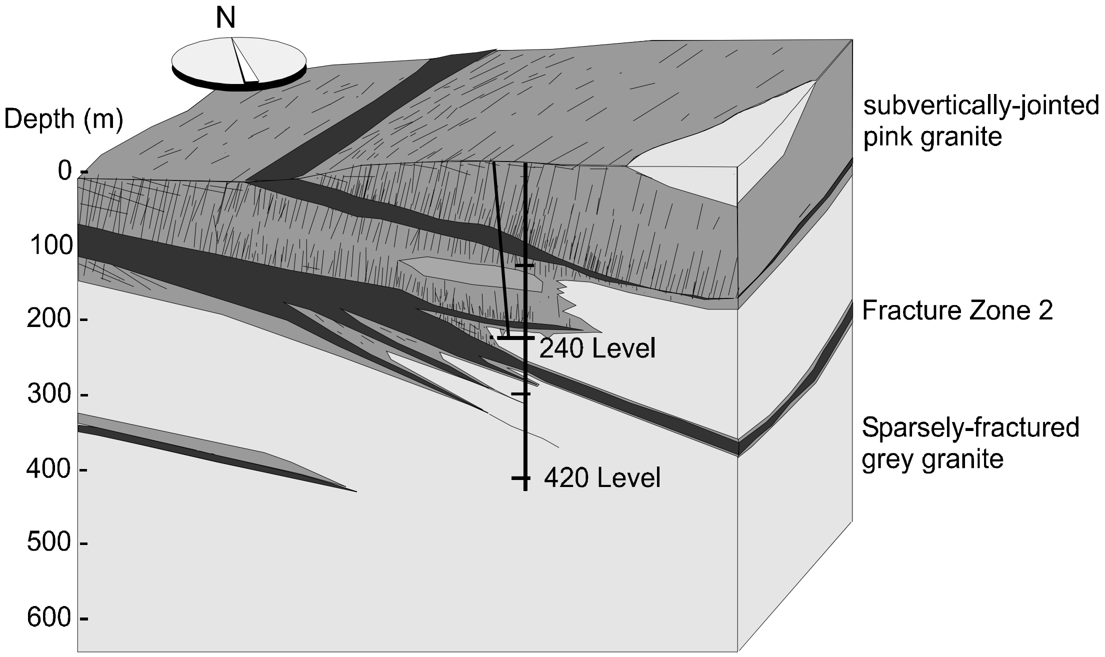


Figure 5-9. *General Geological Conditions at AECL's URL. . (Courtesy of AECL).*

Stress measurements have given a good picture of the impact of stresses on the hydrogeology and the excavation stability. The *in-situ* stresses are an excavation design factor below about 300 m depth.

Large-scale *in-situ* experiments designed and conducted in AECL's URL to address the areas of technology associated with repository sealing system performance, include:

- Thermal Mechanical Stability Studies to develop the design tools necessary for highly stressed sparsely fractured rock, including Room 209 Excavation Response Test, Connected Permeability Tests, Mine-by Experiment, Heated Failure Tests, and Excavation Stability Study.
- Buffer/Container Experiment, which simulated the in-floor borehole emplacement configuration with 50% bentonite/50% sand buffer material using an electrical heater.
- Isothermal Buffer/Rock/Concrete Plug Interaction Test, which was an ambient temperature test of a rock/50% bentonite and 50% sand buffer/concrete plug system.
- Thermal-Hydraulic Studies, which used laboratory and *in-situ* tests to determine the thermal-mechanical-hydraulic coupling parameters of the URL rock mass.
- Grouting Tests.
- Tunnel Sealing Experiment, which is studying the performance of a concrete bulkhead and a clay bulkhead under hydraulic pressure heads and elevated temperature.

5.3 Excavation of deposition holes and drifts

5.3.1 General

A prerequisite for placing canisters with HLW in a repository is to have prepared suitable space for placing them. This can be made in many fashions as shown in Figure 5-10.

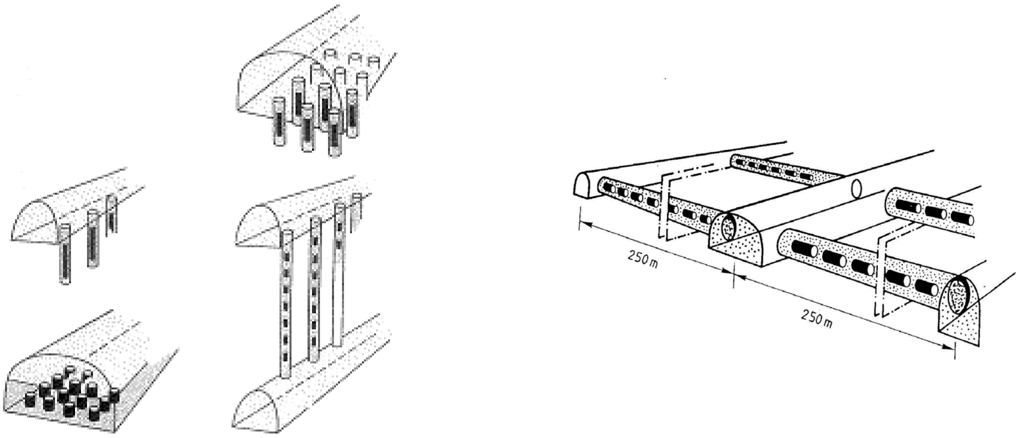


Figure 5-10. *Examples of repository concepts for disposal of HLW in crystalline rock.*

Irrespective of the technique employed for excavation, all CROP Participants have put emphasis on the design of deposition holes and drifts as well as ramps and shafts with respect to the rock stress conditions. There have been detailed studies of the mechanical response of the near-field rock to the boring of large-diameter deposition holes or drifts that included the use of displacement measurements, strain measurements, and geophysical methods. In some cases, such as the one shown to the left in Figure 5-11, acoustic emission techniques have been successfully used and compared to numerical calculations of the stress conditions. In the AECL´s URL, comprehensive experience has been gathered with respect to wall stability and some of the work has been conducted to establish conditions leading to excavation wall instability caused by high primary rock stresses, which is shown to the right in the figure.

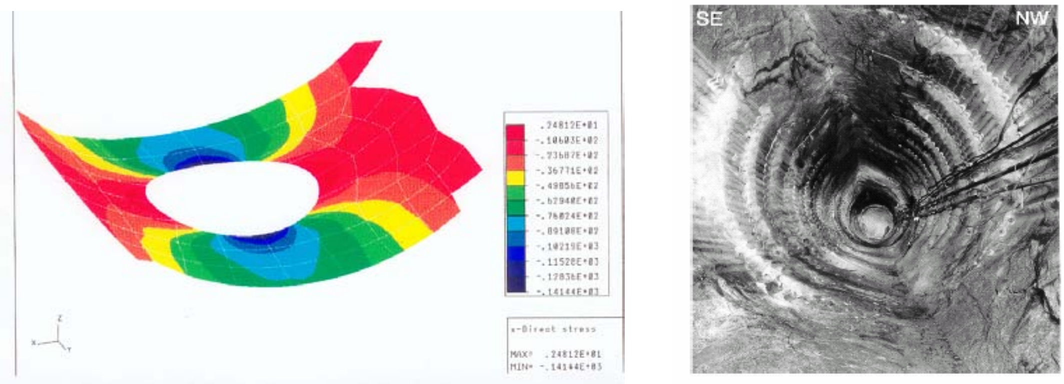


Figure 5-11. *Left: Rock stress conditions in the drift floor around a KBS-3V deposition hole calculated by the boundary element method code BEASY. Primary principal stresses = 25 MPa normal to drift axis (x-direction), 15 MPa parallel to this axis, and 10 MPa vertical. Maximum hoop stress = 141 MPa. Right: Planned excavation breakouts in the circular Mine-by Experiment drift caused by overstressing at the 420 m level of AECL´s URL. Primary principal stresses = 60 MPa, sub-horizontal and normal to drift axis, 45 MPa sub horizontal and parallel to drift axis and 11 MPa sub-vertical. Rock boundary strength is approximately 120 MPa (granite) and approximately 150 MPa (granodiorite). Maximum hoop stress is 169 MPa.*

The selection of excavation/mining methods depends upon the type of host rock. For excavation of drifts in crystalline rock, drill-and-blast and mechanical mining methods are commonly used. The two methods have different impacts on the hydraulic performance, on the rock stress situation and rock disturbance around the excavated openings:

- Mechanical mining by means of (full-face) drift boring machines (TBMs) will result in a single shaped (circular) and sized opening and the repository must be designed accordingly.

- Drill-and-blast-based excavation methods generally offer much higher excavation rates and flexibility in the construction phase, including shaping and sizing the underground openings. One particularly significant benefit vested in drill-and-blast-based mining methods is that they offer very high flexibility in dealing with unexpected rock mass conditions.

5.3.2 EDZ – a matter that requires consideration in construction and performance assessment of repositories in crystalline rock

Drill-and-blast excavation technique

Drill-and-blast-based excavation methods typically weakens the rock around an opening and increases the porosity and hydraulic conductivity in the weakened rock because the very high gas pressure generated by the blast produce new fractures and propagate existing ones. The blast-damaged rock is characterized by a lowered E-modulus, which reduces the hoop stresses around the room and thereby increases its stability, but could increase the axial hydraulic conductivity of the perimeter rock.

Various field experiments have been performed in the Stripa, AEspoe, Grimsel and AECL´s URLs to find out whether the EDZ really is of importance to the transport of water and contaminants in repositories. An early finding was that the degree of mechanical degradation varies along the length of a blasted drift as a function of the distribution of the charge, a typical schematic illustration being shown in Figure 5-12. It means that spot-wise determination of the hydraulic conductivity in short boreholes drilled normal to the rock walls give strongly varying data and that it is difficult or nearly impossible to determine the effective axial hydraulic conductivity over long distance, which depends mainly on the interconnectivity of the induced fractures and less on the local hydraulic conductivities measured in such tests [5-2].

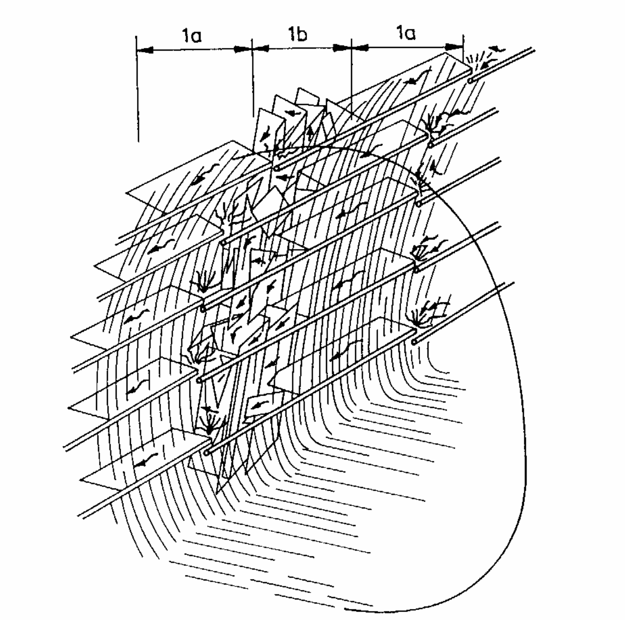


***Figure 5-12.** Major types of damage by drift blasting. 1a-zones are characterized by regular sets of plane fractures extending radially from the central parts of the blast-holes. 1b-zones represent strongly fractures parts at the tips of the blast-holes [5-2].*

Experiments performed at the Pinawa URL suggested that the EDZ of drill-and-blast drifts has a depth varying from about 200 mm to 1 000 mm in the absence of notch formation. The hydraulic conductivity of the rock is E-12 m/s or lower and the hydraulics conductivity of the EDZ is about E-8 m/s. Where notches were formed in the walls of the excavated drift the hydraulic conductivity in the process zone of notch tip was approximately E-6 m/s. Large-scale EDZ experiments made in AECL´s URL by constructing dams in drill-and-blast drifts for measuring axial flow along them indicated that the hydraulic conductivity of the near-field rock below the floor could be as high as E-6 to E-8 m/s in local areas but that this zone of increased conductivity was very limited in space (extended only several tens of mm into the rock), see [5-3].

In contrast, field experiments at Stripa for determination of the hydraulic performance of the EDZ of drifts that had been excavated by use of common drill-and-blasting showed that the excavation-induced disturbance can be very significant. The Stripa test arrangement comprised borehole galleries at each end of a drift for pressurizing and collection of water (Figure 5-13). For eliminating inflow of water into the drift it was filled with a large rubber bladder embedded by Na-bentonite slurry, which was pressurized by the water-filled bladder [5-4].

The average conductivity of the virgin rock was evaluated as 3E-11 to E-10 m/s and the evaluation of the test data showed that the rock from the drift wall to 0.75 m depth had an average hydraulic conductivity of 1.2E-8 m/s, i.e., 2-3 orders of magnitude higher than that of the virgin rock. The rock 0.75 to 3 m from the drift wall, which was taken to represent the stress-induced EDZ, had an average axial conductivity that was 10 times higher than that of the virgin rock, and an average radial conductivity of about one fifth of that of the virgin rock, indicating a “skin” zone.

The project Zone of Excavation Disturbance EXperiment (Zedex) at AEspoe URL separated between the “damaged “ and the “disturbed” zone, the difference being that the first mentioned would be dominated by changes in rock properties which are mainly irreversible while changes in the “disturbed” zone are mainly reversible. A number of measuring techniques were applied in the two drifts, one excavated with low-shock explosives (“normal” smooth blasting), and one with a full-face TBM. The results indicate that the role of the EDZ as a preferential pathway for radionuclide transport is limited to the damaged zone. It was also concluded that the damaged zone could be limited through use of appropriate excavation methods [5-5].

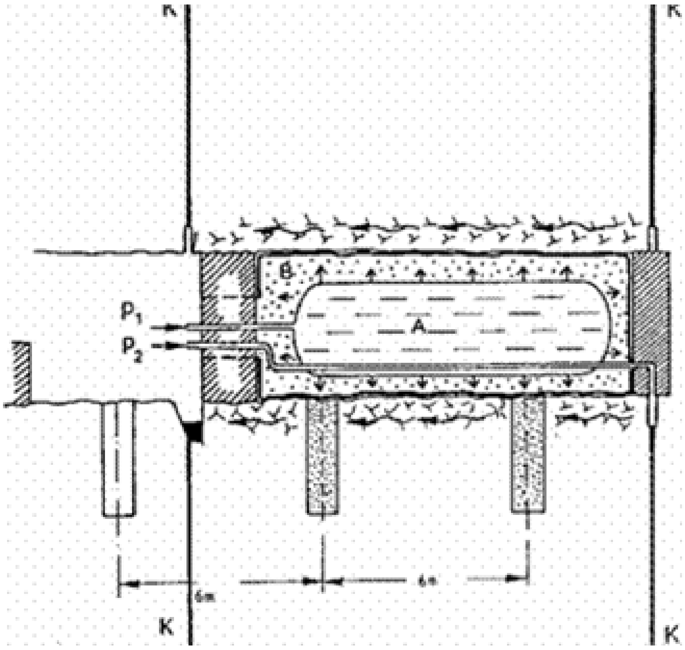


__Figure 5-13.__ Test set-up for evaluating the hydraulic conductivity of the EDZ of the BMT test drift [5-4]. A is the water-filled bladder and B the bentonite slurry that prevented water in the rock to flow into the drift.

German work (BGR) for determining EDZ properties in drill-and-blast drifts and drifts in crystalline rock using spot-wise testing has given similar results. For example, the EDZ of conventionally blasted drifts in the Aare granite at the Grimsel Test Site was characterized by blast-induced macro- and micro-fractures to a depth of about 0.3 m, and had a local hydraulic conductivity varying between E-10 m/s and E-3 m/s.

TBM and similar excavation techniques

Work by BGR in the AEspoe URL using spot testing of small rock volumes has shown that the hydraulic conductivity in the TBM excavated part of the ramp increases from less than E-12 m/s to more than E-10 m/s for the most shallow 10 mm part of the EDZ and that it is E-12 to E-10 m/s within 100 mm distance from the wall [5-6]. Hydraulic and gas testing of samples bored from the wall showed about the same values as reported by Posiva and SKB [5-7], which hence indicate that the impact on the hydraulic conductivity by excavation using only TBM and similar techniques is much less than that caused by drill-and-blast. In the Grimsel URL only, slightly enhanced matrix permeability was detected in a zone between 0.1 and 1 m from the drift wall. The hydraulic conductivity of this zone was about 2-3xE-11 m/s, while at larger distance a hydraulic conductivity of 2xE-12 m/s was measured.

The overall characteristics of the EDZ at Stripa or AEspoe is illustrated by the following calculation exercise on the hydraulic impacts of an assumed 80 m^2 EDZ around a 25 m^2 drill-and-blast drift as well as around a 25 m^2 TBM excavated one, see Table 5-2. It shows the estimated change in axial flux across the entire near-field, 80 m^2 around the drift section. These 80 m^2 are composed of the blast-affected EDZ equaling 20 m^2 and of the surrounding stress-induced EDZ of 60 m^2. For TBMs with the same drift size, the EDZ extending to 0.1 m into the rock represents 18 m^2. For comparison of the two cases the net flux across the same section area 80 m^2 was considered.

Assuming the conductivity of the virgin rock to be E-11 m/s and that of the blast-disturbed zone to be E-8 m/s and taking the axial conductivity of the stress-affected EDZ around the drill-and-blast drift to be E-9 m/s, one finds the total flux across the 80 m^2 near-field section area to be about 100 times higher than that for a TBM drift and the transport capacity of a cross section corresponding to the total near-field of TBM drifts to be about 1% of that of drill-and-blast drifts [5-8].

Table 5-2. Approximate water flux across the assumed 80 m^2 near-field of a drift under the hydraulic gradient i=unity distributed over the various EDZ components. The backfilled drift is assumed to be impermeable [5-8].

Case	**Permeated cross section, m^2**	**Hydraulic conductivity, m/s**	**Water flux, m^3/s**
Virgin rock, no drift	80	E-11	8E-10
Blasted drift	20		2.6E-7
* Drill and blast-EDZ	20	E-8	2E-7
* Stress-EDZ	60	E-9	6E-8
TBM drift	80		2.6E-9
* Stress-EDZ	18	E-10	2E-9
* Virgin rock	62	E-11	6.2E-10

5.3.3 Special experience from excavation of deposition holes and drifts

General

For deposition holes and drifts there are special demands on the boring depending on which of the following principles is to be followed: 1) moderate or low quality of the holes with acceptance of relatively rugged walls and some variation in straightness, orientation and diameter, or 2) high-quality holes with perfect straightness and wall smoothness for obtaining small clearances and a good fit between the buffer/canister.

The first principle makes it possible to use slot-drilling or very careful blasting of closely drilled holes, or, as tested at AECL´s URL, water jet cutting. Slot-drilling and very careful blasting have been tried at Stripa with the outcome that 14 m deep holes with a diameter of about 1 m could be prepared with a diameter variation of about +/- 5 % and irregular walls with an amplitude of about 50 mm [5-9]. This technique makes application of canisters and buffer easy but the amount of buffer is somewhat higher than for core drilling or TBM excavation, following the second principle. The slot drilling and very careful blasting caused considerable disturbance and a high hydraulic conductivity of the EDZ, which is advantageous for speeding up the hydration of initially incompletely saturated clay buffers and for easy release of gas that has migrated through the buffer, but negative with respect to radionuclide migration. (Figure 5-14).

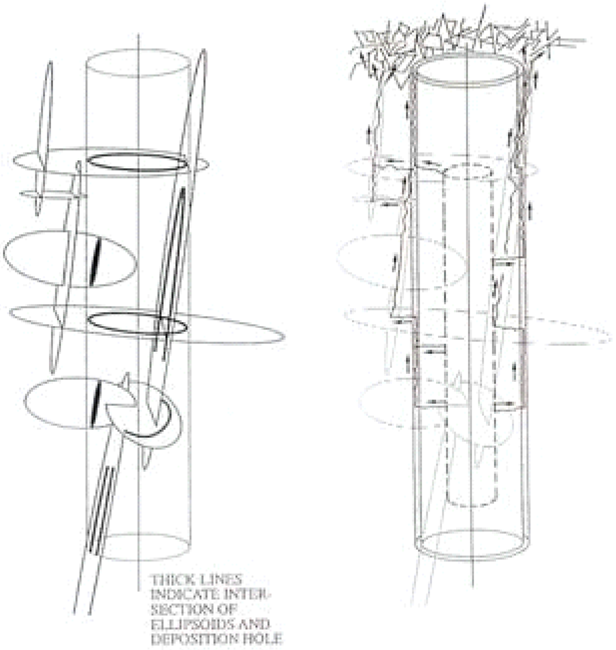


Figure 5-14. *Major transport paths for radionuclides and gas in the near-field of deposition hole with canister embedded in buffer clay. Left drawing shows generalized fractures intersecting the hole or being parts of a fracture network in the rock [5-2].*

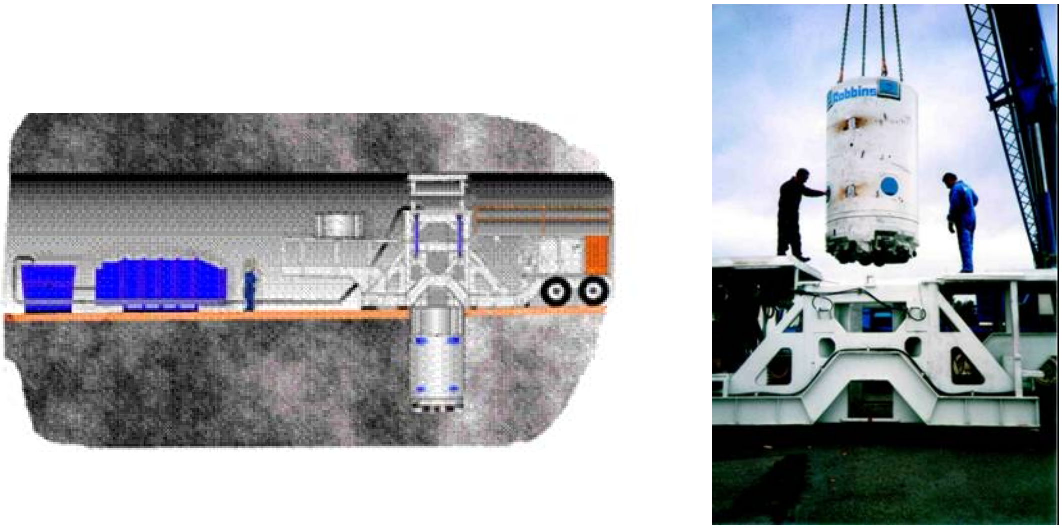


Figure 5-15. *TBM-type equipment (Robbins) used for boring of vertical deposition holes with 1.8 m diameter and 8 m depth.*

Excavation of deposition holes

High-quality emplacement/deposition holes can be obtained by using the TBM technique (Figure 5-15) [5-9] or the reversed raise boring method [5-11]. Both have been developed by Posiva and SKB, and both can provide straight holes with almost constant diameter and smooth rock walls [5-11]. Under favorable conditions the holes can be made only a few centimeters wider than prefabricated buffer blocks. For the Stripa project, holes representing half-scale of KBS-3V concept were excavated by core drilling, which gave perfectly smooth walls allowing the space between buffer blocks and the rock wall to be minimized [5-9]. At AECL´s URL, a 1.25 m diameter hole was core-drilled to a depth of 5 m for use in experiments. It should be possible to develop this technique for preparing also full-scale deposition holes of KBS-3V type.

The water jet-drilling technique tested at the AECL´s URL gave rather rugged rock walls. The method was affected by factors including stress and was much less productive at 240 m depth than at the ground surface [5-12]. This technique would require a significant development program to optimize it for deposition hole boring, but it could be considered for certain purposes in URLs such as cutting of recesses and shallow troughs for cables, pipes etc.

Drift excavation

TBM-excavation of horizontal and inclined drifts and shafts has the same impact on the rock as excavation of steep deposition holes. However the rock structure and stresses can cause more problems with the drift stability because larger rock volumes will be affected.

Drill-and-blast has several practical effects on the rock. It causes relaxation reducing the risk of spalling, and it increases the hydraulic conductivity very significantly to a depth of as much as several hundred millimeters into the rock wall. Since blasting was introduced in underground excavation more than 100 years ago, various accidents and unexpected rock fall have made miners realize that this sort of excavation has a strong impact on the residual rock, which, in combination with the fact that overbreakage is expensive, has led to development of techniques for careful blasting. The importance of the rock structure is obvious in this context: the reflection of pressure waves and dynamic shear waves cause separation and relative movement of rock blocks along existing open fractures and latent weaknesses, by which blocks of various size may become unstable.

5.4 Engineered Barrier Systems

5.4.1 Role of engineered barriers

One commonly distinguishes between three major phases in the performance of the EBS. There is a first phase comprising application and evolution of the buffer that includes water uptake and swelling under hydraulic and thermal gradients and high neutron and gamma radiation fields, leading to maturation, a second phase during which the matured buffer is exposed to a successively reduced thermal gradient and radiation fields, and a third phase during which the repository may be affected by tectonics or glacial events under low temperature conditions but significant hydraulic gradients. The phases may vary in time for different repository designs based on e.g., the thermal output of the waste and the availability of water to the buffer.

The first phase may involve complex physical/chemical processes during the maturation of the buffer, partly influencing its long-term performance. It is regarded as important and has, therefore, been the focus for international URL-related RTD work on buffers hitherto. The subsequent two phases, of which the second one is the most important, have been far less studied. Although significant mineral changes in the buffer will not take place according to most smectite conversion models, some cementation may take place that will affect the self-sealing potential of the clay and this issue has not been fully analyzed. Gas penetration is also expected but the involved mechanisms and consequences are not fully understood. These issues are therefore still being studied by most of the CROP Participants.

5.4.2 EBS components

The major EBS components are:

- Canisters containing the waste.
- Buffer and backfill.
- Plugs and other stabilizing and sealing structures.

In URLs the heat production of the waste associated with the radioactive decay is simulated by electrical heaters, and in some experiments, for example the LOT at AEspoe (Appendix 1) or the Febex project at Grimsel (Appendix 1), the migration of radionuclides emanating from leaking canisters is simulated by emplaced packages with small amounts of radioactive elements in solution.

5.4.3 Canisters

Different metal canister designs are under consideration at the moment. For example, in the KBS-3V and H disposal concepts, corrosion-resistant metal canisters (copper vessel supported by an iron insert) will be used to contain and isolate the dissolution-resistant waste forms. These and other types of canisters proposed by the Participants will be made of materials with well-known and favorable properties and predictable performance that will provide the primary containment of the wastes and ensure their effective isolation throughout the period it is required.

SKB has established a canister laboratory near the AEspoe URL. A number of canisters have already been constructed to establish suitable techniques for manufacturing and quality checking and control of the canisters. Several of these canisters are installed in the current Prototype Repository project at the AEspoe URL, using a specially designed placement machine that includes remote handling techniques for placing the canisters in the deposition holes.

The SKB canister placement machine demonstrated at the AEspoe URL [5-13] is in prototype form. Practical testing has also been made at AEspoe URL using a simple version of the machine with now simulated radiation shield around the canister (Figure 5-16).

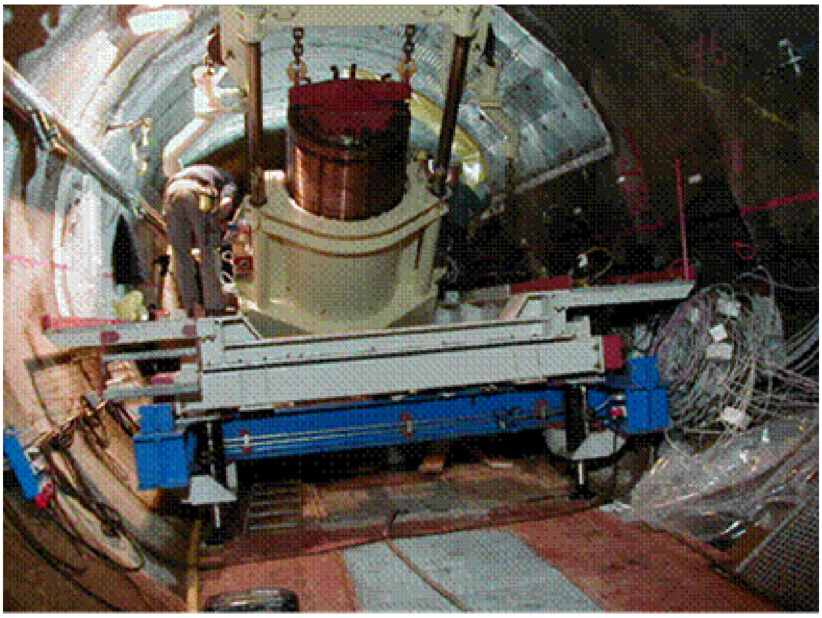


Figure 5-16. *Equipment for future remote placement of SF canister in KBS-3V boreholes [5-13].*

5.4.4 Buffers and backfills

Materials

Clay-based materials, such as smectite clay alone and mixed with other materials, are proposed as buffers and backfills in repositories in crystalline rock. Systematic and comprehensive studies have been conducted by several CROP Participants, e.g., Andra, Enresa, GRS, Nagra, OPG (AECL) and SKB, to determine the most important physical and physical/chemical properties of a number of commercially available smectitic clays. Clays of montmorillonite-type ("aluminum") with Na as dominant cation or converted to Na-form by soda treatment of natural Ca-rich material, and saponite ("magnesium") smectite and kaolinitic or micaceous mixed-layer clays (FoCa-7, Friedland Ton) [5-14] have been thoroughly investigated and their function in the early phase of the evolution of a repository is sufficiently well known for candidature. The long-term performance is less well understood and needs additional study.

Buffer

The excellent sealing properties of smectite-rich clay suggest that pure clay of this type should be used for the most demanding function of the EBS, i.e., the buffer immediately around the waste canisters, where the requirements are:

- Hydraulic conductivity should be so low that diffusive transport of dissolved matter dominates as the mass transport process. In practice, this means that the hydraulic conductivity of the buffer should not exceed about E-10 m/s.
- Diffusion rate of dissolved matter emanating from the canisters should be as low as possible, implying that the effective clay dry density of the surrounding material should be as high as possible.
- Buffer should have a sufficiently high expandability to maintain effective contact with the canisters and surrounding rock or backfill and have some self-sealing ability if disturbance by shrinkage, shearing or expansion takes place or if partial conversion of the smectite to non-expandable minerals takes place. It is valuable if the buffer can provide some positive pressure on the surrounding rock.
- Bearing capacity must be sufficiently high to prevent the canisters from sinking to the base of the deposition holes or drifts.
- Long-term retention capacity of the buffer must be retained for the required period of time, which ranges between a hundred thousand and one million years depending on the disposal concept.
- Density and water activity of the material adjacent to the waste canister must immobilize or eliminate microbial activity that would be detrimental to the longevity of the canister.
- Concrete and cement grouts can be used if the expected degrading effects on buffer and backfill can be accepted according to safety analyses.
- Clay grouts may well be used but injected in boreholes they require mechanical support by cement grout.

All these criteria are believed to be fulfilled using ordinary commercial smectite-rich clay in the form of Na bentonite if the density in water-saturated form is at least 1 900 kg/m^3 and the temperature lower than about 95^{o}C. Nevertheless, additional study is necessary to evaluate the requirements in greater detail.

For certain purposes, such as backfilling of shafts, the hydraulic conductivity does not have to be as low as for the buffer and mixtures of clay material. Glacial sedimentary soil or crushed rock can be considered. Comprehensive fieldwork on these issues has been made in the AEspoe URL.

Buffer of different types have been used in the URLs. At AECL´s URL the buffer consisted of *in-situ* compacted mixtures of smectitic clay and glacial sand. The application was made in hundred-millimeter thick layers yielding a dry density of about 1 700 kg/m^3 below and around a steel cylinder that was later removed to create an opening for the simulated canister (i.e., an electrical heater). Quartz sand was placed in the gap between the canister and the clay/sand buffer for improving heat transfer and for stabilizing the canister [5-12].

At Stripa, AEspoe, and Grimsel (Febex project) blocks were prepared by compaction of clay powder or granules and placed in the deposition holes and drift, respectively. The size, shape and weight of the blocks have varied from the first field test (Figures 5-17 and 5-18) in which isostatically compacted blocks of handable size were used, to handable sector-shaped blocks for the Febex project at Grimsel (Figures 5-19 and 5-20) and further to 2 Mg monolithic blocks for experiments at AEspoe (Figures 5-21 and 5-22). The latter figure illustrates that a practical technique for placement of such big blocks has been worked out.

Characteristic physical properties of buffer materials used in various field tests are illustrated by the data in Table 5-3.

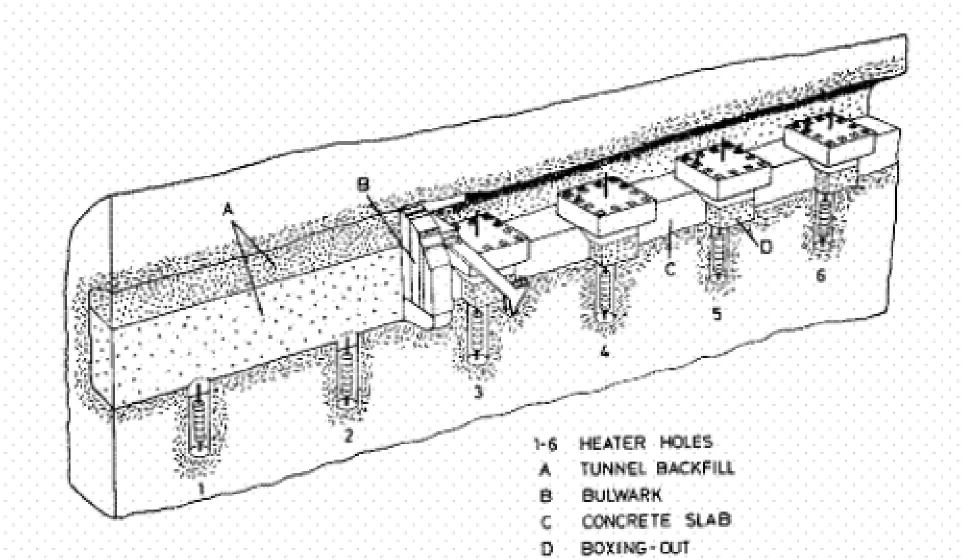


Figure 5-17. *Overview of the Stripa Buffer Mass Test (Appendix 1). Six 3m deep deposition holes were core-drilled to about 3 m depth with 0.76 m diameter. The simulated canisters were equipped with electrical heaters and surrounded by highly compacted Na bentonite blocks (MX-80) and covered by a bentonite/ballast mixture. The inner more wet part of the drift was backfilled according to Figure 5-24. The two test sections were separated by a plug made of a steel/concrete [5-9].*

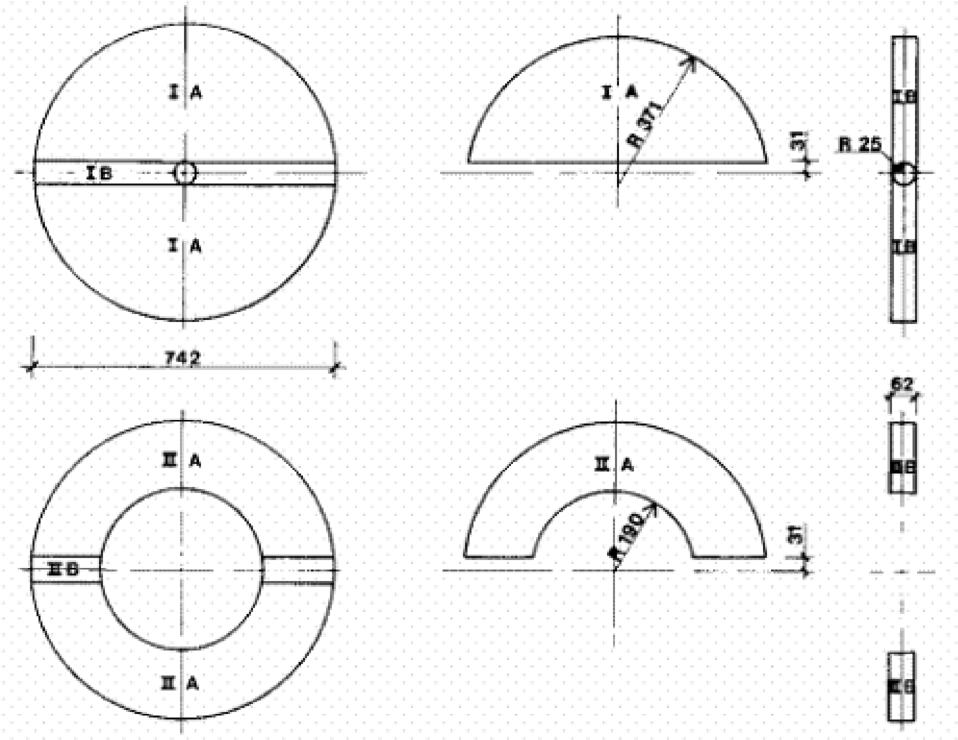


Figure 5-18. *Geometry of blocks for the Stripa BMT experiments. They were sawed from 2 m long columns of isostatically compacted Wyoming bentonite (MX-80) with 0.52 m diameter [5-9].*

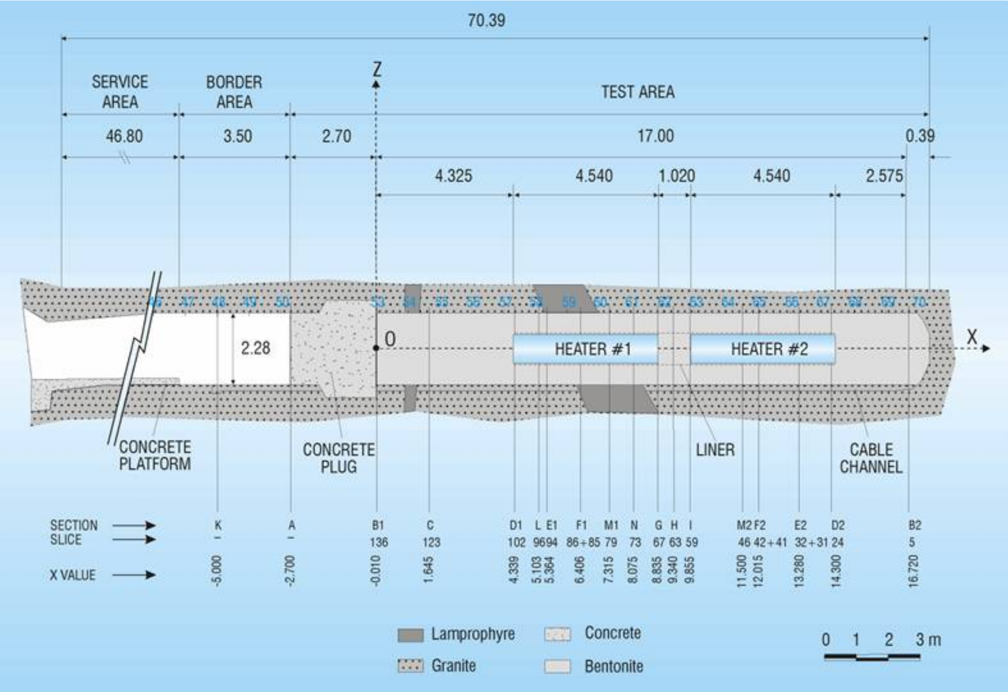


Figure 5-19. *Overview of the Febex field experiment at Grimsel. The diameter of the TBM drift is 2.3 m. Two test sections with steel canister in central perforated steel tube for placement in cylindrical space left after putting the compacted buffer blocks in place [5-15].*

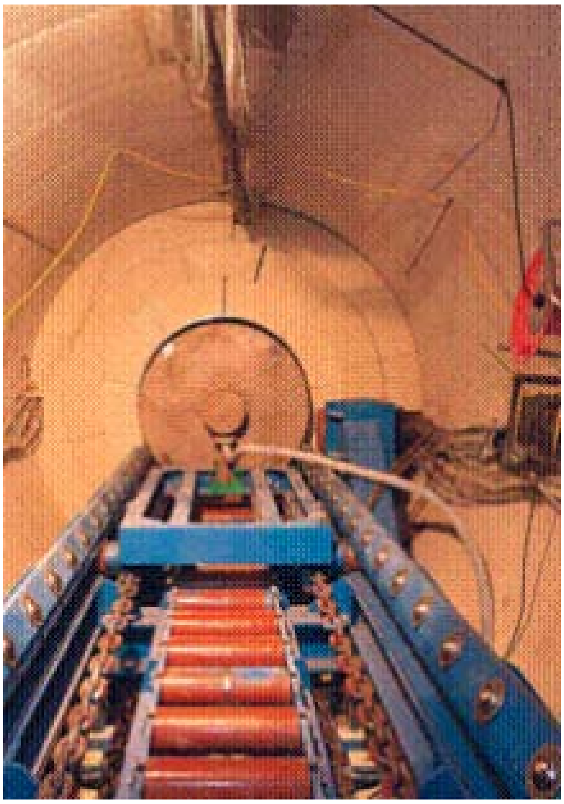


***Figure 5-20**. Appearance of buffer blocks placed in the Febex test drift at Grimsel [5-15].*

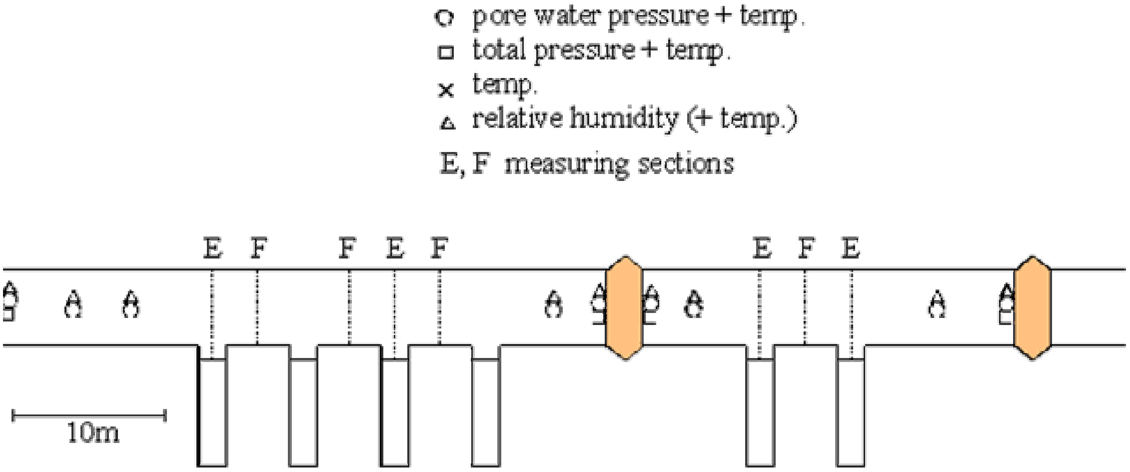


***Figure 5-21.** Schematic section of the Prototype Repository project (Appendix 1) at AEspoe URL. Six deposition holes were full-face bored to about 8 m depth with 1.8 m diameter. The drift was backfilled with a mixture of 30 % Greek Na-converted bentonite and 70 % crushed rock. The project is a full-scale version of a KBS-3V repository drift. The inner part is planned to be in operation for up to 20 years [5-16].*

***Figure 5-22**. Application of a 2 Mg precompacted buffer block of MX-80 bentonite in a KBS-3V type waste emplacement hole [5-16].*

Table 5-3. Typical hydraulic conductivity (K) and swelling pressure (ps) of various clays saturated with water with low (L) and high (H) electrolyte contents [5-17].

Material	**Dry density, kg/m^3**	**Density at fluid saturation, kg/m^3**	**K, m/s (L/H)**	**p_s, kPa (L/H)**
Na-bentonite	630	1400	E-11/E-9	100/0
Na-bentonite	1 270	1800	E-12/E-11	800/300
Na-bentonite	1 750	2100	E-14/E-14	10 000/10 000
Ca-bentonite	630	1400	>E-6	0
Ca-bentonite	1 270	1800	E-11/-10	500/50
Ca-bentonite	1 750	2100	E-13/E-13	10000/10000
10/90 Na-bentonite/ballast	1 750	2100	E-9/E-7	100/20
30/70 Na-bentonite/ballast	1 750	2100	E-10/E-9	500/200
50/50 Na-bentonite/ballast	1 750	2100	E-12/E-10	2000/1000
Friedland Ton	1 270	1800	E-10/E-9	100/50
Friedland Ton	1 590	2000	5E-12/5E-11	900/500
Friedland Ton	1 750	2100	<E-13/E-12	2000/1500

Backfills

For repository concepts that propose to place canisters in holes bored from a drift, e.g., KBS-3V, KBS-3H, OPG/AECL borehole emplacement configuration, the part of the drifts from which the vertical deposition holes extend, have to be backfilled with a suitable low-compressible soil material [5-17]. Backfilling of these areas and also transport drifts, ramps and shafts should be made so that the backfilled openings do not represent flow paths in the repository. The related criteria are hence 1) the average bulk hydraulic conductivity must not exceed the average hydraulic conductivity of the surrounding rock mass, 2) a minimum swelling pressure of about 100 kPa must be exerted for maintaining contact with the rock and for supporting it, and 3) the performance must be acceptable for the design life of the repository. Material selection and techniques for meeting these criteria have been identified but rather substantial problems, particularly when there is water flowing into the rooms during the backfilling operation, make it necessary to further investigate the placement of these backfills. Experience has been gained from the large-scale field experiments at Stripa and AEspoe URLs as summarized below.

The fieldwork was preceded by laboratory mixing and compaction tests as well as determination of the hydraulic conductivity and compressibility of the material. As indicated by Figure 5-23 the room backfill in the Stripa BMT case was differently composed in the upper and lower parts. The lower two-thirds consisted of a mixture of 10 % MX-80 clay and 90 % ballast of glacial origin that was mechanically compacted, while the upper part was a mixture of 20 % MX-80 clay and 80 % ballast applied by use of shotcreting technique (Figure 5-24). The parameters for the shotcreting backfill method had been investigated in preliminary full-scale pilot tests in which suitable water content was established. The tests also showed that it was necessary to add angular quartzite for cleaning the nozzle of the ejector during shotcreting placement of the upper part of the backfill.

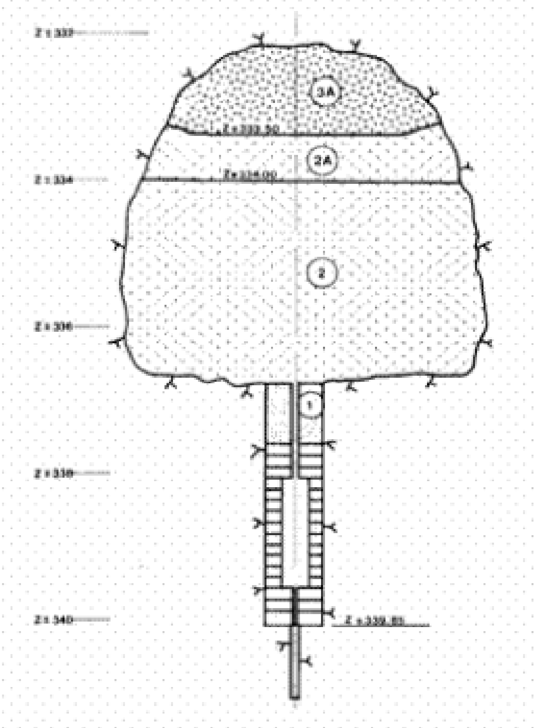


Figure 5-23. *Cross section of the BMT drift [5-11, 5-12]. Encircled figures mean: 1), 2) and 2A: Mixture of 10 % MX-80 clay and 90 % graded glacial silt/sand/gravel. 3A): Mixture of 20 % MX-80 clay and 80 % graded glacial silt/sand/gravel with quartz particles added for cleaning the nozzle.*

Backfilling of the Buffer Mass Test (BMT) started with applying 15 mm thick horizontal layers with 10 % clay up to about two thirds of the height of the drift – somewhat more in the inner part – and compacting them by 10-15 runs of a 400 kg electrically powered plate vibrator.

The upper part of the drift was filled by blowing in a mixture with 20 % bentonite clay using the equipment shown in Figure 5-24. The backfill was applied to form a mass with a very steep sloping face that successfully moved back to the confining bulkhead, at which precompacted blocks were placed for filling the last few cubic meters.

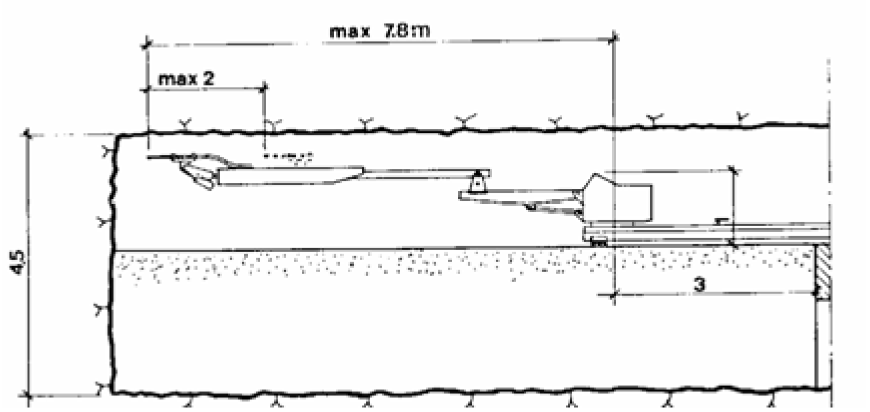


Figure 5-24. *Schematic picture of the robot aggregate for blowing-in the backfill with 20 % clay [5-9]. (Dimensions in m.).*

Figure 5-24 shows a section of the Stripa Buffer Mass Test (BMT) drift with the various backfill components. The perspective view of the drift is seen in Figure 5-17.

The following main conclusions were drawn from the preparation, application and assessment of the Stripa backfilling tests:

- Preparation of mixtures with suitable grain size distribution can be made on a large scale but the procedure is tedious if more than two constituents are involved, which is the case if the ballast is made up of two ballast fractions and clay and water are added to the ballast.

- Compaction of mixtures with 10 % clay is very effective using even light tools such as vibrator plates. The dry density can be as high as 2 000 kg/m^3 corresponding to more than 2 200 kg/m^3 at fluid saturation. However, spot-wise determination of the density showed that the variation in density was significant and lower closer to the rock than in the centre.

- Shotcreting of mixtures with 20 % clay can give a dry density of up to about 1 600 kg/m^3 but the variation in density was strong and led to the conclusion that this technique was not adequate for producing homogeneous, dense backfills consisting of 20 % clay mixtures.

- No problems with piping, erosion or slaking occurred under the prevailing hydraulic conditions, i.e., at an inflow of 3 liters per day per meter length of the test drift.

The backfilling experiments at the AEspoe URL comprised:

- Field Test of Drift Backfilling [5-18].
- Backfill and Plug Test [5-19].
- Prototype Repository [5-16].
- Field test using Friedland Ton [5-14].

The materials used in the first mentioned two tests were mixtures containing 10%, 20% and 30% MX-80 bentonite and crushed rock with a maximum grain size of 20 mm. The Prototype Repository project used Greek sodium-converted calcium bentonite instead of MX-80. Friedland Ton is a German mixed-layer clay with about 50 % expandables which was applied in dried and ground form [5-14].

The *Field Test of Drift Backfilling* was conducted in a TBM-drift with a measured water inflow of about 600 liters per day per meter drift length [5-18]. Horizontal layers were applied and compacted up to about 1.55 m above the floor. The rest of the drift was filled and compacted in layers with about 35 degrees inclination. The compaction of the horizontal layers with a final thickness of 300, 200 and 150 mm was not successful because the water seepage into the drift was rather high and when being sorbed by the backfill mixture the material became liquid under the 4.5 Mg vibrating roller. The application of the inclined layers in the subsequent test, in which water was drained off through tubes from the inflow spots, was made by moving material up by a telescopic truck with a pushing tool for bringing it all the way up to the roof. Compaction was made by use of a vibrating plate. This part of the project went well although the dry densities near the rock were reported to be low, i.e., less than 1 500 kg/m^3.

The *Backfill and Plug Test* was performed in a 28-m long drill-and-blast drift (ZEDEX drift) [5-19]. The water inflow rate to the drift was deemed to be too large for performing backfilling experiments and the wet innermost half of the drift was therefore filled with coarse material that was kept drained during and after the backfilling operation.

The remaining part was then backfilled using the inclined layer principle with backfill material consisting of 30% bentonite and 70% crushed rock. For this part the average dry density was found to vary between 1 650 kg/m^{3}and 1 700 kg/m^3.

Figure 5-25 shows the procedure for filling and compacting backfills including the use of a vibratory roof compactor for densifying material close to the roof. The intention was to obtain the same density in the *Backfill and Plug Test* drift as in a TBM drift, but this required more intense compaction and longer time than were practical in the test.

The *Prototype Repository* backfilling was made in the same fashion as the second phase of the Field Test of the Drift Backfilling, i.e., by application of backfill consisting of 30% bentonite and 70% crushed rock using the inclined layer principle [5-16]. The results were similar in these tests with respect to the distribution of densities but higher values for the backfill close to the rock walls were obtained.

The full-scale field test with natural, ground and dried Friedland Ton was made with the same equipment as in the Backfill and Plug Test. The best results were obtained with rather coarse and moist material. The conservatively predicted net dry density, about 1 600 kg/m^3, was slightly higher than actually achieved [5-14].

The following main conclusions were drawn from the AEspoe backfilling experiments:

- Water inflow into drifts on the order of 600 liters per day and meter length of drift makes backfilling by use of layer-wise application and compaction impossible unless drainage is arranged. This was achieved in demonstration tests by applying drained filters over the parts of the rock that gave off much water but this approach will hardly be possible in a real repository.
- Total dry density decreases and the density of the clay fraction increases with increasing bentonite content. The net effect is that increasing the clay content reduces the average hydraulic conductivity but this is counteracted by the lower density that can be achieved. Since the placed backfill densities achieved in the AEspoe URL field tests were low, more effective compaction technique is required.
- Using the currently proposed application/compaction methods there will be considerable variations in backfill density and the required dry density will not be reached in all parts of the backfill. More effective compaction tools, particularly for the peripheral parts of the backfill, should be developed.

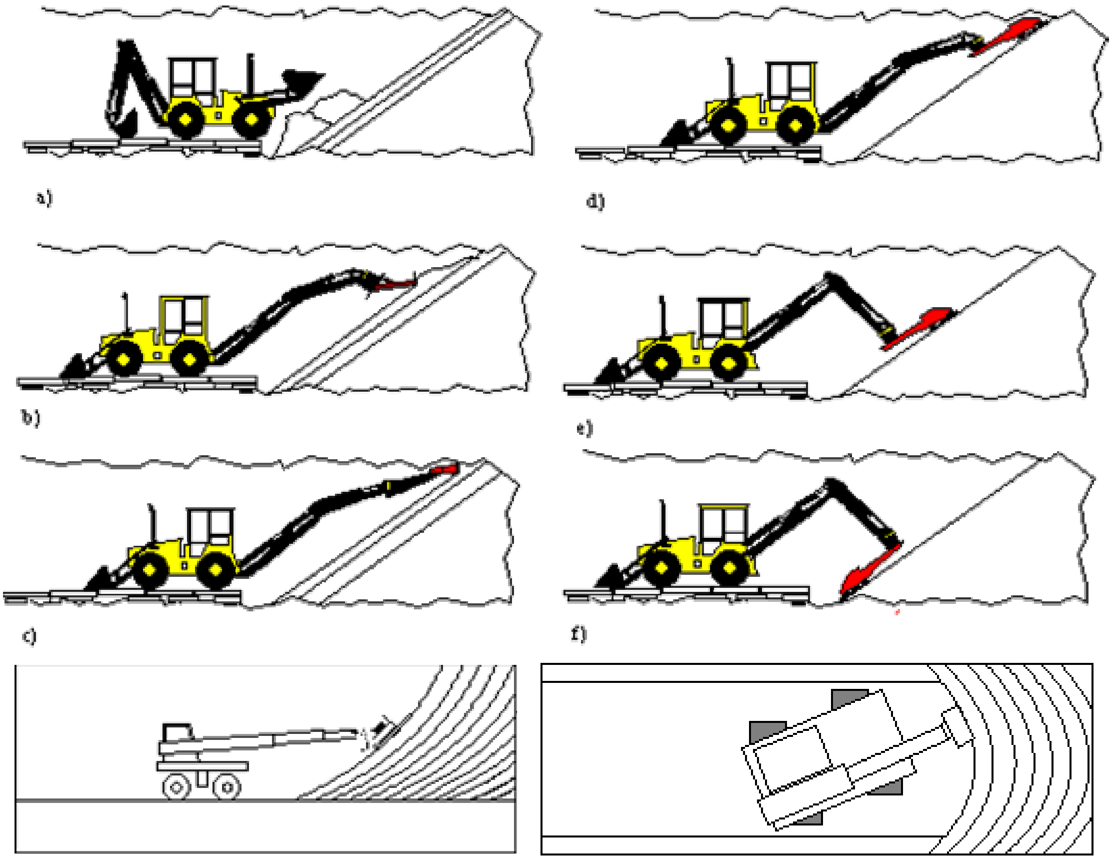


Figure 5-25. *Illustration of application (a, b, c) and compaction (d,e,f) of backfill according to the latest version of the "inclined layer principle" including use of a vibratory roof compactor for densifying material close to the roof. The use of the "near-roof" compactor is not shown. The two lower pictures show the concave form of the layers that could be achieved by the mobility of the carrier and easy turn of the holder of the vibratory plate [5-16].*

Buffer from granular bentonite (pellet filling experiments) – the Nagra concept

Nagra's present concept for HLW disposal in clay rock (Chapter 6) implies that the canisters are placed horizontally within deposition drifts having circular cross sections on a foundation ("sarcophagus") of highly compacted smectite-rich blocks so that it initially becomes located in the centre of the cylindrical vault. The upper part of the deposition drift is backfilled with blown-in or augured smectite pellets [5-20]. The method may be applicable also to crystalline rock although Nagra´s formal concept for crystalline rock is to use blocks of compacted clay such as Enresa's although of larger size. Additional testing of this new emplacement concept is needed and will be carried out within the integrated project "ESDRED" (EC-project, Contract No. F16W-CT-2003-508851).

