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Evolution of gas migration properties in a field-scale bentonite engineered barrier system

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The large-scale gas injection test (Lasgit) was a full-scale demonstration experiment based on the Swedish KBS-3 repository concept, conducted at 420 m depth at the Äspö Hard Rock Laboratory. Six gas injection tests were conducted: four in a canister filter towards the bottom of the deposition hole (GT1/2/4/6) and two in a filter towards the top of the canister (GT3/5). The main conclusions were: (1) The movement of gas occurred at a pressure close to the local total stress; (2) Peak gas pressure was linked to the hydraulic permeability of the buffer and the ease at which gas could exit the deposition hole. Therefore, the maturity (hydraulic conductivity) of the buffer was a secondary control on gas entry and movement; (3) Gas was transported through a limited number of dilatant pathways. The pathways were small in relation to the total volume of the buffer, and temporally variable; (4) Over the timescale of the project, pathways sealed. Repeat gas injection tests showed partial re-activation of pathways formed in previous tests, which may have exploited the same weakness in the system on repeat testing; (5) (Gas movement did not weaken the KBS-3 engineered barrier system, with gas release being controlled.

Keywords: bentonite/flow characteristics/gas flow/KBS-3/radioactive waste disposal

Introduction

In the Swedish KBS-3 repository concept for spent nuclear fuel (SKB, 2022), copper/steel canisters containing spent fuel will be placed in large diameter (~1.8 m) deposition holes drilled into the floor of repository tunnels. The space around each canister will be filled with pre-compacted bentonite blocks and pellets (buffer), which over time, will draw in the surrounding groundwater and swell, closing any remaining construction gaps. Once hydrated, the buffer will act as a low permeability diffusional barrier, severely limiting the migration radionuclides from the canister after closure of the repository. While the copper/steel canisters are expected to have a very substantial life, it is important to consider the possible impact of groundwater penetrating a canister through some form of defect. Corrosion of the ferrous canister insert under anoxic conditions will lead to the formation of hydrogen (Horseman *et al.*, 1997; Sellin and Hedin, 2013). Radioactive decay of the waste and the radiolysis of water will produce additional gas. Depending on the gas production rate and the rate of diffusion of gas molecules in the pores of the buffer, it is possible that gas will accumulate in the void space of each canister (Horseman, 1996; Horseman *et al.*, 1997, 1999; Ortiz *et al.*, 2002; SKB, 2011; Weetjens and Sillen, 2006; Wikramaratna *et al.*, 1993). Gas will then enter the buffer when the gas pressure exceeds some critical entry pressure.

The quantitative treatment of gas migration in compact clays is highly complex (Rodwell *et al.*, 1999). The state of knowledge

pertaining to the movement of gas in initially saturated bentonite prior to the current experiment was based on small-scale laboratory studies (Donohew *et al.*, 2000; Harrington & Horseman, 1999; Horseman *et al.*, 1999, 1997; Hume, 1999; Pusch *et al.*, 1987, 1985; Tanai *et al.*, 1997). These laboratory tests demonstrated the importance of the boundary condition on gas migration (Harrington and Horseman, 2003; Horseman *et al.*, 2004). Advective gas movement is strongly dependent on the degree of water saturation of the buffer. At water saturations from <70% (Tanai *et al.*, 1997) to around 80%–90% (Hume, 1999), bentonite contains an interconnected network of air voids resulting in little or no pressure threshold for gas flow. As full saturation is approached, gas entry pressure increases rapidly (Gray *et al.*, 1996; Hume, 1999), with gas flow accompanied by local dilation of the clay (Horseman *et al.*, 1999). Pathway dilation results in an increase in pore water pressure and total stress within the buffer. The maximum gas pressure attainable during a discharge event relates to the geometry and spatial distribution of both the gas pathways within the buffer and the characteristics of the fractures distributed along the walls of the deposition hole.

While improvements in our understanding of the gas-buffer system had taken place (Harrington and Horseman, 2003), laboratory work had highlighted several uncertainties (Horseman *et al.*, 2004), notably the sensitivity of the gas migration process to experimental boundary conditions and possible scale-dependency of the measured responses. As determined by Sellin and Harrington (2006), these issues were

best addressed by undertaking a **Large-Scale Gas Injection Test** (or Lasgit), where large refers to a full-scale KBS-3 demonstration experiment.

Lasgit was operated by Svensk Kärnbränslehantering AB (SKB) at a depth of 420 m at the Äspö Hard Rock Laboratory (HRL) in Sweden between February 2005 and February 2021 (data logged for 5782 days/15.8 years). The aim of the experiment was to perform a series of gas injection tests through water-saturated bentonite in a full-scale KBS-3 deposition hole. The objective was to provide quantitative data to improve process understanding and test/validate modelling approaches used in repository performance assessment. The installation phase was undertaken from 2003 to early 2005 and consisted of the design, construction, and emplacement of the infrastructure necessary to perform the experiment (Cuss *et al.*, 2022). Lasgit started on 1 February 2005 following the closure of the deposition hole and consisted of two operational stages: a hydration stage and a gas injection stage. The hydration stage aimed to raise the saturation of the buffer up to full saturation and achieve equilibration of buffer properties. High water saturations in bentonite >95% can take a considerable time to achieve in field-scale tests (Huertas *et al.*, 2005), and therefore it was decided to undertake a series of preliminary gas and hydraulic measurements to examine the effect of buffer maturity on the hydraulic and gas transport parameters. As a result, the gas injection stage included six detailed gas injection tests.

Five papers have been published on Lasgit to date (Cuss *et al.*, 2011, 2014; Bennett *et al.*, 2012, 2014; 2015) and the complete experimental history has been reported in detail in Cuss *et al.* (2022). In Cuss *et al.* (2014), we showed that the gas entry pressure in the first three gas injection tests was dependent on the local stress state at the injection filters, confirming what had been shown in laboratory experiments. In this paper, we introduce the results from three more gas injection tests and discuss how the gas injection pressure is only primarily described by the local stress state with a secondary control observed over the longer time-frame of the experiment. This secondary control is only apparent because of the extended nature of Lasgit and has not previously been described.

