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Full-scale test of the Dome Plug for KBS-3V deposition tunnels

Gas tightness test

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Keywords: Dome plug, Bentonite seal, KBP1016, Gas tightness.

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Abstract

This report describes the outcome from the project directive for the last phase of the project KBP 1016 "*Dismantling and evaluation of tunnel plug*", according to which it should be investigated whether the dome plug experiment could be used to verify the gas tightness requirement. SKB has earlier presented analyses which indicated that diffusion through an air-filled slot appeared to be the mechanism that potentially can contribute to the most significant inflow rates of oxygen through the tunnel plug. Such processes are however very slow, and in order to test whether the plug is gas tight or not, it was decided that a gas pressure difference would be applied over the plug.

A gas tightness test was therefore implemented by draining the water from the filter, by pressurizing the filter with helium gas to 0.4 bar gauge, and by monitoring the gas pressure evolution. During a period of 18 hours it was found that the gas pressure increased with 3 kPa, which indicated that a noticeable inflow of water occurred during this measurement. The monitoring was also complemented with a sniffer leak search along the entire front surface of the concrete plug. No detectable concentrations were however found. The test therefore verified that the seal was gas tight.

The actual rate of oxygen transfer through the plug therefore appears to be governed by diffusion of oxygen dissolved in water through the water filled pore-spaces in the filter as well as in the bentonite seal.

Sammanfattning

Denna rapport beskriver utfallet från projektdirektivet för den sista fasen av projektet KBP 1016 ”Brytning och utvärdering av valvplugg”, enligt vilket det skall utredas ”om försöksuppställningen kan användas för att verifiera kravet på gastäthet”. SKB har tidigare presenterat analyser som indikerar att diffusion genom en luftfylld spalt framstår som den mekanism som potentiellt kan bidra till det mest betydande inläckaget av syre genom pluggen. Sådana processer är dock mycket långsamma och för att kunna testa om pluggen är gastät eller ej beslutades det att en tryckskillnad skulle appliceras över pluggen.

Ett gastäthetstest genomfördes därför genom att dränera vatten från filtret, trycksätta filtret med helium upp till 0,4 bar (r), samt genom att övervaka gastryckets utveckling. Under en period av 18 timmar noterades att gastrycket ökade med 3 kPa, vilket indikerade att ett betydande vatteninflöde till filtret ägde rum samtidigt som mätningen pågick. Tryckövervakningen kompletterades med en läcksökning med så kallad sniffer över hela framsidan av betongpluggen, dock utan att några detekterbara koncentrationer kunde noteras. Testet kunde därmed verifiera att bentonittätningen var gastät.

Den faktiska transporthastigheten för syrgas genom pluggen tycks därför bestämmas av diffusion av syre löst i vatten genom det vattenfyllda porutrymmet i filtret och bentonittätningen.

Contents

1 Introduction

The KBS-3V method is proposed by SKB for the disposal of spent fuel packaged in copper canisters with cast iron inserts in a crystalline host rock. The long-term safety principles are based on isolation and containment of radioactive waste through the choice of a stable geological environment at depth and the use of a multi-barrier system consisting of engineered barriers (canister, buffer, backfill, and closure) and the host rock. The canisters are emplaced in vertical holes, containing pre-compacted blocks of bentonite buffer, below horizontal deposition tunnels which are backfilled with bentonite blocks and pellets, and finally closed with a deposition tunnel plug.

Owing to the potential for water flow to erode the bentonite buffer in the deposition holes, the water flux across the plug must be low. The initial requirement on water tightness is achieved by contact grouting of the concrete dome which is completed approximately 100 days subsequent to casting. The plug design includes a filter that drains water past the structure in order to delay the pressurization of the plug until the concrete has cured and developed sufficient strength. To assure that low hydraulic conductivity is provided for the full service life of 100 years, a watertight seal composed of swelling bentonite clay is also used in the reference design. After the bentonite seal has saturated, the leakage requirement on the concrete dome is redundant and the main purpose of the concrete dome is to act as support and carry the loads of the water and swelling pressure from the deposition tunnel.

In addition to restricting the water flow from the deposition tunnel, "*the plug also needs to be reasonably gas tight to stop convection of air during the operational period*" (Posiva SKB 2017). This requirement was first addressed in a request from SSM in which SKB was asked to present a calculation of the extent of leakage of oxygen through the tunnel plug and how this will influence the degradation processes on the copper canister. In SKB's reply (SKB 2014) it was stated that: "*SKB defines gas tight as a situation where no gas phase is present in the hydraulically sealing partof the plug*" and that the "*requirement for gas tightness … can be assumed to be fulfilled if a water column is maintained … in the filter section of the plug … throughout the operational period of the entire repository*" [1]. The reply from SKB also included calculations of the inflow of oxygen for hypothetical cases in which the tunnel plug wasn't gas tight. In brief, the following estimates were presented:

- The amount of oxygen that will be trapped in a deposition tunnel (300 m long and with 50 deposition holes) at the time of installation is approximately 14 400 mole.
- If all the oxygen in the trapped air is assumed to be consumed immediately after installation then this would lead to a reduction of the gas pressure to approximately 80 % of the initial level. This could therefore imply an *advective* inflow of oxygen. The total amount of oxygen that potentially could be introduced in this way is 25 % ((1–80 %)/80 %) of the original amount, i.e. 3 700 mole, which thereby is a fairly marginally addition.
- A *diffusive inflow of oxygen through an air-filled slot* is determined by the concentration gradient, the diffusion coefficient and the section area of the slot. In SKB's case these quantities were estimated to 9.4/4 mole/m^3/m, 2×10^{-5} m^2/s and 0.25 m^2 (25 m circumference and 10 mm slot width), respectively, which results in an inflow of 360 mole/year. This would mean that the total inflow during a period of 40 years would be equally large to the initial amount in the tunnel. However, a slot width of 10 mm were deemed to be totally unrealistic.
- Finally the *diffusive inflow of oxygen through a water-filled filter* was estimated. In SKB's case the concentration gradient, the diffusion coefficient and the section area of the slot were estimated to 0.3/0.6 mole/m^3/m, 10^{-9} m^2/s and 20 m^2, respectively. This would thereby imply that the inflow of oxygen during a period of 100 years would amount to approximately 30 mole.

[1] All quotations from SKB documents in this section was translated from Swedish by the author.