Present ideas about future work on alternative backfilling techniques

Backfilling of KBS-3V drifts by use of highly compacted smectitic blocks has not been systematically tested on a large scale but this technique is believed to offer a way of rapid backfilling of drifts, ramps and shafts. Attempts have been made in a shaft at Stripa that was effectively sealed by use of highly compacted MX-80 blocks [5-2, 5-21], and in drifts at AEspoe [5-18].

In recent time a technique has been proposed for applying solid chemical waste in drifts that can be used also for backfilling (EC-project "LowRiskDT", Contract No. EVG1-2000-00020, [5-22]) and that may be applicable where water inflow is relatively strong. The clay material is Friedland Ton possibly representing a technico/economic optimum. Figure 5-26 shows the basic approach to drift backfilling when only little water is given off from the rock. Under this condition the block masonry can be left with a gap to the surrounding rock, water will be absorbed spot-wise, and some flow of disintegrated clay emanating from the wetting blocks will take place.

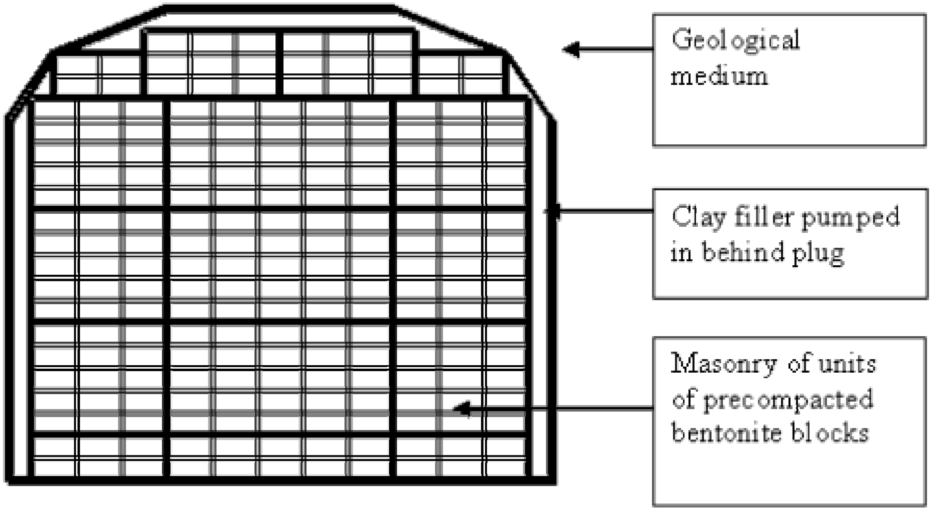


Figure 5-26*. Drift backfill by clay block masonry with clay slurry (grout) filling the gap between the blocks and the rock. Pellet clay fill may replace the slurry. [5-22].*

It yields variations in density and time for fluid saturation, which in turn can cause minor block movements and some heterogeneity. These disadvantages can be minimized by placing a suitable fill material in the gap (e.g., a suitable grout of highly compacted, well graded clay pellets). The grout could be placed in the gap behind a temporary (shotcrete) shield that can resist the grout pressure. This technique can also be applied section-wise where there is relatively high inflow of water. The grout should be so composed that it initially has a low viscosity and then undergoes quick strengthening, for instance by mixing in strongly compacted smectite pellets and "low-pH" cement, i.e., a cement yielding a leachate with a pH below 11. The grout can be made chemically compatible with the block material and given a dry density of 1 200-1 400 kg/m^3, by which the ultimate density of the saturated backfill will be up to 2 000 kg/m^3.

5.4.5 Plugs

Plugs are required for confining backfills in repository drifts and shafts in the waste application phase and in the final phase of closing the repository, respectively. Temporary plugs that only need to provide support and tightness for weeks and months can be of simple type, such as shotcrete coatings. However, in practice it may be required that many temporary plugs are strong and tight even for rather short periods of time [5-23].

A basic plug is a bulkhead that would seal the opening to a filled drift and must withstand the swelling and water pressures exerted by the contacting backfill. The pressures combine to give a force of more than 10 000 Mg in a KBS-3V repository, which makes it necessary to design the bulkhead so that concrete and reinforcement stresses are acceptable, and so that slip of the bulkhead along the bulkhead/rock contact is prevented.

Concrete bulkheads can be cast against the drift walls over a sufficiently long distance to transfer the force to the rock and be equipped with a grout curtain to seal off the EDZ. Alternatively, the bulkheads can be keyed in notches or recesses for transferring the force on it to the rock and for cutting off the EDZ. A bulkhead test of the first mentioned type was made as part of the Stripa project while plugs of the latter type have been constructed and tested in the AEspoe and AECL´s URLs [5-24, 5-25].

Location of plugs

Plugs for isolating backfills in KBS-3V drifts should be located in fracture-poor rock for causing minimum groundwater flow around the plug and this principle was followed in one of the SKB cases, i.e., the Backfill and Plug Test at AEspoe. In the other case, the Stripa test, the plug was placed where a diabase dike with poor contact with the granitic mass intersected the site for testing the sealing potential of the bentonite "O-ring" that was part of the plug construction.

Design principles

An important plug design question is the time during which the plug has to serve as an effective isolation. The basis of the design depends on a number of issues, the main ones being:

- Required operational time.
- Required tightness with special respect to the EDZ performance.
- Need for sealing off the plug/rock contact.
- Need for redirection of water in the surrounding rock.
- Risk of chemical degradation of cement in the plug and clay seals placed in the plug.

Operational time

Since concrete is not considered to be chemically stable because of dissolution of the cement and, in reinforced concrete, dissolution of some types of reinforcement, and the hydrogen gas production associated with this dissolution can cause piping of adjacent backfills, the operational lifetime of such plugs is estimated to be on the order of one to a few hundred years. Since they may have a degrading effect on other EBS components they may have to be removed and replaced by backfills or masonries of compacted clay blocks in conjunction with the closure of the repository. Plugs with no reinforcement or with non-dissolving reinforcement, such as glass or carbon fibers, might have a substantially longer functional life. In URLs such plugs naturally serve well.

Tightness

Proper location of plugs with respect to the groundwater flow is a major issue for making them effective in cutting off groundwater flow. Leakage through them can take place along discontinuities caused in the construction phase or along reinforcement bars and great care must be taken to minimize it where the water pressure is very high and the plug is backfilled only on one side. The required depth of the recesses to seal off the EDZ has to be determined by considering the rock structure and stress conditions. In certain cases the tightness does not have to be very effective as when only mechanical support is needed in rock with a low bulk hydraulic conductivity.

While the design of the concrete body, and reinforcement if used, is a relatively simple issue, the problem of anchoring the plug in the rock without causing stress conditions that favor flow along or close to the plug is more difficult. Thus, the very strong force acting on the plug must be transferred to the rock without causing significant fracturing or displacement. The rock structure and mechanical properties of the rock as well as the initial stress conditions must therefore be sufficiently well known for making the design.

Tightening of the plug/rock contact

Significant leakage along the plug/rock contact can strongly reduce the sealing function of a plug with an “O-ring”-type seal of smectite-rich clay placed in the form before casting the concrete. Grouting by injecting clay-based or suitably composed low pH-cement can be made after constructing the plugs. This technique can also be made for improving the overall sealing function of the surrounding rock, i.e., by redirecting the groundwater flow on a larger scale.

Chemical degradation

Concrete plugs have been used in Stripa, AEspoe and AECL's URLs with focus on stability and tightness under high axial pressure, without considering chemical degradation. For use in real repositories the matter of long-term chemical performance of concrete, especially with respect to the interaction with adjacent smectite buffers and backfills, needs to be investigated in greater detail.

5.4.6 Grouting

Various attempts have been made to seal rock fractures by use of cement and clay grouts. Injection under static or dynamic pressure conditions have been successful if used as pre-treatment of the rock, i.e., from the front of rock to be excavated, while post-grouting from the walls and roof of excavated drifts is of very limited value [5-26, 5-27].

5.5 Instrumentation and monitoring

5.5.1 General

In the project and in the present report it has not been useful to specify the various instruments used in the URLs since several of them are no longer manufactured and other types have been superseded by improved versions or totally new instruments in the evolutionary process of manufacturers to develop more accurate tools. Instead, the aim has been to collect and provide information on which processes are sufficiently important to the safe performance of a repository to require recording, and whether relevant parameter values can be measured with acceptable accuracy in URLs. These processes and suitable types of instruments are briefly described here. More detailed information on the instruments used and their performance is provided in the CROP CAs, see Section 9.1 in the references Chapter.

Data collection and processing have generally been very successful in the respective URLs. Safe backups and data transfer to data bases are standard procedures as well as automatic transmittal of data from certain gauges to national or international receivers on a regular basis for processing by the involved organizations, wherever their home base is situated. A very important practical issue is to install “watch dogs” for automatic signaling if processes in the EBS yield values beyond limits set and to control the current and voltage etc of the power.

5.5.2 Measuring principles and assessed types of gauges

Temperature evolution in buffers, backfills and near-field rock.

This information is required: to back analyze the *in-situ* thermal properties of components of operating experiments, to obtain data to project physical and chemical processes and for correcting the data from temperature-sensitive instruments, and to verify that the models used to analyze experiments, and that would be used in repository design, reasonably simulate the resulting temperatures and temperature gradients. For this purpose, the required instrument accuracy is limited. Moderately detailed information on the heat distribution in the near-field rock will provide a possibility to evaluate the effect of heat on rock stability and tightness as well as on chemical processes. However, higher accuracy (e.g., +/- 0.1°C) may be needed to correct for thermal expansion and thermal sensitivity in instruments, and to investigate the possibility of using the temperature evolution as indirect information on the hydration rate.

A general conclusion is that thermal elements of common types sustain the harsh conditions in maturing buffer and backfill, including high pressure and strain. However, their sensitivity to chemical attack by the pore water may cause quick breakdown and special metals or metal coatings, etc, should be considered for application in demanding chemical environments.

Stress and strain measurements in EBS and near-field rock.

Data from such measurements are valuable for upgrading and testing the validity of theoretical models for predicting hydration of buffers and backfills, changes in fracture apertures in the near-field rock and displacement of canisters. However, there are difficulties in obtaining accurate data, the major problem being water leakage along tubings and cables, which has caused some incorrect interpretations of the AEspoe Canister Retrieval Test and Prototype Repository project and which was the major cause of water leakage from AECL's Drift Sealing Experiment during the ambient-temperature pressurization phase.

Wire- and multipoint extensometers are valuable for measuring strain in rock and buffers because of the very good accuracy, i.e., +/- 1-10 µm for the most accurate types. Temperature-dependency information provided by the manufacturers of these instruments is required in order to correct for thermal expansion and thermal sensitivity.

A general conclusion is that stress and strain gauges are relatively big and the recordings may only represent an average pressure or deformation of a rather large part of the rock and soil. Also, bending, irregular pressure and lack of effective support of the gauges combine to induce uncertainty to the measured values. The major difficulty when conducting tests with these types of instruments in crystalline rock is, however, the potential for leakage of groundwater along cables and tubing, causing water to access the measuring point much earlier than would be the case if no instruments were present [5-28]. Stress/strain gauges are known to be sensitive to deformations in the embedding buffer and backfill, and may stay operative for a short time only. The risk of chemical degradation must be considered and suitably inert metals such as titanium should be used.

Hydration measurements

Psychrometers and other gauges for measuring the water content in a maturing clay buffer are being used in most clay buffer experiments to supply the information on the rate of wetting and drying required for calibrating and upgrading theoretical THMC models. Many of these instruments operate accurately only up to a certain degree of fluid saturation or above a certain fluid content, and the combination of two different types of gauges is recommended. However, obtaining information on how uniform the wetting and drying is in the clay buffer requires a large number of gauges, which may cause practical spatial problems in the locating of gauges, cables and tubing.

A general conclusion is that among the sensors used are the sensors for recording wetting processes the least reliable of all instruments and the first to fail according to the experience gained in several URLs. The risk for chemical degradation must be considered and suitable inert metals such as titanium should be used.

Gas percolation, mineral changes, ion migration and microbial activity

For measurement of gas percolation, filters attached to tubes that reach out from the buffer can be used. They have not been used extensively in the URLs but are known to work. For evaluation of ion migration and determination of microbial activity, cups can be installed for sampling at the termination of the test. Mineral changes can only be evaluated by physical and chemical examination after the experiments have terminated.

A general conclusion is that the risk of chemical degradation must be considered and suitable inert metals such as titanium should be used for instruments.

5.5.3 Special aspects

There are some major issues regarding instrumentation that affect both its application in URLs and future application for repository monitoring. Additional development and testing are required to ensure that instruments will either provide stable operation for many decades in harsh environments or be readily maintainable or replaceable in service.

Some general development and design issues are:

- Longevity of the portion of instrument systems that is not accessible during a particular application in a harsh geological environment, for example the sensors installed within an experiment, the connections from sensors, etc..
- Thermal sensitivity of sensors and connections to accessible locations must be either minimized/eliminated or methods of gathering data to make accurate corrections must be developed.
- Instrumentation systems must gather data that truly represent the processes being monitored and are not artifacts of the system, for example leakage along connects changing local conditions, sensor size inappropriate for gathering data, or chemical interaction between the sensor and the local environment. This is illustrated by the Prototype Repository project where in an example the evolution of the swelling pressure was clearly misinterpreted because of water flow along cables to gauges that reacted much earlier than un-instrumented buffer clay at the same distance from the periphery of the deposition holes (Figure 5-27), [5-28].

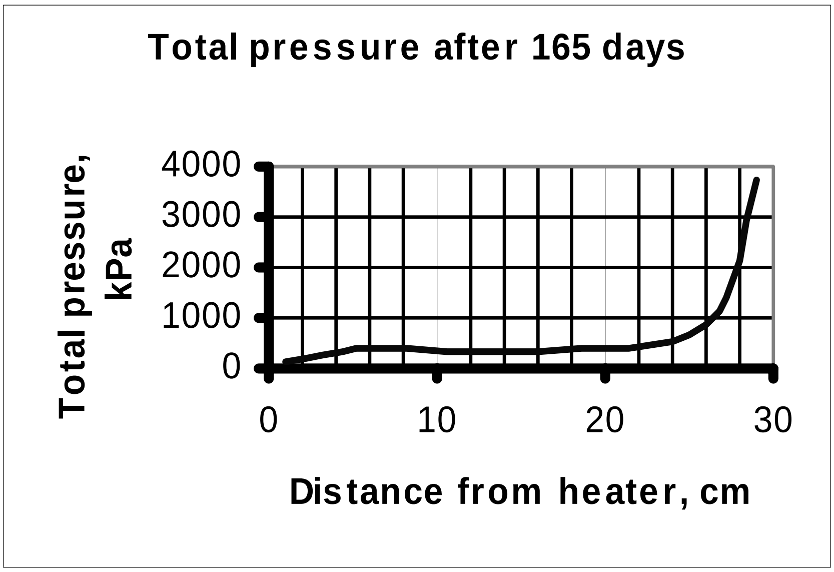


Figure 5-27. *Example of anomalous development of the total pressure in a typical buffer test at AEspoe URL caused by the instrumentation. The buffer was wetted at its outer boundary (300 mm from the heater) and the pressure would only be expected to increase close to this boundary in the first 165 days. The recorded pressure rise to several hundred kPa close to the heater is explained by water flow along the cables to the pressure cells.*

5.6 Modeling

5.6.1 General

Process modeling is an important matter in the national programs and has primarily focused on the following THMC issues under URL conditions:

- Temperature evolution in the near-field.
- Geohydrological evolution in the repository region.
- Maturation of buffer and backfill, including hydration, expansion, consolidation and creep under transient temperature conditions.
- Chemical evolution in the buffer and backfill.

Certain other processes have also been modeled, usually by applying simple finite element methods (FEMs) or analytical methods, such as flow around plugs, with or without considering temperature conditions. In this chapter basic principles and experience from the modelings are referred to for illustrating the type of results that have been obtained and for showing what the difference between theoretical predictions and actual performance can be. The various codes used by the CROP Participants are described in the CAs and will not be presented here while major differences are addressed in Chapter 4.8.4.

5.6.2 Selected issues

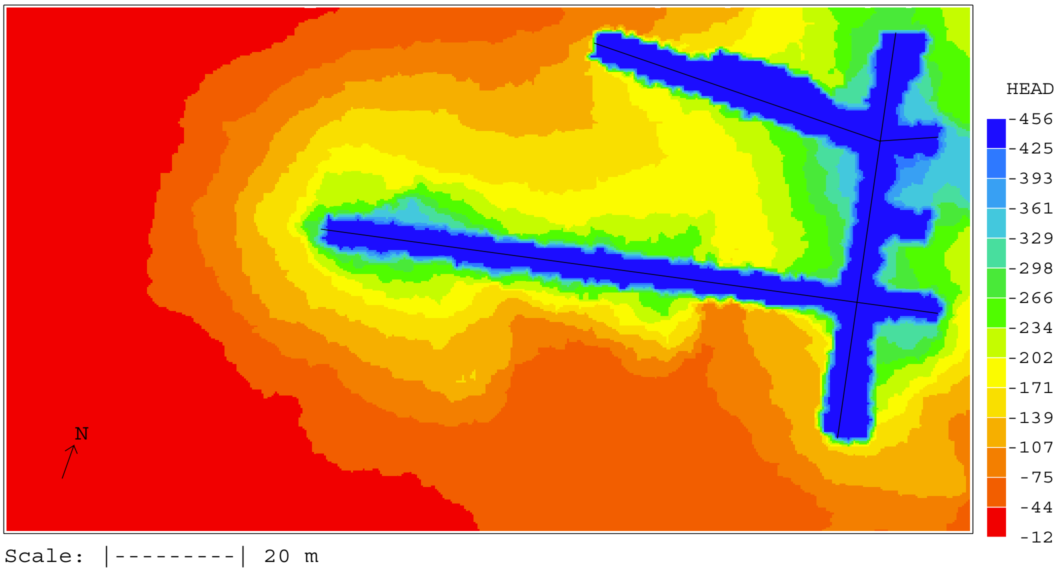
Summarized below is a listing and discussion of issues deemed particularly important to the safe performance of a repository by the CROP Participants.

Evolution of piezometric conditions in rock mass hosting URL or repository

For crystalline rock the changes in piezometric and flow conditions in the near-field are of great importance as input to calculation of the maturation of clay-based EBS in URLs and repositories and to assess transport of dissolved elements including radionuclides in the far-field. An example of such calculations, which agree to a reasonable degree with what has been recorded in field experiments, is shown in Figure 5-28.

Temperature prediction

This prediction is an important modeling exercise because almost all disposal concepts require that a certain maximum temperature should not be exceeded on one or more components of the repository system. Furthermore, heat is normally an important driving force for all physical and chemical processes in the near-field rock, buffer, and backfill. Thermal calculations are relatively straightforward and simple and if the basic thermal properties of the materials are well known, they provide adequately reliable results. It is, however, important that all inhomogeneities are realistically accounted for in the thermal analyses. The problem at present is to include inhomogeneities in the near-field system of the type shown in Figure 5-29 and simplifications commonly have to be made, for example omitting the open gap between the canister and the buffer blocks. If there is no temperature constraint on the canister, this is not an important matter for the long-term physical performance of the system. However, it will lead to an under-prediction of the peak canister temperature, which generally occurs before buffer saturation and maturation. The high temperatures may affect the performance of the buffer by cementation and permanent collapse of the smectite clay close to the canister.



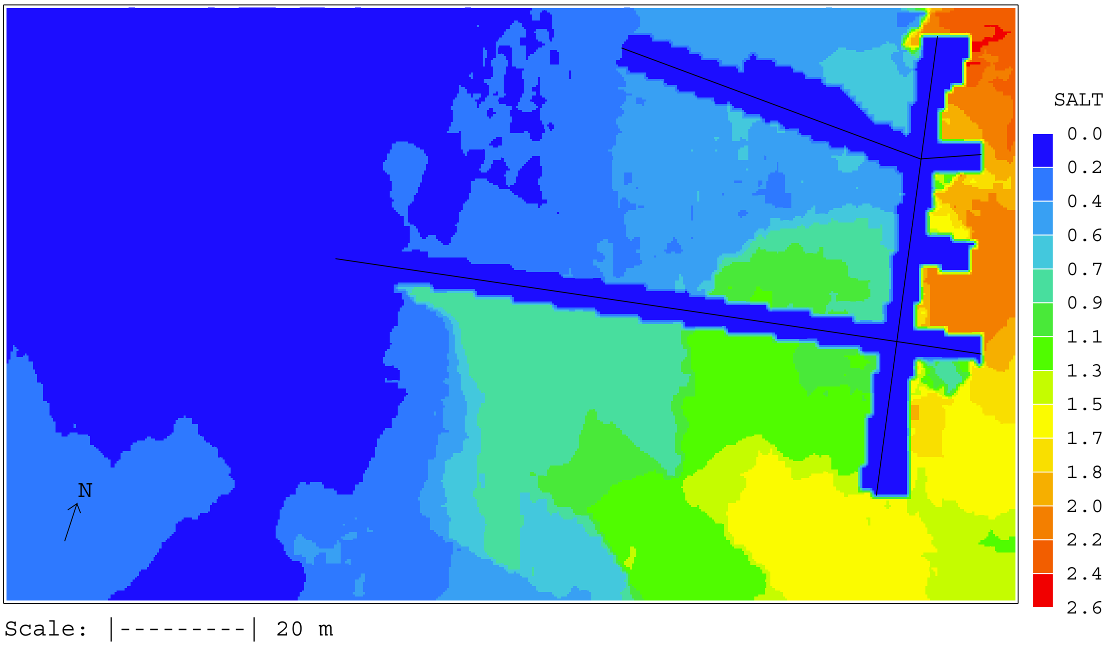


Figure 5-28. *Example of FEM-calculated distribution of the hydrogeological and geochemical conditions at 447 m depth in the AEspoe URL caused by the construction work [5-29]. Upper: Pressure head in meters. Lower: Salt content in %.*

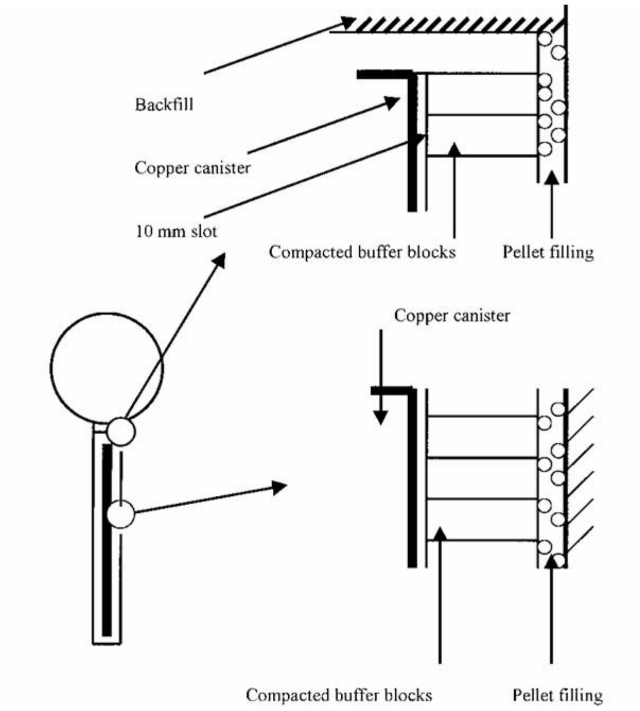


Figure 5-29. *Interacting EBS components of a KBS-3V deposition hole. The processes include 1) Redistribution of initial pore water generated by the thermal gradient across the buffer. 2) Homogenization and subsequent consolidation of the pellet fill under the swelling pressure exerted by the hydrating and expanding dense blocks. 3) Uptake of water from the rock and backfill leading to hydration of the buffer. 4) Expansion of the uppermost part of the buffer which displaces the overlying backfill, and 5) Consolidation and shearing of the buffer caused by the canister load.*

Hydration of buffers and backfills

The hydration of the clay-based EBS should be modeled for crystalline rock conditions to predict rate of desiccation and hydration and time to full maturation of buffers and backfills, the associated chemical effects and the effects of long-term drying. These calculations are totally dependent upon the thermal gradient and the potential capacity of the near-field rock to give off groundwater to the buffer. The potential capacity of the near-field rock to give off groundwater to the buffer cannot be predicted presently with any significant degree of certainty. Thus, the availability of groundwater for buffer maturation is not known until the deposition holes and drifts have been excavated. Furthermore, it varies locally in the repository, which makes “average” hydration analyses unreliable. Also, as illustrated in Figure 5-30, the piezometric pressures of water provided to the system play a role.

Theoretical THM modeling has given good representation of the progress of hydration of clay buffers when the buffer has good access to water and the saturation process mainly depends of the properties of the bentonite buffer. One example, from the Febex experiment, is shown in Figure 5-31.

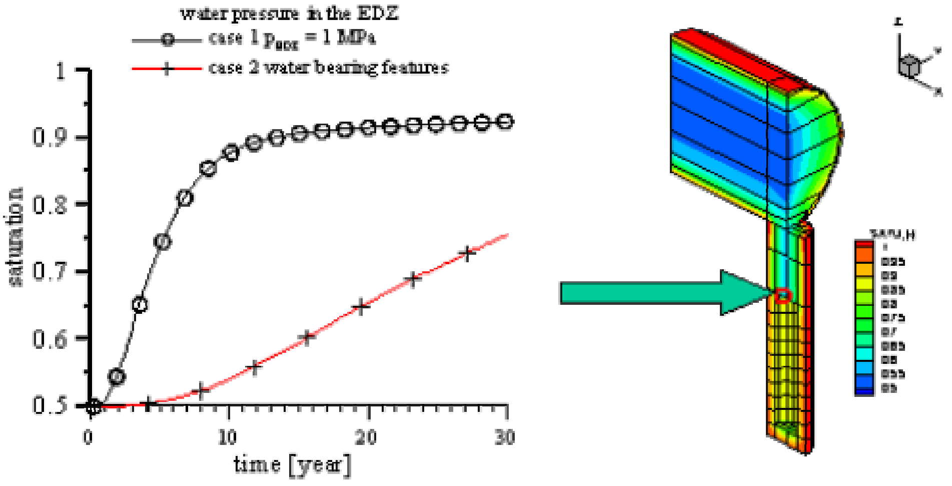


***Figure 5-30**. Calculated water saturation versus time for two cases in KBS-3V deposition mode, both with permeable EDZ. The black curve shows hydration under 1MPa water pressure and the red curve shows hydration under no water pressure [5-6].*

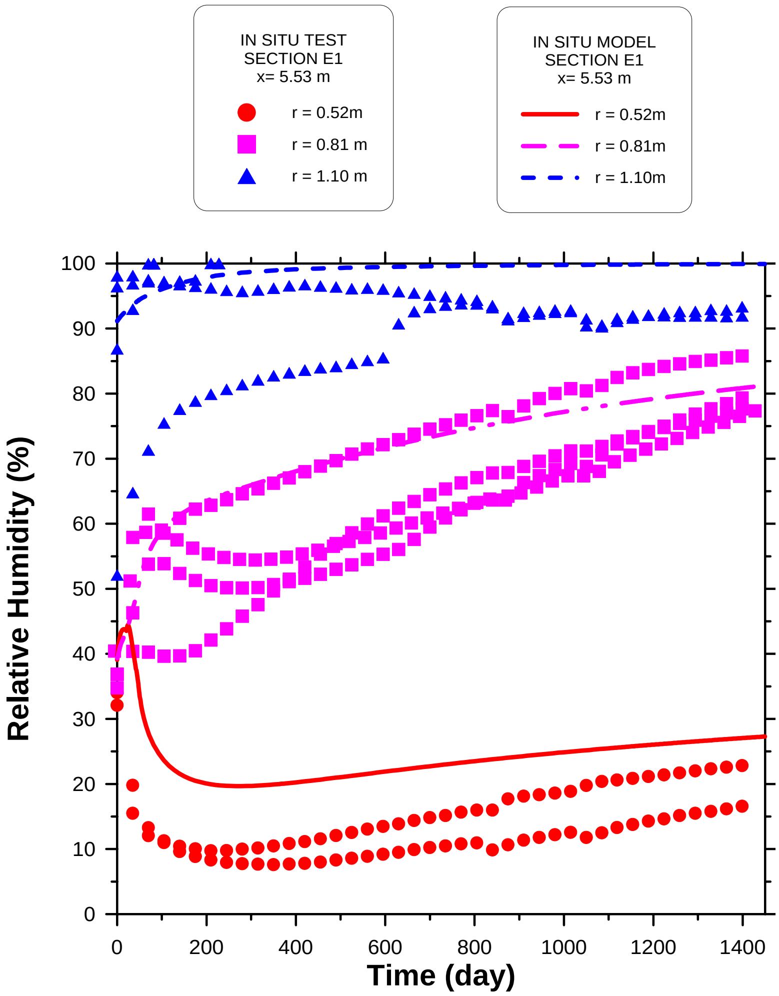


***Figure 5-31.** Evolution of the relative humidity for some selected points of the buffer. Observations and computed results (CODE_BRIGHT). "r" denotes the radius from the deposition drift centre, 0.52 m being the surface of the canister and 1.1 m 50 mm from the interface between buffer and rock.*

Stress/strain prediction

This prediction is of value for ensuring that the pressures acting in and on the rock and on the canisters and supporting structures are not higher than those accepted by the formulation of the respective concept. The results of this type of calculations normally depend on the initial stress state, material properties, constitutive equations, temperature evolution, and for clay-based materials the fluid saturation rate and the magnitude and duration of the thermal flux.

The theoretical THM modeling has indicated that accurate simulation of the mechanical response in bentonite buffers to water saturation is more difficult. The differences observed in *in-situ* tests also tend to exaggerate the difficulties because the evolution of the buffer is as well affected by the natural measurement errors and variability of the observations of total stresses observed in the buffer. This is demonstrated by a comparison between observations and computations carried out for the Febex *in-situ* test in the Grimsel URL and the half-scale mock-up test located at CIEMAT´s facility in Madrid. Figure 5-32 shows the predicted and measured radial stresses in the bentonite buffer, and Figure 5-33 shows the predicted and measured stresses in the buffer in the mock-up test. The mock-up test represents a more controlled system and the reproduction of the computed swelling pressure increase with hydration is quite satisfactory. The similarity in the measurements of different sensors indicates high measurement reliability.

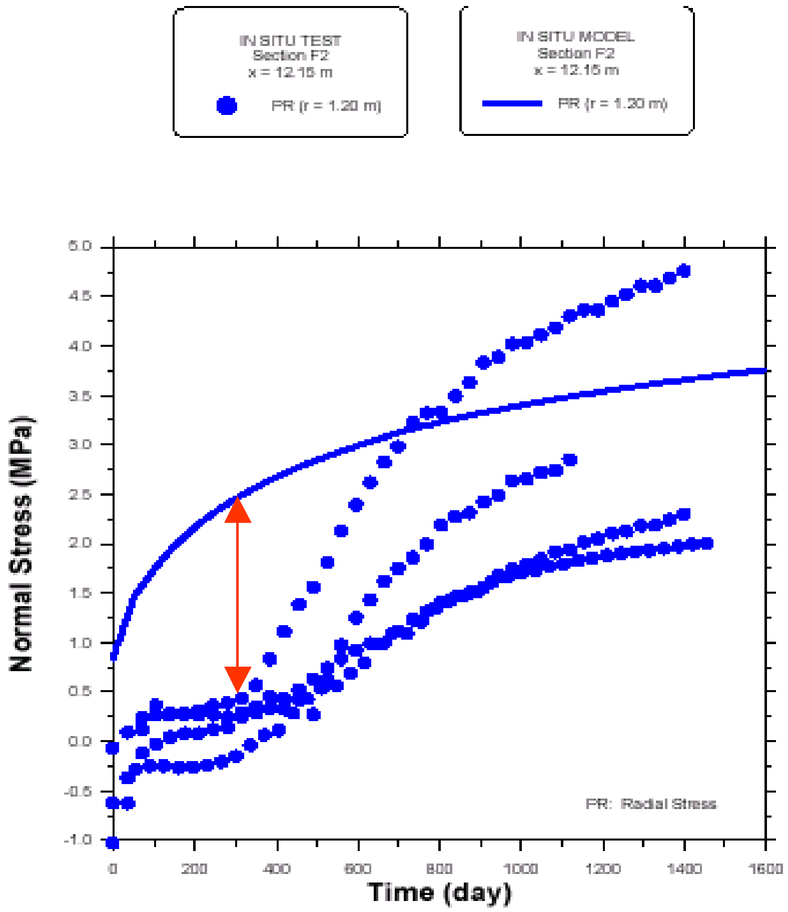


Figure 5-32. *Evolution of radial stress in the bentonite buffer at the interface between buffer and rock in Febex in-situ experiment. The full curve is the prediction and the dotted observations at four different places along the perimeter in one cross section.*

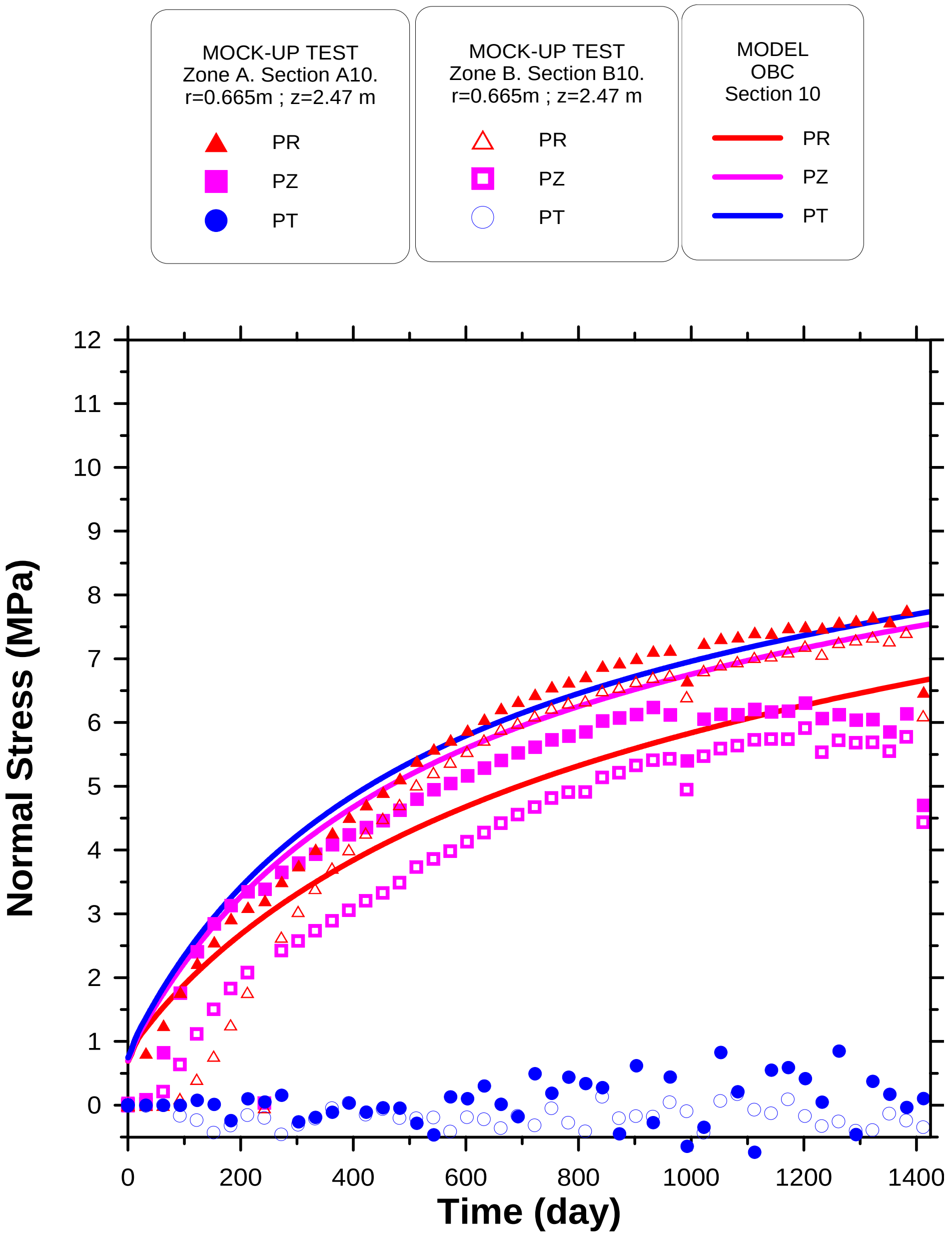


Figure 5-33. *Evolution of normal stress in bentonite buffer in Febex mock-up experiment. The full curves are the predictions and the dotted ones show the measured pressure in different parts of the buffer. PR denotes radial, PZ axial and PT tangential measurements. Sections A10 and B10 are located on each side of the two heaters between the heater ends and the confining vessel ends, i.e., at a distance of 2.47 m from the middle of the vessel. r=0.665 denotes the distance from the canister centre and indicates a location close to the outer periphery of the buffer. The PT sensor has failed in both Section A10 and Section B10.*

Chemical processes

In particular, those processes concerning mineral changes in the clay-based sealing materials need to be predicted for acceptance of the disposal concepts. Based on the results obtained from accelerated tests conducted in the CROP Participants' URLs, only insignificant mineral changes are expected in the sealing materials presently planned for use in repositories in crystalline rock for temperatures below about 95^{o}C. Although accelerated experiments have been done and can be done again for testing the validity of models describing mineral changes, a major current challenge is that the conceptual models and the understanding of the processes involved remain to be adequately verified on laboratory, bench and room scales. This should be a focus area for future RTD. For canister temperatures higher than 130-150^{o}C, there is evidence of substantial changes in the physical status and properties of the clay-based sealing materials as exemplified by Figure 5-34.

Microbial activity

It is generally accepted that microbial activity will be insignificant with the exception of spores, provided the bentonite-buffer density near the container and the buffer/container-contact pressure are sufficiently high. However, this relationship remains to be demonstrated for some of the canister placement arrangements and all ground water chemistries currently considered by the CROP Participants. Hence, additional RTD should focus on the development of accurate recording techniques and theoretical models for survival, multiplication and migration of important microbes.

Figure 5-34. *Appearance of FoCa-7 clay buffer after termination of an almost 4 year long buffer clay test in the Stripa URL. The sector-shaped clay sample was almost 75 mm in radial direction and was in contact with an iron heater with 170°C surface temperature at the right end and with rock at the other. The dark part near the heater had converted into claystone and mineral changes had significantly changed the physical properties of the entire buffer [5-30].*

5.6.3 Examples of commonly used theoretical models (THMC)

The major features of the models used in predicting and evaluating the THMC processes in buffers and backfills concern [5-31]:

- Hydration of the buffer and backfill.
- Build-up of swelling pressure in the buffer and backfill.
- Displacement of the canisters in the deposition holes.

Some models used by Participants for these analyses are discussed in this section. Some codes are not commercially available and access to them has to be negotiated with the respective Participants.

CODE COMPASS

Basics

Partly saturated soil is considered as a three-phase porous medium consisting of solid, liquid and gas. The liquid phase is considered to be pore water containing multiple chemical solutes and the gas phase as pore air. A set of coupled governing differential equations can be developed to describe the flow and deformation behavior of the soil.

The main features of the formulation are:

- Moisture flow considers the flow of liquid and vapor. Liquid flow is described by a generalized Darcy’s Law. Vapor transfer is represented by a modified Philip and de Vries approach.
- Heat transfer includes conduction, convection and latent heat of vaporization transfer in the solid and vapor phase.
- Flow of dry air due to the bulk flow of air arising from an air pressure gradient and dissolved air in the liquid phase are considered. The bulk flow of air is again represented by the use of a generalized Darcy’s Law. Henry’s Law is employed to calculate the quantity of dissolved air and its flow is coupled to the flow of pore liquid.
- Deformation effects are included via either a non-linear elastic, state surface approach or an elasto-plastic formulation. In both cases deformation is taken to be dependent on suction, stress and temperature changes.
- Chemical solute transport for multi-chemical species includes diffusion dispersion and accumulation from reactions due to the sorption process.

Basis for formulation of governing equations

Heat conduction and flow are expressed using classical physics but are generalized by including the velocities of liquid, vapor and air respectively. For unsaturated soil the heat capacities of solid particles, liquid, vapor and dry air are considered in addition to the degree of saturation with respect to liquid water.

The velocities of pore liquid and pore air are calculated using a generalized Darcy's law with special respect to the chemical solute concentration gradient and the conductivity of the air phase and the pore air pressure. Also, an osmotic flow term in the liquid velocity is included for representation of liquid flow behavior found in some highly compacted clays.

Air in partly saturated soil is considered to exist in two forms: bulk air and dissolved air. In this approach the proportion of dry air in the pore liquid is defined using Henry's law.

Where a chemical solute is considered non-reactive and sorption onto the soil surface is ignored, the governing equation for chemical transfer can be expressed in terms of diffusion and dispersion, as derived in primary variable form. The approach has been extended to a multi-chemical species form with a sink term introduced to account for mass accumulation from reactions due to the sorption process. This is then coupled to a geochemical model.

The total strain, ε, is assumed to consist of components due to suction, temperature, chemical and stress changes. This can be given in an incremental form, without loss of generality, as:

$$d\varepsilon = d\varepsilon_{\sigma} + d\varepsilon_{c_s} + d\varepsilon_{s} + d\varepsilon_{T} \qquad \text{5-1}$$

where the subscripts σ, c_s, T and s refer to effective stress, chemical, temperature and suction contributions.

A number of constitutive relationships have been implemented to describe the contributions shown in Equation (5-1). In particular for the net stress, temperature and suction contributions both elastic and elasto-plastic formulations have been employed. To describe the contribution of the chemical solute on the stress-strain behavior of the soil, as a first approximation, an elastic state surface concept was proposed which described the contribution of the chemical solute via an elastic relationship based on osmotic potential.

A numerical solution of the governing differential equations presented above is achieved by a combination of the FEM for the spatial discretisation and a finite difference time stepping scheme for temporal discretisation. The Galerkin weighted residual method is employed to formulate the finite element discretisation. For the flow and stress/strain equations shape functions are used to define approximation polynomials.

Software

The software package, COMPASS, has been developed to implement the numerical approach detailed above. The package has a modular structure to aid the implementation of suitable code and documentation management systems. It has two main components, namely, a pre and post processor and an analysis ‘engine’. Evaluation of integrals is achieved via Gaussian integration. For the elasto-plastic based stress equilibrium equations a stress return algorithm is required.

CODE_BRIGHT

Basics

A porous medium composed by solid grains, water and gas is considered. Thermal, hydraulic and mechanical aspects are taken into account, including coupling between them in all possible directions. As illustrated in Figure 5-35, the problem is formulated in a multiphase and multispecies approach. The three phases are:

- Solid phase *(s)*: minerals.
- Liquid phase *(l)*: water + air dissolved.
- Gas phase *(g)*: mixture of dry air and water vapor.

The three species are:

- Solid *(-)*: mineral particles.
- Water *(w)*: as liquid or evaporated in the gas phase.
- Air *(a)*: dry air, as gas or dissolved in the liquid phase.

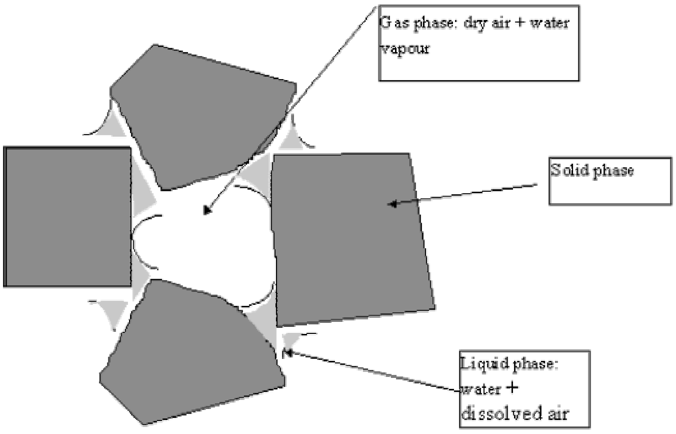


Figure 5-35. *Schematic representation of an unsaturated porous material.*

The following assumptions are considered in the formulation of the problem:

- Dry air is considered a single species and it is the main component of the gaseous phase. Henry's law is used to express equilibrium of dissolved air.
- Thermal equilibrium between phases is assumed. This means that the three phases are at the same temperature.
- Vapor concentration is in equilibrium with the liquid phase, the psychrometric law expresses its concentration.
- State variables (also called unknowns) are: solid displacements, *u* (three spatial directions), liquid pressure, P_l, gas pressure, P_g, and temperature, *T*.

- Balance of momentum for the medium as a whole is reduced to the equation of stress equilibrium together with a mechanical constitutive model to relate stresses with strains. Strains are defined in terms of displacements.
- Small strains and small strain rates are assumed for solid deformation. Advective terms due to solid displacement are neglected after the formulation is transformed in terms of material derivatives (in fact, material derivatives are approximated as eulerian time derivatives). In this way, volumetric strain is properly considered.
- Balance of momentum for dissolved species and for fluid phases are reduced to constitutive equations (Fick's law and Darcy's law).
- Physical parameters in constitutive laws are function of pressure and temperature. For example: concentration of vapor under planar surface (in psychrometric law), surface tension (in retention curve), dynamic viscosity (in Darcy's law), are strongly dependent on temperature.

The governing equations that CODE_BRIGHT solves are: 1) Mass balance of solid, 2) Mass balance of water, 3) Mass balance of air, 4) Momentum balance for the medium, and 5) Internal energy balance for the medium.

Associated with this formulation there is a set of necessary constitutive and equilibrium laws. The constitutive equations establish the link between the independent variables (or unknowns) and the dependent variables. There are several categories of dependent variables depending on the complexity with which they are related to the unknowns.

Basis for formulation of governing equations

The resulting system of partial differential equations is solved numerically dividing the operation into spatial and temporal discretizations. The FEM is used for the spatial discretization while finite differences are used for the temporal one.

The mechanical stress-strain relationship of the buffer clay is defined by means of an elasto-plastic model specially designed for unsaturated soil and is known as the "Barcelona Basic Model". The early difference in physical state between the zone with pellets and the blocks of bentonite is considered by using different parameters but the same model. Rock is considered elastic in all the analyses.

A new version of CODE_BRIGHT has been recently developed which is able to analyze THMC problems in a coupled manner. The types of processes that can be considered include complex formation, oxidation/reduction reactions, acid/base reactions, precipitation/dissolution of minerals, cation exchange, sorption and radioactive decay. This is in fact a tool that most probably will be used in the future, once all the geochemical information from the experiment is collected.

CODE ROCKFLOW/ROCKMECH

Basics

Completely coupled thermo/hydraulic/mechanical models considering the non-linear effects caused by, for example, permeation under unsaturated conditions and the elasto-plastic behavior of the buffer clay, are basic to the BGR model. For the buffer, one also needs to consider the influence of desiccation fractures, swelling and microstructural changes. Major processes in the saturation and subsequent percolation of the buffer are:

- Reduction of the permeable pore space by the expansion of the smectite clay particles and thereby the hydraulic conductivity.
- Changes in effective stress and strain in the saturation phase, which affect the mechanical behavior of the clay. Here, changes in temperature, water content and stress conditions in both the buffer clay and confining rock play a major role.
- Formation and transport of vapor.
- Osmosis.

The following principles and concepts are basic to the model:

- Effective stress and consolidation concepts (Biot, Terzaghi).
- Mohr-Coulomb failure concept including the influence of internal friction, cohesion, and dilatancy.
- Drucker/Prager's (1952) model of the first invariant of the total stress tensors and the second invariant of stress deviators.
- Roscoe/Schoefield/Burland's (1958-1971) Cam-Clay-Model.

Basis for formulation of governing equations

Four unknown field functions are to be determined: gas pressure, p_g, water pressure, p_W, solid displacements, u,, and equilibrium temperature, T. In addition to physical changes (stress/strain, drying and wetting) and chemical alteration, some of the properties used for modeling, such as alteration of the heat conductivity of buffer under saturation, and microstructural changes, have to be taken into consideration.

One can identify impacts in the form of hydromechanical, thermomechanical and hydrothermal effects. For non-isothermal processes in partially saturated porous media it is more convenient to separate dry air and vapor and formulate a mass balance equation for both liquid species, i.e., liquid and liquid vapor.

Concepts for formulations are compositional or phase-related. The first approach consists of balancing the species rather than the phases. The compositional approach is adopted to establish the mass balance equations.

Hydromechanical effects

Water saturation and swelling of the buffer lead to changes on the microstructural level, such as changes in porosity, hydraulic conductivity and deformation modulus.

Thermomechanical effects

Temperature-dependent desiccation changes the stress/strain behavior of the buffer clay and causes a need for developing thermo-plastic stress/strain material models and extension of the models describing visco-elastic and visco-plastic strain.

Hydrothermal effects

The most important hydrothermal effects are related to:

- Redistribution of the initial pore water content in the buffer including vapor formation and condensation.
- Changes in viscosity and hydraulic conductivity of water in different temperature regions.
- Influence on pore water pressure and saturation rate by the groundwater pressure in the rock.
- Alteration of the heat conductivity of buffer under saturation.
- Chemical alteration of the pore water and mineral phases (disregarded so far in the model).

Modeling of the EDZ surrounding a borehole with respect to water uptake and hydraulic pressure distribution in the bentonite buffer

A model has been developed for predicting the hydration of the initially unsaturated buffer with respect to the interaction with the surrounding rock. The inflowing water from the rock is distributed over the EDZ, which can be supplied with water from discrete water-bearing fractures that intersect the deposition holes. A basic principle of the model is that the hydraulic behavior of the EBS is controlled by the saturation of the buffer and vice versa.

The transient groundwater flow in the system is described by:

$$S_0 \frac{\partial h}{\partial t} + \nabla v = q \qquad 5\text{-}2$$

where h is the piezometric head, t is the time, S_0 is the specific storativity, v is the average fluid velocity vector, and q is the fluid sink/source.

The velocity is given by the three-dimensional, linear Darcy law:

$$v = -K \cdot \nabla h \qquad 5\text{-}3$$

where K is the hydraulic conductivity tensor, or by the general form of various non-linear laws for fracture or tubular flow.

FEM is used for the numerical simulation of transport and time derivatives are evaluated by using different schemes with various order of accuracy. The stability of numerical solutions depends on the reference point in time of difference formulae. In general, a distinction is made between explicit and implicit schemes. A number of approximate schemes with respect to stability and consistency are examined. The Neumann stability criterion states that the intrinsic values of the amplification matrix of the discretised equation must be lower or equal to unity. Important stability criteria are stated in terms of the Courant number, *Cr*.

CODE THAMES

Basics

The mathematical formulation for the model utilizes Biot's theory with the Duhamel-Neuman's form of Hooke's law, and an energy balance equation. The governing equations are derived with fully coupled thermal, hydraulic and mechanical processes, and under the following assumptions:

- The medium is poro-elastic.
- Darcy's law is valid for the flow of water through a saturated-unsaturated medium.
- Heat flow occurs in solid and liquid phases (impact of vapor is not considered).
- Heat transfer among three phases (solid, liquid and gas) is disregarded.
- Fourier's law holds for heat flux.
- Water density varies depending upon temperature and the pressure of water.

Rheology

The Terzaghi effective stress principle and Bishop and Blight's extended definitions an equation for saturated and unsaturated media is used:

$$\sigma_{ij} = \sigma'_{ij} + \chi \delta_{ij} \rho_f g \psi \qquad 5\text{-}4$$

where σ'_{ij} is the effective stress, δ_{ij} is the Kronecker's delta, ρ_f is the unit weight of water, g is the acceleration of gravity and ψ is the pressure head. Subscript f means "fluid". Parameter χ is defined as: $\chi = 1$ (Saturated zone), $\chi = \chi(S_r)$ (Unsaturated zone). The effect of temperature on the stress/strain behavior of an isotropic linear elastic material follows the constitutive law:

$$\sigma'_{ij} = C_{ijkl} \varepsilon_{kl} - \beta \delta_{ij} \left(T - T_o\right) \qquad 5\text{-}5$$

where $\beta = (3\lambda + 2\mu)\alpha_T$, C_{ijkl} is the elastic matrix, ε_{kl} is the strain tensor, T is the temperature, λ and μ are Lamé's constants, and α_T is the thermal expansivity coefficient. Subscript o means that the parameter is in a reference state.

Moisture transport

The equation of pore water motion is expressed by Darcy's law. The physical/chemical state of the gaseous phase in soil is not modeled and in the present case pores in the buffer clay are assumed to be filled with only a liquid phase. This means that the ground water does not change in phase from liquid to gas or vice versa and that the thermal conductivity of the gaseous phase is disregarded. Since the heat conductivity of the gaseous phase is smaller than that of the liquid and solid phases, the heat conductivity of the composite material is not affected much by the volume of the gaseous phase.

Basis for formulation of governing equations

The behavior of the buffer material is influenced by the interdependence of thermal, hydraulic and mechanical phenomena. To treat the water/vapor movement and heat-induced water movement, the continuity equation used in the extended THAMES code contains terms representing the isothermal water diffusivity, the volumetric water content, the water potential head and the intrinsic permeability (*K)*. This equation means that the water flow in the unsaturated zone is expressed by a diffusion term and in the saturated zone by the Darcy's law.

The stress/strain relationship at equilibrium takes the swelling behavior into account and considers the elastic matrix, the density of the medium and the body force. The effective stress in the unsaturated zone and in the saturated zone is a function of the thermal expansion. The swelling pressure is assumed to be a function of the water potential head.

CODE ABAQUS

Basics

The FEM code ABAQUS has been extended to include special material models for rock and soil and ability to model moisture transport associated with stress and strain on various scales. The hydro-mechanical model consists of porous medium and wetting fluid and is based on equilibrium, constitutive equations, energy balance and mass conservation using the effective stress theory.

The simplified equation used in ABAQUS for the effective stress is:

$$\bar{\boldsymbol{\sigma}}^{*} = \boldsymbol{\sigma} + \chi\, u_{\mathrm{w}} \mathbf{I}. \qquad 5\text{-}6$$

where $\boldsymbol{\sigma}$ is the total stress, u_w is the pore water pressure, χ is a function of the degree of saturation (usual assumption $\chi = S_r$), and **I** the unitary matrix.

Moisture transport

Vapor flow is modeled as a diffusion process driven by a temperature gradient. Flow of liquid water is expressed in terms of Darcy's law corrected with respect the degree of water saturation.

Coupling of thermal and hydro-mechanical solutions

In ABAQUS, the coupled problem is solved through a "staggered solution technique" as shown in Figure 5-36.

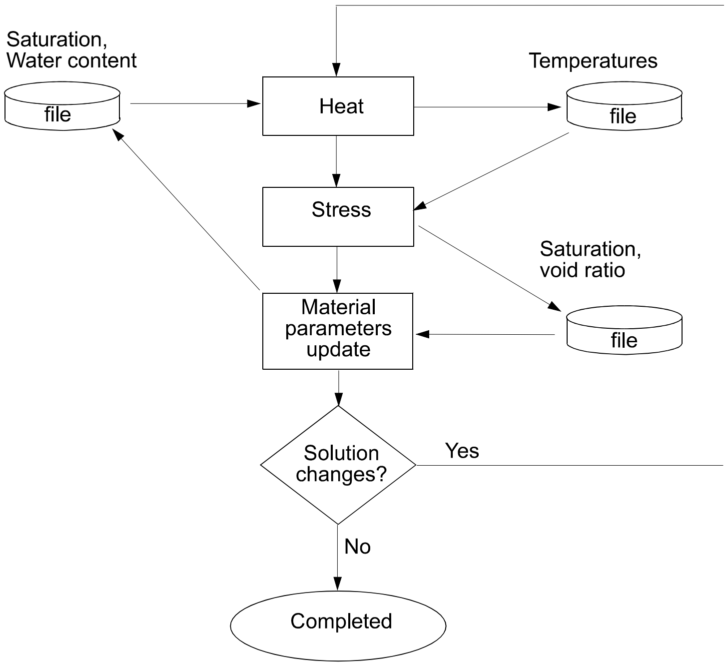


Figure 5-36. *In ABAQUS, heat transfer calculations and hydro-mechanical calculations are decoupled but data are sequentially updated between calculation steps. By using the iteration procedure schematically shown above, the effects of a fully coupled THM model are achieved.*

Basis for formulation of governing equations

Heat transport

Thermal flux by conduction is modeled as thermal conduction using the conventional theory with thermal conductivity and specific heat as variables.

Moisture transport

The water flux in the liquid phase is modeled by Darcy's law with the water pressure difference as driving force in the same way as for water saturated clay. The magnitude of the hydraulic conductivity, K_p, of partly saturated clay is a function of the void ratio, the degree of saturation and the temperature. K_p is assumed to be a function of the hydraulic conductivity, K, of saturated clay and the degree of saturation, S_r.

Water vapor flow is modeled as a diffusion process driven by the temperature gradient and the water vapor pressure gradient (under isothermal conditions).

Hydraulic coupling between the pore water and the pore gas

The pore pressure, u_w, of the unsaturated buffer material is always negative and expressed as a function of the degree of saturation, S_r, independent of the void ratio. ABAQUS also allows for hysteresis effects, which means that two curves may be given (drying and wetting curves).

Mechanical behavior of the particle skeleton

The mechanical behavior has been modeled with a non-linear Porous Elastic Model and Drucker-Prager Plasticity model. The effective stress theory as defined by Bishop is applied and adapted to unsaturated conditions. The shortcoming of the effective stress theory is compensated for by a correction called “moisture swelling” that is a function of the degree of saturation.

Thermal expansion

The volume change caused by the thermal expansion of water and particles is modeled but only expansion of the separate phases is taken into account. The possible change in volume of the particle structure by thermal expansion (not caused by expansion of the separate phases) is not modeled. However, a thermal expansion in water volume will change the degree of saturation, which in turn will change the volume of the structure.

