Technical Report 07-01

Grimsel Test Site
Investigation Phase IV

Borehole Sealing

April 2008

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for the Disposal of
Radioactive Waste

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This report was prepared on behalf of Nagra. The viewpoints presented and conclusions reached are those of the author(s) and do not necessarily represent those of Nagra.

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Foreword

Concepts which envisage the storage of radioactive waste in geological formations are crucially dependent on a thorough knowledge of the host rock and neighbouring rock strata. Since 1984, NAGRA has been operating the Grimsel underground rock laboratory (Felslabor Grimsel – FLG), which complements NAGRA’s work on repositories. This laboratory, which provides a generic test rock environment, lies 450 m below the eastern flank of the Juchlistock. It is located in the granitic rock of the Aar-Massif, at a height of 1730 m and can be reached via a horizontal access tunnel.

The most important purposes of the Grimsel underground rock laboratory are:

• The accumulation of know-how in planning, execution and interpretation of underground experiments in various scientific and technical fields.

• Acquisition of practical experience in the development and use of those experimental methods, measurement procedures and equipment which could be used in the search for potential sites.

• Experimental investigation of processes crucial to the safety of a radioactive waste repository.

In 1984, as part of a German/Swiss collaboration, various experiments were initiated by NAGRA and its German partner, the Federal Institute for Geosciences and Natural Resources (Bundesanstalt für Geowissenschaft und Rohstoffe – BGR) together with the Research Centre for Environment and Health (Forschungszentrum für Umwelt und Gesundheit – GSF). Work performed by the German partner was sponsored by the Federal Ministry for Education, Science, Research and Technology (Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie – BMBF).

International collaboration in the FLG has been strengthened through the years by collaboration agreements with the following partner organisations: ANDRA (France), ENRESA (Spain), EU (European Union), PNC (Japan), SKB (Sweden) and US-DOE (United States).

Within the context of the Phase IV (1994 - 1996) research and development activities at the Grimsel Test Site (GTS), Nagra developed, in collaboration with the Agence nationale pour la gestion des déchets radioactifs (Andra), an investigation project for the sealing of boreholes drilled from underground.

The field work and analysis of the data was finalised in 1998 but due to other commitments of one of the authors the final reporting was postponed until 2006/2007.

The work was carried out in close co-operation with the following institutions and companies: Sandia National Laboratories (concept), University of Freiberg (literature study, fabrication of granular bentonite, laboratory tests on bentonite), CEA (characterisation of granular and pelletized bentonite), Deutsche Montan Technologie GmbH (pneumatic transport of granular bentonite), Mesy GmbH (design, manufacturing and testing of metal packers) and Solexperts AG (field equipment and testing of the seals at GTS).

The authors would like to thank the following scientists for their contributions to this work, which were crucial for the success: A. Cournut, R. E. Finley, H.R. Fisch, C. Gatabin, H. Gloth, Ch. Imbert, H. Karsch, A. Macek, M. Marteau, H.-J. Roski, F. Rummel, P. Sitz, H. Strauss and R. Wollenberg.

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\(^{3}\) Now: Japan Atomic Energy Agency, Japan (JAEA)
Vorwort


Das Felslabor Grimsel dient folgenden übergeordneten Zielsetzungen:

- Aufbau von Know-how in der Planung, Ausführung und Interpretation von Untertageversuchen in verschiedenen wissenschaftlichen und technischen Fachgebieten
- Erwerb praktischer Erfahrung in der Entwicklung und der Anwendung von Untersuchungsmethoden, Messverfahren und Messgeräten, die für die Erkundung von potentiellen Standorten in Frage kommen
- Experimentelle Untersuchungen von Prozessen, die für die Sicherheit eines Endlagers für radioactive Abfälle entscheidend sind.

Auf der Basis eines deutsch-schweizerischen Zusammenarbeitsvertrages begannen 1984 verschiedene Versuche der NAGRA und der deutschen Partner, der Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) und dem Forschungszentrum für Umwelt und Gesundheit (GSF). Die Arbeiten der deutschen Partner sind durch das Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie (BMBF) gefördert worden.

Die internationale Zusammenarbeit im FLG wurde im Verlauf der Jahre durch Zusammenarbeitsverträge mit folgenden Partnerorganisationen ANDRA (Frankreich), ENRESA (Spanien), EU (Europäischen Union), PNC (Japan), SKB (Schweden) und US-DOE (Vereinigte Staaten) ausgebaut.


Die dargestellten Arbeiten wurden in enger Zusammenarbeit mit den folgenden Institutionen / Firmen durchgeführt: Sandia National Laboratories (Konzept), Universität Freiberg (Literaturstudie, Herstellung des granularen Bentonits, Laboruntersuchungen an Bentonit), CEA (Charakterisierung von granularem Bentonit and Bentonitpellets), Deutsche Montan Technologie GmbH (pneumatischer Transport von granularem Bentonit), Mesy GmbH (Design, Herstellung and Testen der Metallpacker) und Solexperts AG (Testequipment und Testen der Versiegelung im FLG).


4 heute: Gesellschaft für Anlagen- und Reaktorsicherheit (GRS)
5 heute: Bundesministerium für Wirtschaft (BMWi)
6 heute: Japan Atomic Energy Agency, Japan (JAEA)
Préface

Lors de l’élaboration de concepts concernant le stockage final des déchets radioactifs dans des formations géologiques, il est nécessaire de bien connaître la roche d'accueil et les formations encaissantes. En complément de ses recherches sur les sites de stockages potentiels, la Nagra exploite depuis 1984 le laboratoire souterrain du Grimsel (LSG), qui permet de poursuivre des expériences indépendamment du site qui sera sélectionné ultérieurement. Aménagé à 450 mètres au-dessous du flanc est du Juchlistock, dans les roches granitiques du massif de l'Aar, à une altitude de 1730 m, il est accessible par une galerie horizontale.

Le laboratoire souterrain du Grimsel poursuit les objectifs suivants:

- Elaboration d'un savoir-faire en matière de planification, de réalisation et d'interprétation d'essais souterrains réalisés dans différents domaines scientifiques et techniques.
- Acquisition d'une expérience pratique dans le développement et l'utilisation de méthodes d'investigation, de procédures et d'instruments de mesure qui permettront d’étudier des sites potentiels.
- Analyse expérimentale de processus déterminants pour la sûreté d'un dépôt final pour déchets radioactifs.

Sur la base d'un accord de coopération germano-suisse, la Nagra et ses partenaires allemands, l'Office fédéral BGR, Bundesanstalt für Geowissenschaften und Rohstoffe, et le Centre de recherche GSF, Forschungszentrum für Umwelt und Gesundheit, ont lancé différents essais en 1984. Les travaux des partenaires allemands étaient soutenus par le Ministère allemand de l'éducation, de la science, de la recherche et de la technologie (BMBF).

Au cours des années suivantes, d'autres accords de coopération ont pu être conclus avec les organisations partenaires suivantes: ANDRA (France), ENRESA (Espagne), UE (Union Européenne), PNC (Japon), SKB (Suède) et US-DOE (Etats-Unis).

Dans le cadre de son programme de recherche et de développement au LSG, phase IV (1994 – 1996), la Nagra a développé, en partenariat avec l’ANDRA (Agence nationale pour la gestion des déchets radioactifs), un programme de recherche sur le scellement de forages effectués en galerie.


Les travaux présentés ont été réalisés en étroite collaboration avec les organismes et entreprises suivants: Sandia National Laboratories (concept), Université de Freiberg (étude bibliographique, fabrication de la bentonite granulaire, essais de laboratoire sur la bentonite), CEA (caractérisation de la bentonite granulaire et des billes de bentonite), Deutsche Montan Technologie GmbH (injection pneumatique de bentonite granulaire), Mesy GmbH (conception, fabrication et test des obturateurs en métal) et Solexperts AG (équipement de test et test de scellement au LSG).


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7 aujourd’hui: Gesellschaft für Anlagen- und Reaktorsicherheit (GRS)
8 aujourd’hui: Bundesministerium für Wirtschaft (BMWi)
9 aujourd’hui: Japan Atomic Energy Agency, Japan (JAEA)
Location of Nagra's underground test facility at the Grimsel Pass in the Central Alps (Bernese Alps) of Switzerland.
Grimsel area (view to the west)

1 Grimsel Test Site       2 Lake Raeterichsboden  3 Lake Grimsel       4 Juchlistock

Grimsel Test Site (GTS)
Abstract

Within the context of the Phase IV (1994 - 1996) research and development activities at the Grimsel Test Site (GTS), Nagra developed, in collaboration with the Agence nationale pour la gestion des déchets radioactifs (Andra), an investigation project for the sealing of boreholes drilled from underground. The project had the following goals:

- Sealing of boreholes drilled from underground facilities with a length of up to 500 m
- Sealing of boreholes with mainly irregular shape (e.g. breakouts of borehole wall)
- Ensuring a hydraulic conductivity of $10^{-11} - 10^{-12}$ m/s for the seal
- Ensuring reliable quality control in routine production

Nagra’s new concept developed in this project was to use highly compacted bentonite pellets or granular bentonite while Andra evaluated the use of a cylindrical block of bentonite. This report deals with Nagra’s concepts only. The two techniques tested by Nagra were:

1. Pneumatic injection of granular bentonite into a borehole using a grain size distribution of 4-10 mm
2. Emplacement using a modified core barrel (MACMET tool) for transport and compaction of bentonite pellets.

Following a detailed literature study and the development of appropriate concepts, the necessary tools were developed and successively tested in the laboratory.

An appropriate test field was established and characterized at GTS where both techniques were tested in situ to estimate their performance under realistic field conditions. The swelling pressures were monitored for 4 months after seal emplacement until an almost constant value was attained. Finally, the hydraulic and mechanical performances of the seals were tested. It was found that the conductivities measured across the seal were at least equivalent to the matrix properties of the surrounding rock ($3-6 \cdot 10^{-12}$ m/s). The hydraulic testing also showed no linear preferential flow along the seals.
Zusammenfassung

Im Rahmen der Forschungs- und Entwicklungsprogramme der Phase IV (1994 -1996) im Felslabor Grimsel (FLG) entwickelte die Nagra, zusammen mit ihrem Partner Andra (Agence nationale pour la gestion des déchets radioactifs), ein Untersuchungsprogramm zur Versiegelung von untertägigen Bohrungen. Das Projekt hatte die folgenden Ziele:

- Versiegelung von untertägigen Bohrung mit einer Länge von bis zu 500 m
- Versiegelung von Bohrungen mit nicht-zylindrischem Querschnitt (z.B. Bohrungen mit signifikanten Ausbrüchen der Bohrlochwand)
- Sicherstellung einer effektiven hydraulischen Durchlässigkeit von höchstens $10^{-11} – 10^{-12}$ m/s
- Sicherstellung einer zuverlässigen Qualitätskontrolle bei Routinearbeiten

Nagra's neues Konzept, das in diesem Projekt entwickelt und getestet wurde, sieht die Nutzung von hochkompaktierten Bentonitpellenets oder granularem Bentonit vor, während Andra den Einsatz von zylindrischen Bentonitblöcken untersuchte. Dieser Bericht konzentriert sich auf die durchgeführten Arbeiten für das Nagra Konzept. Es wurden zwei Techniken getestet:

1. Pneumatische Injektion von granularem Bentonit mit Partikelgrössen von 4-10 mm in ein Bohrloch.
2. Einbringung und Transport von Bentonipellenets mit einem modifizierten Kernrohr (MACMET Tool)


Nach der Erstellung und Charakterisierung eines adäquaten Testfelds im FLG wurden dann beide Techniken unter realistischen Bedingungen eingesetzt und ihre Vor- und Nachteile untersucht. Nach dem Einbau der Versiegelungsstrecken wurde der Quelldruck über ca. 4 Monate beobachtet, bis er annähernd einen konstanten Wert erreicht hatte. Anschliessend wurden die hydraulischen und mechanischen Eigenschaften der Versiegelung untersucht. Es zeigte sich, dass die Durchlässigkeiten kleiner oder gleich derjenigen des intakten, ungekläfteten Granits (Matrixdurchlässigkeit) war ($3-6 \cdot 10^{-12}$ m/s). Die hydraulischen Untersuchungen ergaben auch keinen Hinweis auf eine erhöhte Durchlässigkeit entlang der Versiegelungsstrecke.
Résumé

Dans le cadre de son programme de recherche et de développement au laboratoire souterrain du Grimsel (LSG), phase IV (1994 – 1996), la Nagra a développé, en partenariat avec l’Andra (Agence nationale pour la gestion des déchets radioactifs), un programme de recherche sur le scellement de forages effectués en galerie. Le projet visait les objectifs suivants:

- scellement de forages en galerie d’une longueur jusqu’à 500 m,
- scellement de forages à section non cylindrique (p. ex. forages dont la paroi est considérablement endommagée),
- garantie d’une conductivité hydraulique effective inférieure à 10^{-11} – 10^{-12} m/s,
- garantie d’un contrôle de qualité fiable pour les travaux de routine.

Le nouveau concept développé et testé par la Nagra dans ce projet prévoyait l’utilisation de bentonite granulaire ou de billes de bentonite hautement compactées, l’Andra examinant quant à elle l’utilisation de blocs cylindriques de bentonite. Le présent rapport concerne les travaux menés par la Nagra. Deux techniques ont été testées:

1. Injection pneumatique de bentonite granulaire dans un forage, avec une taille des granulés de 4 – 10 mm.
2. Apport et mise en place de billes de bentonite à l’aide d’un carottier modifié (outil MACMET).

A la suite d’une étude bibliographique détaillée, des concepts ont d’abord été développés, ainsi que les outils nécessaires à leur réalisation. L’équipement a été testé en laboratoire avant d’être utilisé sur le terrain.

Après l’installation et la caractérisation d’un site de test adéquat au LSG, les deux techniques ont été mises en œuvre dans des conditions réalistes, et leurs avantages et inconvénients ont été examinés. Après la mise en place de tronçons de scellement, la pression de gonflement a été suivie durant 4 mois environ, jusqu’à ce qu’elle atteigne une valeur à peu près constante. Ensuite, les propriétés hydrauliques et mécaniques du scellement ont été examinées. Les perméabilités se sont avérées inférieures ou égales à celles du granite intact et non fissuré (perméabilité de matrice de 3 à 6·10^{-12} m/s). En outre, les essais hydrauliques n’ont révélé aucun indice de perméabilité accrue le long du tronçon de scellement.
Contents

Abstract ............................................................................................................................................. I
Zusammenfassung .............................................................................................................................. II
Résumé ............................................................................................................................................... III
Contents ............................................................................................................................................... IV
List of Tables ..................................................................................................................................... VI
List of Figures ................................................................................................................................... VII
1 Introduction .................................................................................................................................... 1
  1.1 Objectives ............................................................................................................................... 2
  1.2 Planning ....................................................................................................................................... 2
2 Concepts ......................................................................................................................................... 5
  2.1 Original Concept ..................................................................................................................... 5
  2.2 Injection Tool .......................................................................................................................... 5
  2.3 Pneumatic Injection ............................................................................................................... 6
3 Sealing Material ............................................................................................................................. 7
  3.1 Selection of Appropriate Sealing Material ............................................................................. 7
  3.2 Emplacement Density of Pellets / Granular Bentonite ......................................................... 8
  3.3 Swelling Tests on Pellets and Granular Bentonite in Pressure Cells ................................. 12
    3.3.1 Wyoming Bentonite (MX80) ......................................................................................... 12
    3.3.2 Compactonit .................................................................................................................. 17
  3.4 Swelling Tests under Simulated Borehole Conditions ....................................................... 18
4 Equipment Development ............................................................................................................. 23
  4.1 Mechanical confinements ....................................................................................................... 23
    4.1.1 Test of Aluminum Packer at GTS ................................................................................ 23
    4.1.2 Development of Copper and Stainless Steel Packers ................................................ 27
  4.2 Mechanical Injection Tool .................................................................................................... 31
    4.2.1 General Idea .................................................................................................................. 31
    4.2.2 Systematic Test in the Workshop .................................................................................. 32
  4.3 Pneumatic Injection Device ................................................................................................. 32
    4.3.1 Laboratory Test Set-up ............................................................................................... 32
    4.3.2 Laboratory Test Results ............................................................................................... 33
5 Preparation of the Test Field ..................................................................................................... 39
  5.1 Site Selection .......................................................................................................................... 39
  5.2 Drilling ...................................................................................................................................... 39
  5.3 Geological Core Mapping and Geophysical Logging ......................................................... 39
  5.4 Hydraulic Characterization of the Site ............................................................................... 41
    5.4.1 Step 1 Hydraulic Testing ............................................................................................. 41
    5.4.2 Step 2 Hydraulic Testing ............................................................................................. 44
    5.4.3 Example Test Sequence and Analysis ......................................................................... 46
6 Emplacement of the Bentonite Seals ................................................................. 49
6.1 Instrumentation .............................................................................................. 49
6.2 Emplacement of the MX-80 Bentonite Seal in BOS 95.001 using Pneumatic Injection ................................................................................................. 49
6.3 Emplacement of Compacetonit Seal in BOS 95.002 using the MacMet tool .... 52
7 Performance of Seals ...................................................................................... 55
7.1 Long-term Monitoring of Hydraulic- and Swelling-Pressure ......................... 55
7.2 Active Hydraulic Testing .................................................................................. 58
7.2.1 BOS 95.001 ................................................................................................. 58
7.2.2 BOS 95.002 ................................................................................................. 60
7.2.3 Summary of Hydraulic Testing Results ......................................................... 62
7.3 Mechanical Stability of the Bentonite Seals .................................................... 62
7.3.1 Instrumentation for Mechanical Stability Testing ............................................ 63
7.3.2 Hydraulic Loading with Packers Inflated ....................................................... 65
7.3.3 Hydraulic Loading with Packers Deflated ..................................................... 67
7.3.4 Mechanical Loading with Packers Deflated .................................................. 70
8 Conclusion ....................................................................................................... 71
References ........................................................................................................ 73
List of Tables

