R-09-50

Plugs for deposition tunnels in a deep geologic repository in granitic rock

Concepts and experience

D A Dixon, AECL

L Börgesson, Clay Technology

D Gunnarsson, Svensk Kärnbränslehantering AB

J Hansen, Posiva

November 2009

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co

Box 250, SE-101 24 Stockholm
Phone +46 8 459 84 00

ISSN 1402-3091
SKB Rapport R-09-50

Plugs for deposition tunnels in a deep geologic repository in granitic rock

Concepts and experience

D A Dixon, AECL

L Börgesson, Clay Technology

D Gunnarsson, Svensk Kärnbränslehantering AB

J Hansen, Posiva

November 2009

Abstract

Regardless of the emplacement geometry selected in a geological repository for spent nuclear fuel, there will be a requirement for the access tunnels to remain open while repository operations are ongoing. The period of repository operation will stretch for many years (decades to more than a century depending on disposal concept and number of canisters to be installed). Requirements for extended monitoring of the repository before final closure may further extend the period over which the tunnels must remain open. The intersection of the emplacement rooms/drifts and the access tunnels needs to be physically closed in order to ensure that the canisters remain undisturbed and that no undesirable hydraulic conditions are allowed to develop within the backfilled volume. As a result of these requirements, generic guidelines and design concepts have been developed for "Plugs" that are intended to provide mechanical restraint, physical security and hydraulic control functions over the short-term (repository operational and pre-closure monitoring periods).

This report focuses on the role and requirements of plugs to be installed at emplacement room/tunnel/drift entrances or in other locations within the repository that may require installation of temporary mechanical or hydraulic control structures. These plugs are not necessarily a permanent feature of the repository and may, if required, be removed for later installation of a permanent seal. Room/Drift plugs are also by their defined function, physically accessible during repository operation so their performance can be monitored and remedial actions taken if necessary (e.g. increased seepage past the plug).

A considerable number of sealing demonstrations have been undertaken at several research laboratories that are focussed on development of technologies and materials for use in isolation of spent nuclear fuel and these are briefly reviewed in this report. Additionally, technologies developed for non-nuclear applications where plugs are needed in an underground environment are also examined and their potential for use in a repository application is discussed.

Several generic plug designs have also been developed by SKB and Posiva as part of their repository engineering programs and these are presented, together with a brief discussion of some of the key advantages, disadvantages and issues associated with them. Based on this review it would seem that the most appropriate plug for use in a spent-fuel repository will be some form of a composite construction, consisting of both low-pH concrete and compacted swelling clay components. Final design of plugs will of course be site-dependant and must be tailored to the field conditions.

Sammanfattning

Oavsett vilken placeringslayout som väljs i ett geologiskt förvar för använt kärnbränsle, kommer det att vara ett krav på att hålla stamtunnlarna öppna under driftskedet. Detta skede kommer att sträcka sig över flera år (decennier till mer än hundra år beroende på valt förvaringskoncept och antal kapslar som ska deponeras). Krav på förlängd övervakning av förvaret innan slutlig förslutning, kan komma att ytterligare förlänga den period som tunnlarna måste hållas öppna. Deponeringstunnlarna måste vara fysiskt avskilda från stamtunneln för att säkerställa att kapslarna förblir opåverkade och att inga oönskade hydrauliska förhållanden utvecklas i den återfyllda volymen. Som ett resultat av dessa krav har generiska riktlinjer och designkoncept utvecklats för ”Pluggen” som är ämnade att ge mekaniska begränsningar, fysiskt skydd samt hydraulisk kontrollfunktioner över en kortare tid (driftskede och övervakning innan förslutning).

Denna rapport fokuserar på funktion och krav på pluggen som ska installeras vid ingången till deponeringstunnlarna eller på andra ställen inom förvaret som kan kräva installation av temporära mekaniska eller hydrauliska kontrollkonstruktioner. Dessa pluggar behöver nödvändigtvis inte vara för permanent bruk i förvaret och kan om det krävs, senare avlägsnas för att istället installera en permanent förslutning. Tunnelpluggar är genom sin funktion fysiskt tillgängliga under driftskedet, därför kan funktionen övervakas och korrigerande åtgärder omedelbart vidtas om det skulle bli nödvändigt (t ex ökat läckage genom pluggen).

Ett antal förslutningstester/demonstrationer har utförts på olika forskningslaboratorier där det har fokuserats på att utveckla teknologier och material för att isolera använt kärnbränsle, dessa tester beskrivs övergripande i denna rapport. Dessutom diskuteras teknologier för icke nukleära applikationer där pluggar behövs i underjordsmiljö samt deras potential för att kunna användas i ett slutförvar.

Flera generiska pluggkoncept har utvecklats av SKB och Posiva som en del av teknikutvecklingsprogrammet för ett slutförvar, dessa presenteras, tillsammans med en sammanfattning av huvudsakliga fördelar, nackdelar och frågor associerade till respektive pluggkoncept. Baserat på denna sammanställning ser det ut som att det mest lovande pluggkonceptet i ett förvar för använt kärnbränsle är en struktur av både låg-pH betong och kompakterade svällande lerkomponenter. Den slutliga designen av pluggen kommer förstås att vara platsberoende dvs. designen måste skräddarsys efter förhållandena på platsen.

Contents

1 Background

1.1 Repository concepts

A number of national programs are, or have considered, deep geologic disposal in granitic rock formations (e.g. Canada, Finland, France, Japan, Spain, Sweden and Switzerland). In particular, Sweden and Finland are focusing their attention on granitic media for repository construction. One of the key advantages of the deep geologic disposal concept in granitic media is that it provides a means of safely isolating this material in a location that is removed from locations that might in the future be prone to unintentional human intrusion.

Deep geologic disposal, regardless of the geologic medium selected, has the goal of ensuring that any contaminants that might ultimately be released from the corrosion-resistant emplacement canisters are isolated from the biosphere until they are no longer a hazard. While many of the details of the deep geologic repository concepts considered by various national programs differ, they all include corrosion-resistant canisters holding radioactive materials that are to be installed in rooms, tunnels or drifts specifically excavated for that purpose. These excavated volumes must subsequently be backfilled and sealed to ensure that any contaminant migration is limited, protecting the biosphere /OECD 2003, EC 2004/.

Figures 1-1 and 1-2 present the generic layouts of the in-floor, vertical emplacement concept (KBS-3V) and the horizontal borehole concept (KBS-3H) concepts respectively. These concepts are being considered by Sweden and Finland.

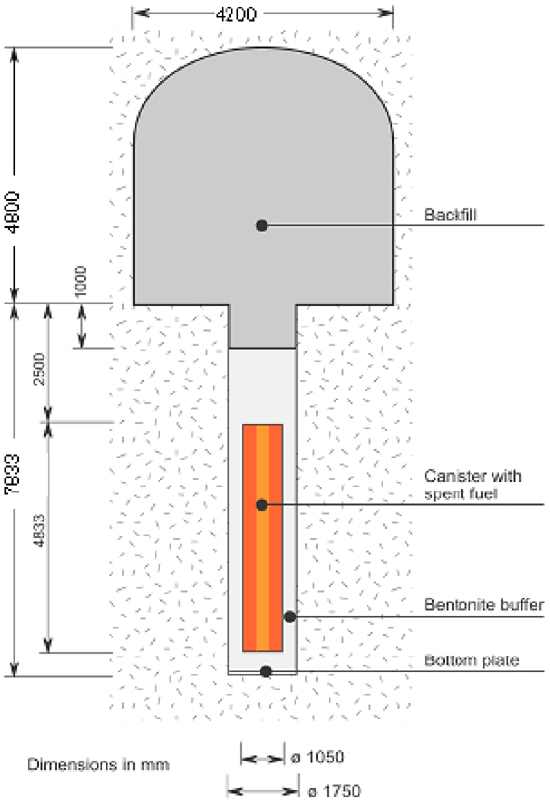


Figure 1-1. *In-floor emplacement concept /Wimelius and Pusch 2008/.*

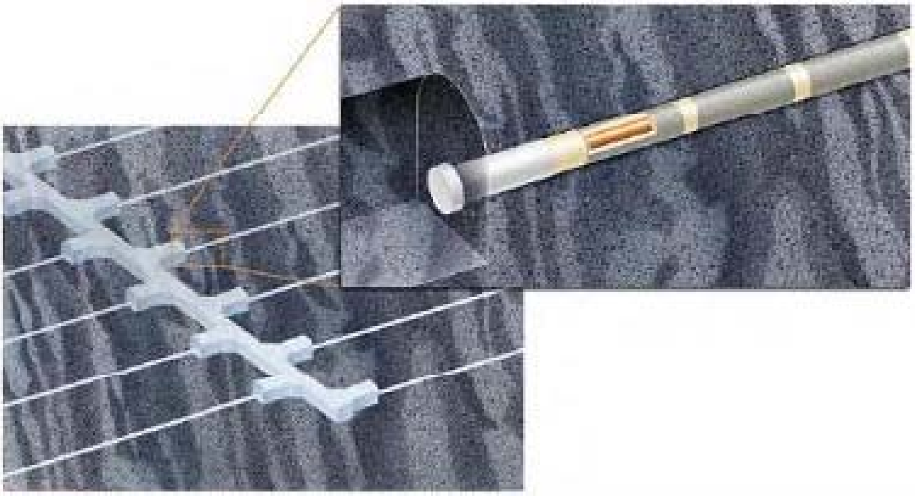


Figure 1-2. *Horizontal emplacement concept /SKB 2005/.*

Regardless of the emplacement geometry selected, there will be a requirement for the access tunnels to remain open while repository operations are ongoing. The period of repository operation will stretch for many years (decades to more than a century depending on disposal concept and number of canisters to be installed). Requirements for extended monitoring of the repository before final closure may further extend the period over which the tunnels must remain open. This means that tunnels that run past rooms/drifts that have already have canisters installed within them and that have been subsequently backfilled to the point of intersection with the access ways must be kept accessible. The intersection of the emplacement rooms/drifts and the access tunnels need to be physically closed in order to ensure that the canisters remain undisturbed and that no undesirable hydraulic conditions are allowed to develop within the backfilled volume. As a result of these requirements, the generic guidelines produced by most national programs considering deep geologic repositories call for the installation of plugs at the junction of the emplacement room/drift and the access tunnels.

In order to distinguish between constructions that are intended to provide short- or long-term performance, the terms “plug” and “seal” are used very specifically in this report. “Plugs” are those constructions that are intended to provide mechanical restraint, physical security and hydraulic control functions over the short-term (repository operational and pre-closure monitoring periods). Constructions that are to prove longer-term performance (post-closure) are termed “Seals”. Seals are therefore permanent installations while plugs may or may not have a sealing function over the longer term (Plugs may become Seals at the time of repository closure). The distinction between these two functions may seem subtle but is important when it comes to defining their performance requirements.

This report focuses on the role and requirements of the plugs that are to be installed at emplacement room/tunnel/drift entrances or in other locations within the repository that may require installation of temporary mechanical or hydraulic control structures. An example of where such a structure is needed is where a section of an emplacement tunnel is found to be unsuitable hydraulically and requires remedial action to prevent unacceptably high water influx to occur into adjacent areas. These plugs are not necessarily a permanent feature of the repository and may, if required, be removed for later installation of a permanent seal. Room/Drift plugs are also by their defined function, physically accessible during repository operation so their performance can be monitored and remedial actions taken if necessary (e.g. increased seepage past the plug).

Short-term plugging or longer-term sealing of underground openings is not a new issue in mining and geotechnical engineering and much can be gained by examining the experiences of non-nuclear applications.

1.2 Purpose of short-term plugs

SKB has described the main purpose of the tunnel plug to be that of a temporary feature that functions until final closure of the repository. Its role is generically defined to be to:

1. Cut off the water flow along the tunnel.
2. Resist the pressure exerted by the backfill and the water.

Associated with these generic roles is the need for the plug to ensure that the backfill or buffer materials it restrains remain where they were installed. They must also not undergo any reduction in their hydraulic or swelling capacity as the result of interaction with the plug itself.

Extensive work done on the performance of the sealing system components located closest to the canister (buffer and backfill), but the plugging/sealing of the emplacement rooms has not received detailed of attention until the last few years. There has been a general recognition that plugs are necessary, especially during the operational period of the repository. Their defined or required functions have typically been expressed in terms of how they might interact with the buffer/backfill that they contact or effects on adjacent groundwater chemistry. It has also been generally accepted that much of the information needed to design and install adequate tunnel plugs can also be applied to shaft plugs and seals.

Most international concepts that include a room/drift plug call for the plug to be composed of some form of massive concrete installation, usually working in conjunction with a swelling clay material. The concrete component of this plug is normally described in generic terms as being a low pH material having adequate strength and volumetric stability to effectively seal the opening into which it is installed. In order to provide more than simple mechanical restraint, physical isolation and limited resistance to seepage, there will be the need for installation of swelling clay at upstream of the concrete structure. Pre- and/or post-installation grouting of the rock adjacent to the concrete may also be necessary. It is these materials that will provide the plug with a much of its hydraulic plugging capacity. Ultimately, when it is time for repository closure, plugs that have proven to be effective hydraulic barriers may be left in-place as seals. Alternatively the plugs may be removed and replaced with more elaborate seals or else removed and their volume filled with backfilling materials if massive concrete plugs/seals are deemed to be undesirable.

In a geologic setting where the rock is sparsely fractured and water supply to the plugged excavation is limited, it may be possible to install a plug that is simple and whose performance can be relied on for the required duration. However, if the system is hydraulically active with substantial quantities of water being supplied to the volume isolated by the plug, then containing water pressures of 5 to 7 MPa (associated with hydraulic heads of 500 to 700 m), as well as whatever swelling pressure is generated by the adjacent sealing materials will be more challenging. This is particularly true where the rock in the vicinity of the seal is damaged, either by pre-existing fissures, joints or cracks, or by the excavation of the room/drift (an EDZ).

The intersection of room/drift excavations and access tunnels is one location that will require plugging but they will also be needed to deal with hydraulic features that intersect the emplacement room/drifts or tunnels (Figure 1-3). These high-flow features may be a considerable distance from the end of the room and may be so hydraulically active that they are an issue with regards to the ability to place backfill or buffer and also may cause erosion of these materials once they are placed. High water inflow features within the repository are generally viewed as persisting only during the pre-closure and pre-saturation period of the repository when high hydraulic gradients exist. Once the repository is closed, these gradients will decrease until only the very much lower regional groundwater gradients persist. Constructions installed within the rooms/drifts and that provide protection from groundwater influx or backfill/buffer erosion will be effectively inaccessible once backfilling progresses beyond them and so they will also need to provide a longer-lived, localized barrier. There is therefore the need to have a range of plug/seal design options and experience available to the repository engineers so that plugs/seals that are appropriate to the specific location and role can be selected.

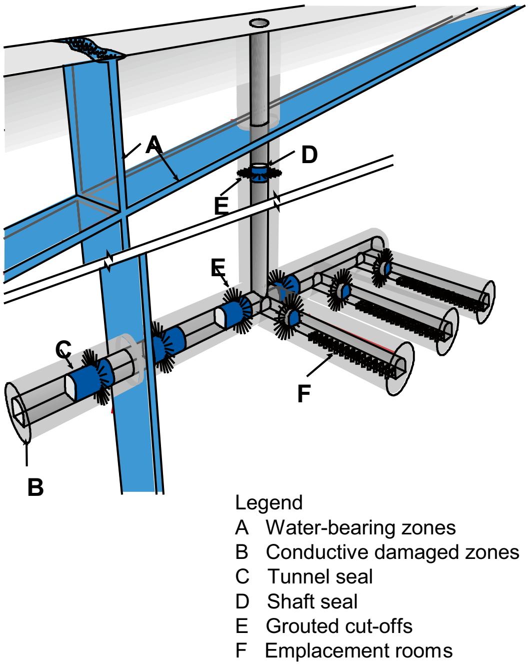


Figure 1-3. *Locations within a repository that may require plugs and seals /AECL 1994/.*

The performance criteria for a room/drift plug for a geologic repository are only vaguely defined. For a plug of short-duration requirement (10's to 100's of years), performance can be measured against its role to "cut-off" water flow from the room (thereby prevented erosion of the contained materials) and to physically resist pressures that may be generated within the room (hydraulic and swelling). These performance goals may seem straightforward but accomplishing them may prove problematic and depend on the rock conditions encountered. In order to assess how various plug designs will perform it will be necessary to construct a variety of test plugs and then monitor their performance under a range of hydraulic conditions. A number of tunnel plug/seal tests have been conducted by various organizations interested in deep geologic disposal of used nuclear fuel, but there also exists a considerable literature on the performance of plugs/seals installed for other purposes (e.g. mining operations, hydroelectric, environmental remediation). These experiences are briefly reviewed in Section 3 of this report.

The development of design options for plugs also has cost implications for the repository. Given that there will be the need for hundreds of plugs to be constructed (at least one at the entrance to each room/drift), the ability to select from design options ranging from simple mass-poured (and grouted) concrete plugs through to more complex composite systems (concrete, bentonite, grout) will be desirable. Costs of the various plug construction options are not considered in this document but a general rule is the more complex the plug, the more expensive it will be.

2 Approaches to tunnel plugging and sealing

2.1 Factors influencing plug design

Installation of tunnel plugs intended to protect one area of an underground facility from unacceptable water influx or to redirect water flow from one pathway to another (e.g. water diversion tunnels for hydroelectric facilities) is not an entirely new application. /Barcena et al. 2005/ and /Kirkwood and Wu 1995/ discuss the philosophy and approach to plug construction in mines (typically coal mines) while /Fuenkajorn and Daemen 1995/ and /Auld 1996/ discuss more generic issues related to sealing and sealing approach. All of this information and the approaches to plugging discussed by the previously listed authors can be applied to any situation where an underground excavation needs to be isolated. /Barcena et al. 2005/ describe the need for geological and hydrological assessments to be made for each plug and from these the specific plug design is developed. In the geological assessment step, the approach described by /Barcena et al. 2005/ calls for locating sound, homogeneous rock that for at least 3 plug lengths that is free of structural weaknesses such as faults, fissures, friable or soft materials. Once the initial geological assessment is done the hydrological assessment where potential connections between the two sides of the plugged tunnel are identified and changes in the hydrological regime due to plug placement are assessed. Assessment of cracks, joints and other features is necessary to evaluate what fractures and fracture fill exists in the isolated section of tunnel and the risk of erosion and increase in flow evaluated. Finally, hydrogeochemical conditions and potential to affect the plug need to be evaluated.

On completion of geologic and hydrological assessments, plug design can progress. /Barcena et al. 2005/ noted that a rough rock/plug interface is essential to provide frictional bond and reduce the hydraulic gradient along interface. The plug itself needs to be designed to resist failure from 5-possible modes:

1. Hydraulic jacking of rock surrounding plug.
2. Sear failure through concrete, along contact/rock contact or through rock.
3. Deep beam flexure failure.
4. Excessive seepage around plug and potential backwards erosion.
5. Long term chemical/physical breakdown of concrete, grout or surrounding rock.

Reinforcing of the plug, and anchoring it into rock without causing stress conditions that favour flow along or close to plug is also recommended. For a plug/seal that is to be left in place in a repository re-enforcing, anchoring/re-enforcing may not be appropriate due to the introduction of large quantities of steel into the repository (other re-enforcing media exist, e.g. resin rods, glass fibre but would need to be assessed for compatibility with the geosphere). Rate of water flow past a plug will also depend on hydraulic gradient and so the longer the flow path induced, the lower the gradient will be. Resistance of rock openings to water flow will generally be improved by pregrouting. /Barcena et al. 2005/ also noted that pH effects, geochemistry and dissolution of concrete under hydro-geochemical conditions must be evaluated. All of these issues are relevant in a plug installed in a repository and need to be considered in the design process.