Experimental setup

The Lasgit experimental setup is shown in Figure 1 and Table 1. The experiment was commissioned in a vertical deposition hole (DA3147G01) with a length of ~8.5 m and diameter of ~1.75 m. Prior to the emplacement of Lasgit, the deposition hole was mapped fully (see Cuss *et al.*, 2022). A full-scale KBS-3 copper canister with iron insert was modified with 13 circular filters of varying dimensions located on its surface in three separate arrays (see Figure 1 and Table 1; FL9xx [lower], FM9xx [mid], and FU9xx [upper] filters), to provide point sources for gas injection simulating potential canister defects. These filters could also be used to inject water during the hydration stage to help locally

saturate the buffer around each test filter. As seen in previous field-scale studies, such as FEBEX (Huertas *et al.*, 2005), high water saturations in bentonite (>95%) can take a considerable time to achieve. Consequently, filter mats were placed in strategic positions both within the buffer [FB90x] and on the rock-wall [FR90x] to aid hydration. The canister was surrounded by specially manufactured pre-compacted bentonite blocks, all of which had initial water saturations of >95% (Cuss *et al.*, 2022). Bentonite pellets were used in the gap between the pre-compacted bentonite rings and the rock-wall. As the buffer (bentonite blocks and pellets) began to saturate, it swelled to fill the construction gaps and formed a seal around the canister. The emplacement hole was capped by a conical concrete plug retained by a reinforced SS2172 carbon steel lid capable of withstanding over 5000 kN force.

The deposition hole, buffer, and canister were equipped with instrumentation to measure the total stress [PR9xx, PB9xx, PC90x], pore-water pressure [UR9xx, UB9xx], and relative humidity [WR90x] in 32, 26, and 7 positions, respectively (see Figure 1 and Table 1 for sensor locations). Additional instrumentation continually monitored variations in temperature, relative displacement of the lid and canister, and the restraining forces on the rock anchors. The experiment was monitored and controlled from a temperature-controlled gas laboratory that allowed remote control and monitoring of the test. A full description of the experimental setup is given in Cuss *et al.* (2022).

The boundary conditions of the experiment were those dictated by the pore water pressures and stresses built up within the buffer during hydration and was conducted at ambient temperatures. The canister lid was pre-stressed to 1300 kN to impose a force comparable with that expected for back filling of galleries. The full test history is summarised in Table 2 and Figure 2. The initial 843 days of the experiment aimed to re-saturate the buffer and to establish swelling pressure within the deposition hole through both natural hydration from water producing fractures in the rock wall and artificial hydration using the filter mats and canister filters. Artificial hydration was continued until Day 3745, from when only natural hydration occurred.

Gas injection tests GT1, GT2, GT4, and GT6 were conducted in filter FL903 on the lower canister array (see Figure 1) in 2007, 2009–2010, 2012–2014, and 2019, respectively, to examine the progression of hydration of the buffer and evolution of gas entry properties. Two gas injection tests were conducted in filter FU910 on the upper canister array (see Figure 1) in 2009–2012 and 2019, respectively, to examine the gas transport behaviour in a section of buffer at a lower stress. Two-step constant head hydraulic tests were conducted in the injection filter before and after gas injection. However, a repeat hydraulic test was not conducted in test GT4 as gas was shut-in for a prolonged period.

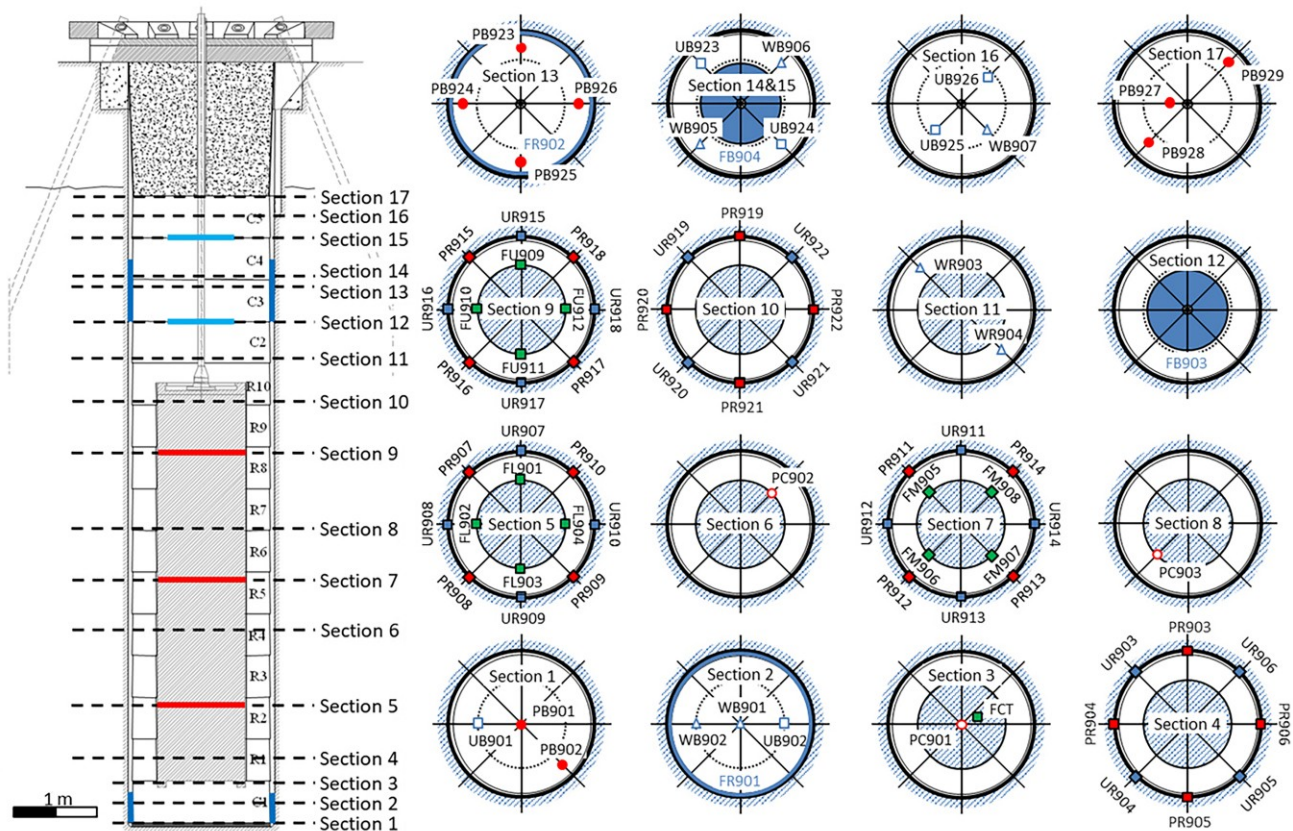


Figure 1. Location of all sensors at 17 intervals in the deposition hole. Note: FCT = full canister test filter; PC = total stress sensor on canister surface; PR = total stress sensor at rock wall; PB = total stress sensor within the buffer; UR = pore water pressure at the rock wall; UB = pore water pressure within the buffer; WR = relative humidity; FB = filter mat between bentonite segments; FR = filter mat at the rock wall; Can = position of the canister