Tab. 3-1: Advantages and disadvantages of sealing materials .......................................................... 7
Tab. 3-2: Configurations for simulated boreholes ............................................................................. 9
Tab. 3-3: Results of the dry-density emplacement tests .................................................................. 11
Tab. 3-4: Physical and mineralogical characteristics of MX-80 granular bentonite ....................... 12
Tab. 3-5: Specifications for the oedometer tests with MX-80 .......................................................... 14
Tab. 3-6: Physical and mineralogical characteristics of Compactonit® 8/200 pellets according to the CEA Laboratory ................................................................. 17
Tab. 3-7: Specifications and results for the oedometer tests with Compactonit® pellets ......... 18
Tab. 3-8: Specifications and results for swelling tests conducted in a simulated sandstone borehole. .......................................................... 20
Tab. 4-1: Material properties of copper and stainless steel used for construction of metal packers. .................................................................................................................. 28
Tab. 4-2: Results of metal packer expansion tests conducted in a test pipe ................................. 29
Tab. 4-3: Technical data for laboratory tests of the pneumatic injection system ......................... 33
Tab. 5-1: Technical data of boreholes BOS 95.001 - 95.003 ......................................................... 39
Tab. 5-2: Step 1 borehole instrumentation details ......................................................................... 41
Tab. 5-3: Summary of Step 1 test results ....................................................................................... 43
Tab. 5-4: Step 2 borehole instrumentation details ........................................................................... 45
Tab. 5-5: Summary of Step 2 test results ....................................................................................... 46
Tab. 7-1: Swelling pressures of the bentonite seals at the end of the monitoring period .......... 57
Tab. 7-2: Input parameters for GTFM simulation of BOS 95.001-i2: RI/RIS ................................. 58
Tab. 7-3: Input parameters for GTFM simulation of BOS 95.002-i2: RI3/RIS3 ............................ 60
Tab. 7-4: BOS 95.001: summary of hydraulic conductivity values estimated during the BOS experiment ................................................................................................................. 62
Tab. 7-5: BOS 95.002: summary of hydraulic conductivity values estimated during the BOS experiment ................................................................................................................. 62
Tab. 7-6: Testing configurations for mechanical stability testing .................................................. 63
List of Figures

Fig. 3-1: Results of dry-density emplacement bench tests (explanation of Test No. see Tab. 3.3) ................................................................. 10
Fig. 3-2: Swelling pressure observed during Tests No. 1 and 2 in oedometer tests .............. 13
Fig. 3-3: Hydraulic conductivity values during Test No. 2 in an oedometer test. The dashed line shows data from bentonite blocks compacted from powder (reference material) ......................................................................................... 15
Fig. 3-4: Test configuration for oedometer Test No. 3 ...................................................... 16
Fig. 3-5: Photo of the partly excavated bentonite plug in a sandstone block (test 2). The lighter colors on the plug indicate the contact points of the larger granules with the borehole wall ................................................................. 19
Fig. 3-6: Photo of the bentonite plug (test 2) after recovery. The homogeneity and the plasticity of the bentonite plug can be seen when the plug was cut with a thin wire. ........................................................................................................ 19
Fig. 3-7: Swelling pressure during Test Nos. 1 and 2 within a simulated borehole (smoothed data; data of Test No.2 are not completely shown) ................................................................................................. 20
Fig. 4-1: Map showing location of the borehole used for testing the aluminum packer (BOS 95.004) and the field test (BOS) ................................................................. 24
Fig. 4-2: Schematic drawing of the aluminum packer .......................................................... 25
Fig. 4-3: Plot of Packer Inflation Pressure -vs- Time of the aluminum packer at GTS ...... 25
Fig. 4-4: Plot of Pressure -vs- Time for the packer and interval pressure during the hydraulic push-out test conducted on the aluminum packer ................................................................. 26
Fig. 4-5: Plot of Pressure -vs- Time during the mechanical push-out test conducted on the aluminum packer ................................................................. 27
Fig. 4-6: Fluid Pressure in the rubber packer elements – vs – Circumferential Deformation measured on the outer surface of the aluminum and steel pipes ...... 29
Fig. 4-7: Photos of the metal packers. a) before inflation and b) after inflation in the aluminum pipe (packer and pipe cut out to demonstrate contact between these elements) ................................................................. 30
Fig. 4-8: Schematic representation of the emplacement technique using a modified core barrel (MACMET tool) ................................................................. 31
Fig. 4-9: Laboratory set-up for testing of the pneumatic injection system ....................... 33
Fig. 4-10: Results of tests conducted in a 100 m simulated borehole .................................. 34
Fig. 4-11: Plot showing grain size distribution before and after transport over 100 m distance ................................................................................................. 34
Fig. 4-12: Plot showing grain size distribution before and after transport over 500 m distance ................................................................................................. 35
Fig. 4-13: Results from the laboratory tests on pneumatic emplacement of granular bentonite ................................................................................................. 36
Fig. 5-1: Borehole configuration for Step 1 hydraulic characterization .............................. 42
Fig. 5-2: Composite pressure responses during Step 1 hydraulic characterization

Fig. 5-3: Borehole configuration for Step 2 hydraulic characterization (hydraulic characterization with temporary borehole seals - packers of similar size as planned seals)

Fig. 5-4: Composite pressure responses during Step 2 hydraulic characterization

Fig. 5-5: BOS 95.001-i2 (Step 2): constant rate injection test overview

Fig. 6-1: Borehole configuration for the borehole sealing demonstration experiment

Fig. 6-2: Configuration of the pneumatic injection system used to install the MX-80 bentonite seal in BOS 95.001

Fig. 6-3: Pressure plot recorded at the lower end of the seal section in borehole BOS 95-002 during the emplacement of the Compactonit® pellets (details see text)

Fig. 7-1: BOS 95.001 (Bos1; MX-80 seal): pressure cell and interval pressures

Fig. 7-2: BOS 95.002 (Bos2; Compactonit® seal): pressure cell and interval pressures

Fig. 7-3: Comparison of pressures in BOS 95.001 (Bos1) and BOS 95.002 (Bos2) to testing activities in conducted in BOUS 85-003 (BOUS3)

Fig. 7-4: BOS 95.001 (Bos1)1&2-Step 3: swelling pressures of the bentonite seals calculated from total and interval pressure

Fig. 7-5: BOS 95.001-Step 4: GTFM simulation of RI1 and RIS1

Fig. 7-6: BOS 95.002-Step 4: GTFM simulation of RI3 and RIS3

Fig. 7-7: Instrumentation of BOS 95-001 during stability tests of scenario 2 (details see text)

Fig. 7-8: Instrumentation of BOS 95-001 during stability tests of scenario 3 (details see text)

Fig. 7-9: BOS 95.001: pressure response in the injection interval (i2) and observation interval (i3) during HPO1 (hydraulic loading with all packers inflated)

Fig. 7-10: BOS 95.001: pressure response in the observation interval (i3) during HPO1 (hydraulic loading with all packers inflated)

Fig. 7-11: BOS 95.002: pressure response in the injection interval (i2) during HPO1 (hydraulic loading with all packers inflated)

Fig. 7-12: BOS 95.002: pressure response in the observation interval (i3) during HPO1 (hydraulic loading with all packers inflated)

Fig. 7-13: BOS 95.001 5: multi-plot showing a) displacement and velocity of the deflated packer system, and b) the hydraulic- or mechanical-loading pressure

Fig. 7-14: BOS 95.002: multi-plot showing a) displacement and velocity of the deflated packer system b) the hydraulic- or mechanical-loading pressure

Fig. 7-15: BOS 95.001 5: close-up plot of the early HPO2 phase showing displacement of the deflated packer system and the hydraulic- loading pressure
1 Introduction

The Swiss National Cooperative for the Disposal of Radioactive Waste (Nagra) is conducting research projects and site characterization work for underground repositories for low- / intermediate-level and high-level waste in Switzerland. For the program on low- and intermediate-level waste the site investigations concentrated at the Wellenberg site in Central Switzerland before the site was abandoned after a negative referendum on the project. The first two phases of investigations at Wellenberg from the surface were completed in 1996 and a final geo-scientific synthesis of the field measurements has been published (Nagra 1997). In parallel, an exploration concept for additional characterization work from underground had been developed. This concept was based on investigations from a 3 km long exploration tunnel drilled into the host rock and includes a large number of investigation boreholes. Many of these boreholes drilled from underground were planned to dip sub-horizontally. Although the borehole locations were selected in such a way that they would not disturb the integrity of the site by creating new preferential pathways for water flow in the direct repository area, there was a chance that several boreholes could be more critical, e.g. in cases where boreholes would potentially shortcut existing fracture zones.

Therefore, a reliable borehole sealing technique was needed to ensure that such boreholes would not act in the future as a preferential flow path during the operational phase or the post closure phase of a repository. Given the proposed repository host rock at the Wellenberg site (marl) and the exploration concept mentioned above, a sealing concept for this special purpose was designed in such a way that boreholes can be sealed even if the borehole:

- contains breakouts
- is sub-horizontal
- has a length of approximately 500 m
- has a diameter of between 76 and 146 mm

Additional requirements for the performance of the seal were related to the expected geotechnical and hydraulic characteristics of the Palfris Formation (marl formation at Wellenberg) at the planned tunnel location. As it was observed that even overpressures less than 5 MPa (Nagra, 1997) could cause hydraulic fracturing in planes of weakness, the swelling pressure of the sealing material had to be limited. On the other hand it was required that the seals should reach a hydraulic conductivity in the same order of magnitude as the host rock \( K = 10^{-11} - 10^{-12} \text{ m/s} \).

The research project designed to evaluate and test borehole sealing concepts was started in 1994 and was based on previous studies conducted by Nagra (Brenner, 1988; Brenner & Jedelhauser, 1989). In particular, due to the boundary conditions mentioned above, it was not possible to use the existing methods for borehole sealing (e.g. Pusch et al., 1987; Fuenkajorn & Daemen, 1996). Therefore, the project was structured in such a way that it was possible to use experience with existing techniques to develop them further and to introduce new ideas and concepts. Special emphasis was placed on development of emplacement techniques but, at the same time, assessment of material behavior remained an equally important objective of the project.

Following a literature study (Sitz et al. 1994), a first concept was formulated (Finley, 1994). This concept required laboratory testing of the sealing material chosen and development and testing of emplacement tools. The emplacement tool foreseen for the test was basically a special container to transport the bentonite into the borehole equipped with a compaction head for in-
situ compaction. Due to very high frictional forces during the ejection of the bentonite pellets, parts of the tests failed and it became necessary to refine the old, and even to develop a second concept for borehole sealing (pneumatic emplacement). Both concepts were then tested in the laboratory and finally in situ at the Grimsel Test Site (GTS), Nagra’s underground laboratory in crystalline rock in the Swiss Alps.

1.1 Objectives

The objective of the project was to develop a technique to seal abandoned exploration boreholes drilled underground from tunnels and rooms in an underground radioactive waste repository. The sealed boreholes had to perform in such a way that they would not act as preferential flow paths and thus reduce the safety of the repository.

The research and development had to focus on: (a) the development of suitable sealing materials for a multi-component seal, (b) the development of a sealing technology and (c) the field demonstration of the applicability of the method.

1.2 Planning

The planning of the project was carried out in close cooperation with R. E. Finley (SNL) and is summarized in a technical note (Finley, 1994).

Borehole and facility sealing are integral parts of all the international radioactive waste disposal programs. Borehole sealing is also performed for the abandonment of oil and gas wells. The oil and gas industry typically uses borehole cements where the details of their composition (e.g. expanding cements) and plug geometry are specified and regulated by the responsible authorities. In addition, heavy barite mud and or mechanical plugs may be used in accordance with regulations and company policies.

There are at least two specific issues regarding borehole sealing for the nuclear waste programs that need to be solved:

- Selection and characterization of suitable materials for the different components
- Development of emplacement method

Multiple component seals are the preferred concept of most radioactive waste disposal programs, where at least three different materials are under consideration: (i) dense bentonite or bentonite / sand mixtures, (ii) cements and (iii) reconsolidated crushed rock. In the multi-component sealing approach one component serves as mechanical confinement to another weaker component, whose primary purpose is to restrict fluid flow. The use of multiple components enhances both the mechanical stability and the hydrologic performance of the seal system. Multiple components are also used in cases where one component is not expected to exhibit the required fluid flow performance for the design life of the seal system.

In addition to material selection and testing of the individual seal components in the laboratory, a key point to be investigated is the emplacement technique of the seals especially the evaluation of the flexibility of the proposed methods to cope with boreholes of different diameters, lengths and orientations. Typical emplacement techniques used to emplace cements in vertical boreholes include the dump bailer, tremie pipe and squeeze cementing. Techniques for emplacement of clayey materials, such as bentonite, include pre-compaction in perforated emplacement pipes (e.g. Pusch et al. 1987), loose emplacement and in situ compaction.
The following investigation steps were planned to achieve the objectives of the project:

1. Literature study
2. Evaluation of detailed concept
   - Potential sealing and abutment materials
     (availability, physical and hydrological properties)
   - Feasibility of production of sealing materials
   - Emplacement strategy of sealing material
3. Production of adequate bentonite-based sealing material
   - Density of bentonite pellets / granules
   - Evaluation of emplacement (bulk) density
4. Laboratory tests on sealing material
   - Mineralogical composition
   - Swelling capacity
   - Hydraulic parameters
5. Evaluation of mechanical confinement
   - Frictional particulate material (sand, gravel)
   - Metal packer system (copper, stainless steel)
6. Emplacement tests of granular bentonite
   - In-situ compaction
   - Pneumatic emplacement
7. In-situ emplacement test
   - Site characterization
   - In-situ compaction
   - Pneumatic emplacement
8. Hydraulic and mechanical testing of the in-situ test system

This report documents the developed basic concepts (chapter 2) followed by the selection and testing of appropriate sealing materials (chapter 3). The development and testing of different metal packers and individual components of the emplacement equipment is described in chapter 4. The remaining part of the report is dedicated to the on-site testing of the sealing technology at GTS and includes the site characterization (chapter 5), the emplacement procedures of the borehole seals (chapter 6) and the results of the hydraulic and mechanical performance tests of the final seal (chapter 7).
2 Concepts

In accordance with Nagra’s general borehole sealing concept formulated by Brenner & Jedelhauser (1989), the sealing system of a borehole consists of 3 elements: the sealing element in the center and two confinements that enclose the sealing element on both sides. The sealing element is responsible for limiting the water flow through the borehole, while the confinements lock up the sealing material to guarantee an optimum build-up of the swelling pressure, to protect the seal against erosion and to prevent the seal to being displaced in the borehole due to high hydraulic gradients in the operational (short-term) phase of the repository.