5.6.4 Basis for selecting parameters in detailed modeling – supporting laboratory and bench-scale investigations of EBS components

Systematic RTD focusing on EBS properties and EBS performance has been conducted by the CROP Participants for many decades. Some of this RTD was conducted in the form of multi-national collaborations and joint ventures, and the results have been frequently published in national report series and discussed in and at a large number of different international fora. This type of collaboration and information exchange forms the basis for the development of generally accepted conceptual and theoretical models for predicting the behavior of the EBS.

The difference between the various existing models applied to similar engineered barrier materials or to similar host rocks are generally limited to the range of processes included and the degree of coupling amongst processes. They usually yield similar results when applied to practical cases, namely the EBS testing conducted in the URLs, if similar processes and degrees of coupling are included in the models. In this report the COMPASS code developed by University of Cardiff is taken as an example of the models used by the Participants.

Based on the experience gained by the CROP Participants to date, the significant tests on laboratory-, bench- and room-scales concern the material properties and processes are summarized in Table 5-4, for soil-type buffer and host rock.

Table 5-4. Important ”small-scale” experiments

Item	Clay buffers & backfills	URL host rock
Hydraulic conductivity	X	X
Swelling, consolidation	X	
Thermal conductivity, capacity	X	X
Gas conductivity	X	X
Cation and anion diffusion	X	X
Shear strength	X	X
Rheology (creep)	X	
Rate of hydration	X	
Mineral stability	X	X
In-situ strength and stress/strain moduli	X	X
Presence, viability and mobility of microbes	X	X

5.6.5 Agreement between predictions and actual performance of the near-field

Limitations of modeling approach

The modeling approach is based on a mechanistic formulation. Hence there is a need for validation at all stages to ensure that the physical and chemical processes are correctly represented. For example, for the vapor flow processes in densely compacted clays, there is currently a limited availability of data. Also, the stress-strain models employed in the THM modeling work are based on conventional partly saturated soil constitutive models, for example elasto-plastic suction based approach. Applicability of such models to highly swelling, densely compacted clay merits further investigation.

Except for laboratory experiments, there are rather few examples of comparison of predictions and actual performance of the near-field rock and the EBS. The evolution of temperature and hydration rate of buffers and backfills, as well as the hydration-dependent growth of swelling pressure in buffer clay, are examples of cases for which the agreement can be evaluated. Typical cases are referred to here.

Rock characterization and construction of underground openings

Comprehensive rock characterization has been done in the CROP Participants’ URLs. For crystalline rock, the focus has primarily been on structural modeling of the far-field and near- field with an attempt to correlate rock structures and groundwater flow. Although this modeling has been successful in cases involving large discontinuities, one of the most important tasks, the prediction of piezometric conditions in moderately fractured, near-field rock and of inflow of water in deposition drifts and hole on the basis of structural models, has not been equally successful. Hence, more work is required to refine these models.

Various types of numerical models, ranging from linear-elastic to visco-elastic and elasto-plastic have been used to design stable openings in crystalline rock. Recent findings indicate that the Particle Flow Code (Itasca Consulting Group Inc., Minneapolis, USA 55401) appears to be particularly promising in modeling the extent of instabilities.

Comparison of predictions and actual data of a basic case – the AEspoe Prototype Repository project

The work presented comprises 3D or axisymmetric hydraulic analyses of the temperature evolution, hydration and build-up of swelling pressure in the buffer assuming unlimited access to water from the rock, which corresponds to the conditions in the wettest deposition hole of the Prototype Repository project at SKB´s URL at AEspoe [5-32].

The geometry of the model for 3-D FEM calculations is shown in Figure 5-37 and details of the installation are shown in Figure 5-29. Special definitions regarding number of deposition holes considered and boundary conditions are specified by each modeling group.

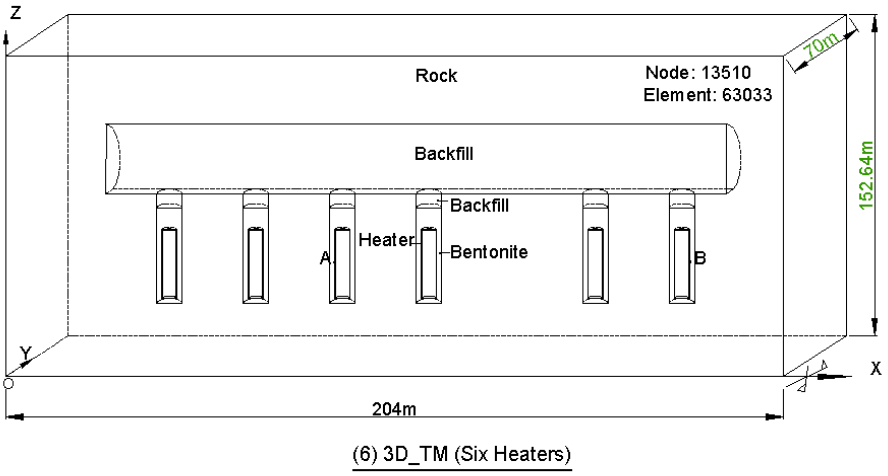


***Figure 5-37**. Schematic view of generalized 3-D model.*

The calculations have been based on the following data:

- Material data provided by SKB.
- The initial temperature throughout the domain was set at 12-14°C.
- The heat generation of the electric power was taken as 1 000-1 800 W.

CODE COMPASS

A full 3-D model of the Prototype Repository incorporating all of the primary features of the drift has been developed. The model domain measures 200 m by 100 m by 200 m and is shown in Figure 5-38a. This model has been discretised using 8-noded hexahedral elements and consists of 158,175 elements and 146,380 nodes and is shown in Figure 5-38b. The mesh has been refined in and around the buffer with a coarser mesh discretization used in the far-field rock. The size of the model has been reduced by 50% via the introduction of a vertical symmetry plane along the centre of the drift and hence the computational requirements of the model are considerably reduced. This geometrical model has been used for the majority of the numerical modeling work with smaller three-dimensional and two-dimensional models being implemented to investigate the mechanical response of the buffer and pellets under thermal and hydraulic gradients.

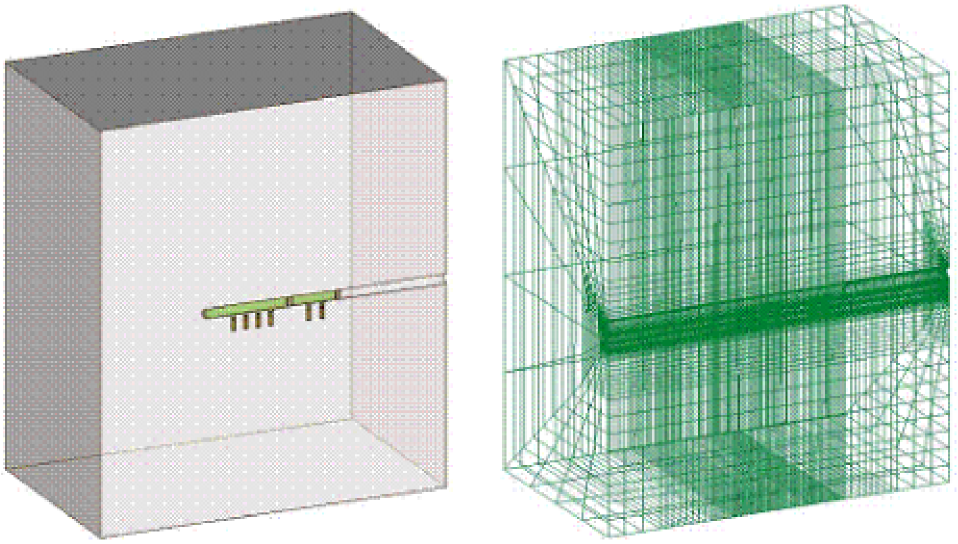


Figure 5-38 a) *3-D drift domain.* ***5-38b)*** *3-D drift mesh.*

A large number of coupled thermal-hydraulic-mechanical analyses have been performed to investigate the complex flow patterns that occur in the Prototype Repository following heater activation. In order to establish an understanding of these processes, a comprehensive step-wise approach to the modeling has been adopted. A full range of 3-D drift section and 2-D axisymmetric analyses have been undertaken with the results being presented previously. However, more recently a full three-dimensional, analysis has been performed. Recent research has shown that the micro- and macro-structure of a bentonite buffer material may have a pronounced effect on the saturation rates of the material. It was proposed that as water enters the buffer the majority of it becomes adsorbed within the micro-pores and hence becomes unavailable for further flow. Depending on the degree of mechanical restraint, swelling of the micro-pore will lead to some reduction in the size of the macro-pores. As the only water available for flow is contained in the macro-pores, the swelling of the micro-pore in a restrained material would tend to ‘choke’ moisture flow and further reduce the effective hydraulic conductivity of the material. The hydraulic conductivity relationship used here has been accordingly modified.

Temperature at mid-height canister

The power adopted in the coupled thermal-hydraulic-mechanical analyses has been taken from the recorded power of Canister. This approximates to a constant power of 1 800 W in the first year, and a gradual reduction of 20 W per year thereafter. Figure 5-39 shows both the simulated and experimentally measured temperature plots after 900 days for the 3 different radii positions in innermost borehole – Hole 1 at the mid-height of the canister. It can be seen that there is excellent agreement between the sets of results. At a radius of 0.585 m, the temperature has been simulated to be 71.5 ºC after 717 days. The corresponding measured value was 71.4 ºC. and at a radius of 0.685 m the simulated and recorded temperatures after 717 days were 64.8 ºC and 65^{o}C, respectively.. These results illustrate that the temperature regime is well understood and captured by the model in Hole 1.

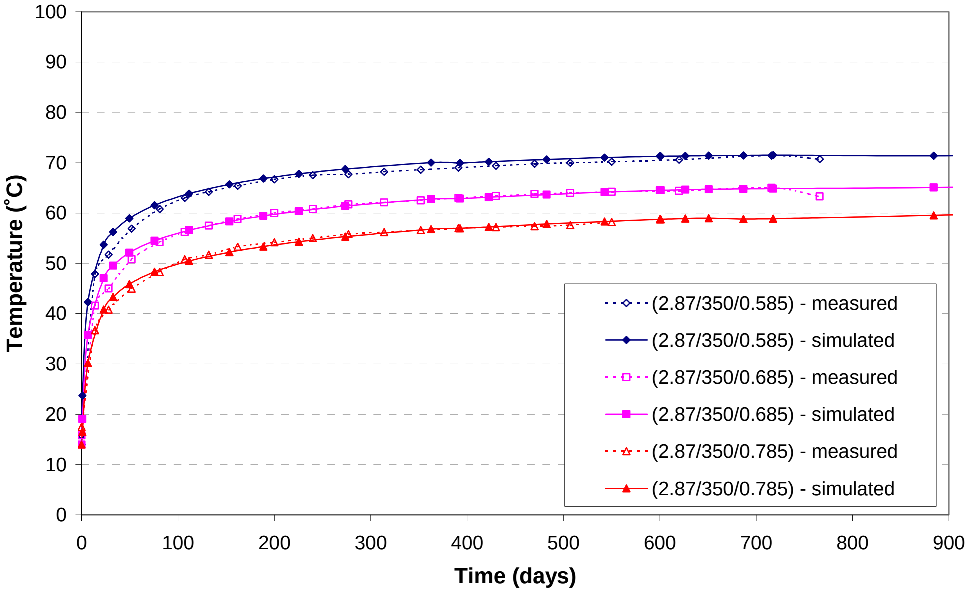


Figure 5-39*. Measured and simulated temperature plots for innermost borehole, Hole1/Ring 5. In the legend 2.87 is the distance from the hole bottom (i.e., mid-height canister), 350^{o} is the angle from the axis along the drift (i.e., almost parallel to the drift), and 0.585, 0.685 and 0.785 are the distances from the hole center. The radius of the canister is 0.525 m and of the deposition hole 0.875 m.*

Hydration of buffer at mid-height canister

In order to capture the rate of re-saturation of the buffer in Hole 1 it is essential to accurately model the supply of water from the rock including water bearing fractures. Based on the simulated inflow rates into Hole 1 as detailed in previous work the hydraulic conductivity of the granite was assumed to be E-11 m/s with one representative fracture intersecting the borehole. Figure 5-40 shows the simulated and experimentally measured degree of saturation plots for 3 different radial positions in Hole 1 at the mid-height of the canister. It can be seen that initially there is an overestimation of the drying in the buffer. At a radius of 0.785 m, a minimum value of 78.6 % is reached after approximately 20 days. Experimentally, the buffer closest to the rock exhibits immediate recharge following heater activation with the pellet-filled region appearing to have very little effect in terms of retarding the rate of re-saturation in the more centrally located buffer. After 100 days, the correlation between the experimental and simulated results is much improved, with almost complete saturation being achieved after approximately 400 days in both cases.

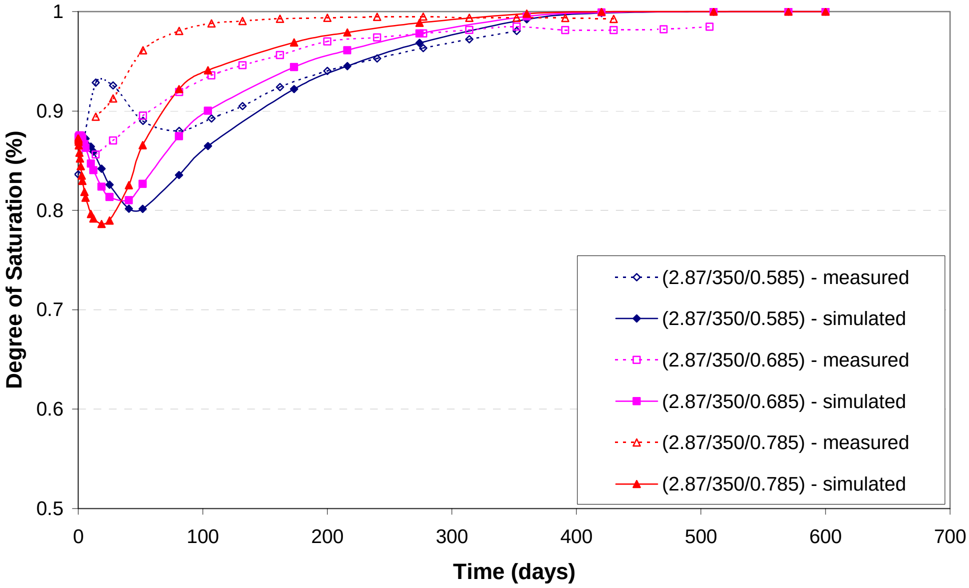


Figure 5-40. *Measured and simulated degree of saturation plots for Hole 1 at mid-height canister. The legend is explained in Figure 5-39.*

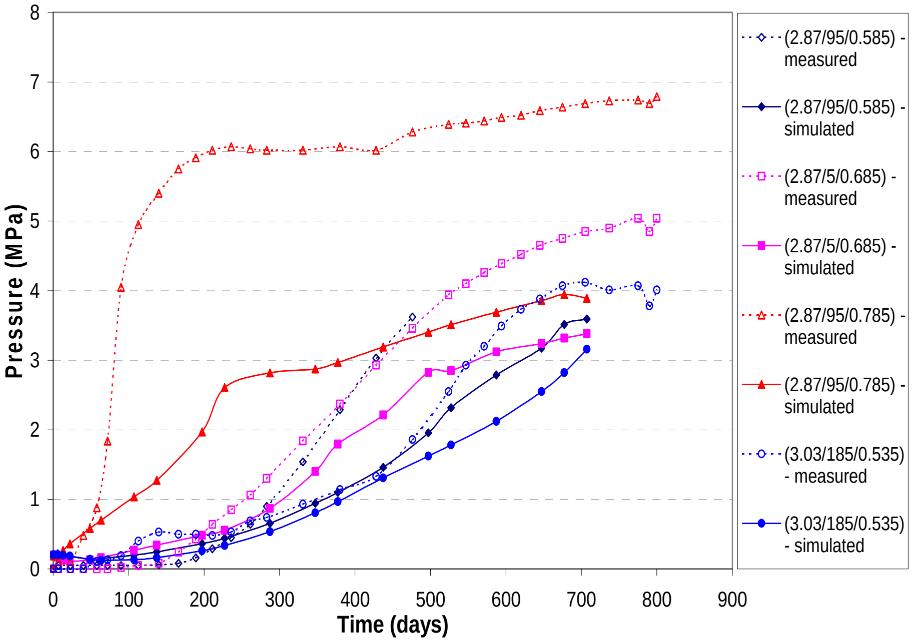


Figure 5-41. *Measured and simulated total pressure plots for Hole 1 at mid-height canister. The legend is explained in Figure 5-39.*

Total pressure in buffer

Figure 5-41 shows both the simulated and experimentally measured total pressure plots in the buffer at 4 different positions in Hole 1. There is good qualitative correlation between the results and quantitatively the simulation has captured the development of swelling pressures in the buffer well except close to the rock/ buffer interface, where the buffer experiences the highest swelling pressure caused by recharge of water from the granite. Closest to the canister surface, the simulated swelling pressure approached 3.2 MPa while the actual measured pressure was 4.1 MPa after 700 days. At the location closest to the rock / buffer interface, the simulated pressure of 3.9 MPa can be compared with the experimentally measured value of 6.7 MPa. It is believed that this difference is due to an overestimation of the compressibility of the pellet fill region between the buffer and the rock leading to a relief of some of the swelling pressure developed on saturation.

While Hole 1 can be taken as “wet”, all other deposition holes in the Prototype Repository project drift have very little inflow of water and probably represent the majority of deposition holes in a repository constructed in crystalline rock. The theoretically derived and actual evolution of temperature, hydration and total pressure are therefore described here in condensed form.

Figure 5-42 shows temperature plots after 624 days for 3 different radial positions in Hole 3. At r=0.585 m, the temperature has been simulated to be 76.1 ºC after 624 days, and at r=0.785 m as 68.6 ºC. The measured results are 77.1 ºC and 67.2 ºC respectively. Again, these results illustrate that the temperature regime is well understood and captured by the simulation.

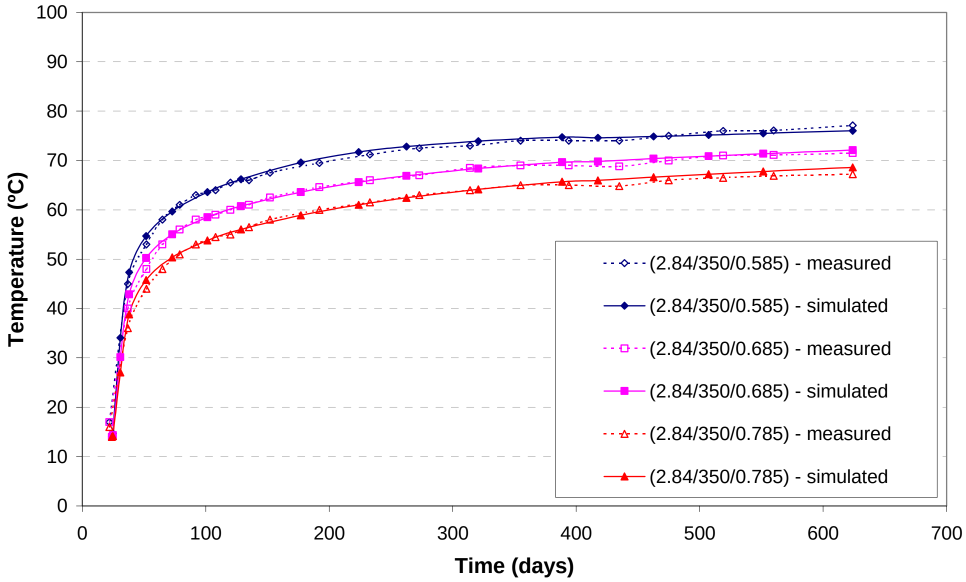


Figure 5-42*. Measured and simulated temperature plots for Hole 3 at mid-height canister. The legend is explained in Figure 5-39.*

Figure 5-43 shows a comparison between simulated and measured degree of saturation for three different positions in the buffer in Hole 3 at mid-height canister. Initially, there is a decrease in saturation throughout the buffer for both the simulated and measured results as the temperature rises. Drying takes place in the buffer as a consequence of the movement of vapor away from the hotter regions closest to the heater. At r=0.585 m, the predicted degree of saturation reaches a minimum of 71.8 % after 225 days and hence follows the measured trends with minimum degree of saturation of 70.4 % after 230 days. In both cases re-saturation begins to take place slowly at a similar rate. This behavior can also be seen at r=0.685 m for both the simulated and measured results, but with less overall drying taking place due to the larger distance to the heater. At r=0.785 m, there is an initial over-prediction of drying that may be a result of an over-estimation of suction in the nearby pellet region. However, as this region begins to re-saturate, the simulation matches the measured behavior. Overall, the correlation between the experimental and numerical results is encouraging.

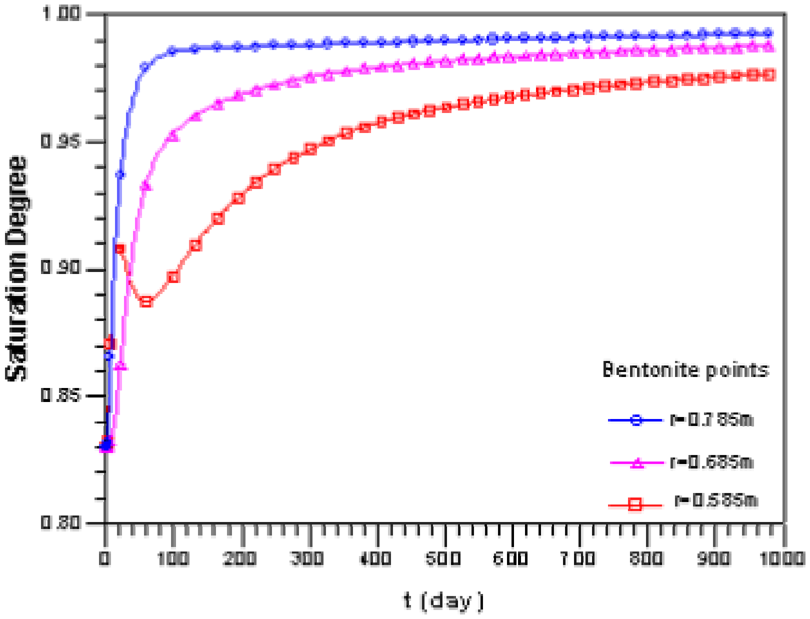


***Figure 5-43**. Simulated degree of saturation plots for Hole 3 at mid-height canister. r is the distance from the hole center. The radius of the canister is 0.525 m and of the deposition hole 0.875 m.*

Total pressure

Figure 5-44 shows the simulated and measured total pressure plots in the buffer at 3 different positions in Hole 3. It can be seen that very little swelling pressure develops in the first 600 days and that there is no major change from the initial conditions. These patterns follow the slow rate of re-saturation in the buffer as illustrated in Figure 5-44. It is expected that as the buffer in Hole 3 further re-saturates the swelling pressures will increase accordingly.

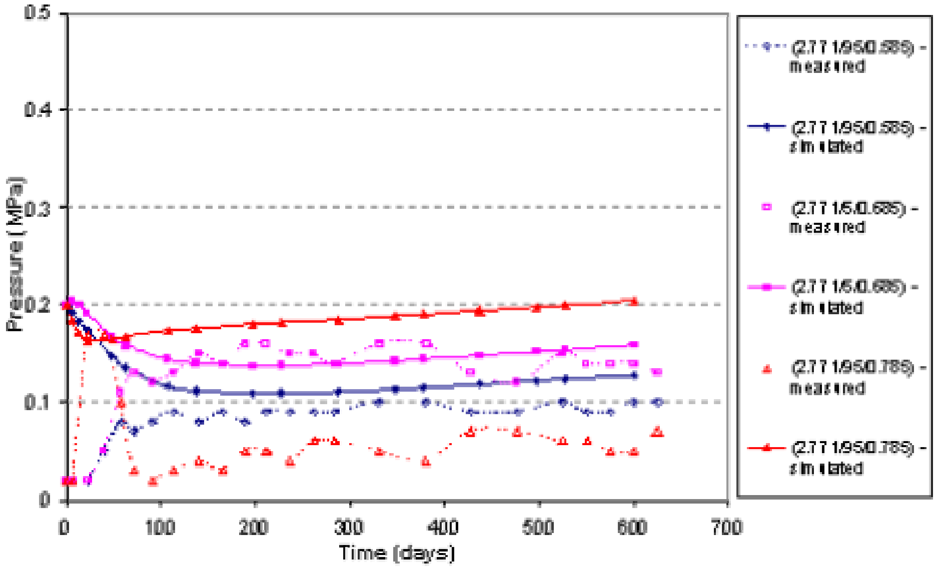


Figure 5-44*. Measured and simulated total pressure plots for Hole 3 at mid-height canister. The legend is explained in Figure 5-39.*

CODE_BRIGHT

This section describes the predictions made for the Prototype Repository project using the CODE_BRIGHT. Although the model predictions are not compared with measured data in this Section, these comparisons are provided in Section "Recordings" below.

Temperature at mid-height canister

Different geometries were used to analyze the thermal problem and finally, a fully 3-D geometry was considered. However, when the analysis was coupled with the hydraulic and the mechanical problem, only quasi-3-D (i.e.,, axisymmetric) conditions were used, in order to avoid large computing times. The results in terms of temperature distribution were not too different except for some 3-D effects due to the interaction between canisters, which can be taken into account using appropriate boundary conditions. Figure 5-45 presents a summary of the numerical results, including the evolution of temperature for three typical points of the buffer.

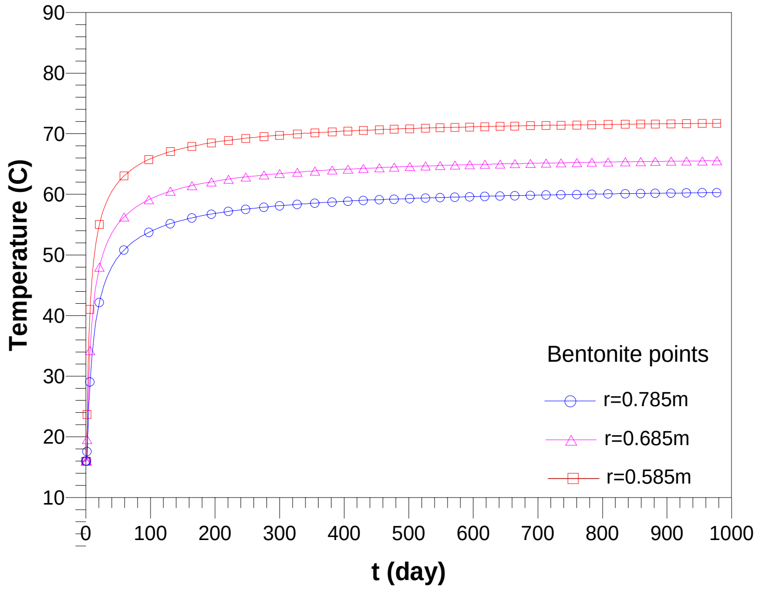


Figure 5-45. *Evolution of temperature computed for three points in the buffer. The legend is explained in Figure 5-39.*

Hydration of buffer at mid-height canister

Figure 5-47 presents the evolution of degree of saturation against time for the mid plane of Hole 1. It should be pointed out that the parameters used in the analyses were the same for all deposition holes, except for the initial conditions (i.e., Hole 1 was initially wet, whereas Hole 3 was initially dry). That approach may give average predictions when comparing measurements with calculations. Obviously, a better fit would have been achieved by using different parameters for each deposition hole, but this is not reasonable if the geometry and the basic properties are the same for both. According to the calculations, note that after 1000 days the saturation is practically complete (99%) in a point close to the rock.

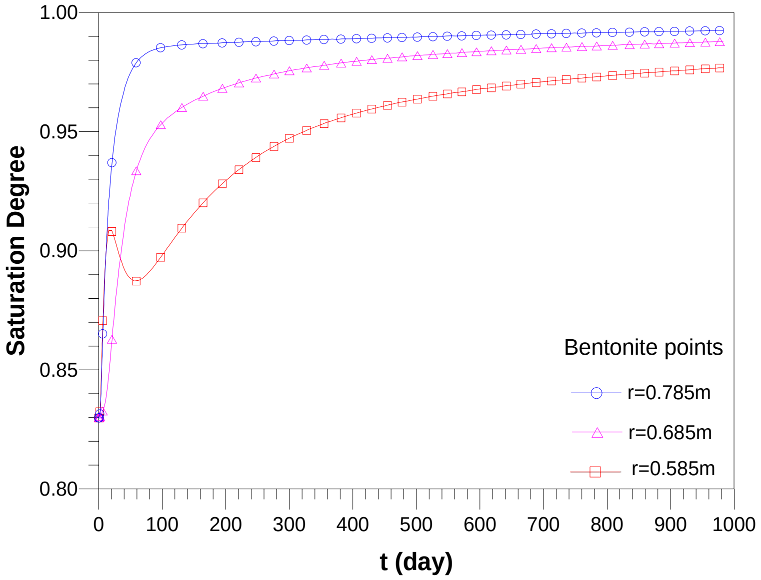


Figure 5-47. *Predicted degree of saturation at mid-height of heater in Hole 1 (the wettest hole). The legend is explained in Figure 5-39. Near the rock saturation is practically complete (99%) after 1 000 days.*

Total pressure in buffer

A summary of the analyses is presented in Figure 5-47. It can be seen that after 600 days a pressure of almost 7 MPa is predicted for a point close to the rock where saturation is quicker. Points close to the heater give 4.2 MPa after 600 days. The comparison of this variable with measurements may be less fair than in the previous cases (i.e., temperature or saturation degree), due to the limited accuracy of the pressure cells. Considering those difficulties, the predictions seem reasonable.

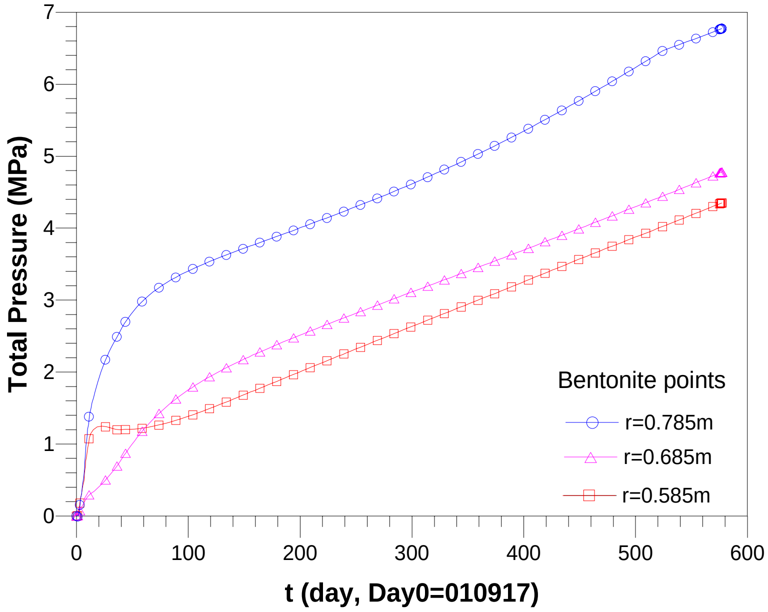


Figure 5-47. *Computed evolution of total pressure for three points. The legend is explained in Figure 5-39.*

CODE THAMES

This section describes the predictions made for the Prototype Repository project using the CODE THAMES. Although the model predictions are not compared with measured data in this Section, these comparisons are provided in Section “Recordings” below.

Temperature at mid-height canister

A constant heat power of 1 800 W was applied to each heater. As the boundary conditions, temperature was fixed on the top and the bottom surface, and no heat flux was applied to the side surface. Figure 5-48 shows the predicted temperature evolutions at the expected points. The temperature steadily increases with time and does not terminate to the steady state even after 1 000 days.

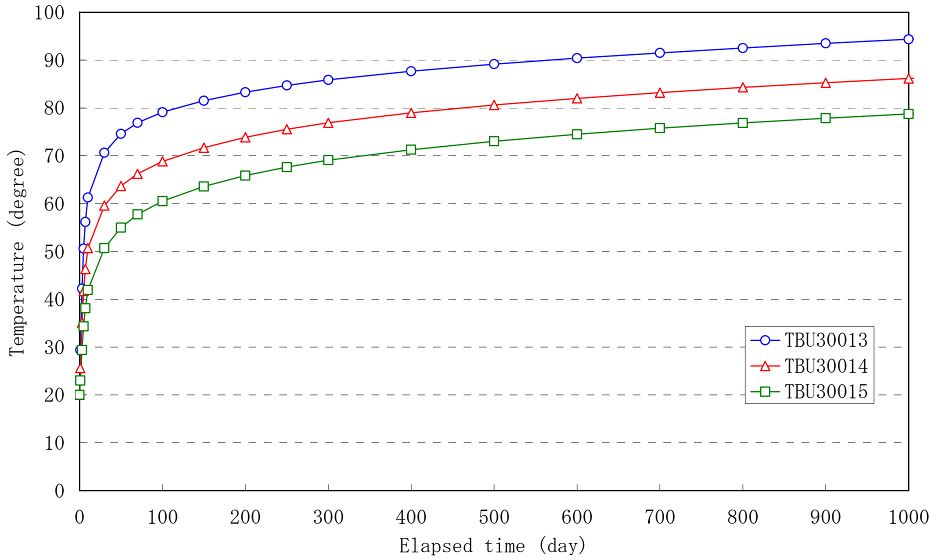


Figure 5-48. *Predicted temperature (3-D analysis) in Hole 3. TBU denotes "temperature sensor", TBUs 13, 14 and 15 are located mid-height canister and at a distance of 0.585 m, 0.685 m and 0.785 m from the hole center respectively. The angle for all three sensors is 90*^{o}.

Hydration of buffer at mid-height canister

The initial water content of 17 % for the buffer represents a degree of saturation of approximately 60 %, and a relative humidity of about 80 %. The evolution of the relative humidity and the degree of saturation are shown in Figures 5-49 and 5-50. The relative humidity at each point steadily increases and reaches saturation after around 700 days. No drying process can be expected according to the simulation.

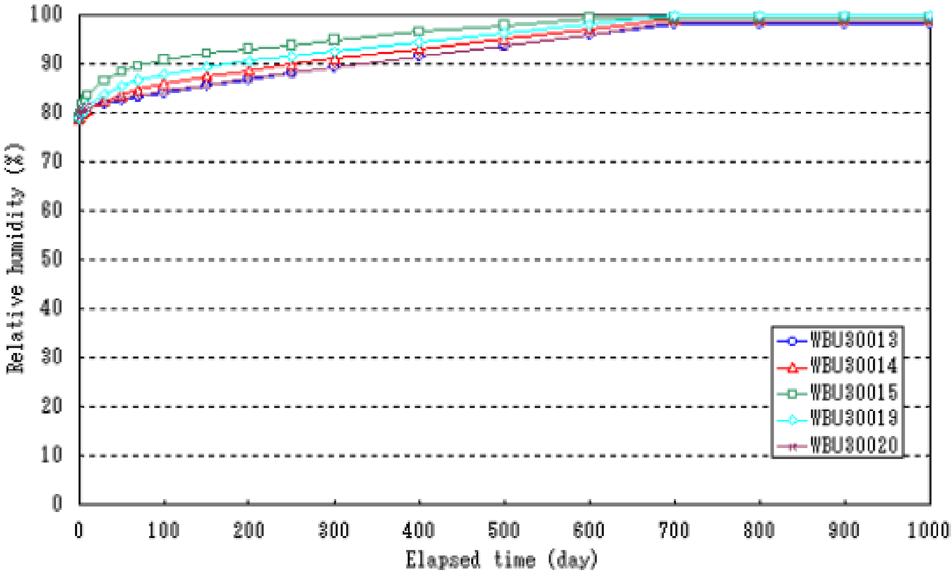


Figure 5-49. *Predicted relative humidity (3-D analysis) in Hole 3. WBU denotes the sensor type. All five sensors are located at mid-height canister. WBUs 13, 14 and 15 are located at an angle of 350*^{o}*, and at a distance from the hole center of 0.585 m, 0.685 m and 0.785 m respectively. WBUs 19 and 20 are located at an angle of 180*^{o}*, and at a distance from the hole center of 0.535 m and 0.685 m respectively.*

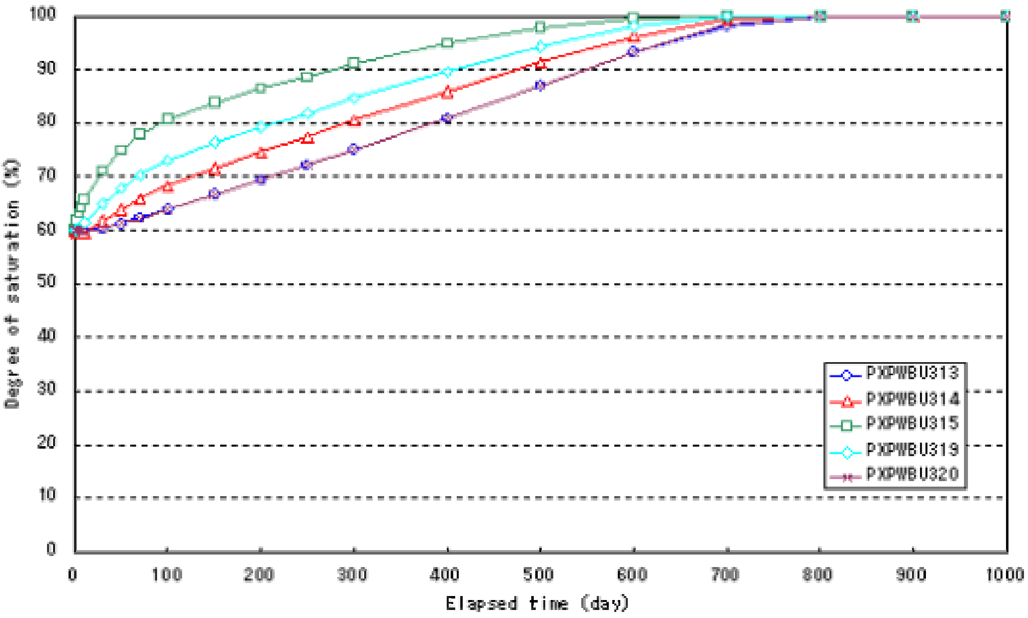


Figure 5-50. *Predicted degree of saturation (3-D analysis). Based on Figure 5-49.*

Total pressure in buffer

Figure 5-51 gives the evolution of the total pressure at mid-height canister in a hole with unlimited access to water for saturation of the buffer (Hole 1). The main contribution to the stress increment is the swelling pressure of the buffer. Therefore, the stress increases with respect to the evolutions of relative humidity. The magnitude of the stress is governed mainly by the maximum swelling pressure.

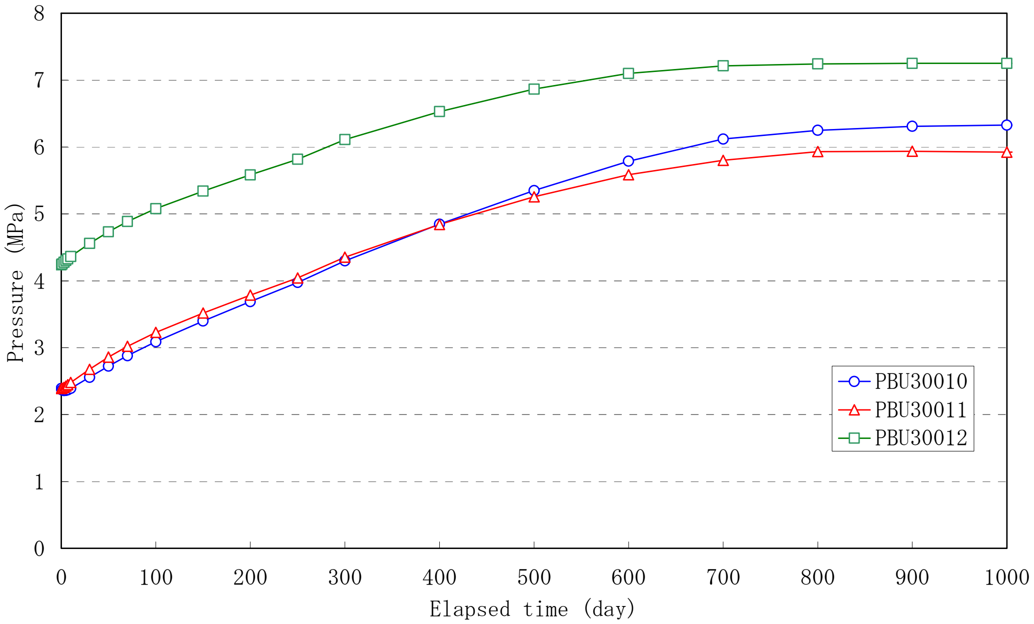


Figure 5-51*. Predicted total stress at mid-height canister in Hole 3. PBU denotes the sensor type. PBUs 10, 11 and 12 are located at a distance from the hole center of 0.535 m, 0.685 m and 0.825 m respectively.*

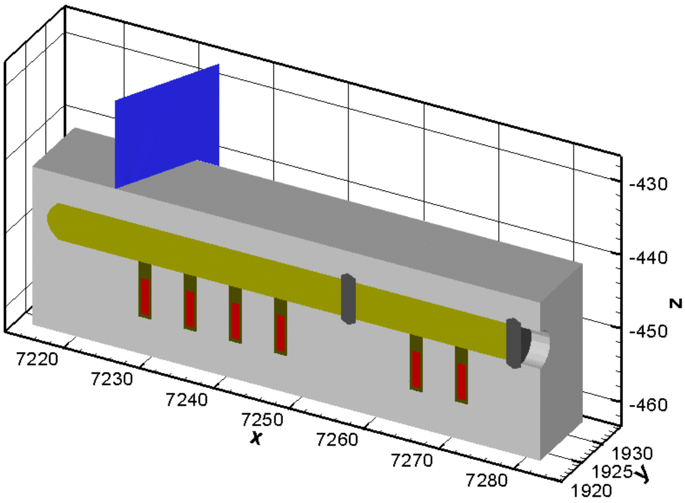


***Figure 5-52**. Geometry used for 3-D FEM calculations with code ROCHFLOW/ROCKMECH.*

CODE ROCKFLOW/ROCKMECH

This section describes the predictions made for the Prototype Repository project using BGR´s code Rockflow. Although the model predictions are not compared with measured data in this Section, these comparisons are provided in Section "Recordings" below.

The saturation and resulting swelling pressure of a deposition hole and drift system filled with bentonite under consideration of the EDZ with the help of the two-phase flow theory.

The work presented here has comprised 3-D analyses of the temperature evolution, hydration and build-up of swelling pressure in the buffer assuming unlimited access to water from the rock, which corresponds to the conditions in Hole 1 of the Prototype Repository project at AEspoe.

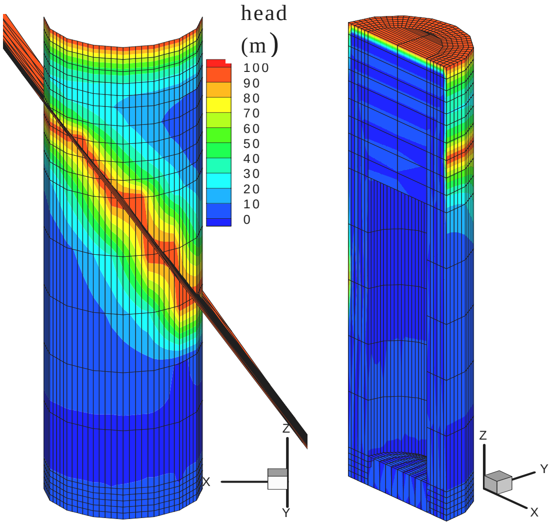
The geometry of the model for 3-D FEM calculations is shown in Figure 5-52.

Hydration of buffer and backfill

The progress of the water uptake under different piezometric and rock structure conditions is analyzed in [5-32]. One case refers to the condition with the deposition hole being intersected by 2 vertical water-bearing fractures, and the other to rock with no such fractures. The ambient water pressure is assumed to be 1 MPa, driving water into fractures and further into the EDZ. One finds that complete water saturation requires many decades in the fracture case and at least a hundred years for the fracture-free case. Still, for the first mentioned case a high degree of saturation is reached already after about 8-10 years. The pressure at the canister surface reaches and proceeds beyond 5 MPa after 3 years. The initial temperature was taken as 18^{o}C and the temperature as 100^{o}C after 100 days.

A key question in the saturation process is the EDZ and its ability to act as a water-transmitting component for wetting the unsaturated bentonite. But modeling work has indicated that the EDZ is not particularly effective in supplying water to the buffer.

Even if the first 10mm of the EDZ is assumed to be100 times more permeable than the undisturbed rock, the same result is obtained. Figure 5-53 shows the distribution of the groundwater pressure in an EDZ that is intersected by a fracture .



$w_{EDZ} = 10$ mm
$K_{EDZ} = 10^{-10}$ m/s

Figure 5-53. Distribution of hydraulic head (scale in meters) after a few years in an EDZ having a thickness of 10 mm. The groundwater pressure is high only in the uppermost part of the bentonite and in the part of the EDZ that is adjacent to that fracture.

Hydration of buffer at drift, mid-height canister and near the fracture

Figure 5-54 shows the change in degree of water saturation at mid-height of Hole 1 and in the overlying drift. One finds that complete water saturation at the canister requires much more than 3 years.

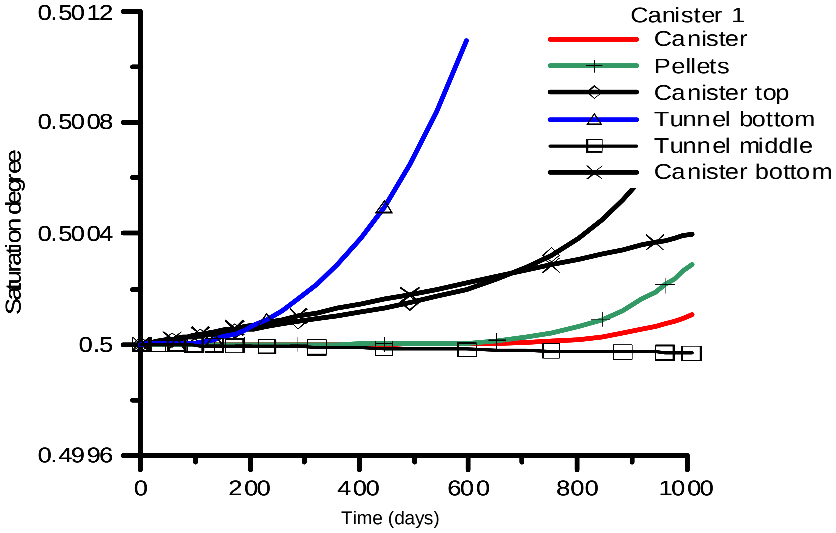


***Figure 5-54.** Saturation of the buffer in Hole 1 at different parts as a function of time.*

Figure 5-55 shows the pressure evolution at the upper end of Hole 1 including the effect of upward movement of the canister. The maximum pressure at the canister surface (red curve) proceeds beyond 5 MPa after 3 years.

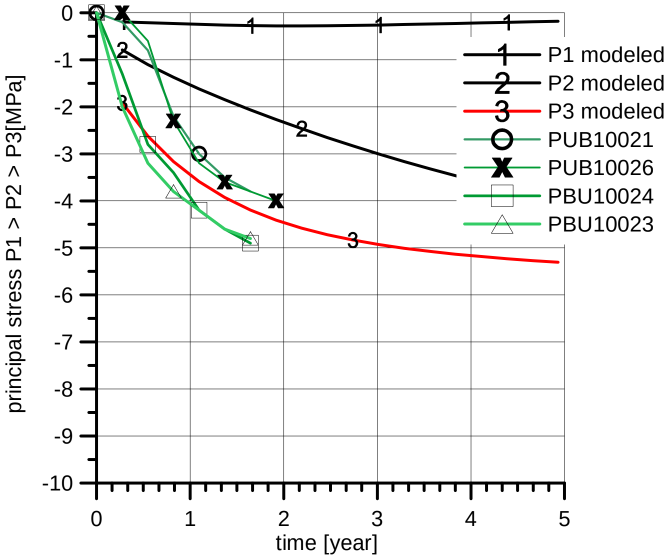


***Figure 5-55**. Pressure evolution at the top part of the canister in Hole 1 including the effect of upward movement of the canister (negative pressures represent compressive stresses). With the standard description for location of instruments used in e.g., Figures 5-39 to 5-42 are the location of the PUB sensors in the legend defined by: PUB10021 (5.558/90/0.635), PUB10026 (6.567/5/0.585), PUB10024 (5.558/180/0.635) and PUB10023 (5.558/190/0.735).*

CODE ABAQUS

This section describes the predictions made for the Prototype Repository project using the ABAQUS. Although the model predictions are not compared with measured data in this Section, these comparisons are provided in Section "Recordings" below.

A constant power of 1 050 W was assumed in the initial calculation, which was based on 75°C as constant temperature of the (metal) canister surface. It gave a maximum temperature in the buffer close to the canister surface after 2 years of about 60^{o}C and 45^{o}C at the rock giving an average temperature gradient across the 350 mm thick buffer of 0.042^{o}C per mm radial distance. Converting this to the actual 1 800 W in the test and assuming the initial temperature to be 10^{o}C, the temperature in the buffer adjacent to the canister would be about 100^{o}C and 63^{o}C at the rock surface.

Hydration of buffer at mid-height canister

The calculation is made for the simplified case with the initial density, which is different for the pellet filling and buffer blocks and gaps, smeared out over the entire volume. It is concluded from Figure 5-56 that complete saturation is reached after around 3 year.

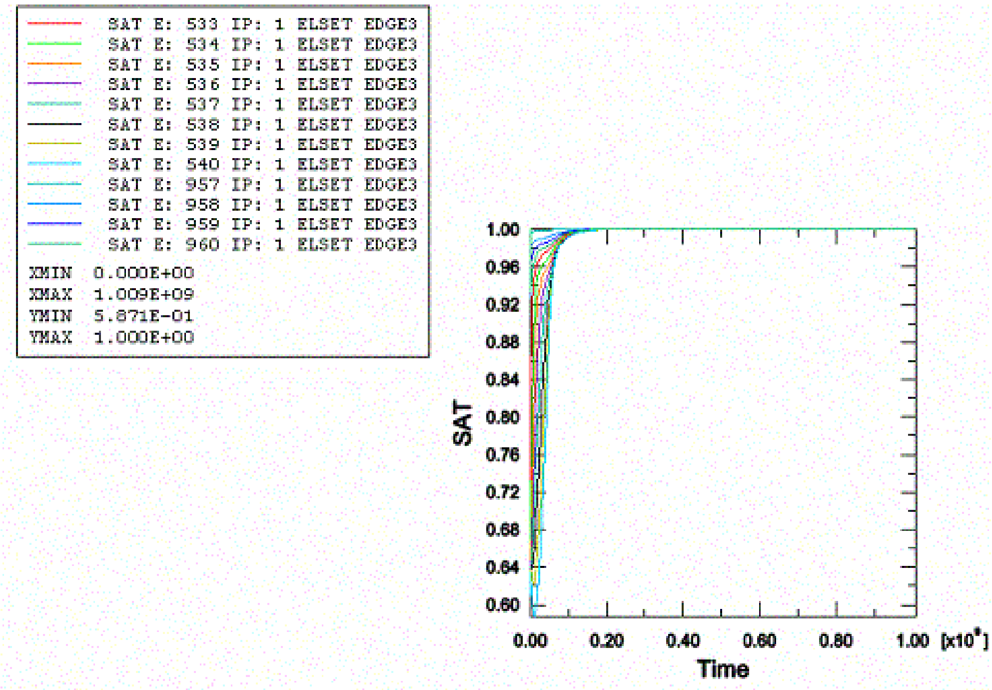


***Figure 5-56.** Predicted degree of saturation at mid-height canister in the wettest deposition hole (Hole 1). Time is given in seconds. The curves represent equally spaced distances from the rock surface (Blue is the rock boundary, the curve to the right is the canister surface). Complete saturation of the entire buffer is reached after about E8 seconds, i.e., around 3 years.*

Total pressure in buffer

The calculation shows that full swelling pressure (about 8.3 MPa) will be reached after about 3 years nearly irrespective of the distance from the rock (Figure 5-57). No external water pressure was assumed and the values therefore represent also the total pressure.

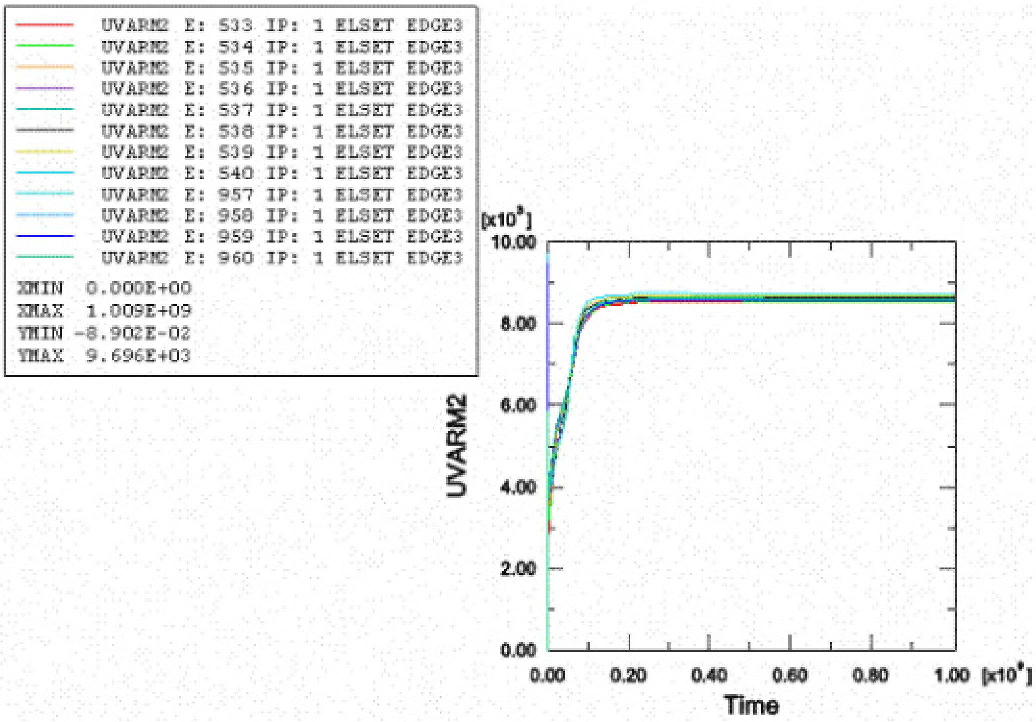


Figure 5-57. *Predicted total pressure at mid-height canister in the wettest deposition hole. Time is given in seconds. No external pressure is assumed and the data therefore represent the swelling pressure as well. The curves represent equally spaced distances from the rock surface (Blue is the rock boundary). The pressure is about 8.3 MPa in the entire buffer after about E8 seconds or around 3 years.*

RECORDINGS

This section describes briefly the data collected from monitoring the Prototype Repository project during the first 800 days of heating. With some qualifications for the assumptions made in the modeling activities described above, the modeling predictions can be compared to these data.

Temperature at mid-height canister

The temperature is still rising after more than 2 years. It reached about 72°C in the clay adjacent to the canister surface and around 60°C at the rock after about 700 days, or around 2 years as shown by Figure 5-58. The average temperature gradient is about 0.034°C per millimeter radial distance. Almost the same temperature figures were also registered by the Vaisala RH meters as shown in Figure 5-59. The heater power has been about 1 800 W.

Hydration at mid-height canister in the wettest hole

The hydration process can be interpreted from the output of the Vaisala relative humidity (RH) meters an example is given in Figure 5-59). The results indicate that the clay between the canister and the rock in Hole 1 had reached RH values of 92-94% after about one year. The present understanding is that at high RH the values are approximately equal to the degree of water saturation, which indicates that a very high degree of water saturation has been reached in the buffer between the canister and the rock.