Results

Six gas injection tests have been conducted (GT1–GT6). The first two of these were described in Cuss *et al.* (2011) and GT3 was reported in Cuss *et al.* (2014). In the following section, we describe GT4–GT6 before comparing all gas injection test results. **Note:** In Figures 3–5, 7, and 9 water pressure and/or radial stress is shown with individual sensor values translated along the Y-axis for display purposes. This method means that the magnitude of the change in pressure/stress is preserved, while the overall magnitude of the measurement is lost. Changes in pore water pressure and radial stress are small compared to the magnitude of readings, the detail of variations resultant from pathway movement is not seen if translation is not adopted.

Gas injection test 4 (day 2726–3283)

Gas Injection Test 4 (Figure 3) was conducted in filter FL903 (see Figure 1) on the lower array of filters on the canister surface. It comprised two stages: (1) a two-stage hydraulic test to determine the hydraulic properties of the bentonite; (2) gas pressure was

raised from background levels up to a maximum (peak) gas pressure using four distinct pressure ramps, being held at constant pressure in between. A repeat two-stage hydraulic test was not conducted as the filter was shut-in for a prolonged period after gas injection had stopped.

Each pressure ramp was conducted by filling a gas/water interface vessel with a known volume of gas and water was injected into the base of the vessel at a constant rate using a Teledyne/ISCO syringe pump. This generated an exponential pressure increase assuming gas was not entering the buffer. Test GT4 comprised four pressure ramps. The results for first three ramps are summarised in Table 3, showing that little gas was entering the buffer and small flows were observed when the pressure was held constant.

The final pressure ramp started at Day 3163.04 (Event 7, Figure 3) using a constant injection rate of 0.35 ml.h^{-1} . This raised pressure from 4854 to a maximum of 6174 kPa at Day 3205.31 (42 days), following which injection continued for a further

Table 1. Summary of all sensors at 17 intervals in the deposition hole, including manufacturer and maximum rating of sensors

Section	Height from base (mm)	Filters / filter mats HiPro Model 1000: 20 MPa	Pore pressure in bentonite UB Geokon SI: 20 MPa	Stress in bentonite PB Geokon 4800-1X: 20 MPa	Pore pressure on rock wall UR Geokon SI: 20 MPa	Stress on rock wall PR Geokon 4800-1X: 20 MPa	Stress on canister PC Druck PTX660: 13 MPa	Relative humidity WB Wescor: 95%–100%RH
17	7512	—	—	PB927-929	—	—	—	—
16	7280	—	UB925 UB926	—	—	—	—	WB907
15	7048	FB904	—	—	—	—	—	—
14	6602	—	UB923 UB924	—	—	—	—	WB905 WB906
13	6529	FR902	—	PB923-926	—	—	—	—
12	6043	FB903	—	—	—	—	—	—
11	5050	—	—	—	—	—	—	WB903 WB904
10	5029	—	—	—	UR919-922	PR919-922	—	—
9	4124	FU909-912	—	—	UR915-918	PR915-918	—	—
8	3520	—	—	—	—	—	PC903	—
7	2916	FM905-908	—	—	UR911-914	PR911-914	—	—
6	2312	—	—	—	—	—	PC902	—
5	1709	FL901-904	—	—	UR907-910	PR907-910	—	—
4	803	—	—	—	UR903-906	PR903-906	—	—
3	501	FC901	—	—	—	—	PC901	—
2	351	FR901	UB902	—	—	—	—	WB901 WB902
1	0	—	UB901	PB901 PB902	—	—	—	—

Table 2. List of test stages during the complete history of lasgit. # including interruptions

Test stage	Duration
Total test duration	Day 0–5782
Artificial hydration of filter mats	Day 0–4340 [#]
Hydration stage 1	Day 0–843
Gas Injection Test 1 in filter FL903	Day 843–1110
Hydration stage 2	Day 1110–1472
Gas Injection Test 2 in filter FL903	Day 1472–2084
Gas Injection Test 3 in filter FU910	Day 2086–2722
Gas Injection Test 4	Day 2726–3283
Hydration Stage 3	Day 3283–5138
Gas Injection Test 5 in filter FU910	Day 5133–5306
Gas Injection Test 6 in filter FL903	Day 5138–5264
Full Canister Test	Day 5264–5689
Decommissioning	Day 5689–5782+

78 days. Up until gas entry, STP flow into the buffer ranged from 4.52×10^{-9} to $5.71 \times 10^{-9} \text{ m}^3 \cdot \text{s}^{-1}$, showing a small flow into the buffer. The first evidence of gas entry occurred at Day 3203.73

(Event 8) when flow into the buffer began to increase at a gas pressure of 6141 kPa, with pore water pressure at UR905 and UR908 reacting (Figure 3(b)).

Gas pressure peaked at Day 3205.31 (Event 9) at a gas pressure of 6174 kPa following increases in UR908 (Figure 3(b)) and PR908 (Figure 3(c)) of 12 and 10 kPa, respectively. At this time, flow into the buffer became greater than flow into system, with gas peak pressure corresponding with increases in UR905, PR905, PR907, and a decrease in PR909. The form of the pore pressure responses at UR905 and UR908 was similar (Figure 3(b)), with an initial stepped increase followed by a partial recovery of pressure. The form of the radial stress response was quite different (Figure 3(c)). Sensor PR908 showed two short lived peaks in stress, which quickly recovered. At PR905 and PR907 stress increased rapidly, followed by a slow recovery of radial stress. At UR909 a stepped response was seen, although this was a decrease in stress. In all sensors, the variation in response was small, with a maximum of ~ 20 kPa variation in pore water pressure and ~ 14 kPa in radial stress. Gas peak pressure resulted in a single