The design of the confinements is influenced by the emplacement technique, the geometric boundary conditions (dip, diameter etc.) and the expected water flow and pressure. The material used for these plugs can be cement, gravel or even metal. Whereas cement plugs can be the standard for vertical and downward dipping boreholes, they show problems for sub-horizontal or upward directed boreholes. Special metal packers (see below) were developed for these more problematic cases.

The material for the sealing element which has to act as a barrier for water flow on the short and long term was chosen according to laboratory (Brenner & Jedelhauser, 1989) and field tests (Pusch et al., 1987) to guarantee longevity and adequate performance. It was decided to use two different compacted bentonite pellets (MX-80 and Compactonit®).

The positioning of the seal is based on the key zone concept which is a multi-component concept: the sealing element is placed in intervals of the borehole with intact rock (key zones) while the intervals between key zones are backfilled with cement. Consequently, the sealing material has to attain hydraulic properties similar to those of the intact rock.

2.1 Original Concept

All concepts, the original one at the start of the project and the finally realized ones, foresee the use of granular bentonite to effectively seal the abandoned borehole. The original concept, based on ideas developed by Finley (1994), envisaged the development of injection tool which consisted of a bailer for the granular bentonite and a built-in compaction head. The tool was designed to be mounted on a drill string or tubing and placed close to the end of the seal section. The planned operational mode included the extrusion of the granular bentonite with a piston through an opening of the compaction head. The subsequent in-situ compaction of the ejected granular material was to be performed by a combined pushing / rotation operation with the compaction head via the drill string.

The first test of the original concept to eject material from a bailer under the given conditions clearly showed its limitations. Because of the assumption of a nearly horizontal borehole it was impossible to empty the bailer by gravity alone and the necessary force to eject the material with a piston proved to be too high because of the friction of the sealing material on the bailer wall but even more because of the reduced diameter of the opening in the compaction head and the associated normal forces.

2.2 Injection Tool

Keeping these problems in mind, a modification of the concept was made by Nagra’s former drilling engineer A. Macek. The new injection tool kept the principal idea of the original
concept of ejection and compaction. The basic tool is described in chapter 4.2.1 and consists mainly of a modified core barrel. Instead of taking the rock core during drilling, the core barrel was to be filled with the granular bentonite. The drill string is placed in the borehole with its end close to the end of the sealing section. The modified and filled core barrel is then hydraulically pumped into the drill string until it arrived at the final position and locked itself. By increasing the hydraulic pressure a piston in the core barrel is activated and the granular bentonite material extruded. The bentonite is then mechanically compacted by pushing the drill string with the locked piston against the granular material. Finally, the wireline core catcher is pumped into the drill string and the core barrel will be retrieved. Afterwards the procedure is repeated until the sealing section is completely filled.

The method proved to work with some bentonite products but failed with highly compacted MX-80 bentonite, Nagra’s reference sealing material because of the friction during ejection. In addition, the method was extremely time-consuming for longer seal sections.

2.3 Pneumatic Injection

The final concept was completely different to the original idea of bringing the sealing material via a material container to the seal section and using an in-situ compaction technique to receive the proposed material density. The basic idea of this method is to inject the granular bentonite pneumatically into the seal section.

This general idea which had already been evaluated at the beginning of the project had initially been dropped because of two reasons: (a) after initial laboratory tests it seemed to be impossible to achieve the necessary bulk densities of the bentonite without compaction and (b) the injection into a water-filled borehole was not possible.

Some basic changes of the initial ideas and results from additional investigations in a workshop showed that the principle was after all still feasible. The densities became higher as expected due to the blowing procedure itself. The friction of the granules on the wall of the pipes during transport produced rounded granules on one hand and additional fines on the other hand which resulted for long transport distances (as necessary for a borehole of several hundred meters length) in densities even higher than necessary. The second problem was solved by using a tubing with an external casing packer (ECP) to guard the seal zone. The ECP has to be positioned at the upper end of the seal section and inflated. Afterwards the blow pipe is installed and used to eject the drilling fluid by air lift technique. After this operation the seal section is dry and the granular bentonite can be emplaced pneumatically using a standard shotcrete machine.
3 Sealing Material

This chapter focuses on the selection and laboratory testing of core sealing material for multi-component borehole seals. Substantial research has been conducted regarding the properties of various sealing materials. Existing literature has been summarized in Brenner (1988), Brenner & Jedelhauser (1989), and Sitz et al. (1994). These documents provide the basis for developing a borehole sealing concept, and identify open questions that need to be addressed.

3.1 Selection of Appropriate Sealing Material

Selection of an appropriate sealing material for the core of multi-component seals is dependent on factors such as chemical and physical characteristics of the host rock and formation water, the required longevity of the seal, and the geometry of the boreholes. Possible sealing materials include crushed marl or claystone, cement, bentonite, bentonite/sand mixtures, and barite. The advantages and disadvantages of the various materials are summarized in Table 3-1.

Tab. 3-1: Advantages and disadvantages of sealing materials.

<table>
<thead>
<tr>
<th>Sealing Material</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barite</td>
<td>- Chemically inert&lt;br&gt;- Density increases and hydraulic conductivity decreases with time (sedimentation and self-compaction)</td>
<td>- Can only be used in vertical and inclined (up to approx. 50° from vertical) boreholes&lt;br&gt;- Minimum attainable K-value is initially ~ 10^-9 to 10^-10 m/s</td>
</tr>
<tr>
<td>Bentonite</td>
<td>- K-values in the range 10^-11 to 10^-13 m/s are attainable&lt;br&gt;- Variety of chemical and physical forms are readily available&lt;br&gt;- Long-term stability in adequate environment&lt;br&gt;- High plasticity</td>
<td>- Low strength&lt;br&gt;- Relatively high cost&lt;br&gt;- Erosion possible&lt;br&gt;- Chemical long-term stability depends on environmental conditions</td>
</tr>
<tr>
<td>10%Bentonite/90%Sand Mix (by weight)</td>
<td>- High mechanical strength&lt;br&gt;- Low cost</td>
<td>- Minimum attainable K-value is ~ 10^-9 m/s&lt;br&gt;- Segregation during emplacement possible</td>
</tr>
<tr>
<td>20%Bentonite/80%Sand Mix (by weight)</td>
<td>- K-values in the range 10^-10 to 10^-11 m/s are attainable&lt;br&gt;- Low cost</td>
<td>- Lower Strength (sand/sand grain contact is lost)&lt;br&gt;- Emplacement over long distances may be difficult due to material segregation</td>
</tr>
<tr>
<td>Cement</td>
<td>- Readily available&lt;br&gt;- Low cost&lt;br&gt;- High initial strength</td>
<td>- Difficult to ensure effective emplace in horizontal boreholes&lt;br&gt;- Poor long-term stability&lt;br&gt;- Shrinkage (and associated cracks) possible&lt;br&gt;- Low plasticity</td>
</tr>
<tr>
<td>Crushed marl or claystone</td>
<td>- Readily available&lt;br&gt;- Low cost</td>
<td>- Crushing promotes pyrite oxidation (chemical instability)&lt;br&gt;- Minimum attainable K-value is ~ 10^-10 to 10^-12 m/s</td>
</tr>
</tbody>
</table>
Brenner (1988) concluded that bentonite is the most suitable material for cores of multi-component seals in boreholes because of its swelling properties and attainable low permeabilities. The main disadvantage of bentonite, being its relatively low strength, is minimized by the placement of confinements on either side of the bentonite. The high cost of bentonite is a minor disadvantage considering the relatively small volumes required for sealing boreholes. Therefore, BOS Project focuses on using bentonite as the core sealing material.

The potential swelling pressure and permeability of a given bentonite seal is dependent on the density at which the bentonite can be emplaced. Higher emplacement density results in higher swelling pressure and lower permeability. A bulk dry density range of 1.3 to 1.5 Mg/m$^3$ provides the hydraulic-conductivity range required for the BOS Project ($10^{-12}$ to $10^{-13}$ m/s).

Bentonite is available in a variety of physical forms including powder, granules and pellets. Powdered and granular bentonite can be pressed into other forms, such as pellets and cylindrical plugs that can be emplaced in boreholes. The dry density attainable through pressing decreases with the size of the pressed object. The cylindrical plugs can be produced with a dry density of 1.8 to 1.9 Mg/m$^3$, compared to 2.0 to 2.2 Mg/m$^3$ for pellets.

Cylindrical plugs must expand enough to fill the annular space between the plug and the borehole wall. This may result in an effective bulk dry density less than that required for effective borehole sealing, especially for borehole sections containing severe breakouts. Therefore, cylindrical plugs are not considered for the BOS Project. Bentonite in pellet or granular form is the main material considered for use in the Project.

Bentonite varies in chemical form, mainly with respect to Sodium and Calcium content. Brenner (1988) summarized existing data on the performance of Na- and Ca-bentonite in the forms of MX-80 (Wyoming bentonite) and Monitgel, respectively. Both products are available in granular form. The properties of the two products are quite comparable. MX-80 delivers a slightly better swelling pressure at low emplacement densities. However, the most important factor in selecting a particular bentonite is compatibility with site-specific groundwater chemistry. To minimize alteration of the montmorillonite to other, less swelling clays such as illite, Ca-bentonite should be used in Ca-dominated groundwater and Na-bentonite in Na-dominated groundwater.

A third commercially-available form of bentonite, Compactonit®, was also evaluated for use in the BOS Experiment. Compactonit® is a pelletized bentonite used mainly to seal water wells and engineered to retard its initial swelling capacity. The delayed swelling capacity allows emplacement in a water slurry and in-situ compaction of the bentonite. Brenner (1988) discounted Compactonit® as a viable sealing material because of relatively low emplacement densities. Laboratory work performed in the preparation of the borehole sealing, however, has shown that higher densities can be achieved through insitu compaction.

### 3.2 Emplacement Density of Pellets / Granular Bentonite

The effectiveness of a borehole seal is largely dependent upon the bulk dry density of the emplaced sealing material. Factors affecting the bulk dry density of the emplaced seal include the density of the individual particles (e.g. that of a single pellet or granule), particle shape, the grain-size distribution of the particles, and the method of emplacement.

Bulk dry density can be maximized by having a particle-size distribution that corresponds to the so-called Fuller Curve (Fuller & Thompson 1907) which was developed for maximizing the density of concrete aggregates. The Fuller Curve is described by the equation:
\[
p = \left[ \frac{d}{D} \right]^n \times 100
\]

where:
- \( p \) = percent, in weight, passing through a sieve of size \( d \)
- \( d \) = sieve size
- \( D \) = largest grain size
- \( n \) = 0.5

A series of laboratory tests conducted at the Technical University of Freiberg investigate the effects of the physical form of bentonite (i.e. size and shape) on the dry density attainable in a simulated borehole (Gloth & Strauss, 1995). The objectives of the tests were:

- to evaluate the effects of grain size and grain size distribution
- to evaluate the effects of borehole orientation

Pellets were produced from MX-80 bentonite using a roller press, achieving an average dry density of up to 2.3 Mg/m³. The pellets were then run through a grinder to produce a maximum grain-size diameter of 16 mm. After separating grain-size fractions through sieving, various grain-size distributions were re-constructed, some designed to match the Fuller Curve. The grain-size mixtures were then emplaced into simulated boreholes (pipes) to evaluate the bulk dry density values attainable under various conditions.

The emplacement tests were conducted in transparent tubes in vertical and horizontal orientations. Four borehole configurations were simulated (Tab. 3.2). Various dry granular mixtures were emplaced into the simulated boreholes and the resultant dry densities were measured.

Tab. 3-2: Configurations for simulated boreholes

<table>
<thead>
<tr>
<th>Configuration</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borehole Diameter</td>
<td>76 mm</td>
<td>76 mm</td>
<td>variable (76-152 mm)</td>
<td>variable (76-152 mm)</td>
</tr>
<tr>
<td>Borehole Orientation</td>
<td>vertical</td>
<td>horizontal</td>
<td>vertical</td>
<td>horizontal</td>
</tr>
</tbody>
</table>

For the vertical configurations, the granulate was poured from a height of approximately 1.5 m via a shaker table and funnel into the test pipe. In certain cases, the dry density in the simulated borehole was measured, 1) after the initial emplacement, 2) after 30 drop cycles (lifting the test apparatus a short distance and dropping it on the floor), and 3) after 50 drop cycles. In other cases, the bentonite was added in either 5 or 10 cm lifts that were compacted using a tamping rod.

Emplacement in the horizontal configurations was accomplished in lifts of approximately 5 and 10 cm. The lifts were compacted with a cylindrical tamping-rod, slightly smaller in diameter than the borehole.
Details and results of the dry-density emplacement tests are presented in Fig. 3-1 and Tab. 3-3. The following observations are made from the laboratory testing:

- Bentonite granulate mixed to match the Fuller Curve produced significantly higher bulk dry density values than narrow grain-size distributions (i.e. 10-16 mm).
- Matching the Fuller Curve appears to be a good method to achieve dry densities greater than 1.5 Mg/m$^3$.
- Even under ideal conditions (vertical orientation, short interval, mechanical compaction every 5 to 10 cm) the attainable bulk dry densities for narrow grain-size fractions are at or below the lower bound of the "acceptable" range values (1.3 - 1.5 Mg/m$^3$).
- Efforts to increase compaction by dropping the test apparatus a short distance (up to 50 drop cycles) results in a maximum increase in density of 2.5%.
- Emplacement of dry granulate in a horizontal, or near-horizontal borehole by means of a tamping rod results in significant bridging of the bentonite, even if the bentonite is emplaced in 5 cm lifts.

The above results clearly illustrate the importance of variable grain size in achieving suitable dry bulk density values in borehole seals. In practice, however, it may be difficult to maintain an engineered grain-size distribution over long distances due to natural sorting during transport.
Tab. 3-3: Results of the dry-density emplacement tests

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Borehole Config.</th>
<th>Grain-Size Range (mm)</th>
<th>Emplacement Method / Comments</th>
<th>Dry Density (Mg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(see Tab. 3-2)</td>
<td></td>
<td></td>
<td>initial</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0 - 16</td>
<td>Shaker Table</td>
<td>1.584</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>0 - 10</td>
<td>Shaker Table</td>
<td>1.534</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>0 - 10</td>
<td>Shaker Table / (reduced small grain-size fraction)</td>
<td>1.592</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>0.63 - 16</td>
<td>Shaker Table</td>
<td>1.511</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>0.63 - 10</td>
<td>Shaker Table</td>
<td>1.479</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>1 - 16</td>
<td>Shaker Table</td>
<td>1.466</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>1 - 10</td>
<td>Shaker Table</td>
<td>1.442</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>0 - 24</td>
<td>Shaker Table</td>
<td>1.622</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>10 - 16</td>
<td>Shaker Table</td>
<td>1.270</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>10 - 16</td>
<td>Shaker Table, compacted in 5 cm lifts</td>
<td>1.316</td>
</tr>
<tr>
<td>11</td>
<td>1</td>
<td>10 - 16</td>
<td>Shaker Table, compacted in 10 cm lifts</td>
<td>1.311</td>
</tr>
<tr>
<td>12</td>
<td>2</td>
<td>10 - 16</td>
<td>Tamping Rod, 5 cm lifts / Bridging problems</td>
<td>1.168</td>
</tr>
<tr>
<td>13</td>
<td>2</td>
<td>10 - 16</td>
<td>Tamping Rod, 10 cm lifts / Bridging problems</td>
<td>1.085</td>
</tr>
<tr>
<td>14</td>
<td>3</td>
<td>10 - 16</td>
<td>Shaker Table</td>
<td>1.281</td>
</tr>
<tr>
<td>15</td>
<td>3</td>
<td>10 - 16</td>
<td>Shaker Table, compacted in 5 cm lifts</td>
<td>1.328</td>
</tr>
<tr>
<td>16</td>
<td>3</td>
<td>10 - 16</td>
<td>Shaker Table, compacted in 10 cm lifts</td>
<td>1.292</td>
</tr>
<tr>
<td>17</td>
<td>4</td>
<td>10 - 16</td>
<td>Tamping Rod, 5 cm lifts / Bridging problems</td>
<td>1.277</td>
</tr>
<tr>
<td>18</td>
<td>4</td>
<td>10 - 16</td>
<td>Tamping Rod, 10 cm lifts / Bridging problems</td>
<td>1.249</td>
</tr>
</tbody>
</table>

1) Grain size distribution in accordance with Fuller curve
3.3 Swelling Tests on Pellets and Granular Bentonite in Pressure Cells

A second laboratory study focused on the physical and chemical characteristics of the granular bentonite chosen for in situ tests at the GTS, MX-80 and Compactonit® (Gatabin & Imbert, 1995, Gatabin & Marteau 1997). The objectives of the study were to determine the following:

1. the mineralogical make-up of the bentonite pellets,
2. the physical properties of the pellets in a "dry" state,
3. the swelling characteristics in a confined pressure cell
4. permeability properties as a function of time

3.3.1 Wyoming Bentonite (MX80)

Oedometer tests were conducted at the CEA Laboratory on MX-80 granular bentonite (Gatabin & Imbert, 1995) that had been produced at the Technical University of Freiberg. The granules were supplied in two grain-size ranges, 10 - 25 mm for Batch 1, and 5 - 10 mm for Batch 2. Mineralogical and "dry"-state properties of the granules are presented in Table 3-4.