SSM subsequently requested a clarification of this reply concerning the oxygen transport through fractures in the rock connecting the deposition tunnel with the transport tunnel. SKB's reply to this (SKB 2015) presented calculations of diffusion of oxygen for two different cases: in dehydrated rock and in water saturated rock. In the first case, the oxygen transport was calculated to 3.1 mole/year, which was deemed insignificant, and in the second case the calculated flow rate was significantly lower than in the first case. These calculations therefore indicated that diffusion through an air-filled slot (3rd point in the list above) appeared to be the mechanism that potentially can contribute to the most significant inflow rates of oxygen.

The issue of gas tightness of the tunnel plug has subsequently been addressed in the Dome plug experiment (Grahm et al. 2015). In the project directive for the final phase of the project (KBP 1016 dismantling and evaluation of tunnel plug) it was explicitly stated that it should be investigated "*whether the test setup can be used to verify the gas tightness requirement*". This report presents the outcome from this directive. An overview of the Dome plug experiment is presented in Chapter 2. The performed gas tightness test and the evaluation of this is presented in Chapter 3. Finally, some concluding remarks from these investigations are given in Chapter 4.

2 Domplu field experiment

2.1 Background

The deposition tunnels in a planned repository for spent nuclear fuel will be sealed with a plug at the end of the tunnels in order to withstand the swelling of the backfill and to seal off out-flowing groundwater. The principle design of the plug includes several components, among which the most important are the concrete dome, the bentonite seal and the filter. The groundwater leakage past the plug has to be small enough in order to build up a water pressure inside the plugged volume, and to prevent loss of bentonite from the deposition holes due to erosion throughout the operational phase of the repository. In addition, the construction site must be kept free from water during construction of the plug system and while the concrete dome cures until it is finally grouted for a tight contact to rock. Wet tunnels therefore require a filter section which can drain the water coming from the inner parts of the tunnel and temporarily let it by-pass the plug.

These issues and demands were addressed in the joint SKB and Posiva project "System design of dome plug for deposition tunnels". The project has aimed at ensuring that the reference configuration of the KBS-3V deposition tunnel end plug works as intended, and within the framework of this project a full-scale test, denoted "DOMPLU", has been performed at 450 m depth at Äspö Hard Rock Laboratory in cooperation between SKB and Posiva (Grahm et al. 2015).

2.2 Design

The full-scale test consists of a number of components, each with its own purpose (Figure 2-1). The innermost component is a 1.1 m backfill zone which consists of a stack of bentonite blocks with a surrounding pellet filling. The next component is the filter section which is composed of 0.3 m thick LECA-beams and a 0.3 m layer of gravel (2–4 mm). The filter serves for drainage of groundwater during construction as well as for artificial wetting of the bentonite seal when the drainage is finally closed. The gravel and the bentonite seal are separated by a geo-textile which also facilitates distribution of water into the seal. The bentonite seal consists of a 0.5 m stack of highly compacted MX-80 bentonite blocks with a surrounding MX-80 pellet filling closest to the rock. A compilation of the dry densities and volumes of the bentonite-based components is given in Table 2-1.

The restraining concrete structure is designed as an unreinforced octagonal dome plug, cast in situ by low-pH concrete. The diameter of the concrete dome is 8.8 m while the concrete thickness is 1.79 m in the hub. An important feature of the dome plug is the internal cooling system which enable shrinkage of the dome prior to the contact grouting of the joint between the plug and the rock, which in turn has contributed to an efficient sealing of the plug. A preliminary design basis is that the plug shall withstand 7 MPa of total pressure.

Besides extensive monitoring of the concrete dome structure, the inner plug components are instrumented with sensors for measurement of total pressure, pore pressure, relative humidity and displacements at several positions. The bentonite-based components and the filter were installed in January 2013, while the concrete dome was cast in March 2013. Pressurization by natural groundwater inflow began in October 2013. The artificial pressurization was increased to 4 MPa in February 2014 and was maintained at this level until June 2017 (day 383 to 1 583 in Figure 2-2).

Table 2-1. Dry density and volume for bentonite based components.

Quantity	Bentonite seal Blocks	 Pellets	Backfill Blocks	 Pellets
Material	MX-80		Asha NW BFL-L 2010	Cebogel
Dry density	1 682 kg/m^3	~ 900 kg/m^3	1 750 kg/m^3	~ 900 kg/m^3
Volume[1]	8.4 m^3	1.5 m^3	14.8 m^3	8.5 m^3
Mean dry density[2]	1 560 kg/m^3		1 440 kg/m^3	

[1] Based on areas and depths of block stacks and tunnel profiles.

[2] Calculated as weighted means.