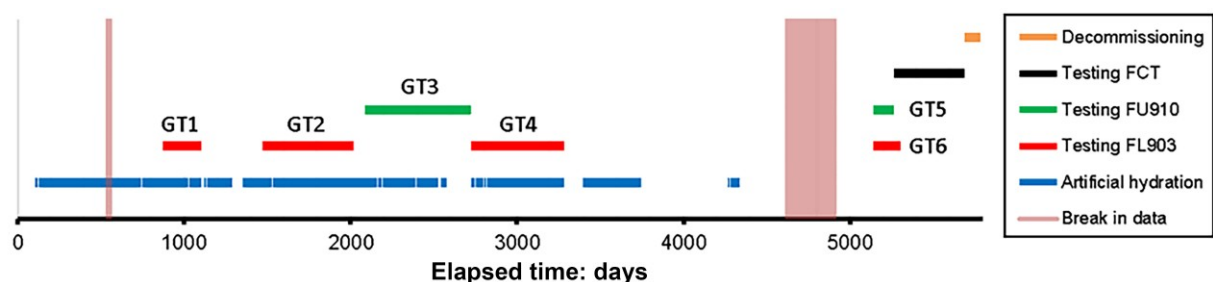


Figure 2. Summary test history of the Lasgit experiment

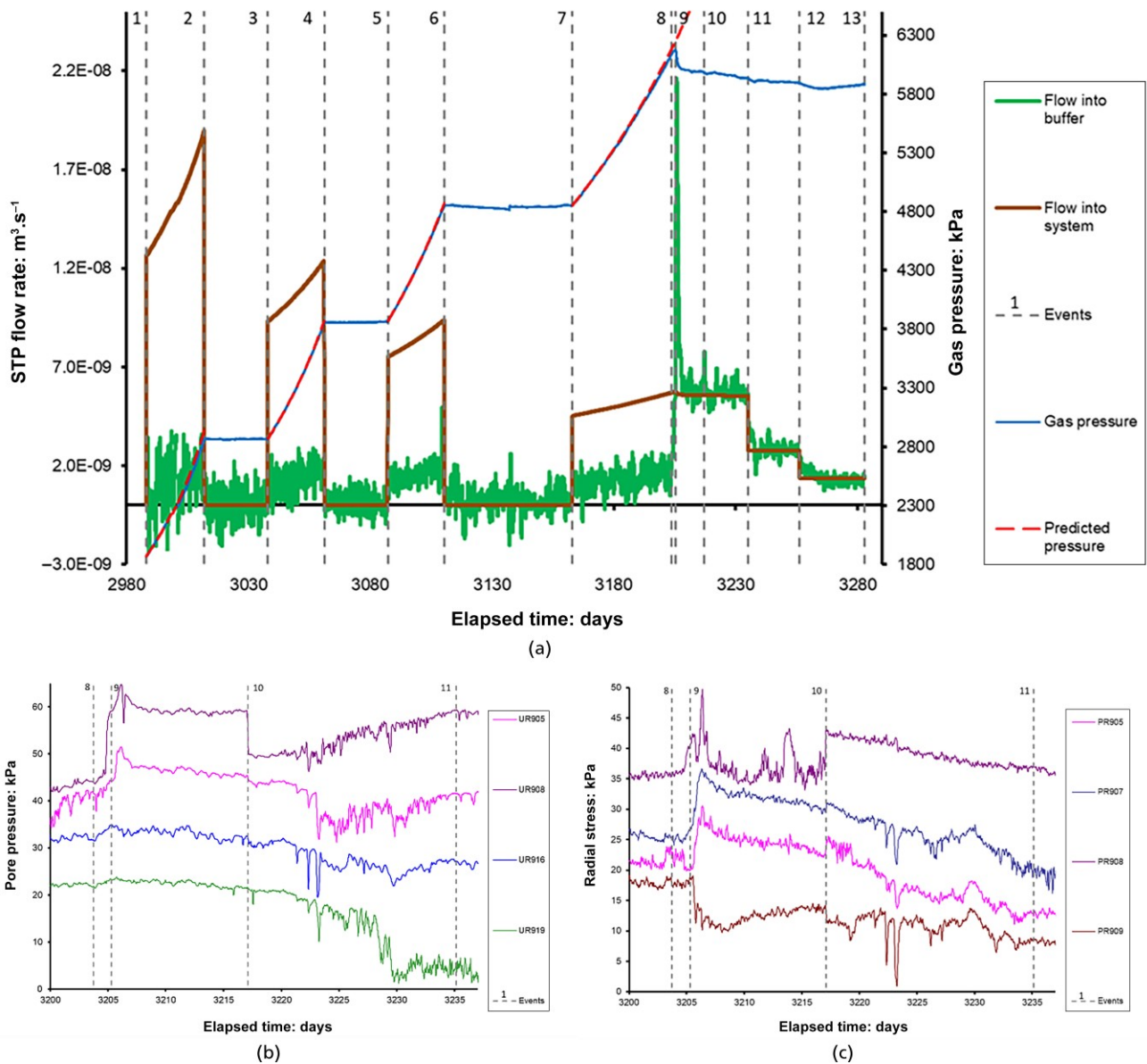


Figure 3. Gas Test 4. (a) Flow of gas into the system and the buffer; (b) pore pressure response at the deposition wall around the time of peak gas pressure; (c) radial stress on the deposition wall around the time of peak gas pressure. Note: For display purposes in (b) and (c) each sensor has undergone translation along the y-axis

peak in flow of $3.27 \times 10^{-8} \text{ m}^3.\text{s}^{-1}$ at Day 3205.72. The peak in flow was short-lived with flow into the buffer matching flow into the system within four days. From then onwards the flow into the buffer was slightly greater than the flow into the system, giving a slow reduction in gas pressure.

Event 10 (Figure 3) occurred at Day 3217.11, when a short-lived increase in flow into the buffer occurred. This corresponded with a reduction in pore water pressure at UR908 of nearly 10 kPa and radial stress variations in PR905, PR907-PR909 of $<\pm 10$ kPa.

The flow rate of the injection pump was lowered in two steps, approximately halving flow at each step. Flow into the buffer approximated flow into the system, with slightly higher flow into the buffer resulting in the continued reduction in gas pressure. In the final stage the flow into the buffer reduced, resulting in an increase in gas pressure.