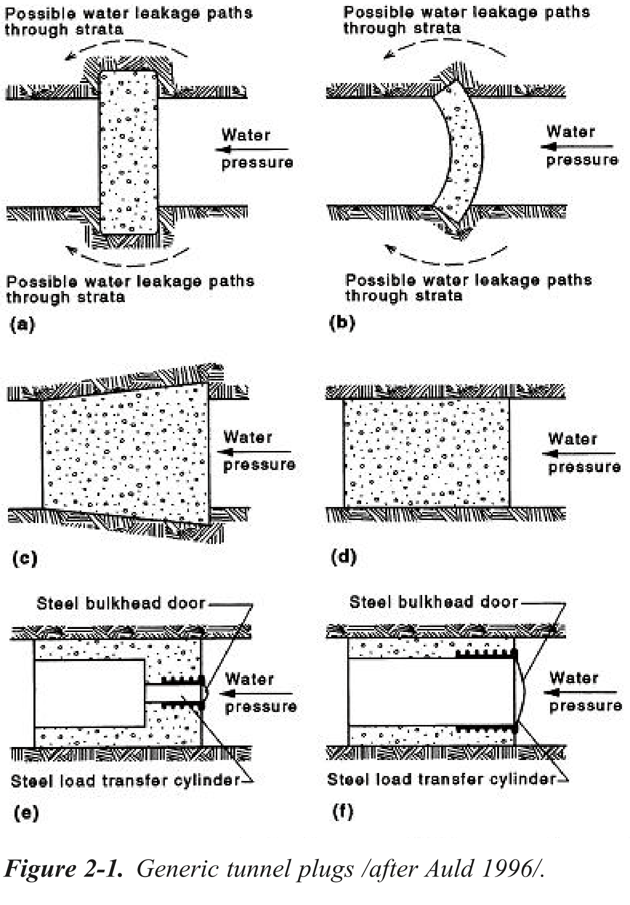
/Akgun and Daemen 1999/ examined various aspects related to the design of friction plugs for abandoning underground workings. This type of plug relies solely on the frictional bond between the walls of the tunnel and the concrete plug and does not involve keying or any other means of transferring the load to the surrounding rock. The key factors identified regarding the stability of a friction-type concrete plug are identified as:

1. Interface strength increases with decreasing plug radius and with increasing plug length.
2. Axial strength decreases as a power law of plug radius.
3. Increase in the modulus ratio (ratio of plug modulus to rock modulus) increases interface strength until it levels off at a ratio of about 5.0. As a result short plugs may not be stable for longer time periods.

As a result of these factors, friction plugs with a length to radius ratio of at least 8 were recommended for long-term stability where the stress modulus ratio of 0.233 is present. The importance of considering rock stress conditions when designing a concrete plug is also noted by /Akgun and Daemen 1999/. Beyond the frictional and compressive stresses associated with a massive concrete plug, it is necessary to consider the tensile stresses generated at the upstream end of the plug/rock system when a pressure gradient exists. Tensile stress may also act in tandem with tensile stresses already present in the rock as the result of the excavation of the room/tunnel (this consideration is particularly important in excavations made in rocks having high differential stresses (e.g. at Canadian URL, at Forsmark Sweden or Okuloto Finland)). If the tensile stresses are high enough they could lead to localized failure (cracking) or development of a more extensive excavation damaged zone in the rock. This will likely result in higher seepage past the plug and might in extreme cases result in mechanical failure of the plug.

/Auld 1996/ also discussed tunnel plugging applications and considerations. He identified 4 types of plugs and 8 factors that need to be considered in the design of these plugs. Examples of the types of tunnel plugs described by /Auld 1996/ are presented in Figure 2-1. The four types of plugs are:

1. Precautionary Plugs – to limit area affected if a large water influx were to occur.
2. Control Plugs – Sealing off or controlling influx from adjacent excavations.
3. Emergency Plugs – required due to unexpected inrush of water into open excavations.
4. Temporary or Consolidation Plugs – allow water inflow to be controlled or stopped while grouting or remedial activities to control water inflow are done.



(a) Reinforced slab (insufficient leakage resistance)
(b) Unreinforced arch (insufficient leakage resistance
(c) Unreinforced concrete tapered plug (good leakage resistance
(d) Unreinforced concrete parallel plug
(e) Unreinforced concrete cylindrical plug w. human access
(f) Unreinforced concrete cylindrical plug w. roadway access.

Figure 2-1. Generic tunnel plugs /after Auld 1996/.

The factors identified by /Auld 1996/ to consider when designing a plug are:

1. Identify which of the four types of plug you are designing.
2. What is the nature of the excavation being plugged.
3. Where is the plug to be located, is the location flexible or defined.
4. What is the shape of the plug to be installed.
5. What hydraulic head must be restrained.
6. What are the local rock and stress conditions.
7. What is the strength and stress conditions in the plug.
8. How is the plug to be constructed.

The approach proposed by /Auld 1996/ is particularly helpful in bringing plug design and construction approaches in a geologic repository into focus. In most situations where emplacement tunnels or drifts are to be plugged, the plugs to be installed are control plugs that can be installed as required. From this basis the evaluation of the factors affecting plug design can be assessed.

2.2 Plug construction options

There are as many plug designs as there are plugs installed, each is unique in its application and the environment into which it is placed. There are however several generic methods of plug construction that have been identified from the literature. These include:

1. Conventionally placed massive poured concrete installations.
2. Grout/Cement paste injection of pre-placed aggregate.
3. Shotcrete (Sprayed concrete).
4. Composite plugs constructed using concrete in conjunction with other materials.
5. Plugs constructed using unconventional materials such as Polyurethane Foam.

2.2.1 Conventionally placed concrete plugs

The most commonly used approach to plugging or sealing of tunnels in use today is the installation of massive concrete structures. These can be installed quite readily in most geologic environments but factors such as shrinkage and debonding at the rock-concrete interface and chemical influence on the surrounding rock and groundwater systems must be carefully considered. These structures typically require grouting of the rock in the vicinity of the plug in order to close any hydraulic pathways that may exist in the rock surrounding the plug. If concrete plugs are expected to withstand a substantial hydraulic head, they are also typically keyed into the rock to provide a means of increasing their shear resistance. Notching can also aid in reducing seepage by increasing the seepage path length at the rock-concrete interface and interrupting the EDZ. Notching can also result in the generation of a more extensive EDZ if it is not done carefully /Kirkwood and Wu 1995/. Examples of this type of construction are described in Section 3. These plugs are also usually installed with grout curtains into the surrounding rock mass as well as post emplacement grouting of the rock-concrete interface to remediate any shrinkage-related openings or other volumes that were not filled by the concrete. For applications where very tight plugs are required, such as for a nuclear waste repository, specialty grouts have been developed that allows very tiny cracks to be filled /Ahrens and Onofrei 1996/.

2.2.2 Pre-placed aggregate concrete plugs

A variation of the conventional concrete plug is the construction of a massive concrete plug using pre-placed aggregate materials and then grouting the aggregate mass to generate concrete. These plugs are commonly installed in locations where very high hydraulic heads exist and very high quality control of the as-placed aggregate and cementitious grout components of the concrete is critical. This type of structure is also typically built in conjunction with rock grouting before plug placement and rock-plug interface grouting afterwards. Examples of these plugs are discussed in Section 3.

2.2.3 Shotcrete concrete plugs

Shotcrete involves air-placement of concrete materials using a sprayer. Generally, this technique provides a good contact between rock and concrete even at roof level so issues of poor contact at roof level are lessened. Forms and formwork is also not required, simplifying installation. The thickness of each shotcrete application is however generally limited to 30–40 cm at a time. If multiple layers are installed to provide for a thicker final plug there may be contact and interface issues between the layers, potentially affecting plug effectiveness. This concrete placement technique is commonly used when installing supports to underground tunnels and openings. It is also used to line excavations and structures when rapid placement is desired and serves both a structural and seepage-control function. Examples of this type of plug are discussed in Section 3. It should also be noted that there are few cases where this technique, on its own is considered adequate in terms of seepage control. These plugs are usually installed in association with extensive grouting operations intended to treat the plug-rock interface as well as to tighten up the surrounding rock by filling any fractures or joints that might allow the plug to be bypassed.

2.2.4 Composite plugs

Composite plugs are typically concrete plugs installed in conjunction with grouting and installation of clay-based materials. These plugs are by their very nature, more complex to construct due to the use of several materials, each of which must be carefully placed. These plugs are more commonly intended to provide long-term seals in backfilled tunnels where seepage control is critical and hydraulic protection of the concrete portion of the plug is desired. The complexity cost and need for system robustness generally means that this type of plug is actually more of a permanent seal rather than a shorter-term plug (see Section 3 for examples).

2.2.5 Plugs constructed using non-conventional materials

Materials other than those that are concrete- or clay-based have been tested and installed in a variety of underground applications (typically, for water or ventilation control in near-surface excavations e.g. coal mines). These materials include polyurethane foam (PUF) that can be pumped into a section of tunnel and then expands to fill the excavation. This approach, while applicable in some near-surface and mining situations, is not appropriate for use in a repository due to the composition of the foam (organics) and the unknown long-term performance of these materials. The PUFs are also typically used in situations where there is only limited hydraulic head that needs to be restrained. As a result these limitations, this construction option is not discussed further in this report.

3 Experiences in tunnel plug design, construction and performance monitoring

Plugging or sealing of underground excavations is needed for a wide variety of reasons. For the purposes of discussion, plugging applications and approaches have been broken down into four categories and are discussed in detail in Sections 3.1 through 3.4. The categories are:

1. Civil Construction Industry – Hydro-electric, civil applications.
2. Construction of Natural Gas Storage Caverns.
3. Mining Industry
   a. Operational Plugs,
   b. Plugs for Closure,
   c. Environmental Control and Remediation.
4. Nuclear Waste Isolation.

Each of these applications has different goals and functional requirements that need to be met. In many cases, especially in mining and mine remediation applications, the definition of a "successful" plug may not be applicable to what is needed in a repository. For many mine applications the plug is needed predominantly to reduce the inflow of water to levels that can be managed by mine dewatering pumps or net discharge from a facility to be limited to levels that can be dealt with by the water treatment facilities. Similarly in many applications the plugs need to restrain entirely water-filled excavations where un-restrained flow could have catastrophic consequences. These situations are less likely to exist in a repository where the excavations will already have been backfilled with very low permeability materials. In the repository application the goal of the short-term room/drift plug is predominantly to controlling seepage and preventing backfill erosion into still open areas. A repository may also require installation of mine-type plugs in locations where a highly conductive joint or fissure is intersected and must be isolated for safety and operational reasons. The range of functional requirements for plugs and seals highlights the need to develop a range of solutions to deal with whatever should ultimately be encountered.

3.1 Tunnel plugging for hydro electric and civil engineering applications

In the construction and operation of high-head hydroelectric facilities there is the need to be able to turn on/off and control the rate of supply of water to the penstocks and turbines. Water supplied through unlined pressurized tunnels is typically controlled by use of plugs installed at the entrance to the penstocks and in inspection tunnels /Bergh-Christensen 1989, Auld 1996/. These plugs typically consist of concrete plugs that fill most of the tunnel and a centrally-located perforation that can be mechanically opened and closed to control water supply past that point as shown in Figure 2-1. In particular, in Norway where high-head hydroelectric facilities are commonly constructed, there can be hydraulic heads as high as 900 m, making these facilities not unlike a repository where a connection has been made to some water-bearing feature.

Construction of plugs for hydroelectric facilities is commonly done by pre-grouting of the surrounding rock mass, pouring the concrete plug and then doing extensive contact grouting to reduce flow past the plug. Grouting is often a process that is repeated several times until flow is reduced to levels deemed acceptable. It was reported that 90% of the leakage past these plugs is at the rock-concrete interface, even after grouting is completed /Bergh-Christensen 1989/. Grouting can include cement grouting or use of chemical or polymer grouts that can further reduce seepage. Even with extensive grouting the plugs are designed to be 3.5% to 4.6% of the hydraulic head, this would relate to 17.5 to 23 m length for a 500-m hydraulic head. Additionally, seepage past these structures can range between 300 L/h and 18,000 L/h at hydraulic heads in excess of 400 m and is affected by the hydraulic gradient across the plug /Bergh-Christensen 1989/. It is unlikely that seepage rates of that magnitude would be acceptable in a geologic repository but experience in the hydroelectric industry highlights the technical challenges involved in design and construction of a very tight tunnel plug.

3.2 Construction of natural gas storage caverns

Construction of natural gas storage facilities in geologic formations has not been an uncommon activity over the past few decades. These facilities allow for storage and stockpiling of critical hydrocarbon supplies closer to the market than the source. These facilities, located deep underground often use abandoned mines as they supply large, already excavated volumes capable of withstanding the very substantial (e.g. 12.5 MPa /Pacovský 1999/) pressures at which the natural gas is stored. In some ways the construction of plugs for natural gas storage is not dissimilar to what will be required in a repository. In both cases there will be the potential of very high pressure on the upstream face of the plug and the need to prevent any transfer of material (gas or water) past the plug.

The approach described by /Pacovský 1999/ for an instrumented test plug for one of these gas storage facility in a plutonic (granitic) rock mass 950 m below the surface, involved installation of a fibre shotcrete. This plug was installed in several steps in recognition of the limitations of the shotcrete application. Fibre re-enforcement is a conventional approach to increasing the strength and stability of shotcrete by addition of fibres to the mix as it is blown into place. These fibres can be metallic or polymer depending on the specific needs or application and avoid the need of massive re-enforcing steel (or other materials) to the plug. The plug was 4.5 m long and was keyed 1.7-m into the walls of tunnel having a nominal diameter of 3 m. This plug had the typical "rubber stopper" shape adopted for many tunnel plugs where it is intended that the surrounding rock will support the plug via mechanical transfer the load from the pressured end rather than purely frictional resistance (Figure 3-1). As a result of this keying into the rock it is possible to shorten the plug length without compromising its ability to withstand considerable loading at its upstream face.

The results of the test plug described by /Pacovský 1999/ were such that two operational plugs were actually constructed and are still functioning in a gas storage facility in the Czech Republic (Pacovský J, personal communication, July 2006).

3.3 Plugging of mine – related excavations

3.3.1 Operational plugs

In many mining environments situations develop whereby old mine excavations require plugging in order to allow for ongoing operations elsewhere. In plugging these old openings the intent is to reduce water inflow into the operational sections of the mine to rates that can be handled by mine dewatering pumps. As a result what is often defined as plugging in mine operational terms would not be sufficient as a true plug/seal in a repository. /Littlejohn and Swart 2004/ mention the residual (post-plug installation) water-tightness for the plugs built in one application was specified to be 1 to 3×10^{-7} m/s, a value much higher than would be deemed acceptable in a repository if the plug

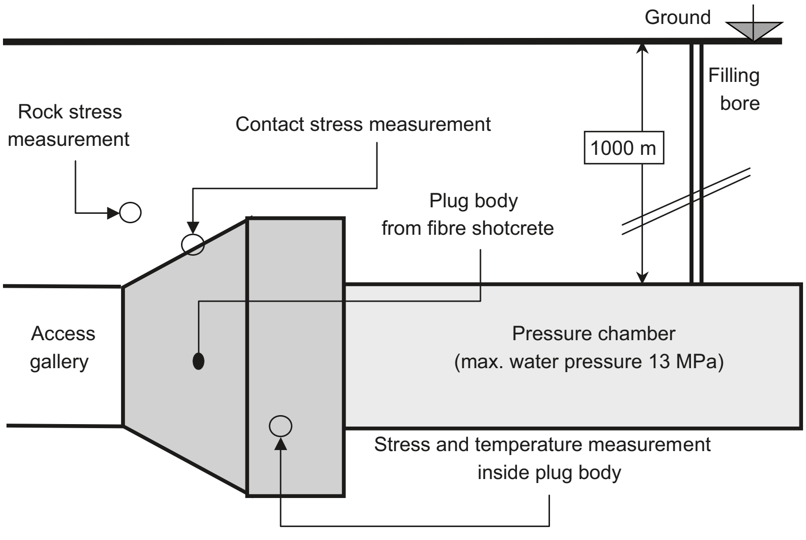


Figure 3-1. Fibre-Reinforced shotcrete test plug for a natural gas storage facility /Pacovský 1999/.

were required to serve a sealing function. /Littlejohn and Swart 2004/ also note that grouted aggregate plugs have in the past experienced “obvious and extensive” water leakage, but no structural failures were known. It is possible that in some situations in a repository that mine-type plugs might be necessary as an engineering expedient in locations where hydrological conditions are so bad that continued water influx could threaten adjacent excavations in areas where the hydrogeologic conditions are suitable for canister installation. Experiences in mine plug construction and operations are therefore of importance in developing approaches to repository construction and operation.

Mining is also an industry where tunnels, drifts and shafts may remain open for very long durations and so plug design and performance requirements in some mines begins to become particularly relevant to a repository where plugs may need to remain in place and effective for as much as 100 years /Littlejohn and Swart 2004/.

Excellent examples of the relevance of mine plugging to a geologic repository can be found in some of the very deep gold mines in South Africa. A number of papers outlining the design requirements, construction process and performance of a number of pre-placed aggregate concrete plugs for South African gold mines were presented /Bruce et al. 2004, Littlejohn and Swart 2004, Brawner et al. 2005, Murray and Roberts 2006/. In the situations described by /Littlejohn and Swart 2004/, the bedrock consisted of very high strength and stiff materials (quartzite and lava) and the plugs needed to restrain a hydraulic head that ranged from 12.5 MPa to 15 MPa. In an extreme case, /Murray and Roberts 2006/ had to deal with a hydraulic head of 28 MPa in their application. In order to deal with the tendency of groundwater to flow around the plugs through pre-existing joints or damage, the rock in the vicinity of the plugs described was always grouted. In one of the plug construction descriptions it was noted that bentonite-geotextile curtains of 20 mm-thickness (having a hydraulic conductivity of $\sim 10^{-11}$ m/s), was installed between segments of the plug /Bruce et al. 2004/. This was done in order to reduce the rate at which chemically aggressive groundwater could interact with the concrete and ensure that the concrete survived its 100 year design life /Brawner et al. 2005, Littlejohn and Swart 2004/.

In order to place the highest quality concrete plug special handling, preparation and placement processes for the tightly specified aggregate component (quartzite) used in the South African mine plugs. When completed, these plugs were very long (20–40 m) and were installed in segments of 6.25 to 7.5-m-length. They were not keyed into the surrounding rock mass (to avoid further damage to rock) and so relied on their length and frictional bond to the rock to resist the water pressure.

3.3.2 Plugs for closure

At the end of the service life of mines there is a need to install plugs and seals at critical locations. These plugs often serve dual purposes, preventing accidental or intentional intrusion into the old mine workings and to hydraulically isolate the mine workings from the surface environment. Examples of closure-related plugs that serve an environmental protection function are provided in Section 3.3.3.

Plugs intended to prevent physical intrusion into the mines come in a variety of types, depending on the nature of the excavations, the risk of intrusion (intentional or accidental) and the environmental hazard that exists if they are breached.

3.3.3 Environmental control and remediation

One of the more serious issues facing the metals mining industry in recent years is that of acid mine drainage and associated heavy metals contamination of mine discharges. One way of dealing with this issue once ore extraction has been completed and mine decommissioning is desired is to seal the mine workings and limit future percolation of groundwater through and subsequent discharge into the surface environment. Sealing of mine tunnels and shafts has to accomplish these goals has therefore received considerable attention. Techniques and technologies used and proposed to seal these underground workings can provide considerable useful information for the design of plugs and seals for nuclear waste isolation.

Drainage from the abandoned workings of metal mines is typically highly acidic (pH 3–4) and as a result will cause much more rapid and substantial damage to concrete, grout or clay materials than would be anticipated in a repository where pH conditions are more likely to be closer to neutral (typically assumed to be in the pH 7–8 range). As a result, if concrete, grout and clay sealing materials can be demonstrated to perform adequately under acidic conditions then they will likely provide adequate performance as plugging materials for at least the shorter-term (Repository operational period when short-term plugs need to be effective).

A number of massive concrete and grout tunnel plugs have been installed in former mine sites but one major site in Canada has received considerable attention and generated considerable publicly-available literature. This site is known as the Britannia Mine in British Columbia Canada where a century-old copper-zinc mine was closed and abandoned in the mid 20th Century. This mine originally discharged several thousand m^3 of highly acidic and metaliferous drainage water to the coastal waters. As part of a mine remediation, wastewater treatment and technology evaluation process the Government of British Columbia has undertaken an ongoing program of monitoring and treatment. As part of this program the installation of a massive concrete plug at the point of major mine water egress and the detailed design of a "millennium" plug to control mine drainage was planned.

A concrete plug was installed approximately 35 years ago in an access drift at a lower level of the former mine workings and experiences hydraulic heads of approximately 2.5 MPa. Some of the concrete plug design and performance information can be found in documents by /BCMEM 2002/ and /Parkinson and Bryan 2005/. The concrete plug is a massive concrete structure composed of conventional, high-lime, portland-cement-based concrete (26 MPa strength that was poured in stages in a rock mass having an average rock permeability in the order of 10^{-7} m/s. The concrete plug has nominal dimensions of 8-m-length and 4.5-m-diameter and adopts the friction plug approach with extensive grouting of the rock adjacent to it. The concrete plug has operated at a hydraulic head of approximately 2.5 MPa and is estimated to have a seepage rate of approximately 0.005 L/sec (0.3 L/min) above that supplied by the local rock itself /Parkinson and Bryan 2005/. This water is at pH of ~ 3.5 (whereas surrounding "formation" water has a pH of ~ 6.8) and so is very aggressive. For mine-water control purposes this rate of seepage past a tunnel plug is considered to be excellent and seepage water (~ 432 L/day), is collected for treatment as part of the mine-water management process. For repository purposes this rate of seepage would not likely be acceptable for a room seal during repository operation.