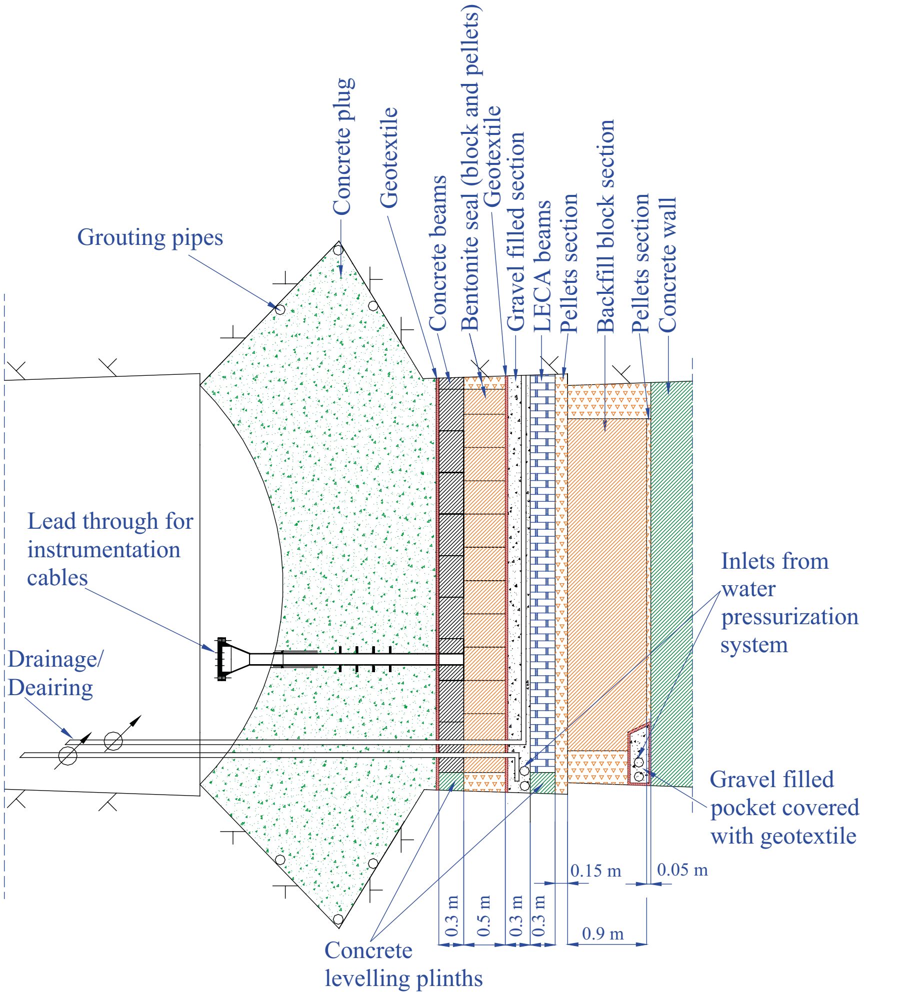

Figure 2-1. *Schematic drawing of the Domplu plug and the different materials included.*

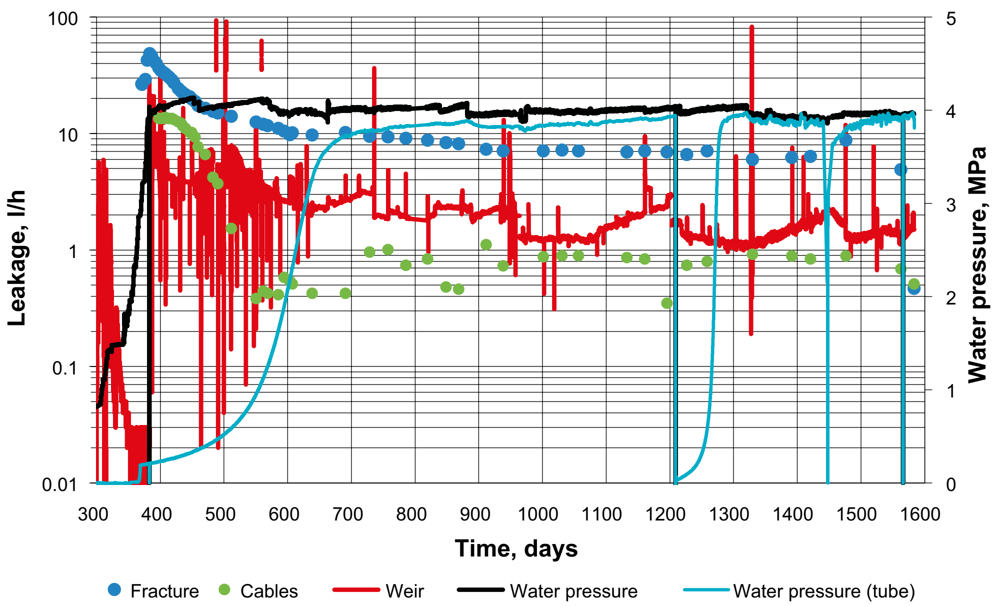

Figure 2-2. *Evolution of water pressure (lines): in filter (black), lead through tube (blue) and collected in embankment (red); and leakages (symbols): through rock (blue) and cable lead-through (green).*

2.3 Results

The sensors data reflects the hydration of the bentonite and build-up of swelling pressures in the seal.

The evolution of RH in the bentonite seal is shown in Figure 2-3, and it can be noted that RH has been very close to 100 % in all operational sensors in the midsection since day 800. In the backfill all operational sensors exceed RH 95 %.

All pore pressure sensors (installed in the floor or in the ceiling) have shown values in the range 3.6 to 4.0 MPa. This is consistent with the pressurization of the filter, although the cause of the range in pore pressure is not known. A water pressure of 4 MPa has also been registered in the lead-through tube through the concrete dome (Figure 2-1 and Figure 2-2).

The total pressure values have increased successively and ranged between 4.1 and 5.8 MPa prior to the relief of the pressurization in June 2017 (Figure 2-4). In order to analyze the swelling pressure this can be evaluated as an effective stress so that the water pressure is subtracted from the total pressure. A compilation of such evaluated swelling pressures is shown in Figure 2-5. It can be noted that the swelling pressure values in measuring section 1 was only 0.2 to 0.4 MPa, with the exception for the sensor in the lower part towards the plug where the swelling pressure was 1.7 MPa. The swelling pressure in the peripheral parts of sections 3/4 was 0.5 to 1.0 MPa, while the swelling pressure towards the filter in section 4 was 1.0 to 1.4 MPa. Corresponding pressure towards the filter in section 5 (in the backfill) was 1.0 to 1.7 MPa.

The leakage from the pressurized filter can be divided in three parts: i) into the rock and out through a fracture in the main tunnel perpendicular to the experiment tunnel; ii) along cable lead-through in the concrete (not to be confused with the lead though pipe from the seal); and iii) past the concrete plug and collected in the embankment (weir) in front of the concrete plug (Figure 2-2). The latter part was approximately 1–3 liters per hour throughout the entire test period. According to Grahm et al. (2015) there was a noticeable leakage through the interface between the concrete dome and the rock in the top of the slot “at 13 o’clock”. Some leakage could also be noticed in the tunnel ceiling just outside the concrete dome left side.

The swelling pressure towards the upper part of the concrete beams was surprisingly low, in particular since the pressure on both sides of the filter was significantly higher. An explanation for this may be that estimated 240 kg bentonite was lost via the lead-through tube when the filter was filled with water and the drainage system was tested (Grahm et al. p 143). If significant amounts of water flowed through the pellets filling close the ceiling and along the sensor cables to the lead-trough tube, then this could explain the low swelling pressure in the upper part of the seal towards the concrete beams as well as the noticeable leakage along the interface close to the ceiling and also the high water pressure in the lead-trough pipe.