Gas injection test 5 (day 5133–5306)

Gas Injection Test 5 (Figure 4) was relatively short because of time restrictions and unlike all prior tests, overlap existed between

Table 3. Summary of first three gas ramps conducted in test GT4

GT4	Units	Gas ramp 1	Gas ramp 2	Gas ramp 3
Start time	day	2988.07	3038.04	3087.24
Start volume	ml	3750	2570	1960
Injection rate	ml.h ⁻¹	2.45	1.2	0.725
Start pressure	kPa	1868	2868	3867
End pressure	kPa	2867	3856	4852
Ramp duration	days	23.9	23.1	23.2
STP flow during flow	m ³ .s ⁻¹	1.25–1.48 × 10 ⁻⁸	0.93–1.24 × 10 ⁻⁸	7.51–9.41 × 10 ⁻⁹
Pressure hold duration	days	26.0	26.1	52.6
Flow during hold	μmol.d ⁻¹	282	538	651

the hydraulic stages of gas tests 5 and 6. Gas Injection Test 5 was the second test conducted using filter FU910. The limited test period meant the test was conducted differently from previous tests, with a single gas injection ramp starting at a higher gas pressure comparable with when a fourth gas ramp would begin.

The pressure ramp started at Day 5183.26 (Event 1, Figure 4(a)) using a constant injection rate of 2.1 ml.h⁻¹. This raised pressure from 4230 to a maximum of 5347 kPa at Day 5202.57 (19 days), following which injection continued for a further 18 days. Up until gas entry, STP flow into the buffer (Figure 4(a)) averaged $2.06 \times 10^{-9} \text{ m}^3.\text{s}^{-1}$, showing a small flow into the buffer. Gas pressure peaked at a pressure of 5347 kPa at Day 5202.57 (Event 2), with a peak in flow rate of $4.12 \times 10^{-6} \text{ m}^3.\text{s}^{-1}$ resulting in a reduction in gas pressure of 185 kPa. This resulted in a change in several UR sensors (Figure 4(b)), showing either a stepped increase in pore pressure (UR911, UR913, UR915, UR917–UR918) followed by a slow decrease in pressure, the start of a series of pressure steps (UR914, UR922), or the initiation of a slow pressure increase (UR921). The maximum pore pressure increase was ~90 kPa in UR914. Several PR sensors (Figure 4(c)) also changed (PR909–PR922), showing a maximum stepped change of 155 kPa. Coincident with Event 2, gas directly travelled 90° clockwise around the canister to filter FU909 and slowly towards PC903, 60 cm below the injection filter and 45° anticlockwise around the canister (see Figure 1).

Following the initial reduction in gas pressure, flow into the buffer reduced to below flow into the system, resulting in an increase in gas pressure. A second gas entry event occurred around Day 5206 (Event 3, Figure 4) with a second peak in gas flow of $1.47 \times 10^{-6} \text{ m}^3.\text{s}^{-1}$. This event corresponds with variations in pore water pressure and radial stress, with a reduction in canister stress seen at PC903 and a change in slope of the gas injection pressure. This shows a secondary flow event, suggesting that a new pathway, or network of pathways, had formed. At Day 5220.94 (Event 4, Figure 4), a third flow event was seen with a peak in flow into the buffer of $7.05 \times 10^{-7} \text{ m}^3.\text{s}^{-1}$. An error with the logging system means that the changes in pore pressure and radial stress at this time were not

observed. This is interpreted to be the break-through of gas from the buffer into the surrounding rock. Each successive flow event saw a reduction in peak flow. The three flow events are interpreted as: (1) gas entering the buffer and migrating to filter FU909 and PC903; (2) movement of gas towards the mid-plane of the deposition hole; (3) the exit of gas from the deposition hole, possibly through an interface between blocks.

Gas injection test 6 (day 5138–5264)

Gas Injection Test 6 (Figure 5) was the fourth test conducted using canister filter FL903 and was also a relatively short test because of time restrictions. The limited test period meant that GT6 was conducted similarly to GT5 with an elevated starting gas pressure and a single gas injection ramp.

The pressure ramp started at Day 5230.28 (Event 1, Figure 5(a)) using a constant injection rate of 2.1 ml.h⁻¹. This raised pressure from 4829 to a maximum of 6437 kPa at Day 5241.94 (~12 days), following which injection continued for a further 22 days. Up until gas entry, STP flow into the buffer (Figure 5(a)) averaged $1.41 \times 10^{-9} \text{ m}^3.\text{s}^{-1}$. The first evidence of gas entering the buffer occurred at a gas pressure of 5827 kPa at Day 5238.13 (Event 2, Figure 5), with a short-lived spike in flow into the buffer that peaked at $4.52 \times 10^{-8} \text{ m}^3.\text{s}^{-1}$. This event only correlated with a subtle change in PB925, a stress sensor within the bentonite above the canister. Following this, gas pressure continued to increase until peak pressure was seen at Day 5241.92, with a gas pressure of 6437 kPa (Event 3, Figure 5(a)), with a peak flow rate of $4.12 \times 10^{-6} \text{ m}^3.\text{s}^{-1}$. This event corresponds with changes in pore water pressure (Figure 5(b)) and radial stress (Figure 5(c)). The form of the pore water pressure variation differs, with UR905, UR906, and UR908 showing a peak in pressure, followed by a slow reduction in pressure, while UR907, UR909, and UR910 show stepped increases that are short lived and step back to values close to the starting value. The largest change in pore water pressure occurred in UR908 with an increase of ~45 kPa. The form of radial stress variation shows several forms, with PR905–PR907 showing a stepped increase in stress, PR903–PR904 showing a slower increase in stress to a new raised plateau, and PR909–PR910