The millennium plug proposal for the Britannia mine (Figure 3-2), was developed as a proposed long-term mine water management solution and closely resembles the approach considered for plugs in many repository concepts. The millennium plug was suggested to be a "permanent" solution to mine water control with a 1,000-year life. Constructed using concrete, local rock, sand and bentonite this plug is intended to hold water in the mine workings until it is intentionally discharged for treatment. The use of a composite system was proposed to provide for a low permeability plug that included a downstream bentonite clay-based plug to retard any seepage that occurred around the concrete. Again, as is the case of the actually-present concrete bulkhead at the Britannia mine, the water that percolated through the plug could be collected and treated and the plug was only expected to be at least as good as the surrounding rock mass at retarding seepage. Its main advantage was its anticipated longevity relative to a grouted concrete plug and therefore its low/no maintenance requirement. It should be noted that although planned, designed and reviewed, only the concrete plug is present and the other portions of the Millennium Plug were not constructed.

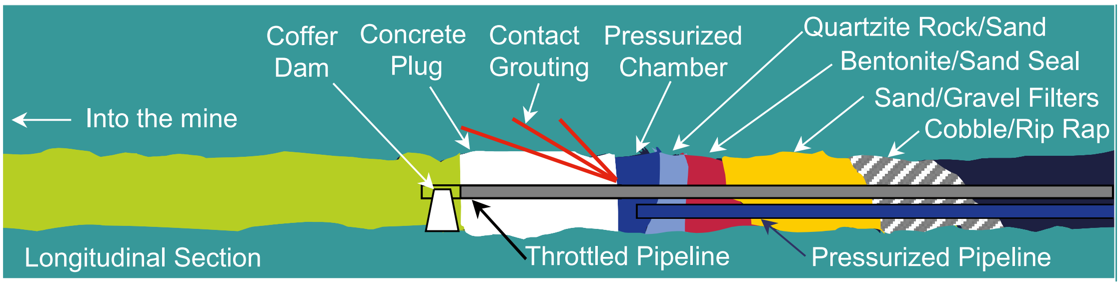


Figure 3-2. *Proposed Millennium Plug (Innovation Canada /CERM3 2004/ Website).*

4 Experiments and demonstrations related to repository sealing

Plugging and sealing of excavations made in the course of building and operating a deep geologic repository requires a level of engineering not typically required for plugging of underground structures. As described in the preceding sections of this report, most plugs are intended to provide water control rather than near complete isolation. For nuclear waste management purposes water control is not necessarily adequate and the intention is to seal the excavation to a level that it is as good as or better than the host rock in resisting water movement. Additionally, the movement of contaminants across the plug needs to be limited to diffusion-dominated rates.

Room, Tunnel and Shaft sealing studies and trials have been conducted at a number of underground research laboratories over the past 30 years. In addition to activities intentionally designed to examine plugs and seals a number of other experiments and demonstrations have been carried out that provide information that can be directly or indirectly used in plug design. This chapter will review various international activities related to plugging and sealing of underground openings. Specifically sealing studies carried out in Sweden, Belgium, Canada, Germany and Switzerland are examined as they have the greatest relevance to plugging in a repository. A number of the projects described were conducted as part of international co-operative projects, however for the purposes of this report the various sealing studies are discussed based on the country where the study was done. For the purposes of comparison of the various tests and demonstrations, the data provided has been extrapolated to values that might be expected at a depth of 600-m and where circular drifts are considered a diameter of 1.8-m (KBS-3H drift dimension) is used to normalize the data. This provides a means of comparing the various tests but should not be taken as an assumption that the seals installed would actually function at that hydraulic head.

A general review of the various underground research laboratories and their activities has been published by the IAEA /IAEA 2001/ and the general approaches taken in a variety of geologic media has also been prepared by that organization /IAEA 2003/.

There is an additional large body of work that has been done in characterizing sealing materials and approaches as part of bench-scale studies but the focus of this document is on field demonstrations so they are not discussed here. A number of countries are also in the process of building or developing underground research laboratories in which large-scale plugging tests will eventually be done (e.g. France (Bure site), Japan (Mizunami and Horonobe sites), Czech Republic (Josef Underground Educational Facility), Korea (Underground Research Tunnel) and Switzerland (Mont Terri)). Again as these facilities are not yet doing tunnel-plugging studies they are not yet able to provide information on the most effective approaches to take.

4.1 Sealing studies in Sweden

Sweden has, as part of the activities of SKB conducted and participated in a large number of projects intended to examine various aspects of sealing openings excavated in crystalline rock. Over a 30-year period two underground research laboratories have operated in Sweden with the purpose of supporting development of technologies required for safe disposal of used reactor fuel. These laboratories are the STRIPA Mine (1980–1992) and the Äspö Hard Rock Laboratory (1995–present).

4.1.1 Studies at the Stripa Mine

The International Stripa Project was the first of the underground research facilities where large-scale engineering demonstrations and trials were conducted in granitic rock. Stripa was a cooperative project carried out by a number of countries within the Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development (OECD). At various times during the Stripa project the following countries were involved in one or more activities (Canada, Finland, France, Japan, Spain, Sweden, Switzerland, UK and the USA). The project was managed by the

Swedish Nuclear Fuel and Waste Management Company (SKB). The Stripa mine is a disused iron ore mine that provided underground access to a granitic rock mass located adjacent to the mine workings. The general findings of the Stripa Project were summarized by /Fairhurst et al. 1993, Gray 1993 and Gnirk 1993/ and in a large number of technical reports and papers related to sealing have been published by SKB /e.g. Pusch 1987, Pusch et al. 1987a, b/.

Testing of a shaft and a tunnel seal was conducted during the second phase of the Stripa program (1983–1988) and were designed so determine the effectiveness of swelling clay-based seals in limiting water flow at interfaces between concrete bulkheads and backfilled excavations. In many respects the only real difference between the shaft and tunnel seals was the orientation of the plugs. Both sealing trials had the same goal of limiting the movement of water past the plug and evaluating the role of the excavation damaged zone (EDZ) in this flow. For the purposes of discussion in this report the EDZ is defined as the rock that has had its hydraulic conduction characteristics discernibly altered as the result of excavation. There may be stress disturbances or other measurable changes in some of the other rock properties as the result of excavation but if they do not alter the basic hydraulic characteristics they are not considered to be excavation damage.

Tunnel Plugging Experiment

The tunnel plugging experiment was conducted in a 35-m-long dead-ended tunnel at approximately 380-m depth /Gray 1993/. The tunnel was excavated using careful drill and blast techniques that were intended to limit the EDZ. The tunnel plug was designed and constructed so as to allow passage past the plug via an axial access tube shown in Figure 4-1 /Pusch et al. 1987b/. As a result the focus of this plugging experiment was to evaluate the performance of the approximately 2.2-m-long concrete bulkheads together with inset gaskets (O-rings) of highly compacted bentonite (HCB) of approximately 0.5-m length and depth.

As shown in Figure 4-1, construction of the concrete portion of this test was fairly complex, with a post-tensioning system intended to keep the concrete in compression at all times. The hydraulic conditions in the rock surrounding the tunnel plug were such that hydraulic heads in the order of 1 to 1.5 MPa should have been present within 3 to 5-m of the excavation surfaces /Gray 1993/. The geology in the region of the excavation where the tunnel plug was installed was not homogeneous and a number of water-bearing joints and fractures intersected both the excavations beyond the plug as well as at locations along its length. The relatively short length of the plug as well as the hydraulic and geologic conditions were such that this test was considered to be a measure of the effectiveness of the HCB gasket and not a comparison of gasketed and non-gasketed tunnel plugs /Gray 1993/. It should also be noted that there was no treatment (e.g. grouting or keying) applied to the rock surrounding the tunnel plug, despite the knowledge that this region was highly heterogeneous and hydraulically connected features existed.

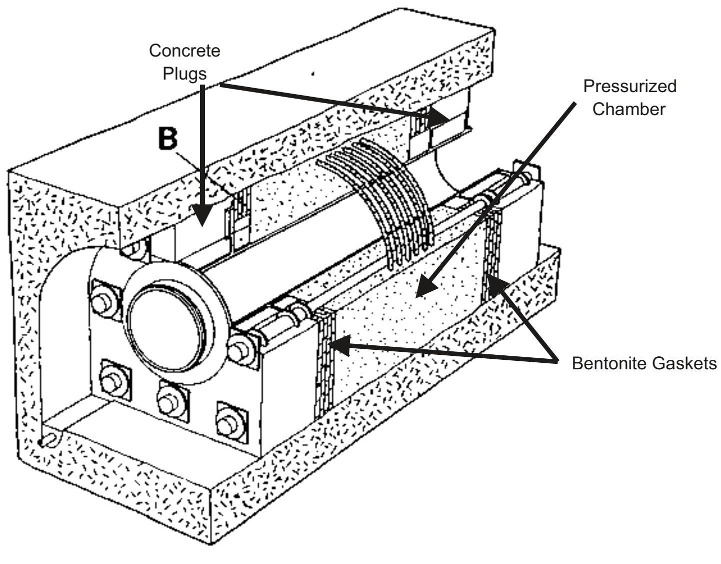


Figure 4-1. *Layout of the Tunnel Plugging Test /after Pusch et al. 1987b/.*

The materials used in the tunnel plugging experiment were heavily steel reinforced, conventional concrete having an unconfined compressive strength of 40 MPa and highly compacted MX-80 bentonite having a dry density of approximately 1.6 Mg/m^3 (saturated bulk density 2.0 Mg/m^3). The hydraulic head in the isolated section of the tunnel-plugging test was capable of being pressurized to 3 MPa. The operational phase of this test was 21 months in duration (April 1984 until Jan 1986) and the hydraulic pressures in the chamber were cycled several times during this period /Pusch et al. 1987b and Gray 1993/. The geological structural features that intersected the tunnel plug resulted in the majority of seepage water bypassing of the outer plug. The monitoring of flow rate past the tunnel plug was observed to decrease with time and this was attributed to the gradual closure of some of the interface flow paths as the result of the swelling of the bentonite. It was estimated that were there to be no bentonite gasket present, the seepage rate past the concrete bulkhead would have been in the order of 1,000 L/hr at a hydraulic head of 3 MPa (2,000 L/h at 6 MPa). With the bentonite gasket in place the seepage past the bulkhead at 3 MPa hydraulic head was reduced from 1,000 L/hr to approximately 75 L/hr /Pusch et al. 1987b/.

Of interest in this test were some of the observations made during the early stages of operation. In particular there was an observation of high leakage rates at the rock-concrete interface on the downstream end during the first few days of operation at relatively low hydraulic pressure (100 kPa) /Pusch et al. 1987b/. This feature subsided within a few days and after a month no localized seepage could be visually detected. Tests of the outflow did not detect any bentonite in the water, indicating that the flow was occurring along a discrete plane and any internally eroded bentonite actually acted as a grout, plugging the flow paths. With such a self-grouting process then the seepage would have been choked off and the overall HCB plug would then be able to hydrate and close off this interface. This same type of hydraulic behaviour was also observed in the Tunnel Sealing Experiment conducted in Canada between 1998 and 2004 /Dixon et al. 2004/ described in Section 4.3 of this report.

The tunnel plugging test at the Stripa mine established that it was possible to construct a composite concrete and HCB plug and that HCB could substantially reduce the seepage that would otherwise occur at or near the rock-concrete interface. This test also highlighted the importance of the geologic conditions in the region where a plug is to be installed and the potential limitations of trying to install a plug without grouting of the rock adjacent to it. The tunnel plugging test should also be put into context as a sealing test rather than designing and testing of a practical tunnel plug as it included very extensive steel reinforcing and tensioning components that would not likely be acceptable in a repository environment.

Shaft Sealing Test

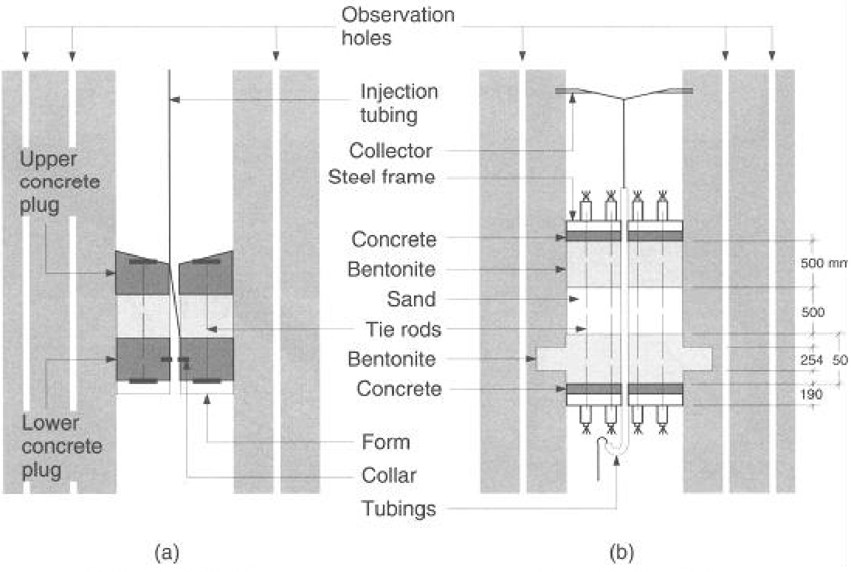
The Shaft Sealing Test at the Stripa Mine was conducted in a 14-m-long tapered shaft /Pusch et al. 1987a and Gray 1993/. The shaft was 1.3-m-diameter at its base and 1-m-diameter at its top. This shaft was not bored but was excavated in two manners. On one half of the circumference the shaft was excavated by line drilling and on the other half by careful blasting, thereby generating two different EDZ conditions and a means of testing the ability of HCB to seal rock of differing roughness. As was the case with the Tunnel Plugging Test at Stripa, water was supplied under pressure to a central portion of the seal and seepage past different types of plugs could be monitored (see for shaft plug test layouts).

The shaft sealing test was composed of two separate tests, one to examine water flow around a concrete plug and the other to examine the seepage past keyed and unkeyed sections of the shaft in the same locations that the concrete-only test was installed. In the second shaft seal HCB was used to fill a keyed lower section that was intended to cut off any EDZ that may have been generated as the result of excavation.

The concrete shaft plug test shown in Figure 4-2a consisted of two, 0.5-m-thick mass poured concrete plugs that sandwiched a sand-filled chamber. The chamber was used to supply pressurized water to the plugs and seepage past these plugs could be monitored. The concrete plugs were not keyed into the rock and no special surface treatments were done to try and improve the bond between the concrete and the rock. As was the case with the tunnel plug test described previously in this document, the concrete segments were tied together with steel rods and as a result no displacement of the concrete segments was possible. This meant that the test did not evaluate the bond-strength of the concrete-rock contact. The sand-filled portion of the concrete shaft seal test was pressurized to 100 kPa during the testing phase. Flow past the plug was considerable even at 100 kPa, with approximately 8–9 L/h being collected. If this seepage rate were extrapolated to a 6 MPa hydraulic head and a 1.8-m-diameter opening (KBS-3H) the flow would have been in the order of 540 L/h. Observations of the regions where flow was occurring indicated that most of the seepage was associated with geological features that spanned the concrete plug. There also did not seem to be discernible seepage past the portions of the concrete plugs that did not intersect the identified geologic features.

The main shaft sealing test was conducted in exactly the same physical location as the concrete test, once the concrete was entirely removed and the surface cleaned of any residual materials. As can be seen in Figure 4-2b and Figure 4-3, the HCB-based shaft-sealing test examined the ability of unkeyed and keyed segments filled with HCB to reduce flow along the rock-bentonite interface and along the combination of the interface and the EDZ respectively. This test was done using hydraulic heads of 100 and 200 kPa. It was noted that the seepage past the plugs reduced to approximately 0.3 L/hr at 200 kPa hydraulic head as compared to the 8–9 L/hr in the concrete-only test section /Pusch et al. 1987a/. The bentonite plugs were observed to have expanded into the fractures and joints that had previously been the conductive features from the pressure chamber to the external collection sites /Pusch et al. 1987a/. It should be noted that at a hydraulic head of 200 kPa that at a seepage rate around the plugs of 0.3 L/hr in a 1.2-m-diameter shaft would translate to an outflow in the order of 9 L/hr at a hydraulic head of 6 MPa and approximately 18 L/hr assuming a 2.4-m-diameter circular opening (e.g. the KBS-3H concept /Autio et al. 1996/) and flow being directly related to perimeter length.

The shaft plugging test at Stripa was a very effective initial demonstration of the ability of bentonite to reduce water flow along hydraulically conductive features in the walls of an excavation. These tests like the tunnel plugging test did not provide any measure of the mechanical stability of these types of plugs because they were self-restraining and were of extremely short duration (a few months). These plugs were also extremely short and so interconnected hydraulic features would likely have been more important in determining the seepage than would occur in plugs of greater length. What they do provide is an indication of the effectiveness of a composite system in reducing seepage past/around tunnels or shafts. They also provide a basis for designing of larger, repository-scale plugging trials that would demonstrate the effectiveness of such seals in isolating an emplacement room or drift and ultimately what would be required in design of a shaft plug.



(a) Concrete Plug Test

(b) Bentonite Plug Test

Figure 4-2. Schematic of the arrangement of the Concrete and HCB Shaft Sealing Tests /Gray 1993/.

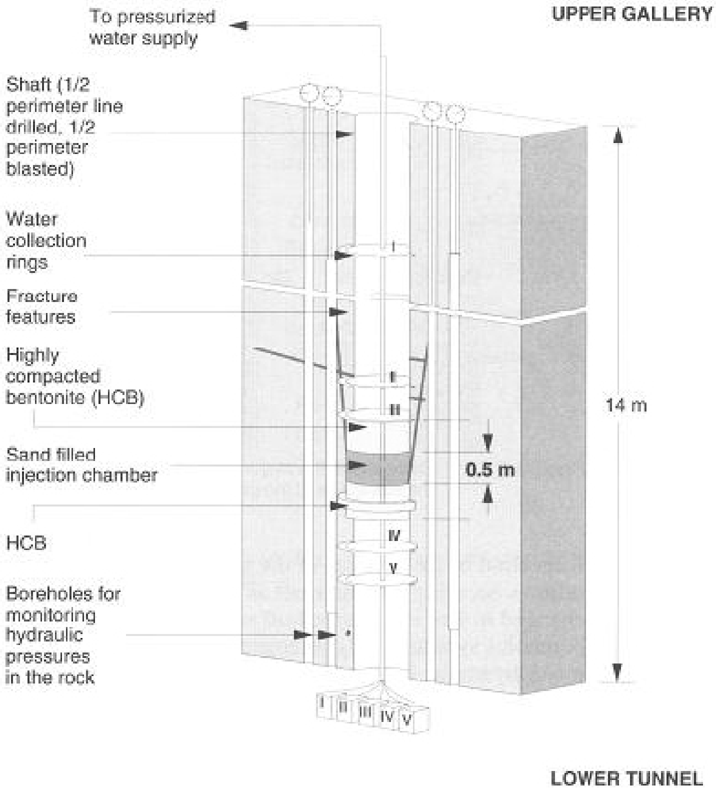


Figure 4-3. *Layout of the Stripa Shaft-Sealing Test: Clay Seal Test /Pusch et al. 1987, Gray 1993/.*

4.1.2 Studies at Äspö

The Äspö underground laboratory in Sweden was built and is operated by SKB with the purpose of developing and demonstrating technologies ultimately required for use in an underground repository for used nuclear fuel. The Äspö facility also provides a location where issues related to repository evolution and environmental questions can be examined in a realistic geologic environment. Operating since 1995, Äspö represents a successor to the Stripa facility and provides a geologic environment that was undisturbed prior to its excavation. Figure 4-4 presents the layout of the Äspö facility and the locations of some of the key activities /SKB 2005/. Within the Äspö facility a number of tests and demonstrations related to the sealing of tunnels and drifts have been and are being carried out /SKB 2005/. These sealing tests include the Prototype Repository (PR) and the Backfill and Plug Test (BPT). Activities such as the Temperature Buffer Test (TBT) and the Large Scale Gas Injection Test (LASGIT) and the KBS-Method with horizontal emplacement (KBS-3H) also have components that may provide valuable information on water seepage past plugs and what will be required to construct effective plugs.