A question of importance for the gas tightness of the plug is the extent of water saturation in the bentonite seal. In principle this should be possible to predict, but the question is complicated by at least three circumstances: i) the deformation of the blocks against the pellets filling and the components inside the plug (i.e. filter and backfill); ii) the high water pressure (in relation to the swelling pressure); and iii) the uncertainty regarding the path of the wetting (only from the filter, or in some way via the concrete beams). Since the measured RH in the midsection of the bentonite seal was very close to 100 % after the spring of 2015 it was considered likely that the seal was close to full water saturation at the time of the gas tightness test in June 2017. The dismantling operation scheduled for early 2018 will reveal the actual extent of water saturation of the bentonite seal.

A high degree of water saturation should imply that the seal is gas tight. Nevertheless, the noticeable water leakage in the ceiling through the interface between the concrete dome and the rock could imply that the bentonite seal is weakened in this part. This could perhaps also imply that the seal would be permeable for gas in this part. On the other hand, it could also reflect the advective water transport through the water saturated bentonite or through water-bearing fractures in the rock.

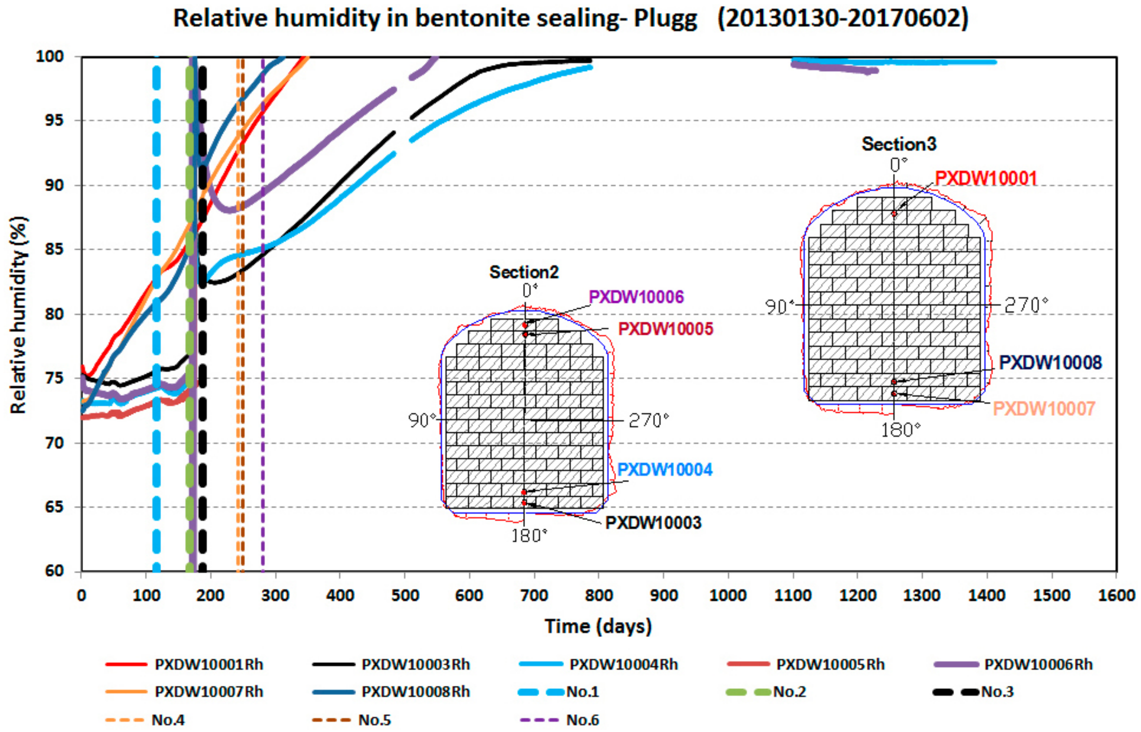

Figure 2-3. *Evolution of RH in bentonite seal.*

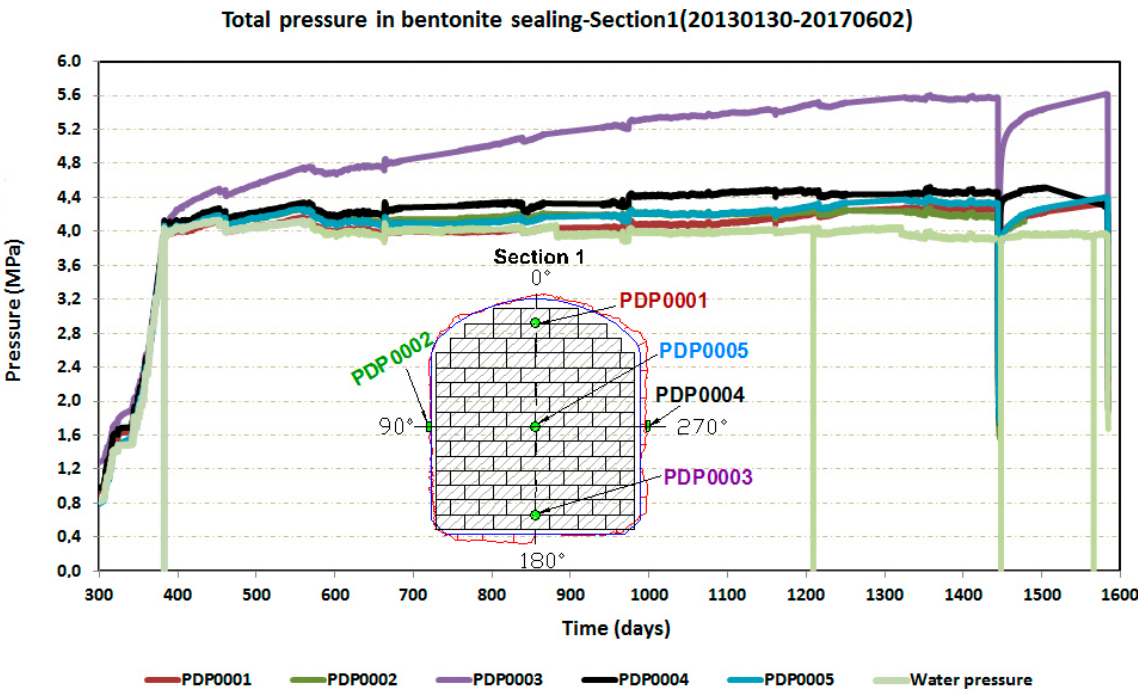

Figure 2-4. *Evolution of total pressure in bentonite seal Section 1.*

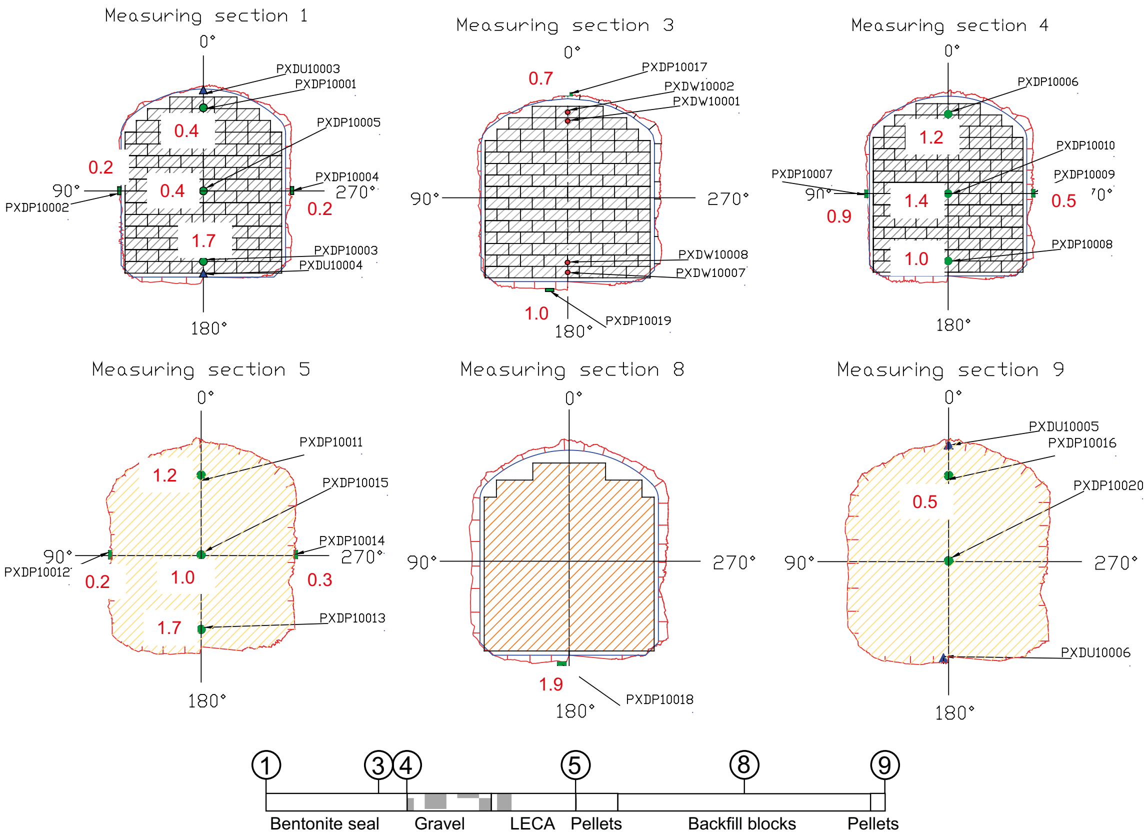

Figure 2-5. *Evaluated swelling pressure (in MPa) at total pressure sensor positions at day 1 583. The sensor PXDP10020 was deemed to be out of order. Positions of measuring sections illustrated at the bottom.*

3 Gas tightness test

3.1 General considerations

The analyses mentioned in Chapter 1 indicated that diffusion through an air-filled slot appeared to be the mechanism that potentially can contribute to the most significant inflow rates of oxygen. Such processes are however very slow, and in order to test whether the plug is gas tight or not, it was decided that a gas pressure difference would be applied over the plug.

It was subsequently specified that the following procedure would be used: i) drainage of the water from the filter; ii) pressurization of the filter with gas (helium) and closing all ports; and iii) monitoring of the gas pressure evolution. For safety reasons the pressurization was limited to 0.5 bar gauge.

3.2 Experimental work