Tab. 3-4: Physical and mineralogical characteristics of MX-80 granular bentonite

<table>
<thead>
<tr>
<th>Property</th>
<th>Batch 1 (10 - 25 mm)</th>
<th>Batch 2 (5 - 10 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density of a single granule</td>
<td>2.36 Mg/m³</td>
<td>2.26 Mg/m³</td>
</tr>
<tr>
<td>Water Content (gravimetric)</td>
<td>1.86 %</td>
<td>4.4 %</td>
</tr>
<tr>
<td>True dry density</td>
<td>2.32 Mg/m³</td>
<td>2.17 Mg/m³</td>
</tr>
<tr>
<td>Granule Porosity</td>
<td>12.5 %</td>
<td>18.1 %</td>
</tr>
<tr>
<td>Mineralogy</td>
<td>Montmorillonite 82 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Plagioclase 11 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Quartz 3 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Calcite 2 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Orthoclase 1 %</td>
<td></td>
</tr>
</tbody>
</table>

Three separate tests were conducted using the MX-80 granular bentonite, as outlined in Tab. 3-5. Test No. 1 resulted in a final swelling pressure of 0.4 MPa (Fig. 3-2). The sample was saturated simultaneously from the top and bottom of the cylinder with a water source at atmospheric pressure. Development of the swelling pressure was hindered because complete saturation of the macroscopic pore space was not achieved early in the test period. The air was purged from the test cylinder several times in order to enhance saturation, causing perturbations in the test data.
Fig. 3-2: Swelling pressure observed during Tests No. 1 and 2 in oedometer tests
Tab. 3-5: Specifications for the oedometer tests with MX-80

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Test No. 1</th>
<th>Test No. 2</th>
<th>Test No. 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bentonite Batch No.</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Diameter of Test Cell (mm)</td>
<td>120</td>
<td>57</td>
<td>120</td>
</tr>
<tr>
<td>Height of Test Column (mm)</td>
<td>320</td>
<td>90.23</td>
<td>316.5</td>
</tr>
<tr>
<td>Mass of Bentonite (g)</td>
<td>4300</td>
<td>300</td>
<td>4158</td>
</tr>
<tr>
<td>Bulk Dry Density (Mg/m³)</td>
<td>1.166 1)</td>
<td>1.249 2)</td>
<td>1.113 1)</td>
</tr>
<tr>
<td>Porosity</td>
<td>56 %</td>
<td>52.9 %</td>
<td>58 %</td>
</tr>
<tr>
<td>Results</td>
<td>$P_s$</td>
<td>$P_s, K$</td>
<td>$P_s$</td>
</tr>
</tbody>
</table>

1) Granular bentonite was emplaced in the pressure cell without additional compaction.
2) Granular bentonite was compacted in the pressure cell with a tamping rod (~10 % compaction).

The saturation method was altered for Test No. 2 from that used for Test No. 1 to provide a rapid, and thus more complete, filling of the macroscopic pore space. Saturation occurred in the following steps:

1. To quickly fill the macroscopic pore space, water was pumped into the bottom of the cylinder at a constant rate for the first 3.5 minutes with the valve at the top of the cylinder open,
2. Then, the top valve was closed and the sample was saturated from the bottom of the cylinder with a water source at atmospheric pressure. The swelling pressure stabilized at approximately 0.4 MPa,
3. After approximately 82000 minutes, the sample was exposed to a water over-pressure of 5 kPa from both the top and bottom of the cylinder, after which the swelling pressure increased from 0.4 MPa to approximately 1 MPa. The sudden increase in pressure is due to the additional saturation and swelling of bentonite at the top of the cylinder.

When the swelling pressure stabilized, a 50 kPa over-pressure was applied to the bottom of the test cylinder. Hydraulic conductivity was estimated at 4 points in time based on Darcy’s Law (Fig. 3-3). The K-values show a distinct decrease with time. When considering the K-values, it should be noted that the steady-state flow rate (Q) was calculated based on the volume of water injected over a time period of at least 65 hours. This method of Q-estimation could cause significant error, especially at the beginning of the over-pressure period where an instantaneous volume change occurs due to the compressibility of the sample medium. A 5th K-value was estimated after the over-pressure was increased from 50 to 100 kPa. The apparent increase in K is probably from an over-estimated Q (due to compression of the bentonite), rather than a true change in hydraulic conductivity. A comparison of the hydraulic conductivity of the saturated granular bentonite with those achieved with standard compacted powder show that the highly compacted granules homogenize very slowly resulting in higher hydraulic conductivities in the early time. Nevertheless, the results in Fig. 3-3 clearly show that the final hydraulic conductivity reaches similar values to those from the reference bentonite blocks made from powder.
Fig. 3-3: Hydraulic conductivity values during Test No. 2 in an oedometer test. The dashed line shows data from bentonite blocks compacted from powder (reference material)
A third test was conducted primarily to improve and accelerate the saturation and swelling methods for laboratory testing (Fig. 3-4) and to adapt the methods for field applications. Saturation was carried out in the following steps:

1. The test cylinder was filled with granular bentonite
2. The test cylinder was placed under a vacuum for approximately 10 minutes.
3. The test cylinder was then flooded from the bottom and top using a pressure vessel with a 1.2 MPa nitrogen gas head.
4. Once the macroscopic pore volume was filled, the sample was saturated from the bottom with water at atmospheric pressure.
5. After approximately 4000 minutes, the sample was saturated from both the top and bottom, resulting in a rapid increase in swelling pressure to a final value of approximately 0.5 MPa.

The above method for saturation significantly decreased the time required for saturation and development of swelling pressure.

Fig. 3-4: Test configuration for oedometer Test No. 3
3.3.2 Compactonit

The commercial product Compactonit® 8/200 was also characterized in the CEA laboratory (Gatabin & Marteau, 1997). These pellets have a beige color and a nearly cylindrical form. The diameter of these cylinders is approximately 8 mm and the length 5-10 mm. The mineralogical composition was derived by a spectral analysis of the pellets. The dominant phase of this product is interstratified illite / montmorillonite. Secondary phases are kaolinite and illite and minor components are quartz, goethite and magnetite. The mineralogical and physical characteristics of Compactonit® 8/200 are summarized in Tab. 3-6.

Tab. 3-6: Physical and mineralogical characteristics of Compactonit® 8/200 pellets according to the CEA Laboratory

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density of a single pellet</td>
<td>2.07 Mg/m³</td>
</tr>
<tr>
<td>Water content (gravimetric)</td>
<td>10.6 %</td>
</tr>
<tr>
<td>True dry density</td>
<td>1.87 Mg/m³</td>
</tr>
<tr>
<td>Pellet porosity</td>
<td>29 %</td>
</tr>
<tr>
<td>Mineralogy</td>
<td>interstratified Illite / Montmorillonite dominant</td>
</tr>
<tr>
<td></td>
<td>Kaolinite secondary</td>
</tr>
<tr>
<td></td>
<td>Illite</td>
</tr>
<tr>
<td></td>
<td>Quartz minor</td>
</tr>
<tr>
<td></td>
<td>Goethite</td>
</tr>
<tr>
<td></td>
<td>Magnetite</td>
</tr>
</tbody>
</table>

The laboratory experiments were designed to support and explain the field tests. Therefore a test procedure was defined that simulates the proposed in-situ compaction of the Compactonit® pellets in two tests. Only in the third test was a slightly different approach used.

The following testing steps were used in test 1 and 2:

- Emplacement of the pellets into the pressure cell
- Precompaction with 44 kPa
- Extraction of air with vacuum pump for about 10 min (partial pressure of about 1 kPa)
- Hydration of the pellets
- Uniaxial compaction of pellets under drained conditions (max. 1 MPa)
- Hydration under atmospheric pressure until the swelling pressure stabilised
- Measurement of hydraulic conductivity (only in test 2)

Test No. 3 differed in so far as that the compaction was carried out with dry pellets using higher compaction pressure (max. pressure 4.2 MPa). The technical details and the results of the tests are given in Tab. 3-7. The results of test No. 3a are from measurements taken after a first expansion of test No. 3.
Tab. 3-7: Specifications and results for the oedometer tests with Compactonit® pellets

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Test No. 1</th>
<th>Test No. 2</th>
<th>Test No. 3</th>
<th>Test No. 3a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of Test Cell (mm)</td>
<td>120</td>
<td>57</td>
<td>57</td>
<td>57</td>
</tr>
<tr>
<td>Height of Test Column (mm) after Precompaction</td>
<td>231</td>
<td>93</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mass of Wet Bentonite (g)</td>
<td>3161</td>
<td>285</td>
<td>240.3</td>
<td>240.3</td>
</tr>
<tr>
<td>Gravimetric Water Content (%)</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
<td>10.6</td>
</tr>
<tr>
<td>Bulk Dry Density (Mg/m³) after Precompaction</td>
<td>1.09</td>
<td>1.08</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Porosity after Precompaction (%)</td>
<td>59</td>
<td>59</td>
<td>(56)</td>
<td>(56)</td>
</tr>
<tr>
<td>Maximum Pressure for Final Compaction (MPa)</td>
<td>1</td>
<td>1</td>
<td>4.2</td>
<td>4.2</td>
</tr>
<tr>
<td>Height of Test Column (mm) after Final Compaction</td>
<td>180</td>
<td>72</td>
<td>50</td>
<td>51</td>
</tr>
<tr>
<td>Bulk Dry Density (Mg/m³) after Final Compaction</td>
<td>1.4</td>
<td>1.4</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>Saturation Time (d)</td>
<td>30-40</td>
<td>30-40</td>
<td>21-30</td>
<td></td>
</tr>
<tr>
<td>Swelling Pressure (MPa)</td>
<td>0.32</td>
<td>0.39</td>
<td>0.98</td>
<td>0.58</td>
</tr>
<tr>
<td>Results</td>
<td>$P_s$</td>
<td>$P_s$, $K$</td>
<td>$P_s$</td>
<td>$P_s$</td>
</tr>
<tr>
<td>Hydraulic Conductivity (m/s)</td>
<td>-</td>
<td>$9 \cdot 10^{-12}$</td>
<td>$1 \cdot 10^{-11}$</td>
<td>-</td>
</tr>
</tbody>
</table>

The results of these tests give an estimate of the relation of dry density and swelling pressure. The minimum bulk dry density of the Compactonit® pellets after compaction should be 1.4 Mg/m³ to reach hydraulic conductivities in the order of $K = 1 \cdot 10^{-11}$ m/s.

3.4 Swelling Tests under Simulated Borehole Conditions

The laboratory tests discussed above were performed in smooth-walled steel cylinders. In practice, borehole seals will be emplaced in rock, which has rougher texture and is significantly more permeable to water. Therefore, additional laboratory testing was conducted at the Technical University of Freiberg, Germany (Gloth, 1998) to evaluate if the bentonite seals develop in a significantly different manner in a true borehole. An additional goal of the testing was to investigate the viability of emplacing bentonite pellets in mud slurry made from a less-swelling clay ("Friedländer" clay).

Two separate tests were conducted with MX-80 granular bentonite in blocks of sandstone in which 92 mm boreholes were drilled. Specifications and results for the two tests are summarized in Table 3-8. Bentonite pellets were emplaced by hand into the boreholes, along with a pressure sensor and a 6 mm diameter mud-injection line. A mechanical packer, through which all lines and cables were fed, was expanded at the mouth of the borehole. After expanding the packer, the mud slurry was injected into the bottom of the borehole until the mud began to flow out of the over-flow line. The sandstone block was then fully immersed in a water tank. The highly porous and permeable sandstone allowed saturation of the bentonite to occur through the host rock (Fig. 3-5 and 3-6).
Fig. 3-5: Photo of the partly excavated bentonite plug in a sandstone block (test 2). The lighter colors on the plug indicate the contact points of the larger granules with the borehole wall.

Fig. 3-6: Photo of the bentonite plug (test 2) after recovery. The homogeneity and the plasticity of the bentonite plug can be seen when the plug was cut with a thin wire.
Development of the swelling pressures during Test Nos. 1 and 2 are shown in Fig. 3-7. Due to a technical failure of the data acquisition equipment the early data of Test No. 1 was lost. The maximum pressure achieved in Test No.1 reached approximately 1.2 MPa, whereas a maximum of 1.15 MPa was reached in Test No. 2. The slightly lower swelling pressure is attributable to the lower dry density of the bentonite emplaced in Test No. 2 (Tab. 3-8).

Fig. 3-7: Swelling pressure during Test Nos. 1 and 2 within a simulated borehole (smoothed data; data of Test No.2 are not completely shown).

Tab. 3-8: Specifications and results for swelling tests conducted in a simulated sandstone borehole.

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Test No. 1</th>
<th>Test No. 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borehole Diameter</td>
<td>92</td>
<td>92</td>
</tr>
<tr>
<td>Borehole Length</td>
<td>617</td>
<td>620</td>
</tr>
<tr>
<td>Pellet-Diameter Range [mm]</td>
<td>10 - 16</td>
<td>8 - 10</td>
</tr>
<tr>
<td>Emplacement Dry Density [Mg/m³]</td>
<td>1.329</td>
<td>1.278</td>
</tr>
<tr>
<td>Test Length [hours]</td>
<td>490</td>
<td>1800</td>
</tr>
<tr>
<td>Final Swelling Pressure [MPa]</td>
<td>1.2</td>
<td>1.15</td>
</tr>
<tr>
<td>Time required to reach 90% of the maximum swelling pressure [hours]</td>
<td>~ 300</td>
<td>~ 130</td>
</tr>
<tr>
<td>Distance that mud invaded into the sandstone [mm]</td>
<td>~ 1</td>
<td>~ 5</td>
</tr>
</tbody>
</table>
The maximum swelling pressure developed more rapidly in Test No. 2, probably due to the smaller grain size of the pellets. The smaller pellets, having more total surface area, have therefore more contact to water at the beginning of the saturation process.

The final step of the experiment was to excavate the bentonite seals by cutting away the sandstone around the boreholes to observe the seal material and the contact to the host rock. Several noteworthy observations were made during the excavation:

- The seal material invaded the sandstone to a distance of a few millimeters (max. 5 mm).
- For Test No. 1, the seal material exhibited a distinct mottling, indicating that the bentonite and mud had not mixed into a homogeneous material. The seal material in Test No. 2 appeared more homogenous, due to either the longer test time, or to the smaller size of the bentonite granules.
4 Equipment Development

The laboratory testing described in the previous chapter focuses on the characteristics of the bentonite seal materials. The borehole sealing experiment also involved the development and modification of equipment for field application. Specifically, these efforts are concentrated on 1) confinements for the multi-component seals, and 2) bentonite emplacement equipment.

4.1 Mechanical confinements

Mechanical confinements serve to protect the cores of multi-component borehole seals, which have relatively low shear strength and are easily erodable. Confinements must contain the swelling core material, must anchor the seal in the presence of high differential pressures, and must separate the core material from high-permeability zones that could potentially wash the material away. The integrity of confinements is especially important during the active phase of a repository when the differential pressure across a seal may reach up to 5.0 MPa. Confinements must also exhibit a low hydraulic conductivity during the emplacement and swelling of the core.