KBS-3H

The KBS-3H study involved the boring of two horizontal boreholes at the 220-m-level at Äspö and ultimately installation of a simulated supercontainer and drift plugging components will be constructed. A supercontainer is a canister and highly compacted bentonite buffer overpack that is treated as a single entity. The installation demonstrations will be done using a prototype emplacement machine and will test the feasibility of this emplacement concept. Figure 4-5 presents the layout of the KBS-3H test. Also associated with the KBS-3H study are tasks intended to evaluate the functionality of the buffer placed in this orientation and the plugging/sealing of the horizontal boreholes.

Although not definitively established at the time of writing this report, the sealing and plugging components of the KBS-3H emplacement concept will be very important in the evaluation of this concept. The KBS-3H plug test will need to deal with a system that is supplying considerable amounts of water to the region where the plug is to be installed and so approaches that deal with

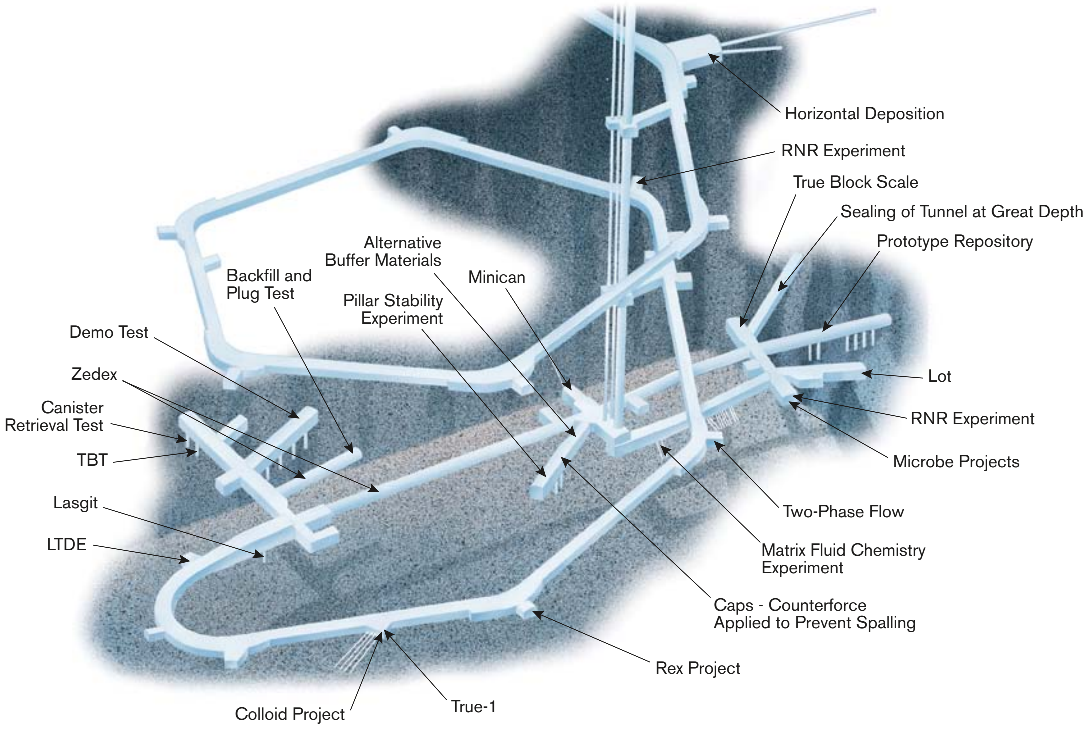


Figure 4-4. *Layout of the Äspö Facility /SKB 2005/.*

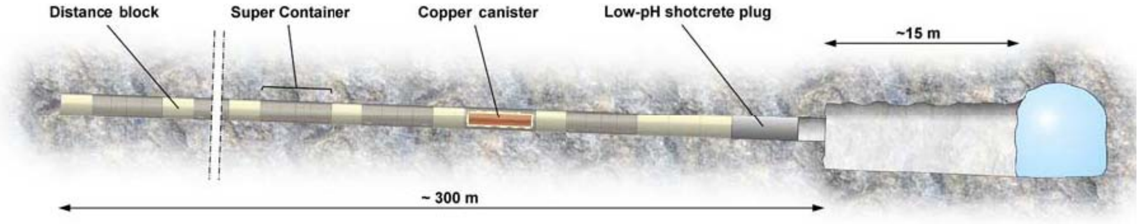


Figure 4-5. *KBS-3H Simulation.*

this condition will need to be developed. Design of the sealing materials and plugging concepts will rely heavily on the results of previous sealing studies. The conduct of the sealing demonstrations as part of this emplacement study will also provide valuable information and advance the knowledge of how to design larger-scale shaft and tunnel seals.

Temperature Buffer Test

The TBT is being conducted at Äspö by ANDRA, in co-operation with SKB. Located at the 420-m-level, the TBT is examining the behaviour of bentonite buffer at temperatures in excess of 100°C /SKB 2005/. The primary purpose of the TBT is to evaluate the water uptake and migration in an in-floor borehole supplied with water and into which heat generating canisters have been installed (Figure 4-6). The TBT borehole does however contain a concrete cap that is mechanically tied into the surrounding rock mass via tensioned cables. As a result of its construction the TBT is not able to measure the mechanical stability of the cap portion but it could provide some information on the seepage of water from the water supply system installed along the perimeter of the borehole.

The TBT has had a liquid mass balance monitoring active over the course of the test and the perimeter of the cap is inspected regularly. There have been no recorded occurrences of liquid water escaping from the cap, excepting a few discrete leakage events at cabling ports. There has however been a discernible discrepancy between the fluid that has entered the TBT and the volume available internally. By mid 2006 this difference had reached at least 700 litres. It is speculated that this loss has occurred by water entering the surrounding rock mass from the pressurized test perimeter.

Figure 4-6. *The Temperature Buffer Test /after SKB 2005/.*

If this is the case and there is no/non-discernible water loss from the cap of the TBT then the combination of a substantial thickness of HCB and a concrete plug appears to have succeeded in plugging a large diameter (1.8 m) bored opening. In many respects these results are mirrored by the Composite Seal Experiment described in Section 4.3.

Backfill and Plug Test (BPT)

The BPT is located at the 420-m-level at Äspö and monitoring was initiated in 1999 and hydration proceeded until 2003 when flow testing was initiated. It consists of a 28-m-long installation in a blind drift and contains three major test sections (Figure 4-7) /SKB 2005/. The innermost section contains 6 segments where backfill of various compositions are installed. The water uptake, hydraulic and mechanical behaviour of the backfill is monitored on an ongoing basis. The second test section consists of a volume occupied by crushed rock and having bentonite blocks and pellets installed in the crown regions where effective backfilling was not possible. The outermost section of the BPT is a concrete plug. This plug is a poured concrete structure that is designed to resist the swelling pressure generated by the backfill as well as the hydraulic pressures that would be generated by the hydraulic head. It is also intended to provide a water seal to prevent seepage into the adjacent openings under the 450–540 kPa hydraulic head applied to the backfilled volume. To accomplish the mechanical and sealing function, the concrete plug was constructed with a 1.5-m-deep triangular slot that includes an O-ring of HCB at the inner rock contact (Figure 4-8).

The effectiveness of the concrete and HCB plug is monitored on an ongoing basis with a gradual decrease observed over the course of the experiment (Figure 4-9). As of the end of 2004 the seepage past the bulkhead at 450 kPa hydraulic head was approximately 0.6 L/hr and by the end of 2005 at a hydraulic head of 530 kPa the seepage rate was approximately 0.75 L/min. Were the hydraulic head to be increased to 6 MPa and darcian flow behaviour observed, then the seepage past the concrete bulkhead would increase to approximately 8.5 L/hr. At 8.5 L/h seepage gradual localized erosion of the bentonite gasket material may occur if the seepage path(s) are not confined to the EDZ or are concentrated in only a few discrete locations that are wide enough to allow for material removal.

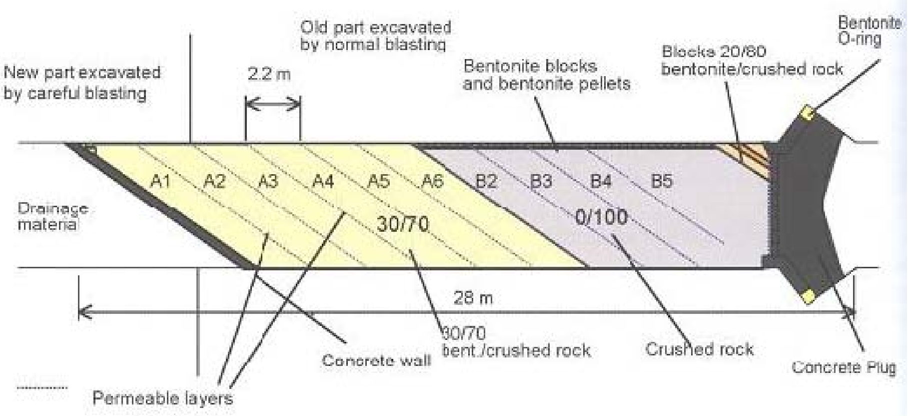


Figure 4-7. The Backfill and Plug Test /Gunnarsson et al. 2002, Gunnarsson and Börgesson 2002/.

Figure 4-8. The keyed portion of the Backfill and Plug Test and the downstream face of the completed plug /Gunnarsson et al. 2002/.

Prototype Repository (PR)

The PR represents a full-scale simulation of a bored deposition tunnel at the 450-m-level of the Äspö facility and was installed beginning in 2001. In the floor of the tunnel 6 full-scale emplacement holes have been drilled. In these emplacement holes, canisters of the same dimensions of an emplacement canister but containing electrical heaters to simulate the heat generated by an actual used fuel canister were installed. The canisters have been surrounded by HCB of the type and density proposed for use in a repository and then the regions overlying the boreholes have been backfilled and a tunnel plug has been installed to isolate the backfilled tunnel. The PR actually consists of two sections of tunnel, an inner section where 4 canisters were installed and an outer section where a further 2 emplacement boreholes were installed (Figure 4-10). The two sections of tunnel are separated from one-another by a cast concrete plug that is intended to provide hydraulic isolation and allow for partial disassembly of the PR.

The PR provides an opportunity to study many aspects of repository evolution and tunnel plugging. Of particular interest to the evaluation of tunnel plug design and performance is the outermost plug in the PR, shown in Figure 4-11. This plug consists of a steel-re-enforced concrete dome that is keyed into the rock to provide mechanical restraint to the pressurized tunnel. Beyond this plug is tunnel backfill consisting of 30% MX-80 bentonite and 70% crushed rock aggregate, compacted in situ. This backfill was placed in the region upstream of the restraining wall until only about 25% of the height remained and in situ compaction was no longer viable. The remaining volume was filled with precompacted blocks of 20% bentonite and 80% crushed rock and bentonite pellets and highly compacted bentonite materials placed at its upstream face (Figure 4-12).

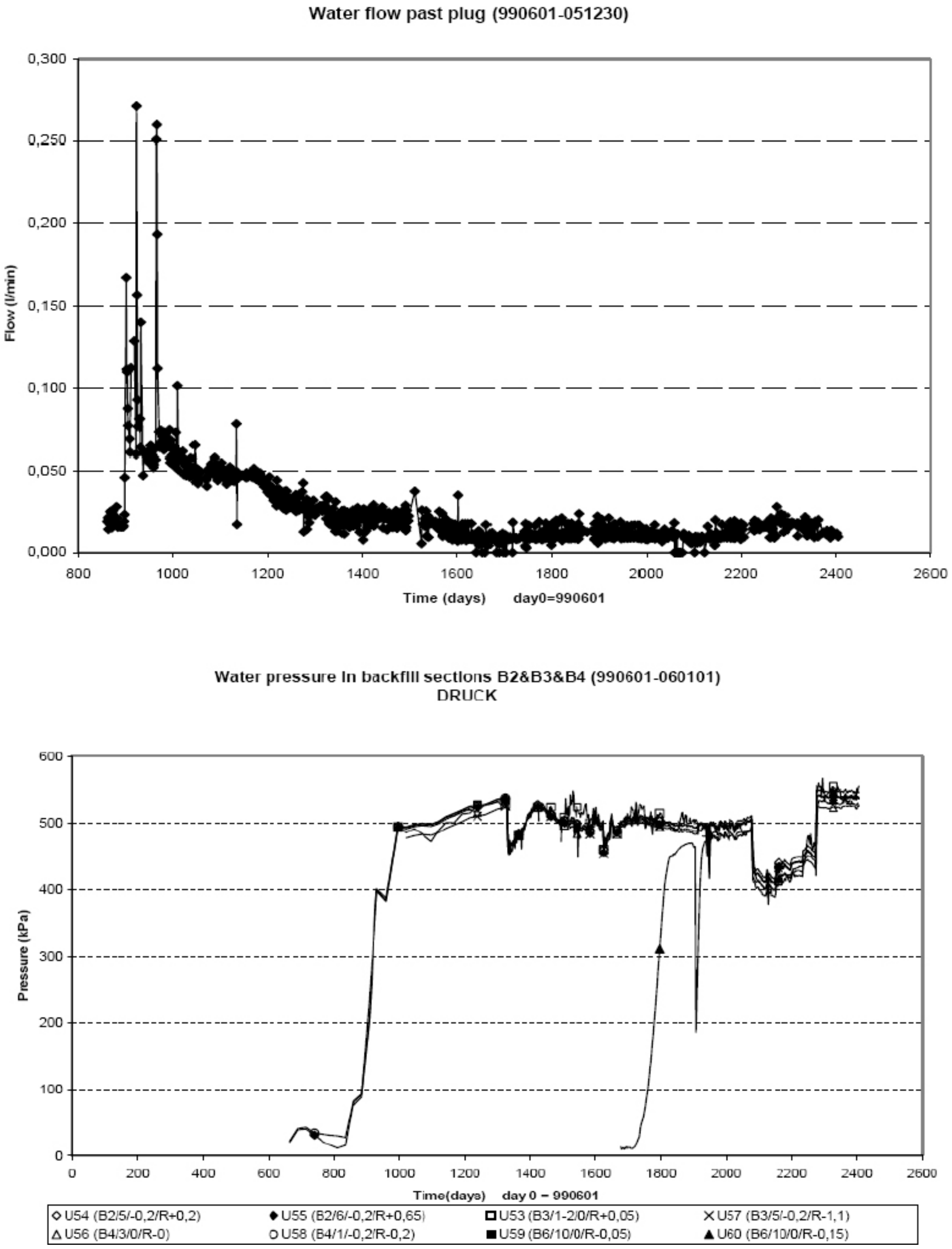


Figure 4-9. *Measured Water Flow Past the Concrete Plug Portion of the BPT /after SKB 2005, Goudarzi et al. 2006/.*

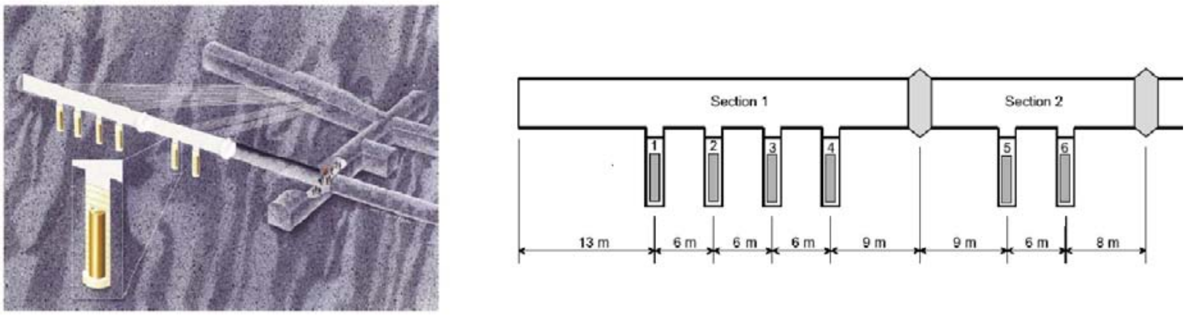


Figure 4-10. *The Prototype Repository simulation at Äspö /SKB 2005/.*

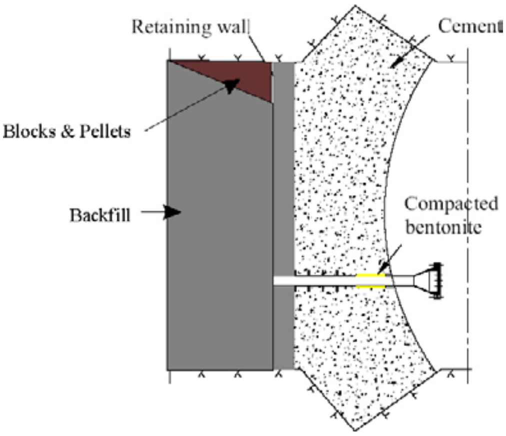


Figure 4-11. *Schematic of outer plug for the Prototype Repository /after Johannesson et al. 2004/.*

(a) Upper Region to be filled with pellets

(b) Installation of blocks and pellets

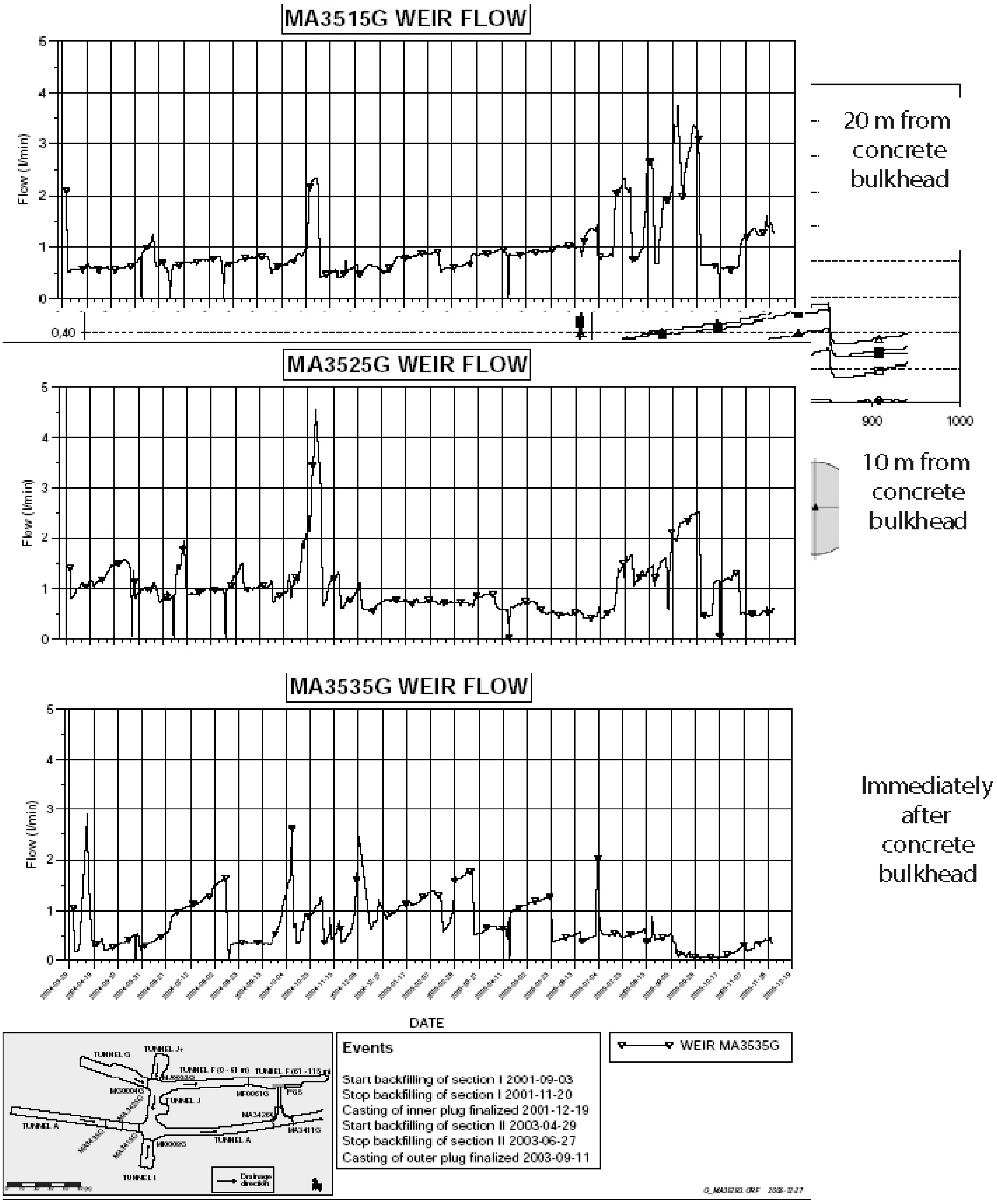
(c) Retaining wall before construction of concrete dome

Figure 4-12. *Construction of the outer plug in the prototype repository /Johannesson et al. 2004/.*

The PR test at Äspö also provides valuable information about water influx into open excavations at 450-m depth. Adjacent to the backfilled and sealed PR (Tunnel A) are three tunnels, two shorter tunnels (I, J+) are excavated at right angles to the PR and Tunnel G excavated almost parallel to the PR. Seepage into these excavations is monitored on an ongoing basis and provides some indications of what might be expected to be entering the PR. Figure 4-13 presents the seepage past the concrete plug of the PR and the seepage into open Tunnels G, I and J+.