Drainage and gas filling of filter

The filter was emptied from water and filled with helium gas by keeping the drainage pipe open to the atmosphere (via a water hose) and by keeping the deairing pipe connected to a gas tube during a period of approximately three days (Figure 3-1). The gas filling was controlled by a gas regulator attached to the tube. The water volume was quantified with a water meter connected to the outlet of the hose. The readings from the water meter are shown in Figure 3-2, and this data therefore suggests that the pore volume of the filter was 3.0 m^3.

Gas tightness test

The test was performed in two steps: i) the pressurization step and; ii) the monitoring step.

The pressurization was performed through the deairing pipe and by keeping the drainage pipe closed. Two 20 liters gas tubes were used for the filling, and the pressure drops in these tubes were quantified to 38 to 28 bar, and 200 to 152 bar, respectively. The total pressure reduction in the tubes (Δp_T) therefore amounted to 58 bars. The simultaneous pressure increase in the filter (Δp_F) was logged with a pressure gauge to 0.4 bar (Figure 3-3). An evaluation of these pressure changes and the tube volume (V_T) therefore indicates that the filter volume is 2.9 m^3 (since $V_F \times \Delta p_F = V_T \times \Delta p_T$). This value is quite consistent with the water meter readings presented above.

During the monitoring step which lasted for 18 hours, a pressure increase from 39 to 42 kPa gauge was registered (Figure 3-3). This indicates that a noticeable inflow of water occurred during this measurement. The pressure monitoring was complemented with a sniffer leak search by using an Oerlikon Leybold Phoenix L300i Helium Leak Detector. The front surface of the entire concrete plug was systematically investigated (Figure 3-4). However, no detectable concentrations were found.

Assessment of water inflow into filter

Due to the observed gas pressure increase during the monitoring step of the gas tightness test, an attempt was made to assess the water inflow into the filter. This was performed by keeping both the drainage pipe and the aeration pipe open to the atmosphere and by measuring the water outflow through the drainage pipe with a simple “bucket and watch” technique. A compilation of readings are shown in Figure 3-5 which shows that the outflow displayed a decreasing trend with time. The last and lowest measurement amounted to 0.09 liter per minute. This value is therefore the best available assessment of the water inflow, although it is likely that the outflow rate would decrease even further with time.