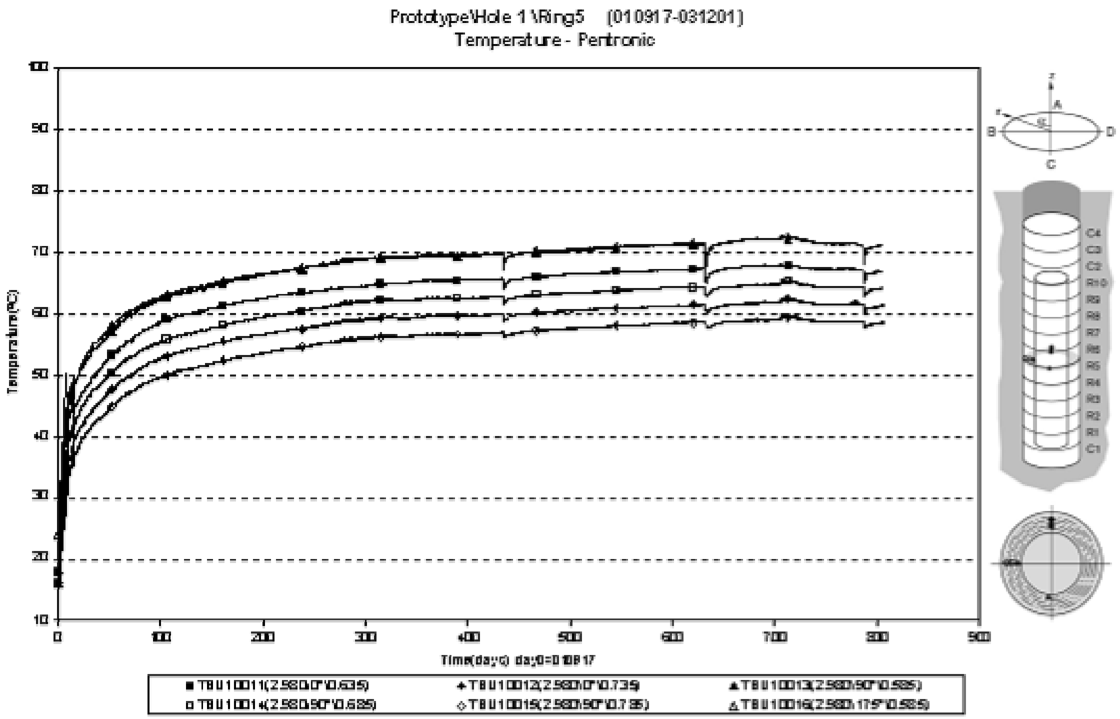


***Figure 5-58**. Temperature at mid-height canister in the wettest hole (Hole 1).The legend denotes the instrument and where it is located: example TBU10011 (2.980\0^o\0.635) where TBU is gauge type (here temperature sensor), 10011 is gauge number, 2.980 is distance from hole bottom, 0^o is coordinate angle from drift axis (see top figure at right), and 0.635 is distance from hole centre.*

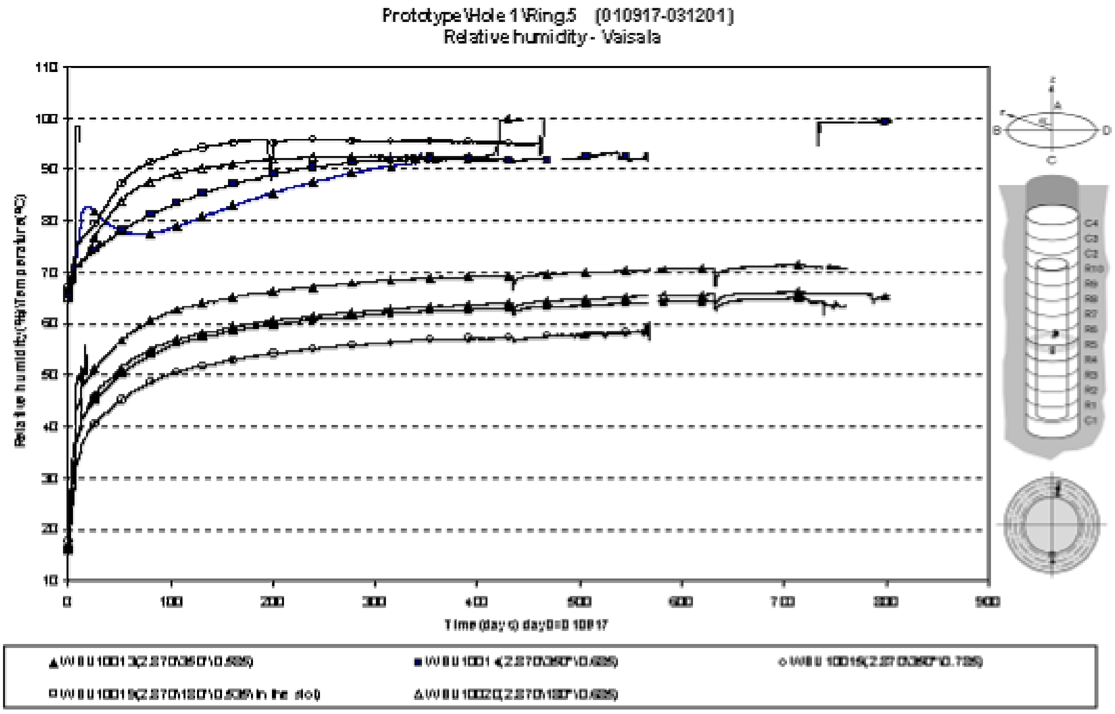


***Figure 5-59**. RH and temperature distributions in the buffer in the wettest hole (Hole 1). The legend is explained under Figure 5-58. WBU denotes relative humidity (RH) sensors. The data can be approximately taken as the degree of water saturation. The upper curve set shows the RH readings and the lower set gives the temperature.*

Total pressure at mid-height canister in the wettest hole

The total pressure was measured by two types of gauges of which the Geokon sensors were concluded to be the most reliable ones. The homogeneous distribution of water according to the RH measurements should also correspond to a uniform distribution of the pressure but the obvious variations in pressure shown in Figure 5-60 indicate that full maturation of the buffer had not taken place within 2-2.5 years. It may be that the degree of water saturation varies more than indicated by the RH measurements and also that complete, homogeneous embedment of the pressure cells requires rather long time for the involved creep, expansion, consolidation and moisture redistribution. It may also be that the cables connecting the Vaisala gauges to the recording units served as water conductors and caused local wetting and earlier saturation at the spots where the gauges are. This may explain the slight drop of RH after reaching a maximum value for one of the gauges (Figure 5-59).

It is estimated that nearly complete homogeneity will require several years because the hydration rate is lower than expected.

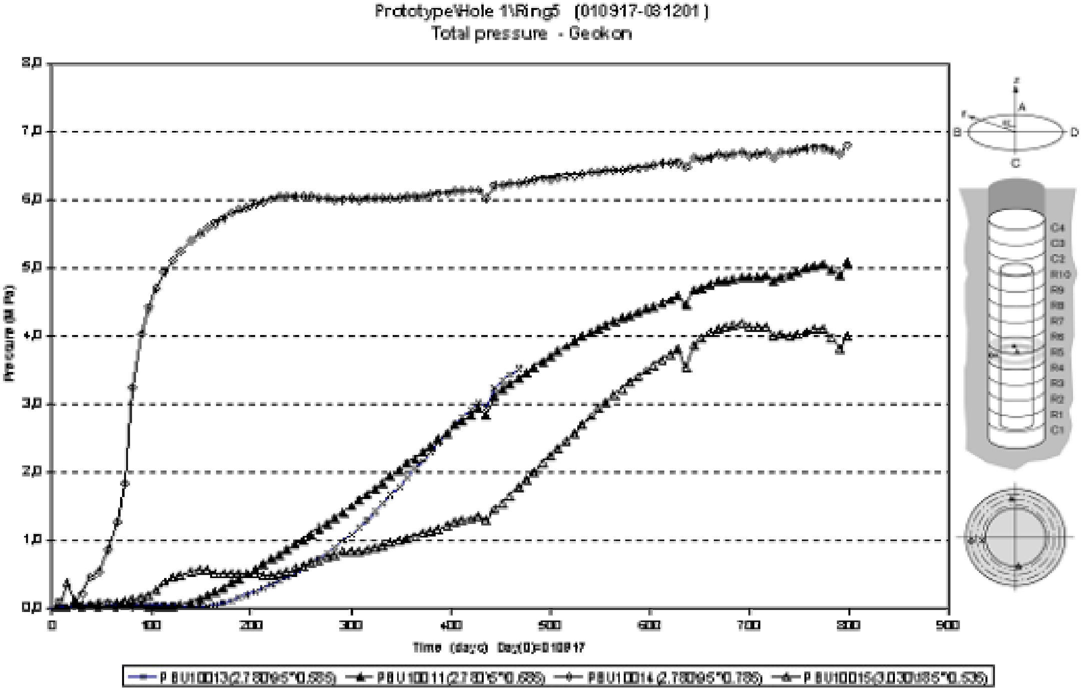


Figure 5-60. *Evolution of total pressure at mid-height of the buffer in the wettest hole. The legend is explained under Figure 5-59. PBU denotes total pressure sensors. The highest pressure, about 6.7 MPa, was reached after about 2 years while the lowest pressure (4 MPa) was signaled from a cell close to the canister.*

Temperature evolution

The predicted and actual temperatures at the rock and the canister surface at mid-height canister level of the canister in the "wet rock" represented by Hole 1 are shown in Table 5-5. One finds that two of the models give adequate data while one (THAMES) somewhat exaggerates the temperature. For the BGR calculation, the canister temperature was selected to be 100°C, which hence controlled the heat evolution of the entire buffer. For ABAQUS the boundary conditions were here set to yield maximum 83°C in the canister and the results were not coupled to the wetting.

Table 5-5. Actual and expected temperature in degrees centigrade at the canister and rock surfaces at mid-height in the wettest hole after 1 and 2 years from start of heating

Location	Recorded	COMPASS (UWC)	CODE_BRIGHT (CIMNE, Enresa)	Rockflow (BGR)	THAMES (JNC)	ABAQUS (ClayTech, SKB)
Canister	1 y=69 2 y=72	1 y=70 2 y=72	1 y=70 2 y=72	1 y=100[1)] 2 y=100[1)]	1 y=87 2 y=92	1 y=67[3)] 2 y=70[3)]
Rock	1 y=56 2 y=60	1 y =56 2 y=59	1 y=57 2 y=60	1 y=92[2)] 2 y=96[2)]	1 y=71 2 y=76	1 y=44 2 y=47

1) Set by modeler, 2) Controlled by 1), 3) No real prediction. Boundary conditions set to yield maximum 83°C in canister and results not coupled to the wetting.

Hydration

The predicted and actual degrees of saturation are difficult to compare since the uncertainty in the "measured", which could be that the actual rock conditions deviate from the assumption of unlimited access to water, see Table 5-6. Still, all the models appear to exaggerate the rate of wetting.

Table 5-6. Actual and expected degree of saturation in percent at the canister and rock surfaces at mid-height in the wettest hole after 1 and 2 years from start of heating

Location	Recorded	COMPASS (UWC)	CODE_BRIGHT (CIMNE, Enresa)	Rockflow (BGR)	THAMES (JNC)	ABAQUS (ClayTech, SKB)
Canister	1 y=90-100 2 y=90-100	1 y=96 2 y=100	1 y=95 2 y=97	1 y=76 2 y=84	1 y=79 2 y=99	1 y=75 2 y=100
Rock	1 y=90-100 2 y=90-100	1 y=98 2 y=100	1 y=99 2 y=99	1 y=95 2 y=98	1 y=94 2 y=100	1 y=100 2 y=100

Pressure evolution

Table 5-7 shows the predicted total pressure, which deviates significantly from the actual data in some cases. ABAQUS predicts too rapid pressure build-up at the canister while the predicted and measured pressures at the rock agree well. COMPASS predicts too slow pressure growth.

Table 5-7. Actual and expected pressure in MPa at the canister and rock surfaces at mid-height in the wettest hole after 1 and 2 years from start of heating

Location	Recorded	COMPASS (UWC)	CODE_BRIGHT (CIMNE, Enresa)	Rockflow (BGR)	THAMES (JNC)	ABAQUS (ClayTech, SKB)
Canister	1 y=1.0 2 y=4.0	1 y=0.8 2 y=3.2	1 y=3.0 2 y=5.1	1 y=3.5 2 y=4.8	1 y=4.7 2 y=6.2	1 y=5.3 2 y=6.8
Rock	1 y=6.0 2 y=6.7	1 y=2.8 2 y=3.9	1 y=5.0 2 y=7.2	1 y=3.5 2 y=4.8	1 y=6.4 2 y=7.2	1 y=5.3 2 y=6.8

Overall conclusions of the work performed

Comparison of the theoretical models with actual measurements has led to the following major conclusions:

- The geohydraulic and geochemical modeling refer to stages that have not yet been reached in the repository test area and no safe conclusions concerning their applicability can yet be made. Predictions of access to water from the rock in the deposition holes are uncertain and future work related to rock structure on different scales appears to be required for adequate modeling of the hydration of buffers and backfills.
- All the theoretical models give data that are in fair agreement with the measurements and can be used for rough prediction of the temperature, hydration and pressure build-up in buffer of the type used in the Prototype Repository project.
- Best agreement between predictions and measurements is obtained for the temperature evolution. Some models overestimate the temperature for the first two years, hence yielding a safe, conservative prediction, while the others give very accurate forecasting. There are indications that the thermal conductivity of the buffer is higher than assumed and that the heat transfer is assisted by some undefined mechanism such as convection through vapor flow.
- The hydration rate is more difficult to predict than temperature. A first and major problem is the risk of water migration along cables to moisture sensors, which may have given incorrect information on the rate of hydration of buffer. Thus, the measured values to be compared with the predictions may not be adequate. In spite of this it is concluded that almost all the models have yielded data that are fairly well in agreement with the recordings and that the models provide sufficiently safe information on the wetting rate for practical use concerning deposition holes with “unlimited” access to water from the rock. The predicted rate of saturation is generally too high, indicating that all processes involved in the moisture migration and maturation of the buffer are not fully understood.
- For deposition holes with limited access to water for hydration the situation is more uncertain. One of the models could fairly accurately predict the hydration in a “dry” hole by basing the calculation on measured inflow before applying the buffer in Hole 3, but it seems more difficult to foresee the wetting in planning a repository with much less information on the hydraulic performance of the near-field rock. This matter should be in focus in future RTD.
- The prediction of the evolution of pressure and mechanical response of the buffer is the most difficult task because it requires that fracturing in the driest part and displacements in all the buffer are included in the models. Also, the interrelation of hydration/dehydration and swelling/drying are relevant. Since prediction of the hydration rate appears to be uncertain, forecasting of the mechanical response is even more uncertain. However, the models manage to give data that are not too different from the recordings and that are sufficiently accurate for practical purposes. Like for the measurement of rate of hydration, some pressure and mechanical response gauges may respond to results of water migration along cables and hence over-estimate the rate of maturation of the buffer. The evolution of pressure in the buffer in “dry” deposition holes is even more difficult to predict but stable conditions may require several tens of years according to models such as the one proposed by BGR.

5.7 Performance/safety assessment approaches

The development of PA/SA strategies and procedures are normally evolving with time. For example, SKB's PA/SA has turned from a conservative dose conversion factor for well water to more realistic conditions. Also, new numerical tools for PA/SA, or rather risk analysis are under development. The prediction of possible radionuclide movement from leaking canisters to the biosphere requires identification of a number of processes in the near- and far-fields and ways of making quantitative estimates of the transport rates. The following issues are among those that affect the basis for repository safety analyses:

- The large-scale rock structure, which determines the groundwater flux in the host rock mass, is of fundamental importance to the safety with respect to radionuclide transport to the biosphere. The structural/hydrological codes used by the Participants are adequate but rock structure models are uncertain partly due to difficulties in identifying fracture zones, their continuity and their degree of interconnection and partly because of the need to model their interaction with respect to groundwater flow.

- A relatively high groundwater flow rate in the host rock can be compensated by more effective EBSs, the function of which has to persist for a very long period of time. This is, in fact, a safety-related philosophy in some programs, which implies for those programs that the rock is considered primarily as a mechanical protection of the EBS.

- Permanent or temporary failure of the buffer may be caused by hydrothermally induced changes in mineral content.

- Gas pressure build-up may cause temporary failure, gas penetration into clay buffer and probably unwanted channeling. The mechanisms leading to gas penetration and the conditions controlling it are currently under investigation. The ongoing Canister Retrieval and Prototype Repository project at the AEspoe URL and the GMT test at the Grimsel URL offer possibilities to investigate these processes further. Nevertheless, further testing is needed for assessments of the processes associated with the development of high gas pressures and gas release.

- Clay buffer may release colloidal particles that can possibly carry radionuclides sorbed by them. Minute smectite crystallites may act as colloids, forming aggregates that can be released from the buffer if either the pore water or gas flow rate is sufficiently high. Sufficiently high pore water flow rates are unlikely under the expected regional hydraulic gradients that would prevail in crystalline rock bodies after closing the repository but gas movement may drive these colloids into the surrounding geosphere. Sampling of the content of colloids in water-bearing fractures that intersect deposition holes and drifts in experiments might provide some useful information in assessing this process.

- Bacteria, of which sulfate-reducing ones are a particular threat to the canisters, may stay alive and multiply in smectite clay. They usually carry a negative surface charge and can move through soft clay. However, the very limited void space in wet MX-80 clay at densities higher than 1 900 kg/m^3 prevents multiplication and even survival of bacteria. Only spores may be operative at these clay densities but the present working hypothesis is that there will ultimately be eradication of all life forms in the buffer [5-31]. This hypothesis needs to be validated.

- The most important radionuclides for repository safety analyses are the long-lived ones with high mobility in the EBS and host rock. In SKB's safety analyses, the dose-dominant radionuclides I-129, C-14, Cl-36 and Mo-93 are identified as important. Conditions for transport of these nuclides are reliably simulated by use of existing THMC models applying conservative assumptions and parameter values.

5.8 Lessons learned and potential areas for improvements

5.8.1 Design and construction

The construction of URLs and repositories in crystalline rock offers no great difficulties and the huge experience in underground mining in crystalline rock in most countries certifies that a repository with stable rooms can be prepared even in rather poor rock. Very high rock stresses have an impact on the selection of the depth of repository, and the orientation of the principal stresses and certain rock structural features need to be considered in selecting the design and geometry of the rooms for optimal utilization of the host rock mass. A significant problem is caused by high water inflow into drifts and shafts in the backfilling stage. New techniques for the placement of sealing materials under these conditions are under discussion but need to be tested on a full scale for making sure that concepts, such as the KBS-3V, are applicable without reservations or changes.

In principle, design and construction of URLs and repositories in crystalline rock is a straightforward procedure once a suitable location of the repository has been determined. A major requirement for future work is to develop the techniques for identifying, characterizing and modeling rock structure both in the near-field and the far-field.

5.8.2 Instruments

Processes of major interest for assessing the performance of near-field rock, buffers and backfills are: 1) Temperature evolution, 2) Hydration of buffers and backfills, 3) Development of swelling pressure, 4) Displacements (canister movements), 5) Chemical changes (mineralogy and pore water), and 6) Biological changes. They are referred to as the THMCB processes.

Recording of the temperature evolution of the canister-embedding clay is well-demonstrated in crystalline rock using corrosion-protected temperature sensors or fiber optics and advanced data acquisition systems. Recording of water uptake has been demonstrated in SKB's, Enresa's, AECL´s and Nagra's field experiments using psychrometers, electrical resistance technique and time-domain reflectometry. Swelling pressure and piezometric pressure have been measured by use of Gloetzl and vibrating string techniques and displacements have been measured by applying extensometers and electronic gauges. Measurements of chemical changes in the pore water of clay in on-going experiments have not been successful, but such measurements have been made with accuracy after termination of the tests. Biological processes have not been studied in EBS components *in-situ*, but have been studied in samples taken during the disassembly of experiments.

As a whole, the instrumentation used in the various URLs appears to work satisfactorily although several important processes cannot be recorded, such as chemical and mineralogical changes of the buffer clay in the course of the hydrothermal EBS tests. Such changes, which are expected, cannot be identified and quantified until samples can be taken when the experiment is being disassembled.

The Participants concluded that practical instrumentation of experiments in URLs is more difficult than assumed in the planning stage, primarily because the sensors are sensitive to the harsh conditions prevailing in the near-field, i.e., high temperature and high concentration of groundwater electrolytes, and because cable connections can serve as flow paths to disrupt the normal moisture movement. The solution to the latter defect has not yet been demonstrated and is the main reason why instrumentation systems for the near-field of real repositories cannot be said to be available at present.

Considerable development of instruments and probably wireless transmission techniques are needed and steps must be taken to prevent the presence of the instruments from influencing the performance of rock and EBS.

The types of instrumentation required for long-term repository monitoring have been identified but development work must continue on longevity of the instrumentation and systems, maintenance, replacement and calibration of the instrumentation *in-situ*, and effective monitoring after repository closure without using invasive installations that might affect the passive safety of the repository.

5.8.3 Experimental procedures

The experiments in the crystalline rock URLs turn out to be fairly similar and focus on rock testing with special emphasis on rock mass stability and groundwater flow in the near- and far-fields, and on the interaction of rock and EBS (e.g., buffer, backfill and plugs). Experiments can only be conducted for a limited period of the very long repository lifetime and hence only provide indications on the short- and medium-term performance of repository systems. Typically, experiments and tests performed to date essentially provide data on the very first phase of the evolution of the EBS and on the functional performance of buffers and backfills. These EBS components undergo hydrothermal changes for thousands of years and these processes cannot be well predicted at this time. Processes that are considered to be of importance from a repository safety perspective but that have not yet been fully studied are: gas transport and possible channeling in the buffer, release of colloidal clay particles from the buffer, and microbial processes affecting EBS components.

It is both an important and an attainable task to design and conduct experiments identifying possible changes of clay buffers in crystalline rock in both short- and long-term perspectives. Among the most important processes are gas penetration experiments and sampling of the content of colloids in water-bearing fractures that intersect deposition holes and drifts in future experiments. Bacteria, of which sulfate-reducing ones are a particular threat to the canisters, and spores may stay alive and multiply in smectite clay. Their occurrence, survival and potential impacts should be further investigated in field experiments.

5.8.4 Conceptual and mathematical models

Hydrological models for prediction of large-scale groundwater movement and evaluation of measured data appear to be sufficiently good for general use in planning and running experiments in URLs and repositories in crystalline rock. For the EBS in general and buffers and backfills in particular, the maturation, including hydration, expansion and consolidation, can be predicted if the potential of the near-field rock to give off water is known. However, this is seldom the case and the true THMCB evolution of the clay-based EBS components can therefore not be predicted with accuracy for the first few tens to hundreds of years. The prediction of mineral changes can be made with some confidence but validating field tests with the temperature conditions implied by the repository concepts would require many hundred of years and can therefore not be made.

Theoretical THMCB modeling based on the current conceptual models cannot be made with any accuracy if the knowledge of the structural and hydrological properties of the near-field rock is not well understood. Thus, a potential area for improvement is modeling of the structure and associated flow properties of the near-field rock. These characteristics determine the rate of hydration of the buffer and thereby some of the chemical and mineralogical evolution in it that affect both the short- and long-term physical performance. It is concluded that the models for predicting mineral changes such as dissolution and precipitation need to be confirmed by long-term tests and by examining natural geological evidences.

5.8.5 Summary and conclusions

The crystalline rock information presented in this report synthesizes the information provided by SKB, Posiva, Nagra and OPG with support of Andra and Enresa on the successful design, construction and operation of the Stripa URL, AEspoe URL, Olkiluoto URL, Grimsel URL and AECL´s URL respectively. Crystalline rock has brittle characteristics and contains fractures, which form patterns of groundwater transport pathways from a repository to the ground surface. The existence of these fractures systems and their transport characteristics are the major factors that must be considered in the long-term safety case. The application of the multi-barrier principle, however, puts the main burden on the engineered barrier system, in contrast to the situation in salt and clay host rocks that benefit more from the containment provided by the natural barrier. Still the natural radionuclide retardation properties of the host rock are important, although safety case credits can be taken only for verified conditions.

Ongoing work on improvement/optimization of crystalline rock repositories addresses several issues.

- Canister design and manufacturing, as well as the performance of different materials, have been investigated in detail, and differences among the Participants in the choice of designs and manufactures are based on national philosophies but with all programs using the same knowledge base. The safety case is a combination of the interacting performance of the waste, the canister, the buffer/backfill/plugs and the surrounding rock mass.

- An important parameter for the design of the repository is the maximum temperature allowed in the near-field and in many programs the temperature on the surface of the canister. In addition, the careful design and direction of drifts at depth is essential because of the state of stress and conditions for groundwater flow are influenced by the excavation orientation and shape.

- Selection of excavation method requires an understanding of the consequences that the different methods have on the future properties of increased fracturing and of the EDZ including the excavation damaged zone, i.e., the rock volume around the drift that will have changed properties after excavation compared to before. But, well-proven excavation methods exist for all purposes underground, and these may fulfill repository requirements.

- Grouting as a means for sealing drift walls against inflowing water needs to be developed from the materials and techniques used in current practice, as ordinary cementitious material (high pH) in large quantities may be detrimental to the long-term safety of the repository.

- Swelling clay alone or mixed with other materials is an outstanding material for use in buffer, backfill and plugs and has been thoroughly investigated for some 30 years. Manufacturing of different sizes of highly compacted blocks has been verified for some types of bentonite.

- Emplacement and deposition methods have been tested in full scale for vertical in-hole emplacement. Programs are going on for testing of horizontal emplacement and are considering large waste packages containing both canister and surrounding buffer.

- Backfilling of deposition drifts in the KBS-3V vertical in-hole emplacement method (SKB and Posiva) has been tested in full scale for fresh water to slightly salt groundwater, but is not verified for groundwater salinities of 3.5%TDS (ocean waters) and for waters of higher TDS being considered in other programs. There is still work required to develop backfill composition and placement techniques that will provide adequate emplacement density in all situations.

- Performance of different designs of plugs and seals has been investigated but the outline of a detailed sealing strategy for a repository remains to be made in all concepts.

- The types of instrumentation required for long-term repository monitoring have been identified but development work must continue on longevity of the instrumentation and systems, maintenance, replacement and calibration of the instrumentation *in-situ*, and effective monitoring after repository closure without using invasive installations that might affect the passive safety of the repository.

- Continued work to develop, refine and apply coupled modeling capability and to compare model results to field data from large scale *in-situ* experiments.

6 Clay rock

Clay rocks (see definition used in this report in Section 6.1 below) represent very good conditions for hosting repositories for long-lived radioactive waste because of their low hydraulic conductivity [6-1, 6-2] and self-sealing ability provided that they do not contain continuous permeable layers of silt and sand. The ongoing RTD work in Belgium, Spain, France and Switzerland presently focuses on solving potential practical problems such as rock stability, predicting the long-term waste isolation function of undisturbed and disturbed clay host media (e.g., diffusion experiments, EDZ investigation) and the effect of coupled processes (e.g., heat-induced pore water pressure changes) as well as release of repository-generated gas. Depending on the mechanical properties and the state of stress, the construction of the shafts, drifts and rooms may be more difficult than in other potential host rocks (salt and crystalline), especially for non-cemented normally or slightly over-consolidated clays. Therefore, special emphasis will be given to rock mechanical issues in planning and construction of repositories in this type of geological medium.

6.1 National repository concepts

Argillaceous clay media, which are under discussion as host rock for radioactive waste disposal, cover a wide range of rocks or soils, and are thus difficult to describe as a single rock type. Sedimentation processes (marine or alluvial), as well as burial, up-lift and temperature history, have formed materials which are quite individual, differ in water and clay mineral content, and therefore have very different mechanical, physical and hydrogeological properties.

Two different categories of clay materials are so far being investigated by the Participants for a repository. They are in this report summarized as “clay rock”:

- Soft (or poorly indurated) clays (e.g., Boom Clay) with relatively high water content, which behave in a somewhat ductile or viscous manner.
- Hard or stiff (indurated) clays (e.g., clay shale, claystone or argillite) with quite low water content that tend to deform and fail more like brittle materials because of cementation effects and show only limited viscous behavior.

Depending on state parameters (stress field and pore pressure) and the mechanical properties of the clays, some of the concepts for emplacement cells (drifts or boreholes) require massive liners or rock reinforcements, while others can rely on the strength of the host rock and need little ground support during the operational phase.

These differences in material properties require different layouts to ensure an adequately safe repository and have consequences for the operational phase as well as for long-term safety assessments. In addition, national regulations, waste quantities and waste types differ among the countries. Therefore, the national concepts described below show significant differences, although some basic design elements also show similarities, which are clay specific. In most cases clay layers have, in contrast to crystalline rocks or salt rock domes, only limited thickness on the order of hundred to a few hundred meters. This limited vertical extent of the host rock provides some natural limitations on the design of the repository. Most designs basically place the repository in the centre of the clay layer and keep its vertical extension at a minimum to maximize the thickness of the clay barrier, both above and below the repository. This basic criterion restricts design possibilities and has the following consequences - on the one hand, the repository plane has to have the same inclination as the clay layer and, on the other hand, in-room emplacement or horizontal emplacement boreholes are the favored basic geometrical layouts. Vertical emplacement boreholes, even short ones, such as in the KBS-3V concept from Sweden for crystalline rocks, are presently considered less suited for clay.

6.2 Description of national repository concepts

The countries considering disposal of long-lived radioactive waste in clay, i.e., Belgium, France, Spain and Switzerland, have different repository concepts. They are briefly described below.

6.2.1 Belgium

The Boom Clay Formation, considered as the candidate repository host formation, is of marine origin, 30 to 35 million years old (Rupelian, Middle Oligocene). The Ypresian Clay (Eocene, 50 to 56 million years old), which is also of marine origin but stiffer than the Boom Clay, is considered an alternative. The Boom Clay Formation shows a rather constant chemical and mineralogical composition. However, there are variations in grain size, organic matter, and carbonate content, resulting in the typical layering of the deposit.

The Boom Clay Formation has a downward inclination of 1% in NE-direction. The bottom of the formation is therefore at some 400 m at the Northern border of Belgium, and down to 1 000 m in the Roerdal Slenk at the NE of Belgium, where the formation has been affected by tectonic faults related to the Roermond Graben. These faults are essentially oriented in an NNW-SSE direction. Near the Mol site, there is a small satellite fault (Rauw). The principal stresses in the Boom Clay Formation are nearly lithostatic. At the Hades URL (see Section 6.2), the theoretical vertical stress value (overburden pressure) of 4.5 MPa mostly exceeds the measured values. However, this is due to the difficulties related to total stress measurements. Horizontal stresses are lower than the vertical stress. Some measurement techniques (e.g., hydrofracturing) indicate a factor of 1:2, but usually a smaller differential stress value is observed.

The current repository design for disposal of HLW/SF [6-3] is shown in Figure 6-1 is based on a horizontal network of disposal galleries. Access to the underground facility is secured by means of two shafts of about 6 m diameter. The disposal gallery lining is composed of concrete vault stones. The vault stones will probably be of the “wedge blocks” type, which were used as gallery lining elements for the connection gallery in the Hades URL, constructed in 2002. These wedge blocks are precast, non-reinforced concrete ring elements, which are placed against the excavated gallery wall with special mechanical equipment. Key wedge blocks, inserted with a certain pressure as a last step, provide the necessary expansion force to keep the ring elements in place.

The design of the disposal gallery itself has not yet been finalized. The original design (also called “SAFIR-2”) [6-4], has been abandoned in favor of 3 alternative designs. In the original design, the HLW-containers with their overpack were emplaced in a central tube in the gallery axis, with the space between this tube and the gallery lining being backfilled with precompacted backfill blocks. The experiences with the OPHELIE mock-up, the preparations for the PRACLAY experiment, and the review of the SAFIR-2 report resulted, however, in the identification of a number of unresolved questions regarding the practical implementation of the reference design. In general, these questions were related to feasibility (transport and emplacement of the HLW packages, and assembly of central tube), and reliability (interaction of disposal tube with the backfill around it). Furthermore, the material selection and dimensions for some engineered barriers (e.g., overpack) seemed not sufficiently justified and documented.

These unresolved questions clearly indicated that the SAFIR-2 reference design still needs further development and modifications. To meet this need, and at the same time provide for a broader basis of justification of a proposed design, a special task force (called Groupe Travail Architecture - GTA), is reconsidering this design for a repository facility in the Boom Clay, based on a systematic step-by-step approach. The approach included the elaboration of a number of alternative technically feasible designs, followed by the selection of the best option, but without excluding the others. Detailed reporting and easy traceability of the evaluation are other important goals of the GTA work.

Three designs have been proposed and two of them are based on “in gallery” emplacement (supercontainer and sleeve design), and one is based on “in borehole” emplacement (Borehole design).

The supercontainer design is based on the encapsulation of an overpack with HLW containers in a large concrete package (cylinder of about 2 m in diameter and 4 m long). Two types of concrete are considered: ordinary Portland cement (OPC), which is a “high pH” type, and inorganic phosphate cement (IPC), which is a “neutral pH” type. In the sleeve design, the waste packages are disposed within concrete sleeves lying in the disposal gallery. Each concrete sleeve contains one waste package. This concrete sleeve is installed in the disposal gallery just before the waste package is inserted. Each new concrete sleeve is aligned against its predecessor by means of a key stone. A shielding plug closes off the already disposed waste in the gallery and thus provides radiological protection. The plug is removed before the arrival of each new waste package, and put back in place after the waste package is inserted.

In the Borehole design, the disposition of the waste packages occurs in shallow vertical holes drilled perpendicular to the centerline of the disposal gallery and only long enough to fit one package of waste. After drilling, the boreholes are immediately equipped with a stainless steel liner, thick enough to withstand the forces exerted by the surrounding clay. At the bottom of the gallery lining is a circular opening that provides access to the borehole. The actual space for disposition of the waste overpack is inside the above-mentioned metal liner, which is fitted into the borehole and fixed to the concrete bottom of the disposal gallery before waste emplacement. The inner diameter of this liner is somewhat larger than the outer diameter of the overpack. After the waste has been disposed, the borehole is closed off with a plug of radiological shielding material. On top of this plug is a lid of stainless steel, overlain by a concrete block, which is level with the floor of the disposal gallery. An alternative configuration exists in horizontal boreholes instead of vertical ones.

A selection of the most suitable design has been made. It involved the performance of a multi-criteria analysis [6-5]. The results of this analysis gave a clear advantage to the Supercontainer with high pH buffer (OPC), while the IPC Supercontainer was selected as the preferred alternative option. This outcome is primarily due to the fact that the Supercontainer design allows the formation around the overpack of a buffer environment with engineered and sustainable corrosion-favorable characteristics. A buffer material made of OPC-based concrete has the advantage over an IPC-based buffer in that the former material has a much broader experience and knowledge basis, which is especially important with regards to the interaction with the surface of the overpack. The formation of a corrosion-protective layer of passive material on the surface of an embedded carbon steel body under the influence of a high pH alkaline environment is a well-known phenomenon.

The outcome of the multi-criteria analysis reflects the current state of RTD. It does not mean that the alternative designs are rejected. The selection of the reference design, which is intrinsically an iterative and continuous process, should be reviewed after more information has become available. Until then, the Supercontainer with OPC-based buffer will serve as the reference EBS design.

6.2.2 Spain

The generic clay formation potentially capable of hosting a deep geological disposal facility is composed of lutites and mass clays of lacustrine origin with a high degree of plasticity [6-6]. Its longitudinal extension exceeds 8 km and it measures more than 4 km in the transverse direction. The upper boundary of the layer, which measures approximately 200 m in thickness, is located some 150 m from the surface. The reference depth selected is 250 m. The state of stress at this depth is about 6.4 MPa for the vertical principal stress and 6.2 MPa and 4.3 MPa for the maximum and minimum horizontal principal stresses, respectively.

The system is a multiple-layer hydrogeological arrangement with subhorizontal flows in the more permeable formations lying above and below the clay formation. Descending subvertical flows are considered to exist in the latter, due to the hydraulic gradient existing between the overlying and underlying formations in the recharge zone. In contrast, ascending vertical flows are considered to exist in the area of discharge to the surface. All the formations are considered to be saturated. The "*in-situ*" permeability of the host formation is 4.2E-12 m/s.

The repository geometry is conditioned by the fact that the underground installations are operationally divided into two completely separate work areas: one regulated (disposal) area, where canisters containing the radioactive wastes are transported and one non-regulated (excavation) area, where conventional mining activities are performed. Each of these areas has independent access routes, systems and services, and specific personnel.

Two duly separated disposal areas are planned - the largest and most important is for the disposal of HLW, and the smaller one is for ILW. Both areas have basically the same layout, with the small diameter disposal drifts arranged longitudinally and in modular fashion. The waste is transported on an access ramp while the main access is through the main shaft. In addition, a service and a ventilation shaft exist.

Given that clay is a low-strength medium, the volume of open areas has been minimized and the number of tasks to be carried out inside the facility has been reduced. Wherever possible, work will be performed at the surface, with only those tasks that are strictly necessary being carried out in the central area, which is located between the HLW and ILW disposal zones.

The main gallery connects the central regulated area with the disposal drifts, while the service gallery between the non-regulated area and the disposal drifts is used for the transport of all the elements required for excavation activities. In addition, ventilation galleries are foreseen to serve both the disposal and the excavation areas.

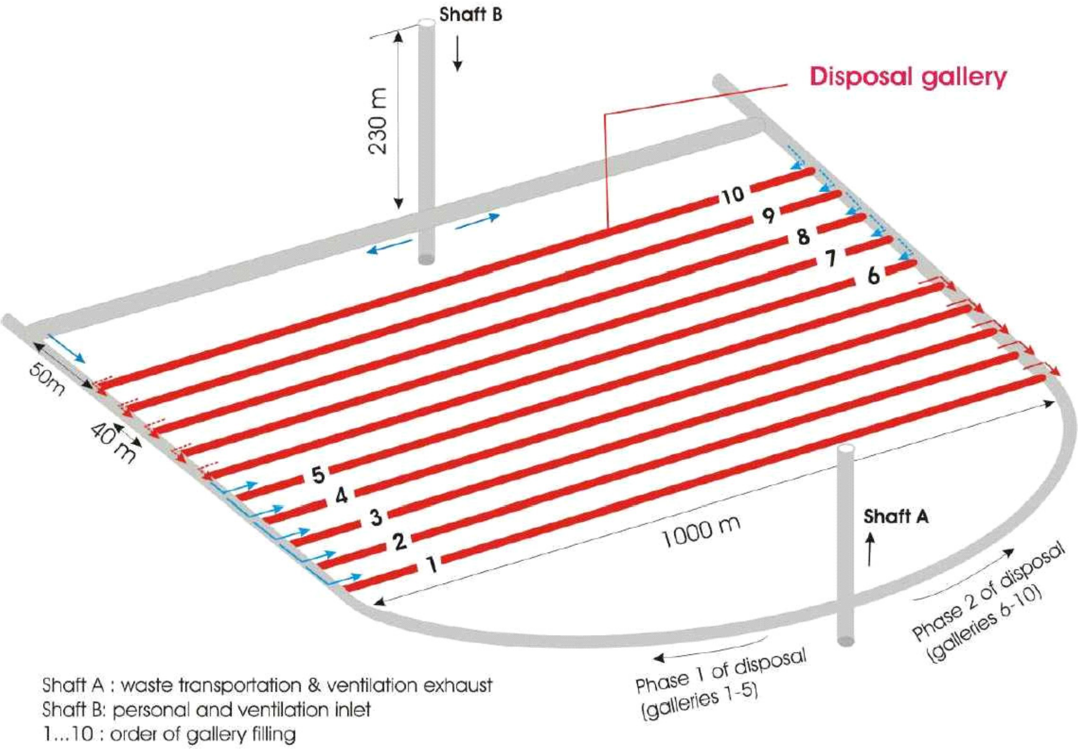


***Figure 6-1**. Basic design concept with long emplacement drifts (example from the Belgium program) for HLW / SF disposal in clay. (Courtesy of SCK-CEN).*

The HLW disposal zone occupies a surface area of 2 100 000 m^2 (3 500 x 600) and is divided into disposal modules, with their respective sections of distribution galleries. The modules are drifts arranged perpendicular to the distribution galleries and are used for the disposal of the waste canisters. The drifts measure 500 m in length and 2.4 m in effective diameter. Each module consists of 8 or 9 such drifts, separated by 85 m in order to meet the thermal requirements. The canisters are separated in the drifts by 1 m, as a result of which 87 canisters are stored in each drift, with 42 disposal drifts being required.

Within the ILW disposal zone, the ILW may be stored in caverns or silos, however, in view of the low strength of clay, in this concept the ILW is also disposed of in small diameter drifts, similar to those in the HLW disposal area. The surface area occupied amounts to 60 000 m^2 (500 x 120).

6.2.3 France

The proposed host formation [6-7] belongs to the eastern margin of the intracratonic Paris Basin. This marine clay deposit is dated from middle Callovian to lower Oxfordian. The layer is virtually horizontal with a slight dip of 1° to 1.5° towards the west and the centre of the Paris Basin.

In horizontal extension, this Callovo-Oxfordian shale layer has roughly the same composition throughout the survey area. Within the formation, slight vertical variations in mineralogical composition of the rock can be distinguished, concerning the content of carbonates, quartz and type of clay minerals. These variations are related to the sedimentary history connected with the sea level changes, at the origin of three sedimentary sequences.

In the Callovo-Oxfordian, the clay minerals are combined with re-crystallized carbonates (geochemical diagenesis) and quartz. Hence, the shale formation has very small pores. These properties and the fine grain distribution explain the very low hydraulic conductivity (between 5.6E-13 to 5.6E-14 m/s). The clay minerals, especially smectite, display high retention capacity for radionuclides and the chemical composition of the interstitial water appear to be in equilibrium with the rock.

A set of preliminary concepts were selected in 1999 [6-8, 6-9, 6-10] to address the issues raised by the feasibility analysis of a potential repository, in particular for the year 2001 report [6-11, 6-12, 6-13] on clay (step report for the final report in 2005 according to the French law on high-level and/or long-lived radioactive waste management in December 1999). In 2002, a new evaluation defined the concepts to be studied until 2005. These concepts have in common a single repository level located approximately in the centre of the nearly horizontal Callovo-Oxfordian clay formation, to allow a significant clay thickness to retain the radionuclides on either side of the disposal level.

The layout of the potential repository distinguishes between separate disposal zones dedicated respectively to B wastes (ILW), C wastes (HLW), UOX and mixed oxide fuel (MOX) respectively. Each zone is divided into modules, to segregate the waste types and to guarantee the flexibility of the repository to adjust to potential variations in inventory or waste management modes. The separation and physical distance between the disposal zones (several hundred meters) and between the modules (several tens of meters) aim at simplifying the assessment of THMC processes, in particular the independence between waste types, including those aspects pertaining to reversibility. Furthermore, within the B waste zone, the waste is separated according to the gas generation and/or the content of organic materials. For example the bituminized sludge will be disposed of separately from the other B wastes.

The disposal concept for HLW and SF disposal packages is short drifts of about 40 meters length and with a diameter of 0.7 m to 2.5 m for the HLW and 2.5 m to 3 m for SF. A smectite-based buffer is foreseen for the SF, but not for the HLW. However, an alternative concept with a smectite-based buffer is studied also for the HLW. The carbon steel container of the SF packages is dimensioned to provide total containment until around 10 000 years after disposal. For the HLW, a carbon steel over-pack is considered and its thickness is dimensioned to provide total containment until around 4 000 years. For both HLW and SF, in each drift, the disposal packages are emplaced into a carbon steel central tube that is the liner for the reference concept of HLW. For the SF, a carbon steel perforated liner is foreseen to provide a mechanical stability of the drift during the operation period and to allow the saturation of the buffer by the argillites.

The B wastes primary packages are grouped into cementitious disposal containers, which are filled by cement or granular material. Then the waste disposal packages are disposed in horizontal drifts (diameter around 10 m to 11 m, length around 250 m). A cement buffer is foreseen in order to ensure a stable chemical environment (alkaline buffer) for several thousands to tens of thousands of years at minimum. Cements with pH 11-12.6 (OPC or Blast Furnace Slag based) will be used. The general characteristics of the cement buffer and the cement disposal container are still not fully defined (for example water/cement ratio), pending further input on gas management and reversibility.

All the disposal cells are oriented in the direction of the major principal horizontal stress in the mid-plane of the Callovo-Oxfordian argillites in order to minimize the EDZ around the excavated openings.

The disposal infrastructure is to be constructed progressively: as soon as the disposal modules have been built, they are brought into operation, while subsequent modules are being built. The coexistence of working and operating zones continues throughout the operating period of the disposal site (several decades). The disposal concepts are based on a separation of all the materials flows relative to construction and operation of the installations: personnel, equipment, ventilation air, as well as cuttings and building materials in the construction period and waste packages in the operating period. To achieve this objective, shafts and galleries that serve the disposal modules have to be dedicated specifically to one of these activities.

As mentioned above, the concepts consider the possibility of keeping the entire disposal infrastructure accessible and ventilated throughout the repository-operating period.

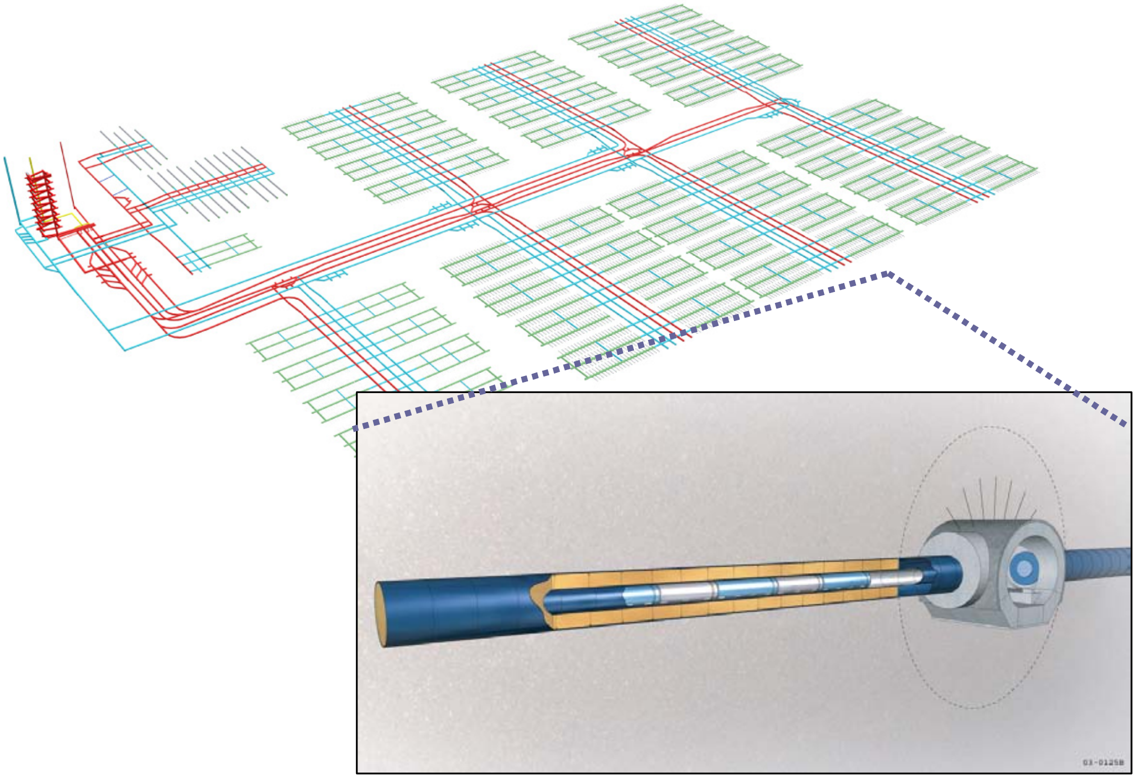


Figure 6-2. *Basic design concept with short emplacement boreholes drifts (example from the French program) for HLW / SF disposal in clay. (Courtesy of Andra)*

The repository closure is envisaged in successive steps: the first step is the closure of the disposal cells and modules, followed by the closure of the different disposal zones, and the closure of related access galleries and finally the sealing of shafts. Sealing the different access drifts involves constructing low permeability seals based on swelling clay or concrete, and backfilling the rest of the drifts.

6.2.4 Switzerland

The proposed repository host rock [6-14] is an overconsolidated Jurassic claystone of the Dogger Formation (about 180 million years old) termed Opalinus Clay (including the clay-rich Murchisonae Beds in an Opalinus Clay facies). At the potential site, the Dogger formation is made up of an approximately 200 m thick sequence of fine sandy claystones and marls with intercalated limestones, calcareous sandstones and iron oolites. The Opalinus Clay at the proposed site in the Zuercher Weinland (thickness approx. 100 m, dip about 6°) generally consists of dark grey, silty, calcareous and micaceous claystones. To a varying extent, these bear thin silt and sandstone inclusions, lenses and laminae, as well as brownish siderite concretions. At the proposed siting region, the Murchisonae Beds (thickness approx. 20 m) above the Opalinus Clay consist of black silty to fine sandy, calcareous claystones and are thus similar, in terms of lithology, to the uppermost Opalinus Clay.

The magnitudes of the principal stress components measured at the potential siting region (Zuercher Weinland) at about 650 m depth are: i) major principal stress of 20-23 MPa (horizontal, direction nearly NS), ii) intermediate principal stress of 15-16 MPa (vertical), and iii) minor principal stress of 15-16 MPa (horizontal). The mechanical properties of the Opalinus Clay have been found to be strongly anisotropic (transversely isotropic). The dependence of the elastic properties and strength parameters on water content confirms the mechanical interactions between rock deformation and pore pressure (hydro-mechanical coupling).

The hydraulic conductivities measured at a depth of about 600 m in the Opalinus Clay vary between 2E-14 m/s and E-13 m/s. Information from an exploration boreholes (borehole Benken - 1 fracture zone of about 150 mm thickness over the whole host rock section of about 120 m) and the 3-D seismic survey indicate that the number of distinct features and fracture zones are very limited in the potential siting region. The few natural fracture zones tested in the Opalinus Clay (e.g., borehole Benken [6-15] and the Mont Terri URL) do not show a measurable increase in hydraulic conductivity in the fractures compared to the intact rock.

The pore water composition reflects a complex series of processes comprising pore water expulsion during compaction, in- and out-diffusion during different burial and uplift phases, and rock/water interaction. Investigations on Opalinus Clay and adjacent aquifers provide large-scale profiles of various pore water components, indicating that diffusion is the major process governing solute transport. Pore waters in the vicinity of the only identified minor fracture zone at Benken indicate no associated geochemical anomaly. The mineralogy investigations show that the phyllosilicate fraction contains mainly kaolinite, illite and illite/smectite interlayer minerals in about equal amounts. The carbonate content is rather high ranging from 10 to 50%, and dominated by calcite. Quartz is also present in relatively large quantities (~ 20%). The presence of pyrite and siderite, which show no signs of oxidation, indicate the reducing nature and the high redox buffering capacity of the Opalinus Clay. The content of organic matter is about 0.5%.

The layout of the underground structures is based on an “in-room” emplacement concept [6-16, 6-17]. HLW / SF canisters will be placed in disposal drifts surrounded by a bentonite buffer. In this case, the bentonite buffer will consist of a combination of blocks and granular material. The dominant part of the layout is the main repository with the disposal drifts for HLW and SF. The approx. 800 m long drifts (diameter of 2.5 m) with 40 m spacing are oriented in the direction of the major principal horizontal stress in the mid-plane of the Opalinus Clay. They branch off at an angle of 60° from the operations drift, which is more or less in the strike of the formation and thus approximately horizontal and open at the other end into the construction drift, which runs parallel to the operations drift (Figure 6-14). The inclination of the disposal drifts, which are located in the centre of the host rock layer is approximately 6% and follows the general dip of the host formation. The construction and operation of the main repository are preceded by the HLW/SF pilot repository. This facility consists of two short disposal drifts and an observation drift and is constructed along the same principle as the main repository. The easy accessibility on all sides allows installation of monitoring and control equipment.

Two disposal drifts (diameter about 9 m and length about 100 m) for ILW have a similar orientation to the HLW/SF disposal drifts, one disposal drift is planned as an extension of the operational drift. For operational reasons they are arranged horizontally. To prevent interaction with the main HLW/SF repository, the three ILW drifts are located at the end of the operations drift, far away and separated by seals from the HLW/SF disposal drifts.

The underground facilities are linked to the surface by an access drift (ramp) and a construction shaft, which also serves as a ventilation shaft and emergency exit. The ramp passes over the disposal zone and allows sensors to be introduced (e.g., from boreholes above the disposal drifts) for monitoring. Due to the operational plan, construction of emplacement drifts and emplacement of waste are done concurrently. This allows the open period for emplacement drifts to be kept to a minimum (less than 2 years). The layout of the repository is based on the principle that construction and emplacement can be carried out without interfering with each other by having separate access drifts and a shaft/ramp permitting, from a radiological point of view, separated protected and non-protected areas.

6.3 Required performance of the repository

6.3.1 General

Performance requirements are defined by the appropriate laws and regulations in the different countries. They are not host rock specific. The national requirements are quite different in the different European countries. SA or PA studies are carried out using pessimistic or conservative assumptions for determining whether or not these specific long-term radiological safety requirements are met. To account for unforeseen FEPs, a large number of scenarios and parameter variations (impact analysis and sensitivity analysis) are investigated to assess the robustness of the proposed disposal system. Sufficient mechanical stability of repository drifts and rooms in the construction and waste emplacement phases is a fundamental operational requirement and since clays commonly have a rather low shear strength and exhibit significant anisotropy, while the rock stresses can be as high as in other geological media, this issue needs consideration.

The regulating authority in Belgium has not yet determined any dose or risk limit for the deep disposal of conditioned long-lived radioactive waste. Belgian legislation and regulations normally conform, or are being brought into line, with ICRP recommendations (as included in the basic standards of the IAEA and the EU). A maximum limit for the dose constraint (used for exposures that are expected to occur) has been defined at 0.3 mSv/a. Also a risk limit (used for potential exposures, i.e., which may or may not occur) has been defined as the product of the probability of exposure to a certain dose and the likelihood of death as a result of that dose. A factor of about 5E-2 per Sv is used by ICRP for this likelihood, and for a dose constraint of 0.3 mSv/a, we obtain a risk constraint of 1 to 2E-5 per year.

In Switzerland, the requirements are outlined in the regulatory guideline R21 from the authorities [6-18] stating that a dose rate of 0.1 mSv/a may not be exceeded at any time. The allowed dose rate is very low in comparison to the natural dose rates, which depend very much on local conditions and range, e.g., in Switzerland, from 1 to about 20 mSv/a.

The radioactive waste will be disposed of in a geological repository at a certain depth and, in principle; it is not envisaged to retrieve the waste at a later stage (disposal not storage). Nevertheless, governments may require evaluation of proof of retrievability or reversibility concepts. There could be different reasons for a retrieval of the waste, for example:

- Social or political considerations.
- Monitoring or new research results indicate that the repository is not safe.
- Part of the ‘waste’, especially the SF, is needed as a resource for further use.

In all cases, the waste has to be retrieved without generation of any unacceptable risk for workers, people living in the vicinity of the repository or for the environment.

Host rocks such as clays, especially soft clay, may cause more difficulties in developing a retrievability plan than hard rocks. Liners or any other support that keep drifts open are likely to degrade with time due to alteration and corrosion. In addition, support may fail due to the additional thermal stress being induced during the thermal pulse. Therefore, significant technical effort could be necessary to retrieve the waste. Depending on the appropriate regulations in the different countries, different levels of emphasis are given to retrievability or reversibility. If it has a high priority, the layout of the emplacement units favors smaller units, which means rather than several hundred-meter-long emplacement drifts (containing a large number of containers), shorter emplacement drifts or boreholes are preferred.

In principle, retrievability in clay, regardless of the type of clay, is feasible at nearly any time but becomes more and more difficult as re-saturation of the repository progresses. Therefore, most countries are following a staged approach. During the different stages, retrievability is always possible but has different technical implications. The different stages could be defined in the following simplified way:

6.3.2 Stage 1: Operation

At this stage, all access, operational and construction drifts are open and accessible, trained crews are available and the re-saturation of the buffer is at a very early stage because of the very low hydraulic conductivities of the host rock and the absence of water-conducting features. This means the buffer and probably the seal material (bentonite) can be easily retrieved and the emplacement be reversed.

6.3.3 Stage 2: Monitoring

The emplacement is finished, part of the drift network is backfilled and sealed, but the access drifts and ramps are still open. Limited trained manpower is available but all necessary information on the construction and emplacement work is available. The re-opening of the backfilled access and operational drift system is standard mining work and no radiological shielding is necessary. The retrieval of the waste from the emplacement unit will be more difficult because the buffer material is probably partly saturated and has built up a significant swelling pressure and temperature will have increased significantly. The retrieval of the bentonite associated with the reinforcement of the drift support is time consuming but feasible, as has in principle been shown in the URLs. Short emplacement units clearly have an advantage in such a situation.

6.3.4 Stage 3: Post-closure

At this stage, all underground structures are backfilled and the repository is not accessible anymore. Detailed studies have to be made of how to re-access the closed repository, whether by opening old access ramp or shafts or by constructing new ones. Retrievability during this stage is very time consuming and expensive but still feasible.

Depending on the different programs, additional stages could be necessary or appropriate but they are not being discussed in this report.

Monitoring starts with the initial characterization of a repository site. The changes of the baseline conditions due to construction, operation and closure can then be followed. The monitoring program in tight rocks such as clays will probably be significantly different from that in hard and brittle rocks as, e.g., changes in water levels or hydraulic heads at some distance from the underground drifts can hardly be detected.

From a technical and scientific point of view, long-term monitoring is not mandatory for a repository that is designed to be passively safe, but it is requested by government or public in most countries. Such monitoring has to be designed to ensure that safety of the repository is not compromised by the monitoring system. This means that sensors should not be placed too close to the waste and cables should be avoided (hydraulic shortcut). To avoid undesirable effects due to monitoring, some countries plan to build a pilot repository close to, but hydraulically isolated from the main repository. This pilot repository would contain a small but representative amount of waste in a configuration that mimics the conditions in the main repository (e.g., see Swiss concept described above). This pilot repository could then be monitored during a special extended monitoring phase and closed at a later stage. Monitoring programs are not defined at the moment and research work is conducted in existing and upcoming projects to define monitoring strategies in more detail.

6.3.5 Current repository design principles

The design of the different clay repositories is based on the concept of a multi-barrier system and the regulatory requirements, which differ from country to country. All concepts for the disposal of HLW and SF in clays provide safety by a combination of EBSs (see Section 6.5) and the natural geological barriers. The geological barriers provide a stable protected environment for the EBS, ensuring their longevity. The clay host rock also provides retardation of radionuclides that escape from the EBS. This is achieved through siting of the repository in a low-permeability host rock, with favorable groundwater chemistry, in a tectonically stable location. In general, the clay layer is identified in most programs as the main barrier against the transport of radionuclides from the repository, because of the physical and hydraulic properties of the clay and the relatively large thickness in comparison with the EBS. In general, the following design requirements can be specified:

Design requirements related to safety

The safety-related requirements are based on the general design requirements and safety strategy. The disposal system must provide physical containment (water tightness and limitation of water influx) during the thermal phase of the repository, delay and disperse the escape of radionuclides (from the waste matrix and through the disposal system), dilute the concentration of radionuclides escaped from the disposal system, and limit access to the disposed waste.

- The EBS has been attributed the role in the disposal system of ensuring containment of the radionuclides during the operational and thermal phases of the repository. The required time periods may be derived from the consideration that complex interactions between components of the EBS and also radionuclide migration under a significant temperature gradient should be avoided during the thermal phase. Both phenomena are generally considered as potentially enhancing radionuclide releases. The duration of the period during the operational phase, in which the waste overpack and its immediate environment are exposed to the corrosive effects of air, should be minimized. The reliability of the materials used and applied operations should be ensured by a Quality Assurance and Quality Control (QA/QC) Program elaborated for each component (e.g., for welds).