- Tunnel G is approximately 80% of the length of the sealed portion of the PR and is producing water at a consistent rate of approximately 5 L/min (2005 and 2006).
- Tunnel I is only about 30% of the length of the PR tunnel and was producing water at a rate of approximately 3.5 L/min while the PR tunnel closest to the concrete plug was at approximately 500 kPa hydraulic head. This flow dropped to approximately 2 L/min when the PR pressure dropped to 300 kPa. This indicates that there is a strong hydraulic connection between these two tunnels. Tunnel J+ is also approximately 30% of the length of the PR and when monitored during 2005 was producing approximately 1.5 L/min.

In order to provide a rough indication of the influx that might be expected it can be assumed that influx is directly proportional to tunnel length. In this case the tunnels adjacent to the PR G, I, J+ might be expected to produce approximately 6, 12 and 5 L/min respectively were they the same length as the PR. This rate of water influx is well in excess of the 0.6 L/min and 0.35 L/min observed at the downstream face of the PR bulkhead during this same period. The outer bulkhead portion of the PR is therefore allowing less than 7% of the potential influx to exit.



Events
Start backfilling of section I 2001-09-03
Stop backfilling of section I 2001-11-20
Casting of inner plug finalized 2001-12-19
Start backfilling of section II 2003-04-29
Stop backfilling of section II 2003-06-27
Casting of outer plug finalized 2003-09-11

Figure 4-13. *Seepage into PR tunnel beyond the concrete bulkhead /Goudarzi and Johannesson 2006/.*

It should also be noted that the hydraulic pressure near the face of the concrete bulkhead of the PR is only 300–500 kPa. This indicates that the open excavations near the PR are depressing the local groundwater pressures and inflow to this closed tunnel. This is supported by the strong hydraulic connection between the PR and Tunnel I. This same situation would be present in a repository during emplacement operations and for the period leading up to final closure. It is also likely that as larger volumes of the repository are filled that the groundwater pressure will begin to recover since the volume into which the groundwater can drain and decrease the hydraulic pressure in the closed tunnels is reducing. The result will be higher groundwater pressures within the sealed tunnels, potentially associated with higher inflow rates. Also important to consider with hydraulic connections between closed and open tunnel sections is the potential for erosion of tunnel fill materials if the connection is direct and flow is occurring along very discrete pathways.

4.2 Sealing studies in Belgium

Belgium has operated an underground research laboratory at its MOL site and has undertaken a range of experiments and demonstrations.

The Belgian concept for a deep geologic repository calls for excavations to be made in an argillaceous formation. The main underground galleries will be approximately 3.5-m diameter and off these will be the emplacement galleries excavated to allow for installation of reprocessed waste packages. These emplacement galleries will be 2-m-diameter, 800-m-length at 40-m spacings. Into the wall of the gallery, lined emplacement tubes will be installed and the 1.6-m long waste packages will be installed. At time of closure the main galleries will be sealed with at least 2 seals positioned in series /SAFIR2 2001/.

The concrete-lined repository excavations would be filled using a sand-clay backfill that has at least some swelling capacity. Sealing of the main galleries and shafts is to be accomplished by installation of mixtures of highly compacted bentonite pellets and powdered bentonite, installed in an unlined section of the repository where the EDZ has also been removed. This clay-filled section will then be confined by concrete installed at both ends of the installation /SAFIR2 2001/.

The MOL URL has been demonstrating various aspects of the Belgian concept, including activities associated with plugging and sealing of excavations. These studies and demonstrations are part of the PRACLAY demonstration and are planned to run from 1995 to 2015 /SAFIR2 2001/. The large scale in situ portion of PRACLAY is to be installed and operated between 2008 and 2013 and will include construction of a plug at the intersection of the test drift and the access gallery (Figure 4-14).

While the Plug Test portion of PRACLAY is not directly applicable to the current plugging concepts considered by many of the countries considering disposal in granitic rock. It does however contain elements that will allow generic evaluation of the effectiveness of bentonite-based plugs in sealing excavation openings. It should also be noted that if it were decided that ready access to the emplacement drifts is more important that a more massive and durable plug (that may also provide a longer-term sealing function), then short-term plugs in a granitic repository could be constructed in a manner similar to what is proposed for the Belgian PRACLAY experiment or used in the Canadian TSX (see Section 4.3).

4.3 Sealing studies in Canada

Atomic Energy of Canada Limited built and operated an underground research laboratory (URL) near its Whiteshell Laboratory site between 1983 and 2004. During this time a broad range of studies were undertaken, including several related to the sealing and plugging of underground openings. The studies conducted at the Canadian URL that particularly relate to room or drift sealing were the Tunnel Sealing Experiment (TSX) and the Composite Seal Experiment (CSE).

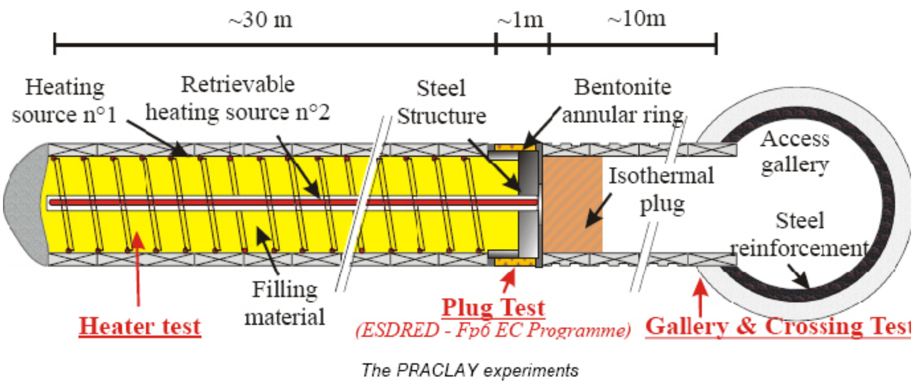


Figure 4-14. *Layout of the PRACLAY experiments /Bernier 2005/.*

4.3.1 Tunnel sealing experiment (TSX)

The TSX was a study that was designed to characterize the sealing potential of two well-constructed bulkheads. The objectives included assessment of technologies for construction of practicable concrete and bentonite-based bulkheads; to evaluate the performance of each bulkhead; and to identify and document parameters that particularly affected performance /Chandler et al. 1998, 2002a, b/. Figure 4-15 shows the layout of this test.

The TSX, excavated by careful drill and blast techniques was located at the 420-m-level of the URL and operated between 1998 and 2004. It consisted of two bulkheads, one composed of an assemblage of precompacted bentonite-sand blocks (70% bentonite-30% sand compacted to approximately 1.95 Mg/m^3 dry density) and the other a mass pour of un-reinforced, low-pH, low-heat, high-performance concrete (LHHPC). The bulkheads were separated by a sand-filled chamber that could be pressurized to full hydrostatic pressure (4.2 MPa). Circulation of hot water in the pressurized chamber allowed evaluation of the effects of temperature on the performance of the bulkheads. Both bulkheads were keyed into the rock in an effort to provide a physical disconnect to the EDZ generated by excavation and subsequent stress-induced rock disturbance /Chandler et al. 1996, Read and Chandler 1997/. It should be noted that these bulkheads were not intended to be demonstrations of bulkhead designs but rather they were intended to allow for evaluation of the strengths and weaknesses of two components of a system that would like be used together in an actual repository application.

The clay bulkhead was approximately 2.6-m in length and occupied a tunnel of 3.5-m-high and 4.375-m-width (Figure 4-16). The bulkhead was vertically keyed to a depth of 1-m for a length of 2 m (the EDZ was measured/estimated to extend no further than 0.5 m into the rock so the keying was expected to interrupt this zone). The clay block assembly extended a distance of 0.3 m on either side of the keyed region. The clay bulkhead required mechanical support in order to remain physically stable and so a steel restraint system was installed at its downstream face. This restraint provided mechanical support only and any water exiting the clay bulkhead could be collected via a series of geotextile filters. This allowed for the locations of water egress to be accurately located.

The clay bulkhead portion of the TSX experienced high seepage during the initial stages of system hydration and pressurization. In many ways the observed high seepage rate events observed in the TSX were similar to those observed for the Tunnel Plugging Test done at Stripa in the mid 1980's /Pusch et al. 1987b/. These high flow events were typically of relatively short duration and involved considerable throughflow but no erosion products (bentonite clay) were detected in the outflow.

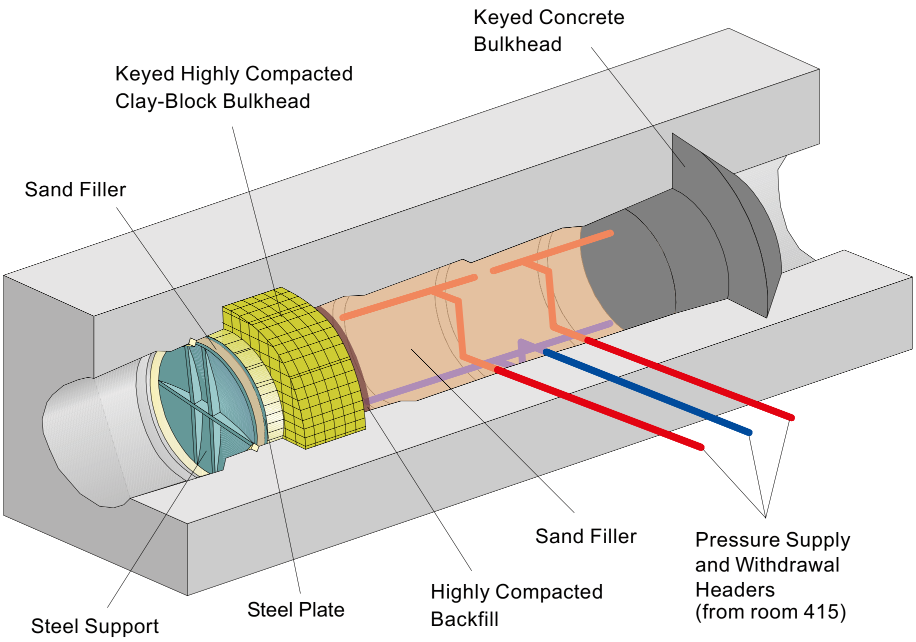


Figure 4-15. The Tunnel Sealing Experiment /Chandler et al. 2002a, b/.

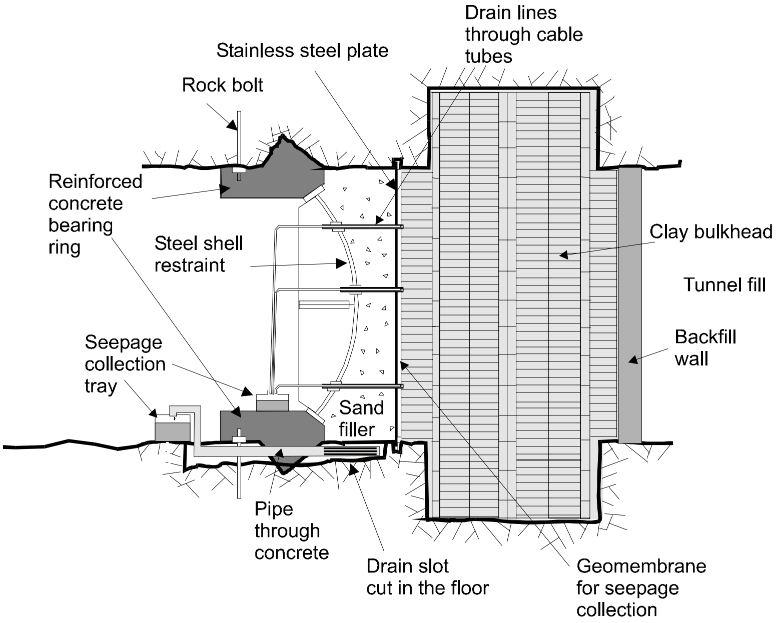


Figure 4-16. Clay Bulkhead Portion of TSX /Martino et al. 2003/.

Like the TPT the large flow events in the TSX were attributed to discrete flow channels or planes that gradually closed as the clay hydrated. Relict features were observed during TSX decommissioning that supported this interpretation /Dixon et al. 2004, Dixon and Martino 2005/. The TSX clay bulkhead showed no large flow events after approximately 8 months of experiment operation and the seepage rate past the clay bulkhead gradually decreased with time (Figure 4-17). The seepage rate also showed darcian flow behaviour with a flow rate proportional to the hydraulic head across the bulkhead. At the time of decommissioning of the TSX the seepage rate past the clay bulkhead had reduced to 0.07 L/h at a hydraulic head of approximately 4 MPa and indications were that most of this was occurring at the perimeter /Chandler et al. 2002a, b, Dixon et al. 2005/.

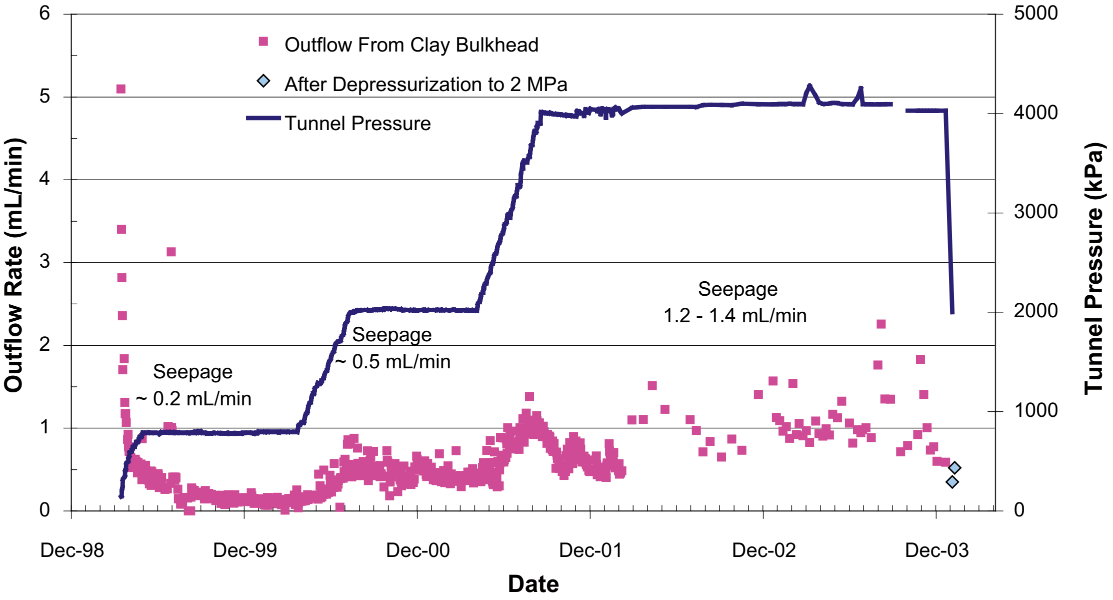


Figure 4-17. Seepage Past the Clay Bulkhead of the TSX /Chandler et al. 2002a, b/.

The concrete bulkhead was 3.5-m-long and was keyed to a maximum depth of 1.75 m for the final 1.75-m of its length (Figure 4-18). It had a 28-day strength in excess of 70 MPa and this strength increases with time. It was installed as a continuously poured mass over an 8-hour period to that no cold-joints existed. Although it is a low-heat concrete, LHHPC does generate some heat during curing and so it was anticipated that at least a small degree of cooling shrinkage would occur. This could potentially lead to shrinkage cracking or loss of bond at the rock-concrete contact. Either of these situations have the potential to result in unacceptable rates of seepage past the concrete bulkhead. In anticipation of interface leakage, the concrete bulkhead had a series of grout lines installed prior to pouring to facilitate remedial grouting. As anticipated, the concrete bulkhead experienced some shrinkage cracking and interface debonding. The locations of debonding and cracking were identified by acoustic emission monitoring and correspond to areas where these features could be expected /Chandler et al. 2002b/.

During the early operational stage of the TSX (fall of 1998), seepage past the concrete bulkhead was observed to be higher than was considered acceptable (96 L/h at 300 kPa hydraulic head) and so grouting was done. It should be noted that this seepage rate equates to an interface transmissivity in the order of 5×10^{-7} m^2/s. Grouting was done using a low-pH grout so as to minimize any disturbance to the local geologic environment and focussed on the interface between the rock and the concrete plug. Grouting proved to be very effective and the seepage rate past the concrete plug was reduced to approximately 0.07 L/h at 400 kPa hydraulic head, a transmissivity of approximately 3×10^{-10} m^2/s as seen in Figure 4-19 /Chandler et al. 2002b/. At the end of the isothermal stage of the TSX the seepage past the concrete bulkhead was measured to be approximately 0.84 L/h at 4 MPa hydraulic head. This seepage rate represents essentially a no-flow condition.

The TSX operated at a 4 MPa hydraulic head for approximately 3 years, and for a portion of this time the system underwent heating to assess the influence of temperature on bulkhead behaviour. Increasing system temperature resulted in no discernible degradation in the ability of the bulkheads to act as effective hydraulic plugs

The TSX demonstrated that it was possible to construct both clay and concrete bulkheads that could effectively cut off most of the water flow from a tunnel/room/drift in a granitic rock mass. Provided that the clay component is provided with mechanical support it proved to provide a lower seepage rate than concrete but was prone to large-seepage events in its pre-saturation stage. A grouted concrete bulkhead exhibited higher seepage rate but did not exhibit un-anticipated flow events. Based on the results of the TSX it can be concluded that a keyed composite seal containing both clay and concrete components would provide a means of cutting off flow along the tunnel axis, would have a self-sealing capacity and would be mechanically stable. The results of the TSX were then taken into account when designing the first of what were to be several Composite Seal Experiments (CSE) conducted in large (1.24-m) diameter boreholes at the Canadian URL.

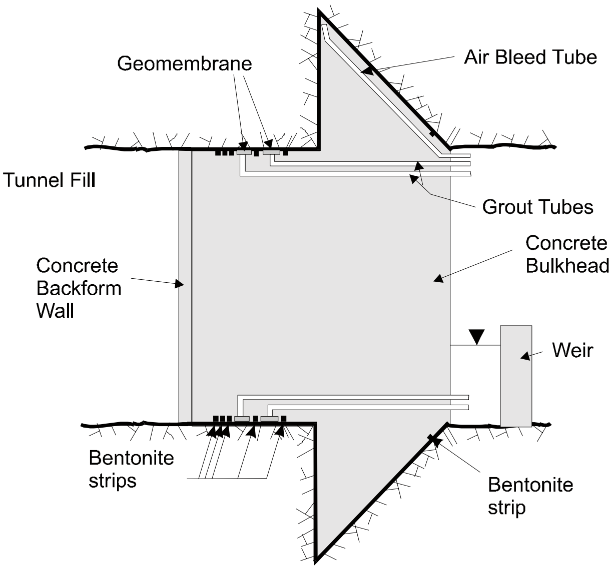


Figure 4-18. Concrete Bulkhead in Tunnel Sealing Experiment /Martino et al. 2002/.