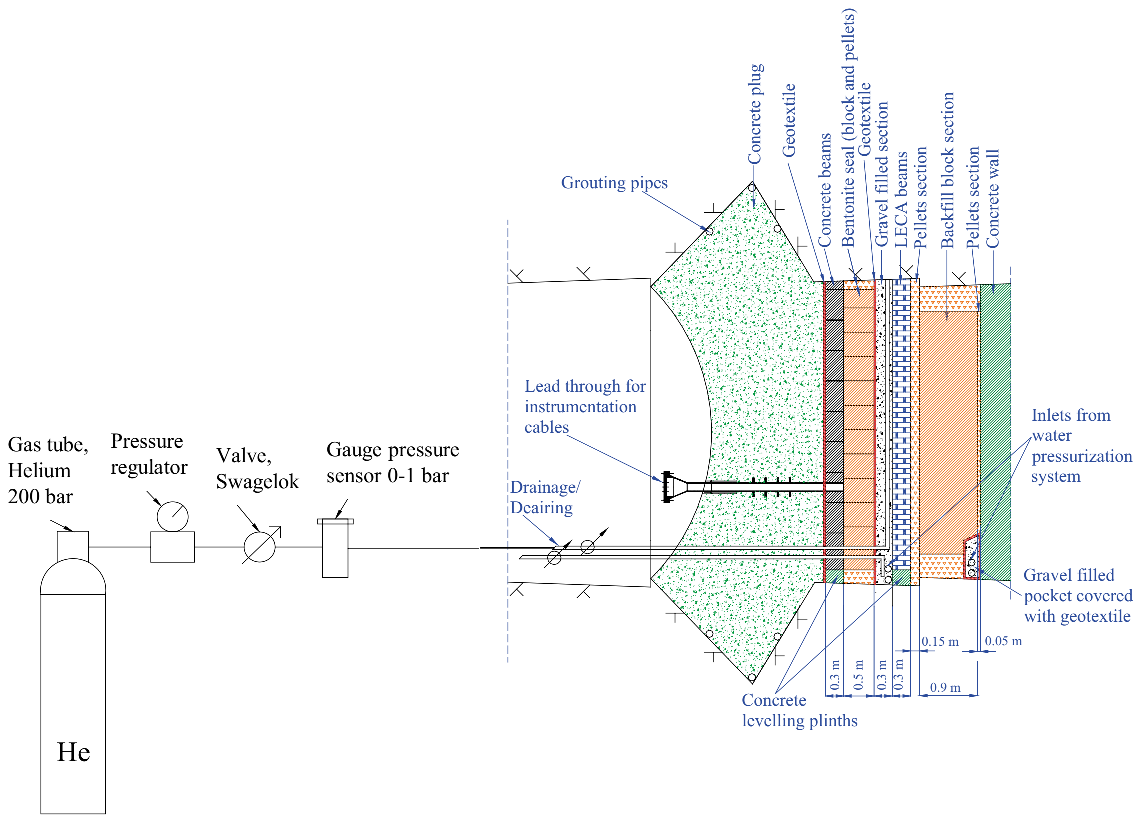

Figure 3-1. *Schematic outline of test setup.*

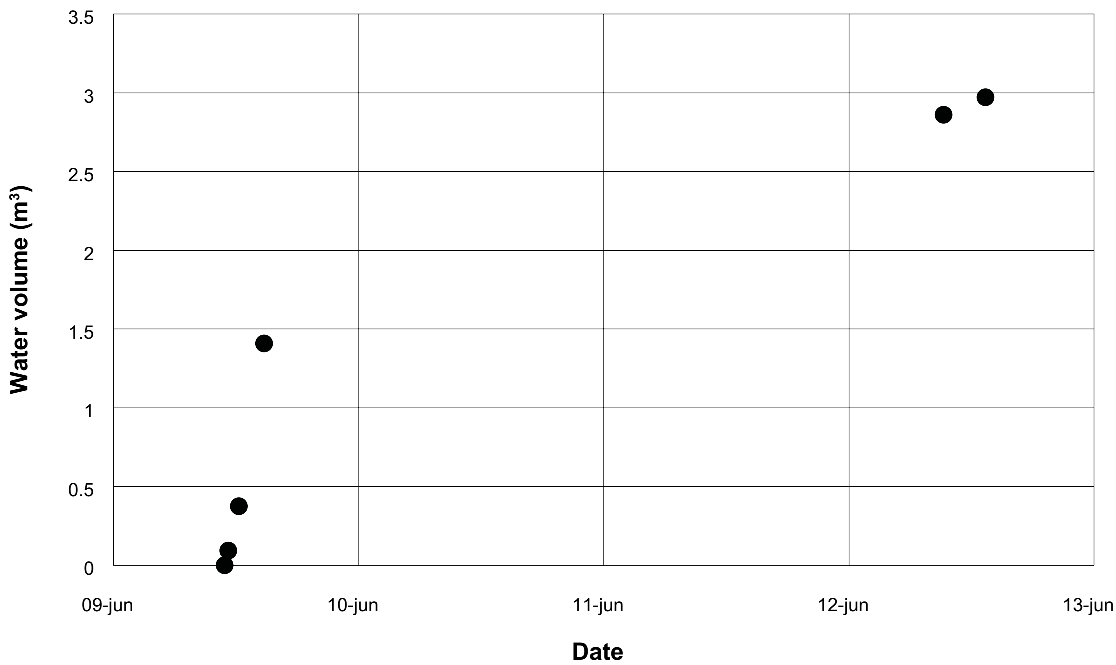

Figure 3-2. *Water meter readings during drainage of filter.*

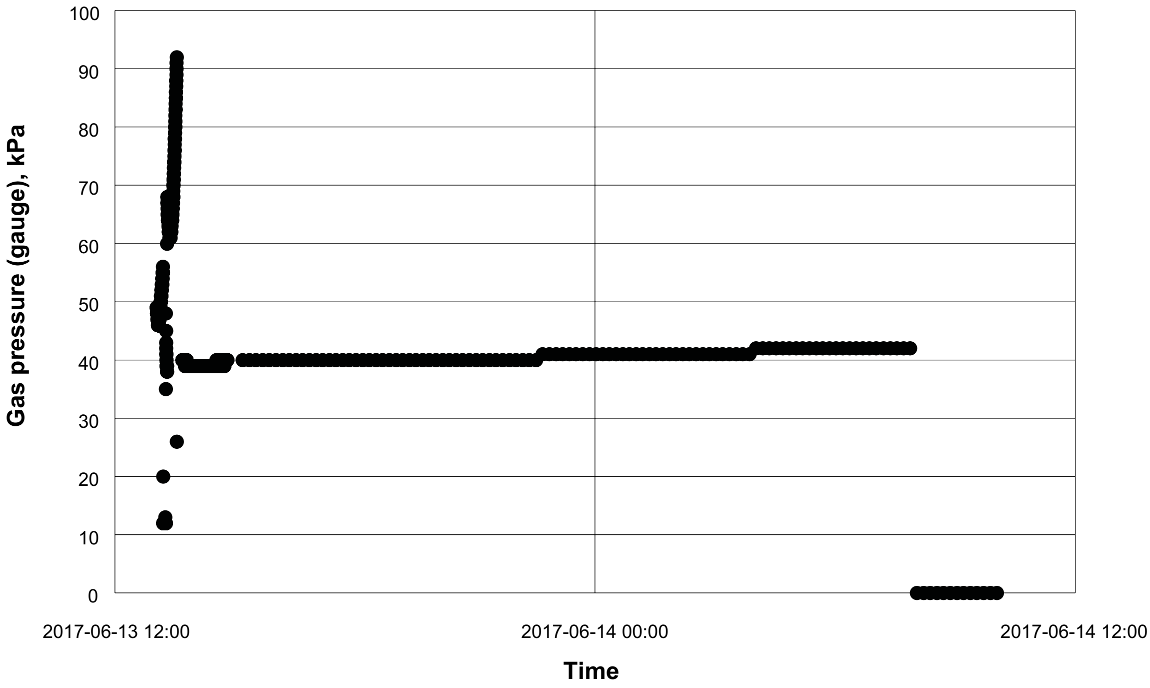

Figure 3-3. *Logged gas pressure during gas tightness tests.*

Figure 3-4. *Photographs from sniffer leak search; equipment (left) and investigation from scaffold (right).*

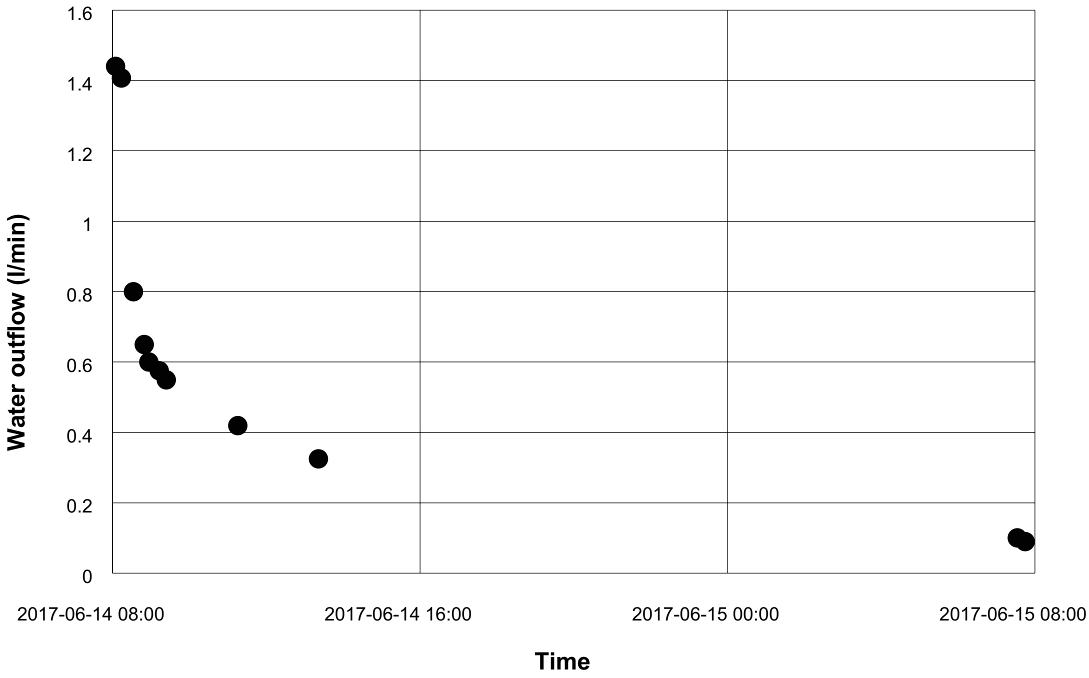

Figure 3-5. *Water outflow versus time. Measurements performed with a simple "bucket and watch" technique.*

3.3 Evaluation

The observed gas pressure increase during the monitoring step of the gas tightness test indicates that a noticeable inflow of water occurred during this measurement. Moreover, an assessment of such inflow rates was performed by quantifying the water outflow. It is therefore plausible that the bentonite seal was gas tight and that the water inflow was the sole process governing the gas pressure. However, if the measured water inflow rate would be