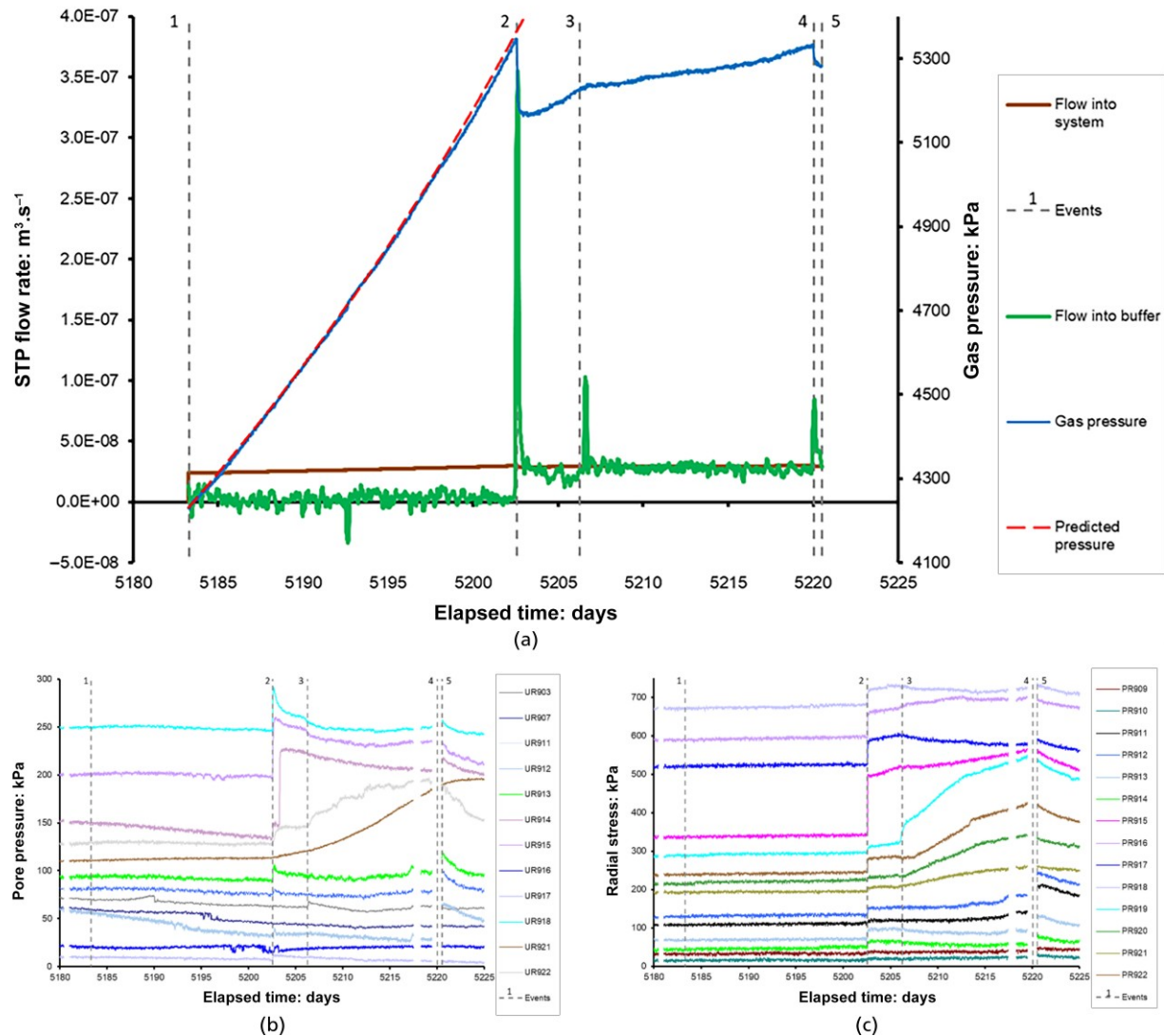


Figure 4. Gas Test 5. (a) Flow of gas into the system and the buffer; (b) pore pressure at the deposition wall around the time of peak gas pressure; (c) radial stress along the y-axis around the time of peak gas pressure. Note: For display purposes in (b) and (c) each sensor has undergone translation along the y-axis

showing a short-term increase in stress that returns to the start value. The largest changes in radial stress occurred in PR906 with an increase of ~60 kPa.

Two further peaks in gas flow occurred at Day 5242.21 (Event 4, Figure 5) and Day 5242.96 (Event 5), when gas flow peaked at 2.11×10^{-7} and $2.42 \times 10^{-7} \text{ m}^3 \cdot \text{s}^{-1}$, respectively. Both events show disturbance of the pore pressure (Figure 5(b)) and radial stress sensors (Figure 5(c)), resulting in both increase or decrease in some readings. The final of the flow events (Event 5) resulted in a stable gradual decrease in gas pressure of 560 kPa, reaching a minimum of 5878 kPa. Event 5 corresponds with the direct

movement of gas to filter FL901, 180° around the canister from the injector, with the two intermediate filters (FL902, FL904) not recording any evidence of gas flow. This showed that gas movement was not direct and was localised. Canister filter FL901 took 8.5 days to reach a pressure of 5400 kPa, ~650 kPa below the gas injection pressure. At this time, the gas pressure in FL903 reached a plateau and it was interpreted that gas was flowing steadily out of the deposition hole.

Comparing tests in FL903

Four tests were conducted in filter FL903 on the lower array of canister filters at a height of 1709 mm in the deposition hole