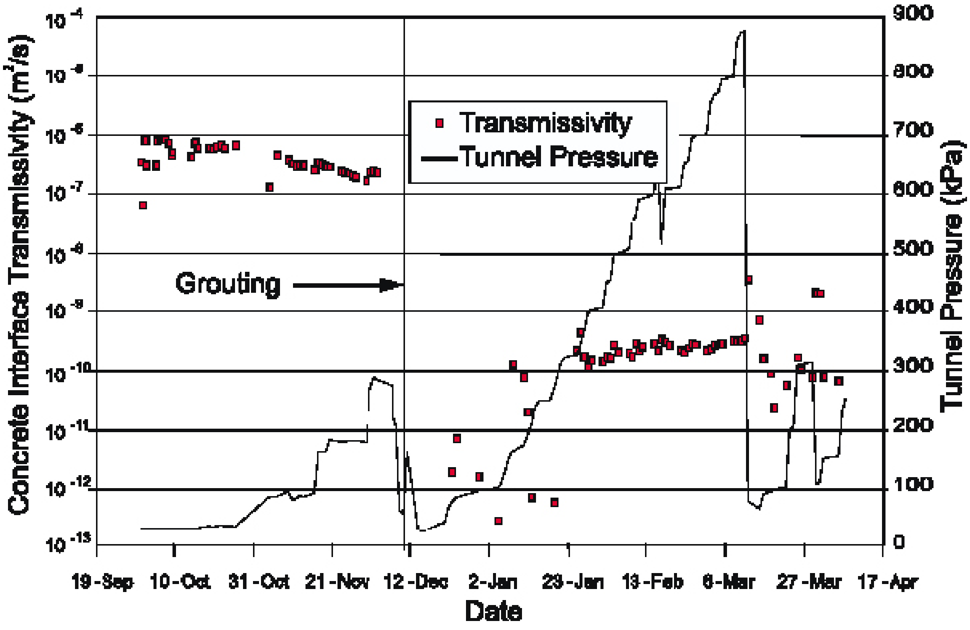


Figure 4-19. *Effect of grouting on transmissivity of the concrete-rock interface /Chandler et al. 2002b/.*

4.3.2 Composite Seal Experiment (CSE)

The CSE was installed in a 6-m-deep by 1.24-m-diameter borehole at the 240 level of the Canadian URL in May 2002. The CSE was an extension of the sealing system design process that included the TSX and was originally envisioned as being the first in a series of tests that examined the performance of a number of composite sealing system designs. Only the first of these tests was installed and run before the closure of the Canadian URL in 2004. Due to the negligible effort to continue monitoring the CSE while the URL decommissioning was occurring, the CSE was left running through 2006 and will likely be disconnected at some point in 2007.

The composite seal consists of a 0.3-m-thick assemblage of highly compacted bentonite/sand blocks (70% bentonite – 30% sand with a dry density of 1.9 Mg/m^3), overlain by a 0.5-m-thick layer of low heat high performance concrete (LHHPC). A layer of compacted, lean clay/sand, non-swelling backfill were placed between the sand fill and the bentonite/sand blocks. A geotextile layer was also installed at the interface of the sand and backfill components to prevent intrusion of the clay into the sand. Underlying these components of the CSE a 1.0-m-thick sand layer fills the remaining borehole volume. This sand-filled section is used as a hydraulic pressurization chamber /Martino et al. 2003 and Kjartanson and Martino 2004/. Figure 4-20 presents the layout of the CSE.

The LHHPC concrete cap portion of the CSE had a 28-day strength that exceeded 70 MPa and a pH of less than 10. This component was mass poured on the upper surface of the clay blocks and was not reinforced or anchored into the surrounding rock. The concrete plug relies entirely on the concrete-rock bond to restrain the hydraulic pressure applied to the base of the CSE (2.35 MPa) /Kjartanson and Martino 2004/. Were the bond and shear resistance of the concrete plug/borehole wall to be exceeded, a separately poured concrete restraint ring would become active. This upper concrete ring is keyed to the borehole wall with steel restraint pins but is not in direct contact with the plug, the plug would need to move upwards a small amount before it would contact the restraint system (Figure 4-20). The concrete plug also had grout tubes installed as part of its construction in case interface flow was such that grouting became necessary. Flow past the concrete plug was such that grouting was never necessary.

The clay layer in the CSE was effectively saturated by early 2003 (12 months after test initiation) and a period of steady pressure head monitoring followed and the seepage rate showed a decrease from a peak of approximately 0.0024 L/h to approximately 0.0015 L/h (hydraulic conductivity of 4.7×10^{-12} m/s) under a hydraulic pressure of 2.35 MPa. The decrease in seepage was attributed to the hydrating clay exerting increased pressure on the clay-rock interface and to the concrete interface

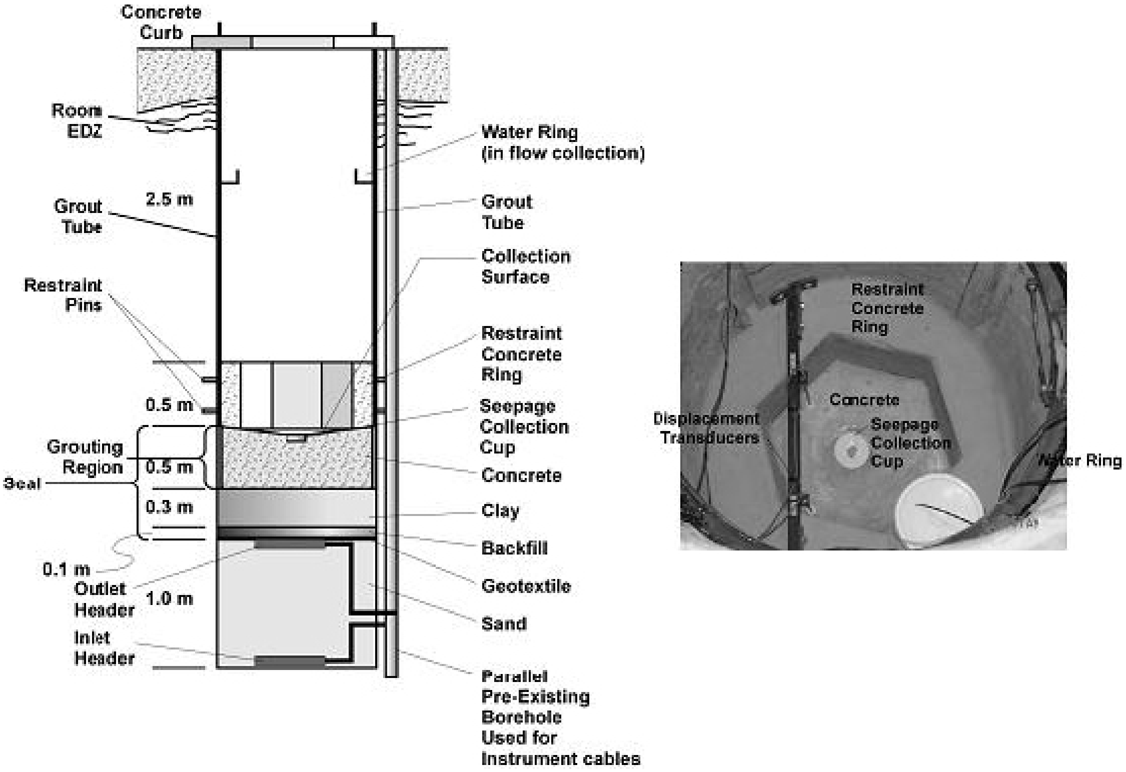


Figure 4-20. Layout of the CSE and the upper surface of the concrete cap /Martino et al. 2003/.

where accumulating fine particles at the contact with the rock-concrete interface resulted in decreasing flow (essentially a clay grouting process), /Martino et al. 2003/. The seepage rate continued to decrease and as a result the effective flow rate between 2004 and 2006 became effectively immeasurable (< 0.0006 L/h).

The flow past the plug in the CSE is nearly two orders of magnitude lower than was observed in the TSX (0.0006 versus 0.048 L/h). There are clearly substantial differences in the rock conditions (EDZ) between the two installations but the CSE clearly illustrated that it was possible to construct a very effective seal in a large-diameter (1.24 m) bored opening in unfractured rock. These results have considerable relevance to repository sealing where options for sealing of bored drifts in the KBS-3H concept or for room and tunnel plugs elsewhere in a repository are being developed. It is anticipated that the lessons learned in the TSX and CSE will be utilized when it comes to design and installation of permanent plugs and seals during the final physical closure of the Canadian URL in 2007 and beyond.

4.4 Sealing studies in Germany

Germany has focussed much of its efforts to evaluating salt as a host medium for radioactive waste isolation. However, in common with all programs, there will be a need to close and plug the excavations made to allow for waste emplacement.

A rectangular test seal measuring 3.2-m by 3.5-m and 5-m in length was installed in a 35 year-old drift in the former potash mine Sondershausen in Germany /Sitz et al. 2002/. The seal was installed in the massive salt formation at 700-m-depth and was tested using a saturated brine solution provided at pressures as high as 8 MPa to one side of the plug. This plug consisted of an assembly of precompacted blocks made from a mixture of 40 to 50% bentonite clay and sand (Figure 4-21). In order to cut off the EDZ the bentonite-filled portion of the plug was keyed in two locations and a prismatic construction consisting of salt bricks was installed at the downstream face to provide mechanical support to the clay bulkhead.

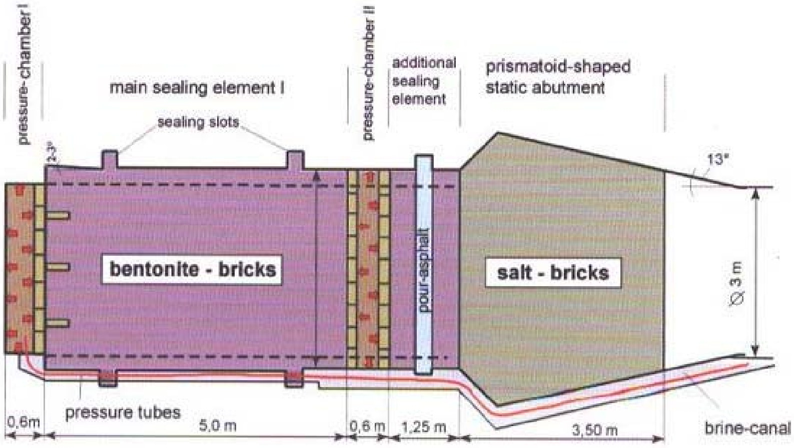


Figure 4-21. *Tunnel Plugging Test in salt /Sitz et al. 2002/.*

This test operated at fluid pressures of 1.5, 2.5, 4 and 8 MPa and seepage was monitored. Unfortunately the restraint system was insufficient to keep the clay plug volumetrically restrained at fluid pressures above 1.5 MPa, resulting in an inability to determine the flow rates past the bulkhead at those pressures. At 1.5 MPa the seepage rate first measured was almost 3 L/h but this decreased to 0.45 L/h after only 30 days /Sitz et al. 2002/.

4.5 Sealing studies in Switzerland

4.5.1 Grimsel test site

Two underground research facilities intended to examine options for nuclear fuel waste disposal have operated in Switzerland. One of these facilities, Grimsel is located in a granitic rock formation and was used to conduct a simulation of a horizontally emplaced waste canister /Huertas et al. 2000, Villar et al. 2005/. This experiment, know as FEBEX included the installation of a bentonite and concrete plug at the intersection of the drift containing the experiment and the access tunnel (Figure 4-22). FEBEX was an international project operated at Grimsel Switzerland and examined the emplacement geometries considered by NAGRA, ENRESA and to a degree the KBS-3H concepts. The concrete plug portion of FEBEX measured approximately 2.7-m in length in a circular borehole of 1.9-m-diameter /FEBEX 1996/. The concrete plug was keyed to a depth of 0.4-m for 1.569-m of its length. Key excavation was accomplished using a radial saw and then mechanical breaking it to minimize the excavation damage into the surrounding rock. The concrete used was a low-heat, low-shrinkage mixture that was cast as 3 sections without reinforcement. As a result it did not provide a tight contact at the top of the concrete. It was also designed to resist a combined swelling and hydraulic pressure of 5 MPa on its upstream face but there were no requirements for it to provide either gas or water tightness.

The bentonite buffer material contained within FEBEX was precompacted into blocks that surrounded heaters that simulated reprocessing waste canisters. The clay was prepared to a dry density of 1.6 Mg/m^3 in order to limit the swelling pressure it could develop to less than 5 MPa. Considerable leakage past the concrete bulkhead was reported in this simulation, predominantly via cable ports but was not quantified.

Mont Terri test site

In addition to the granitic rock site at Grimsel, Switzerland also has the Mont Terri underground research facility constructed in argillaceous rock. This site is being used to examine a number of aspects associated with potential nuclear waste isolation in sedimentary formations. Included in these studies is a plan to install and test of tunnel or drift plugs. As of 2006 these studies are still in the conceptual development and planning stages so there is as-yet no field information available from them.

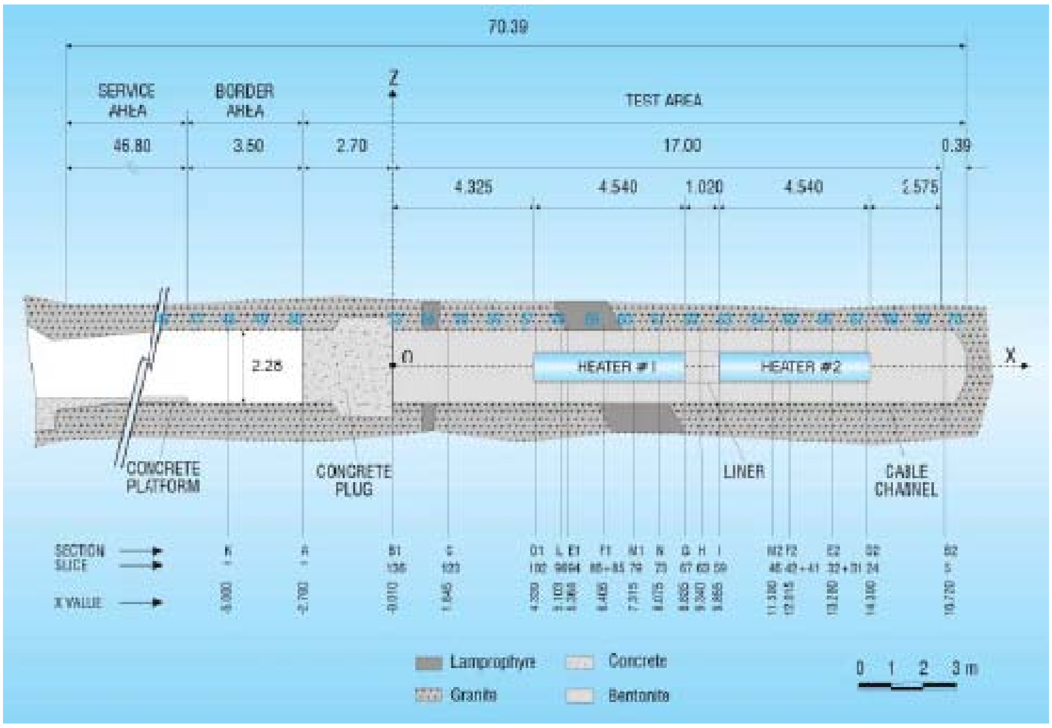


Figure 4-22. *Layout of FEBEX /Villar et al. 2005/.*

4.6 Summary of sealing studies related to repositories and plugging of access rooms and drifts

A number of studies that examine aspects of sealing openings in granitic rock have been conducted since the early 1980s. Various studies and field simulations related to repository applications examined the nature and controlling parameters in effectively sealing tunnels and openings under a range of geologic and hydrogeologic conditions. Beginning with the first large-scale field tests at the Stripa site and then continuing at the Äspö and Canadian URL facilities, the influence of plugging material, length of seal, influence of keying to cut off the EDZ and effect of excavation technique on seepage have been investigated. Valuable insight and knowledge related to seal construction have been gained in these studies. It should also be recalled that none of these demonstrations were specifically intended to test an optimized seal design and in most cases were intended to assess what parameters most affect seepage past a seal.

At Stripa can be concluded from the Shaft Sealing Test that concrete on its own is inadequate to effectively prevent water seepage past a plug and that bentonite provided a considerable self-sealing capacity. It is estimated that flow at 6 MPa in a 1.8-m-diameter opening of the type in the Shaft Sealing Test would see a reduction in flow from 540 L/h to 9 L/h if a section of bentonite is installed (based on the assumptions outlined in Section 4.1.1). The Tunnel Plugging Test conducted at Stripa looked at the effectiveness of a small gasket of highly compacted bentonite in reducing seepage past a massive concrete plug. As was the situation with the Shaft Sealing Test, the seepage past the concrete plug was substantially reduced, from an estimated 2,000 L/h to 150 L/h at 6 MPa (again extrapolating from the pressure the test operated at to a 6 MPa hydraulic head). From these two tests it is clear that bentonite used in conjunction with concrete provides a much more effective seal. These tests were of course run for a very short duration and results obtained at lower hydraulic heads extrapolated linearly to anticipated repository conditions (6 MPa hydraulic head). The longer-term behaviour and effects of groundwater flow on bentonite or fracture-filling materials were not assessed.

At the Canadian URL the Tunnel Sealing Experiment examined the effectiveness of keying in cutting of the EDZ and the nature of seepage past clay and concrete bulkheads installed in a full-scale tunnel at 4 MPa hydraulic head. Concrete was found to require cement grouting in order to reduce seepage that was almost entirely confined to the rock-concrete interface region. An ungrouted tunnel plug composed of concrete at the URL would have seen seepage in the order of 1,920 L/hr if operated at a 6 MPa hydraulic head. Cement grouting of the rock-concrete interface reduced the seepage to 1.2 L/h (based on extrapolation from 4 MPa to 6 MPa hydraulic head).

In the clay bulkhead the seepage past the bulkhead was confined almost entirely to the interface between the clay and the rock (where the clay was of the lowest density). Seepage was observed to gradually decrease with time, this being attributed to swelling of the clay and gradual densification of the materials at the rock-clay interface. The clay bulkhead exhibited a seepage rate that would have corresponded to approximately 0.1 L/h at 6 MPa hydraulic head (again extrapolated from results at 4 MPa). The CSE has taken away one of the major features that had been identified as greatly influencing seepage past a bulkhead, the EDZ. The CSE was installed in a water-jet excavated borehole that has little in the way of an EDZ. Into this excavation a seal consisting of a compacted bentonite-based blocks and a cast-in-place low-pH, high-performance concrete plug were installed. Seepage past the plug was monitored for over 4 years and never exceeded 0.0024 L/h (this would correspond to < 0.01 L/h in a 1.8-m-diameter borehole at 6 MPa hydraulic head).

More recent or ongoing tests at the Äspö facility have extended some of the studies conducted at Stripa or the Canadian URL by incorporating bentonite gaskets into concrete bulkheads or plugs and other structures. The Backfill and Plug Test incorporated both a bentonite gasket in a concrete bulkhead that was keyed into the rock but also contained bentonite-rich materials in the upper regions of the tunnel adjacent to it. The seepage past this type of structure at 6 MPa hydraulic head is estimated to be 13.6 L/h. In the prototype repository test, a similar approach to plugging the tunnel to the BPT was adopted.

Sealing tests done in salt formations as well as argillaceous materials have found that it is the interface between the excavations and the sealing material that control the seepage past a bulkhead. Appropriate treatment of this region will have the greatest influence in limiting seepage from a closed and sealed region of a repository and areas that are still open.

5 Tunnel plug concepts considered for a repository

Based on the experiences related in previous sections of this document and using the generic tunnel dimensioning and geologic information assumed to be valid for a geologic repository in Scandinavia, a number of potential tunnel plug layouts have been developed. This section examines five conceptual designs for a tunnel plug in granitic rock, examines the positive features of each as well as identifying potential difficulties. It should be noted that all of these concepts are based on the fundamental assumption that there is no substantial excavation damaged zone (EDZ) in the rock that requires cutting off. This means that there is no need to key the plug in order to cut off the EDZ and any rock excavation associated with plug installation only serves a mechanical purpose. Activities needed to better evaluate each concept are also provided. These design concepts should not be considered to be optimised or the only ones that might work in a granitic rock environment, rather they represent some initial thoughts on layouts that have the potential to work in a repository.

For ease of reference the five design concepts have been named as follows:

1. Concrete Arch – Bentonite Block Concept (CABB)[1]
2. Concrete Arch – Rock Filter Concept (CARF)[1]
3. Long Concrete Plug with Upstream Filter (LCUF)[1]
4. Long Concrete Plug – Bentonite Block – Upstream Filter (LCBB)[1]
5. Long Concrete Plug – Bentonite Block – Floor Filter (LCBB-FF)[2]

Should it be determined that there are rock stability issues associated with spalling or the presence of a considerable excavation damaged zone (EDZ) then the design of the tunnel plug will need to be reconsidered. In that type of rock condition the tunnel plug will likely need to include a keyed region where the key penetrates to a depth where it interrupts the EDZ. The EDZ is defined here as a damaged region that results in a discernible change in the mass transport characteristics of the rock adjacent to the tunnel openings. Under these conditions the type of tunnel plug represented by the Tunnel Sealing Experiment would be appropriate and would likely include use of a series of swelling clay and concrete components.