- The repository design should minimize perturbation of the barrier performance of the clay host rock. The role of the host rock in the disposal system is to delay and disperse the escape of radionuclides from the waste matrix and through the disposal system. The specific characteristics of the clays may not be irreversibly disturbed by mechanical operations. This may require the use of specialized excavation and construction techniques to make the (circular) galleries with limited dimensions.

- The different components of the EBS should be conceived and chosen in such a way that they do not adversely affect the performance of the host rock

- The horizontal disposal galleries are assumed to be located in the middle part of the clay layer in order to maximize the effective thickness of the layer of clay around the waste.

- The temperature increase in the near-field should be limited (e.g., a maximum temperature requirement of 100°C at the interface between the overpack and the surrounding material has been selected in the Belgium concept). This requirement should minimize the temperature impact on the long-term performance of the EBS and on the performance of the host rock.

Design requirements related to the assessment of long-term radiological safety

- The disposal system should possess a high level of robustness in order to limit the uncertainties related to the assessment of its long-term performance, i.e., the characteristics of its components should exhibit a certain stability or predictability. It is important to avoid as much as possible any occurrence of chemical or physical interactions between the waste, the EBS and the host rock.

- As the decision to suspend reprocessing was made rather recently in some countries, design studies for the disposal of SF have not always progressed as far as the vitrified waste studies. However, as a general rule, the different waste types (HLW, SF and ILW) will be disposed of separately (compartmentalization).

Design requirements related to safety during the operational phase

- The repository design should provide radiological protection to the personnel operating the repository facility. The national legislations with respect to the maximum allowed doses have to be respected.

- Clays, even over consolidated claystones, are comparatively low-strength materials and the current disposal concepts favor keeping emplacement units open for a short time only. Therefore, concurrent construction and emplacement work is planned, which could lead to conflicts in operational radiological safety. In such cases, it is foreseen that emplacement and construction work would occur in separate areas, i.e., regulated and non-regulated areas, with separate access and infrastructure.

Design requirements related to criticality

All the conditions of normal and contingency operation and all the conditions of long-term containment of the waste must be such that they take adequate account of the risks of criticality.

Design requirements related to non-radiological environmental impact

Depending on the specific geological conditions at a given site special design requirements can be specified to minimize the effect of the repository on the environment (e.g., temperature increase in nearby aquifers).

Design requirements related to flexibility

The design concepts are based on the “successive optimization” principle, that is, the design should be flexible enough to adapt to improved knowledge on the host clay formation and on the barrier materials. As a general rule, the development and implementation of a disposal system should follow a step-by-step approach. The concerned time period covers many decades, during which new insights may be acquired or new technologies developed. It should therefore remain possible to reverse or to defer certain decisions based on new findings.

Design requirements related to retrievability of the waste

Retrievability or reversibility of the emplaced waste may become a legal obligation in some countries. Therefore it should be considered for each of the lifetime phases of the repository. However, design options introduced to facilitate retrievability should under no circumstances adversely affect the operational or long-term safety of the repository.

Design requirements related to technical feasibility

The repository design should be shown to be technically feasible. Therefore, the design of the repository components and transportation equipment should be based on well-known components and mechanisms that have proven their effectiveness and reliability in industry.

6.4 National and international URLs

6.4.1 Description of URLs – geological setting

Currently, four URLs are in operation or under construction in clay rock. These laboratories are:

- Hades (High Activity Disposal Experimental Site) URL at Mol, Belgium in Boom Clay (soft, plastic clay)
- Mont Terri URL at St. Ursanne, Switzerland in Opalinus Clay (claystone)
- Tournemire URL in France in hard clay (not described here)
- Meuse/Haute Marne URL at Bure, France in Callovo-Oxfordian argillite (under construction).

Hades URL

The Hades URL (a site-independent or off-site laboratory at the site of SCK-CEN, Mol) is located in the Boom Clay Formation, at a depth of 223 m (axis of gallery). The host clay layer is roughly situated between 190 and 290 m below the ground surface at this site. The Boom Clay formation consists of three members: the Putte member (in which Hades is located), the Terhagen member and the Belsele(-Waas) member. The differences are, however, not significant.

The most abundant minerals in Boom Clay are clay minerals, quartz and feldspars. The clay minerals consist mainly of illite, but also kaolinite, interstratified layers (illite/smectite) with swelling behavior, and some chlorite. Traces of glauconite and pyrite occur both in carbonate concretions as in nodules and tubes around organic remains. No significant variation or trend has been observed with respect to depth.

The Boom Clay is a nearly homogeneous, semi-permeable layer, with a hydraulic conductivity of 2 (vertical) to 4 (horizontal) times E-12 m/s. The hydrostatic pressure of some 2.2 MPa has been observed at the URL level. As a rule of thumb, the water pressure is zero near the permeable lining, and increases by about 0.1 MPa/m in radial distance from the gallery lining and reaches ambient natural pressures within a few tens of meters from the lining.

Mont Terri URL

The Mont Terri URL is a site-independent or off-site laboratory. The investigations focus on Opalinus Clay [6-19, 6-20] the Swiss sedimentary option for the safe disposal of HLW, SF and long-lived ILW. This laboratory is operated as an international project, headed by the Swiss Federal Office of Water and Geology (Division of the Swiss Geological Survey) and managed by the Geotechnical Institute (St. Ursanne). The URL is located in an annex drift of a highway tunnel, which is operated by the Republic and Canton of Jura, Switzerland.

The Mont Terri URL is situated in the Opalinus Clay, a formation consisting mainly of silty and sandy claystones. The formation can be characterized as an over consolidated claystone formation with 40-80% of clay minerals and micas, 10-40% quartz, 5-40% calcite, 1-5% siderite, 0-2 % pyrite and 0.1-0.5% organic carbon. The URL is located in the Folded Jura, a mountain chain created by tectonic deformation in connection with the Alpine orogeny. The main tectonic structure of the area is the Mont Terri anticline.

The hydraulic conductivity of the Opalinus Clay at the Mont Terri URL is on the order of E-12 to E-13 m/s [6-21]. No significant differences in hydraulic properties are observed in the different facies of the formation or in the existing small scale tectonic fractures and fracture zones.

Meuse / Haute Marne URL

The Meuse / Haute Marne site is located in the Parisian Basin, in the northern part of the Haute-Marne and in the southern part of the Meuse Départements. The host rock for the URL is the Callovo-Oxfordian formation, which is located at depth of 450 ± 100m and its thickness is between 110 and 150 m. The Callovo-Oxfordian formation has a very weak and regular dip of 1° to 1.5° towards the North-West. Overall, it is homogeneous. It lies between the limestone formations of the Dogger (lower level) and those of the Oxfordian and Kimmeridgian (upper levels). No faults with vertical displacement have been shown to exist in the Callovo-Oxfordian. On the Research Underground Laboratory site (Bure site), quasi-vertical structures have been located in the subjacent levels of the Dogger. These strike West-North-West and East-South-East and have a small vertical displacement (2.50 m on average).

The Callovo-Oxfordian argillites were deposited between 160 and 150 million years ago. The formation is characterized by three successive sequences of deposition. The transformations undergone by the rock after its deposition are due to various successive processes, first of all a progressive compaction of the sediments with expulsion of water, under the weight of the subsequent deposits, then physical/chemical modifications induced by large amplitude tectonic events that affected the whole of the Paris basin. At the level of the argillites, the temperature always remained below 50°C. The processes that did affect the clays (compaction, expulsion of the water contained in unconsolidated muds) were thus of a relatively moderate nature.

The vertical stress is a principal stress that is equal to the weight of the overburden at the depth considered, taking into account the regular sedimentary structure and the moderately accented topography of the site. The major principal horizontal stress in the Callovo-Oxfordian has an average strike of N155°E and is equal to from 1 to 1.4 times the vertical stress. The minor principal horizontal stress is of the same order of magnitude as the vertical stress (factor of 1 approximately).

The mineralogical composition of the Callovo-Oxfordian argillites provides them with a comparatively high strength for an argillaceous rock. They are not easily deformed and can be damaged only after exceeding a certain load threshold where upon they behave quite brittle at failure. Their significant content in clay minerals limits the domain of reversible deformation, attenuates the brittle behavior (plasticity), tends to reduce the strength of the rock and gives it a noticeable viscous behavior (creep). Hence, three horizons with appreciably different geomechanical behavior, corresponding to slightly different lithological characteristics, can be distinguished in the Callovo-Oxfordian formation. The Callovo-Oxfordian argillites have anisotropic thermal conductivities lying between 1.3 W/m/°C in clayey layers and 1.9 -2.7 W/m/°C in more carbonated ones. Argillites have very low hydraulic conductivity (E-14 to E-13 m/s). Water flows circulating by convection within the Callovo-Oxfordian formation are consequently very limited. Diffusion is the dominant mechanism of transport of solutes in the argillites. The Callovo-Oxfordian argillites provide a reducing environment. Argillites have a strong buffering capacity with respect to any alkaline disturbance.

The Oxfordian limestone (the formation that immediately overlies the argillites) consists of a vertical succession of horizons with hydraulic transmissivities ranging between 5E-9 and 3E-7 m/s. The recharge of this formation comes mainly from the outcrops located east and south of the Bure site. In the Dogger, the borehole tests showed a relatively low permeability (E-8 m/s in the most productive horizons). No productive horizon with regional extension was identified.

The Bure site URL is located on a plateau zone far from the major valleys and located at the head end of a secondary hydrographic network where erosion is slower. A progressive disappearance of the Barrois limestone is considered for the next 300 000 to 600 000 years according to the study assumptions. Except for the zones of influence of the great regional faults (faults of the Marne to the West, graben of Gondrecourt-le-Chateau to the SE), the study sector has great geodynamic stability. The area of the Meuse/Haute-Marne area is believed to have a very low deformation rate and a very low seismic activity.

6.4.2 Design and construction of URLs

Hades

The current Hades facility consists of underground galleries with a total length of some 200 m, at a depth of 223 m (gallery axis), and an inner diameter ranging from 3.5 to 4 m. An overview of the current and planned underground infrastructure is shown in Figure 6-3.

After construction of the first access shaft in 1980, in which both aquifer and clay had been conditioned by freezing, the first gallery, 35 m long, was constructed in 1982 in frozen clay, and has been lined with cast iron segments. The Test Drift, 65 m long, was excavated in 1987, without prior freezing of the clay host rock, and 55 m were lined with concrete lining segments, and the last 10 m was lined with sliding ribs to assess the performance of this type of lining. The experience of excavating in unfrozen clay had been gained from the construction (1984) of an experimental shaft and a drift, whereby it has been shown that excavation in the clay can be better performed without freezing.

All excavations and constructions at this time were performed manually because of the experimental nature of the works, and because of the confined space. The experimental drift has been backfilled, and the experimental shaft is now the subject of a large-scale shaft sealing test (RESEAL).

From 1995 to 1997, a second access shaft was constructed (freezing was only applied to the sand layers and the transition zone, down to a depth of 190 m). As with the first shaft, the excavation of the frozen material was performed in a semi-mechanical way by pneumatic equipment. Experiments with blasting were performed during the excavation of the second shaft to speed up the excavation. This however turned out to be ineffective, as only a limited amount of explosives could be used to avoid the risk of endangering the water-tightness of the frozen wall around the excavated shaft.

A watertight lining was needed for both shafts. For the first shaft, a polymer liner was applied between two concrete linings (cast in place). The second shaft lining was constructed through prefabricated concrete rings with an outer steel jacket. The steel jackets were welded together to obtain a hermetically closed lining.

From the second shaft, a connecting gallery was constructed in 2002 using a mechanized excavation technique (road header with shield), as opposed to the previous excavations, which were performed mainly in a manual way (due to e.g., the confined space). The gallery has been lined with concrete segments, installed through the “wedge block” technique. The excavation and lining techniques used minimized the impact on the host rock (and resulted in minimal EDZ) by increasing the excavation rate (> 2 m/day) and minimizing the over-excavation, thereby reducing the convergence of the clay around the gallery to a minimum.

As all shafts and galleries are lined with a permanent lining, access to the host clay must be achieved through boreholes with diameters between 70 mm up to several hundred mm, and depths up to 40 m. The diameters depend both on the experiment requirements as on the technical feasibility (long boreholes require a larger diameter). Large-scale set-ups (backfilling, combined radiation and heating tests, and ventilation) normally consist of one large diameter hole, with several monitoring boreholes parallel to it.

The construction of a demonstration test gallery (PRACLAY) to perform a long-term heater test is planned in 2006.

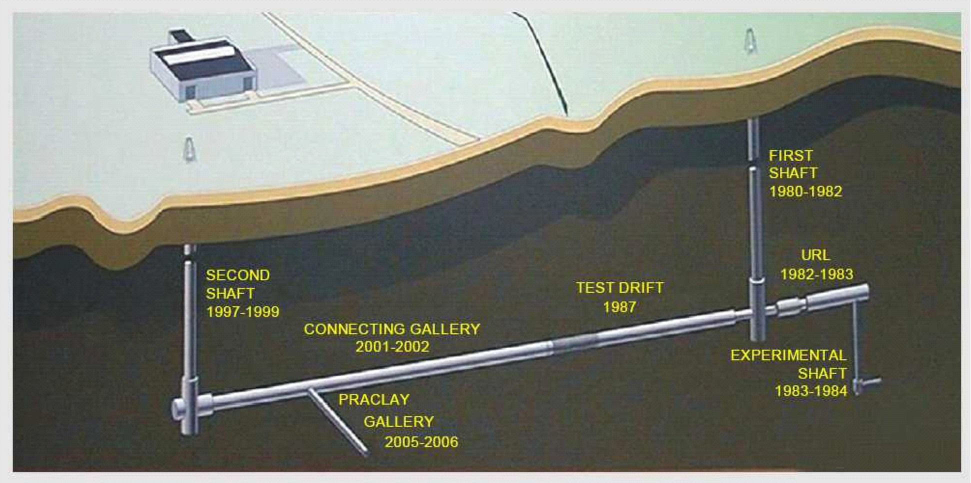


Figure 6-3*. Construction history of the Hades URL. (Courtesy of SCK-CEN).*

Mont Terri URL

The access to the Mont Terri URL is via nearly horizontal drifts, which were constructed outside the URL-project. The Mont Terri URL was constructed from an existing highway tunnel system, the access is through the security (formerly known as the reconnaissance) gallery of the highway tunnel. Drifts and niches (Figure 6-4) are excavated by different techniques. Depending on the objectives of the different experiments, underground excavations were carried out using: drill-and-blast technique, road header, pneumatic hammer or a modified raise boring technique. Most of the drifts were constructed parallel to the existing road tunnel. The axis of these drifts is mainly perpendicular to the strike of the bedding planes and about 45° to their dip. It turned out that mechanical excavation, especially with a conventional road header, is very well suited for this type of rock. For financial reasons (very short excavation length) full face tunnel boring machines (TBMs) have not been tested in the URL so far but a lot of experience from TBM tunneling in Opalinus Clay is available from other projects. Because of the relatively high strength of the Opalinus Clay, the use of a TBM seems to be the optimum excavation technique in this rock type. Drill-and-blast excavation is also feasible but it turned out that neighboring drifts (especially their liners) could be negatively affected by this technique even at distances greater than 20 m if the blasting pattern and the charges were not at an optimum.

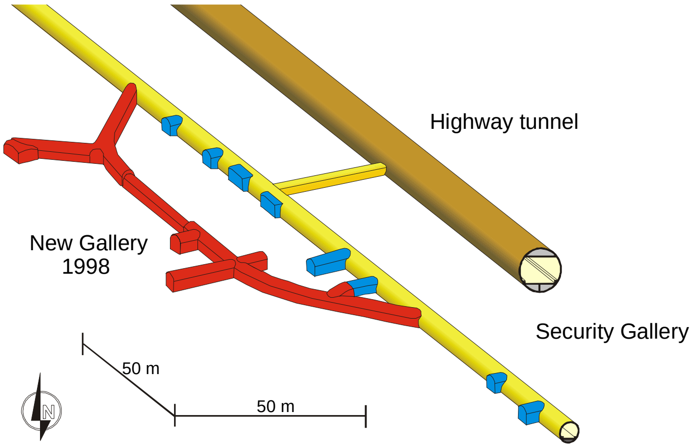


Figure 6-4. *Layout of the Mont Terri URL. (Courtesy of Nagra)*

In general, rock support with steel fiber reinforced shotcrete of less than 0.2 m thickness is sufficient for drifts of 3 to 5 m in diameter. In some cases, depending on drift orientation with respect to the stress field and the bedding planes as well as the existence of fracture zones, drifts may need additional support with rock bolts. One micro drift with a diameter of about 1 m drilled with a modified (horizontal) raise-boring technique did not need any lining.

Meuse / Haute Marne URL

The two access shafts (principal and auxiliary) of the Bure URL are sunk by means of a drill-and-blast method with the length of one blast round being 2.4 m. A temporary support with grouted bolts and wire mesh is set immediately after blasting and removal of the blasted rocks. The definitive concrete lining is installed about 12 m behind the face. Smooth blasting is foreseen for excavating the zone for the experimental study of the hydro-mechanical response of the argillites to the excavation. Support alternatives such as replacing the grouted bolts and wire mesh with arches may also be tested.

The galleries of the Bure URL will also be excavated with a drill-and-blast method. A few experimental sections may be excavated with a different method such as for example a road header machine.

6.4.3 Activities in the URLs

The Hades and the Mont Terri URLs were both constructed as site-independent URLs with Hades in the more plastic Boom Clay formation and Mont Terri in the more brittle Opalinus Clay. A first part of experiments in both these URLs was directly linked to the construction of the underground infrastructure itself and the characterization of the sites. One of the related objectives was to demonstrate the feasibility (technical and economical) of important underground constructions in the projected clay formations (characterized by very low to low mechanical strength and full water saturation).

At the Hades site, important conclusions could be drawn from the construction of shafts through sandy aquifers, and from the construction of galleries in clay with respect to the excavation and supporting techniques in clay or soil conditioning in sands (freezing) or clay (anchoring). The construction itself was usually accompanied by extensive monitoring, to check the design hypotheses or just for safety purposes. A specific set-up, the Mine-by test, was linked to the construction of the experimental shaft and drift at the end of the first gallery, to assess excavation in non-frozen clay. The CLIPEX experimental program assessed the performance of optimized excavation and lining techniques applied at the construction of the connecting gallery.

At the Mont Terri site, access was provided through an existing highway tunnel, thus no experience was gained on the construction of access ramps or shafts. However, similar to the Hades facility, a comprehensive mine-by test [6-22] was conducted to learn basic lessons on the excavation of drifts in a stiff clay.

Following the first, mainly construction-related experiments, new experiments were designed in both URLs to fulfill the needs of site characterization, engineering and safety assessment. The general way to launch and implement such experiments is:

1. Initiation phase.
    - Open questions.
    - Definition of objectives.
    - Drafting of possible realizations.
2. Design phase.
    - Evaluation of possible realizations.
    - Scoping calculations and sensitivity studies.
    - Selection of important parameters
    - Elaboration of preliminary test sequences.
    - Site selection.
    - Selection of instrumentation.
    - Test plan.
3. Implementation phase.
    - Preparation of infrastructure.
    - Instrumentation.
4. Testing.
    - Measurements.
    - Data evaluation.
    - Adaptation of test plans (if necessary).
5. Interpretation and reporting.
    - Numerical back-calculations.
    - Analysis.
    - Report preparation.

The main objectives of the experiments at the two URL sites are:

- Determination of material parameters and their scale dependence (size and time).
- Development of investigation methods and testing of equipment.
- Investigation of processes and system understanding
- Demonstration of repository behavior and design on large scale.

Experiments at Hades

The first experiments intended to assess the compatibility of different materials with the host clay environment. This included many field corrosion trials of waste package components (*in-situ* corrosion experiments) and the hydration of backfill materials (BACCHUS and BACCHUS II).

Another set of experiments dealt with the characterization of the host clay and included tests designed to address the following processes and phenomena: determination of migration parameters through injection and percolation tests, migration/diffusion of gas in a clay environment (MEGAS), thermo-hydro-mechanical behavior of clay (ATLAS), the combined effect of heat and gamma radiation on clay and backfill behavior (CERBERUS, Figure 6-5), and chemical and bacteriological phenomena (ARCHIMEDE) to give some examples.

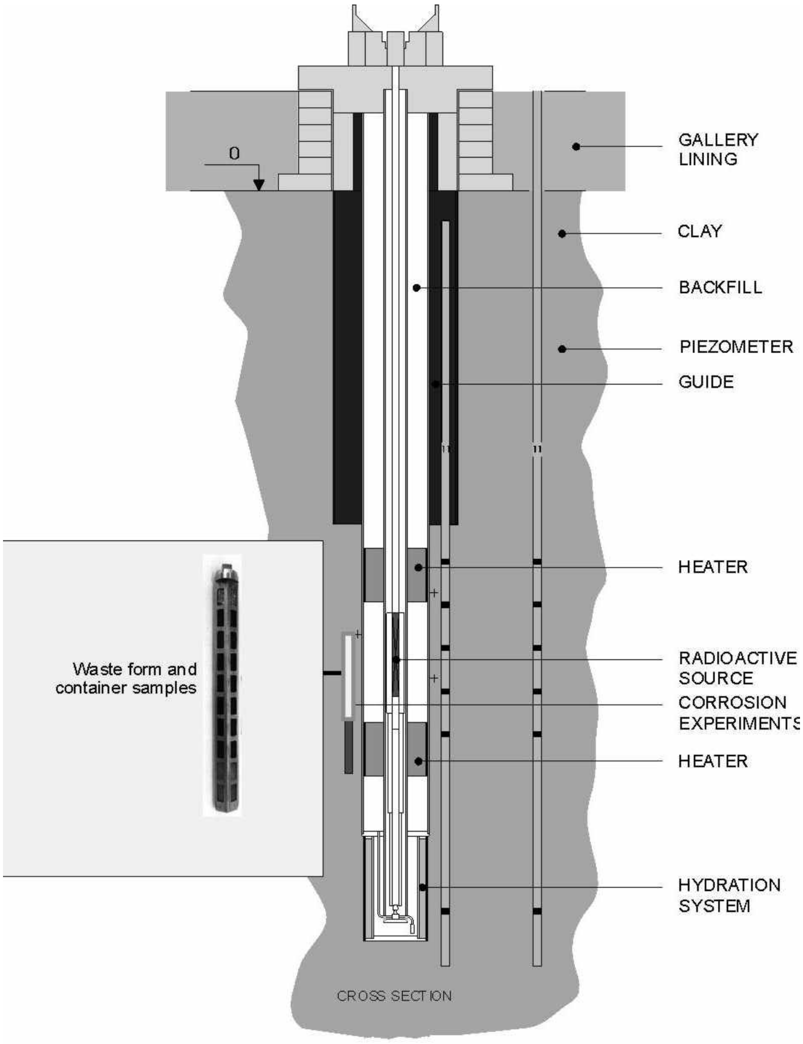


Figure 6-5. *Layout of the CERBERUS experiment at Hades, which is designed to study coupled THMC processes.*

Specific concept parts were tested, dealing with the design and performance of seals (RESEAL), and the corrosion rate of active waste glass samples (CORALUS). At the surface, a mock-up test "OPHELIE" simulating a 5 m long section of a disposal (as far as central tube and backfill buffer are concerned) has been running for almost 5 years. The experiment served both as a test of the intended buffer backfill material and as a preparation (e.g., check of instrument reliability) for the pending full-scale *in-situ* test in the URL. The first full-scale, integrated *in-situ* test of the repository concept [6-23], the "PRACLAY" test, is in the design phase. The final design of this test will be based on the conclusions of the current concept review.

An overview on the experiments at Hades is provided in Appendix 1.

Mont Terri URL

In the starting phase of the international Mont Terri URL, a number of experiments were carried out to characterize the mechanical [6-24] hydraulic [6-21], mineralogical and geochemical [6-25] properties of the Opalinus Clay, e.g., deformation mechanism (DM) experiment, diffusion experiments (DI, DI-A, DI-B experiments), gas permeability (GP) experiment, and pore water chemistry (PC, WS experiments). More integrated experiments followed at a later stage to investigate coupled processes (e.g., EDZ self-sealing experiments (EH and Selfrac)).

With respect to testing repository designs, several integrated experiments (co-sponsored by the EC within the 5th Framework Programme) were carried out. These experiments included:

- The Heater Experiment (HE) is a thermal test in a vertical borehole in a clay formation [6-26]. The main objectives were to analyze the response of the claystone to the thermal stress, and to study the interaction between the clay buffer and the host rock, as well as the validation of coupled codes.

- The Engineered Barrier Experiment (EB) is a full-scale demonstration isothermal test of the emplacement and hydraulic behavior of a new type of buffer [6-27] consisting of a mixture of compacted blocks and granular bentonite (Figure 6-6). The main objectives of this test were to validate the feasibility of this type of backfill and to assess the characteristics of a clay barrier constructed by this method.

- The Ventilation Experiment (VE) is a test studying the influence of drying and wetting phases on the host rock in the vicinity of an emplacement drift (scale test to real case approx. 1:2). Macro-permeability and the hydro-mechanical behavior of the claystone are investigated. The experiment is supported by scoping and back calculations with coupled numerical codes.

A more detailed listing of experiments performed at Mont Terri URL is provided in Appendix 1

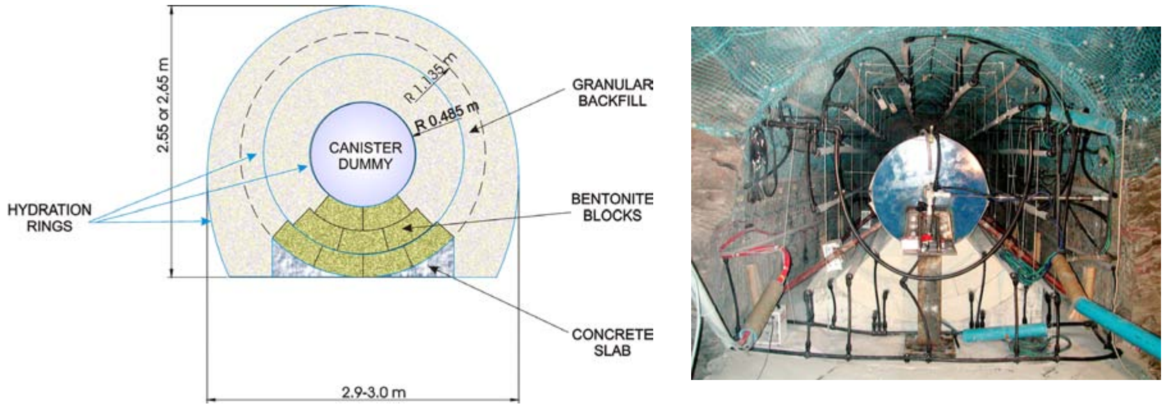


Figure 6-6. *Design of the EB experiment [6-27]. Schematic layout (left) and photo of the situation at Mont Terri URL before the granular buffer material was emplaced (right).*

Meuse / Haute Marne

The purpose of the Bure URL research program is to provide reliable data on both the total disposal system (repository concepts integrated in the Meuse/Haute-Marne geological context) and on processes occurring in the near-field scale. These data are needed both for site PA over the long term (E6 years) and to demonstrate that the repository design allows operation in a reversible and safe manner.

The Bure URL program includes acquisition of geological data throughout the zone considered for PA. Detailed studies of the URL boreholes and 2 km² 3-D seismic survey of the URL site have been completed. An extensive and detailed geological survey is also being performed during excavation of the access shafts and is planned for the galleries.

One of the key points to be addressed is the evaluation of the various means for characterizing property variations within the Callovo-Oxfordian formation. Paleo-environmental reconstruction helped define the sedimentation sequences and provided evidence for the local homogeneity of the Callovo-Oxfordian formation. Past geological history has been studied in detail in order to confirm the geodynamic stability as well as to reconstruct the diagenetic evolution of the sediments. Such data are used as an input for assessing the future evolution of the geological medium hosting the URL and to help define the transport model for radionuclides.

Detailed geological surveys of all the URL infrastructures are planned.

- To identify any gaps in the sediment layers using chronological reconstitution methods.
- To detect and characterize thin layers using new 3-D seismic processing methods.
- To carry out geostatistical analysis of the spatial distribution of physical/chemical properties.
- To investigate potential discontinuities with slanted or horizontally deviated boreholes.

As previously mentioned, a good understanding of the chemical composition of the Callovo-Oxfordian pore water at the Bure site is needed in order to estimate its capacity to limit radionuclide transfer and its effect on the EBS. Therefore, sophisticated pore water sampling and analysis methods will be used to obtain information on various conservative chemical parameters which, together with a site-specific geochemical model, can be used to estimate values for parameters that cannot be measured directly. In addition, water sampling and *in-situ* equilibration measurements are planned at several locations in the URL in order to validate the model-estimated parameters and to reduce the uncertainty associated with certain key parameters such as pH.

The URL research program also aims at validating the model of diffusion and retention processes at the Bure site that has been developed based on the results of through-diffusion tests on centimeter scale samples and batch chemical-retention tests. The URL program consists of number of *in-situ* tracer tests located in different layers of the host formation. These experiments are also dedicated to the evaluation of the physical retention of anionic solutes as well as the transport and chemical retention of neutral or cationic solutes.

Tests on core samples show that the mechanical strength of the Meuse/Haute-Marne Callovo-Oxfordian argillites is sufficient to allow underground galleries to be safely excavated. Scale effects on the measurement of the mechanical characteristics will be investigated by comparing *in-situ* measurements in the structures with measurements on samples taken nearby. The tests designed to measure the time dependent strains of the argillites are complex and the amplitude of the values measured is often very small, near the limit of existing measurement devices. The first experiment in the Bure URL is linked to a European project for the comparison of models, and aims at monitoring the deformations around the access shaft in real-time. In addition, perturbations of host rock properties due to the construction of the repository structures (EDZ investigation) and the state of stress will be investigated.

A heater experiment is planned to investigate the effect of heat release by SF and vitrified waste on the buffer and host rock. The experiments are aiming to verify the thermal properties of the argillites at different levels and to test the ability of numerical models to simulate the argillites response to thermal stress. Other experiments are designed to investigate hydraulic properties of fissures and fractures (especially in the EDZ) and their stress dependence and the effect of ventilation on the host rock and the associated de-hydration.

Geochemical experiments will be carried out to investigate the impact of oxygen on the host rock (pyrite oxidation) and on the chemical composition of the interstitial water and mineralogy.

In the step-by-step approach to reversibility, the choices to be made at each phase require information concerning the progress of phenomena governing the condition and evolution of the repository components. The required repository-monitoring program must be designed to furnish the necessary data on critical processes (mechanical deformation, fracturing, and desaturation).

6.5 Engineered barrier systems

6.5.1 Description of components

High-level radioactive waste and spent fuel

The EBS, which employs large quantities of material with well-known (and favorable) properties and predictable performance, provide the primary containment of the wastes. The planned EBSs are.

- Canister or container.
- Buffer.
- Backfill.
- Seals.

The canisters (cast steel, carbon steel or stainless steel), optionally emplaced in overpacks, ensure a complete effective isolation of the emplaced HLW and SF for about 1 000 to 10 000 years. After canister failure, the bentonite will be a very effective barrier and, therefore, it is expected that most radionuclides will decay to insignificant levels inside the EBS. In most cases, HLW and SF canisters are placed in drifts surrounded by a smectite clay based buffer (e.g., pure bentonite, sand/bentonite mixtures), which has the following functions:

- Keeps the canisters in place and protects them by homogenizing the stress field.
- Mechanically stabilizes the rooms and limits convergence and long-term settlement of overlying formations.
- Acts as a transport barrier for radionuclides and a barrier for colloids.
- Provides a suitable geochemical environment.
- Ensures low corrosion rates for both canisters and waste forms.
- Prevents human intrusion.

In order to provide the functions mentioned above, it is necessary that the buffer is not altered in an unacceptable way by temperature or by chemical interaction with the formation water, rock or corrosion products of the canister. Some national programs envisage that the temperature of the bentonite should always remain below 100°C (e.g., Belgium, Spain and France) while other national programs allow higher temperatures (e.g., Switzerland maintains temperature below 110°C for a significant part of the bentonite but up to 150°C near the canister [6-28]). Buffer material prepared from clay has a very low thermal conductivity in a dry state. During the thermal pulse, this could lead to high thermal load in the near-field. Some concepts plan to add some material with higher thermal conductivity (e.g., graphite) to increase the thermal conductivity of the buffer material.

According to the different national concepts, the emplacement methods for the buffer can vary considerably. Concepts outlined so far for clay repositories favor the following alternative buffer construction techniques:

- Buffer of pre-fabricated blocks or ring elements (Figure 6-7).
- “Super canister” solutions (canister and buffer in a large cylindrical container).
- Buffer of a combination of bentonite blocks at the base of the canister and highly compacted granular bentonite (Figure 6-8).

Each method has advantages and drawbacks: the required densities, quality demands, drift cross section, etc., and these will determine which buffer construction method is the most suited for the concept under discussion. It should be noted that clay host rock properties differ significantly from those of hard crystalline rocks. In the long-term perspective, it has to be acknowledged that after the degradation of the support system, the buffer may be compacted *in-situ* due to host rock convergence/creep, and the post-closure buffer properties may be significantly different than those of the initial buffer.

Some designs are under discussion at the moment for vitrified HLW (e.g., Belgium and France) where the canisters are in direct contact with the host rock and no buffer material is emplaced.

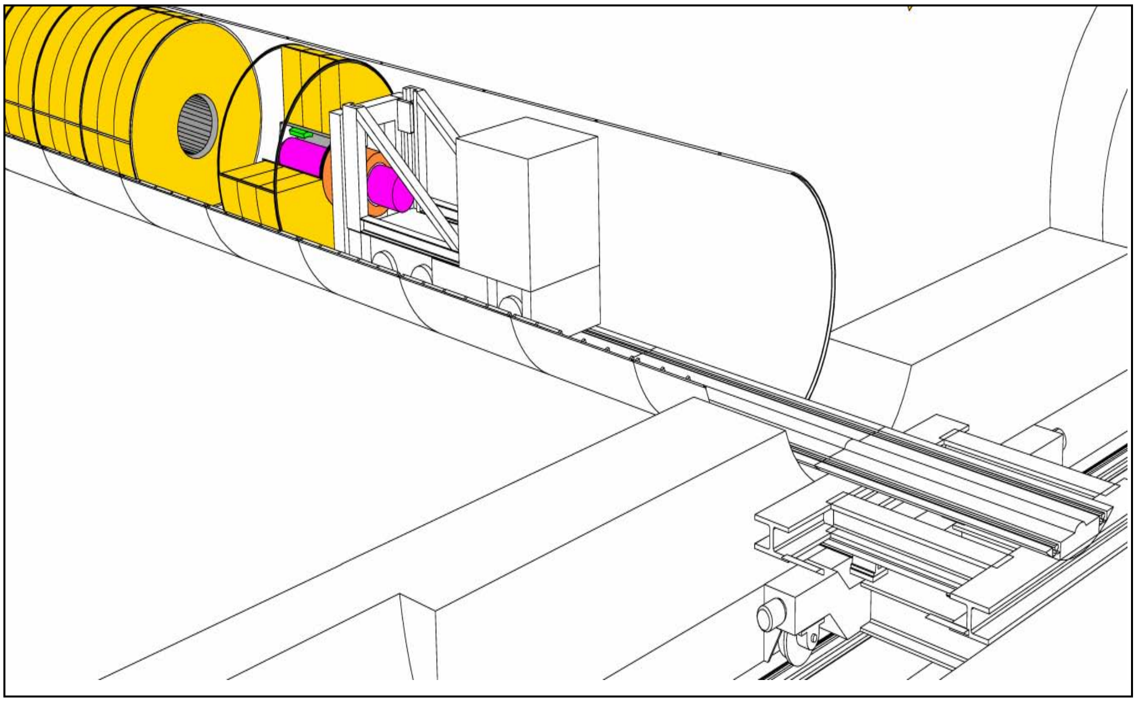


***Figure 6-7**. French buffer concept with bentonite ring elements.*

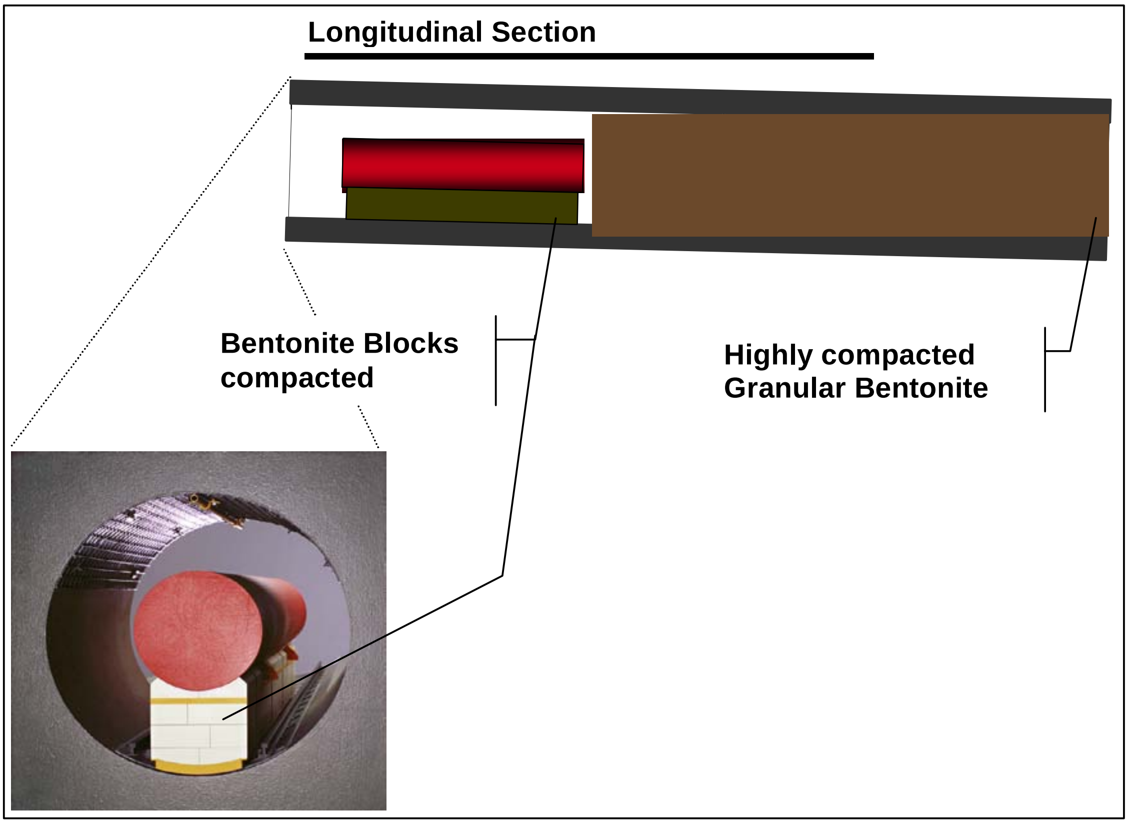


Figure 6-8. *Swiss buffer concept with blocks and granular bentonite.*

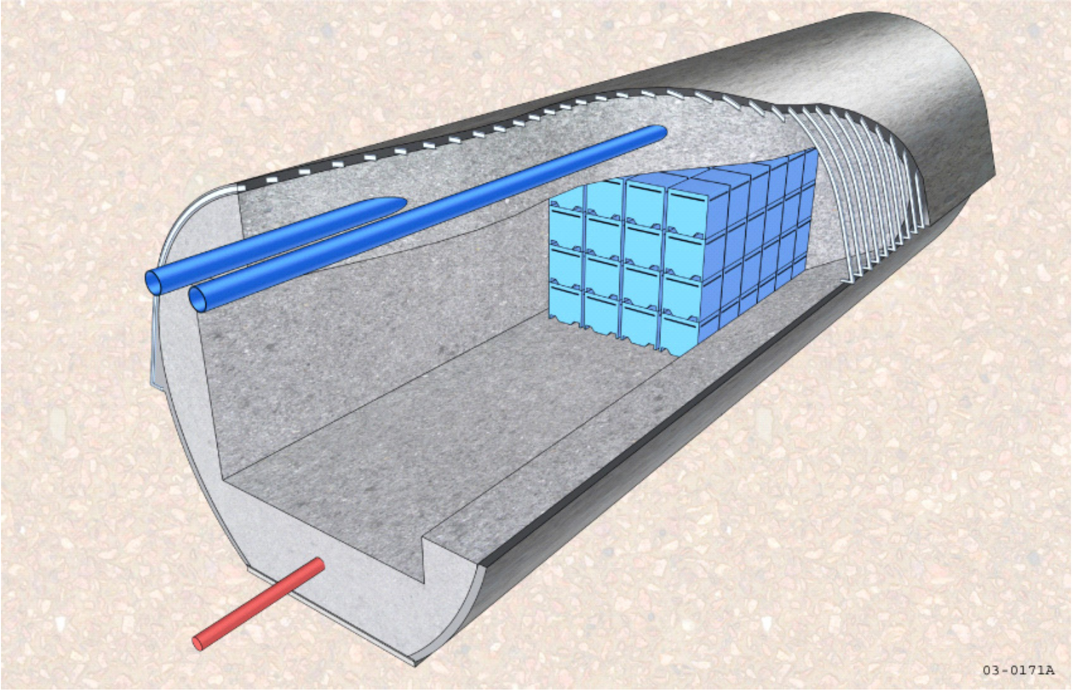


Figure 6-9. *Disposal cell for ILW in clay with cement buffer (French concept).*

Long-lived intermediate-level waste

The envisaged buffer material for the emplacement of long-lived ILW is cement (Figure 6-9). The cement buffer provides a stable chemical environment (alkaline buffer) for a long time (several thousand to ten thousand years at the minimum). Cements with pH ≤ 12.6 (OPC or Blast Furnace Slag) may be selected, e.g., to limit the degradation of bituminized sludges. Very low permeability and diffusion transport rates for such buffer materials are not required.

The cement buffer also provides stability to the underground openings during the operating phases. Cements used as drift support may differ from the cements used as buffer, as the general characteristics of the cement buffer are still not defined. Cement recipes (for example, the water/cement ratio) will depend on different factors and in particular on requirements related to gas management and reversibility.

Seals / Plugs

Seals or plugs are used in the repository at different strategic positions and are part of a general barrier concept. Following are examples on the most common seals among the different repository concepts in clay::

- Emplacement/disposal drift seals just before the intersection with the operation and/or construction drifts to separate single emplacement units.
- Disposal module or compartment seals to separate different waste types (e.g., HLW, SF, ILW) or areas (e.g., regulated from non-regulated, and disposal from monitoring areas).
- Final seals (e.g., shaft, ramp).

The general design of such seals is similar (Figure 6-10) but they sometimes differ in length and detailed design of the individual elements. A basic seal / plug consists of a hydraulic sealing element made from bentonite and one or two bounding support elements that guarantee the mechanical stability of the hydraulic seal. These support elements have to withstand substantial loads caused by swelling pressure of the bentonite and water pressure, especially during the re-saturation period and transient thermal phase. In addition, a significant load may be applied due to high gas pressure build-up during the corrosion of steel and the degradation of the waste.

The hydraulic seal in the centre between the mechanical support elements differs in the national concepts. Generally, bentonite is used as sealing material, but sometimes concrete liners are removed in the seal sections, and sometimes they are kept (e.g., disposal drift plug in the Spanish concept). Some designs even foresee partial (slots or notches) or full removal of the EDZ at the seal location to effectively interrupt preferential flow paths along the drifts and galleries.

The construction material for the mechanical support elements to confine the seals also differs in the national concepts. Most concepts favor the use of concrete but in some cases (e.g., Switzerland) alternative materials are under discussion for the final seals to ensure that the degradation of the cement with time does not influence the function of the seal. Frictional gravel supports or constructions including specially designed rock blocks are being considered.

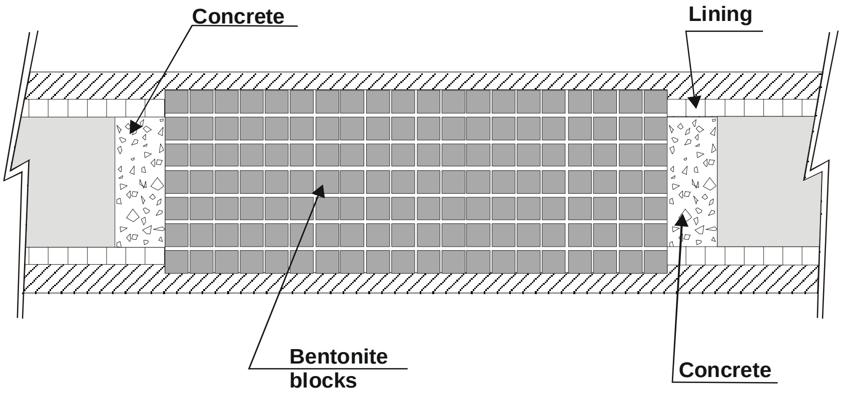


Figure 6-10. *Sealing of central areas in the Spanish concept.*

Backfills

Drifts and underground service areas used for repository construction or operation will be backfilled mostly after the operational phase and otherwise after the monitoring phase to avoid large displacements in the host rock and overlaying sediments that would be caused by a collapse of such excavations when the ground support has degraded. In addition, these backfilled drifts could provide significant additional sorption or retention capacity (depending on the backfill material) and storage volume for gas generated by the degradation of the waste and the containers.

Proposed backfill materials are crushed host rock from the excavation or bentonite/sand mixtures.

6.5.2 Instruments and experimental procedures

Although most of the demonstration experiments at the URLs are designed as long-term projects, a number of tests cannot be run under realistic conditions in clays. Especially those experiments that include the effects of re-saturation of the host rock or saturation of buffers are problematic because of the long time spans needed for these processes to reach equilibrium/steady state in the very tight formations. Artificial saturation has to be used to mimic the natural process but the evaluation of the results is quite problematic as observed reactions (especially for coupled processes) may differ from those expected during natural re-saturation.

In clay rocks, the interaction between the host rock, the buffer and water is much more intense than in hard crystalline rock and the associated coupled processes (e.g., change of rock properties and state) are difficult to predict. The transient thermal phase, where THMC processes are strongly coupled, is especially difficult to assess and predict.

General aspects of instrumentation

The selection of instruments is mainly driven by the objectives of a particular experiment. In cases where the evaluation of a process is the main goal of the experiment, it is straightforward to use reliably tested equipment rather than experimental tools. Newly developed tools will be used and verified in experiments that focus on instrument or method development.

One of the main objectives of the experiments carried out in the URLs is to obtain data on the evolution of the different processes that take place in the EBS and in the host rock under conditions similar to those expected in a real repository. Therefore, instrumentation is usually one of the most important aspects of these experiments. The information provided by the instruments is used to improve the understanding of processes and to provide the data needed to refine, calibrate and validate the models. For this reason, the instruments installed in the experiments must provide, as far as possible, realistic and accurate data.

Instrumentation plans for RTD experiments have to be designed around the proposed objectives of a specific experiment. Each sensor placed in an EBS or host rock, and the associated cable, is a distortion of the system that can negatively influence the performance of the experiment. Therefore, not all parameters can be monitored at every place and at all times. Scoping calculations with parameter variations have to be carried out at the beginning of an experiment to select the most sensitive and important parameters. These parameters need to be recorded in a redundant way using different types of sensors or techniques. It is essential to answer the following questions with respect to the test objectives:

- What resolution is really needed?
- What measurement density is needed?
- Can a non-destructive measurement method be used (e.g., tomography)?
- What is the natural variability of the measured parameter?
- Are point measurements needed or are integral measurements more useful?
- How reliable are sensors and what is known about instrument longevity and instrument drift?

Some of these questions can be answered from past experience, while others require a certain amount of pre-testing. In any case, at the end of every experiment an evaluation of the performance of the different instruments should be carried out to provide input for further projects.

Instruments selection

Two important characteristics of demonstration experiments for nuclear waste disposal are that access to or replacement of instruments is not possible after installation, and that the planned duration of the experiments is far beyond the guaranteed life of the instruments. Working conditions for the sensors are severe, with high pressure, temperature and corrosion potential (especially important in the highly aggressive formation fluids found in marine clays). This implies a careful selection of the instruments, which must be reliable, durable and stable. Ideally, only well proven sensors with good (and known) long-term behavior should be used. The testing of different types of instruments is also an objective of the experiments. The risk of losing data should be minimized by duplicating those instruments for which not enough previous experience exists with other type of measurement.

Installation

The installation procedure must be carried out with care in order to prevent, as much as possible, disturbances, which could directly affect the validity of the data obtained. Mechanical couplings, fittings, etc. should be reliable and not introduce additional noise into the data acquisition system (DAS). A good contact with the surrounding media of concern is also critical.

In clay formations, the rock wall stability, both in galleries and boreholes, is often poor. Especially in boreholes, the instruments must be placed immediately after drilling, to avoid problems associated with rapid borehole convergence or borehole wall failure. All sensors and instruments should be checked in a bench test for tightness and functionality. This is especially important for modified or new purpose-built sensors.

Cables and tubings are always a preferential path for fluid flow. Their layout should guarantee minimum adverse impact on the system. Special care must be taken in passing through sealed parts or tight walls.

Data collection, storage and handling

The DAS, used for the demonstration experiments, has to be designed according to the needs and requirements of the specific sensors. A general centralized DAS is in many cases the best and most effective solution but sometimes sensor-specific DAS have to be used to avoid problems. For example, high frequency seismic measurements have to sample ten thousand data points per second while pore pressure measurements only need to record a few data points per hour. If measurements with such different requirements have to be combined, a centralized DAS should not be used. In cases where several DAS are necessary, it is necessary that all systems use the same time base to allow reliable cross correlations between measurements.

Monitoring and control systems will be designed to include:

- Power supply and signal conversion.
- On- and off-site control and monitoring of special processes.
- On- and off-site control of the experiment.
- On-site data collection, archiving and display.
- Post-processing capabilities for reporting.
- Remote control facilities.
- Data base management.

Data acquisition at Hades

Most measurements are performed by an automated DAS. The distributed nature of the sensor layout throughout the Hades URL has led to a network environment (Ethernet) with distributed data acquisition modules, creating a transparent environment, in which most set-ups can be followed remotely.

The database management system has facilities for the storage of raw data, data reduction, reporting. The detailed design of the data structure (which data to record, organization of data files, etc.) is essential to allow for a good follow-up of the experiment, to detect any anomalies, and to interpret the measurement data in an efficient way.

Data acquisition at Mont Terri

Two different DAS have been successfully tested at the Mont Terri URL. Both systems include a local and a remote monitoring subsystem, which are linked by a modem. An example for the Local Monitoring System (LMS), which was designed and implemented by Aitemin, Spain, and is used in the Mont Terri EB experiment is given in Figure 6-11.

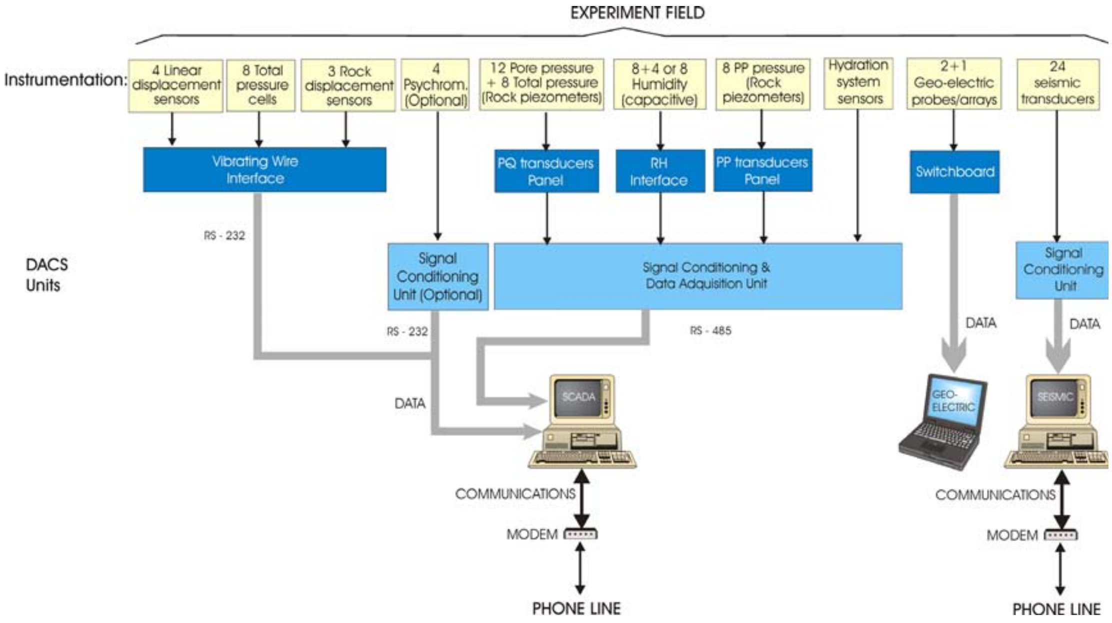


Figure 6-11. *Local Monitoring System (LAS) installed by Aitemin, Spain, for the EB experiment in the Mont Terri URL.*

6.5.3 Conceptual and theoretical models

General

The assessment of the repository performance and safety involves spatial and temporal scales that can only be evaluated by using conceptual and/or mathematical (numerical) models. These models are primarily designed to investigate and understand processes that allow prediction of the waste/EBS/NBS in a way that undesired conditions can be ruled out and the favorable properties of the barriers are not unduly altered. With respect to HLW/SF disposal, the following features or processes have to be investigated:

- Construction of the drifts in a given stress field causes re-distribution of stresses due to the creation of new free surfaces and may cause discrete micro- and macro-scale fracturing (EDZ) even in clays. Time-dependant processes may enhance the EDZ development.

- Drainage into the drift will cause a significant disturbance of the pore water pressure in the host rock surrounding the drifts.

- Before emplacement, parts of the near-drift rock may de-saturate due to drainage effects and ventilation, leading to stiffening and alteration of the clay close to the drifts.
- Re-saturation of the EDZ (with increased permeability) leads to swelling, increased creep rates, probable self-sealing of the EDZ and eventually full pore pressure recovery.
- High temperatures near the canisters may keep bentonite near the canisters dry for decades.
- Re-saturation of the bentonite leads to swelling and homogenization of the buffer and seals the bentonite-host rock interface.
- Convergence of the drift will compact bentonite (decreases porosity, permeability and thermal conductivity).
- A waste-induced temperature rise in the host rock leads to thermally induced increase in pore water pressure and total stress, which in turn may extend the EDZ.
- Gas will be produced due to metal corrosion leading eventually to formation of a free gas phase. Possible consequences are displacement of water by capillary flow, micro-fracturing and pathway dilation.
- The buffer will be compacted due to volume increase of corrosion products from canister corrosion.

Some of these processes take place in the operational or monitoring phase of up to 100 years while other transient phenomena such as re-saturation and the thermal pulse cover time spans of several hundreds to ten thousands of years (Figure 6-12). The time required for the underground environment to recover from the disturbances caused by the construction of underground openings, emplacement of the EBS, disposal of waste, and to reach a new state of equilibrium is defined as the transient phase.

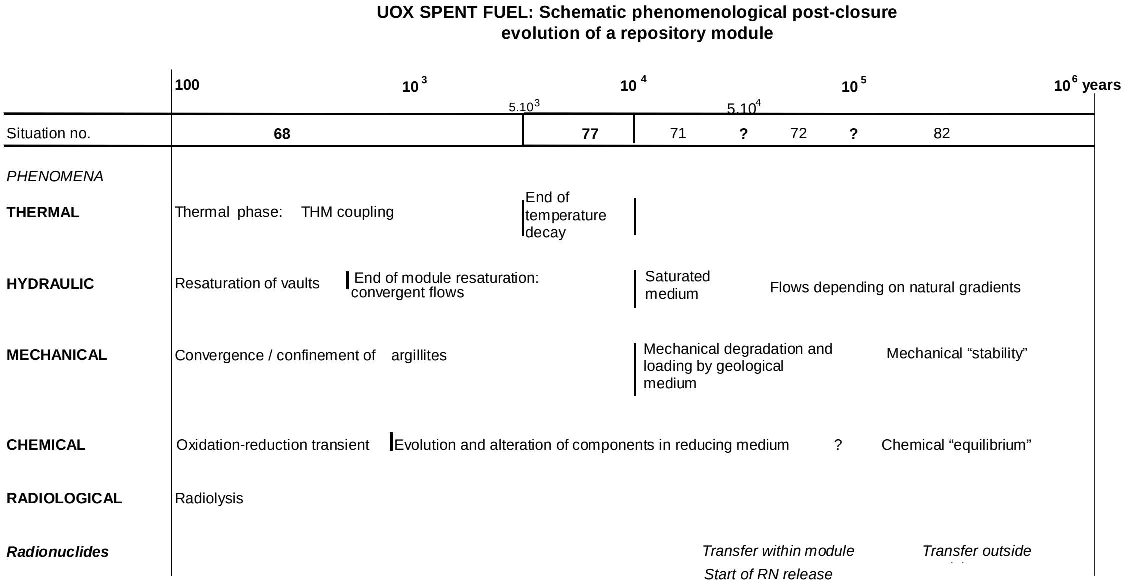


***Figure 6-12**. Phenomenological evolution of UOX-SF repository zones after closure of the engineered structures (operations are assumed to last 100 years).*

Processes investigated in URLs cannot cover all the phenomena listed in Figure 6-12, even if the processes are artificially accelerated. The most important features and processes that have been or are addressed in the clay URLs and that are subject to modeling are mentioned below. More information on experiments is presented in Appendix 1:

- Convergence of drifts and creation of the EDZ (MINE-BY and CLIPEX experiments at Hades, and ED-B experiment at Mont Terri).
- Creation and behavior of fractures, and self-healing of them (SELFRAC experiment at Hades and Mont Terri).
- De-saturation of the host rock (PHEBUS experiment at Hades, VE experiment at Mont Terri).
- Thermal pulse effects on EBS and host rock (ATLAS and CERBERUS experiments at Hades, HE and HE-B experiments at Mont Terri).
- Re-saturation of the host rock and the buffer (BACCHUS experiments at Hades and EB experiment at Mont Terri).
- Seal performance (RESEAL experiment at Hades and SB experiment at Mont Terri)
- Migration and diffusion of gas (MEGAS experiment at Hades and GP/GS experiment at Mont Terri).
- Chemical and bacteriological phenomena (ARCHIMEDE experiment at Hades and MA experiment at Mont Terri).