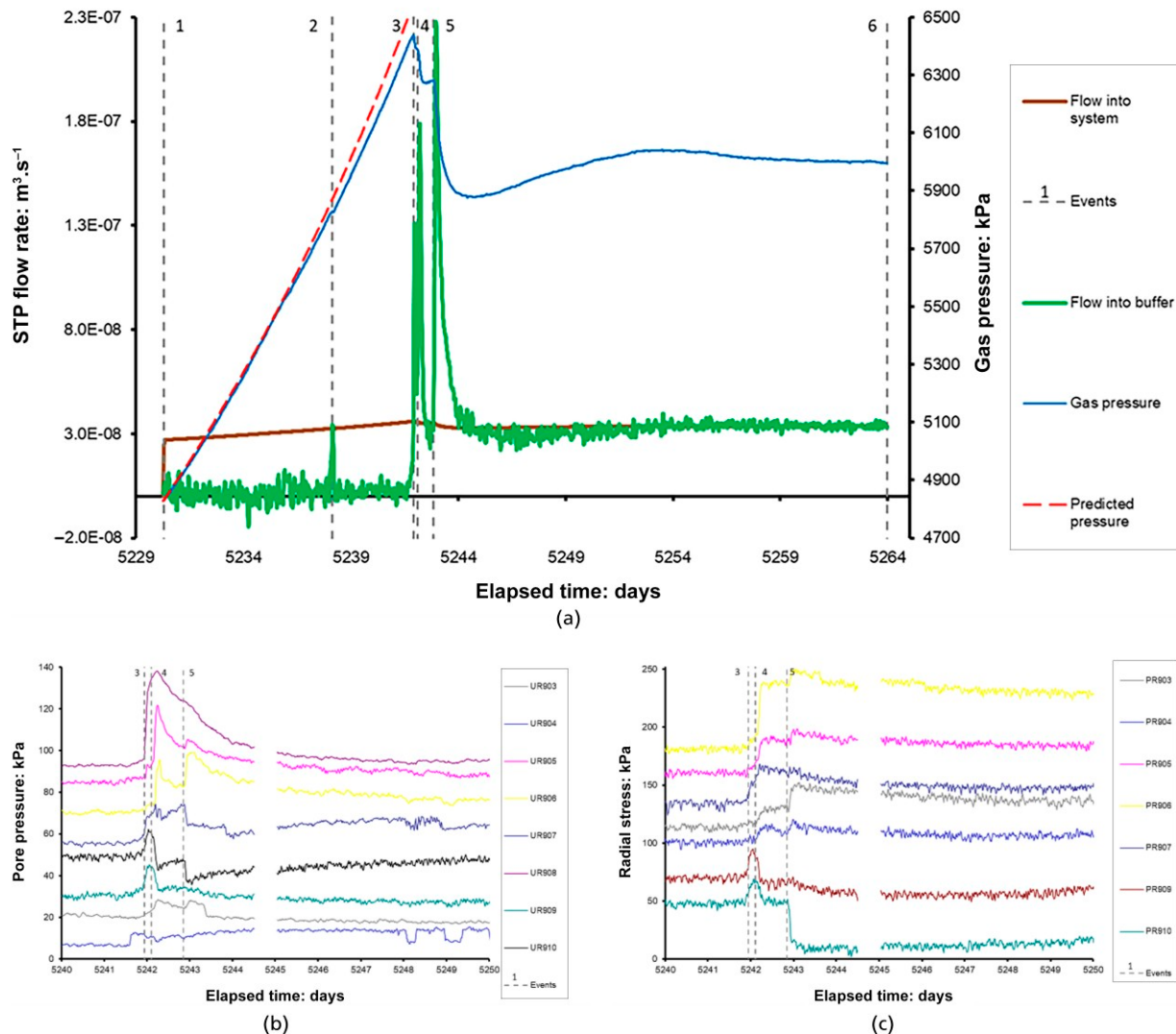


Figure 5. Gas Test 6. (a) Flow of gas into the system and the buffer; (b) pore pressure at the deposition wall around the time of peak gas pressure; (c) radial stress on the deposition wall around the time of peak gas pressure. Note: For display purposes in (b) and (c) each sensor has undergone translation along the y-axis

between Day 917 and Day 5263: GT1, GT2, GT4, and GT6 (Table 4). Figure 6 compares the gas pressure and flow data for these tests and shows that the gas flow into the system varied by a factor of 14.5. The response of the four tests did not vary significantly and it can be concluded that the processes controlling gas entry and movement were not dependent on the rate of pressurisation over the range of injection rates used.

Figure 6 shows some difference in response for flow into the buffer. In GT1, flow into the buffer slowly increased during the final gas ramp, suggesting that gas started to enter the buffer. In the other gas injection tests, flow into the buffer was generally low and only increased around the time of peak pressure. This

may be related to the degree of gas saturation of the pore-fluid within the buffer around the injection filter. Gas started to enter the buffer at a lower pressure than peak pressure, but pathways became unstable and stopped propagating as gas pressure continued to increase at a rate like that seen before the pre-cursor flow event. This may be related to the buffer having not reached full saturation by the time test GT1 was started.

At peak pressure, flow greatly increased and peaked. In GT1 two peaks were seen, a similar pattern was observed in GT2. However, GT4 only had a single peak in flow, while GT6 showed at least 3 peaks. In GT1 and GT2, the initial peak was the greatest flow into the buffer, whereas in GT6, the three peaks increased in

Table 4. Data relating to gas injection tests conducted in canister filters FL903 and FU910

Filter	Test	Gas ramps	Start : days	End: days	Time gap: days	Peak pressure: kPa	Time at peak: days
FL903	GT1	2	917.32	1010.03	917.32	5666	972.24
	GT2	4	1577.40	1967.98	567.36	5868	1769.65
	GT4	4	2988.08	3283.02	1020.11	6174	3205.31
	GT6	1	5230.29	5263.95	1947.26	6437	5235.96
FU910	GT3	4	2257.23	2614.46	2257.23	5192	2490.37
	GT5	1	5183.27	5220.47	2568.82	5347	5202.57