5.1 Concrete Arch – Bentonite Block Concept (CABB)

5.1.1 Description of CABB Concept

The Concrete Arch – Bentonite Block Concept (CABB) is based on the type of mechanical restraint system that was used in the Backfill-Plug Test (BPT) at Äspö (Figure 4-7, Figure 4-8) discussed in Section 4.1.2. In this test a keyed, dome-shaped concrete mechanical plug was installed to prevent material movement out of the tunnel as well as providing a barrier to water flow (Figure 5-1). Experiences gained in the BPT found that there was a need for a more effective sealing system at the rock-concrete interface and the CABB concept attempts to provide this.

In The CABB concept a series of materials are installed to provide both water control during plug construction and materials that will compliment one-another once the plug is in place. Immediately downstream of the backfill material is a layer of crushed rock filter material that is intended to provide a means of diverting water seepage that might be occurring through the backfill (likely near the rock-backfill interface). This seepage would be ongoing in the backfilled tunnel volume and given that the backfill will not have had time to hydrate, swell and seal off water movement in the period immediately following backfill placement then control of seepage is important. High seepage within the backfilled tunnel has both the potential to induce erosion as well as causing considerable difficulty in installing the tunnel plug. A layer of filter material will provide a material that can capture and redirect seepage via drainage pipes (Figure 5-1) from the tunnel and past the location of the main tunnel plug during plug construction.

---

[1] Concept supplied by Clay Technology AB.

[2] Concept supplied by Atomic Energy of Canada Ltd.

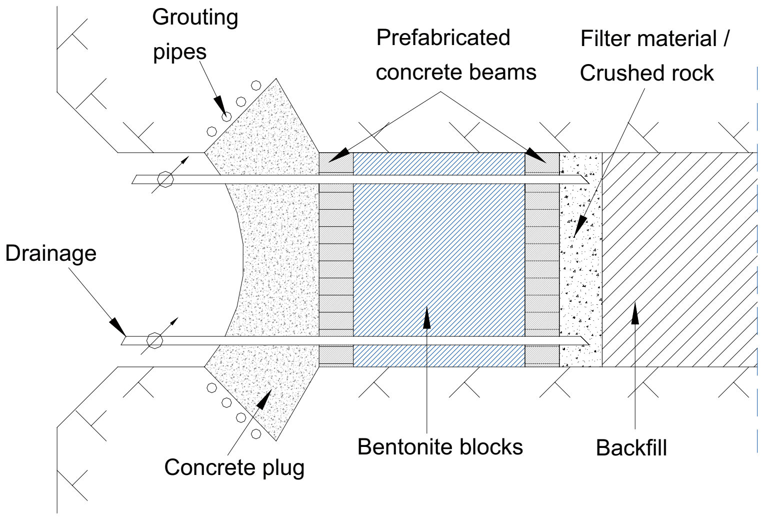


Figure 5-1. *Concrete Arch – Bentonite Block Concept (CABB).*

A wall constructed using pre-fabricated concrete beams is installed prior to the filter wall, providing mechanical constraint to the filter layer and a smooth, dry surface against which the next part of the plug (bentonite blocks) can be installed. This wall is not required to have a particularly effective sealing capacity and is more of a construction expedient than a mechanical component of the seal.

Downstream of the first concrete beam wall is a section of tunnel that contains highly compacted bentonite blocks (Figure 5-1). These blocks would be installed tight against the upstream concrete beam wall and the downstream concrete beam wall. This will provide a rigidly constrained volume into which the HCB blocks can be installed. Being constructed of precast concrete beams and HCB blocks this volume can be assembled stepwise from the floor of the tunnel to the roof. While this assembly is occurring, the upstream concrete-beam wall and filter drainage system will prevent unwanted water from entering the volume where the HCB is being installed.

On completion of the HCB-concrete beam section of the plug then a stable volume is present for the installation of a dome-shaped concrete structure closest to the end of the tunnel. This final section of the plug will require excavation of the key and pre-installation of a cement grouting system to provide a final interface sealing step following the installation of a mass-poured concrete dome.

The final stages of the restraint system construction would be the removal and sealing of the drainage system that penetrates the tunnel plug. Depending on operational considerations it may be desirable to leave the drainage system operational for as long as the upstream filter and seepage collection system remains operational. This would allow for porewater pressure release within the backfilled tunnel and potentially reduce the total pressure acting against the mechanical restraint system.

5.1.2 Advantages and issues associated with CABB Plug Concept

As with any conceptual design there are knowns and unknowns associated with it. In the CABB concept there are perceived advantages but also there are unknowns and potential disadvantages to it. Without judging the suitability of the concept a listing and discussion of some of these aspects are provided below.

Some of the advantages that are evident in the CABB design are:

- The backfilled tunnel does not require a smooth or vertical downstream face in order to install a filter layer.
- Water seepage during plug construction can be controlled via the filter.
- Use of prefabricated concrete beams provides filter material constraint.
- A smooth upstream and downstream surface is provided, against which HCB blocks can be installed.

- Provides a considerable quantity of high-swelling-capacity bentonite that will provide a good seal at the interface with the rock as well as some degree of self-grouting to the upstream face of the concrete plug.
- Provides a smooth back surface against which the concrete plug can be cast.
- Transfer of loads from the backfilled tunnel into a relatively deep section of rock.
- The length of tunnel into which the plug intrudes is relatively small.
- Probably uses less poured concrete than some other concepts and hence lower alkaline influence.
- Can provide porewater pressure control at upstream face for an extended period.

The CABB also has a number of potential difficulties or questions associated with its use, including:

- Will erosion occur at the backfill-rock interface prior to tunnel closure.
- Presence of a porous filter region at the downstream face of the backfill, will it remain as a porous section (if so does it matter?).
- How to install the precast concrete beams and filter layer quickly enough to avoid compromising the backill.
- Determining the ability to withdraw the drainage pipes without leaving a permanent hydraulically weak region.
- The need to cut a keyed region into the rock to transfer load, will the rock be stable and able to support the load.
- The need to install extensive re-enforcement to the concrete plug (steel) in order to give it sufficient strength to support the high loads.
- Complex design is required to ensure that the concrete dome is both strong enough and distributes the load evenly to the surrounding rock.

Many of the items listed as potential difficulties can likely be eliminated in the process developing a detailed design for the plug, however some issues will remain and require addressing prior to adopting this design concept for repository use.

5.2 Concrete Arch – Rock Filter (CARF) Concept

5.2.1 Description of the CARF Concept

The Concrete Arch – Rock Filter (CARF) concept uses the basic concrete arch concept of the CABB concept described above but eliminates the HCB component, moving the filter wall to a region immediately upstream of the concrete plug (Figure 5-2).

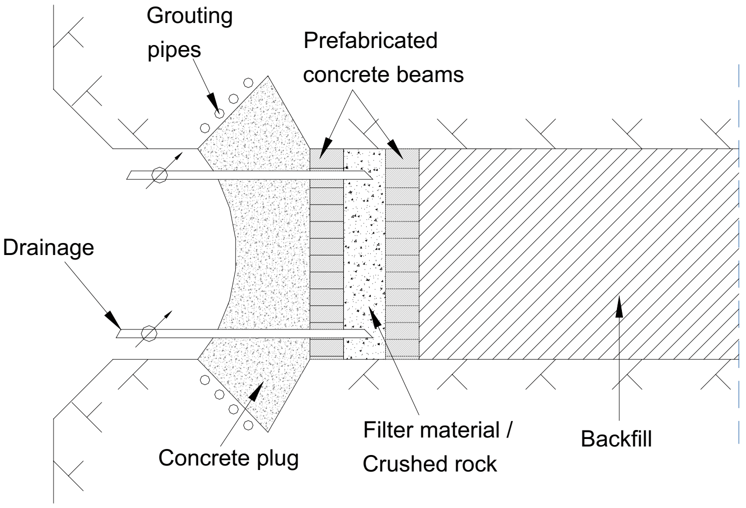


Figure 5-2. Concrete Arch – Rock Filter Concept (CARF).

In the CARF concept the downstream face of the backfilled tunnel must be close to vertical and able to accept installation of precast concrete beams. The upstream wall of concrete beams provides a mechanical restraint to the backfill in the tunnel while a second wall is installed a short distance further downstream. The space between the walls will be filled with a filter material (crushed rock?). This filter material will provide a medium into which seepage water from the backfilled tunnel can be redirected into a drainage system to control water seepage during installation of the structural concrete plug. The concrete arch portion of the plug will be the same in concept to the one in the CABB concept described in Section 5.1.

On completion of the concrete arch portion of the CARF the isolated filter wall can continue to be operated, providing a means of controlling the hydraulic head at the downstream face of the tunnel. Ultimately it may be possible to use the drainage lines to inject grout into the granular fill, removing this potential void volume from the system. The upstream and downstream walls would provide some degree of constraint to grout movement during this process.

5.2.2 Advantages and issues associated With CARF Plug Concept

As with any conceptual design there are knowns and unknowns associated with it. In the CARF concept there are perceived advantages but also there are unknowns and potential disadvantages to it. Without judging the suitability of the concept a listing and discussion of some of these aspects are provided below.

Some of the advantages that are evident in the CARF design are:

- Fewer components than the CABB concept.
- “Simpler” construction process than CABB concept.
- Water seepage during plug construction can be controlled via the filter.
- Use of prefabricated concrete beams provides filter material constraint.
- A smooth upstream and downstream surface is provided, against which the structural supporting plug can be cast.
- Transfer of loads from the backfilled tunnel into a relatively deep section of rock.
- The length of tunnel into which the plug intrudes is relatively small.
- Probably uses less poured concrete and hence lower alkaline influence than some other concepts.
- Can provide porewater pressure control at upstream face of concrete plug for an extended period.

The CARF also has a number of potential difficulties or questions associated with its use, including:

- Will erosion occur along the backfill-rock interface prior to tunnel closure.
- Presence of a permanent porous filter region at the upstream face of the concrete plug.
- How to install the precast concrete beams against the backfill wall in a manner than limits voids at the contact.
- How to limit interface flow between precast concrete beams and concrete plug during plug construction.
- Determining the ability to withdraw the drainage pipes without leaving a permanent hydraulically weak region in the concrete plug.
- The need to cut a keyed region into the rock to transfer load, will the rock be stable and able to support the load.
- The need to install extensive re-enforcement to the concrete plug (steel) in order to give it sufficient strength to support the high loads.
- Complex design is required to ensure that the concrete dome is both strong enough and distributes the load evenly to the surrounding rock.
- The concrete plug requires complete reliance on cement grouting to seal the interface between the rock and concrete plug.
- There is no self-sealing material at the upstream face of the concrete plug.

Many of the items listed as potential difficulties can likely be eliminated in the process developing a detailed design for the plug, however some important issues will remain. Most important of these is the lack of any sealing material immediately upstream of the concrete plug. This and other issues will require addressing prior to adopting this design concept for repository use.

5.3 Long Concrete Plug with Upstream Filter (LCUF)

5.3.1 Description of the LCUF Concept

The LCUF plug concept borrows its concrete plug portion from the long un-reinforced concrete plug concept described in Section 2.1 and shown in Figure 2-1. The LCUF plug concept adds a filter layer at its upstream face (Figure 5-3), which is intended to provide a means of controlling seepage during installation of the massive plug.

Once the upstream seepage collection portion of the plug is installed, their will be a series of rock bolts installed in the rock where the plug is to be installed and a cement grouting system will be pre-installed. The rock bolts are intended to provide mechanical support to the concrete plug, preventing downstream deformation and transfer of load to the surrounding rock. Grouting of the interface between the rock and the concrete will then be conducted, sealing any voids or seepage paths left following concrete casting. This concept relies on the bond between the concrete and the rock to provide both mechanical stability and prevention of seepage past the plug.

The filter layer at the upstream face of the plug can be isolated by removal of the drainage pipes and these pathways will need to be sealed prior to repository closure or else there will be a preferred seepage path left. The drainage lines can be used to supply grout to the filter material in order to reduce seepage to the upstream face of the concrete plug. This grouting cannot however be relied on to be hydraulically robust.

5.3.2 Advantages and issues associated With LCUF Plug Concept

As with any conceptual design there are knowns and unknowns associated with it. In the LCUF concept there are perceived advantages but also there are unknowns and potential disadvantages to it. Without judging the suitability of the concept a listing and discussion of some of these aspects are provided below.

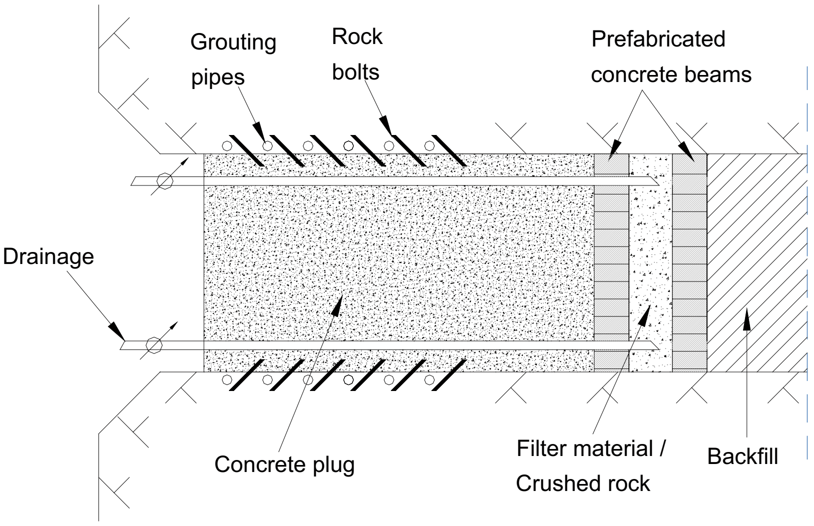


Figure 5-3. Long Concrete Plug with Upstream Rock Filter (LCUF).

Some of the advantages that are evident in the LCUF design are:

- Fewer components than many other concepts.
- "Simpler" construction process than many concepts.
- Water seepage during plug construction can be controlled via the filter.
- Use of prefabricated concrete beams provides filter material constraint.
- A smooth upstream surface is provided, against which the mass poured concrete plug can be cast.
- Transfer of loads from the backfilled tunnel into surrounding rock along a long surface.
- There is no need to excavate keys.
- There is no complex concrete re-enforcement needed.
- Can provide porewater pressure control at upstream face of concrete plug for an extended period.

The LCUF also has a number of potential difficulties or questions associated with its use, including:

- Will erosion occur at the backfill-rock interface prior to tunnel closure.
- Presence of a permanent porous region at the upstream face of the concrete plug.
- How to install the precast concrete beams against the backfill wall in a manner than limits voids at the contact.
- How to limit interface flow between precast concrete beams and concrete plug during plug construction.
- Determining how to withdraw the drainage pipes without leaving a permanent hydraulically weak region in the concrete plug.
- The concrete plug requires complete reliance on cement grouting to seal the interface between the rock and concrete plug.
- There is no self-sealing material at the upstream face of the concrete plug.

Many of the items listed as potential difficulties can likely be eliminated in the process developing a detailed design for the plug, however some important issues will remain. Most important of these is the lack of any sealing material immediately upstream of the concrete plug. This and other issues will require addressing prior to adopting this design concept for repository use.

5.4 Long Concrete – Bentonite Block (LCBB)

5.4.1 Description of the LCBB Concept

The LCBB concept is similar to the LCUF concept described above but rather than rely entirely on the concrete-rock bond and subsequent cement grouting of the rock-concrete interface to stop seepage past the plug, a section of high swelling capacity bentonite is installed.

The LCBB concept has a seepage collection system installed immediately adjacent to the tunnel backfill and this fill is drained via pipes to the downstream end of the tunnel. This should provide a section of tunnel that can be worked in without further water control structures being installed. The filter materials are held in place with a precast concrete beam assembly and a distance further downstream a second wall of precast concrete beams is installed. The volume between these walls will have highly compacted bentonite installed in it and once this installation process is completed the remaining length of the tunnel plug can be installed as a mass pour on concrete.

The HCB-filled section of tunnel provides a hydraulic seal at the upstream end of the long concrete plug and also a self-grouting capacity to the concrete segment should seepage occur. On completion of the plug construction the seepage control system can be used to maintain a low hydraulic head at the upstream face of the plug, potentially limiting the load applied to it. On disconnecting the seepage control system it will be possible to withdraw the pipes in the region occupied by the HCB and then grout the region penetrating the concrete plug. The HCB will then be able to be counted on to provide a self-sealing and auto-grouting capacity to the upstream face of the concrete plug in the region where the pipes were originally installed.

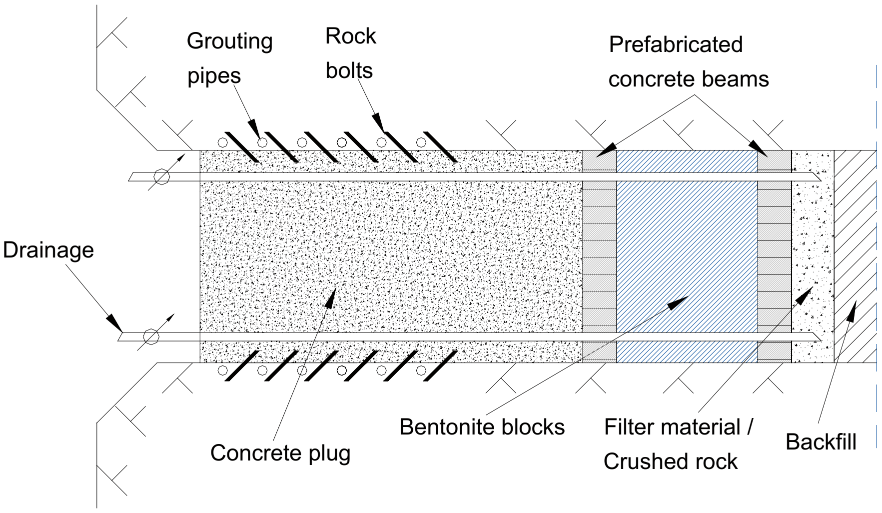


Figure 5-4. *Long Concrete Plug – Bentonite Block (LCBB) with Upstream Filter.*

5.4.2 Advantages and Issues Associated With LCBB Plug Concept

As with any conceptual design there are knowns and unknowns associated with it. In the LCBB concept there are perceived advantages but also there are unknowns and potential disadvantages to it. Without judging the suitability of the concept a listing and discussion of some of these aspects are provided below.

Some of the advantages that are evident in the LCBB design are:

- The backfilled tunnel does not require a smooth or vertical downstream face in order to install a filter layer.
- Water seepage during plug construction can be controlled via the filter.
- Use of prefabricated concrete beams provides filter material constraint.
- A smooth upstream and downstream surface is provided, against which HCB blocks can be installed.
- Provides a considerable quantity of high-swelling-capacity bentonite that will provide a good seal at the interface with the rock as well as some degree of self-grouting to the upstream face of the concrete plug.
- Provides a smooth back surface against which the concrete plug can be cast.
- Transfer of loads from the backfilled tunnel into surrounding rock along a long surface.
- There is no need to excavate keys.
- There is no complex concrete re-enforcement needed.
- Can provide porewater pressure control at upstream face for an extended period.

The LCBB also has a number of potential difficulties or questions associated with its use, including:

- Will erosion occur along the backfill-rock interface prior to tunnel closure.
- Presence of a porous filter region at the downstream face of the backfill, will it remain as a porous section (if so does it matter?).
- How to install the precast concrete beams and filter layer quickly enough to avoid compromising the backfill.
- Determining the ability to withdraw the drainage pipes without leaving a permanent hydraulically weak region.

Many of the items listed as potential difficulties can likely be eliminated in the process developing a detailed design for the plug. Some issues will remain and require addressing prior to adopting this design concept for repository use.

5.5 Long Concrete – Bentonite Block – Floor Filter (LCBB-FF)

5.5.1 Description of the LCBB-FF Concept

The LCBB-FF concept like the LCBB concept described above involves construction of a composite seal that provides mutually supporting components to provide a seal to the tunnel. The LCBB-FF concept approaches water control slightly differently from the generic LCBB layout.

One potential issue in backfilling of a tunnel is water control and prevention of seepage water interfering with installation of the tunnel seal. In all of the concepts presented above water control is provided only at the end of the backfilled tunnel, immediately adjacent to the tunnel plug location and a porous zone is left within the tunnel at the end of sealing activities (Figure 5-5). Given the limited swelling capacity of Friedland-type backfill materials and in some cases the presence of precast concrete segments between the swelling clay and the filter materials, it is unlikely that the filter will ever be effectively sealed.