As mentioned above, some of these processes are strongly non-linear and coupled to each other, which makes their assessment difficult. In addition, the boundary conditions as well as the most important parameters are often not adequately known in the test in the URLs. Therefore, additional surface mock-up tests (e.g., the OPHELIE simulation at Hades) are conducted to verify codes and models on simplified test set-ups with well-defined boundary conditions.

Verification and uncertainties of models

Any numerical and mathematical model is always an abstraction of the real natural process and has its limitation even if appropriate physical or chemical models are used. Especially the natural inhomogeneity of the host rock or disturbances such as fissures, fractures and faults are difficult to analyze in a deterministic way. Therefore, it is virtually impossible to fully validate or verify such models.

The first step to investigate the capacity of a numerical model is to test it against analytical solutions for rather simple problems and to compare it with well-known benchmark tests. After a calibration of the model (mainly based on small-scale laboratory tests), predictive calculations are performed and compared with measured data. Sensitivity studies and back calculations allow the partial verification of the model.

Boundary Conditions

Boundary conditions for modeling are of equal importance to model parameters and the selection of constitutive laws. In contrast to well-defined laboratory experiments or mock-up tests where well-established and controlled boundary conditions apply, experiments conducted in URLs often face large uncertainties in boundary conditions, which have to be measured or inferred. For example, far-field stresses and pore pressures are very difficult to obtain in clay with low hydraulic conductivities as measurement techniques are not always adequate for these conditions.

Modeling has been applied to the following different types of experimental cases:

- HM behavior/response of the host rock to the construction.
- HM effects due to the operation of a repository.
- THM and HM behavior of clay host rock and backfill/buffer material.
- Backfilling and sealing of galleries.
- Changes in host rock chemistry (e.g., change of chemical conditions due to construction/operation of the repository and interaction with EBS) and its influence on the migration of radionuclides.

6.5.4 Comparison of theoretical predictions and experimental data

General

One commonly distinguishes between the construction phase in which stress/strain and rock stability issues are in focus, the operational phase when the waste is emplaced. Although rock stability is still important, the focus is on EBS maturation and the long-term evolution of the disposal system including chemical processes and potential release of radionuclides.

Construction phase

Experiments that simulate the construction of parts of or the full repository (e.g., mine-by experiments) are dealing with the host rock and their neighboring formations. These experiments can be adequately modeled with commercially available FEM or finite-difference codes e.g., FLAC 2-D/3-D [6-29]. A vital issue is to predict the stress situation in the rock during the construction phase and a first step is to estimate whether the hoop stress will be lower than the compressive stress generated by the excavation of drifts and rooms. For normally or very weakly over-consolidated clay, the unconfined compressive strength is usually not much higher than the hoop stress, which means that the safety factor is low and immediate support in the form of a lining is required. This is the case for the Boom Clay, while for the cemented Opalinus Clay the factor of safety ranges between unity and 3, which requires immediate local stabilization. Drifts excavated in more compacted and over consolidated claystone (e.g., Opalinus Clay) may require mechanical support or lining to minimize EDZ development due to creep and progressive failure (cyclic saturation/de-saturation processes, water up-take and associated swelling and softening of the clay). An example of modeling result for

Opalinus Clay is shown in Figure 6-13 [6-14]. The local rock structure determines the risk of rock fall and this requires more detailed modeling in which the stress/strain properties of discrete weaknesses and also scale effects need to be taken into consideration. In this context, the effect of local overstressing of the rock, i.e., the development of the EDZ, is important since it may influence the transport of water and gases in the maturation phase of the EBS. For this work, ordinary FEM or finite-difference codes have been applied, validating the actual appearance of induced fractures to depths of up to 2 m into drift walls.

Due to the nature of clay rocks, it is necessary to use full coupling between hydraulic and mechanical models (HM coupling). In most cases, hydraulic modeling is performed using Darcy’s law, while different constitutive laws are considered for the mechanical part. Models used so far at Hades or Mont Terri are: Mohr-Coulomb, Hoek-Brown, Drucker Prager and

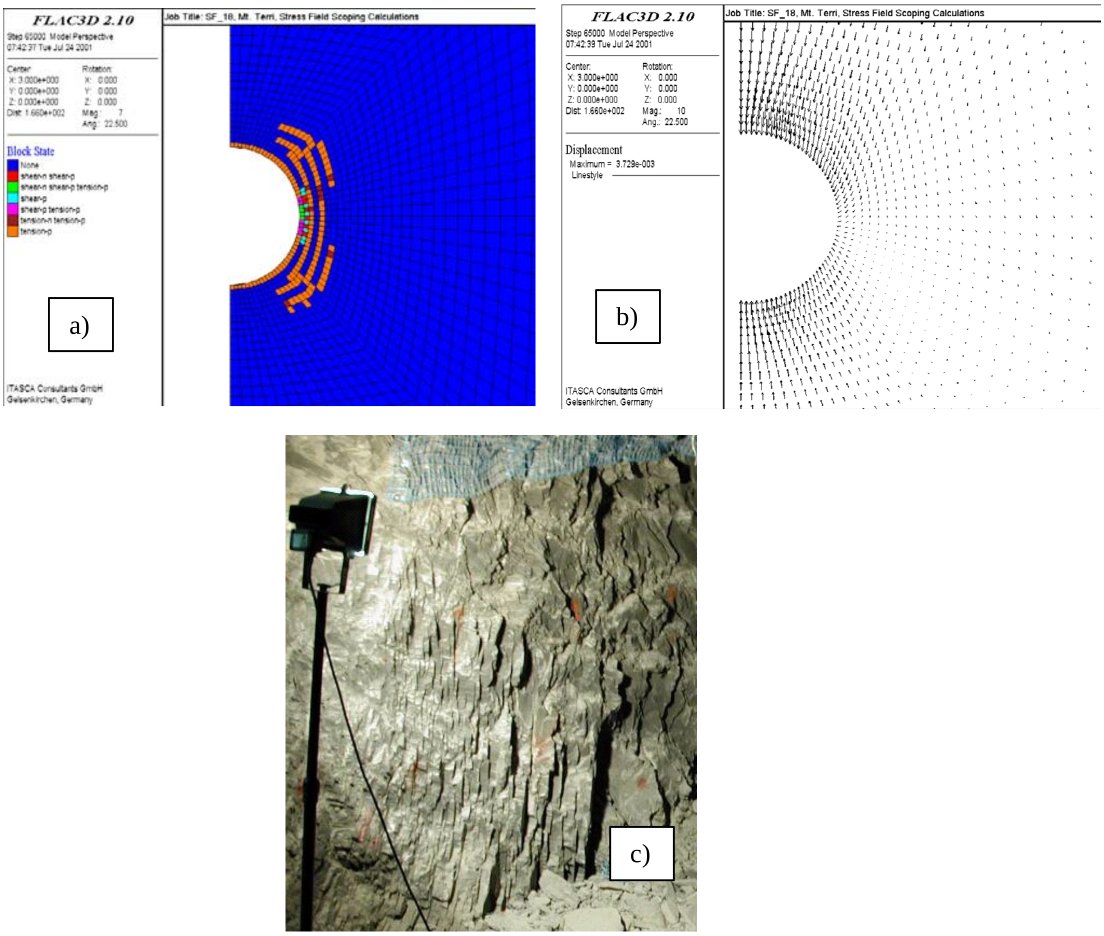


Figure 6-13. *a) modeled EDZ. b) calculated displacements c) observed extensile fractures of the EDZ.*

Cam Clay models. Sometimes these models are modified to account for specific conditions such as viscous flow or coupled with creep models to account for the time-dependent has been deformations of clays. The main modeling approach is based on continuum models, which do not adequately model fracture development. Some modeling has been performed to investigate the influence of discrete fractures (Lagamine, PFC).

The result of the HM modeling [6-30, 6-31] show that trends and general deformation patterns can be predicted very well, but magnitudes of deformations, which show significant lateral variabilities (up to a factor of 2 within 10 m distance at Mont Terri) in the *in-situ* observations, are difficult to match with reasonable accuracy. Uncertainties in the boundary conditions (total stress) and material inhomogeneity may be responsible for this discrepancy. Pore pressures are predicted quite well in the vicinity of drifts, although the variations observed around the connecting gallery (Hades) are significantly larger than expected by the model predictions. Observations on pore pressure changes at large distances (up to 40 m) in Boom Clay cannot be explained by these models so far. Adapted models that are currently being tested are those of Dafalias-Kaliakin (bounding surface), based on an elasto-visco-plastic approach, and the “double bubble” model (elasto-plastic with mixed hardening).

Operational phase

The ventilation of drifts and galleries is necessary during the construction and operation of a repository. This can lead to a de-saturation of the host rock or, even worse, to a cyclic wetting and drying of the drift near-field. The effects of ventilation were investigated in several experiments.

The interstitial pressures around the ventilated opening of the PHEBUS set-up, as well as the water flow rate in the ventilated air, have been predicted through the code Unsat 2R, incorporating a Darcy flow transport model. The predictions indicated a desaturated zone (suction to -7.5 MPa) in the Boom Clay at distances up to 1.5 m (this result specified also the maximum distance of peripheral piezometers). The experiment however indicated a positive pressure (saturated conditions). Also the water flow rate was much lower than expected (2 375 kg water predicted after 350 days of ventilation, versus 188 kg measured).

The difference has been explained by the fact that the capillary pressure applied at the borehole wall was much lower than the value derived from air humidity (33% RH) being ventilated in the central borehole (3 MPa instead of 150 MPa). Indeed, a value of 3 MPa shows a good agreement with the measured values. This means that the sintered steel filter does not transmit the capillary pressure of the air to the borehole wall, and rather just acted as a drain. The water volume extracted was due to the percolation of the clay water through this filter.

The VE experiment, presently being conducted in the Mont Terri URL, is designed to investigate the effect of ventilation on stiff clays. Modeling is done to design the experimental set-up (scoping calculations) and to determine large scale ‘*in-situ*’ parameters of the rock (back calculation). Models describing the associated processes have to be able to account for fully coupled multi-phase flow in porous media (e.g., MHERLIN, THOUGH2, CODE_BRIGHT). Mass and energy flow is handled in these codes by evaluating mass- and energy-balance equations where the mass balance is based on a multi-phase formulation of Darcy’s law. The experiment is still ongoing and the evaluation of data versus prediction is not yet available.

The complex experiments designed to investigate the interaction between the EBS and the surrounding rock during the transient phase where temperature and saturation of both media change significantly is the most complex condition/process in the modeling of the repository behavior. Heat can be conducted in the different media but could also be transported by convection processes and vaporization. Multi-phase flow in the buffer, as well as in the host rock, has to be considered. The mechanical behavior of the host rock and the EBS can be influenced by additional thermal stresses, excessive swelling pressure from the buffer on the host rock or changes in material behavior due to heating, water saturation and swelling (e.g., creep enhancement, strength reduction).

In this phase, time-dependent deformation becomes important, primarily that of the host clay rock since it is expected to lead to significant convergence of drifts and shafts, thereby interacting with the maturing buffer material. This matter has been investigated by considering common theoretical creep models and performance of samples taken from Mont Terri and Meuse/Haute-Marne as well as Boom Clay for evaluating relevant parameter values. In principle, the empirically derived creep strain rate can be taken as:

$$d\varepsilon/dt = \beta T D \ln(t-t_o) \qquad 6\text{-}1$$

where:

ε = angular strain

β = strain parameter evaluated from triaxial tests

D = deviator stress ($\sigma_1 - \sigma_3$) for a limited stress interval.

T = temperature

t_o= integration coefficient

The laboratory tests demonstrated significant scattering of the creep data and the short testing time make the possibility of predicting creep over longer periods of time very uncertain. Major reasons for this variability could be material heterogeneity, sample disturbance, environmental effects during testing or the difficulty to distinguish between consolidation and creep in such tight rocks. In addition, the degree of compaction, OC and cementation have to be taken into account, which could require that a certain threshold value of shear stress has to be exceeded before secondary creep is observed. The OC ratio (OCR) of the Opalinus Clay at Mont Terri, for instance, is 2.5-3 MPa and the apparent cohesion is 2.8 MPa, while in other similar clay rocks the OCR is down to 1.5 to 2.5 while the apparent cohesion can be as high as 9.1 MPa.

For the Boom Clay with a rather low OCR, the creep is appreciable and a very significant change in pressure on the concrete lining is expected, approaching the present overburden pressure in a short time. Heat-induced pore water overpressure and thermally-induced total stress changes will occur in all water-saturated clay rock. Depending on rock parameters this may either lead to reduced effective stress, as observed in the Boom Clay, or to increased effective stress as modeled for Opalinus Clay. Temperature prediction is thus important and will directly influence the repository design (Figure 6-14).

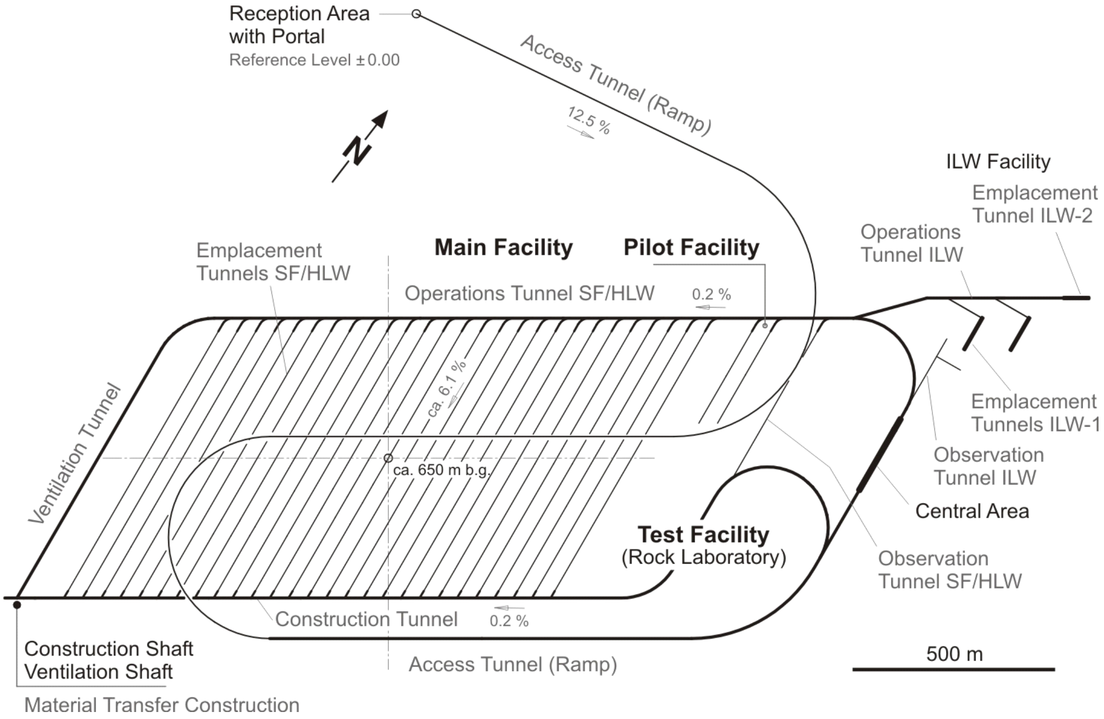


Figure 6-14. *Design principle of the Nagra HLW repository with a spacing of about 40 m of the deposition drifts and a maximum temperature of the canisters of 150°C.*

Long-term phase

Process modeling of the HM evolution of the host rock and bentonite in a long-term perspective has not yet been considered in sufficient detail. The main reason for this is that the models describing time-dependent processes are empirical and not based on physical laws/first principle. Such models cannot be calibrated with laboratory data for the time scales needed to describe the material behavior over very long times. Nevertheless, conservative assumptions can be made to carry out an adequate assessment of the repository's performance [6-32]

Present results from Hades

Comparison of the ATLAS test results with model predictions (Interclay benchmark exercise) shows that the temperature development can be modeled adequately. Regarding the HM modeling, the initial conditions for H and M (drilling of boreholes) seem to be more important than the details of constitutive law for Boom Clay (in the particular case of the ATLAS experiment).

Different models were applied to simulate the CERBERUS experiment. The TH behavior of the Boom Clay around the CERBERUS test has been modeled using the FADES code. The conclusions from this exercise dealt with the importance of understanding well the initial and boundary conditions. A (partial) model calibration was performed during the heating stage, because data were not available for all thermal and thermodynamic parameters. The evaluation during the cooling phase showed, however, the good performance of the model as it reproduced well the temperature decay and pressure evolution. The sensitivity analysis indicated further that the calibrated TH model using data from the heating phase is robust.

The THC modeling was performed using the CORE-LE code. The most important geochemical effects induced in the Boom Clay by the CERBERUS experiment were a slight oxidation and changes in the pore water composition. These changes could be successfully modeled with CORE-LE. Reactive transport codes are therefore suitable for application to predict the long-term behavior of complex systems such as those to be found in HLW repositories.

No conclusions could be drawn for the mechanical data (total pressure), as the total pressure sensors did not survive the radiation field.

The BACCHUS experimental results have been compared with six model predictions within the project “Catsius Clay” (EC-project, Contract No. F14W-CT95-0003). The overall performance of the different models has been assessed for different parameters (e.g., pore pressure, effective stress) at different phases (e.g., natural hydration, artificial hydration, full saturation) of the experiment. In general, although some models performed better than others, no single model was able to reproduce faithfully the complete history of stress and pressure development. It has been pointed out that model predictions were extremely sensitive to some key properties and in particular to the water retention and relative permeability functions. Since available laboratory data always exhibit a significant dispersion, the dispersion of results is a natural outcome of the present state of the art.

The modeling for the OPHELIE mock-up experiment is in a preliminary phase, and no significant conclusions can be drawn yet.

Present results from Mont Terri

One of the most advanced models to account for the complex situation during heating of EBS and NBS is the ‘CODE_BRIGHT’ developed by UPC, Spain [6-33]. In CODE_BRIGHT a three-phase porous medium is considered composed of solid grains, water and gas. THM aspects are taken into account, including coupling between them in all possible directions. The code uses Darcy’s law for advective fluxes of liquids and gas, Fick’s law for non-advective fluxes in vapor and air and Fourier’s law for conductive heat flux. The degree of saturation of the liquid phase is given by the appropriate retention curves, while mechanical constitutive laws are used for the mechanical calculations. CODE_BRIGHT was successfully calibrated and verified in the Febex experiment, see Appendix 1. The use of CODE_BRIGHT in modeling the bentonite buffer in crystalline rock repository concepts is shown in Chapter 5.

The results from the Heater test (HE-A) show that the temperature development can be adequately modeled. Attempts to model the saturation of the buffer in the EB experiments are still showing problems because of the complications arising from the combined use of bentonite blocks and highly compacted granular bentonite. The analysis of this test remains to be finished and the final evaluation of the modeling has to be postponed.

Chemical processes to be considered include the evolution of the chemical environment (e.g., redox processes, dissolution- precipitation, cation exchange), chemical coupled (reactive) transport (e.g., alkaline plume) and transport of radionuclides (e.g., advection, diffusion, sorption).

Different modeling codes are available to account for the evolution of geochemical conditions (e.g., PHREEQE or EQ3/6) and for chemically coupled transport (e.g., Hydrus + PHREEQE)

Evaluation of the modeling results and predictability for longer periods of time

Complex large-scale experiments require detailed planning and thorough execution. Special attention is needed for the modeling tasks because:

- The conceptual and numerical models might be very accurate in terms of physical processes but effects due to heterogeneity of the materials at large scale (e.g., due to the buffer emplacement or natural variability in the host rock) might lead to significant deviation of prediction relative to measured conditions (reality).
- The parameter evaluation determined on small-scale samples might not be adequate (scale effects) especially for clay rocks, which could be significantly disturbed during the sampling process.
- As the HM and THM processes are very complex, their modeling requires a large number of parameters (HM parameters) and initial state conditions (stress and flow fields). A significant uncertainty in these parameters and state conditions must be taken into account in predictive modeling.
- Significant effort is needed to obtain a sufficient database for the “calibration” of the models. This in turn competes with the need for “least possible disturbance” of the test and could lead to data bias.
- Several projects address the question of simplifying assumptions when HM and THM processes are modeled by using different modeling approaches of increasing complexity. The question “what degree of complexity” is required in modeling to obtain a reasonably good answer to the THM processes is still open.

Coupled THM(C) models are good and adequate tools to investigate processes to understand system behavior. Most models for the different, partly non-linear processes employ a combination of pure physical and empirical laws. Empirical laws should be used with care (e.g., for insight calculations to guide design or RTD) for time scales that are significantly longer than the experiments used for calibration. Together with uncertainties in parameters and heterogeneities (mainly in the host rock) this can lead to large discrepancies between observations and model results especially for long periods of time. In addition, some of these codes are very time consuming to apply, especially if the time steps are not updated during the calculations, which may require undesirable long calculation times. Assessments of system behavior should always include parameter variations to investigate the robustness of the prediction and should be limited to answer a few important questions (e.g., maximum temperature in the buffer and host rock, approximate re-saturation time). Detailed predictions of too many parameters could be misleading and be counterproductive because the public could lose confidence in the whole disposal process if predictions are not met, even if such prediction errors would not have any influence on the repository performance.

6.6 Lessons learned and potential areas for improvement

6.6.1 Construction phase

The construction of a repository or a URL is not very different from standard tunneling approaches and mining works. In general, excavation methods, which minimize the impact on the surrounding rock, are favored to reduce the possibility of preferential flow path along drift, ramps and shafts (minimizing of EDZ). The construction phase can be very well simulated in URLs, where different excavation methods have been evaluated. It turns out, that the most suitable methods for all types of clay rock under discussion are mechanical excavation techniques.

Lining or rock support is a key issue to control deformation and extent of the EDZ during the construction and operation phases. If they are applied too early or are designed too strong, difficulties may arise under squeezing conditions at great depth. On the other hand, if they are applied too late or insufficiently strong an extensive EDZ and probably local breakouts may result. In soft clays, the use of a modified road header with a shield combined with a stiff concrete liner using a wedge block technology proved to be very effective in constructing drifts. In hard clay, TBMs is one appropriate solution. The appropriate design of liners or support in these materials has not been evaluated in detail so far. Depending on rock parameters and state of stress, systematic rock bolting with meshes, steel liners or shotcrete could be the appropriate solution.

Local instabilities have to be expected in the vicinity of structural discontinuities and a high degree of anisotropy of material strength may cause construction problems but these problems will be limited to pure mechanical problems. No major water inflow has been observed in the URLs or in drifts in similar rocks at repository depth even in the vicinity of natural fractures or fissures.

Mine-by experiments to investigate the deformations and changes of host rock properties in the vicinity of drifts showed that even in plastic clay, discrete, mainly extensional fractures develop in the EDZ (possible due to unloading or slow pore pressure dissipation). The anisotropy of the mechanical properties of the rock (e.g., bedding related anisotropy) proved to be very important for the extent and severity of the EDZ.

Tools and sensors for the measurement of convergence, deformation and pore pressure change in mine-by experiments exist and proved to be reliable. The measurement of the rock permeability in the EDZ can be done with existing equipment but the interpretation of the data can be quite difficult due to partial de-saturation of the EDZ and the strong rock-water interaction during testing (e.g., borehole collapse). Indirect geophysical measurement techniques (geoelectrics and seismics) are adequate tools to approximate the EDZ extent and observe time dependent developments. A good correlation between indirect geophysical and direct measurements (e.g., deformations, permeability) was observed in several experiments.

The instantaneous response of the rock mass to tunneling is governed by the undrained behavior of the rock due to its low hydraulic conductivity. The time-dependent convergence is influenced by drainage and associated consolidation, rock failure and creation of discrete flow path in the EDZ and ‘creep’ of the rock mass. The analysis of such complex processes requires the use of coupled hydro-mechanical models that include time-dependent deformations or even viscous material behavior. The modeling of mine-by experiments in clay rock showed that the developed models predict the mechanical behavior and pore pressure development in the vicinity of the drifts with reasonable accuracy. Some problems exist in modeling pore pressure changes at large distances in soft clay due to excavation. So far, continuum models have mainly been used for such problems, which cannot address the problems arising from discrete fractures in the EDZ. Especially for stiff clay rocks, it will be necessary to evaluate the possibilities of codes and models that can handle discontinuities in such materials in an appropriate way.

6.6.2 Operational phase

Although this phase is discussed separately, it should be noted that it actually runs concurrent with the construction phase but in specially designated separated areas. The operational phase can, similar to the construction phase, be simulated in URLs. In contrast to hard rock, special emphasis has to be given to rock-water and rock-buffer interaction. Firstly, because the behavior of the rock and the buffer strongly depend on their actual water content and degree of saturation, and secondly, because rock and buffer compete for the available water.

As long as the emplacement drifts or boreholes are not filled with waste and buffer material, the environmental conditions, such as relative humidity and temperature, strongly influence drift convergence and even rock stability. Clay rocks tend to alter or even disintegrate when they experience drying-wetting cycles because of the high capillary forces during drying due to the small pore radii. The proposed concurrent construction and operation work is a consequence of this material behavior of clay rocks. This approach minimizes the open drift phase of emplacement units and avoids over-design of the support systems.

One great advantage of clay rocks during the operational phase is the fact that the buffer and also the backfill can be emplaced under dry conditions (no water inflow). This helps to relax time pressure during emplacement and avoids problems with possible *in-situ* compaction procedures during the installation of the EBS. The EBSs considered in clay include supercontainers, large prefabricated blocks, and a combination of blocks and granular buffer material. The use of the latter material seems to become of more and more interest also to other concepts where gaps between prefabricated buffers and the rock have to be reliably filled. Due to the fact that no water-conducting fractures exist and matrix diffusion is the dominant transport process in the clay host rock, the buffer properties are much less important in the clay case than in the crystalline case. Nevertheless, similar buffer solutions are envisaged in most concepts to increase the robustness of the multi-barrier system.

Large-scale demonstration projects have been carried out (e.g., the EB experiment at Mont Terri) or are planned in the near future (e.g., PRACLAY at Mol) to demonstrate the feasibilities and optimize buffer emplacement technologies. New projects are on the way to demonstrate the applicability of such techniques on a semi-industrial scale (EC-project “ESDRED”, Contract No. F16W-CT-2003-508851). The EB experiment, where the combination of blocks and granular buffer material have been tested for the first time, showed that such methods are feasible in general but that improvements regarding buffer density and homogeneity are still possible and desirable. A high potential for optimization still exists for this new method.

Small scale and full scale ventilation experiments are in progress in URLs to investigate the effect of de-saturation/saturation cycles in hard clays. The tools and sensors for an adequate instrumentation and monitoring of such experiments exist and proved to be reliable. Modeling has been performed to predict the behavior of the clay rock due to ventilation and to evaluate the associated coupled processes. So far, the modeling tools seem to be adequate but a final judgment can only be made when the final analysis of the data has been carried out and the results of predictive and back calculations are compared with the data.

6.6.3 Transient phase

The transient phase is the time when probably the most complex processes and interactions during repository lifetime. The waste still produces heat and the heavily distorted hydraulic and mechanical states are trying to get back to equilibrium conditions. Oxygen trapped in the system causes chemical reactions (e.g., pyrite oxidation) and enhances microbial activity in the repository.

An analysis of all these processes during the transient phase demonstrates their complexity and shows the problems that are faced if this phase is investigated in a laboratory. One major problem is the time because the thermal pulse will last several hundreds to thousands of years and re-saturation processes are delayed because of the low hydraulic conductivity of the clay and the restricted availability of the water. Equilibrium will not be reached before several tens to hundred thousands of years.

From this viewpoint, it becomes clear that full-scale demonstration experiments of the transient phase under realistic conditions (e.g., natural saturation) can not be carried out and compromises in the design of experiments are necessary. Artificial saturation for instance will have several disadvantages. For example saturation lines in the buffer (e.g., see Figure 6-6) are, even greater disturbances in the buffer system than instruments and may cause severe problems during buffer installation or *in-situ* compaction. Furthermore, faster saturation may be quite different than slow saturation and some processes (e.g., salt accumulation in the vicinity of a heated canister) may be overlooked or misinterpreted. Also the saturation process from the buffer towards the near-field rock will be quite different and cause additional processes (e.g., air trapped in the EDZ).

Nevertheless, carefully designed experiments permit study of the associated processes and testing of the capability to model the transient phase. Experiments in Mol and Mont Terri gave interesting and sometimes surprising results. Instrumentation seems to be especially difficult in clay rocks for long-term experiments, which is due to the mostly aggressive formation fluids and large deformations. Corrosion of cables and sensors as well as failure of couplings were observed quite frequently even for careful installations. Another problem is the fact that cables provide a preferential flow path and may cause abnormal and biased measurements (e.g., too high and fast saturation).

Heating effects on the buffer and host rock have been investigated (e.g., HE experiment at Mont Terri) and showed that the buffer behavior can be well understood but consequences regarding host rock deformation (e.g., acceleration of time-dependent deformation, potential increase of EDZ) have not been finally addressed. This is partly due to the reduced scale of the experiment and partly due to the relatively short heating period, which resulted in comparatively small temperature changes in the host rock. In addition, thermally induced uplift at the Earth’s surface and the heating of aquifers above the host rock and the related consequences cannot be studied experimentally due to the limitation in time and availability of total thermal power.

Modeling of the complex THMC coupled processes have started but so far the final evaluation of their capabilities has not been completed. The first results demonstrate that adequate codes (e.g., CODE_BRIGHT) are able to capture the processes well and to predict the important parameters. It seems that the models are so far better in predicting the behavior of the buffer than the host rock. Adoptions of the existing codes to special features of the host rock (e.g., anisotropy, ‘creep’) are probably necessary.

The saturation of the buffer in the EB experiment showed the applicability of granular buffer material and demonstrated buffer homogenization during the saturation process. In addition, interaction of buffer and host rock was observed leading to an *in-situ* compaction of the buffer due to drift convergence. At the same time, EDZ self-sealing was observed. The modeling of such processes as saturation of bentonite blocks and granular material and rock-buffer interaction has started, but all problems have not been finally resolved.

6.6.4 Long-term phase

The long-term behavior of a repository is the most important feature for evaluate the safety and performance of a repository. Nevertheless, no experiments in URLs can be conducted to simulate this phase adequately.

The canisters for HLW and SF used in the proposed repositories are designed for a complete isolation of the waste during thousands of years. So, for the operational and most of the transient phase the canisters provide the safety. Buffer and host rock performance during the post-closure phase is the key issue in PAs in the long-term phase. As this performance cannot be directly tested and PA needs robust system description, it will be necessary to investigate whether or not the transient processes cause irreversible changes in buffer and host rock properties (e.g., illitization). Some of the open questions regarding this phase may come from demonstration experiments in URLs, from laboratory measurements on rock samples, and from natural analogues and ‘bounding’ sensitivity modeling with major simplifications and conservative assumptions.

6.7 Summary and conclusions

The clay rock information presented in this report synthesizes the information provided by SCK-CEN and Nagra in support of Andra and Enresa on the successful design, construction and operation of Hades URL and Mont Terri URL respectively. The clay rocks currently considered for the safe disposal of radioactive waste can be distinguished in the following two different classes: 1) soft (less indurated) clays with relatively high water content which behave in a more ductile or viscous manner, and 2) hard or stiff clays (clay shale, clay stone or argillite) with quite low water content which tend to deform and fail more like brittle materials and show only limited viscous behavior. There are a number of similarities between these two different classes but also significant differences leading to different solutions in the general repository design and disposal concepts.

The disposal concepts in clay rock are based on the general premise of a multi-barrier system but the natural barrier, i.e., the clay host rock, is the most important barrier. In addition, national regulatory requirements give guidance for the specific designs in the different countries. The majority of proposed layouts rely on horizontal emplacement levels, which are positioned in the centre of the host rock. Due to the limited thickness of the clay layers, vertical emplacement cells such as in the KBS-3V design in crystalline rock, are less favored in clays. Proposed layouts favor in-room emplacement in (several hundreds of meters) long horizontal to sub-horizontal drifts or in (several tens of meters) short horizontal (large diameter) boreholes or micro-drifts.

The emplacement strategies, proposed in the different countries, require a separation of the different waste types. Construction and operation (i.e., waste emplacement) of the repositories are planned to be executed concurrently to optimize the work and keep emplacement cells open for a minimum time only (e.g., to minimize drift convergence and EDZ creation, to reduce de-saturation, etc.). This approach requires that these areas have separate accesses (e.g., ramps or shafts), which are reserved for construction and scientific work on one side and for waste handling and emplacement on the other side.

In general, the design needs to be flexible, to allow for necessary changes (“observational method” or “design as you go”) caused by results obtained from the site characterization or the existence of unexpected structural elements in the rock. Such discontinuities can occur especially in stiff clays and could result in local drift instabilities.

Several layouts have been proposed by nuclear waste agencies in different countries to optimize repositories in clays taking into account the local conditions and the rock parameters at candidate or generic sites. Although the design principles are very similar, differences in the national regulations, in the waste inventories and in the geological settings led to different solutions. Not only the geometry or architecture of the proposed repositories differ but also the design of the EBS is specific for the different national programs. In general, the proposed buffer material is a smectitic clay but buffer construction and emplacement techniques cover a wide range from pre-compacted large size ring elements to granular buffer material. Some countries even plan to use no buffer at all for the disposal of SF.

RTD projects have been conducted or are in progress in several URLs in clay rock. These projects mainly cover the investigations of processes during construction and operation of a potential repository. In addition, some experiments have been carried out to investigate the behavior of the EBS-host rock interface during the thermal phase and to evaluate long-term behavior. Although clays proved to be quite complex materials due to highly coupled THMC processes, most of the experiments were quite successful. Instrumentation, which experienced a hostile environment (e.g., corrosion, high pore pressure, large deformation, etc.), proved to be reliable in most cases as long as basic requirements were met (i.e., corrosion resistance, careful installation). Numerical models and codes have been developed or adopted to the special needs in a clay rock and to allow the investigation of complex coupled processes. These modeling results, although in some cases still being far from a perfect matching of observations, provided a better understanding of the different processes. Nevertheless, enough information has been gained to give adequate input to PA. This input allowed PA in several national programs to set up robust, conservative models and to evaluate the long-term performance of a repository in clays.

Comprehensive studies have demonstrated the feasibility of constructing and safely operating and closing repositories in clay rock. Independent reviews of these studies have been carried out and support the conclusion that safe repositories can be built in clay host rocks using existing state-of- the-art technologies. The main source for improvements in the future will be the optimization of proposed techniques and the transfer of research-type to industrial-scale technologies.

7 Overall summary and conclusions

The CROP forum for discussions developed as planned and seven meetings were held at different times at different locations that included all URL sites described in this report. The discussions provided up-to-date information on results achieved and information on plans ahead and improvement needed. The fruitful discussions on technical matters that were conducted during the three-year CROP period also enhanced the knowledge among the Participants about the state of progress in the other Participants´ programs, and the success and potential applicability of components in programs considering other geological media than the one in the Participant's program.

The inter-media comparison is a new issue brought up in this project and lengthy discussions were conducted throughout the whole project as to whether the three media represented by the Participants, i.e., salt rock, crystalline rock and clay rock, could be compared in a meaningful way. The major conclusions reached by the Participants on inter-media comparisons are that a comparison on a general level has merits but a comparison on a detailed level could be grossly misleading because the boundary conditions (laws, regulations, site geology, design criteria, thermal loading, etc.) for each national program and geological medium differed significantly. It was also noted that all studied geological media and repository concepts have satisfied the related national program's safety case, and each of the analyzed geological media has the potential for providing a long-term isolation of the nuclear waste with major margin to the respective program's safety requirements. A related conclusion is that each geological medium exhibits pros and cons that are to a major extent affected by the specific design and the application of an appropriate EBS because the safety case is the result of the combined properties of the NBS and the EBS.

The project discussions also revealed that there are many common RTD issues among the different media, and those commonalities should be brought up in conjunction with item-specific consideration of RTD topics of common interest as implemented in the NET.EXCEL project (EC Contract No. FIR-CT-2002-20212).

Following these unanimous conclusions, the project information was compiled in a sequence of medium-specific CAs with special emphasis on lessons learned and means of improving/optimizing the present URL and repository concepts, including instruments, data acquisition and codes/models. For example, the numerical codes were evaluated on their performance against actual field tests and they showed adequate capability to simulate the key repository processes including the coupled phenomena that took place. In summation, the CAs contain detailed descriptions of the different components of the EBS in each geological medium, the related repository concept and analyses and other important considerations from concept generation through implementation, which will serve as a guide to future URL and repository developments.

Some key observations, conclusions, and lessons learned from each geological medium are presented below.

7.1 Salt rock

Two main disposal concepts have been considered in Germany for vitrified waste (HLW) and SF. The canister design has been identified (among existing types and sizes).

In USA, the WIPP repository for long-lived TRUW was certified in 1998 and it opened in 1999. A variety of waste packages are handled at the WIPP site but none is considered important to the long-term containment and isolation of the TRUW.

In both Germany and USA, the host rock – the salt rock – is the main barrier against radionuclide releases to the biosphere, but a combination of NBS and EBS is required to ensure repository stabilization and sealing. Crushed salt makes a good backfill as stress and creep-induced room closure (convergence) ultimately leads to consolidation of the crushed salt backfill and the complete encapsulation of the emplaced waste. With given weight and size of waste packages, the repository design is a country and site-specific issue, of which WIPP is one of several example. Indeed, all the repository designs are site-specific, including the designs of seals and plugs, which in salt rock are the main EBS.

For the German repository concept in domal salt rock, work remains to be conducted on technical issues supporting the verification/optimization of design details.

Good capability exists both in Germany and USA to model the excavation-induced effects, e. g., the EDZ generation, but the adequate prediction of EDZ healing needs further RTD.

In Germany, the final confirmation of the technical emplacement system for Cogéma canisters, as well as the testing of the feasibility of the emplacement of alternative canisters for SF into 300 m deep boreholes, is pending. *In-situ* testing of suggested drift seal design under representative conditions is also pending.

The THM behavior of crushed salt backfill is largely understood. However, adding geochemical additives to increase sorption of special radionuclides in the near-field has not been tested adequately. According to the recent German report on selection procedures for repository sites prepared by a national expert group (AkEnd 2002), it is necessary to reconsider the conclusions drawn from the research work done to date. For example, the importance of slow migration processes, such as diffusion of carrier fluids such as brines and gases in the whole repository system, increases significantly.

The experience and lessons learned at WIPP include both an operating repository and an on-site URL situated approximately 650 m below the ground surface in a 225-250 million year old, 600 m-thick bedded salt rock formation. The major basis for the successful certification and opening of the WIPP repository is equal advances in both repository-science related issues (site conditions, disposal concept, and performance requirements), and social, science and demographic related issues (local acceptance, political will, and organizational leadership). Although the WIPP repository is already operating and has safely received and disposed of more than 2 000 shipments of TRUW, the development of the WIPP repository is phased and, by law, the safety of the WIPP disposal concept/system has to be recertified at least every five years.

7.2 Crystalline rock

Crystalline rock has brittle characteristics and contains fracture systems. These fracture systems form patterns of groundwater transport pathways from a repository to the biosphere. Hence, the locations of these fracture systems and their transport characteristics are the major factors that must be considered in the long-term safety case. The most common application of the multi-barrier principle in crystalline rock, i.e., a combination of NBS and EBS components, puts the main burden for radionuclide containment and isolation on the EBS. Still, the near-field chemical environment and the natural radionuclide retardation properties of the host rock are very important, although credit in the PA/SA can be taken only for verified conditions.

Ongoing work on improvement/optimization of crystalline rock repositories addresses several issues, including the following:

- Canister design and manufacturing, as well as the performance of different materials, have been investigated in detail. Differences in choice of design and manufacturer are based on national philosophies but all programs use the same knowledge base. In all cases the safety case is a combination of the interacting performance of the waste, the canister, the buffer/backfill/plugs and the surrounding rock mass. The most important parameter for the design of the repository is the maximum temperature allowed in the near-field, which in many programs is specified as the temperature on the surface of the canister. In addition, the design (shape and size) and the orientation of drifts at depth are important because they, in combination with the prevailing state of stress, influence the conditions for groundwater flow.

- The selection of excavation method needs consideration with respect to the consequences that the different methods have on the future properties of the host rock and in particular on the EDZ around the drift, which will have changed properties after excavation compared to before. Well-proven excavation methods exist for all proposed underground openings.

- Grouting as a means for sealing drift walls against inflowing water need to be developed from techniques and materials used in current practice, as ordinary cementitious materials (high pH) are judged to be detrimental to the long-term safety of the repository.

- Swelling clay alone or mixed with other materials is an outstanding material for use in buffer, backfill and plugs and has been thoroughly investigated for some 30 years. Manufacturing of different sizes of highly compacted blocks has been verified for some types of bentonite.

- Emplacement and deposition methods have been tested in full scale for vertical in-hole and for horizontal in-tunnel emplacement. Programs are going on for testing of horizontal emplacement, and are also considering large waste packages containing both canister and surrounding buffer.

- Backfilling of deposition drifts in the KBS-3V vertical in-hole emplacement method (SKB and Posiva) has been tested in full scale for fresh water to slightly salt groundwater, but has not been verified for groundwater salinities of 3.5% TDS (ocean waters) and for waters of higher TDS being considered in other programs.

- Performance of different designs of plugs and seals has been investigated but the outline of a detailed sealing strategy for a repository remains to be made in all crystalline rock repository concepts.
- The types of instruments required for long-term repository monitoring have been identified but development work must continue on improving the longevity of the instruments and DASs: maintenance, replacement and calibration of the instrumentation *in-situ*, and effective monitoring after repository closure without using invasive installations that might affect the passive safety of the repository.
- Work must continue to develop, refine and apply coupled modeling capability and to compare model results to field data from large-scale *in-situ* experiments.

7.3 Clay rock

The disposal concepts in both soft and hard clay rocks (clay shale, clay stone or argillite) have adopted to the fact that the clay layers generally have a limited thickness. This favors in-room emplacement of canisters relative to in-hole emplacement (vertical mode), and a trend exists toward layouts of in-room emplacement in several hundred meters long horizontal to sub-horizontal drifts. The alternative is several tens of meter long horizontal large diameter boreholes or micro-drifts.

The canister and waste package designs vary and improvements of large packages even including the buffer around the canister are being developed and tested. Excavation is normally more complex in clay rocks than in salt rock or crystalline rock, but proven clay excavation technologies exist and can be applied. Major verification of optimum techniques has been made in soft clay in the Hades URL, where the rock needs to be supported by liners to prevent the plastic deformation of excavated openings. Excavation in hard clay also uses proven technology. In all cases, the clay is the main barrier in the multi-barrier system, but the EBS has to be designed and constructed in a way that processes during the transient phase (e.g., potential deformation, compaction) do not jeopardize the long-term safety. Similar to the crystalline rock repositories, a buffer around the canister is part of most EBS concepts in clay rock. Backfilling, sealing and plugging are other EBS components that have many similarities with those in crystalline rock and salt rock.

Testing of different sizes of waste packages addressing both design details and major parameters affecting the design is ongoing. These tests only indirectly address safety related issues and are primarily meant to optimize the efficiency during the operation phase.

Similar design principles are used for making country-, waste- and site-specific repository layouts including the EBS (e.g., buffers, backfill and plugs). Many experiments are going on in URLs to support this work. Others address the transfer of research-type to industrial-scale technologies (scaling).

Emplacement strategies for different waste types are in place in each country.

Concurrent excavation and operation (waste emplacement) are considered to be the optimal solution. The aim is to keep the emplacement cells open for a short time only to minimize drift convergence and EDZ creation and to reduce de-saturation, etc. This approach requires among other things separate accesses (ramps or shafts) for construction and scientific work in one area and for waste handling and emplacement in another area.

The application of an “active design” with enough flexibility to allow for necessary changes that take into account results from site characterization or the existence of unexpected structural elements/discontinuities in the rock. Such discontinuities can occur especially in stiff clays and could result in local drift instabilities.

Repository components such as large waste packages, buffer, backfill, seals and plugs are being investigated and the work in clay rock exhibits many similarities with the work going on in crystalline rock.

7.4 Concluding remarks

From the WIPP success and all other programs advancing towards the licensing of geological repositories, it is very clear that authorities issuing future licenses for repository development will recognize the importance of a sound safety case, good technology, and the acceptance of the public.

The project has further clarified that there exist safe geological disposal concepts, which have been shown to perform in accordance with the respective nations´ safety requirements as well as international standards that have been reviewed and supported by international peer review teams.

These PA/SA rely to a large extent on the results obtained from full-scale testing in URLs of the combined and complex processes that are expected to take place in geological repositories. The processes studied in URLs are limited to those that occur during the construction, operational and early transient phases, where the time scales can be replicated in the URL tests. Due to the temporal and spatial scales involved, the repository performance during the remaining transient phase and the subsequent long-term (post-closure) phase cannot be assessed by tests in URLs and must be assessed by modeling methods simulating the repository performance.

As the objective is to identify, develop and verify methods of simulating processes that occur in a repository and that are important to the design and the safety case, some full-scale verification tests, with extensive process coupling, remain to be done. These tests are different for different geological media and country depending on the state of progress for each country.

The Participants’ URLs have performed according to plans and the ones still in operation and under planning/construction represent a large enough variety of geological conditions for to having the capability to provide credible generic information on repository concepts in all geological media of consideration in the world today except tuff. However, they are not capable of providing the site-specific information that every disposal program requires for final verification and fine-tuning of the safety case and for determining the detailed construction/operation parameters for a repository.

The different geological conditions at the Participants’ URL sites have led to different designs and instrumentation of the aforementioned URLs. However, all the EBSs have a similar function and, despite some obvious differences, many of the medium-specific solutions and techniques developed and documented by the Participants are believed to also be applicable to disposal concepts in other rock types. The results from tests conducted in many different geological media and involving a large number of EBS components are expected to be valuable to all organizations involved in repository development, and it is thus concluded that improved technical solutions and improved repository and URL designs will evolve from the joint analyses conducted and summarized by the Participants in this report.

8 Acknowledgements

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Lastly, the project coordinator would like to express a special gratitude to Roland Pusch, who has acted as the principal science writer all through the project and also coordinated the compilation of this Deliverable.

9 Reference List

9.1 Country Annexes

The following CAs have formed the basis for the information presented in the report. Although they are not published in public report series they or information contained in them may be obtained by direct contact with respective organization listed below.

Project Participant	Country Annex
Agence Nationale pour la gestion des Déchets Radioactifs (Andra) Parc de la Croix Blanche 1-7 rue Jean Monnet 92298 Chatenay-Malabry FRANCE Phone: +33 1 46 11 80 00 Representative: Frédéric Plas E-mail: frederic.plas@andra.fr	WP1 and WP2, Design and construction of engineered barriers (EBS), and Instruments and experimental procedures. Two Appendices. WP3, Conceptual and Mathematical models predicting THMC performance of the Engineered Barrier system. One Appendix. WP4, Preliminary assessment of performance of underground laboratories and repository concepts.
Empresa Nacional de Residuos Radiactivos S.A. (Enresa) Emilio Vargas 7 28043 Madrid SPAIN Phone: +34 91 5 66 81 32 Representative: Fernando Huertas E-mail: fhui@enresa.es	WP1, Design and construction of engineered barriers. Case a) APG –Granite and Case b) APG–Clay. WP2, Instruments and Experimental Procedures. Case a) Granite and Case b) Clay. WP3, Assessment of the function of EBS and the understanding of and capability to model the important properties. WP4, Preliminary assessment of performance of underground laboratories and repository concept.
Gesellschaft fuer Anlagen- und Reaktorsicherheit mbH (GRS) Theodor-Heuss Strasse 4 D-38122 Braunschweig GERMANY Phone: +49 531 8012 226 Representative: Tilmann Rothfuchs E-mail: rot@grs.de	WP1, Design and construction of engineered barriers WP2, Instruments and experimental procedures WP3, Assessment of the function of EBS and the understanding of and capability to model the important processes. WP3, Application of conceptual & mathematical models for predicting THMCB performance. WP4, Preliminary Assessment of Performance of Underground Laboratories & Repository Concepts. GRS-201. ISBN-3-93 1995-68-2
Nationale Genossenschaft fuer die Lagerung Radioaktiver Abfaelle (Nagra) Hardstarsse 73 5430 Wettingen SWITZERLAND Phone: +41 56 437 11 11 Representative: Peter Bluemling E-mail: blumling@nagra.ch	WP1 Design and construction of engineered barriers. WP2 Instruments and experimental procedures. WP3 Assessment of the function of EBS and the understanding of and capability to model the important properties and application of conceptual & mathematical models for predicting THMCB performance. WP4, Preliminary Assessment of Performance of Underground Laboratories & Repository Concepts.
Ontario Power Generation Inc. (OPG) 700 University Avenue Toronto, Ontario, M5G 1X6 CANADA Phone: +1 416 592-2555 Representative: Gary Simmons E-mail: simmonsg@granite.mb.ca	WP1-WP4, Ontario Power generation's input to the European Commission's Cluster Repository Project – A basis for evaluating and developing concepts of final repositories for high-level radioactive waste.

Project Participant	**Country Annex**
Posiva Oy (Posiva) 271 60 Olkiluoto FINLAND Phone: +358 2 8372 31 Representative: Jukka-Pekka Salo E-mail: jukka-pekka.salo@posiva.fi	WP1, Design and construction of engineered barriers. WP 2, Instruments and experimental procedures. WP3, Assessment of the function of EBS and the understanding of and capability to model the important properties. Mathematical models and parameters needed for applying them. WP4, Preliminary assessment of performance of underground laboratories & repository concepts.
Studiecentrum voor Kernenergie- Centre d′étude de l′Energie Nucléaire (SCK-CEN) Boeretang 200, 2400 Mol BELGIUM Phone: +32 14 33 21 11 Representative: Jan Verstricht E-mail: jverstri@sckcen.be	WP1, Design and construction of engineered barriers. WP2, Instruments and experimental procedures. WP3, Assessment of the function of EBS and the understanding of and capability to model the important properties, Combined annex for “Mathematical models and parameters needed for applying them” and “Application of conceptual & mathematical models for predicting THMCB performance”. WP4, Preliminary assessment of performance of underground Laboratories and Repository concepts.
Svensk Kaernbraenslehantering AB (SKB) Box 5864 102 40 Stockholm Sweden Phone:+ 46 459 8400 Representative: Christer Svemar E-mail:christer.svemar@skb.se	WP1, Design and construction of engineered barriers. WP2, Instruments and experimental procedures. WP3, Assessment of the function of EBS and the understanding of and capability to model the important processes. WP4, Preliminary assessment of the performance of underground laboratories and repository.
U.S. Department of Energy Carlsbad Field Office (USDOE CBFO) PO Box 3090 4021 National Parks Highway Carlsbad New Mexico, 88220 USA Phone:+001 505 234-7467 Representative: Mark Matthews E-mail: mark.matthews@wipp.ws	WP1, Design and construction of engineered barriers at the Waste Isolation Pilot Plant (WIPP) salt rock repository site. WP2, Instruments and experimental procedures. WP3, Assessment of the function of the engineered barrier systems and the understanding of and capability to model the important properties at the Waste Isolation Pilot Plant (WIPP) salt rock repository site. WP3, Results from application of models for evaluation and prediction of important near-field repository processes at the Waste Isolation Pilot Plant (WIPP) salt rock repository site. WP4, Preliminary assessment of the performance of underground laboratories and repository concepts at the Waste Isolation Pilot Plant (WIPP) salt rock repository site. WP4. Final assessment of performance of the underground laboratory and repository concepts at the Waste Isolation Pilot Plant (WIPP) salt rock site and recommendations for the design and construction of future safe repositories.

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Appendix 1 Overview of selected experiments

Overview of selected experiments in the Waste Isolation Pilot Plant URL and Air Intake Shaft (USDOE-CBFO)

Project name, acronym, main tests	***Description/objectives related to EBS and near-field***	***Assessment***
Thermal/ structural interaction (TSI) test	A suite of tests conducted in the WIPP URL to address the time-dependent mechanical behavior of rock salt as influenced by: ▪ Excavation effects. ▪ Stress. ▪ Thermal loading. ▪ Waste emplacement. Three main categories of tests were conducted: ▪ Simulated DHLW disposal (e.g., the 18 W/m^2 DHLW Mockup Test and the DHLW Overtest). ▪ Model and design verification tests with emphasis on the evaluation of constitutive models and computer codes (e.g., the Heated Axisymmetric Pillar Experiment and the Geomechanical Evaluation). ▪ Structural properties tests. The objectives and benefits of the major TSI Tests are summarized below.	Provided large-scale, in situ information on: ▪ The extent and nature of the excavation disturbed rock zone. ▪ The stability of excavated rooms during waste emplacement/operation and possible retrieval, including ground control criteria/needs. ▪ Long-term deformation of the disposal rooms and the related encapsulation of the waste. This database was used to develop and validate predictive modeling and calculation techniques for the design and operational and post SAs/PAs of repositories for DHLW and TRUW at the WIPP site. Satisfactory agreement between the measured and predicted response from the simulated DHLW and the model and design verification tests helped validate the constitutive model used at WIPP to predict the behaviour of large rock masses. The structural properties tests provided data for direct use in computer calculations.
18-W/m^2 DHLW Mockup	Addressed: ▪ Rates of salt creep and room closure. ▪ Effects of heat transfer to the host rock. ▪ Validity of predictive methods and techniques. ▪ Suitability of a reference DHLW disposal room. ▪ The effects of excavating adjacent rooms (mine-by experiment).	Provided baseline information on the effects of heat on room closure, opening/structural stability, and waste encapsulation in rock salt using the exact thermal and structural matchesanticipated thermal loading of the Reference Repository Configuration (RRC) for DHLW in bedded salt rock within the limitation of presenting the fields of a large array of rooms with a three-room configuration.
DHLW Overtest	Addressed: ▪ Room closure rate and heat transfer at elevated temperatures. ▪ Validity of predictive techniques. ▪ Long-term effects of heat and room closure. This test used about four times the RRC thermal load to drive the room to failure more quickly. The canister/salt-interface temperature was ~250^{o}C.	Provided creep constitutive thermomechanical model validation verification and structural data on canister response and room failure mechanisms.

Project name, acronym, main tests	***Description/objectives related to EBS and near-field***	***Assessment***
The Geomechanical Evaluation	Addressed: ▪ Effects of varying excavation spans and the influence of the overlying bedded stratigraphy. ▪ A wedge pillar to explore an over-stress failure condition. ▪ A three-dimensional (3-D) intersection to evaluate 2-D and 3-D models. Only the first of the three planned phases was implemented, including the In situ-Stress Determination by Hydraulic Fracturing in the Room G Entry Test described below.	Provided the main data on in situ-stress levels and orientations at the WIPP site based on the hydraulic pressure required to fracture the rock augmented by careful observations as the mining proceeded through the fractured area.
The Heated Axisymmetric Pillar Experiment	Addressed: ▪ Validity of the models and computer codes in predicting the response of heated rock-salt mass. ▪ Behaviour of room and pillar in response to (accelerated) creep. ▪ Mechanical properties and failure modes of salt and other constituents in the testing envelope. ▪ Relationships between (a) actual 3-D response to 2-D models, and (b) in situ data from laboratory-model pillar tests and from other salt mines to applicable models. After acquiring creep information on the pillar and room at ambient temperature for one year, the pillar was covered with an insulating blanket and heated to 70°C. This heating continued until one year before decommissioning to allow a one-year cool-down period. Installed instruments measured temperature, vertical and horizontal room closure, and deformation of and stresses in the rock bordering the room.	Provided ten years of active data on room behaviour at ambient and elevated temperatures that were used in support of other studies and in the WIPP PA.
In situ-Stress Determination by Hydraulic Fracturing in the Room G Entry	Addressed: ▪ In situ-stress conditions in the WIPP repository horizon. ▪ The hydraulic state of stress assumed to exist at the WIPP repository horizon. ▪ Relationships between in situ stress values and data obtained in the laboratory and by calculation. A series of hydraulic fracturing tests, using fluorescent dye, at different intervals in a 125-m deep-borehole along the access drift to room G.	Provided the initial state-of-stress condition used in WIPP calculations.

Project name, acronym, main tests	***Description/objectives related to EBS and near-field***	***Assessment***
Clay Seam Shear Test	Addressed: ▪ The effective friction coefficient of clay seams and partings. ▪ Relationship between in situ and laboratory data. ▪ Relationship between calculated and measured displacements along clay seams.	Provided coefficient-of-friction values for naturally occurring, sliding geologic units.
Acoustic Emissions Monitoring	Addressed: ▪ The onset of yielding and fracturing of a salt rock pillar. ▪ The failure mode of a salt rock pillar. ▪ The correlation between acoustic emission data, pillar deformation, and fracture propagation.	Provided means to detect the location of fracture onset, which was used to estimate factors of safety in pillar design.
The Ambient Temperature Room Test	This was the first test room excavated in the WIPP URL. It was used to: ▪ Test gage installation techniques. ▪ Obtain rock mechanics data at ambient temperature.	Provided baseline data used (a) to establish rock salt constitutive properties and (b) for comparison with data obtained during the DHLW Overtest.
The Scale-Effect Tests	Two cylindrical boreholes of different dimensions were instrumented and observed to resolve the debate over whether the scale of excavations could be responsible for some of the discrepancies between observation and model calculations.	The structural behavior of both tests was accurately predicted by the model, eliminating scale effect as a source of concern in the calculations.
Plugging and sealing (P&S) test	A suite of tests conducted in the WIPP URL to address and support the development of: ▪ Candidate materials and structural systems for long-term plugs and seals in salt rock. ▪ Materials and emplacement techniques for adequate sealing of boreholes, shafts, and drifts in salt rock. ▪ Assessment techniques for predicting long-term performance with field and full-sized tests. ▪ Properties on host rock permeability and plug/seal interactions. Involved laboratory studies and intermediate-scale (m-diameter holes) in situ testing of candidate plug and seal materials. Gas-flow tests were used to characterize the EDZ. The objectives and benefits of the major P&S Tests are summarized below.	Provided the technical basis for an adequate and defensible design for sealing the WIPP repository after decontamination and decommissioning. The long-term sealing strategy utilized the reconsolidation of crushed salt, eventually resulting in a seal that approaches the density, permeability, and strength of the intact host salt. To ensure isolation and prevent fluid intrusion in the time frame before crushed salt reconsolidation is completed, bentonite clay, concrete, and asphalt plugs supplement the primary salt plug.