higher than a flow rate which corresponds to the observed gas pressure increase, then this could indicate a loss of gas, e.g. through escape into the rock, as a leakage past the concrete plug, or through dissolution in the water phase. The following evaluation was performed for this purpose.

The problem is illustrated in Figure 3-6. The pore volume of the filter is denoted V_f, and the gas pressure is denoted p_f. The external atmospheric pressure is denoted p_a. Groundwater enters the filter with the flow rate Q_w. Finally, gas leaks with the flow rate Q_g through a permeable section with an area A, a thickness L and a permeability k.

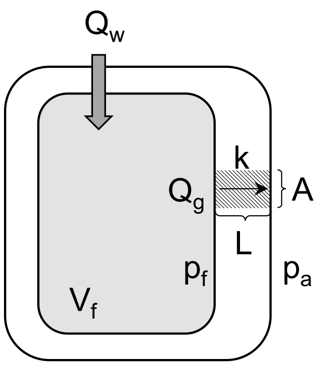

Figure 3-6. *Schematic illustration of filter and relation between water inflow, gas pressure and potential gas leakage.*

The water inflow is assumed to be constant which means that the pore volume of the filter can be described as:

$$\frac{dV_f}{dt} + Q_w = 0 \quad \Rightarrow \quad V_f(t) = V_f(0) - Q_w \cdot t \qquad \text{(Eq 3-1)}$$