The LCBB-FF concept attempts to deal with the issue of sealing filter zones by placing a high-swelling capacity bentonite immediately adjacent to the filter material. In addition to the vertical filter at the downstream end of the backfill, a filter bed is installed in the floor of the tunnel with an overlying layer of high swelling capacity bentonite. On this base the clay blocks will be installed. The coarse floor filter material is intended to provide a water seepage pathway along the tunnel avoiding generation of piping features in the backfill and reducing the erosion of materials. The floor filter would consist of sufficiently coarse materials to prevent upwards wicking of water to the overlying bentonite materials. So long as the system is kept drained there should be no buildup of hydraulic pressure within the backfill. The filter bed is provided with drainage line(s) at the point where it meets the HCB wall and this line is run all the way through the shotcrete segment of the plug located immediately downstream of the bentonite blocks.

The shotcrete layer is installed along the entire face of the bentonite block barrier component to a depth sufficient to provide mechanical support to the tunnel while the massive concrete plug is installed. If desired, in order to avoid any through-going hydraulic connection, the drain line can be terminated at the upstream face of the mass poured concrete plug. Immediately prior to pouring of the concrete plug, the drains can be withdrawn from the bentonite and the void plugged at the shotcrete face. This plug needs only to function long enough for the concrete plug to be poured and then as the result of swelling of the HCB this pathway will be closed.

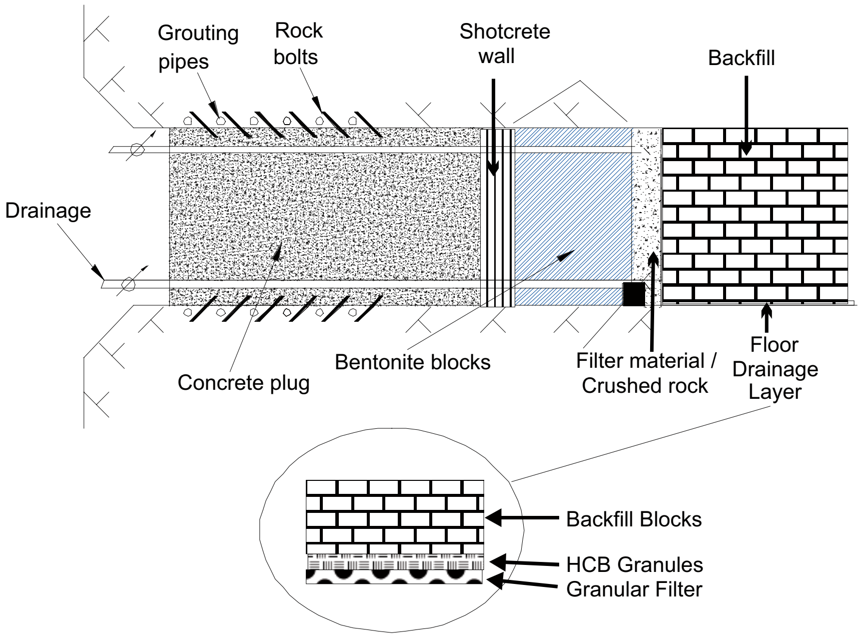


Figure 5-5. Long Concrete Plug – Bentonite Block – Floor Filter (LCBB-FF) Concept.

As with all the concepts described in this document, grouting of the rock-concrete plug interface is anticipated to be necessary in order to ensure effective sealing. The shotcrete and HCB components upstream will provide further sealing and self-sealing capacity to the plug. It is anticipated that the HCB will swell to fill the large porespaces present in the filter wall and floor filter as soon as drainage is terminated and water backs up into these volumes, resulting in hydration of the HCB.

5.5.2 Advantages and issues associated With LCBB-FF Plug Concept

As with any conceptual design there are knowns and unknowns associated with it. In the LCBB-FF concept there are perceived advantages but also there are unknowns and potential disadvantages to it. Without judging the suitability of the concept a listing and discussion of some of these aspects are provided below.

Some of the advantages that are evident in the LCBB design are:

- The backfilled tunnel does not require a smooth or vertical downstream face in order to install a filter layer.
- Water seepage during plug construction can be controlled via the floor and vertical filters.
- Includes a considerable quantity of high-swelling-capacity bentonite that will provide a good seal at the interface with the rock as well as some degree of self-grouting to the upstream face of the shotcrete and concrete plug.
- Allows for plugging of the porous components of the sealing system.
- Provides a smooth back surface against which the concrete plug can be cast.
- Transfer of loads from the backfilled tunnel into surrounding rock along a long surface.
- There is no need to excavate keys.
- There is no complex concrete re-enforcement needed.

The LCBB also has a number of potential difficulties or questions associated with its use, including:

- Will backfill erosion occur at the backfill-rock interface prior to tunnel closure.
- Continuing presence of a porous filter region at the downstream face of the backfill, will it remain as a porous section (if so does it matter?).
- Need to demonstrate the effectiveness of the floor filter in controlling/channelling seepage during construction.
- Determining the ability of the floor filter and HCB layer to support the load of the overlying backfill materials.
- Establishing how effective the self-sealing of the floor filter will be.

Many of the items listed as potential difficulties can likely be eliminated in the process developing a detailed design for the plug. Some issues will remain and require addressing prior to adopting this design concept for repository use.

6 Summary

Relatively short-life (10's or 100's of years) plugs for installation at the entrance of room or drifts in a repository can likely be installed using many of the approaches currently used in the mining and engineering industries provided that a modest amount of seepage past them is acceptable. This "acceptance" of some seepage needs to be examined in terms of the influence of seepage on materials located within the rooms and drifts. In mining or hydroelectric applications seepage is not normally associated with erosion of materials upstream of the seal (although erosion of materials adjacent to the seal may be important) so a repository has a number of different requirements to consider. If seepage can be demonstrated to result in either the erosion of sealing materials within the rooms or adversely affect the transport of contaminants prior to final repository closure then a predominantly plugging function is inadequate. Similarly, if the rock intersecting the excavations beyond the plug contains considerable jointing or fracturing, then installation of a very tight plug will not necessarily provide improved isolation as hydraulic behaviour and mass transport of the materials contained in the sealed volume will be controlled by those fractures.

Considerable experience resides in the mining and engineering industries with regards to plugging of openings, especially tunnels under severe hydraulic and mechanical conditions. The nature and performance of these constructions are not necessarily what is desired of a plug in a geologic repository in that most of the applications where plugs have been installed to limit water seepage can tolerate considerable seepage and still be considered to be fully successful. These plugs also depend considerably on their length to provide the sealing capacity necessary to control water seepage and resist the hydraulic forces normally applied to them and attaining very low permeability plugs using concrete and grout tunnel seals may not be possible.

In order to prevent (severely limit) seepage past a plug, tests conducted at various underground research laboratories indicate that it will be necessary to install a composite seal. A number of generic approaches to design of these plugs have been and are continuing to be examined. Plugging of openings in rock so that substantial water seepage is prevented is a subject of ongoing assessment at Äspö and elsewhere. Based on the experience of previous work it can be concluded that a relatively small number of parameters will control the effectiveness of a plug installed to tightly seal an opening in a granitic (or other rock) mass. These parameters include:

- Pre-existing joints, fractures or other geologic connections in vicinity of plug.
- Presence and extent of Excavation Damaged Zone.
- Interface between the rock and the sealing material.
- The length of the plug.
- The ability to grout, if necessary the rock surrounding the plug.
- The ability to grout the interface between rock and concrete.
- Ability to key the plug to provide mechanical stability and disrupt any hydraulic connection across the plug.
- Resistance of plug component(s) to hydraulic erosion.

The presence or relative importance of each of these parameters will be highly location dependant. What is important at one location will be irrelevant in another, potentially very near-by location where rock conditions are different. As a result a range of approaches to room and drift plugging and sealing must be examined and a variety of generic approaches identified and demonstrated to be effective.

In general it can be concluded that for optimal mechanical and hydraulic performance, a composite concrete-bentonite plug should be used. The concrete should be composed of as low a pH material is practical, have limited heat generation capacity during curing (limit thermal expansion and contraction) and have a minimal impact of adjacent groundwater chemistry. The concrete should have the ability to be contact grouted if necessary as well as being capable of providing enough resistance to water flow to allow the bentonite component to swell and seal the upstream regions without suffering flow-induced erosion. The bentonite clay should be located at or near the upstream end of the plug and must be of sufficient quantity/length to provide a self-grouting capacity to the concrete-rock interface. Should an EDZ be an issue then keying of the plug would be necessary in order to cut this feature off.

The ongoing PR, TPT and other sealing-related tests at Äspö will provide much of the information needed to develop the tools and skills that will be necessary to install effective tunnel plugs. The planned activities related to the KBS-3H demonstrations will provide a similar opportunity to install a full-scale drift plug installed in a drilled excavation and monitor its performance. There is also the need to develop a clear sense of what the hydraulic requirements of plugs will be and how long they will be expected to provide that function. If there are also longer-term sealing requirements of the plugs then it will necessary to assess performance of various plug/seal simulations over an extended time period.

References

AECL (Atomic Energy of Canada Limited), 1994. Environmental impact statement on the concept for disposal of Canada's nuclear fuel waste. Atomic Energy of Canada Limited Report, AECL-10711, COG-93-1.

Ahrens E H, Onofrei M, 1996. Ultrafine cement grout for sealing underground nuclear waste repositories. Rock Mechanics, pp 1509–1514.

Akgun H, Daemen J J K, 1999. Design implications of analytical and laboratory studies of permanent abandonment plugs. Canadian Geotechnical Journal, 36: 21–38.

Autio J, Saanio T, Tolppanen P, Raiko H, Viena T, Salo J-P, 1996. Assessment of alternative disposal concepts, POSIVA-96-12.

Auld F A, 1996. Design of underground plugs, in Sealing of Boreholes and Underground Excavations in Rock, Chapman and Hall, ISBN 0 412 57300 8. pp 225–266.

Barcena I, Llamas B, Bueno J, Garcia-Sineriz J L, Suso B A, 2005. Plug construction to isolate active zones of inactive zones in coal mine: WATERCHEM Project. Proc. 9th International Mine Water Congress.

BCMEM, 2002. Britannia Mine Remediation 4100 Level Test Plug Application. Addendum: Mining and Hydrogeology, British Columbia Ministry of Energy and Mines, CLM02-18.

Bergh-Christensen J, 1989. High pressure plugs for hydroelectric projects, Review and design and operational experiences in Norway. pp 463–470.

Bernier F, 2005. A repository scale in situ programme: The PRACLAY experiments, SEK-CEN website: sckcen.be/sckcen/ScientificReports/2005/.

Brawner C O, Bruce D A, Littlejohn G S, 2005. Intruded Concrete Plugs in a Deep Gold Mine: An Exercise in Quality Control, Assurance, and Performance Verification. Geo-Frontiers Geotechnical Special Publications 130–142 and GRI-18; Sponsored by The Geo-Institute of the American Society of Civil Engineers Geosynthetic Materials Association of the Industrial Fabrics Association International Geosynthetic Institute, January 24–26, Austin, Texas, 15 pp.

Bruce D A, Wells M F, Venter J, 2004. Construction of permanent intruded plugs at South Deep Gold Mine. Colloquium: Water Barriers in Underground Mines. The SA National Museum of Military History, Saxonwold, April 22, 18 pp.

CERM3, 2004. Britannia Mine Millenium Plug, Centre for Environmental Research on minerals, metals and materials Web Documents.

Chandler N A, Kozak E T, Martin C D, 1996. Connected pathways in the EDZ and the potential for flow along tunnels. In Martino, Martin editors. Designing the EDZ for a Nuclear Repository in Hard Rock, Proc. of an EDZ Workshop, Winnipeg, Canada. 1996; pp 25–34.

Chandler N A, Dixon D A, Gray M N, Hara K, Cournut A, Tillerson J, 1998. The Tunnel Sealing Experiment: An in situ demonstration of technology for vault sealing. In Proc. 19th Annual Conference. Canadian Nuclear Society, Toronto.

Chandler NA, Martino J, Dixon D A, 2002a. The Tunnel Sealing Experiment. In Trans. 6th International Workshop on Design and Construction of Final Repositories: Backfilling in Radioactive Waste Disposal. ONDRAF/NIRAS, Brussels, Belgium, 2002 March 11–13.

Chandler N, Cournut A, Dixon D, Fairhurst C, Hansen F, Gray M, Hara K, Ishijima Y, Kozak E, Martino J, Masumoto K, McCrank G, Sugita Y, Thompson P, Tillerson J, Vignal B, 2002b. The five year report of the Tunnel Sealing Experiment: an international project of AECL, JNC, ANDRA and WIPP. Atomic Energy of Canada Limited Report AECL-12127.

Dixon D A, Martino J B, Chandler N A, Guo R, 2004. Performance of the clay bulkhead portion of the Tunnel Sealing Experiment (TSX) under ambient temperature conditions. Ontario Power Generation, Nuclear Waste Management Division, Technical Report 06819-REP-01200-10131-R00.

Dixon D A, Martino J B, 2005. Testing of a bentonite-based tunnel seal for use in a deep geological repository: The Tunnel Sealing Experiment (1998–2004). Canadian Nuclear Society's Waste Management, Decommissioning and Environmental Restoration for Canada's Nuclear Activities: Current Practices and Future Needs Conference, Ottawa, ON, 2005 May 8–11.

EC, 2004. Geological disposal of radioactive wastes produced by nuclear power: from concept to implementation. N.Chapman editor, European Commission, Euratom-Nuclear Fission-Management of Radioactive Waste, Report EUR 21224, Belgium.

Fairhurst C, Gera F, Gnirk P, Gray M, Stillborg B, 1993. OECD/NEA International Stripa Project Overview Volume I: Executive Summary. (SKB), ISBN 91-971906-2-4, Svensk Kärnbränslehantering AB.

FEBEX, 1996. Update of engineering aspects for the in situ test. Febex Technical Report, 70-AIT-L-3-04, Prepared by Aitemin.

Fuenkajorn K, Daemen J J K, 1995. Sealing of boreholes and underground excavations in rock, Chapman and Hall, New York. 329 pp.

Gnirk P, 1993. OECD/NEA International Stripa Project Overview Volume II: Natural Barriers. (SKB), ISBN 91-971906-3-2, Svensk Kärnbränslehantering AB.

Gray M N, 1993. OECD/NEA International Stripa Project Overview Volume III: Engineered Barriers. (SKB), ISBN 91-971906-4-0, Svensk Kärnbränslehantering AB.

Goudarzi R, Johannesson L-E, 2006. Prototype Repository: Sensors Data Report (period 010917-051201) Report Number 14. Äspo Hard Rock Laboratory. SKB IPR-06-14, Svensk Kärnbränslehantering AB.

Goudarzi R, Johannesson L-E, Börgesson L, 2006. Backfill and Plug Test: Sensors Data Report (period 990601-060101) Report Number 12. Äspo Hard Rock Laboratory. SKB IPR-06-02, Svensk Kärnbränslehantering AB.

Gunnarsson D, Börgesson L, 2002. Development of a tunnel backfilling concept for nuclear waste disposal. in, Clays in natural and engineered barriers for radioactive waste confinement: Experiments in Underground Laboratories, ANDRA Science and Technology Series Report, ISBN: 2-9510108-5-0, Chatenay-Malabry Cedex.

Gunnarsson D, Börgesson L, Hokmark H, Johannesson L-E, Sanden T, 2002. Installation of the Backfill and Plug Test. in, Clays in natural and engineered barriers for radioactive waste confinement: Experiments in Underground Laboratories, ANDRA Science and Technology Series Report, ISBN: 2-9510108-5-0, Chatenay-Malabry Cedex.

Huertas F, Fuentes-Cantillana J L, Jullien F, Rivas P, Linares J, Farina P, Ghoreychi M, Jockwer N, Kickmaier W, Martinez M A, Samper J, Alonso E, Elorza F J, 2000. Full-scale engineered barriers experiment for a deep geological repository for high-level radioactive waste in crystalline host rock (FEBEX project): Final Report. European Commission, Nuclear Science and Technology, R and T specific programme 'Nuclear fission safety 1994–98', EUR 19147 EN, Brussels.

IAEA, 2001. The use of scientific and technical results from underground research laboratory investigations for the geological disposal of radioactive waste, International Atomic Energy Agency, Technical Document, IAEA-TECDOC-1243, Vienna.

IAEA, 2003. Scientific and technical basis for geological disposal of radioactive wastes. International Atomic Energy Agency (IAEA), Technical Report Series, #413, Vienna.

Johannesson L-E, Gunnarsson D, Sandén T, Börgesson L, Karlzén R, 2004. Prototype Repository: Installation of buffer, canisters, backfill, plug and instruments in Section II. Äspo Hard Rock Laboratory. SKB IPR-04-13, Svensk Kärnbränslehantering AB.

Kirkwood D T, Wu K K, 1995. Technical considerations for the design and construction of mine seals to withstand hydraulic heads in underground mines. Society for Mining, Metallurgy, and Exploration, Inc. March 1995, SMME pre-print No. 95–100.

Kjartanson B H, Martino J B, 2004. Composite Seal Experiment at AECL's Underground Research Laboratory, 57th Canadian Geotechnical Conference, October 2004, Quebec City.

Littlejohn G S, Swart A H, 2004. Design of permanent intruded plugs at South Deep Gold Mine, Colloquium: Water Barriers in Underground Mines. The SA National Museum of Military History, Saxonwold, April 22, 18 pp.

Martino J B, Chandler N A, Read R S, Baker C, 2002. Response of the Tunnel Sealing Experiment concrete bulkhead to pressurization. Ontario Power Generation, Nuclear Waste Management Division, Technical Report No. 06819-REP-01200-010085-R00.

Martino J B, Dixon D A, Keith S G, Chandler N A, Kjartanson B H, 2003. Sealing studies at the URL, Proceedings of the 56th Canadian Geotechnical Conference, Winnipeg, Canada, Sept. 29 – Oct. 1, 2003.

Murray R, 2006. ERPM still good for another 6 years thanks to water management program. Mining-technology.com.

OECD, 2003. Engineered barrier systems and the safety of deep geological repositories: State of the art report. Nuclear Energy Agency, Organisation for Economic Co-Operation and Development, Paris.

Pacovský J, 1999. Continuous measurements of stress and temperature during tests of a fibre shotcrete pressure plug. Geotechnical and Geological Engineering, 17, pp 335–343.

Parkinson G, Bryan P, 2005. Britannia mine remediation Hydraulic/ Geotechnical monitoring during 2004 hydraulic communications test. B.C. Ministry of Sustainable Resource Management, SRK Project report 1CB012.010.

Pusch R, 1987. Workshop on sealing techniques, tested in the Stripa Project and being of general potential use for rock sealing, Stripa Project 87-05, Svensk Kärnbränslehantering AB.

Pusch R, Börgesson L, Ramqvist G, 1987a. Final Report of the borehole, shaft, and tunnel sealing test – Volume II: Shaft plugging, Stripa Project 87-02, Svensk Kärnbränslehantering AB.

Pusch R, Börgesson L, Ramqvist G, 1987b. Final Report of the borehole, shaft, and tunnel sealing test – Volume III: Tunnel plugging, Stripa Project 87-03, Svensk Kärnbränslehantering AB.

Read R S, Chandler N A, 1997. Minimizing excavation damage through tunnel design in adverse stress conditions. In Proc. of the 23rd General Assembly – Int. Tunnel. Assoc., World Tunnel Congress ’97, Vienna, 1997, 23–28. Balkema: Rotterdam.

SAFIR2, 2001. Safety assessment and feasibility interim report 2. ONDRIF/NIRAS Report, Belgian agency for radioactive waste and enriched fissile materials, NIROND 2001-06-E, December 2001, Belgium.

Sitz P, Koch G, Gruner M, 2002. Results from the large scale in situ drift sealing experiment in the salt mine Sondershausen, in Clays in natural and engineered barriers for radioactive waste confinement: Experiments in Underground Laboratories, ANDRA Science and Technology Series Report, ISBN: 2-9510108-5-0, Chatenay-Malabry Cedex.

SKB, 2005. Äspö Hard Rock Laboratory: Annual Report 2004. SKB TR-05-10, Svensk Kärnbränslehantering AB.

Villar M-V, Garcia-Sineriz J L, Barcena L, Lloret A, 2005. State of the bentonite barrier after five years operation of an in situ test simulating a high level radioactive waste repository, Engineering Geology 80 (3) p 175–198.

Wimelius H, Pusch R, 2008. Backfilling of KBS-3V deposition tunnels – Possibilities and Limitations. SKB R-08-59, Svensk Kärnbränslehantering AB.