Project name, acronym, main tests	***Description/objectives related to EBS and near-field***	***Assessment***
Permeability Measurements (please note that a large number of surface-based tests conducted at the WIPP site is not addressed in this table)	Borehole-based measurements that addressed: ▪ Permeability and porosity of the rock salt. ▪ Permeability variations with distance from the mined face, including the EDZ. ▪ Influence of the interspersed clay and anhydrite seams upon permeability values. ▪ The first phase of the test was conducted with gas and brine, and the pressure decay was measured by guarded straddle packers. In the second phase, the natural formation was replaced by a man-made seal.	Provided baseline information on (a) fluid-flow characteristics of the WIPP host rock, primarily at the repository level, and (b) the performance of seal/plug materials including cementitious grout, clays, and crushed rock salt (based on measured pressure variations and flow rates with time from which permeability was inferred based on calculations).
Plug Test Matrix	Addressed: ▪ Interactions and long-term geochemical stability of candidate seal materials in various salt rock conditions. ▪ Seal emplacement techniques.	Provided information on long-term durability of candidate seal materials in the host-rock environment. (In situ-cured seal samples were used for laboratory tests.)
Borehole Plug	Addressed: ▪ Performance of seals in deep boreholes. ▪ Interactions between host rock and seals. ▪ Seal emplacement techniques. ▪ Stability and durability of recovered borehole-seal materials.	Provided information on seal-material types, seal-emplacement techniques, and performance of seals in deep boreholes in both salt and non-salt rocks.
Moisture Transport and Release	Addressed: ▪ Movement of naturally occurring moisture in the rock. ▪ Quantity, rates, and composition of moisture release to openings in the host-formation as a function of temperature and time. ▪ Relationships between in situ measurements, laboratory data, and model predictions.	Provided information used to develop predictive models for moisture transport, release, and accumulation at WIPP.
Air Intake Shaft (AIS) Performance	Addressed: ▪ Shaft closure in the Salado (repository-host) formation. ▪ Model development for long-term closure predictions. ▪ Near-field (shaft) permeability. ▪ EDZ effects of shaft construction. ▪ Impact of shaft-construction-induced EDZ on the seal design and technology development.	Provided precise information on the structural, hydrological, brine inflow, and geophysical response of the salt rock and overlying units to shaft construction and operation.

Project name, acronym, main tests	***Description/objectives related to EBS and near-field***	***Assessment***
	▪ Hydrological communication between geological units in the lined (uppermost) section of the shaft. ▪ Brine inflow into the shaft. ▪ Net inflow of fluids into the shaft from all sources.	
Small-Scale Seal Performance	Addressed: ▪ In situ-flow performance for various seal systems. ▪ In situ-mechanical performance of the host rock and different candidate seal materials. ▪ Seal emplacement techniques. ▪ The development of numerical predictive capabilities.	Provided information on seal materials and emplacement techniques, including (a) salt-based concrete in both horizontal and vertical boreholes, (b) salt and bentonite blocks and mortar barriers in horizontal emplacements, (c) various salt and bentonite backfill materials in vertical emplacements, and (d) a vertically emplaced concrete seal in fractured anhydrite. This information, in combination with laboratory data, was used to assess the capabilities of the WIPP codes and models for the seal design.
Large-Scale Seal Performance (also referred to as the Bulkhead Test)	Addressed: ▪ Seal-emplacement techniques. ▪ Time-dependent fluid-flow and structural performance of the seal system. ▪ Relationship between in situ data and computer calculations (validation of flow and structural models. ▪ The development of a database for WIPP underground seal design(s).	Provided information on single- and multi-component seals, including a salt centre core surrounded on the sides by salt/bentonite and at the ends by crushed salt blocks.
Backfill Design and Emplacement	Addressed: ▪ Consolidation of candidate backfill materials. ▪ Structural interactions and fluid flow in backfilled rooms. and ▪ Full-scale backfill emplacement techniques and equipment.	Provided ”full-scale” information on (a) techniques for effectively and efficiently backfilling rooms with crushed salt-based material after waste emplacement, (b) seal effectiveness, and (c) room/backfill/waste container interactions.

Project name, acronym, main tests	***Description/objectives related to EBS and near-field***	***Assessment***
Waste package performance (WPP) tests	A suite of tests conducted in the WIPP URL to address: ▪ the durability of waste packages in near-reference and overtest conditions. ▪ the confinement integrity of waste packages. ▪ the effectiveness of engineered barriers for waste confinement. ▪ predictive models and techniques for assessing long-term performance. The WPP Tests evaluated several possible HLW canister materials and examined leaching of candidate glass waste forms of several nations. The objectives and benefits of the major WPP Tests are summarized below.	Provided information on the effects of the WIPP repository environment on waste packages for contact-handled (CH) TRUW, remote-handled (RH) TRUW, and HLW that was used by the USDOE CBFO and other waste management organizations to evaluate the short-term (5 years to 50 years) integrity of different waste packages.
Simulated DHLW Technology Experiments	Addressed: ▪ The performance and confinement integrity of the simulated DHLW packages in a thermal environment. ▪ Interactions of waste canisters, backfill materials, and host rock at near-reference and overtest conditions. ▪ Testing procedures for application to future radioactive tests. ▪ Relationships among in situ test results, laboratory data, and analytical studies. ▪ The development of a technical basis for evaluating the concept of safe disposal of HLW in salt rock. Canister surface temperatures ranged between 90°C and 200°C. The tested backfill materials comprised crushed salt, low-density bentonite/ sand mixture, and entrapped air.	Provided canister material data on 304L stainless steel, mild steel, TiCode-12, and four DHLW Overtest canisters containing simulated DHLW glass waste at near-reference and overtest repository conditions.

Overview of selected experiments in the Asse Mine (GRS)

Project name, acronym, main tests	***Description/objectives related to EBS and near-field***	***Assessment***
Temperature Test 5 in Asse Mine (TV5)	Test was performed in a 7 m deep horizontal borehole, heat duration was 1 year, maximum salt temperature reached was 270°C Addressed: • Thermal stability of accessory minerals in Older Halite Na2 • Migration of water traces into heated (disposal) boreholes • Permeability of rock salt in the vicinity of heated boreholes	Rock salt was heated stepwise to 100°C, 150°C, 200°C, 230°C, 270°C. Microscopy of thin sections taken from the rock salt revealed stability of polyhalite crystals up to 230°C. Knudsen-flow model was found best to simulate fluid flow in low permeable rock salt, but Darcy flow appears to be sufficient, too. Permeability measured in the heated rock salt was less than E-22 m^2.
Brine Migration Test with Co-60 Radiation Sources	Experiment performed in four 7 m deep vertical boreholes of 0.5 m diameter. Two boreholes with, two without Co-60 radiation sources. All boreholes heated by peripheral heaters to maximum salt temperature of 210°C. Addressed: • Migration of traces of formation water into heated (disposal) boreholes • H_2-generation due to gamma irradiation of rock salt and material corrosion • Radiation damage in rock salt • Thermo-mechanical behavior of rock salt as influenced by excavation effects, stress and thermal loading.	Knudsen-flow model was found best to simulate fluid flow in low permeable rock salt, but Darcy flow appears to be sufficient, too. Hydrogen generation was very limited and could be attributed to corrosion of metallic material only. Irradiation of the rock salt (max. dose at borehole wall 5 MGy) did not yield measurable amounts of stored energy at maximum temperature of 210°C. Even in colder areas concentration of colloidal sodium was found to be lower than 0.1 % by volume. Provided data over more than 3 years of room convergence in non-heated and heated phases. Coupled TM-models applied to simulated test behavior were found to be adequate. Room convergence rates agree reasonably with predictions
Development of Borehole Seals for Radioactive Waste Disposal (DEBORA)	DEBORA experiments performed in 15 m deep vertical boreholes of 0.6 m diameter. Backfilled boreholes heated over 2 years in a way representing expected repository conditions Addressed: • Thermo-mechanical behavior of rock salt as influenced by excavation effects, stress and thermal loading • Thermo-hydro-mechanical behavior (compaction) of crushed salt as influenced by stress, thermal loading, rock creep (borehole convergence) • Testing of specially designed measurement equipment	Provided data over more than 1 year of convergence of heated boreholes. Coupled TM-models applied to simulated test behavior were found to be adequate. Provided data over more than 1 year of backfill compaction in heated boreholes. Coupled THM-models applied to simulated compaction behavior were found to be adequate. Specifically developed instrumentation to measure gap width (convergence) in lined boreholes works satisfactory under severe borehole conditions.
Thermal Simulation of Drift Emplacement (TSDE)	TSDE experiment performed in two parallel 60m long drifts of 3 to 4m diameter. Three simulated and heated SF storage casks emplaced in each backfilled drift. System heated up in more than 8 years to maximum temperature of 210°C at cask surface.	2-D modeling was adequate only to simulate the conditions in regions where plane symmetry prevailed. Modeling of the whole TSDE experiment under consideration of end effects, for instance, was only possible by application of complex 3-D-models. With 3-D-models improved in the course of the projects, successful prediction of temperature, stress, and displacements fields as well as of the

Project name, acronym, main tests	***Description/objectives related to EBS and near-field***	***Assessment***
	Addressed: - Thermo-mechanical behavior of rock salt in interaction with crushed salt backfill influenced by excavation effects, stress and thermal loading (drift convergence) - Corrosion of materials under representative *in-situ* conditions - Instrument behavior in backfilled disposal drifts - Gas generation in the backfilled drift due to heat up and corrosion.	attendant properties of compacted backfill, intact rock salt and EDZ was demonstrated. Examined samples taken from the removed backfill and heated rock salt confirmed the temperature and stress dependent compaction behavior, thus demonstrating the capability of entire waste container encapsulation. The alloy Ti99.8-Pd and unalloyed/low-alloyed steels have a high resistance to general and pitting corrosion in rock salt environment and are therefore very promising materials for the manufacture of long-lived waste containers. The materials Hastelloy C4 and C22, cast iron and Cr-Ni steels 1.4306 and 1.4833 exhibited a good corrosion resistance to general and local corrosion. However, it is known from previous investigations that under some severe conditions (e.g., low pH, very high Cl^--content of brine) these materials suffer from pitting corrosion. Most instruments showed only little corrosion after more than nine years testing. Signals were mostly still within manufacturer tolerances and linearity was sufficient, too. Monitored amount of gases such as hydrogen H^2, methane CH^4 and carbon dioxide CO^2 were far below any regulatory limits, but sealing of the backfilled drifts was poor thus rendering plausible interpretation of measurements.
Dam Constructions in radioactive waste repositories in salt rock formations	The DAM-project performed to construct and examine drift seals in two test drifts at the 945m level of the Asse mine. Addressed: - Development of salt concrete recipe - Test construction technology for dam components under *in-situ* conditions (abutments made of salt concrete, seals made of asphalt mixtures, seals made of rock salt bricks) - Sealing capability of dam components - Mechanical behavior of rock salt and dam components.	A suitable recipe for salt concrete was developed capable to be pumped underground The technology to mix and transport salt concrete at the test site was demonstrated and dam components constructed with salt concrete. The construction of an asphalt sealing made of sand asphalt blocks was demonstrated. Due to premature termination of the project the test dam construction could not be finalized. Thus an *in-situ* test on the sealing capability was not performed. Tests in laboratory showed low permeabilities for the asphalt components (k= E-22 m^2) 2D mechanical calculations were applied to decide on the shape of the salt concrete static abutment. A multiple prism-shaped abutment was found to meet the requirements best. Tests in laboratory and in *in-situ* boreholes provided axial strengths of salt concrete between 30 to 33 MPa.

Overview of selected experiments in the Stripa URL (SKB)

Project name, acronym, main tests	***Description/objectives related to EBS and near-field***	***Assessment***
Stripa BMT	Addressed: • Buffer evolution	Provided: • Technique for preparation of big compacted blocks developed. • Instrumentation worked well. • Conceptual model of buffer maturation obtained.
Stripa Plug tests	Addressed: • Construction and testing of drift, shaft and borehole plugs	Provided: • Efficiency of clay seals in concrete plugs demonstrated. • Maturation of clay in borehole modeled. • Techniques for shaft and borehole seals developed.
Stripa rock sealing tests, EDZ and deposition hole.	Addressed: • Determination of the hydraulic properties of the EDZ. • EDZ sealing and sealing of near-field of deposition holes	Provided: • EDZ around blasted drifts is highly conductive close to drifts and extends to several meters from the periphery. After-injection with cement or clay gives poor sealing. • Grouting of deposition holes walls is fairly effective but heating by canisters removes part of the effect.
Tests of French Fo-Ca7	Addressed: • Testing of buffer in 5 year tests with up to 150^{o}C	Provided: • Maturation model validated. • Importance of vapor pressure shown. • Significant mineral conversion and related change in physical properties recorded.
Site characterization and validation tests	Addressed: • Site characterization methodology for prediction of groundwater flow and solute transport. • Methodology for validation of appropriateness of conceptual and numerical models to be used on transports in fractured rock.	Provided: • Structured approach to combine data from site characterization into a conceptual geological and hydrogeological model. • Quantification of the “skin zone” around a tunnel. • Numerical modeling of discrete fracture flow. • Way of interaction between modelers and experimentalists.

Overview of selected experiments in the URLs at AEspoe Hard Rock Laboratory (SKB)

Project name, acronym, main tests	***Description/objectives related to EBS and near-field***	***Assessment***
Zedex – zone of excavated disturbance experiment	Addressed: • Understanding of the mechanical behavior of the EDZ with respect to its origin, character, magnitude of property change, extent and dependence on excavation method. • Understanding of the hydraulic significance of the EDZ. • Testing of equipment and methodology for quantifying the EDZ.	Provided: • Comparison of EDZ in a drill-and-blast drift and a TBM drift under very similar rock conditions. • Understanding of the character and properties of the two different parts of EDZ, the damaged and the disturbed zone. • Experience on methods and equipment to measure and quantify the EDZ and its change in properties during excavation.
Two-phase flow	Laboratory and field tests addressed: • Importance of degassing of groundwater at low pressure on measurements of hydraulic properties in boreholes and drifts. • Other processes causing two-phase flow near excavations. • Conditions under which two-phase flow will occur and be significant. • Time scale for resaturation of a repository. • Development of technology for measurement of saturation.	Provided: • Quantification of de-gassing effects i underground environments. • Experimental and theoretical data base on bubble trappment in fracture networks. • Effect of de-gassing on groundwater inflow to boreholes and drifts (being of no significance under general conditions).
Redox experiment	laboratory and field tests addressed: • Reaction between rock/groundwater and trapped oxygen. • Capacity of rock matrix to consume oxygen. • Time scale for consumption of trapped oxygen in a repository.	Provided: • Time scales of O_2 uptake. • O_2 uptake by geological medium. • O_2 uptake by microbial activity. • Reducing capacity of CH_4 and H_2.
Prototype Repository project	Addresses: • Demonstration of the integrated function of the deep repository components under realistic conditions and to compare results with models and assumptions. • Development, test, and demonstrate engineering standards and quality assurance methods.	Provided: • Knowledge on practical and QA issues for disposal and backfilling of drift. • Data and knowledge on effect of and precautions needed to meet problem with inflowing water in holes and drifts. • Database on THMC processes taking place in buffer, backfill and surrounding rock. • Data on interaction between rock and buffer during saturation in AEspoe rock conditions. • Validated in principle of conceptual model. Problems have been experienced with instrumentation affecting the hydration. Problems have occured with electrical circuits to heaters.

Project name, acronym, main tests	***Description/objectives related to EBS and near-field***	***Assessment***
Canister Retrieval Test	Addresses: • A test set-up for demonstrating the technique for freeing a disposed canister from the swollen bentonite and retrieving it. • THM processes progressing during saturation of the bentonite buffer. • TM processes progressing in the surrounding rock during heating.	Provides: • Data on THM processes in bentonite when there is free access to water at the outer boundary of the bentonite buffer. • Data on T and M changes in the surrounding rock. The freeing/retrieval test will take place in the future.
Long-term test of buffer material (LOT) experiments	Addresses: • Function tests of buffer under normal and adverse conditions. • Max temperature 90 and 130 °C, respectively. • Test times ranging from 1 year to 20 years. • Stressing of C and B processes by doping bentonite samples.	Provided: • Tests after 1 year show no obvious changes for 90-130°C. • Data on C and B processes taking place • Data on tracer mobility in bentonite.
Backfill and Plug Test	Addresses: • Development and test techniques and materials for backfilling of tunnels. • Development and test techniques for temporary plugging of deposition tunnels. • Testing the integrated mechanical and hydraulic function of the backfill and near field rock in a tunnel excavated by blasting.	Provided: • Knowledge on practical and QA issues for backfilling of disposal drifts. • Data and knowledge of in-situ backfilling of 30/70 mixtures (bentonite/crushed rock) and pure crushed rock respectively. • Information on interaction between near-field rock and backfill. • Information on properties of EDZ in floor region. (Supplementary and to some extent contradictory conclusions to the Zedex ones.) Testing of hydraulic and compressibility properties of backfill is pending.
Tracer retention understanding experiments (TRUE)	A suite of tests conducted in the AEspoe URL to address the issue of transport and retention of radionuclides in fractured rock, in different scales: • < 0.5 m transport distance. • Up to 10 m transport distance. • Up to 100 m transport distance.	Provided: • Understanding of fracture and fracture system features. • Basis for development of fracture characterization techniques. • Basis for development of conceptual and numerical tools for simulation of radionuclide migration.

Project name, acronym, main tests	***Description/objectives related to EBS and near-field***	***Assessment***
Radionuclide Retention Experiment	A suite of tests conducted in borehole laboratories in the AEspoe URL to address: • Influence of radiolysis products on the migration of the redox-sensitive element: technetium in bentonite. • Investigation of the transport resistance at the buffer/rock interface. • Migration of actinides in a rock fracture. • Leaching of SF at repository conditions.	Provides: • Data on conditions for oxidation of technetium as compared to "outside .borehole" laboratory data • Data on retention of e.g., Pu, Am, Np, U and Tc along a rock fracture. • Data on diffusion of e.g., Cs, Sr, Tc, I and Co in bentonite clay. • Data on release of radionuclides from SF under repository-like groundwater conditions. • Confidence in the reliability of "surface laboratory" data.
Matrix Fluid Chemistry	Addresses: • Origin and age of fluids/groundwaters in rock matrix pore space	Provided: • Demonstration of sampling of water from the rock matrix • No major difference in chemistry compared to groundwaters from more highly conductive fracture zones in the near-vicinity

Overview of selected experiments in the VLJ Research Tunnel (Posiva)

Project name, acronym, main tests	***Description/objectives related to EBS and near-field***	***Assessment***
Fracture mapping	Detailed fracture mapping in the Research Drift and in the experimental full-scale deposition holes	The fracture data were used in the modeling of hydraulic and tracer tests
Hydraulic and tracer tests around the experimental deposition holes	Hydraulic measurements (inflow of water into investigation boreholes and in the full-scale deposition holes bored later at the same locations) and tracer tests were carried out around the experimental deposition holes in the Research Drift	Tests indicated flow in sparsely-distributed and narrow channels. The non-Fickian dispersion observed is thought to be caused by velocity differences in the channel and by diffusion into stagnant pools in the fracture filling. The rate of inflow of groundwater into the three experimental deposition holes is close to the total rate of inflow into the whole Research Drift (30 liters/hour) before the experimental holes were bored.
Characterization of excavation damage caused by blasting	The damage caused by excavation was studied in field by mapping the fracturing in the Research Drift and experimental deposition holes, and in laboratory using 100mm diameter samples.	The charge densities used in the wall and arch sections were significantly lower than in the floor section and therefore the damage was larger below the floor. The extent of the EDZ below the floor of the drift can be seen clearly in the upper sections of the experimental deposition holes and extends to a depth of about 1 meter below floor level. In this zone, the average fracture intensity is 4.5 fractures/m^2, more than ten times higher than the average fracture intensity in the lower sections of the deposition holes. The zone of increased porosity adjacent to the blast holes penetrates to a depth of some tens of millimeters, while the penetration of the radial fractures is an order of magnitude deeper. The thickness of the damaged zone (excluding discrete fractures penetrating deeper in the rock) described clearly by increased porosity ranged from 10 to around 30 mm from the half barrel surface. The porosities ranged from 0.3% to 0.9%, being by a factor of three to four higher than the porosities of undisturbed rock matrix.
Characterization of EDZ around the experimental deposition holes	Porosity, diffusivity and permeability in the rock was studied by means of the ^{14}C-polymethylmethacrylate (^{14}C-PMMA) and He-gas methods	Measurements showed that the porosity of the rock in the disturbed zone was clearly greater than the porosity of undisturbed rock to a depth of approx. 11 mm. Permeability and diffusivity in a direction parallel to the rock schistocity were found to be quite different from those obtained in a perpendicular direction. A distinct difference between the values for permeability and diffusivity was also found in the case of disturbed and undisturbed rock. Differences in permeability were a single order of magnitude while diffusivity values differed by a factor of between two and three.
Characterization of rock mechanical properties	Compressive strength of the gneissic tonalite rock was studied using 41, 54 and 99 mm samples of different orientations and sizes taken from the Research Drift. The effect of orientation on strength, the failure patterns, scale effect and effect of saturation were studied.	The strength was found to be significantly dependent on the orientation of the schistocity. The uniaxial compressive strength was at a maximum when the rock sample was directed parallel to the schistocity plane. The observed differences in uniaxial compressive strength and other strength parameters between samples of different sizes were well within the standard deviations of the data and were therefore not significant.

Overview of selected experiments in the Grimsel URL (Nagra)

Project name, acronym, main tests	***Description / objectives to EBS and near-field***	**Assessment**
WT: Heater Test	This project was initiated by GSF/Nagra in order to measure the impact of thermal load on the near-field crystalline host rock in a typical repository configuration as studied for HLW in Nagra's Kristallin I approach.	In these early investigations, heaters were emplaced in a borehole without a buffer material. Boreholes drilled parallel to the heater-borehole were used to monitor the host rock reaction. The evolution of the different processes during the successive heating and cooling phases of the 4 years testing period was measured as a basis for modeling. The results of thermo-mechanical axisymmetric modeling (TM-modeling, GSF-Finite element code) were compared with the measurements. The model results compared favorably with the experimental data.
VE: Ventilation test at GTS	The project was initiated by GSF/Nagra and was conceived to focus on the determination of the following parameters/processes in the low-permeability rock (matrix without fractures) in the tunnel near-field: • "Macro"-permeability • Evaporation at the tunnel surface • Unsaturated zone around the tunnel	Different methods were applied to determine hydraulic properties of the heterogeneous host rock. Various observations show that a homogeneous, isotropic equivalent porous continuum model for the flow to the ventilation drift is oversimplified. In addition to simple analytical methods to calculate hydraulic parameters, inverse FE modeling (in combination with geostatistical methods) were used to estimate the hydraulic parameter distributions and their uncertainties.
TN: Tunnel Near-Field Programme	The experiment was conducted by BGR, GRS and Nagra to study, for a crystalline environment, the relevance of the tunnel near field as a key issue for PA	The focal points of the Tunnel Near-Field Programme were: • Development and testing of techniques which are widely applicable in hydraulics, geophysics and rock mechanics for characterizing the near-field of tunnels and caverns. • Development and application of *in-situ* methods for investigating 2-phase flow properties . • Development of conceptual and numerical models for the hydro-mechanical behavior of the EDZ. • Development of conceptual and numerical models for the simulation of 2-phase flow.
BOS: Borehole Sealing	Development of borehole sealing techniques that allow to seal horizontal and inclined boreholes in such a way that the hydraulic conductivity is in the same order of magnitude than the intact rock mass	The developed sealing technique can be used for inclined and horizontal boreholes. Even borehole with irregular borehole geometry (e.g., breakouts) can be sealed because of the use of granular bentonite. There is no limit on the diameter of such boreholes and borehole with a length of several hundred meters can be sealed. This technique can be used in boreholes drilled in crystalline as well as in sedimentary rocks.
GMT: Gas migration in the engineered barrier system	The Gas Migration Test (lead by RWMC) aims at assessing the function of the EBS (in this case a sand/bentonite mixture) and adjacent geosphere with respect to repository-generated gas migration.	The project includes experimental and modeling studies. The experimental work consists of an "*in situ*" test, a "mock-up" test, and a series of laboratory tests. The silo cavern was excavated in a shear zone of the GTS and instrumented with sensors for pressure, temperature, saturation and deformation. The main event of the GMT at GTS consists of a controlled gas injection in a concrete silo surrounded by a bentonite/sand backfill. In terms of modeling, the following items are currently studied: • Two-phase flow (gas-water) within buffer and surrounding rock Hydro-mechanical (HM) behavior of the EBS under partially saturated conditions

Full-scale engineered barriers experiment in crystalline host rock (Febex I and II)	The Febex project has the dual objective of demonstrating the feasibility of manufacturing and assembling the engineered barrier system and of developing methodologies and models for assessment of the thermo-hydro-mechanical (THM) and thermo-hydro-geochemical (THG) behaviour of the near-field. The specific goals for FEBEX II are as follows: Improvement of knowledge of the THM processes in the EBS, especially in the case of a highly hydrated clay barrier, both in the “in situ” test (natural conditions) and in the “mock-up” test (controlled conditions), in order to improve, calibrate and validate the existing numerical codes. Investigation of geo-chemical processes and their link to the THM processes within the barrier system, for the improvement, calibration and validation of the numerical codes being developed. Research on the potential changes that may occur in the key parameters of the buffer material as a result of THM and THG processes, and in particular of the interaction with solutes in the porewater. Investigation into the transport processes of gas and radionuclides across the EBS, in connection with the evolution of the behaviour of the bentonite barrier. Study of corrosion processes in the reference metals, with a view to obtaining information applicable to the assessment of capsule durability. Study of the changes produced in the hydraulic regime of the rock mass as a consequence of the thermal flux and bentonite-rock interaction, through auscultation and modeling of water flows and pressures within the rock, with special emphasis on the EDZ. Verification, on the basis of the quality assurance system applied during the construction of the “in situ” test, of the real effectiveness of the procedures used. Evaluation of the performance of the instruments and monitoring system, and in particular of their long-term behaviour, with regard to the potential implications for the case of a real repository. Research and investigation into the technological aspects associated with canister retrievability, in order to identify potential problems that should be taken into account in the current reference concept.	The following preliminary conclusions have been drawn from the analysis of the results obtained after more than five years of operation and partial dismantling: The feasibility of constructing engineered barriers for the horizontal storage of canisters placed in drifts has been demonstrated. Specifically it has been demonstrated that the manufacturing and handling of bentonite blocks is feasible at industrial scale and that the clay barrier may be constructed with a specified average dry density, in order to achieve the permeability and swelling pressure required for the barrier. Furthermore, highly useful information has been obtained for the design of a repository, in relation to the size of the drifts, the specifications and procedures for the manufacturing and handling of the bentonite blocks and the basic characteristics of the equipment for construction of the clay barrier and insertion of the waste canisters. In addition, useful information has been obtained regarding the behaviour of the instrumentation system. It has also been demonstrated that a Quality Assurance System is applicable, not only to manufacturing and installation of the physical components of the experiment, but also for the research work on processes, parameters and modeling. The numerical THM model CODE_BRIGHT is capable of reasonably approximating the measured results of the two large-scale tests. During this period it has been necessary to modify only minor details of the model, since it has been seen that its core is based on solid physical laws. Fundamental progress has been made in the development of laboratory apparatus, techniques and methods for the determination of the constitutive laws and parameters required by the model. Thus, although complete validation is never possible, the checks performed have significantly increased the degree of confidence in the capacity of the model for the performance assessment of the THM behaviour of a repository near-field. The numerical THM model CODE_BRIGHT is capable of reasonably approximating the measured results of the two large-scale tests. During this period it has been necessary to modify only minor details of the model, since it has been seen that its core is based on solid physical laws. Fundamental progress has been made in the development of laboratory apparatus, techniques and methods for the determination of the constitutive laws and parameters required by the model. Thus, although complete validation is never possible, the checks performed have significantly increased the degree of confidence in the capacity of the model for the performance assessment of the THM behaviour of a repository near-field.

		Great progress has been made in the development of THG numerical tools and analysis methods, from both the experimental and modeling points of view. Two THG codes have been developed and verified: CORE-LE and FADES CORE-LE. These codes reproduce fairly well the geochemical patterns of a large number of laboratory tests, this having generated reasonable expectations as regards their predictive capacity. It is expected that the results of the laboratory analyses of samples taken during the partial dismantling will provide useful information for assessing the predictions made by the models. Important progress has been made in laboratory testing in relation to the determination of sorption and transport processes and parameters and in the chemical analysis of pore water. Particularly important is the demonstration that montmorillonite is not transformed into illite, at least up to 80 ºC, and that the properties of permeability and swelling of the bentonite are not modified as a result of hydration and heating. The present outcome of the experiment is: A database of the THM response of the bentonite buffer and clay host rock to the hydration and heating process. Data on temperature, total pressures, pore pressures in bentonite and rock, humidity and radial displacements in the rock. Analysis of the water and gas released from the rock and electric conductivity mapping of the rock Determination of the mechanical parameters of the host rock and its mineralogical properties. The CODE_BRIGHT code has been adapted to reproduce more accurately liquid pressures in the rock mass and to estimate the volume of infiltrated water. The preliminary results of the experiment are: A suitable bentonite pellet-based granular material has been selected and manufactured. The buffer material has been hydro-mechanically characterised establishing the coupling between hydraulic and mechanical behaviours. A database recording total pressure, water content and displacements in the buffer and rock, and water pressure in the rock is being compiled. The EDZ has been identified and is being characterised by geophysical (seismic and geo-electric measurements) and hydraulic methodologies. The hydro-mechanical model (CODE_BRIGHT numerical code) has been developed, although, some improvements should still be made.

Overview of selected experiments in the AECL´s URL at Pinawa

Project name, acronym, main tests	***Description/objectives related to EBS and near-field***	***Assessment***
Thermal Mechanical Stability Studies (TMSS), including: Room 209 Excavation Response Test, Connected Permeability Tests, Mine-by Experiment (MbE) Heated Failure Tests (HFT), and Excavation Stability Study (ESS). (1997 to 2001)	For the design of stable excavations in sparsely fractured, hard, brittle *crystalline rock*, to: • Develop characterization, monitoring and numerical modeling tools. • Develop and integrated modeling/characterization/ monitoring system that will facilitate forward prediction and back analysis of rock mass response. Provide a rational basis for establishing criteria, specifications and procedures for repository excavation design	• With some identified technological gaps and limitations, the tools and capabilities needed to design a stable opening with minimal excavation damage are either available now or reasonably within reach. A key tool is the Particle Flow Code (PFC) used in conjunction with linear elastic numerical modeling codes to assess the initiation and extent of perimeter instabilities around excavations being designed. The capability to measure the creation and characteristics of excavation damage were demonstrated. An excavation design methodology has been proposed that uses the tools and capabilities available at the end of these studies. • Specific technology gaps were identified as to the resolution of some parameters implementing performance in 3-D developing a complementary continuum damage model, and *in-situ* validation of the modeling approach.

Project name, acronym, main tests	***Description/objectives related to EBS and near-field***	***Assessment***
Buffer/ Container Experiment (BCE) (1988 to 1997)	• Provided experience with experimental methods, geotechnical instrumentation, underground materials handling*, in-situ* buffer compaction and large diameter borehole drilling in granitic rock. • Evaluated and documented the full-scale *in-situ* performance of reference buffer material in a representative geologic setting. • Produced a data base that would allow validation and further development of numerical and conceptual models for processes of heat and moisture transfer, development of swelling pressure and contact stresses and volume changes in buffer. • Provided information for the design and conduct of later experiments in the URL.	• Produced data for use in development of future experiments and new technologies, such as borehole drilling, buffer compaction, instrument selection, managing large in-ground instrumentation systems, interpreting psychrometer data and improved modeling capabilities. • Improved understanding of coupled heat and moisture movement and identified the need to model volume changes that accompany stress and water content variations, and to develop solutions in terms of potentials or suctions in pore water. • Without further study, the relationships between load on the container, water distribution, and wetting of the buffer cannot be quantified. • Drying induced radial cracking in the buffer is reversible upon rewetting. • Heating for 900 days did not alter the bentonite clay mineralogy in ways that affected the physical properties of the clay. • Microbiological activity was investigated and below 15% water content viable microbes were not noted. • Significant increases in pore water pressures in the near-field rock were noted during heating. • The experiment produced data of value in validation of numerical models, but gaps in the materials property information will affect the accuracy of predictive modeling. • Moisture content was not measured with sufficient accuracy.

Project name, acronym, main tests	***Description/objectives related to EBS and near-field***	***Assessment***
Isothermal Buffer/Rock/ Concrete Plug Interaction Test (ITT) (1992 to 1999)	Provided information on the longer-term: • Water uptake by a mass of buffer under steady-state temperature and groundwater supply conditions. • Potential alteration of the buffer material in contact with concrete. Study microbial populations and nutrients in the buffer material	• Measured water uptake. • Determined swelling properties and monitored swelling. • Measured pore water pressure changes in buffer and rock. • Obtained a well documented and detailed set of thermal, stress, strain and hydrogeological information covering over 6 years. • Obtained data on the longer-term performance of some instruments. • Gathered microbial activity information including: collecting gas samples at the concrete/buffer interface. Determined microbe viability in buffer samples • Determined that sulfate reduction process was either just beginning after 6.5 years or was a very slow process as the system still contained considerable oxygen and sulfide levels were low. • Only small amounts of methane could be detected in post-test samples and no methanogens could be cultured in post-test samples. • Complexing capacity of the organics in the buffer were sufficiently large that the potential exists for complexing radionuclides. • Technology gaps identified included: Inadequate *in-situ* measurement of moisture content in buffer and over-prediction of the water-uptake rate of the buffer.

Project name, acronym, main tests	***Description/objectives related to EBS and near-field***	***Assessment***
Thermal-Hydraulic Studies (THS), including: Laboratory studies and the Thermal Hydraulic Experiment (THE) (1995 to 1999)	Provide: • A theoretical basis for the analysis of pore pressures induced by heating of saturated rock. • Method of determining the appropriate material parameters for numerical modeling. • Methods for the verification of numerical codes. • Methods to improve the use of available numerical codes by assigning appropriate material parameters	With some limitations, the following capabilities were developed/demonstrated: • "Dimensionless" numerical solutions which facilitated back analysis of *in-situ* tests. • Numerical modeling of thermoporo-elasticity using FLAC and a method of making models dimensionless that is more efficient and potentially more accurate. • Laboratory tests for low porosity granite that facilitate the direct determination of six thermoporo-elastic constants. • A field test that facilitated the *in -situ* determination of thermal and hydraulic material properties as well as a lumped thermoporo-elastic material property. • A consistent data set on the thermal and hydraulic response of a volume of low porosity granite.
Grouting Field Trials (1987)	Provided: • Experience with mixing and injection of grout using field scale equipment in a realistic underground environment. • Comparison of results from field and laboratory tests • Information on geochemical plume that develops as a result of grout injection • Observations of the tightness or fractures penetrable using microfine grout mixes.	The following observations were made: • A reference grout using sulfate resistant cement reground to a Blain fineness of 600 m^2/kg, and having a water cement ratio between 0.4 and 0.6, with 10% added silica fume and 2% added superplasticizer was mixed easily and retained fluidity and remained pumpable for at least one hour after mixing. • Superplasticizer enabled the water cement ratio to be reduced to 0.4 with a low viscosity maintained for pumping and injection. • The unset grout exhibited no segregation or bleeding. It was capable of penetrating micro-fissures with ap an 20 µm.

Project name, acronym, main tests	***Description/objectives related to EBS and near-field***	***Assessment***
Tunnel Sealing Experiment (TSX) (1997 to present)	Provided: • An assessment of the technologies for construction of practicable concrete and clay-based bulkheads. • Quantification of achievable performance characteristics of the drift seals. • Documentation of the factors affecting drift seal performance.	• The following tasks were completed. • A demonstration of the *in-situ* performance of two drift plugs, one constructed of blocks of highly compacted bentonite/sand and the other of low-heat, high-performance concrete under differential pressures up to 4 MPa and heated to >50°C. • A review of excavation damage assessment methods for sparsely fractured rock. • A review of instrumentation experience as it applies to repository sealing experiments, including instrumentation installed in the rock, clay and concrete. • An investigation of concrete mix designs and placement methodologies to meet experiment requirements. • Development of methods for placement of sand/clay mixtures in large-scale sealing experiments, including pre-compacted blocks, *in-situ* compaction and pneumatic placement. • Measurement of the rate of advective transport of solutes past drift seals under the high experimental hydraulic gradients. • Numerical modeling of rock response to excavation, clay seal hydration, concrete shrinkage, solute transport through/around drifts seals. • An assessment of factors affecting seal performance, including excavation method, bulkhead keys, grouting, treatment of interfaces, rate of clay seal pressurization, swelling/resealing of bentonite, and concrete hydration/shrinkage. • The final assessment of this experiment will take place after the *in-situ* test is decommissioned with extensive physical sampling to determine *in-situ* conditions.

Overview of selected experiments in the Mont Terri URL (Nagra)

Project name, acronym, main tests	***Description/objectives related to EBS and near-field***	***Assessment***
Heater experiment: rock and bentonite thermo-hydro-mechanical processes in the near-field (HE)	The project seeks to gain knowledge about the coupled thermo-hydro-mechanical (THM) processes in both the bentonite buffer and the consolidated clay formation when heated, with a special emphasis on the study of the interaction between rock and bentonite. The basic objectives are as follows: Observation of the coupled THM processes in the near-field. Determination of general mechanical properties of the host rock. Determination of the "*in-situ*" mechanical state of the host rock and changes induced by the experiment. Study of the rock/bentonite interaction. Study of the THG processes in the near-field. Analysis of gasses and water released in the rock by effect of heating. Study of the behavior and reliability of instrumentation and measuring techniques applicable to this type of rock formations. Refining, calibration and validation of existing numerical tools for modeling THM processes.	The present outcome of the experiment is: • A database of the THM response of the bentonite buffer and clay host rock to the hydration and heating process. • Data on temperature, total pressures, pore pressures in bentonite and rock, humidity and radial displacements in the rock. • Analysis of the water and gas released from the rock and electric conductivity mapping of the rock • Determination of the mechanical parameters of the host rock and its mineralogical properties. • The CODE_BRIGHT code has been adapted to reproduce more accurately liquid pressures in the rock mass and to estimate the volume of infiltrated water.
Engineered barrier emplacement experiment in Opalinus Clay (EB)	The project aims the demonstration of a new concept for the construction of a clay-based buffer for high-level waste repositories in horizontal drifts, in competent clay formations. It consists in the combined use of a lower bed made of compacted bentonite blocks and an upper backfill made with a bentonite pellets based granular material. The specific project objectives are: Buffer material definition, fabrication and characterization. Emplacement technique development, testing and validation. Characterization of the EDZ and determination of its influence on the overall performance of the system, and investigation of the hydro-mechanical parameters evolution in the EDZ and clay barrier as a function of the progress of the hydration process.	The preliminary results of the experiment are: • A suitable bentonite pellet-based granular material has been selected and manufactured. • The buffer material has been hydro-mechanically characterized establishing the coupling between hydraulic and mechanical behaviors. • A database recording total pressure, water content and displacements in the buffer and rock, and water pressure in the rock is being compiled. • The EDZ has been identified and is being characterized by geophysical (seismic and geo-electric measurements) and hydraulic methodologies. • The hydro-mechanical model (CODE_BRIGHT numerical code) has been developed, although, some improvements should still be made.

Project name, acronym, main tests	***Description/objectives related to EBS and near-field***	***Assessment***
	Development, calibration and validation of a hydro-mechanical numerical model for prediction of the system behavior as a function of time and progress of hydration process.	
Ventilation experiment in Opalinus Clay (VE)	The project aims to evaluate the alteration of the hydraulic and mechanical conditions of the Opalinus clay induced by ventilation, its magnitude and lateral extent, with the specific objective of: Estimation of desaturation and resaturation times in clay rock, produced by drift ventilation. Estimation of the saturated hydraulic conductivity of the rock and evaluation of the scale effect impacting this parameter. Estimation of evolution of EDZ in terms of changes in hydraulic conductivity and of displacements caused by the generation of drying cracks. Geochemical characterization of the zone desaturated by ventilation. "*In-situ*" determination by non-destructive methods of water content (geoelectric, time domain reflectometry) and water potential (psychrometers, capacitive-type sensors, piezometers) Calibration and validation using experimental data of an appropriate hydromechanical model allowing predictions of the behavior of clay rock with respect to prolonged drift ventilation.	The experiment has been constructed and the desaturation phase started in June 2003. The present outcome is as follows: The Opalinus clay has been hydraulically characterized. A database containing information on temperature and moisture of the rock and the gallery, displacements and water potential in the rock, is being compiled. HM models have been prepared (CODE_BRIGHT and MHERLIN numerical codes) for data interpretation and test behavior prediction.
ED-B: EDZ evolution around gallery (Mont Terri)	Mechanical evolution of the EDZ around a new gallery. The experiment was designed as a classical mine-by experiment. The development of deformations, stresses, pore water pressure and hydraulic conductivity were measured before, (during) and after excavation.	The excavation of the drift (road header) at a depth of approximately 240 m demonstrated that the Opalinus Clay behaves as a typical weak rock, i.e., Clay Shale. Measurements of the loads on the shotcrete liner indicate that the support from the liner is minimal. The observations and measurements at the Mont Terri laboratory have shown that the Opalinus Clay is very sensitive to moisture. The measured extent of the EDZ at the New Gallery at Mont Terri was found to be less than 2r where r is the radius of the drift and is measured from the centre of the drift. The hydraulically most conductive zones are in the side walls (E-7 - E-8 m/s) while the roof and floor show hydraulic conductivities of approx. E-10 m/s. The different conductivities probably relate to the different deformation modes with extension fracturing in the side walls and slip on the bedding planes in the roof and floor.

Project name, acronym, main tests	***Description/objectives related to EBS and near-field***	***Assessment***
		Hydro-mechanical coupled modeling with the code FLAC provided reliable back-calculation of the observed deformations and pore pressures.
EH EDZ self healing experiment and **SE** Selfrac (Mont Terri)	Investigations on the self-sealing capability of the EDZ were carried out to demonstrate that the re-saturation and the mechanical loading of the EDZ (simulation of swelling pressure of the buffer and homogenization of the stress filed due to creep processes) lead to self-sealing of the EDZ.	Two unsaturated fracture systems (1 single fracture and 1 fracture network) in the EDZ were re-saturated. Self-sealing was observed at both sites. The transmissivity of the single fracture decreased by about one order of magnitude to E-9 m²/s within approximately 1 year. The transmissivity of the fracture network decreased from about 5E-7 to about 5E-9 m²/s within approx. 800 days. The mechanical loading of this zone with a plate loading device was carried out to simulate the swelling pressure of the bentonite buffer. The loading up to 5 MPa resulted in an additional decrease of the transmissivity of the saturated EDZ. After a few month the measured conductivity was approx. 5E-11 m^2/s.
GS: Gas-frac Self-healing experiment (Mont Terri)	Laboratory tests were conducted to evaluate the processes of self-sealing. The *in-situ* experiment was set up to verify these processes *in-situ*. After a hydraulic characterization of the test site, a hydro-frac was induced which created an artificial flow path between 4 boreholes. The changes of the hydraulic permeability were measured as a function of time to evaluate the self-sealing of the rock	A fracture was hydraulically induced and its permeability and the development of fracture aperture were measured. Long-term observations indicate clearly that the fracture continuously closes during time. Hydraulic tests after fracture initiation indicate that the transmissivity of the fracture is pressure dependent. For an injection pressure below 2 MPa (approx. an effective normal stress on the fracture plane larger than 2 MPa) the transmissivity is very similar to the one of the intact rock (5E-13 m²/s). Increasing injection pressure constantly leads to an increased transmissivity until a reopening pressure of about 5 MPa is exceeded. The open fracture has a transmissivity of about 2E-8 m²/s. The behavior can be explained with a Barton-Bandis type fracture model. Test, conducted about 6 month following the fracture initiation, do not show significantly different transmissivity than tests immediately after fracturing.

Overview of selected experiments in the Hades URL (SCK-CEN)

Project name acronym, main tests	***Description, objectives related to EBS and near-field***	***Assessment***
CORALUS Corrosion of waste matrix materials	Objective: *in-situ* verification of reliability of long-term predictions (based on small-scale lab tests) on (leaching) behavior of glass matrix. In total, five test tubes are installed. Each test tube consists of three modules, and each module contains eight SON68 reference glass samples: two are non-radioactive, and six are radioactive (PuO_2, NpO_2, $Am2O_2$). The glass samples are in direct contact with buffer material (three types: dried Boom Clay and two bentonite mixtures). The buffer is hydrated by the Boom clay, and can be artificially accelerated. Two different conditions are tested: 30°C, no radiation (long-term condition), and 90°C, with Co^{60} radiation (short-term condition). Operation between 3 and 10 years, followed by retrieval (first one in March 2004, last one in 2014) and analysis of glass leaching and migration of leaching products.	At present, all test tubes are installed and in operation in the Boom Clay without significant problems. All water solutions in buffer exhibit fairly high salt contents (higher for 90°C). pH values are about 1 unit lower at 90°C. Analog to the CERBERUS results, we expect that this will have a beneficial effect on the glass dissolution (i.e., lower dissolution at lower pH). In contrast, redox potentials seem to be higher (less negative) for the test tubes at 90°C. The differences in pH and redox potential might affect the solubility and the speciation of the leached radionuclides, and hence their migration rate.
In-situ corrosion experiments Corrosion of waste matrix materials	Objective: evaluation of the corrosion behavior of a number of candidate overpack materials and predict the long-term corrosion behavior through medium-term interactions (up to 7.5 years). The experiments consisted of inserting waste forms, positioned on a support tube, in the Boom clay. Some samples were brought in direct contact with the host rock (type I), other samples in contact with a humid clay atmosphere (type II), or in contact with a concrete saturated humid clay atmosphere (type III). Tests were performed at different temperatures (16°C, 90°C and 170°C). Installation of the tubes between 1994 to 1995, retrieval between 1988 and 1996.	For the glass waste form samples, the results of the laboratory experiments (leaching tests) were confirmed. For the container samples, only the corrosion-allowance material carbon steel showed measurable corrosion rates (1 to 10µm/year). It also showed severe signs of localized attack (up to 240 µm deep after 2 years at 90°C). The corrosion resistant materials (stainless steel, nickel alloys, titanium alloys) were not attacked. In addition, electrochemical and immersion experiments are performed to study the corrosion processes in more detail on AISI 316L hMo.
BACCHUS I & II Backfill/buffer materials	THM behavior (hydration, swelling, also at elevated temperature) of clay-based backfill/buffer materials. Bacchus one was installed in 1988 and retrieved in 1993, to be replaced by the Bacchus II set-up. This latter set-up focused on the applicability of a clay-	Successful measurements of all parameters (also total pressure). In addition to hydraulic conductivity, also gas injections have been performed. Host rock / backfill interface plays a key role in HM behavior. Swelling pressure about 0.6 MPa. After hydration, the powder/pellets mixture becomes uniform.

Project name acronym, main tests	***Description, objectives related to EBS and near-field***	***Assessment***
	based backfill material on an industrial scale. It consisted of a central filter surrounded by clay-based pellets in a 520mm borehole. Parameters monitored were progress of hydration front, pore water pressure, pressure at interface backfill/Boom clay, *in-situ* permeability of backfill.	
RESEAL – large scale Sealing materials	Objective: demonstration of : (1) feasibility to seal exploratory shaft (Ø 2.20m), (2) low permeability of seal avoiding preferential migration of water, gas, radionuclides along seal / host rock interface, and through excavation disturbed zone, and (3) model predictions of HM behavior of seal. The seal consists of a 2.24 m thick mixture of high density (> 2 g/cm³) FoCa clay pellets mixed with FoCa clay powder (weight ratio of 50/50). The shaft liner (concrete blocks) was removed at the seal level (1999) prior to seal installation. Monitoring in the seal of pore and total stress, water content and displacements. Monitoring of the host rock (pore water pressures) in 1998.	Successful installation of the seal. Liner removal caused suction, followed by fracturing, of the host rock, as observed by the pore water pressure measurements. Successful monitoring. First results show a highly efficient seal.
RESEAL – small scale Sealing materials	Objective: demonstration of feasibility to seal a borehole with precompacted bentonite blocks, investigation of bentonite – host rock interaction, development and validation of HM and transport models. Corrosion of steel is studied through a gas generation experiment. A borehole (Ø 270 mm) has been sealed with precompacted blocks of Serrata and FoCa clay (1997). These blocks were integrated in two compartments of a Ø 250 mm piezometer. A blend of stainless and carbon steel powders was mixed with Boom Clay and placed in two different rooms in contact with the host rock. The chemical composition of the water is followed to detect the gas generation due to steel corrosion.	The bentonite blocks have been hydrated artificially. The water permeability of the borehole seals is about 10 times lower than the host rock. The seal behavior under gas injection condition confirms the feasibility of the sealing of a borehole. Excellent agreement between observations and model predictions shows the good understanding of the bentonite-host rock interaction. A tracer injection through the FoCa seal showed no preferential pathway for radionuclide migration in the borehole seal.
MINE-BY tests Monitoring of underground construction	Monitoring of: construction of experimental shaft and drift (1984), construction of Test Drift (1987), and sliding ribs section (end 1987). Monitoring of construction of second shaft (1997 – 1999).	Demonstration of feasibility and of medium long-term integrity of underground constructions. Fair agreement between numerical simulation and observations (including validation through Interclay I & II benchmarking exercises). Demonstration of big constructions in non frozen clay.

Project name acronym, main tests	***Description, objectives related to EBS and near-field***	***Assessment***
CLIPEX Monitoring of underground construction	Monitoring and model predictions of novel gallery construction method (wedge-block lining, industrial scale, high advance rate). Installation of instrumented boreholes in 1998 (Test Drift front) and 2000 (Second shaft), monitored parameters: pore and total pressure, displacements. Connecting gallery successfully constructed in 2002.	Extensive set of measurement data on pore water pressure and displacements. Model predictions of pore water seem to underestimate impact of excavation on host rock. Issues to improve current HM models have been identified.
PHEBUS Underground construction and hydrology of host rock	Objective: investigation of hydraulic effects in deep clay formations when building and operating disposal galleries. A large, instrumented filtered was installed (1994) at some 15 m from the gallery, in which air was circulated. This air was dewatered and reinjected, to determine the flow rate of water. The clay around the filter was instrumented to monitor water content, pore and total pressures.	No de-hydration of the surrounding clay has been observed.
MEGAS Gas migration in host rock	Objective: provide experimental data for the validation of gas migration models Three piezometers were installed (1992): one for injection of gas (He) and HTO, the two others for detection purposes.	The measured results fit the modeled curve. Self-healing of the Boom Clay after the creation of an artificial gas pathway has also been demonstrated.
ATLAS Thermal effect on host rock	Objective: model comparison for rheological behavior of Boom Clay in a heated field. Set-up according to a reduced scale concept: central heating tube and two parallel monitoring tubes (installed 1992). Model benchmarking within Interclay II project. Two heating phases: 1993 – 1996 (reduced power), 1996 – 1997 (full power). After end of heating: sampling of host rock	Cored samples show no significant difference (CU triaxial tests) from non-thermally exposed Boom Clay Observations show no big changes in effective stresses under thermal loading Modeling: OK for T (modeling conduction is enough), but initial conditions for H & M (drilling of boreholes) seem to be more important than details of constitutive law for Boom Clay (in this case). Computer codes are OK
CERBERUS Integrated test on thermal and radiological influence on host rock	Integrated test to demonstrate combined effects of radiation, heat and drilling (simulation of a vitrified HLW canister after 50 y cooling time, at a borehole disposal configuration). Instrumented borehole with 444 TBq (Co^{60}) radiation sources, 2 x 362 W thermal power, installed in 1988 at 2.5 m under floor of Test Drift.	Sensor performance: only piezo-resistive sensors failed quite rapidly under radiation. H_2 by adsorption on Pd wire very sensitive. Hydrochemistry up to 100°C and 13 MGy during 5 y. Water chemistry: $Na\text{-}HCO_3 \rightarrow Na\text{-}SO_4 \rightarrow Na\text{-}HCO_3$. pH decreases from 8.5 to 7.3. Eh remains reducing: ~ -273 mV (SHE 25°C). Presence of thiosulfate (2E-04 M) and oxalate

Project name acronym, main tests	***Description, objectives related to EBS and near-field***	***Assessment***
	Devices for migration, corrosion and backfill studies, all retrievable. Monitored parameters: dose rate, temperature, total and pore water pressure, water composition (sampling), H_2 generation (radiolysis). Heating, radiation from 1990 to 1994, followed by hydration of buffer material. Analysis of near-field effects between 1996 and 1998.	(4E-04M). No significant effect on migration properties (Am/Tc). No illitization of Boom Clay smectite. Pyrite oxidation produces gypsum around framboids, but maintains its "self-healing" properties. Backfill keeps swelling capacity. Corrosion: glass samples: 20 to 50 % lower weight loss compared to corrosion loops. Metals: welded C-steel: up to 8x higher corrosion rate, with intergranular and pitting corrosion. Cu also pitting.

Appendix 2 Glossary

40CFR191	Code of Federal Regulations, Title 40, Part 191.
40CFR194	Code of Federal Regulations, Title 40, Part 194.
ABAQUS	Commercial numerical code that has been adapted to THM processes in bentonite buffer and crystalline rock.
Absorption	Incorporation within the physical or molecular structure (See: sorption).
Accelerated test method	A procedure, preferably one for which a standard protocol has been developed, that is used in a laboratory to produce in a reasonably short time (days or months), effects that would otherwise be observed only over much longer times (decades to millennia). Generally this requires adjusting parameters such as temperature (and pressure), radioactive' dose rate', etc., that affect the kinetics of a chemical reaction.
Acceptable limit	Limit acceptable to the-regulatory body. (See: authorized limit).
Access shafts	A vertical access from the Earth's surface to underground facilities for personal, material and ventilation, during the construction and operation phases.
Accessible environment	Those portions of the environment directly in contact with or readily available for use by human beings. Includes the Earth's atmosphere, the land surface, aquifers, surface waters, and the oceans'. (See: human environment).
Acid digestion	Treating radioactive waste with acid to chemically decompose a material into its simpler constituents (usually soluble) thereby releasing the radionuclides for subsequent processing. For example, organic material (resins, paper, gloves, etc.) contaminated with alpha-emitting nuclides may be aid digested for subsequent concentration of the nuclides.
Actinide	An element with an atomic number from 89 to 103, inclusive. All are radioactive.
Activation product, neutron	An element made radioactive by bombardment with neutrons.
Active institutional control	(1) Controlling access to a disposal site by any means other than passive institutional controls, (2) performing maintenance operations of remedial actions at a site, (3) controlling of cleaning up releases from a site, or (4) monitoring parameters related to disposal system performance.
Activity	For an amount of radioactive nuclide in a particular energy state at a given time, the quotient of dN by dt is the expectation value of the number of spontaneous nuclear transitions from that energy state in the time interval dt. The special name for the SI unit of activity is becquerel (Bq). The curie (Ci) may be used temporarily.
Adit	Passage from surface to underground rooms.
Adsorbent	A material that has the property of adsorbing radionuclides (see adsorption). Adsorbents may be used, for example, in treating gaseous or liquid waste, or in decontamination procedures.
Adsorption	Adhesion of ions or molecules or particles to the surface of solid bodies with which they come in contact. (See: sorption).

Age of waste	(i) For SF or reprocessed radioactive waste, it is the time after the end of irradiation. (ii) For waste whose activity arises from contact with radioactive materials, it is the time after separation from those materials.
Airborne waste	Radioactively contaminated matter, generally small solid particles or liquid droplets that have become suspended by the air (see: aerosols). Frequently including dust, smoke, or powders, it can lead to uncontrolled spread of contamination or to uptake by unprotected workers.
ALARA	ALARA=As Low As Reasonably Achievable. Concept meaning that the design and use of nuclear facilities, and the practices associated with them, should be such as to ensure that exposures are kept as low as reasonably practicable, with technical, economic and social factors being taken into account.
Alpha-bearing waste	Waste containing one or more alpha-emitting radionuclides, usually actinides, in quantities above acceptable limits for uncontrolled releases. The limits are established by the national regulatory body.
Aluminosilicate glass	A durable type of glass in which some of the silicon atoms that normally form the amorphous, polymeric structures that are characteristic of glasses (networks) are replaced by aluminum atoms. Aluminosilicate glasses are candidate matrices for solidifying some kinds of radioactive waste.
Annual dose Equivalent limit	The value of the annual dose equivalent that must not be exceeded, according to the ICRP system of dose limitation. It is regarded as the lower Boundary of an unacceptable dose region.
Annual limit on intake (ALI)	The smaller value of intake of a given radionuclide in a year by reference man, which would result in either a committed, dose equivalent of 50 mSv or a committed dose equivalent in any organ or tissue established by the national authority.
Anoxic conditions	A chemical condition, often existing in underground waste repositories, in which the partial pressure of oxygen in the groundwater is very low. This affects the oxidation state of chemical species in the groundwater as well as bacteriological processes that can occur.
Aquifer	A water-bearing formation below the surface of the earth that can furnish an appreciable supply of water for a well or spring.
Area survey	One stage of siting a waste repository during which several areas are examined to eliminate obviously unsuitable areas and to identify others, which may contain suitable sites. The other stages are national, regional, and site, and the area survey follows the regional study/survey.
Argillaceous	Applied to all rocks and substances composed of clay or having a notable proportion of clay in their composition.
Arid sites	A term often applied to a shallow land waste disposal site located in an area that receives very little annual precipitation, typically less than 25 cm/year. In these sites there is little potential for radionuclide transport by rainwater moving downward through the soil.
Arisings, waste	See: waste arisings.
Atmospheric pathway	A vector through the air that radionuclides can potentially follow (see: airborne waste). This pathway can contribute to spread of contamination or to radionuclide uptake by man.