Moreover, the gas mass is assumed to be conserved. This is formulated in terms of the number of moles for the gas (n_f) and the molar flow rate (J_f):

$$\frac{dn_f}{dt} + J_f = 0 \qquad \text{(Eq 3-2)}$$

The general gas law gives a relation between the number of moles, the pressure and the volume ($p_f \times V_f = n_f \times RT$), and from this follows the derivative:

$$\frac{dn_f}{dt} = \frac{1}{RT}\left(\frac{dp_f}{dt} \cdot V_f + p_f \cdot \frac{dV_f}{dt}\right) \qquad \text{(Eq 3-3)}$$

A corresponding relation between the molar flow rate and the (volume) flow rate can be written as:

$$J_f = \frac{p_f}{RT} Q_g \qquad \text{(Eq 3-4)}$$

By combining Eq (3-1), (3-2), (3-3) and (3-4), the following differential equation can be derived:

$$\frac{dp_f}{dt} = \frac{p_f \cdot Q_w}{V_f} - \frac{p_f \cdot Q_g}{V_f} \qquad \text{(Eq 3-5)}$$

The volumetric flow rate is assumed to follow Darcy's law for a compressible fluid (Scheidegger 1960, p 93):

$$Q_g = A \cdot \frac{k}{\mu_g} \cdot \frac{(p_f^{\,2} - p_a^{\,2})}{2 \cdot p_f \cdot L} \qquad \text{(Eq 3-6)}$$

where μ_g is the viscosity of the gas.

For simplicity, the parameter κ is defined for the ratio $A \times k \times (2 \times L \times \mu_g)^{-1}$. From this follows that Eq (3-5) and (3-6) can be combined to the following differential equation:

$$\frac{dp_f}{dt} = \frac{p_f \cdot Q_w}{V_f} - \frac{\kappa}{V_f} \cdot (p_f^{\,2} - p_a^{\,2}) \qquad \text{(Eq 3-7)}$$

It should be noted that the pore volume of the filter (V_f) is a function of time according to Eq (3-1).

The differential equation (3-7) was solved numerically with a MathCad program for the conditions: $p_f(0) = 1.39$ bar (absolute); $p_a = 1$ bar (absolute); $V_f(0) = 3$ m^3. Moreover, a base case water flow rate (denoted Q_b) was set to the quantified value 0.09 liters per minute. From this, a base case κ-value (denoted κ_b) was calibrated so that the gas pressure increased to 1.42 bar after 18 hours and was found to be 7.5×10^{-12} ($m^3 \times Pa^{-1} \times s^{-1}$), see Figure 3-7. This would imply a gas leakage of 2 liters per hour (at 1.4 bar absolute).

In addition, two sensitivity cases was performed, for which the κ parameter was varied with a factor 2 and 0.5, respectively, and it was found that this had a significant influence on the pressure evolution. Finally, a simplified case with a pressure evolution similar to the base case could be modelled with a zero κ-value if the water flow rate was reduced to 0.06 liters per minute. This evaluation thus demonstrates that inflowing water would be the sole process governing the gas pressure evolution if the inflow rate would be one third lower than the measured value.

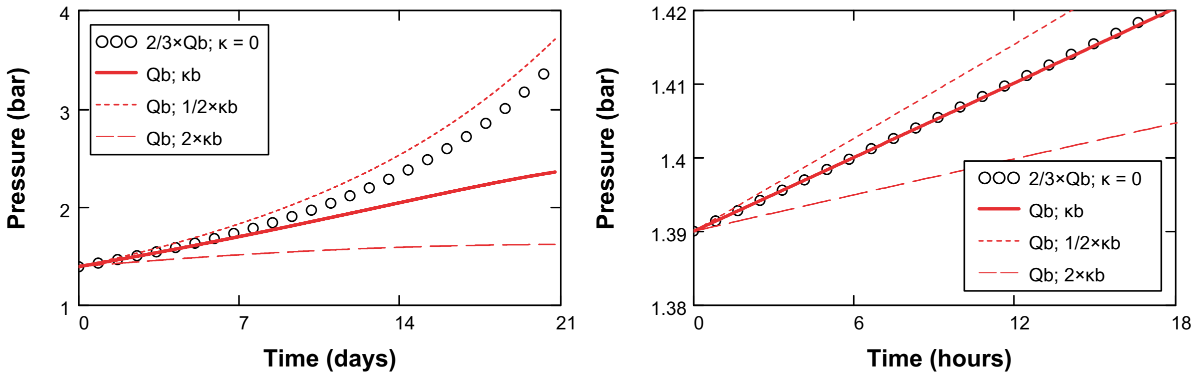

Figure 3-7. *Modelled absolute pressure evolution for the base case (Q_b = 0.09 l/min; $\kappa_b = 7.5 \times 10^{-12}$ $m^3 \times Pa^{-1} \times s^{-1}$) with two sensitivity cases (κ_b/2 and $2 \times \kappa_b$), and one simplified case (2/3 Q_0 and $\kappa = 0$).*

4 Concluding remarks

After more than three years of artificial pressurization at 4 MPa, the measured RH levels indicated that the bentonite seal was very close to water saturation, which in turn should imply that the seal was gas tight. This could be verified by the results from the gas tightness test performed in June 2017: partly due to the increasing gas pressure which was registered after helium gas was shut into the pore space of the filter in the beginning of the test; and partly due to the absence of any detectable concentrations during the sniffer leak search.

The increasing gas pressure was probably caused by inflowing water into the filter, and this was supported by the water outflow rates measured after the gas tightness test. The measured water flow rate was approximately 50 % higher than a flow rate corresponding to the registered gas pressure increase. This level of precision can be regarded as fairly high, considering the large pore volume and the uncertainty in the drainage capacity of the filter. Other processes, such as dissolution of gas in the water phase, gas escape into the rock or as a leakage past the concrete plug, could potentially also explain a slower gas pressure build-up, and therefore constitute a remaining uncertainty.

This result therefore shows that the requirement that the plug "*needs to be reasonably gas tight … during the operational period*" (Posiva SKB 2017) appears to be fulfilled. The actual rate of oxygen transfer through the plug therefore appears to be governed by diffusion of oxygen dissolved in water through the water filled pore-spaces in the filter as well as in the bentonite seal.

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SKBdoc documents will be submitted upon request to document@skb.se.

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SKB is responsible for managing spent nuclear fuel and radioactive waste produced by the Swedish nuclear power plants such that man and the environment are protected in the near and distant future.

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