Various types of confinements for multi-component seals have been considered in the literature. Cement-based confinements are perhaps the most commonly suggested solution because of low cost, availability, and ease of emplacement in many situations. However, the special conditions for sealing near-horizontal, small-diameter boreholes reduce the viability of cement confinements. Inflatable aluminum packers developed for testing in geothermal wells are an option with no inherent disadvantages in horizontal boreholes (Klee and Rummel, 1993). Because limited data exist regarding the performance of metal packers, especially for other metals than aluminum, a portion of the BOS Experiment focused on the development and testing of metal packers. The testing comprised two parts:

1. A field performance test at the GTS using an aluminum packer
2. Laboratory tests on the performance of packers made of metals that are expected to have a longer working life considering the groundwater chemistry in a repository area (i.e. copper and stainless steel).

4.1.1 Test of Aluminum Packer at GTS

The performance of an aluminum packer as confinements was evaluated in a horizontal borehole (BOS 95.004) at the Grimsel Test Site (Rummel, 1997). The 7.33 m-long borehole, which is located near the intersection of the Laboratory and Heat-Test (WT) Tunnels, intersects both tunnels and can thus be accessed from two sides (Fig. 4-1).

The testing, which took place on October 25 and 26, 1995, consisted of three steps:

1. Installation and inflation of the packer
2. A hydraulic push-out test in which a differential hydraulic pressure between 4.0 and 5.0 MPa was applied on the packer
3. A mechanical push-out test in which mechanical pressure was applied directly to the packer using a hydraulic cylinder and steel push rod.
Fig. 4-1: Map showing location of the borehole used for testing the aluminum packer (BOS 95.004) and the field test (BOS)

A schematic drawing of the aluminum packer is presented in Fig. 4-2. The packer is dimensioned so that the borehole wall is reached after deformation of 10%; the material is designed to allow at least 25% deformation prior to failure. The ridges on the outside of the packer facilitate the application of O-ring-like rubber seals that may help insure a temporary hydraulically-tight seal. Such seals were not applied in the test at the GTS.
Fig. 4-2: Schematic drawing of the aluminum packer

Fig. 4-3: Plot of Packer Inflation Pressure -vs.- Time of the aluminum packer at GTS
Packer Installation
The packer was installed to a depth of 3.55 m (measured from the Laboratory Tunnel). To inflate, the packer was pressurized in 5.0 MPa increments until a maximum pressure of 36 MPa was reached (Fig. 4-3). Packer deformation started at 21 MPa. The packer reached the borehole wall at an internal pressure of 31 MPa. Following packer expansion and depressurization, the shear pin was sheared and the central rod was removed from the packer.

Hydraulic Push-out Test
A conventional inflatable packer system was installed to a depth of 3 meters and inflated to 11 MPa in preparation for the hydraulic push-out test. Following saturation, hydraulic pressure was applied in the following steps: 1.25 MPa, 2.25 MPa, and 4.63 MPa (Fig. 4-4). Each step was maintained for approximately 3 minutes. No movement of the aluminum packer was observed.

Fig. 4-4: Plot of Pressure -vs.- Time for the packer and interval pressure during the hydraulic push-out test conducted on the aluminum packer
Subsequently, a long-term push-out test was conducted with a pressure of 4.15 MPa. The pressure was observed for a period of 17 hours, during which time the interval pressure decreased to 0.62 MPa. The pressure response was analyzed, yielding a permeability of approximately 20 μDarcy (hydraulic conductivity \( K \approx 2 \times 10^{-10} \) m/s). No movement of, nor significant leakage around the metal packer was observed.

**Mechanical Push-out Test**

A mechanical push-out test was performed by exerting an axial load on the aluminum packer with a hydraulic cylinder via 2 7/8” drilling tubing. The hydraulic cylinder was pressurized in 5.0 MPa increments to a maximum pressure of 59.3 MPa (force of 67.6 kN). The maximum load, which translated to an effective hydraulic load of 8.6 MPa, was maintained for 1.5 hours (Fig. 4-5). No movement of the aluminum packer was observed.

![Graph showing the plot of pressure vs. time during the mechanical push-out test](image_url)

Fig. 4-5: Plot of Pressure -vs.- Time during the mechanical push-out test conducted on the aluminum packer

**4.1.2 Development of Copper and Stainless Steel Packers**

The test conducted at the Grimsel Test Site confirms the viability of using metal packers for confinements. The long-term stability of aluminum, however, is marginal in a corrosive groundwater environment. Laboratory tests were performed to evaluate the suitability of other metals considered to be more stable in groundwater environments (Rummel, 1997). In addition to corrosion resistance, the following selection criteria were applied in choosing the metals:

- Ductility at constant stress for permanent deformation
- Weldability
Based on the above criteria, copper and stainless steel were chosen for the laboratory tests. The material properties of copper and stainless steel are presented in Table 4-1.

Tab. 4-1: Material properties of copper and stainless steel used for construction of metal packers.

<table>
<thead>
<tr>
<th>Material Property</th>
<th>Copper</th>
<th>Stainless Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIN¹ No.</td>
<td>2.0090</td>
<td>1.4301</td>
</tr>
<tr>
<td>Tensile Strength [MPa]</td>
<td>220 - 260</td>
<td>500 - 700</td>
</tr>
<tr>
<td>0.2% yield strength [MPa]</td>
<td>140</td>
<td>185</td>
</tr>
<tr>
<td>1% yield strength [MPa]</td>
<td>-</td>
<td>239</td>
</tr>
<tr>
<td>Fracture strain, A5, %</td>
<td>42</td>
<td>45</td>
</tr>
<tr>
<td>Fracture strain, A10, %</td>
<td>36</td>
<td>-</td>
</tr>
<tr>
<td>Density [kg/m³]</td>
<td>8960</td>
<td>7900</td>
</tr>
<tr>
<td>Modulus of elasticity, E [GPa]</td>
<td>125</td>
<td>200</td>
</tr>
<tr>
<td>Chemical Reaction Coeff. [V]</td>
<td>+0.35</td>
<td>-0.44 (Fe)</td>
</tr>
</tbody>
</table>

As with the aluminum packer tested at the GTS, the stainless steel and copper packers (90 mm o.d.) were designed to reach the wall of a 4” borehole (~100 mm i.d.) after 10% deformation. Design wall thickness for the stainless steel and copper packers were 5 and 6 mm, respectively.

The objectives of the laboratory testing in test pipes were to determine the following:

- The setting pressures necessary to expand the metal packers
- The effective pressure transmitted to the test pipe (i.e. borehole wall) during packer expansion
- The anchoring capacity of the packers

Strain gauges were mounted on the outside of steel and aluminum test pipes in order to determine the circumferential deformation of the test pipe, and thus the effective pressure transmitted to it. The test pipes were calibrated by inflating standard rubber packers and observing the circumferential deformation. Results of the calibration are shown in Fig. 4-6. The calibration exercise indicates 1) that the relationship between packer fluid pressure and circumferential deformation is linear for both aluminum and steel test pipes, and 2) that greater deformation, thus better measurement resolution, is achieved using an aluminum test pipe.
For the final laboratory tests, the metal packers were placed in 105.5 mm o.d. aluminum test pipes and expanded with water (Fig. 4-7). Results of the expansion tests are summarized in Table 4-2.

Tab. 4-2: Results of metal packer expansion tests conducted in a test pipe

<table>
<thead>
<tr>
<th></th>
<th>Copper</th>
<th>Stainless Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Required to Start Packer Expansion [MPa]</td>
<td>20</td>
<td>26</td>
</tr>
<tr>
<td>Pressure Required to Reach Test Pipe Wall [MPa]</td>
<td>24</td>
<td>53</td>
</tr>
<tr>
<td>Maximum Setting Pressure Applied [MPa]</td>
<td>40</td>
<td>95</td>
</tr>
<tr>
<td>Effective Setting Pressure against Test Pipe [MPa]</td>
<td>9</td>
<td>21</td>
</tr>
<tr>
<td>Effective Pressure/Maximum Pressure</td>
<td>22.5%</td>
<td>22.1%</td>
</tr>
<tr>
<td>Push-out Pressure [MPa]</td>
<td>~9 1)</td>
<td>&gt;10.6 1)2)</td>
</tr>
</tbody>
</table>

1) Leakage was observed around the packer
2) No Packer movement was observed
The main conclusions from the laboratory testing on metal packers are the following:

- The performance of the stainless steel and copper packer meets the expectations for confinements.

- The effective setting pressure (i.e. the pressure exerted by the packer against the test pipe or borehole wall) is approximately 20% of the maximum packer inflation pressure. Note that in real applications it needs to be verified that under the given in-situ stress conditions no fracturing will be induced (sleeve fracturing).

- The metal packers do not form a water-tight seal against smooth-walled test pipes. When set in natural rock, the packers may form a better seal. However, some form of flexible seals for temporary sealing on the outside of the packers should be incorporated into the final design.
4.2 Mechanical Injection Tool

4.2.1 General Idea

The hydraulically operated mechanical emplacement system (Fig. 4-8) was designed by Nagra’s former drilling engineer A. Macek (now at GeoWell GmbH, Switzerland) in such a way that existing but modified standard drilling equipment could be used to emplace the material. This has the advantage that a normal drilling crew can handle the tool (MACMET tool) without special training or additional specialists. In general, the material is emplaced using a modified core barrel that allows the transport and ejection of the material. This system has the advantage that the area to be sealed in a borehole is constantly under control. Immediately before the emplacement of the sealing material the borehole interval can be cleaned by normal flushing operation and the material can be emplaced without removing the drill string.

After positioning the drill string directly above the mechanical abutment which confines the seal at its lower end, the modified core barrel containing the pellets is pumped to the end of the drill string. After reaching its final position, the pressure on the system is increased and the pellets are ejected. Due to the weight of the drilling string and the injection pressure it is possible, with simple manipulations from the drilling rig, to control the pressure used to eject and compact the sealing material in situ. When the modified core barrel is empty, a catcher is pumped down the hole to retrieve the core barrel. This procedure can be repeated until the planned section is fully sealed.

![Fig. 4-8: Schematic representation of the emplacement technique using a modified core barrel (MACMET tool)](image-url)
4.2.2 Systematic Test in the Workshop

The first tests in the workshop were conducted to evaluate the performance of the material emplacement tool. A simple test system was used where the core barrel was pumped hydraulically to the bottom of a horizontally fixed drill string and ejected the bentonite pellets. The core barrel had a length of about 1 m.

Sealing materials used for these tests were:

- MX 80 sodium bentonite
- Compactonit® pellets

Both materials were tested under dry and water saturated conditions. Using dry pellets caused problems for both materials as the friction of the pellets in the core barrel resulted in most cases in a blockage of the system even with ejection pressures of more than 4 MPa. Systematic changes of the filling of the core barrel demonstrated that reliable performance for dry MX-80 and Compactonit® was reached only when the core barrel was filled to a maximum of 0.5 m. Assuming a borehole diameter of 100 mm and an inner diameter of the core barrel of 60 mm the material would even without in situ compaction fill just 0.18 m in the borehole. A compaction of the material by 20 - 30% would thus mean that a borehole section of only 0.12-0.15 m could be sealed in one step.

The tests in the laboratory showed that the granules of highly compacted bentonite (MX-80) could not be used with this system as it was impossible to reliably eject the material due to friction and/or very fast swelling of the material in the core barrel. Therefore, it was decided to test other commercially available bentonite pellets to determine if they could be used satisfactorily with the modified tool. The product Compactonit® was tested and it was possible to achieve satisfactory results in the laboratory when the material was placed in a water-filled core barrel.

4.3 Pneumatic Injection Device

Pneumatic injection is a method commonly used in industry for transporting and emplacing dry granulates. A series of laboratory and field tests were conducted to evaluate the feasibility of using existing pneumatic injection technology for emplacing granular bentonite in horizontal and upwardly-inclined boreholes (Roski, 1997).

4.3.1 Laboratory Test Set-up

Three field scenarios were initially simulated in the laboratory:

- A 100 m-long horizontal borehole
- A 500 m-long horizontal borehole
- A 40º upwardly-inclined borehole (500 m injection line)

The laboratory set-up of the pneumatic injection system consisted of the following components (Fig. 4-9):

- Air compressor
- Rotary Pellet Feeder
- Simulated borehole (4” PVC pipe)
• Injection line (1½" pipe)
• Back-flow Filter (for bentonite mass balance calculations)
• Pressure and air-flow measuring sensors
• Water feed (only for the upwardly-inclined borehole)

General technical data for the various laboratory tests are summarized in Table 4-3.

Tab. 4-3: Technical data for laboratory tests of the pneumatic injection system

<table>
<thead>
<tr>
<th></th>
<th>100 m borehole</th>
<th>500 m borehole</th>
<th>upwardly-inclined borehole</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotary Feeder Speed [rpm]</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Air flow volume [m³/min]</td>
<td>1.0 - 2.8</td>
<td>5.8</td>
<td>5.8</td>
</tr>
<tr>
<td>Injection Velocity [m/s]</td>
<td>13.2 - 25.7</td>
<td>30.6 - 36.5</td>
<td>31.1 - 32.5</td>
</tr>
</tbody>
</table>

Fig. 4-9: Laboratory set-up for testing of the pneumatic injection system

4.3.2 Laboratory Test Results

100 meter transport distance

A number of tests were conducted using the test configuration designed to simulate a 100 m-long horizontal borehole. Variables for the various tests included, bentonite granule size, distance from the injection nozzle to the abutment, injection velocity and use of an impact plate (to prevent material from entering the annulus between the injection line and the borehole). Results of the tests are presented in Fig. 4-10.

Bulk dry density values ranging from 1.365 - 1.491 Mg/m³ were achieved for the experiments. The various test configurations do not yield significantly differing results. No clear relationship was established between the emplacement density and the factors that were varied during
testing. The volume of back-flow material collected in the by-pass filter was less when the injection nozzle was held 1 m away from the target than when the distance was 0.5 m.

![Graph showing dry density vs. pellet size range for different injection distances with and without impact plate.]

**Fig. 4-10:** Results of tests conducted in a 100 m simulated borehole

Grain-size analysis of the bentonite pellets before and after emplacements indicate that the pellets are abraded during transport. The abrasion increases the proportion of smaller grain sizes and results in a grain-size distribution that crudely matches the Fuller Curve (Fig. 4-11).

![Graph showing undersize distribution vs. width of mashes for initial state, conveyed state, and Fuller curve.]

**Fig. 4-11:** Plot showing grain size distribution before and after transport over 100 m distance
500 meter transport distance

Three tests were also conducted to evaluate the feasibility of using the pneumatic injection technique for distances up to 500 m. Two of the tests were conducted using granular bentonite in the 4 - 10 mm range; the third test, which was performed with 10 - 16 mm pellets, was unsuccessful due to clogging of the rotary feeder and the injection pipe.

The first and second tests resulted in bulk dry densities of 1.198 and 1.587 Mg/m³, respectively. The main difference between the two tests was the amount of material to be emplaced. The first test, in which 10 kg of granular bentonite were emplaced, indicated a volume loss of 38%. By reducing the amount of granular bentonite to be emplaced to 7 kg in the second test, volume loss was reduced to 15% and the bulk dry density was increased by 33%. The cause of the excessive volume loss in the first test was most likely the proximity of the injection nozzle to the target area at the end of the injection period.

Grain-size analysis before and after emplacement show a greater increase in the finer fractions in comparison to the tests for 100 m transport distance (Fig. 4-12). The degree of grain-size reduction is clearly a function of transport conditions.

Fig. 4-12: Plot showing grain size distribution before and after transport over 500 m distance

Upwardly-angled boreholes

Three additional tests were conducted to evaluate the feasibility of using pneumatic injection in upwardly-inclined boreholes. The injection was configured as for the 500 m transport distance test, except that the target zone was angled upwards at 40º and that a water feed was installed near the end of injection line. The water feed served to moisten the granular bentonite, causing them to stick upon emplacement, rather than simply falling back along the annulus between the inclined borehole and injection tubing.
A bentonite seal was successfully emplaced, with a bulk dry density of just 0.961 Mg/m³. Although the dry density value is relatively low, the experiment indicates that emplacement of bentonite seals is feasible in upwardly-inclined boreholes using pneumatic injection. Optimization of the methods would certainly improve the achievable dry density in such boreholes.