Authorized limit	Limit set for a given radionuclide or source or for a given environment by a national or international environmental authority. (See: acceptable limit.)
Back end of the fuel cycle	The part of the fuel cycle that includes SF storage, fuel reprocessing, mixed oxide fuel fabrication and waste management, including SF disposal.
Backfill	Artificially prepared material used to fill deposition rooms, drifts, drifts and shafts.
Ballast	Soil of rock-forming minerals used as inert component ("aggregate") of clay mixtures or concrete.
Barrier (natural or engineered)	Any material or structure that prevents or substantially delays movement of water or radionuclides toward the accessible environment. For example, a barrier may be a geologic structure, a canister, a waste form with psychical and chemical characteristics that significantly decrease the mobility of radionuclides, or a material placed over and around waste, provided that the material or structure substantially delays movement of water or radionuclides.
Basalt	A dark colored igneous rock, commonly extrusive, composed primarily of calcic plagioclase and pyroxene, the fine-grained equivalent of gabbro. Basalt was considered to be a possible host medium for high-level radioactive waste repositories in the USA but was deferred in 1987.
Becquerel	The SI unit of radioactivity, equivalent to 1disintegration per second (approx. 2.7 x E11Ci).
Bedded salt rock	A sedimentary salt rock formation in which the salt layering typically is roughly horizontal, laterally extensive and relatively thin in the vertical direction (approx. 200 meters), however the host formation for WIPP, the Salado Formation, is more than 600 m thick.
Bedrock	Undisturbed natural rock.
Bentonite	A soft plastic light-colored clay formed by chemical alteration of volcanic ash. It is composed essentially of montmorillonite and related minerals of the smectite group. The properties of bentonite depend largely on its ion-exchange characteristics. Bentonite is ideally suited for use as a buffer material for surrounding waste packages in a deep repository.
Bentonite clay	Smectite clay of volcanic origin.
Biointrusion barriers	An engineered barrier designed to prevent plant roots or burrowing animals from coming into contact with buried waste, and thereby prevent transport of radionuclides by these vectors.
Biosphere	That portion of the Earth's environment inhabited by any living organisms. It comprises parts of the atmosphere, the hydrosphere (ocean, seas, inland waters and subterranean waters) and the lithosphere. The biosphere includes the human habitat or environment in the widest sense of these terms. (See: accessible environment and human environment).
Bitumen	Wide range of hydrocarbons with high molecular weight, commercially available as a residue of petroleum or coal refining. There are 2 major components: asphaltene components, which give bitumen colloidal properties, and malthene compounds, which impart viscous liquid properties. Bitumen is used as a matrix for the immobilization of low and intermediate-level radioactive waste and can also be used for tightening shafts.
Bituminization	The process of incorporating wastes into a bitumen matrix as a means of immobilization.

Boom Clay	Soft, plastic sedimentary clay formation
Borehole	A cylindrical excavation, made by a rotary drilling device. Wastes are disposed of in the excavations. For disposal at relatively shallow depth, boreholes can be drilled from the surface. For deep disposals they can be drilled from an access shaft in a mine.
Borehole plug	An engineered barrier, usually a cementitious material, used to close a filled borehole in order to prevent intrusion by water, animals, or roots.
Borosilicate glass	(i) A super cooled liquid based on a random lattice of silica tetrahedra, modified with boron and other cations. (ii) A glass composition used as an immobilization matrix for a radioactive waste. (See: glass).
BRAGFLO	Brine And Gas FLOw, a two-phase flow code used in support of the WIPP PA.
Brine	Salt solution of high concentration.
Buffer	Embedment of waste containers, commonly smectitic clay.
Buffer material	Any substance, frequently a natural material/clay, placed around a waste container in a repository. Often a primary purpose of such material is to serve as an additional barrier to prevent water from contacting the waste container and, by adsorption, to reduce the rate that radionuclides can migrate from the waste into the repository, the far-field and to the biosphere.
Buffer zone	A controlled area surrounding a nuclear installation (e.g., a waste repository) established to ensure an adequate distance between the installation and places used by or accessible to the public.
Burial ground	An area of land that has been dedicated for the shallow disposal of low or medium-level radioactive waste. Access by the public as well as future use of the land will probably be restricted.
Calcine	To heat a substance to a temperature below its melting point, in air, to bring about a loss of moisture and volatile products and to transform the constituents of interest into stable oxides. Such oxides or mixture of oxides are termed 'calcine'.
Calcinier	High-temperature process equipment used to convert waste solutions into a solid mixture of oxides (calcine).
Canister	A closed or sealed container for SF or other radioactive waste materials.
Cask	A massive container to transport and/or store irradiated nuclear fuel and other radioactive materials. It provides chemical, nuclear and radiological protection and dissipates heat from the fuel.
Cavern	Large underground room.
Cement	A standard material used by the construction industry that has many uses in waste management because of its low cost and ease of handling. Properties of cement mixtures and of the final solid product can be modified considerably by the use of additives. The mixture or final product is referred to: as "concrete" if it contains aggregate (usually small stones) or without aggregate, a "grout".

Cementation	The process of incorporating wastes into a concrete matrix as a means of immobilization.
Ceramic materials	Solid materials, usually containing quartz (SiO_2) and metal oxides that generally require fabrication at an elevated temperature (typically 800^{o}C) and elevated pressure. Their microscopic structure is crystalline which distinguishes them from amorphous glasses. They are very stable and have been considered as good candidates for solidifying high-level radioactive waste.
Ceramic melter	A furnace used for melting together mixtures of wastes and glass-forming additives in order to vitrify the waste, i.e., to convert it to a stable glass. The inside of the melter is lined with a refractory ceramic that can resist corrosion by the molten glass. The melter is heated electrically.
Certification	Any action taken by the US Environmental Protection Agency pursuant to section 8(d) (1) of the Waste Isolation Pilot Plant (WIPP) Land Withdrawal Act of 1992 (LWA).
Chemical digestion	A chemical process for softening or solubilizing a material with heat and moisture.
Chemisorption	An adsorption process in which the adsorbed material is chemically bound to the adsorber. This is in contrast to physical adsorption in which the adsorbed molecules might only be trapped, for example. Chemisorption occurs in some off-gas systems and in many ion exchange processes.
Cladding (material)	An external layer of material (usually of Zircaloy, stainless steel, magnesium), directly surrounding nuclear fuel or other substance that seals and protects it from the environment and protects the environment from radioactive material produced during irradiation. For HTR fuel particles, the multi-layer protective claddings are known as coatings.
Cladding waste	Radioactive waste comprised of cladding hulls and assembly grid: spacers for nuclear fuel elements. It is generated during reprocessing when SF assemblies are disassembled and the fuel is dissolved. (See: hulls and Spacers.)
Clay	Soil or rock composed of minerals that are essentially hydrous aluminum silicates occasionally hydrous magnesium silicates, with sodium, calcium-, potassium and magnesium cations. Also denotes a natural material with plastic properties, which is essentially a composition of fine to very fine clay particles. Clays differ greatly mineralogically and chemically and consequently in their physical properties, especially because of their large surface areas, most of them have good sorption characteristics.
Clay rock	The term is used in this report for both: soft (or poorly indurated) clays (e.g., Boom Clay), and hard or stiff (indurated) clays (e.g., clay shale, claystone or argillite).
Closure	Final backfilling of the underground facility and the sealing of shafts and boreholes.
CODE_BRIGHT	COupled DEformation, BRIne, Gas and Heat Transport problems Numerical code for modeling of THM processes in salt rock, clay buffer, crystalline rock, and clay rock. Developed by the Geotechnical Engineering and Geosciences Department, Technical University of Catalunya – Center for Numerical Methods in Engineering (UPC-CIMNE, Barcelona).
Cold testing	Testing of method, process, apparatus or instrumentation with the highly radioactive materials replaced by non-radioactive materials or materials which may contain radioactive tracers.

Compaction	The reduction in bulk volume of a material, hence an increase in its density (weight per unit volume), by application of external pressure. Often it is an economical way to aid in the safe handling of low-level solid radioactive wastes. Compaction of soil materials covering a repository is used to reduce its permeability.
Compartment	Any part of the environment which may conveniently be considered as a single entity. (Used for environmental modeling).
COMPASS	Numerical code for modeling of THM processes in clay buffer and crystalline host rock. Developed by University of Cardiff.
Competent authority	An authority designated or otherwise recognized by a government for specific purposes in connection with radiation protection and/or nuclear safety.
Complexation	A chemical term that refers to complex formation in which a central metal ion is chemically bonded to atoms surrounding it. Depending on the circumstances, complexation can be used to remove radionuclides from solution, or by the formation of a neutral molecule, it may greatly enhance the mobility of a radionuclide in the environment.
Component's compatibility	Components are mutually compatible (chemically).
Compressive strength	The load per unit of area under which a solid block fails by shear or splitting.
Computer code	See: computer model.
Computer model	A mathematical description of a facility or sequence of events which is evaluated via a computer. Computer models are usually indispensable for performing a safety analysis of a waste facility. In particular, models are used extensively to evaluate long-term events associated with a waste repository that cannot be tested directly, and to predict the resulting radiation dose to man.
Concrete	The product that results from mixing cement, water, and aggregate (see cement). As a standard construction material it finds many uses in engineered waste facilities. It may also be a major component of decommissioning waste.
Conditioning of waste	Those operations that transform waste into a form suitable for transport and/or storage and/or disposal. The operations may include converting the waste to another form, enclosing the waste in containers, and providing additional packaging.
Conductivity, hydraulic	See: hydraulic conductivity.
Confinement (or isolation) of waste	The segregation of radionuclides from the human environment and the prevention of their release into that environment in unacceptable quantities of concentration.
Conceptual model	A description of performance and function.
Concerted action	A joint activity of most or all involved Member States of the European Union under auspices of the European Commission, in order to develop a common understanding or to develop a common opinion concerning a specific topic.

Consequence analysis, biosphere	A safety analysis that estimates potential individual and collective radiation doses to humans, based on radionuclide releases and transport from a nuclear facility (e.g., a waste storage or disposal site) to the human environment as defined by hypothetical release and transport scenarios.
Construction	Excavation of the underground facility and erection of any ancillary surface facilities in preparation for waste emplacement.
Constructability	Conditions for construction underground and how different techniques and methods can be applied in order to adapt to these conditions.
Container, waste	The vessel into which waste is placed for disposal: conversely the final barrier protecting the waste from external intrusions. For example, molten HLW glass would be poured into a container where it would cool and solidify. In a multibarrier system the sealed container would then become the final barrier protecting the glass against intrusion by water.
Containment	The confinement of radioactive waste within a designated boundary.
Contamination, radioactive	The presence of a radioactive substance or substances in or on a material or in a place where they are undesirable or could be harmful.
Controlled area	An area where workers might receive doses in excess of three-tenths of the occupational dose equivalent limits during the anticipated working period and where appropriate controls (such as restricted access) are applied.
Corrosion	A chemical attack on the surface of a material, thereby destroying the surface. Continual corrosion may penetrate or consume the material. In waste management the term is often applied to glasses and ceramic waste forms as well as to metals.
Cost-benefit analysis	A systematic examination of the positive effects (benefits) and negative effects (costs) of undertaking an action. For example, cost-benefit analysis may be used for optimization studies in radiation protection practice.
Creep	The deformation of a material at a very slow rate due to external forces and/or its own mass.
Criteria	Principles or standards on which a decision or judgment can be based. They may be qualitative or quantitative. Acceptability criteria are set by a regulatory authority. (Some Member States use terms such as 'protection goals' instead of 'acceptability criteria'.)
Critical group	For a given radiation source, the members of the public whose exposure is reasonably homogeneous and is typical of individuals` receiving the highest effective dose equivalent or dose equivalent (whichever is relevant) from the source.
Critical pathway	The dominant environmental pathway through which a given radionuclide reaches the critical group.
Crystalline rock	Largely unweathered igneous or metamorphic rock.
Cumulative fraction released (or cumulative penetration)	A term for expressing leach rates of radionuclides from solidified waste forms based upon depletion of the radionuclide to a certain sample depth.
Curie (Ci)	A unit of activity equal to 3.7E10 becquerels.
D1	CROP Deliverable 1, also referred to as Work Package 1.

D2	CROP Deliverable 2, also referred to as Work Package 2.
D3	CROP Deliverable 3, also referred to as Part 1 of Work Package 3.
D4	CROP Deliverable 4, also referred to as Part 2 of Work Package 3.
D5	CROP Deliverable 5, also referred to as Part 1 of Work Package 4.
D6	CROP Deliverable 6, also referred to as Part 2 of Work Package 4.
Darcy	A measure of the permeability of a rock. One Darcy equals a permeability such that one milliliter of fluid, having a viscosity of one centipoises, flows in one second under a pressure differential of one atmosphere through a porous material having a cross-sectional area of one hundred square millimeter and a length of ten millimeters.
De minimis	Part of the maxim "de minimis non jurat lex" (the law does not concern itself with trifles), sometimes used with reference to sources of radiation which a competent authority may decide to exempt from defined regulatory requirements because individual and collective effective dose equivalents received from them are both so low that they may be ignored.
Decommissioning	Detachment for closedown.
Decontamination	The removal of radioactive contaminants with the objective of reducing the residual radioactivity level in or on materials, persons or the environment.
Decontamination factor	The ratio of the initial level of contaminating radioactive material to the residual level achieved through a decontamination process.
Deep geologic repository	A repository constructed, usually in consolidated rock, at a depth of several hundred meters or more in a continental formation.
Deep-well injection	The discharge of liquid wastes via deep wells into permeable but confined geological formations deep underground as a means of isolating the wastes from the human environment.
Denitration	Conversion of the nitrate ion (NO^{-3}) to another chemical entity, normally a volatile nitrogen oxide. This may be done by thermal, chemical or electrolytic methods. Because nuclear fuel reprocessing is usually done in a nitric acid medium, denitration can be an important step in waste processing.
Deposition hole	The deposition hole can be either a borehole or a hole made by micro-drifting.
Derived air concentration (DAG)	A concentration of a given radionuclide in air, obtained by means of a stylized model for the constantly maintained activity concentration ($Bq.m^{-3}$) of that radionuclide in air, which if breathed by the reference man for a working year of 2000 hours under-conditions of light physical activity breathing rate $1.2m^3/h$) would result in an inhalation of one ALI (annual limit air intake). Also the concentration which for 2000 hours of air immersion would lead to the irradiation of any organ or tissue to the appropriate limit.
Deterministic analysis	A classical technique for studying a system behavior mathematically using the laws of science and engineering provided that all system parameters, events and features are deterministically (as opposed to probabilistically) defined.
Detriment	The mathematical expectation of the harm (damage to health and other effects) incurred from the exposure of individuals or groups of persons in a human population to a radiation source, taking into account not only the probabilities but also the severity of each type of deleterious effect.

Devitrification	The spontaneous change of a glass, in which the atoms display no long range order in their locations, to a crystalline material in which atoms display a high degree of ordering. A glass is usually less stable than an assembly of crystals having the same composition, hence devitrification can occur at elevated temperatures or over long times. The ability of a devitrified material to resist leaching, for example, may be greatly different than for the parent glass.
Diffusion	Diffusive transport of water and ions.
Discontinuity	Fracture, fracture zone, weathered zone, boundary between rock or soil units.
Dispersion	The summed effect of those processes of transport, diffusion and mixing which tend to distribute materials from wastes or effluents through an increasing volume of water or air. The ultimate effect appears as a dilution of the materials.
Disposal	Permanent isolation of SF or radioactive waste from the accessible environment with no intent of recovery, whether or not such isolation permits the recovery of such fuel or waste. For example, disposal of waste in a mined geologic repository occurs when all shafts to the repository are backfilled and sealed.
Disposal gallery/drift	The disposal gallery is either the gallery in which the waste is disposed or the gallery or drift from which boreholes are made.
Disposal system	Any combination of engineered and natural barriers that isolate SF or radioactive waste after disposal.
Disruptive event	An event (e.g., earthquake, meteorite impact) that disrupts a waste repository.
Disturbed zone	That portion of the controlled area in which the physical or chemical properties have changed as a result of underground facility construction, the emplacement of the radioactive wastes or the heat generated by the emplaced radioactive wastes such that the resultant change of properties may have a significant effect on the performance of the geologic repository.
Distribution coefficient	A quantitative measure of how a given chemical species partitions itself between two phases at equilibrium. In waste processing this parameter is used to predict the effectiveness of separation methods such as solvent extraction, ion exchange, or gas scrubbing. In environmental studies the quantity is sometimes used to predict how soils or backfill materials can retard radionuclide movement.
Documentation	Written, recorded or pictorial information describing, defining, specifying, reporting or certifying activities, requirements, procedures or results.
Domal (or dome) salt rock	A local geologic formation of salt rock in which the salt thickness is greater vertically than laterally. The top of the formation may bear resemblance to a dome or to a mushroom.
Dose	A term used in radiation protection with two meanings: 1. as a measure of the "quantity of radiation" present in, or "given" by, a radiation field - a concept now known as exposure, and 2. as a measure of the radiation "received" or "absorbed" by a target.
Dose assessment	An estimate of the radiation exposure of an individual or a population group usually by means of predictive modeling techniques, sometimes supplemented by the results of measurements.

Dose equivalent	The product of absorbed dose and appropriate factors to account for differences in biological effectiveness due to the quality of radiation and its spatial distribution in the body. The unit of dose equivalent is the “rem” (“sievert” in International Standard [SI] units).
Drift	Underground passage without surface connection. The word drift is generally used in this project.
Drum	A type of waste container similar in appearance to an oil drum, which may be sealed by a fitted lid. It can be encased in concrete for intermediate-level radioactive wastes requiring some shielding. A typical volume for drums is 200 liters.
Drucker-Prager	
Dynamic leach test	A laboratory test that simulates a situation in which flowing water enters a repository and contacts the waste form. The waste form to be tested will then be subjected to flowing water (and perhaps heat, pressure or other expected conditions) and its rate of dissolution measured.
Effective dose	The sum over specified tissues of the products of the dose equivalent received following an exposure of, or an intake of radionuclides into, specified tissues of the body, multiplied by appropriate weighting factors. This allows the various tissue-specific health risks to be summed into an overall health risk.
Effluent, radioactive	Airborne or liquid radioactive materials which are discharged into the environment.
Electropolishing	An electrochemical process used to produce a smooth polished surface on metal objects. In this process the object to be polished serves as the anode of an electrochemical cell. When used as a decontamination method, radioactive contaminants trapped in the surface layer are removed along with this layer of metal by anodic dissolution.
Emanition	Radioactive gas formed by decay of a radioactive solid. The emanation may or may not be retained within the pore space of the solid phase.
Embeddning	A process of putting solid or liquid waste into a matrix to form a heterogeneous waste form.
Emplacement	Placing the waste in its location for storage or disposal.
Emplacement density	Amount of waste emplaced per unit area or volume of a storage or disposal site (e.g., canisters per hectare).
Engineered barrier	See: barrier
Engineered storage	The storage of radioactive wastes, usually in suitably sealed containers, in any of a variety of structures especially designed to protect them and to help keep them from leakage to the biosphere by accident or sabotage. They may also provide for extracting heat of radioactive decay from the waste.
Entombment decommissioning	Placement of radioactive wastes and structural materials within an entombment structure (often comprising a portion of the existing production structure) for permanent disposal. Only those materials with hazardous lifetimes, as determined by radiological assessments, less than or equal to the expected lifetime of the entombment structure are intended to be so placed. Other radioactive materials are removed from the site for disposal.

Environment	1. The surroundings of an installation. (The immediate surroundings are termed the environs.): 2. The sum total of all the conditions and influences that surround an organism, human or otherwise, that affect its life, survival and development.
Environmental compartment	Any part of an environment which is convenient to consider as a single entity in modeling studies.
Environmental impact statement	Complete description of the impacts a repository will have on the environment above and under ground.
Environmental transfer models	Mathematical techniques for representing the transfer (of radionuclides or other pollutants or tracers) through the environment (usually to man).
Evapo-transpiration	The sum total of water lost from the land by evaporation and plant transpiration.
Excavation-disturbed zone	The part of the host rock of which the mechanical, hydraulic or chemical properties have been changed, due to the excavation activities during the construction and during the evolution of the repository.
Exclusion area	A term used in some countries to designate a zone which may be established around a nuclear facility or other radiation source, to which access is permitted under controlled conditions and in which residence is normally prohibited.
Exposure	Irradiation of persons or materials. Exposure of persons to ionizing radiation may be either: 1. external exposure, irradiation by sources outside the body, or 2. internal exposure, irradiation by sources inside the body. The term occupational exposure refers to exposure of a worker received or committed during a period of work.
Exposure rate	The quotient of dX by dt, where dX is the increment of exposure in the time interval dt.
Far-field	Rock formations outside of the repository, including the surrounding strata, at a distance from the waste disposal site such that, for modeling purposes, the site may be considered as a single entity, and the effects of individual waste packages are indistinguishable in the effects of the whole.
Field experiment	A test conducted under ambient conditions outdoors, usually with regard to a shallow land burial site or to migration in the environment. The test may be contained in such a way that radionuclides cannot leave the area.
Filtration	The process of separating solids from liquids or gases moving through the interstices of a solid medium.
Fission gas	A fission product in gaseous form at ambient temperature (e.g.,^{85}Kr, $^{3}H_2$).
Fission product	A nuclide produced either by fission or by the radioactive decay of nuclides formed by fission.
Fissure	An extensive crack, break or fracture in the rock.

Fixation (of radionuclides)	The practice of immobilizing radionuclides so that they are not easily dispersed. The term often refers to the application of paint or a similar material to a contaminated surface in order to prevent the radionuclides from becoming airborne or transferred by casual contact.
Flocculation	A process of removing finely divided solid particles, frequently colloids, from waste slurry by neutralizing their electrical charges and allowing the neutralized particles to agglomerate and settle out. The neutralization is usually effected by chemical means through introducing charges of an opposite sign by the addition of either an electrolyte or another colloid.
Fluidized bed technology	Technology to suspend solid particles in a loose bed of material by a rapidly moving upward stream of gas for enhancing chemical or physical reaction.
Food-chain (or web)	A figure of speech for the dependence for food organisms upon others in series, beginning with plants or scavenging organisms and ending with the largest carnivores. A web is a network or series of food-chains.
Fracture	A crack, joint, fault, or other break in rock. In underground repositories, fractures are of concern as possible paths for water flow and radionuclide migration.
Front end of the fuel cycle	Mining, milling, enrichment and fabrication of nuclear fuel. Sometimes reactors are included.
Fuel assembly	Complete fuel element.
Fuel cycle	See: nuclear fuel cycle.
Fuel reprocessing plant (FRP)	Plant where SF elements are dissolved, waste materials removed and reusable materials are segregated.
Gaseous waste	Process off gases or air streams containing controlled levels of radioactivity, aerosols or chemical constituents. Typically, the gas or air stream would be considered a gaseous waste at the point at which it is released to the environment.
Geohydrology (or groundwater hydrology)	A science that is concerned with the properties, distribution and movement of water below the surface of the land (i.e., in the soil and underlying rocks).
Geologic barrier	In the context of deep underground disposal, this is the barrier provided by the stable formation in which the repository is constructed.
Geologic repository	A system which is intended to be used for, or may be used for, the disposal of radioactive wastes in excavated geologic media. A geologic repository includes: (1) The geologic repository operations area, and (2) the portion of the geologic setting that provides isolation of the radioactive waste.
Geologic setting	The geologic, hydrologic, and geochemical systems of the region in which a geologic repository operations area is or may be located.
Glass	As used in this project it refers to an amorphous waste matrix material with a molecule distribution similar to that of a liquid but with a viscosity so great that its physical properties are those of a solid. Glasses used in the solidification of liquid high-level radioactive waste are generally based on silicon-oxygen network. Additional network formers such as aluminum, or modifiers such as boron, lead to aluminosilicate or borsilicate glass.

Glass corrosion	A chemical attack, frequently by groundwater, on the surface of vitrified waste that can alter the surface and potentially release the radionuclides. (See: corrosion).
Glass leaching	The transfer of radionuclides on or near the surface of vitrified waste into an ambient solution. The process occurs coincidentally with corrosion.
Glass-ceramic	The product resulting after a glass has been transformed into a crystalline material by a controlled process such as heating. The product may retain the desirable properties of both a glass and a ceramic (see: ceramic materials).
Granite	Broadly applied, any holocrystalline quartz-bearing plutonic rock. Granite formations are being considered as possible hosts for high-level radioactive waste repositories deep underground.
Gray (Gy)	The SI unit of absorbed dose equal, for ionizing radiation, to 1 joule of radiant energy absorbed in l kilogram of the material of interest. (1Gy = 100rad).
Groundwater	Water below the land surface in a zone of saturation.
Groundwater transport	The principal means by which radionuclides can be mobilized from an underground repository and moved into the biosphere. Avoiding such transport is the basis for selecting and designing repository systems.
Grout	A relatively low-viscosity slurry of water, cement and other fine solids (see cement). Liquid radioactive wastes or waste slurries can be used to make grouts and hence solidify the waste. Grouts can be pumped or injected into geological formations.
Hades	High Activity Disposal Experimental Site (URL) at Mol, Belgium
Half-life	In physics, the time required for the transformation of one-half of the atoms in a given radioactive decay process, following the exponential law (physical half-life). By analogy, in biology this term is used in connection with the clearance of a substance from a tissue, an organ or the whole body (when the kinetics of such a phenomenon roughly follow an exponential dependence) to mean the time for one-half of this substance to be eliminated (biological half-life). The time necessary for a radioactive material in a living organism to be reduced to one half of its initial value by a combination of biological elimination and radioactive decay is termed effective half-life.
Heat generating waste	Waste, which is sufficiently radioactive that the energy of its decay significantly increases the temperature of its surroundings. SF elements require active cooling, for example in a water-filled basin, for several years after discharge from the reactor. The heat-generating period of HLW in a repository may last several hundred years.
HEPA filter (High-Efficiency Particulate Air) filter	Filter used for removing sub-micrometer and larger particles from a gaseous stream.
High-level radioactive waste (HLW)	(i) The highly radioactive liquid, containing mainly fission products, as well as some actinides, which is separated during chemical reprocessing of irradiated fuel (aqueous) waste from the first solvent extraction cycle and those waste streams combined with it. (ii) Spent reactor fuel, if it is declared a waste. (iii) Any other waste with a radioactivity level comparable to (i) or (ii).

High-level waste tank	A tank intended for storage of liquid high-level waste. Such tanks likely will be double-walled, contain provisions for cooling the waste, and be well shielded. They will be subjected to strict quality assurance measures.
Host rock (or host medium)	A geological formation in which a repository is located.
Hulls and spacers	Radioactive waste, comprised of cladding hulls and assembly grid spacers, generated during reprocessing when SF assemblies are disassembled and the fuel is dissolved.
Human environment	Those portions of the Earth that are inhabited by humans or are readily accessible to them. (See: accessible environment).
Human intrusion	Any human activity that results in inadvertent damage to the natural or engineered barriers of a waste repository.
Humid sites	A near surface repository located in an area at which annual precipitation exceeds water loss by evaporation, hence there is a significant downward flux of moisture through the soil which could transport radionuclides. Uptake of radionuclides by plant roots may also be significant in a humid site.
Hydration	The chemical combination of water with another substance.
Hydraulic conductivity	Ratio of flow velocity to driving force for viscous flow under saturated conditions of a specified liquid in a porous medium.
Hydrofracture process	A process for permanent disposal of medium-level liquid waste in which wastes in the form of a slurry containing hydraulic binders (grouts) are injected to induce fracturing in a deep underground formation (such as a nearly impermeable shale formation) considered to be isolated from the surface. The slurry solidifies *in-situ*, ensuring fixation of the waste at the location of injection.
Hydrogeology	The study of the geological factors relating to the Earth's water.
Hydrologic modeling	The construction of mathematical models, usually for use on a computer that describes water flow through and around a specific underground repository. The model is intended to predict possible transport, via water, of radionuclides from the repository.
Hydrology	The study of all waters in and upon the Earth. It includes underground water, surface and rainfall, and embraces the concept of the hydrological cycle.
IAEA directives and guidelines	International Atomic Energy Agency guidelines and directives.
ICRP limit	A primary dose equivalent limit recommended by the International Commission on Radiological Protection (ICRP). Dosimetric models may be used to derive the annual limit on intake (ALI) and derived air concentration (DAC).
Immobilization of waste	Conversion of a waste to a solid form that reduces the potential for migration or dispersion of radionuclides by natural processes during storage, transport and disposal.
Incineration	The process of burning a combustible material to reduce its volume and yield an ash residue.

Incinerator ash	The non-combustible residue remaining after burning waste in a specially designed unit. The volume of radioactive ash will be much less than that of the original waste, and the ash will usually be incorporated into a solid matrix for disposal.
Ingest	Take into the body by way of the digestive tract.
***In-situ* testing**	Tests conducted within a geologic environment that is essentially equivalent to the environment of a potential repository. A special underground laboratory may be built for *in-situ* testing or tests may be done in an actual repository excavation. Only in such a facility can the full range of repository properties and waste-repository interactions be measured.
Institutional control	Control by an authority or institution designated under the laws of a country or state. This control may be active (monitoring, surveillance, remedial work) or passive (land use control).
Interim storage (storage)	Storage of radioactive materials such that: (a) isolation, monitoring, environmental protection and human control are provided, and (b) subsequent action involving treatment, transport, and disposal or reprocessing is expected.
Intermediate-level radioactive waste (or medium-level waste)	Waste of a lower activity level and heat output than high-level radioactive waste, but which still requires shielding during handling and transportation. The term is used generally to refer to all wastes not defined as either high-level or low-level. (See: alpha-bearing waste and long-lived radioactive waste for other possible limitations).
Intrusive rock	A body of igneous rock that has forced itself into an existing rock formation.
Ion exchange	A usually reversible exchange of one ion with another, either in a liquid, or on a solid surface, or within a crystalline lattice.
Ion exchange resin	An organic polymer that exhibits technically useful ion exchange characteristics.
Isolation	Inhibiting the transport of radioactive material so that amounts and concentrations of this material entering the accessible environment will be kept in within prescribed limits.
Isolation of waste	See: confinement of waste.
Joule melters	An electrically powered glass-making furnace in which the molten glass itself carries the electric current and is thereby heated. Such a design is considered to be well suited for vitrifying radioactive waste.
Leachability	The susceptibility of a solid material to having its soluble, sorbed and/or suspendable constituents removed by the dissolving or erosive action of water or other fluids.
Leachate	A solution, typically groundwater that has been in contact with radioactive waste and as a result may contain radionuclides.
Leaching	(i) Extraction of a soluble substance from a solid by a solvent with which the solid is in contact. (ii) The term is often used in waste management to describe the gradual dissolution/erosion of emplaced solid waste or chemicals there from, or the removal of sorbed material from the surface of a solid or porous bed.

Leach rate	The rate of dissolution or erosion of material from a solid. The term may be used to describe the rate of gradual dissolution/erosion of emplaced solid waste or the removal of sorbed material from the surface of a solid or porous bed.
Leach test	A laboratory test conducted to determine the rate radionuclides are released from a waste form that is in contact with water. These tests are considered to be essential for judging and comparing waste forms. Many different test parameters have been used, and a number of protocols have been published.
Lining	Material placed against the wall of excavated cavities (e.g., galleries, shafts, boreholes) to make them stable.
Lithosphere	The solid part of the Earth below the surface, including any ground water contained within it.
Lithostatic pressure	Pressure underground due to the weight of overlying rock and/or soil and/or water.
Long-lived nuclide	For waste management purposes, a radioactive isotope with a half-life greater than about 30 years.
Long-lived radioactive waste	Radioactive waste that will not decay to an acceptable activity level in a period of time during which administrative controls can be expected to last. (See: short-lived radioactive waste). Also, the classification of radioactive waste differs among countries and the term long-lived radioactive waste is used in this report to cover spent nuclear fuel (SF) and other high-level radioactive wastes (HLWs) as well as long-lived transuranic (TRUW) and intermediate-level (ILW) radioactive waste, and low-level radioactive/reactor waste (LLRW).
Long-term	In waste management, refers to periods of time, which exceed the time during which administrative controls can be expected to last.
Low-level radioactive/reactor and intermediate-level radioactive waste (LLRW and ILW)	Radioactive wastes containing enough radioactive material that require action to ensure the protection of workers and the public for shot or extended periods of time. The two classes/categories includes a rang of materials from just above exempt levels to those with sufficient high levels of radioactivity to require use of shielding containers and in some cases periods for cooling off. LLRW and ILW may be subdivided into categories according to the half-lives for the radionuclides it contains, with “short-lived” being less than 30 years and “long-lived” greater than 30 years.
Lysimeter	A device that provides containment for conducting migration experiments under ambient outdoor conditions. A typical lysimeter could be a large diameter (2m or more) pipe emplaced vertically in the ground, with its open end several cm above the surface and its lower end sealed. Rain water percolating through a mixture of waste and soil would reach the closed end where it would be pumped back to the surface for analysis.
Main gallery	Gallery giving access to the disposal galleries.
Mathematical model	Mathematical description of processes, function and performance among other things based on the conceptual model.
Matrix	In waste management, a non-radioactive material used to immobilize radioactive waste in a monolithic structure. Examples of matrices are bitumen, cement, various polymers, etc.
MAUS	2-D FEM codes for M analysis

Mechanical stability	Mechanical stability of the different components of the disposal system (e.g., linings, crossing, disposal tube, overpack) during the operational period, including the period of retrievability.
Membrane filtration	Passing of aqueous solutions through solid filters with small pores to remove impurities or to separate chemical constituents.
Migration	The movement of materials through a rock medium or some other solid substance, e.g., radionuclide migration.
Mill tailings (tailings)	Finely ground residues resulting from the processing of ore for recovery of uranium and thorium. Uranium mill tailings consist of two major fractions: 1. Slimes - the lighter, finer particles in the tailings (including particles in the micron and sub-micron range) made-up of the clays and other very fine particles: 2. Sands - the heavier, coarser range of particles.
Milling	Operation of processing ore to obtain uranium or thorium for conversion into reactor fuel.
Mixed waste	Radioactive waste that also contains chemicals that could cause undesirable effects in the environment. Such wastes present a number of technical and regulatory problems for processing and disposal.
Model	In applied mathematics, an analytical or mathematical representation or quantification of a real system and the ways that phenomena occur within that system. Individual or sub-system models can be combined to give system models. Deterministic and probabilistic models are two types of mathematical models.
Mohr-Coulomb	
Molecular sieve	A material with a rigid, uniform pore structure which completely excludes molecules larger than the structure pore openings and can sorb certain classes of small molecules from a fluid in contact with the material.
Monitoring	The methodology and practice of measuring levels of radioactivity either in environmental samples or en route to the environment. Examples include ground water monitoring, gaseous effluent (stack) monitoring, and personnel monitoring.
Multibarrier	Two or more independent obstructions that prevent or delay the transport of radionuclides of other contaminants (e.g., chemical) from the waste repository to the biosphere.
Natural analogues	Radioactive minerals or mineral deposits whose migration history over very long times can be determined and used to forecast the possible behavior of chemically similar waste radionuclides.
Near-field region	The excavated repository including the waste package, filling, or sealing materials, and those parts of the host medium whose characteristics have been or could be altered by the repository or its content.
Non-high-level waste	Intermediate or low-level radioactive waste.
Nuclear fuel cycle	Processes connected with nuclear power production, including obtaining, using, storing, reprocessing and disposing of nuclear materials used in the operation of nuclear reactors.

Nuclear waste	Unwanted radioactive by-products from the nuclear fuel cycle. (See: radioactive waste).
Off-gas	The gas streams which arise from a process. Typical processes in radioactive waste management facilities such as dissolution, evaporation, incineration, vitrification, bituminization, and cementation, will generate process off-gases which contain water vapor, acid vapors, aerosols, radioactive constituents and gaseous chemical constituents.
Off-gas treatment	The removal of radioactive components or chemical pollutants from gases prior to their release under controlled conditions into the atmosphere.
Opalinus Clay	
Operating records	A set of documents, such as instrument charts, certificates, log books, computer print-outs and magnetic tapes, kept at each nuclear facility and organized in such a way that they provide a complete and objective history of the operation of the facility.
Operational period	The period during which a nuclear facility is being used for its intended purpose until it is shut down and decommissioned.
Operations, waste management	Broad classification of waste management activities in terms of their basic function (e.g., waste storage, treatment, transportation or disposal).
Operator	Any person, government or other entity that conducts or carries on operations at a nuclear facility.
Osmosis	The passage of solvent through a semi-permeable membrane from a dilute solution into a more concentrated one. (A semi-permeable membrane allows passage to the molecules of the solvent but not to the molecules of the solute).
Overpack	A secondary (external) container over a radioactive waste canister for additional containment of the radioactive waste in a geologic repository.
Package, waste	See: waste package.
Particulates	Solid aerosols or particles carried in process off-gases or airstreams or suspended in the air. Virtually all facilities that handle radioactive waste use high-efficiency particulate air (HEPA) filters to remove particulates from the process off-gases.
Passive institutional control	(1) permanent markers placed at a disposal site, (2) public records and archives, (3) government ownership and regulations regarding land or resource use, and (4) other methods of preserving knowledge about the location, design and contents of a disposal system.
Pathways model	A mathematical description, usually in the form of a computer algorithm, that determines the relative significance of possible radionuclide transport vectors, e.g., air, ground water, surface water, intrusive roots, animals, etc.
Percolating groundwater	Groundwater that seeps via saturated flow conditions through soil or rock strata (see saturated zone).
Performance allocation	Assignment of an expected or design level of performance for each barrier of a repository such that all barriers together will achieve the required level of safety.

Performance assessment	An analysis that (1) identifies the processes and events that might affect the disposal system, (2) examines the effect of these processes and events on the performance of the disposal system, and (3) estimates the cumulative releases of radionuclides, considering the associated uncertainties, caused by all significant processes and events. These estimates shall be incorporated into an overall probability distribution of cumulative release to the extent practicable.
Performance confirmation	Tests carried out at a repository, usually after waste emplacement but prior to license termination, to confirm that the repository is performing as anticipated when emplacement of wastes was authorized.
Permeability (of rock)	The capacity of a porous or pervious rock for transmitting a fluid. (See: Darcy).
Personnel dose	Individual radiation dose.
Physical separation	(i) Separation by geometry (distance, orientation, etc.). (ii) Separation by appropriate barriers. (iii) Separation by a combination of both concepts (i) and (ii).
Physisorption	A type of adsorption in which the sorbed species is retained by the adsorber by physical means (as opposed to *chemical* bonding). Such an adsorption method can be used in off-gas treatment systems, for example.
Plasma arc	A metal cutting technique in which an electrical discharge supplies heat for burning through the metal. This is a standard technique that is well suited to use in a contained, radioactive facility because no combustible gases are required.
Plasticity	The property of a material, e.g., rock salt that enables it to undergo permanent deformation without appreciable volume change or elastic rebound, and without rupture.
Plug	Temporary, or permanent construction in deposition rooms, drifts and shafts for supporting backfills or buffers or for minimizing water flow into or along such rooms and for preventing access to emplaced radioactive waste.
Polymer modified cement	A cement to which substances made from long-chain organic molecules (polymers) have been added to modify either its mixing or handling characteristics, or characteristics of the final product.
Population of CCDFs	All possible complementary cumulative distribution functions (CCDFs) that can be generated from all disposal system parameter values used in PAs.
Population of radiation dose or radionuclide estimates	All possible estimates of radiation doses and radionuclide concentrations that can be generated from all disposal system parameter values used in compliance assessments.
Porosity	The ratio of the aggregate volume of interstices in a rock or soil to its total volume.
Porous media	Material that contains pores or cracks through which water or gas can flow. Often the term is applied to the geological formations around a waste repository and could denote an undesirable situation.

Post-sealing period	The period after a waste repository has been shut down and sealed.
Precipitation	1. A standard chemical method that can be used in treatment of liquid radioactive wastes. Radionuclides are removed from the liquid by either forming or being carried by the insoluble product of a chemical reaction made to occur within the liquid. 2. A meteorological term that refers to the total amount of water (rain, snow, etc.) that falls on a site.
Preliminary site selection	The second stage of siting a waste repository during which a manageable number of potentially suitable sites is examined, using existing information or information from limited explorations, to determine whether one or more regions contain sites suitable for additional site confirmation studies.
Pre-treatment of waste	Any step carried out prior to operations which have been defined as treatment, conditioning, off-site transport or disposal. Pre-treatment techniques and practices include: - collection and segregation - size reduction - chemical adjustment.
Primary waste	As generated form and quantity of a waste.
Pyrolysis	A chemical decomposition of a substance by heat.
Quality assurance	Those planned and systematic actions that are necessary to provide adequate confidence that the disposal system will comply with the disposal regulations. Quality assurance (QA) includes quality control (QC), which comprises those actions related to the physical characteristics of a material, structure, component or system that provide a means to control the quality of the material, structure, component, or system to predetermined requirements.
Quality control	Actions providing a means to contro1 and measure the characteristics of an item, process, facility or person in accordance with quality assurance requirements.
Radiation damage	Deleterious changes in the physical or chemical properties of a material resulting from exposure to ionizing radiation. This term does not apply to biological systems.
Radiation protection or radiological protection	(i) All measures associated with the limitation of the harmful effects of ionizing radiation on people, such as limitation of external exposure to such radiation, limitation of bodily incorporation of radionuclides as well as the prophylactic limitation of bodily injury resulting from either of these. (ii) All measures designed to limit radiation-induced chemical and physical damage in materials.
Radiation stability	Capability of a material to withstand the action of ionizing radiation without changing its essential characteristics.
Radioactive material	A material of which one or more constituents exhibit radioactivity.
Radioactive source term	An expression used to denote information about the actual or potential release of radioactive material from a given source, which may include a specification of the composition, the amount, the rate and the mode of the release.

Radioactive waste	Waste containing radioisotopes.
Radioactive waste management	All activities, administrative and operational, that are involved in the handling, treatment, conditioning, transportation, storage and disposal of waste.
Radiodecay heat	Heat generated by the absorption of energy released by the decay of radionuclides.
Radiolysic effect	An effect caused by radiolysis, e.g., radiation-induced degradation of chemical compounds.
Radiolysis	Chemical decomposition by the action of ionizing radiation.
Radionuclide migration	The movement of radionuclides through various media due to fluid flow and/or by diffusion.
Radionuclide transport	The action of a particular vector that results in movement of radionuclides in the environment, e.g., radionuclide transport by groundwater. This specific term does not refer to the intentional transportation of radioactive materials by man: transportation of nuclear wastes in transport casks, etc.
Ramp	Inclined drift.
Reactor waste	Waste arising from the routine operation of a nuclear reactor.
Release scenario	See: scenario analysis.
Rem	A unit of dose equivalent equal to one hundredth of a sievert (1cSv).
Remedial action	Corrective measures imposed at a near surface repository to prevent a previously unforeseen circumstance from causing unacceptable releases of radionuclides.
Repository	A deep geological system, typically a specifically mined underground facility designated for disposal of radioactive wastes.
Repository system	A repository and all its supporting facilities and infrastructures.
Reprocessing	A generic form for the chemical and mechanical processes applied to fuel elements discharged from a nuclear reactor. The purpose to remove fission products and to recover fissile (U-233, U-235, pu-239), fertile (Th-232, U-238) and other valuable materials for re-use or special treatment.
Reprocessing, fuel	Recovery of fissile and fertile material from irradiated nuclear fuel by chemical separation from fission products and other radionuclides (e.g., activation products, actinides). Selected fission products may also be recovered.
Resuspension	A vector for the environmental transport of radionuclides in which contaminated particles are picked up and carried by the wind.
Retardation	A reduction in the velocity of radionuclide movement through the environment due to reversible adsorption on an immobile matrix. Soils often retard movement of waterborne nuclides, and the degree of retardation can be quantified.
Retrievability	The capability to remove waste from where it has been placed.
Retrieval	The act of intentionally removing radioactive waste from the underground location at which the waste had been previously emplaced.

Reverse osmosis	Movement of a solvent out of a solution under pressure through a semi-permeable membrane into pure solvent or a less concentrated solution at lower pressure (see: osmosis.) This process can be used to extract essentially pure (fresh) water from polluted or salt water.
Reversibility	Characteristics of a geologic repository system that allow the reversal of the steps taken during its development for whatever reason.
Risk	For the purposes of radiation protection, the probability that a given individual will incur any given deleterious stochastic effect as a result of radiation exposure.
Risk analysis	An analysis of the risks associated with a technology wherein the possible events and their probabilities of occurrence are considered together with their potential consequences, the distribution of these consequences within the affected population(s), the time factor and the uncertainties of these estimates.
Robustness	The robustness of a disposal system is defined as the measure (at a given stage in the development of the repository) of the independence of its true operation relative to the uncertainties that have not been resolved by safety assessments.
Rock	To the geologist any mass of mineral matter, whether consolidated or not, which forms part of the Earth's crust is a rock. Rocks may consist of only one mineral species, in which case they are called monomineralic, but they more usually consist of an aggregate of mineral species.
Rock cavern, rock vault	Excavated openings in rock overburden.
Routine discharges	A reduction in the velocity of radionuclide movement through the environment due to reversible adsorption on an immobile matrix. Soils often retard movement of waterborne nuclides, and the degree of waterborne nuclides, and the degree of retardation can be quantified.
Routine discharges	Planned and controlled release of radionuclides to the environment. Such releases will meet all restrictions imposed by appropriate regulatory authorities.
Safety	Protection of all persons from undue radiological hazard.
Safety analysis	The analysis and calculation of the hazards (risks) associated with the implementation of a proposed activity.
Safety assessment	A comparison of the results of safety analyses with acceptability criteria, its evaluation, and the resultant judgments made on the acceptability of the system assessed.
Salt	Rock consisting of KCl or NaCl Sediment.
Salt dome	A dome-like salt structure resulting from the upward movement of a salt body.
Saturated zone	A subsurface zone in which all the interstices are filled with water under pressure equal to or greater than that of the atmospheric pressure. This zone is separated from the unsaturated (vadose) zone, i.e., zone of aeration, by the water table.
Scenario analysis	Part of a safety analysis that identifies and quantitatively defines phenomena, their probabilities and their interactions, which could initiate and/or influence the release and transport of radionuclides from a source to humans. A release scenario defines the phenomena relevant to release of radionuclides from a radioactive (e.g., waste) source. A transport scenario defines the phenomena relevant to transport of the released radionuclides.

Scrubbing system	A system which contacts process off-gases and ventilation airstreams with water, chemical solutions or non-aqueous solvents. A typical scrubber design is a column with baffles or packing material through which the liquid flows countercurrent to the gas or air stream. Typical uses for scrubbing systems include humidifying and cooling of ventilation air, recovery of aerosols and chemical constituents from process off-gas and cooling process off-gas.
Seal of disposal galleries	Sealing to avoid or delay transport of water, gas, contaminants through the gallery.
Secondary waste	A form and quantity of waste which is a by-product of the process from applying a waste treatment technology to a primary waste.
Sedimentary rock	Sediment solidified by diagenesis.
Seepage basin	A pond into which very slightly contaminated water is discharged. In principle the pond provides a holding point for decay of some radionuclides and controlled release of others, either through seepage or evaporation out of the pond.
Segregation	A pretreatment step for solid waste in which the wastes are sorted according to some property (e.g., combustibility) that will facilitate later waste treatments.
Self-healing	Ability of faults and cracks present at a certain time in a host rock of self-repairing and hence further disappearing.
Sensitivity analysis	An analysis of the variation of the solution of a problem with changes in the values of the variables involved. Two types of sensitivity analysis can be recognized. In simple parameter variation, the sensitivity of the solution is investigated for changes in one or more input parameters within a reasonable range about selected reference or mean values. In perturbation analysis, the sensitivities of the solution with respect to changes in all input parameters can be obtained by applying differential and/or integral analysis.
Shaft	Steep underground passage with surface connection.
Shallow-ground disposal (e.g., shallow-ground burial)	Disposal of radioactive waste, with or without engineered barriers, above or below the ground surface, where the final protective covering is of the order of a few meters thick. Some States consider shallow-ground disposal to be a mode of storage rather than a mode of disposal.
Shield, radiation	A material interposed between a source of radiation and persons, or equipment or other objects, in order to attenuate the radiation.
Shipping cask (transport cask)	A heavy protective container which shields and contains radioactive materials, dissipates heat, and prevents criticality during transport and handling.
Short-lived nuclide	For waste management purposes, a radioactive isotope with a half-life shorter than about 30 years, e.g., ^{137}Cs, ^{90}Sr, ^{85}Kr, ^{3}H.
Short-lived radioactive waste	Waste which will decay to a level considered to be insignificant from a radiological viewpoint, in a time period during which administrative controls can be expected to last. Such waste can be determined by radiological assessment of the storage or disposal system chosen. (See: long-lived radioactive waste).
Shutdown	Actions taken at a repository after disposal operations have ceased in order to prepare the facility for abandonment. This includes decommissioning of ancillary facilities and sealing the repository. Shutdown may occur immediately or after a period of surveillance following the final emplacement of waste.

Sievert	The SI unit of effective dose and equal to 100 rem or one joule per kilogram. The abbreviation is “Sv”.
Site	The area containing a nuclear installation, (e.g., a waste repository) that is defined by a boundary and which is under effective control of the implementing organization.
Site confirmation	Actions involved in establishing the suitability of an intended repository site. Extensive on-site investigations will be made to assure its capability for achieving all performance criteria, especially radiation protection requirements. The type of waste to be emplaced and the proposed repository design are of importance in this assessment.
Siting	The process of selecting a suitable site for an installation, including appropriate assessment and definition of the related design bases.
Slurry feeding	The practice of feeding a liquid waste slurry directly onto the surface of molten glass in a ceramic melter, without an intermediate step of drying or calcining the waste.
Soil	Clastic mineral spontaneously dispersed in water.
Solid waste, radioactive	Untreated waste that possesses physical properties commonly associated with the solid state.
Solidification	Conversion of liquid or liquid-like materials into a solid.
Solidified waste, radioactive	Liquid waste or otherwise mobile waste materials (ion exchange resins, etc.) that have been immobilized by incorporation (either physical or chemical) into a solid matrix by some specific treatment.
Sorption	A broad term referring to reactions taking place within pores or on the surfaces of a solid. Its use avoids the problem of technical distinction between absorption and adsorption reactions. Absorption is generally used to refer to reactions taking place largely within the pores of solids, in which case the capacity of the solid to absorb is proportional to its volume. Adsorption refers to reactions taking place on solid surfaces, so that the capacity of a solid is proportional to its effective surface area. An example of the latter process is ion exchange, whereby ions occupying charged sites on the surface of the solid are displaced by ions from solution.
Source term	See: radioactive source term.
Speciation	A term that refers to the chemical form(s) and properties of a radionuclide under a particular set of environmental conditions (pH, eH, ligands present, etc.). Speciation study is valuable because the environmental behavior of a nuclide is largely determined by its chemical form.
Specific activity	(i) The activity per unit mass of a pure radionuclide. (ii) The activity of a radioisotope per unit mass of that element present in the material. (iii) The activity per unit mass or volume of any sample of radioactive material.
Spent fuel/spent nuclear fuel	Irradiated fuel units not intended for further reactor service.
Spent fuel container	A vessel for storing used fuel rods from a reactor. After an initial period of cooling in a water-filled basin, SF rods might be placed into a specially designed container for longer-term storage. Among other considerations, the container will provide passive cooling and be designed to prevent accidental criticality.

Spent nuclear fuel	Uranium pellets in claddings.
Static leach test	A type of Mach test in which the leachant does not flow past the waste form (see: leach test). Leachant solutions may be sampled or changed according to a specified routine.
Storage	Retention of SF or other radioactive wastes with intent and capability to readily retrieve such fuel or waste for subsequent use, processing, or disposal. (See: Interim storage.)
Subsequent control	Any long-term safety measures, such as land-use restrictions, imposed to assist in achieving repository safety after shut-down and sealing has been completed and after the operating license for the repository has been cancelled.
Subsidence	Sinking or caving in of the ground surface. This results from the inability of the upper layers of the Earth's crust to support their own mass, or that mass with additional surface load, over an area containing poorly compacted material and/or voids. Such voids can be man-made, as in the case of mines.
Supercontainer	Integrated package of canister and cement or clay buffer.
SUPERMAUS	2-D FEM code for coupled TM analysis
Surface water	Water which fails to penetrate into the sub-soil and flows along the surface of the ground eventually entering a lake, a river or the sea.
Surveillance	All planned activities performed to ensure that conditions at a nuclear installation remain within the prescribed limits. For a waste repository, surveillance continues well past the periods of operation and closure.
Synroc	The name given to a group of specially formulated zirconium-based ceramics that were originally developed by Australian scientists for immobilizing high-level waste.
Tailings	See: mill tailings.
Tailored ceramic	A ceramic material whose composition has been specially formulated to optimize the incorporation of a particular set of radionuclides into the crystalline matrix. The composition of the waste form is thus tailored to fit a particular waste stream (see: ceramic materials, Synroc).
TAUS	2-D FEM codes for T analysis
Thermal gradient	A quantitatively measurable change in sensible heat as a function of distance. In a deep geological repository the thermal gradient produced by radioactive decay heat can potentially alter the host rock and water flow paths.
Thermal loading	The quantity of heat-generating materials placed in a given area or volume. Units are power per area or per volume, respectively.
Thin film evaporator	A device designed to de-water liquid waste by evaporation, the liquid being spread on a thin film over the heat-transfer surface.
Topography	(i) The configuration of (a portion of) the Earth's surface, including its relief and relative positions of its natural and man-made features. (ii) The practice of graphical representation of the same.

Transmissivity hydraulic	Rate at which water is transmitted through a unit width of aquifer under a unit hydraulic gradient. It is expressed as the product of the hydraulic conductivity and the thickness of the saturated portion of the aquifer.
Transuranic radioactive waste (TRUW)	Waste containing quantities of nuclides having atomic numbers above 92Curie content and age above limits established by national regulatory bodies. (See: alpha-bearing waste).
Treatment of waste	Operations intended to benefit safety or economy by changing the characteristics of the waste. Three basic treatment concepts are: a) Volume reduction. b) Removal of radionuclides from the waste. c) Change of composition. (See: conditioning of waste).
Tuff	One of a series of pyroclastic rocks composed of consolidated ash from fragmental volcanic material blown into the atmosphere by volcanic activity. Tuff is investigated in the USA as a potential host medium for high-level radioactive waste disposal.
Underground disposal	Disposal of waste at an appropriately safe depth below the ground surface.
Unsaturated flow	The flow of water in undersaturated soil by capillary action and gravity.
Unsaturated zone	A subsurface-zone in which at least some interstices contain air or water vapor, rather than liquid water. Also referred to as "zone of aeration". (Seer saturated zone).
Uptake	Amount of radioactive material absorbed into the extra cellular fluids. Also used to denote the process.
Validation	Validation is a process carried out by comparison of model predictions with independent field observations and experimental measurements. A model cannot be considered validated until sufficient testing has been performed to ensure an acceptable level of predictive accuracy. (Note that the acceptable level of accuracy is a matter of judgment and will vary depending on the specific problem or question to be addressed by the model).
Waste	Materials that have served a purpose and are no longer of use or are byproducts of a process
Waste arisings	Radioactive wastes generated by any stage in the nuclear fuel cycle.
Waste disposal	See: disposal.
Waste form	The physical and chemical form of the waste materials (e.g., liquid, in concrete, in glass, etc.) without its packaging.
Waste glass	The vitreous product that results from incorporating waste into a glass matrix.
Waste management	See: radioactive waste management.
Waste package	The waste form and any containers, shielding, packing, and other absorbent materials immediately surrounding an individual waste container.

Waste retention system	A system for storage or disposal of liquid and/or solid wastes generated by the uranium or thorium mining and milling process.
Water table	(i) The upper surface of the groundwater. (ii) The upper surface of a zone of groundwater saturation.
Vault	An above- or below-ground reinforced concrete structure containing an array of storage cavities, each of which could hold one or more SF unit or waste package. Shielding is provided by the exterior of the structure. Heat removal is principally by forced or natural movement of gases over the exterior of the cavities. Heat rejection to the atmosphere is either direct or via a secondary cooling system.
Verification	A mathematical model, or the corresponding computer code, is verified when it is shown that the code behaves as intended, i.e., that it is a proper mathematical representation of the conceptual model and that the equations are correctly encoded and solved.
Vermiculite	A group of micaceous clay minerals closely related to chlorite and montmorillonite and having the general formula $(Mg,Fe,Al)_3(Al,Si)_4 0_{10}(OH)_2.4H_2 0$. Because of its sorptive properties, vermiculite is often used in packaging small quantities of liquid waste.
Vitrification	Any process of converting materials into a glass or glass-like form.
Vitrified	Materials transformed into a glass or glass-like matrix/material.
Volume reduction	A treatment that decreases the physical volume of a waste. Volume reduction is used to facilitate subsequent handling, storage, transportation or disposal of the waste. Typical treatments are mechanical compaction, incineration, or evaporation. Volume reduction results in a corresponding increase in radionuclide concentration.
Volume reduction factor (VRF)	The ratio of the volumes of radioactive waste prior to and following treatment. In concentration processes the VRF is greater than one. In dilution systems, the VRF is less than one.
'Worst-case' scenario	The scenario for release and transport of radionuclides from a nuclear installation or facility (e.g., a waste storage or disposal site) to the biosphere that represents the most severe accident situation conceivable on the basis of pessimistic assumptions. Agreement on a 'worst-case' scenario may be difficult. Thus, the terminology '"conservative, but realistic scenarios" is frequently used to define a set of scenarios that can be used in sensitivity and uncertainty analyses for safety assessment purposes.
WP1	CROP Work Package 1.
WP2	CROP Work Package 2.
WP3	CROP Work Package 3.
WP4	CROP Work Package 4.
WPP	Waste package performance (suite of large-scale *in-situ* tests at WIPP).
Zeolite	A generic term for a group of hydrated alumino-silicates of Na, Ca, Ba, Sr, and K, characterized by their easy and reversible loss of water of hydration. Many are also characterized by a significant capacity for ion exchange.