Final tests with varying transport distances

Additional laboratory test have been performed to validate the findings of the initial tests described above. The transport distances were artificially increased up to 1000 m by transporting the granular bentonite twice along the 500 m injection line in the workshop (re-used material). The summary of all laboratory test results (Fig. 4-13) clearly shows the dependence of the emplacement bulk density on the transport distance. Data points at 0 m transport distance indicate results from various drop tests before the pneumatic conveyance of the granular bentonite.

Fig. 4-13: Results from the laboratory tests on pneumatic emplacement of granular bentonite

Conclusions

The feasibility tests conducted on pneumatic injection tool indicate the following:

- Emplacement of seals with bulk dry densities ranging from 1.4 to 1.6 Mg/m³ are feasible in horizontal boreholes in lengths of 100 - 1000 m.
- Emplacement density depends on transport distance
- Abrasion of the granular bentonite during transport increases the fraction of small grain sizes and results in a crude match of the Fuller Curve. Manufacture and preparation of a Fuller-type granular mixture to maximize dry density is, therefore, unnecessary if transport distances are sufficiently large (100 m or more).
- Quality control is feasible by careful mass-balance measurements. The use of a bypass filter provides quantification of the mass of material that is blown out of the seal zone.
- Techniques to install bentonite seals in upwardly-inclined boreholes, while feasible, require additional optimization to achieve acceptable emplacement densities.
5 Preparation of the Test Field

5.1 Site Selection

The test location at the GTS for the performance of the sealing tests was selected in such a way that realistic emplacement tests could be guaranteed and, at the same time, optimum monitoring and testing of the sealing element would be possible. The chosen site (Fig. 4-1) allowed sub-horizontal boreholes (dip about 1°) in intact granitic rock from the main access tunnel to be drilled to the laboratory tunnel, allowing instrumentation and testing of the seal from both sides. Due to the distance between the two tunnels of more than 30 m, the seal could be placed far away from the excavation disturbed or unsaturated zones close to the tunnel walls.

5.2 Drilling

Three boreholes were drilled in a niche of the main access tunnel to the Nagra Grimsel Test Site using a diamond drill bit with a nominal diameter of 96 mm for BOS 95-001 and 95-002 and a double core barrel. Borehole BOS 95-003 was drilled with a diameter of 86 mm because of the requirements given by Andra for their own sealing experiment (not reported in this report). Standard Grimsel tap water was used as drilling-fluid. The planned targets in the laboratory tunnel were hit with a maximum deviation of about 0.2 m. The technical data are summarized in Table 5-1.

Tab. 5-1: Technical data of boreholes BOS 95.001 - 95.003

<table>
<thead>
<tr>
<th>Borehole</th>
<th>BOS 95-001</th>
<th>BOS 95-002</th>
<th>BOS 95-003</th>
</tr>
</thead>
<tbody>
<tr>
<td>y coordinates (Northing)</td>
<td>667496.09</td>
<td>667496.15</td>
<td>667496.08</td>
</tr>
<tr>
<td>x coordinates (Easting)</td>
<td>159215.33</td>
<td>159217.94</td>
<td>159216.46</td>
</tr>
<tr>
<td>z coordinates (masl)</td>
<td>1731.57</td>
<td>1731.56</td>
<td>1731.56</td>
</tr>
<tr>
<td>Azimuth (degrees)</td>
<td>253</td>
<td>286</td>
<td>263</td>
</tr>
<tr>
<td>Borehole deviation (from horizontal in degree)</td>
<td>-0.9</td>
<td>-1.4</td>
<td>-1.0</td>
</tr>
<tr>
<td>Length of borehole</td>
<td>38.28 m</td>
<td>31.10 m</td>
<td>34.58 m</td>
</tr>
<tr>
<td>Borehole diameter</td>
<td>96 mm</td>
<td>96 mm</td>
<td>86 mm</td>
</tr>
<tr>
<td>Core diameter</td>
<td>66.5 mm</td>
<td>66.5 mm</td>
<td>72 mm</td>
</tr>
<tr>
<td>Start of drilling</td>
<td>01.09.95</td>
<td>05.09.95</td>
<td>21.08.95</td>
</tr>
<tr>
<td>Completion</td>
<td>04.09.95</td>
<td>12.09.95</td>
<td>24.08.95</td>
</tr>
</tbody>
</table>

5.3 Geological Core Mapping and Geophysical Logging

The entire length of the three boreholes passes through a leucocratic rock with varying biotite content which, in the region of the Grimsel Test Site, is termed "Central Aare Granite" (CAGR). Macroscopic analyses have shown that the mineralogical composition is as follows: quartz approx. 35-45 vol.%, potassium feldspar 20-30 vol.% and plagioclase approx. 20-30 vol.%. Accessories include the rock-forming minerals biotite, muscovite, chlorite and some epidote. This composition corresponds largely to that determined in previous investigations (cf. Nagra 1985).
The rock is homogeneous and massive and has a porphyritic structure. All the drill cores contained feldspar phenocrysts sensu lato with hypidiomorphic crystals up to 10x30 mm in size.

The varying biotite content is the reason for the local colour change of the rock from leucocratic to meso-melanocratic. The biotite content also influences the texture of the rock. Melanocratic areas with increased biotite content have a clear to marked parallel texture, while leucocratic areas have only traces of parallel texture.

**Cleavage and deformation phenomena**

Cleavage in the three boreholes tends to be weak, i.e. continuous cleavage planes are almost entirely absent and are indicated only by the surface orientation of mica layers. The porphyroblastic feldspars often show clear to marked stretching in the same direction as the oriented mica layers.

Actual fault zones such as kakirites and cataclastic faults were not observed in the drillcores. Local mylonitic deformations were, however, identified. These often pass completely through the core in bands up to 20 mm thick, but are also observed to split and wedge out in the core. The mylonite bands are fine-grained and differ from the surrounding, less deformed rock in that they have a mostly even grey colouring.

Compared to the other boreholes, the drillcores from BOS 95.002 show frequent fracturing. The fractures are generally oriented normal to the core axis and have a dip of up to 20° relative to the core axis. It is not clear whether these features are due purely to mechanical loading induced by the drilling process or whether they are relaxation features.

**Joints, joint mineralization and discontinuities**

A large number of joints run parallel to the cleavage. In addition, there is a further conjugate joint system running at a steep angle and intersecting the cleavage-parallel system.

With few exceptions, the mineralization is restricted to formation of biotite, chlorite and muscovite. The joints in the boreholes are always completely filled and the proportions of the individual minerals cannot be estimated exactly in the closed joints. In addition to the enrichments of these sheet silicates which clearly trend discordantly to the cleavage, the joints also include continuous mineralization surfaces which are approximately parallel to the cleavage. Enrichment of layer silicates is the reason why a large number of joints are broken open, although these joints can be assumed to be closed within the rock structure.

A few joints contain epidote with sericite and, very rarely, granular, intensively green chlorite. Quartz as a fracture infill was observed only in isolated joints up to 100 mm thick and in cores from BOS 95.003 and 95.001.

**Geophysical logging**

Geophysical logging was reduced to a minimum to address the remaining open questions after geological core description. As mentioned above, it was not always possible to distinguish from the cores the origin of observed fractures (natural or drilling induced). Televiewer measurements, which image the borehole wall precisely, were selected as an adequate tool to provide the missing information and to detect all natural fractures, fissures, joints and irregularities of the borehole wall.
The careful analysis of the borehole wall images permitted selection of the appropriate zones for the seal section (key zone) containing no features which could act as preferential flow paths. In addition, the televiewer data (traveltime data) provided very high accuracy measurements of the borehole diameter (relative resolution ca. 1 mm) to evaluate the borehole volume of the seal section and thus providing the basis for QC measures during emplacement of the sealing material (mass balance).

5.4 Hydraulic Characterization of the Site

Hydraulic testing was conducted in two phases to complete the site preparation activities. The objectives of the hydraulic testing were:

- Step 1: to confirm the hydrogeologic suitability of the site (i.e. does the site exhibit hydraulic parameters typical of undisturbed matrix, or are any highly-conductive features present that might adversely affect the results of the sealing experiment?)
- Step 2: to characterize hydraulic responses when a temporary borehole seal (inflatable packer) is placed in the zones targeted for emplacement of the bentonite seals. These data provide a comparative basis for evaluating the results of testing to be conducted after seal emplacement.

5.4.1 Step 1 Hydraulic Testing

Step 1, which was conducted in September and October of 1995, consisted of isolating 9.08 m and 10.2 m sections in BOS 95.001 and BOS 95.002, respectively (Fig. 5-1 and Tab. 5-2). Packer seats were chosen based on core inspection. The isolated sections include the 2 m-long intervals targeted for emplacement of bentonite seals. The test intervals were isolated by installing two 85 mm-diameter single-packer systems run in on 2" stainless-steel tubing in each borehole, one from the Access Tunnel and one from the Laboratory Tunnel. Following packer installation and expansion, the test interval was filled with water. Once saturated, the test interval was shut-in and the pressure recovery phase was begun. Subsequent to the pressure recovery phase, hydraulic testing was conducted to determine the overall hydrogeologic characteristics of the intervals.

Tab. 5-2: Step 1 borehole instrumentation details

<table>
<thead>
<tr>
<th>Borehole / Interval #</th>
<th>Interval Length (m)</th>
<th>Nominal Interval Volume (l)</th>
<th>Packer Inflation Fluid</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>measured from access tunnel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BOS 95.001 / [1-1]</td>
<td>15.50 - 24.58</td>
<td>9.08</td>
<td>65.7</td>
</tr>
<tr>
<td>BOS 95.002 / [2-1]</td>
<td>11.00 - 21.20</td>
<td>10.2</td>
<td>73.8</td>
</tr>
<tr>
<td>BOS 95.003 / [3-1]</td>
<td>0.8 - 34.5</td>
<td>33.7</td>
<td>196</td>
</tr>
</tbody>
</table>

The pressure responses in all intervals during the entire Step 1 testing period are depicted in Fig. 5-2. Results for the individual test events are presented in Table 5-3. The best-estimate hydraulic conductivity values for BOS 95.001 and BOS 95.002 are $2 \times 10^{-12}$ and $6 \times 10^{-12}$ m/s, respectively. These are comparable to values obtained for granitic matrix at the GTS (EDZ-Experiment and Ventilation Experiment). Based on these results, the site was deemed suitable for the BOS Experiment.
Fig. 5-1: Borehole configuration for Step 1 hydraulic characterization
Fig. 5-2: Composite pressure responses during Step 1 hydraulic characterization

Tab. 5-3: Summary of Step 1 test results

<table>
<thead>
<tr>
<th>Interval</th>
<th>Interval Length</th>
<th>Test Event</th>
<th>T [m²/s]</th>
<th>K [m/s]</th>
<th>Radius of Influence 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1-1]</td>
<td>9.08 m</td>
<td>PI1</td>
<td>3.3·10⁻¹¹</td>
<td>3.6·10⁻¹²</td>
<td>~ 2.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PI2</td>
<td>2.3·10⁻¹¹</td>
<td>2.5·10⁻¹²</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>RI ¹)</td>
<td>1.8·10⁻¹¹</td>
<td>2.0·10⁻¹²</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>RI ³)</td>
<td>2.5·10⁻¹¹</td>
<td>2.8·10⁻¹²</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Best Estimate</strong></td>
<td>2.4·10⁻¹¹</td>
<td>2.7·10⁻¹²</td>
<td></td>
</tr>
<tr>
<td>[2-1]</td>
<td>10.2 m</td>
<td>PI1</td>
<td>5.7·10⁻¹¹</td>
<td>5.6·10⁻¹²</td>
<td>~ 3.5 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PI2</td>
<td>5.7·10⁻¹¹</td>
<td>5.6·10⁻¹²</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>HI ⁵)</td>
<td>6.0·10⁻¹¹</td>
<td>5.9·10⁻¹²</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>RI ²)</td>
<td>6.0·10⁻¹¹</td>
<td>5.9·10⁻¹²</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>RI ³)</td>
<td>5.1·10⁻¹¹</td>
<td>5.0·10⁻¹²</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>RIS ¹)</td>
<td>4.7·10⁻¹¹</td>
<td>4.7·10⁻¹²</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Best Estimate</strong></td>
<td>5.5·10⁻¹¹</td>
<td>5.4·10⁻¹²</td>
<td></td>
</tr>
</tbody>
</table>

1) Cooper-Jacob straight-line (RI) or Horner (RIS) analysis
2) Spherical flow analysis after Barker, 1988 (Assumption: s = 0)
3) Steady-state approximation (Assumptions: specific storage Ss = 5·10⁻⁷ m⁻¹; skin s = 0)
4) The radius influence is estimated using the equation RI = 1.5 √(Δt T/S) and the steady-state approximation (Assumptions: Ss = 5·10⁻⁷ m⁻¹; s = 0)
5) Incomplete flow data during HI. The presented result is a GTFM- parameter estimation
5.4.2 Step 2 Hydraulic Testing

Step 2 was conducted from October 1995 to January 1996. During Step 2, temporary seals were emplaced in BOS 95.001 and BOS 95.002 by installing 2 m-long inflatable packers in the zones targeted for bentonite seal emplacement (Fig. 5-3 and Tab. 5-4). To accomplish this, the single-
packer systems installed from the Laboratory Tunnel were replaced with double-packer systems. The single-packer systems installed from the Access Tunnel during Step 1 remained in place. After a pressure recovery period, hydraulic testing was then conducted on the resulting 4 intervals (2 intervals in each borehole) created by the new packer configurations.

Tab. 5-4: Step 2 borehole instrumentation details

<table>
<thead>
<tr>
<th>Borehole / [Interval #]</th>
<th>Interval Length (m) measured from access tunnel</th>
<th>Nominal Interval Volume (l)</th>
<th>Pressure Transducer Range (MPa)</th>
<th>Packer Inflation Fluid</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOS 95.001 [1-2-i1]</td>
<td>15.50 - 17.58</td>
<td>2.08</td>
<td>15.1</td>
<td>0 - 2 Water</td>
</tr>
<tr>
<td>BOS 95.002 [2-2-i1]</td>
<td>11.00 - 15.20</td>
<td>4.2</td>
<td>30.4</td>
<td>0 - 2 Water</td>
</tr>
<tr>
<td>BOS 95.002 [2-2-i2]</td>
<td>17.20 - 21.20</td>
<td>4.0</td>
<td>29.0</td>
<td>0 - 2 Water</td>
</tr>
</tbody>
</table>

The pressure responses in all intervals during the entire Step 2 testing period are depicted in Fig. 5-4. Results for the individual test events are presented in Table 5-5. The transmissivity values are consistent with the values obtained during Step 1.

Fig. 5-4: Composite pressure responses during Step 2 hydraulic characterization
Cross-interval pressure responses across the temporary seal were observed during the long-term constant-rate injection tests in BOS 95.001 and BOS 95.002 after approximately 30 and 15 hours respectively. The responses indicate spherical flow conditions (as do log-log plots of the pressure change in the injection interval). The lack of instantaneous responses across the seal indicate that no significant excavation disturbed zone exists around the borehole.

Tab. 5-5: Summary of Step 2 test results

<table>
<thead>
<tr>
<th>Interval</th>
<th>Interval Length</th>
<th>Test Event</th>
<th>( T ) [m²/s]</th>
<th>( K ) [m/s]</th>
<th>Radius of Influence 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2-i1</td>
<td>2.08 m</td>
<td>PI1</td>
<td>7.7·10⁻¹²</td>
<td>3.7·10⁻¹²</td>
<td>~ 4.3 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PI2</td>
<td>6.0·10⁻¹²</td>
<td>2.9·10⁻¹²</td>
<td></td>
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<td></td>
<td></td>
<td>RI ²)</td>
<td>6.2·10⁻¹²</td>
<td>3.0·10⁻¹²</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>RI ³)</td>
<td>8.5·10⁻¹²</td>
<td>4.1·10⁻¹²</td>
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<td>7.0·10⁻¹²</td>
<td>3.4·10⁻¹²</td>
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<td>7.0·10⁻¹²</td>
<td>3.4·10⁻¹²</td>
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</tr>
<tr>
<td>1-2-i2</td>
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<td>PI1</td>
<td>1.3·10⁻¹¹</td>
<td>2.2·10⁻¹²</td>
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<td>2.2·10⁻¹²</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>RI ²)</td>
<td>1.2·10⁻¹¹</td>
<td>2.4·10⁻¹²</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>RI ³)</td>
<td>1.5·10⁻¹¹</td>
<td>3.0·10⁻¹²</td>
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<td>1.3·10⁻¹¹</td>
<td>2.6·10⁻¹²</td>
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</tr>
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<td>2-2-i1</td>
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<td>PI1</td>
<td>2.3·10⁻¹¹</td>
<td>5.5·10⁻¹²</td>
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<td>PI2</td>
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<td>3.6·10⁻¹²</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>RI ²)</td>
<td>2.2·10⁻¹¹</td>
<td>5.2·10⁻¹²</td>
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<td>5.2·10⁻¹²</td>
<td></td>
</tr>
<tr>
<td>2-2-i2</td>
<td>4.0 m</td>
<td>PI1</td>
<td>2.2·10⁻¹¹</td>
<td>5.5·10⁻¹²</td>
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<td></td>
<td></td>
<td>PI2</td>
<td>1.8·10⁻¹¹</td>
<td>1.5·10⁻¹²</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>RI ¹)</td>
<td>1.3·10⁻¹¹</td>
<td>3.2·10⁻¹²</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>RI ³)</td>
<td>2.1·10⁻¹¹</td>
<td>5.3·10⁻¹²</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>1.8·10⁻¹¹</td>
<td>4.5·10⁻¹²</td>
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<tr>
<td>Best Estimate</td>
<td></td>
<td></td>
<td>1.8·10⁻¹¹</td>
<td>4.5·10⁻¹²</td>
<td></td>
</tr>
</tbody>
</table>

1) Cooper-Jacob straight-line analysis
2) Spherical flow analysis after Barker, 1988 (Assumption: \( s = 0 \))
3) Steady-state approximation (Assumptions: Specific storage \( S_s = 5 \cdot 10^{-7} \text{ m}^{-1} \); skin \( s = 0 \))
4) The radius influence is estimated using the equation \( RI = 1.5 \sqrt{\Delta t T/S} \) and the steady-state approximation (Assumptions: \( S_s = 5 \cdot 10^{-7} \text{ m}^{-1}; s = 0 \))

5.4.3 Example Test Sequence and Analysis

The sequence for interval BOS 95.001-2-i1 is typical of the BOS hydraulic testing that was conducted in Steps 1 and 2. The entire test sequence, consisting of PSR-PI1-RI-RIS-PI2 (PSR = pressure recovery; PI = pulse injection; RI = rate injection; RIS = rate injection shut-in), is depicted in Fig. 5-4. The constant-rate sequence is shown in Fig. 5-5. Both the log-log
The diagnostic plot and the standard semi-log plot indicate a flow model other than infinite-acting radial flow (IARF). The specialized plot of $\Delta P$ vs. $1 / \sqrt{\Delta t}$ indicates a straight line which suggests spherical flow conditions. The majority of constant-rate injection test responses observed in Steps 1 and 2 did not exhibit Infinite-Acting Radial Flow conditions. A spherical-flow model appears to best describe the observed test responses.

Fig. 5-5: BOS 95.001-i2 (Step 2): constant rate injection test overview
6 Emplacement of the Bentonite Seals

Bentonite seals were installed in BOS 95.001 and BOS 95.002 for the final stage of the project. Two types of seals were installed; in BOS 95.001, MX-80 bentonite was emplaced using pneumatic injection (chapter 4.3); in BOS 95.002, Compactonit® bentonite was emplaced using the MACMET tool (chapter 4.2). The boreholes were instrumented on either side of the bentonite seals to monitor the development of the bentonite over time and to perform hydraulic testing in the intervals adjacent to the bentonite. The instrumentation for the borehole sealing demonstration at GTS was designed to provide a controlled experiment and to optimize data collection, while maintaining a close analog to conditions expected in actual sealing situations.

6.1 Instrumentation

Inflatable packer systems were placed adjacent to the bentonite seals to act as confinements. In comparison to metal packers, the inflatable systems provide a greater degree of flexibility with respect to monitoring of pressures, performance of hydraulic testing adjacent to the seals, and incorporation of a guard packer to ensure safety during testing.

The inflatable double-packer systems with pressure cells and rigid quartz-sand filters were placed on either side of the bentonite (Fig. 6-1). These systems made it possible to monitor the total pressure at the bentonite face (i.e. swelling pressure + hydraulic pressure) and the hydraulic pressure within the adjacent interval without placing any tubes or instruments within the bentonite material. The pressure cells were dual sensors with an electronic pressure sensor, and in case of failure, the pressure cells could also be measured mechanically. In addition, the outside packer functioned as a guard packer for extra anchoring strength and to provide another monitoring interval. Each interval had pressure measurement and injection lines that connected to control units placed in the tunnels. Interval pressures were monitored using electronic pressure sensors placed at the control units.

All electronic sensors were connected to a data acquisition system that continuously monitored pressures in the isolated intervals and at the bentonite face. A modem connection at the site provided remote access to and control of the monitoring system. The data acquisition system was also utilized for hydraulic testing in the latter part of the experiment.

6.2 Emplacement of the MX-80 Bentonite Seal in BOS 95.001 using Pneumatic Injection

The borehole seal in BOS 95.001 was installed on April 10, 1996. The equipment configuration for the pneumatic injection system is presented in Fig. 6-1. The injection system is essentially the same as that used for the laboratory tests in a 100 m borehole as described in Section 4.3. The configuration was a closed system, with the bentonite granules and dust that were blown back through the annulus being collected in a filter, thus allowing a mass balance calculation for quality control.
Fig. 6-1: Borehole configuration for the borehole sealing demonstration experiment
The installation occurred in the following steps:

1. In preparation for emplacement of the bentonite, a double-packer system with pressure cells and rigid quartz-sand filters was installed and inflated from the Laboratory Tunnel in BOS 95.001 (Fig. 6-1). Afterwards the borehole was filled with water.

2. Next, 75 mm o.d. temporary casing with an external casing packer was installed from the Access Tunnel side (Fig. 6-2). After inflating the external casing packer to isolate the target zone, a 48 mm o.d. air-injection pipe was installed within the temporary casing.

3. The injection pipe was pushed in until it reached the pressure cell installed from the Laboratory Tunnel side; water in the target zone was then blown out by injecting air into the interval.

4. The injection pipe was then pulled back to a point 1.2 m from the pressure cell in preparation for injecting the first 1 m lift of granular MX-80 bentonite (4 - 10 mm diameter).

5. The first lift of bentonite was injected (injection time = 73 seconds).

6. The injection pipe was pulled back an additional meter, after which the second lift of bentonite was injected (injection time = 66 seconds).

7. The injection pipe was pulled back an additional 0.5 m, after which a lift of pea-gravel was injected (injection time = 25 seconds). The pea-gravel is designed to act as an additional confinement.

8. The external casing packer was deflated and the temporary casing was removed. The casing packer acted as a swabbing tool, removing the water present in the annulus between the temporary casing and the borehole.

9. A double-packer system with pressure cells and rigid quartz-sand filters was installed and inflated from the Access Tunnel. The system was installed such that the pressure cell butted up directly against the gravel confinement.

10. After inflating the packers, a suction pressure was applied in the interval adjacent to the bentonite seal (Interval 3) by means of a vacuum pump.

11. Water was then injected into the interval in order to saturate the bentonite and interval.

12. Interval 4 was then saturated in a similar manner.

13. All intervals were shut-in and long-term pressure monitoring commenced.

The emplacement density (bulk dry density) calculated from the geometrical borehole data (televiwer data), the positions of the packers and the net mass of the injected material for the MX-80 seal was 1.365 Mg/m³. This value is well within the target range of 1.3 to 1.5 Mg/m³.
6.3 Emplacement of Compactonit Seal in BOS 95.002 using the MacMet tool

The borehole seal in BOS 95.002 was emplaced on March 27, 1996 using the MACMET tool developed by Nagra. Details of the MACMET tool are described in Section 4.2. The MACMET tool facilitates bentonite seal emplacement using a standard drilling rig.

The installation occurred in the following steps:

1. In preparation for emplacement of the bentonite, a double-packer system with pressure cells and rigid quartz-sand filters was installed and inflated from the Laboratory Tunnel in BOS 95.002 (Fig. 6-1).
2. Installation of a small drill rig in the niche of the Access Tunnel. A special sensor was installed to measure the force between drill rig and a fix point on the rock surface.
3. Running of the drill string into the borehole until contact with the lower packer (pressure sensor) was established. Retreat of the drill string by a few centimeters
4. Circulation of drilling mud (pressure effect can clearly be detected in the pressure plot of Fig. 6.3 at about 10 minutes)
5. Loading of the MACMET tool with approx. 5.65 kg of Compactonit®, filling of the remaining space with water and closing the upper end of the tool with a plug from wetted Compactonit® (approx. 0.175 kg).
6. Pumping of the MACMET tool with water pressure into the drill string until it launched at the end of the string (acoustic control).
7. Ejection of the Compactonit® pellets with high water pressure while controlling the force between drill rig and fix point. Stepwise retreat of the drill rig to avoid forces above 2.5 kN (force necessary to keep drill rig in place)

8. Measurement of the net movement of the drill string during operation (approx. 0.45 m)

9. Retreat of the drill string by approx. 1 m and water circulation. Note, that the outflowing water was slightly colored (clay color) but no outflowing pellets were observed.

10. Injection of core barrel catcher and pulling the MACMET tool out of the drill string

11. Check and cleaning of the MACMET tool. No, or only a few pellets (2-6 pellets for run 2-5) remained in the modified core barrel

12. Forward movement of the drill string of about 1 m to again get in close contact with the already emplaced bentonite.

13. Repetition of steps 5 to 12 until a section of about 2.2 m was filled with pellets (a total of 5 runs)

14. Removal of the drill string and drill rig

15. Setting of packer system

The procedure of backfilling and sealing of the borehole section was controlled with the sensors installed at the end of the seal section (Fig. 6.3). The total pressure sensor (Glötzl cell) clearly measured the pressure exceeded on the cell during the first emplacement step of the bentonite (about 0.8 MPa). The subsequent steps showed only minor (step 2) or no pressure response indicating significant friction between the borehole wall and the previously emplaced bentonite plug.

During the operation a total length of 2.18 m borehole section was filled with 28.98 kg of Compactonit®. Assuming a borehole diameter of 96 mm (nominal diameter) this results in an average wet density of 1.84 Mg/m³.

![Fig. 6.3: Pressure plot recorded at the lower end of the seal section in borehole BOS 95-002 during the emplacement of the Compactonit® pellets (details see text)](image-url)
7 Performance of Seals

The performance of the bentonite seals was assessed in a 3-part testing program. The objectives of the testing program are detailed below:

- To monitor the swelling pressures of the bentonite seals and the pressure within the adjacent interval.
- To test the effectiveness of the seals through hydraulic testing in the intervals adjacent to the seals. The hydraulic testing results provide hydraulic conductivity values for comparison to the results of Steps 1 and 2, as well as flow model identification to characterize the nature of flow away from the test interval.
- To test the stability of the seals under various loading situations analogous to what could be expected in an underground repository.

7.1 Long-term Monitoring of Hydraulic- and Swelling-Pressure

The hydraulic pressure within the isolated intervals and the pressure exerted on the pressure cells adjacent to the bentonite seals were monitored from the time of installation until August 6, 1996 for the purpose of documenting the development of the swelling pressure of the bentonite seals. The interval and pressure-cell pressures for BOS 95.001 and BOS 95.002 are shown in Fig. 7-1 and 7-2, respectively.

Fig. 7-1: BOS 95.001 (Bos1; MX-80 seal): pressure cell and interval pressures

A number of sudden changes in the pressure development were observed during Step 3 monitoring. These observations can be correlated with testing activities in the BK Experiment conducted by BGR (Fig. 7-3). It is noteworthy that the pressure trends are inversely related to the activities in the BK experiment (i.e. pressures in the BOS experiment decrease when BK pressures are increased, and vice-versa). This appears to be a hydro-mechanical effect resulting from the re-distribution of stress along the border of a large block of rock. Similar effects were
observed in the EDZ experiment during the same time period. An in-depth discussion of this phenomenon is beyond the scope of this document and is partly considered by Flach & Noell (1989), who observed a significant tilting of a large rock body as a result of a pressure change in borehole BOUS 85-003. However, this may be a subject worthy of further study.

![BOS2-Step3: Pressure Summary](image1)

**Fig. 7-2:** BOS 95.002 (Bos2; Compactonit® seal): pressure cell and interval pressures

![BOS1 & BOS2: Influence of BGR Testing Activities](image2)

**Fig. 7-3:** Comparison of pressures in BOS 95.001 (Bos1) and BOS 95.002 (Bos2) to testing activities in conducted in BOUS 85-003 (BOUS3).
The actual swelling pressures of the bentonite (Tab. 7-1 and Fig. 7-4) are calculated using the following formula:

\[ P_{sw} = \left[ P_{pc} + 0.1 \right] - P_{int} \]

where:
- \( P_{sw} \) is the swelling pressure [MPa]
- \( P_{pc} \) is the measured pressure cell total pressure (relative) [MPa]
- \( P_{int} \) is the hydraulic pressure measured in the interval (absolute) [MPa]

Fig. 7-4: BOS 95.001 (Bos1)&2-Step 3: swelling pressures of the bentonite seals calculated from total and interval pressure

Tab. 7-1: Swelling pressures of the bentonite seals at the end of the monitoring period.

<table>
<thead>
<tr>
<th>Pressure cell location</th>
<th>Final swelling pressure [MPa]</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOS 95.001-i2</td>
<td>0.5</td>
<td>decreasing trend after reaching a maximum of 0.53 MPa</td>
</tr>
<tr>
<td>BOS 95.001-i3</td>
<td>0.75</td>
<td>slightly increasing trend</td>
</tr>
<tr>
<td>BOS 95.002-i2</td>
<td>0.43</td>
<td>slightly increasing trend</td>
</tr>
<tr>
<td>BOS 95.002-i3</td>
<td>0.32</td>
<td>slightly increasing trend</td>
</tr>
</tbody>
</table>
7.2 Active Hydraulic Testing

Hydraulic testing was conducted to evaluate the effectiveness of the bentonite seals. The objectives of the testing are the following:

- To estimate hydraulic conductivities of intervals directly adjacent to the bentonite seals. These values can be compared to the values from Step 2 testing in which no bentonite was present. Any significant increase in permeability would be attributable to the bentonite. If the hydraulic conductivity remains the same, the bentonite seals can be considered to have hydraulic conductivity less than or equal to that of the host rock.

- To characterize the controlling flow model for flow away from a test interval directly adjacent to the bentonite.

7.2.1 BOS 95.001

A constant-rate injection (RI) and recovery (RIS) test was performed in BOS 95.001-i2 with a flow rate of 1 g/hr (Fig. 7-5a). Log-log diagnostic plots of the RI and subsequent RIS periods are shown in Fig. 7-5b&c. The nature of the pressure responses for the injection and recovery periods is significantly different due to variable wellbore storage, which is approximately an order of magnitude smaller for the RIS period \(2.0\times10^{-11}\) m³/Pa than for the RI period \(2.3\times10^{-10}\) m³/Pa. An increasing slope is observed in the RI-period during the wellbore storage-dominated period (Fig. 7-5b), indicating that the wellbore storage varied significantly at low pressures. During the pressure recovery period, the wellbore storage remained constant as indicated by the unit slope observed in Fig. 7-5c. The derivative for the RI period does not clearly indicate a specific flow model. However, the RIS derivative has a negative slope of 0.5 during late time, which may be indicative of spherical flow conditions.

The wellbore simulator, GTFM (Grisak et al., 1985) was used to analyze the RI and RIS test periods. GTFM can take into account variable wellbore storage, as well as various flow dimensions. Input data for the GTFM simulation are provided in Tab. 7-2. A best-fit simulation (Fig. 7-5b&c) was achieved using a hydraulic conductivity value of \(9.5\times10^{-13}\) m/s and a flow dimension of 2.5, which would indicate a flow model somewhere between radial and spherical flow. The simulated pressure and derivatives for flow dimensions 2 and 3 are also shown on the plot for reference.

Tab. 7-2 Input parameters for GTFM simulation of BOS 95.001-i2: RI/RIS

<table>
<thead>
<tr>
<th>Hydraulic Conductivity [m/s]</th>
<th>Specific Storage [m^{-1}]</th>
<th>Wellbore Pressure [kPa]</th>
<th>Storage C - Value [m^3/Pa]</th>
<th>Flow Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>(9.5\times10^{-13})</td>
<td>(5\times10^{-7})</td>
<td>400</td>
<td>(2\times10^{-10})</td>
<td>Variable</td>
</tr>
<tr>
<td></td>
<td></td>
<td>600</td>
<td>(3.7\times10^{-11})</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1800</td>
<td>(2\times10^{-11})</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 7-5: BOS 95.001-Step 4: GTFM simulation of RI1 and RIS1
7.2.2 BOS 95.002

A constant-rate injection (RI) and recovery (RIS) tests were performed in BOS 95.002-i2 with a flow rate of 1.5 g/hr (Fig. 7-6a). Log-log diagnostic plots of the RI and subsequent RIS periods are shown in Fig. 7-6b&c. As occurred in BOS 95.001-i2, the nature of the pressure responses for the injection and recovery periods are significantly different due to variable wellbore storage, which is approximately half an order of magnitude smaller for the RIS period \(1.6 \times 10^{-11} \text{ m}^3/\text{Pa}\) than for the RI period \(5.2 \times 10^{-11} \text{ m}^3/\text{Pa}\). An increasing slope is observed in the RI-period during the wellbore storage-dominated period (Fig. 7-6b), indicating that the wellbore storage varied significantly at low pressures. During the pressure recovery period, the wellbore storage remained constant as indicated by the unit slope observed in Fig. 7-6c. The derivative for the RI period does not clearly indicate a specific flow model. However, the RIS derivative has a negative slope of 0.5 during late time, which may be indicative of spherical flow conditions.

The wellbore simulator, GTFM (Grisak et al., 1985) was used to analyze the RI and RIS test periods. Input data for the GTFM simulation are provided in Table 7-3. A best-fit simulation (Fig. 7-6b&c) was achieved using a hydraulic conductivity value of \(4.5 \times 10^{-12} \text{ m/s}\) and a flow dimension of 2.5, which indicates a flow model somewhere between radial and spherical flow. The simulated pressure and derivatives for flow dimensions 2 and 3 are also shown on the plot for reference.

<table>
<thead>
<tr>
<th>Hydraulic Conductivity [m/s]</th>
<th>Specific Storage [m^3/\text{m}^3]</th>
<th>Wellbore Pressure [kPa]</th>
<th>Storage C - Value [m^3/\text{Pa}]</th>
<th>Flow Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>(4.5 \times 10^{-12})</td>
<td>(5 \times 10^{-7})</td>
<td>210</td>
<td>5.6 \times 10^{11}</td>
<td>Variable</td>
</tr>
<tr>
<td></td>
<td></td>
<td>655</td>
<td>9.6 \times 10^{-12}</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4312</td>
<td>4.8 \times 10^{-12}</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 7-6: BOS 95.002-Step 4: GTFM simulation of RI3 and RIS3
7.2.3 Summary of Hydraulic Testing Results

The hydraulic testing conducted in the BOS Experiment provides indications of the hydraulic conductivity of the test site before and after installation of the bentonite seals. A summary of the hydraulic conductivity values estimated in the various phases of the experiment are presented in Tables 7-4 and 7-5. The results indicate no increase in hydraulic conductivity after installation of the bentonite seals.

Tab. 7-4 BOS 95.001: summary of hydraulic conductivity values estimated during the BOS experiment.

<table>
<thead>
<tr>
<th>Test Phase</th>
<th>Hydraulic Conductivity [m/s]</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 1 (preliminary characterization)</td>
<td>2.7·10^{-12}</td>
<td>Measured over a single 9.8 m section</td>
</tr>
<tr>
<td>Step 2 (preliminary characterization)</td>
<td>3.0·10^{-12}</td>
<td>Average value from 2 sections</td>
</tr>
<tr>
<td>Final Phase (after bentonite seals were installed)</td>
<td>9.5·10^{-13}</td>
<td>Value for a 1.06 m-long section adjacent to the bentonite seal</td>
</tr>
</tbody>
</table>

Tab. 7-5 BOS 95.002: summary of hydraulic conductivity values estimated during the BOS experiment.

<table>
<thead>
<tr>
<th>Test Phase</th>
<th>Hydraulic Conductivity [m/s]</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 1 (preliminary characterization)</td>
<td>5.4·10^{-12}</td>
<td>Measured over a single 9.8 m section</td>
</tr>
<tr>
<td>Step 2 (preliminary characterization)</td>
<td>5.0·10^{-12}</td>
<td>Average value from 2 sections</td>
</tr>
<tr>
<td>Final Hydraulic Testing Phase (after bentonite seals were installed)</td>
<td>4.5·10^{-12}</td>
<td>Value for a 1.06 m-long section adjacent to the bentonite seal</td>
</tr>
</tbody>
</table>

7.3 Mechanical Stability of the Bentonite Seals

The final portion of the BOS Experiment was designed to test the stability of the seals under loading conditions analogous to situations that can be expected in an underground repository. The performance of the seals was evaluated in the following three scenarios:

With the confinement in place on the low-pressure side of the bentonite seal and with the maximum expected formation pressure exerted hydraulically on the high-pressure side.

With a disintegrated confinement on the low-pressure side and the maximum expected formation pressure exerted hydraulically on the high-pressure side.
As No. 2 above, except that the pressure is exerted mechanically (instead of hydraulically) on the high-pressure side.

### 7.3.1 Instrumentation for Mechanical Stability Testing

The test configurations used for simulating the above scenarios are summarized in Table 7-6 and described in the text that follows.

<table>
<thead>
<tr>
<th>Scenario / Borehole</th>
<th>Packer System Laboratory Side</th>
<th>Packer System Access Side</th>
<th>Injection Interval</th>
<th>Displacement Transducers</th>
<th>Mechanical Push Side</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1: BOS 95.001</td>
<td>Inflated</td>
<td>Inflated</td>
<td>i2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Scenario 1: BOS 95.002</td>
<td>Inflated</td>
<td>Inflated</td>
<td>i2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Scenario 2: BOS 95.001</td>
<td>Inflated</td>
<td>Deflated</td>
<td>i2</td>
<td>Access</td>
<td>-</td>
</tr>
<tr>
<td>Scenario 2a: BOS 95.001</td>
<td>Deflated</td>
<td>Inflated</td>
<td>i3</td>
<td>Laboratory</td>
<td>-</td>
</tr>
<tr>
<td>Scenario 2: BOS 95.002</td>
<td>Inflated</td>
<td>Deflated</td>
<td>i2</td>
<td>Access</td>
<td>-</td>
</tr>
<tr>
<td>Scenario 3: BOS 95.002</td>
<td>Removed</td>
<td>Deflated</td>
<td>-</td>
<td>Access</td>
<td>Laboratory</td>
</tr>
</tbody>
</table>

Scenario 1       The down-hole configurations from hydraulic characterization were utilized for Scenario 1 (Fig. 6-1).

Scenario 2       The packers on the Access Tunnel side were deflated. Displacement transducers were installed on the central tubing of the deflated packer systems to monitor movement of the bentonite seals that would be transferred directly to the packer system (Fig. 7-7). A hydraulic pressure was then applied in i-2, across the bentonite from the deflated system.

Scenario 2a      (BOS 95.001 only) The packers on the Laboratory side were deflated. Displacement transducers were installed on the central tubing of the deflated packer systems to monitor movement of the bentonite seals that would be transferred directly to the packer system. A hydraulic pressure was then applied in i-3, across the bentonite from the deflated system.

Scenario 3       (BOS 95.002 only) The packer system was removed from the Laboratory Tunnel side and replaced with a mechanical push system (Fig. 7-8). The mechanical-push system consisted of a 90 mm diameter plate connected via 2 3/8-inch EU tubing to a 23-ton hydraulic press mounted on the tunnel wall.
Fig. 7.7: Instrumentation of BOS 95-001 during stability tests of scenario 2 (details see text)

Fig. 7.8: Instrumentation of BOS 95-001 during stability tests of scenario 3 (details see text)
7.3.2 Hydraulic Loading with Packers Inflated

Hydraulic pressure ranging from 4 to 5 MPa was applied in i2 of each borehole. These tests were conducted to simulate high hydraulic pressure on one side of the seal and an intact confinement on the low-pressure side of the seal, as well as to evaluate the safety aspects of proceeding with the subsequent test phases in which the packers on the low-pressure side would be deflated.

In BOS 95.001, HPO1 was started directly after a constant-rate injection test by increasing the injection flow rate from 2 g/hr to 10 g/hr (Fig. 7-9). This provided a gradual transition to the target injection pressure. The pressure cell and interval pressures across the bentonite seal are shown in Fig. 7-10. Although a pressure disturbance was caused by changing a transducer, a clear response with a significant time lag (between 10 and 20 hours – large uncertainty because of pressure disturbance) is observed in both the pressure cell and the interval. At the end of the injection period, these pressures decreased back to the approximate original pressures. That the cell pressure did not remain elevated indicates that the observed response was a hydraulic response, and not due to movement of the bentonite seal.

The response in BOS 95.002 was similar to that in BOS 95.001 (Fig. 7-11 and 7-12). The pressure responses across the bentonite seal indicated a lag time of approximately 15 hours. As in BOS 95.001, the pressure responses are reversible together with the long lag in response indicates a hydraulic, rather than a dynamic cause (i.e. movement of the bentonite seal) of the pressure response.

Fig. 7-9: BOS 95.001: pressure response in the injection interval (i2) and observation interval (i3) during HPO1 (hydraulic loading with all packers inflated).
Fig. 7-10: BOS 95.001: pressure response in the observation interval (i3) during HPO1 (hydraulic loading with all packers inflated).

Fig. 7-11: BOS 95.002: pressure response in the injection interval (i2) during HPO1 (hydraulic loading with all packers inflated).
7.3.3 Hydraulic Loading with Packers Deflated

The second push-out tests (HPO2) were conducted with the packers deflated on the Access Tunnel side. Displacement transducers mounted on the central tubing of the packer systems monitored the movement of the bentonite seals which were in direct contact with the packer systems. Hydraulic pressure ranging from 4 to 5 MPa was applied simultaneously in i2 of both boreholes. These tests simulate borehole sealing with a defective confinement.

Fig. 7-13 and 7-14 show the responses during HPO2, including the displacement and velocity of the deflated packer systems. The packers were deflated a day prior to the start of injection on the other side of the bentonite. Upon release of the packers, movement was observed immediately in BOS 95.002 and after approximately 6 hours in BOS 95.001 (Fig. 7-15). This movement is caused by expansion of the bentonite seals due to the release of the swelling pressure against the pressure cells on the packer systems. The spikes in the velocity curves displayed in Fig. 7-13 and 7-14 between November 28 and December 04, 1996 are caused by adjustments of the test set-up (e.g. inflation or deflation of packers).

A clear acceleration is observed in BOS 95.002 during the hydraulic loading period across the seal. The acceleration is clearly indicated by the changing velocity of the system during the test and is most pronounced after the second pressure pulse. The bentonite seal decelerated when the hydraulic loading was stopped.

In contrast to BOS 95.002, BOS 95.001 did not respond to the hydraulic loading on the laboratory side of the seal (Fig. 7-15). To test whether the lack of movement was due to the nature of the different sealing materials, or to the asymmetry of the bentonite seal (i.e. a gravel confinement was installed on the Access Tunnel side), the test configuration was reversed for
BOS 95.001-HPO3 such that the hydraulic load was applied on the Access Tunnel side and the displacement was measured on the Laboratory Tunnel side.

In general, the velocity during BOS 95.001-HPO3 is markedly greater than that observed on the Access Tunnel side. It is possible either that the gravel serves to anchor the seal on the Access side, or, less likely, that the seal was highly compressed during the preceding loading on the Laboratory Tunnel side and therefore expanded at a higher rate. The seal also appears to accelerate and decelerate in response to loading and unloading on the Access Tunnel side (Fig. 7-13, right side). This observation supports the hypothesis that the gravel pack was an effective mechanical confinement during the push-out test HPO2 in BOS 95.001 after an initial settlement phase while for HPO3 no such mechanical confinement was acting because of the asymmetry of the seal. Comparing HPO2 and HPO3 in BOS 95.001, it is obvious that a gravel pack increases the mechanical stability of a borehole seal.

Fig. 7-13: BOS 95.001 5: multi-plot showing a) displacement and velocity of the deflated packer system, and b) the hydraulic- or mechanical-loading pressure.
Fig. 7-14: BOS 95.002: multi-plot showing a) displacement and velocity of the deflated packer system b) the hydraulic- or mechanical-loading pressure.

Fig. 7-15: BOS 95.001 5: close-up plot of the early HPO2 phase showing displacement of the deflated packer system and the hydraulic- loading pressure.
### 7.3.4 Mechanical Loading with Packers Deflated

The loading test, BOS 95.002-HPO2, clearly indicated that the bentonite seal could be mobilized by applying a hydraulic load. Knowledge of the point at which the movement becomes catastrophic, i.e. total failure of the seal, is also of interest. However, application of a hydraulic load greater than 5 MPa was not feasible because of safety considerations. Instead, a mechanical load (MPO1) was applied to the seal as shown in Fig. 7-8. First, a 5.0 MPa mechanical load was applied for a number of days (Fig. 7-14). Then the load was increased to 7.5 MPa. The displacement observed during MPO1 appears to be due to expansion of the seal, and does not correspond to the mechanical loading on the seal.

The fact that the seal could not be mobilized with a mechanical load is most likely related to the physical differences in hydraulic and mechanical loading. In the case of hydraulic loading, the pore pressure is elevated throughout the seal and enables the mobilisation of the entire seal. In mechanical loading, the pore pressure elevates only locally, bleeding away around the push plate. This results in differential compression in the seal and an increase of the normal forces on the borehole wall which in turn increase frictional resistance against axial movement of the entire mass.
8 Conclusion

With the research and development project described, we were able to formulate two borehole sealing concepts, construct the tools which are necessary for the technical implementation of the methods, conduct laboratory and in-situ tests and verify the performance of the seals.

It was demonstrated that the emplacement techniques work even for underground sub-horizontal boreholes and that the hydraulic conductivities of the seals are equal or even lower than that of the intact granite at the GTS (approx. $3-6 \cdot 10^{-12}$ m/s) for both emplacement techniques and both sealing materials used. At least for the seal with MX80 granular bentonite, it is expected that the real hydraulic conductivity is one order of magnitude lower than the measured one in the field but could not be resolved because of the hydraulic conductivity of the surrounding rock.

The different techniques allow adequate sealing procedures to be selected for given boundary conditions. Both techniques have different advantages – while the modified core barrel (MACMET tool) needs no additional specialists on site but can be performed by a normal drilling crew, the pneumatic injection technique is advantageous in cases where very long sections have to be sealed or the use of highly active bentonite is required. Both methods can be used for vertical or downwards inclined boreholes. For borehole from underground openings which are upwards directed the use of the MACMET tool is more suited than the pneumatic method although first tests have indicated that the latter technique could also be used if water is added during the blowing process similar to shotcreting with dry cement mixtures. Nevertheless, more tests are necessary to make this technique reliable under such conditions.

It was shown that the sealing elements need mechanical abutments especially if a high fluid pressure gradient exists along the seal. The use of pea-gravel or even quartz sand seems to be an adequate solution for confinement if sufficient length is selected. This technique is very promising for the pneumatic technique as seal and abutment can be emplaced without removing the blow pipe. Alternatively, the metal packers developed within this project can provide an adequate long-living mechanical abutment.

The laboratory tests showed that the granular bentonite has the capacity to give emplacement bulk dry density as high as 1.6 Mg/m$^3$, thus qualifying also as buffer material in emplacement tunnels for high-level radioactive waste. If such an application is envisaged, it will become necessary to solve the dust problem associated with pneumatic emplacement. This problem could be solved either by using appropriate bulk heads and filters or by completely changing the emplacement technique (e.g. using conveyors or auger systems).
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