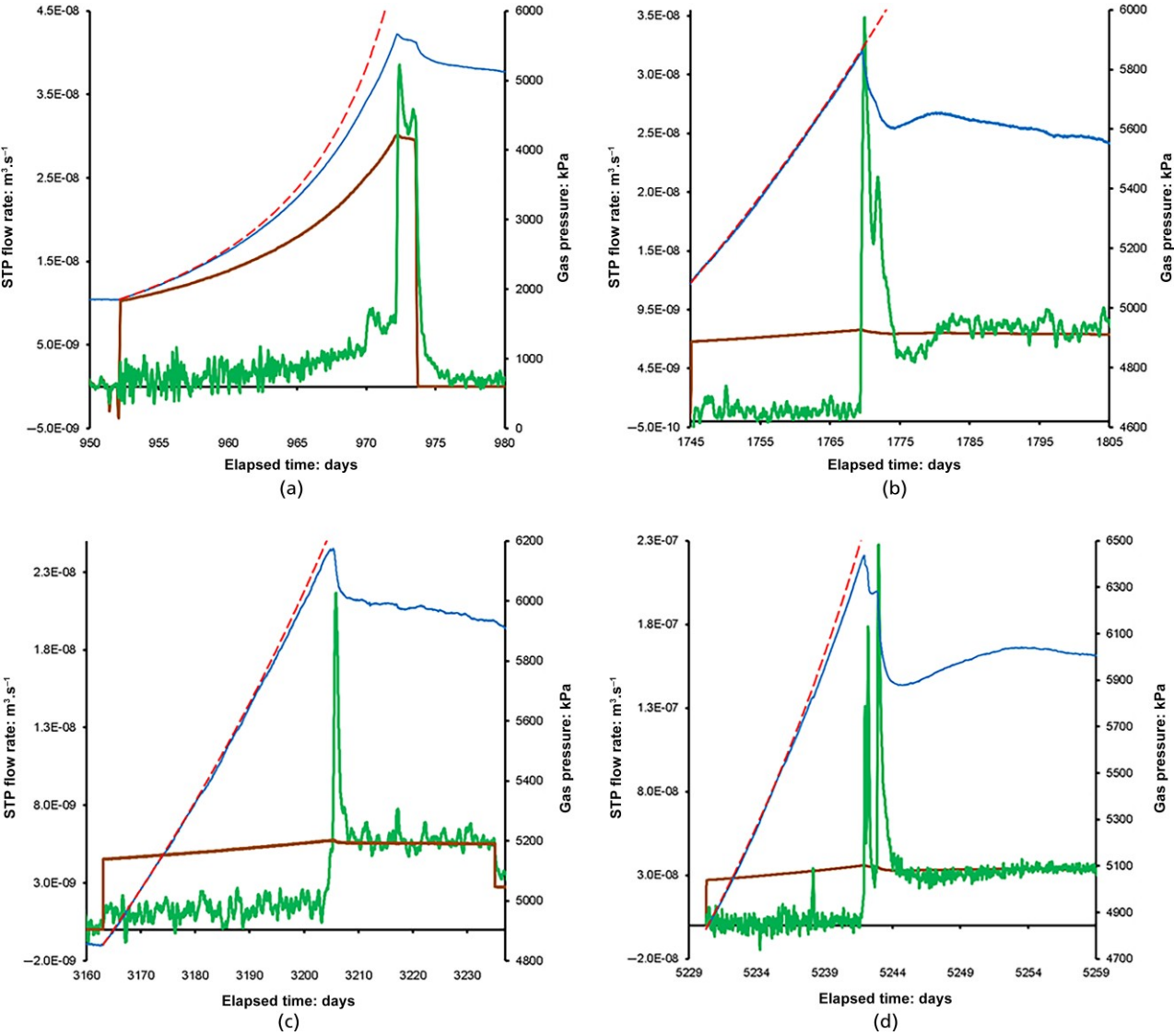


Figure 6. Comparison of gas entry behaviour for the four tests conducted in canister filter FL903: (a) Gas Test 1; (b) Gas Test 2; (c) Gas Test 4; (d) Gas Test 6

magnitude for successive events. A peak in flow is created as new volume is generated, that is, as pathways form. The effective volume occupied by the gas increases, resulting in a reduction in pressure. When a subsequent peak is observed it means that the effective volume occupied by the gas has increased again. This might be because of gas encountering a sink (void or porous region), the formation of a new pathway network, or might mean that gas flowed along existing pathways out of the buffer. The peaks may also indicate that gas had intercepted a different type of buffer component, for example, gas can either enter the buffer or move along the buffer/canister interface. It is likely that these two zones of the buffer will have different properties.

Early in the test, the bentonite rings swelled and closed the 10 mm engineered gap between the canister and buffer. This means that the bentonite in contact with the canister had swelled and would have slightly different properties to that of the buffer interior. This was observed in differences in geotechnical properties close to the canister compared to within the middle of the annular rings (Cuss *et al.*, 2022). Therefore, gas was more likely to move within this region at, or near, the canister/buffer interface. However, to exit the KBS-3 system, it had to either propagate through the buffer or exploit an interface between individual rings. It was interpreted in GT1 that gas moved initially down the canister following the prevailing stress gradient (Cuss *et al.*, 2011), before exiting the deposition hole through the interface between rings R1 and R2, or R1 and C1. The first peak seen in GT1 thus represents the formation of pathways and movement along the canister/buffer zone, while the second peak represents the pathways exploiting weaknesses between bentonite rings or through the buffer.

During decommissioning (Cuss *et al.*, 2022), it was noted that negligible mechanical self-healing had occurred between bentonite blocks and during excavation, clean surfaces were created when the buffer had been extracted. However, the axial stresses generated within the system will have resulted in mechanical self-sealing of the bentonite block interfaces. In Lasgit, it was expected that initial formation of pathways would require the greatest energy and that the propagation of pathways would be easier. GT6 suggests that the initial formation of pathways resulted in new pathway formation. It is likely that the second peak occurred as a previous pathway was intercepted or when an interface between rings was reached, with the third peak because of gas breakthrough; a considerable loss of pressure suggesting that gas had exited the deposition hole.

GT2 and GT6 had similar characteristics. Flow into the buffer rapidly decreased as gas pressure loss slowed, with the flowrate into the buffer becoming lower than the flowrate into the system, that is gas pressure increased. This over- and under-shooting of flow has been seen in laboratory-scale experiments (e.g. Harrington and Horseman, 2003; Harrington *et al.*, 2017). With time, flow

into the buffer matched flow into the system, meaning that steady-state flow was established. Test GT1 was not conducted for long enough to know whether it would have seen the same behaviour. However, GT4 just showed a single peak in flow, resulting in a loss of gas pressure followed by a stable reduction of gas pressure. This suggests that pathways formed in previous tests were re-activated with relative ease or that a single pathway quickly formed that allowed gas to reach the outside of the deposition hole.

The qualitative gas flow behaviour shown in Figure 6 was similar for all four tests, apart from the differences that have been accounted for above. GT2 was conducted using neon as a tracer, instead of the usual helium. There was no significant difference for GT2 to suggest that the type of gas used had a detectable influence on the advective gas transport behaviour.

Figure 7 compares the response seen in selected pore pressure [UR9xx] sensors around the time of peak stress and gas entry. Test GT1 (Figure 7(a)) saw a distinctive form in UR905. Pressure started to increase, before a secondary feature resulted in a much greater pressure increase. This quickly peaked and then decayed back to the starting pressure over several days. Several other sensors showed a single peak of similar form to the initial pressure rise seen in UR905, while UR909 saw a pressure decrease. During GT2 (Figure 7(b)), the form of UR906 and UR909 was very similar to that seen in GT1. However, the pressure increase at other locations was largely absent. This may suggest that GT1 showed virgin formation of pathways, with GT2 re-activating pre-existing sealed pathways. Test GT4 showed a different response altogether (Figure 7(c)). Small steps in pore pressure were seen in UR905, with UR908 showing the greatest increase in pore pressure. This suggests that GT4 showed different propagation response than GT1 and GT2 and that some new pathways formed. Test GT6 (Figure 7(d)) showed similar response to GT1 and GT2, with some comparison to GT4. UR905 was again the dominant pore pressure response but as in GT4, UR908 also showed pressure increase. This suggests that sealed features formed in GT1 and reactivated in GT2 were again reactivated but additional features formed in GT4 were also reactivated. The form of the response for GT6 is more like GT1 and may suggest that a degree of self-sealing had occurred.

The pore pressure responses show that in GT1 new pathways formed in the buffer. Certain characteristics suggest that gas pathway propagation was in a similar direction (Figure 8), possibly re-opening sealed pathways. In all tests, gas moved towards the bottom of the deposition hole, following the prevailing stress gradient. In tests GT2 the gas reached 180° around the canister surface, not intercepting the intermediate filters. A degree of self-sealing occurred between GT2 and GT4 with previous pathways only partially re-opening in GT4. The final gas injection test (GT6) then showed gas propagation in the directions that matched all three previous gas injection tests to some

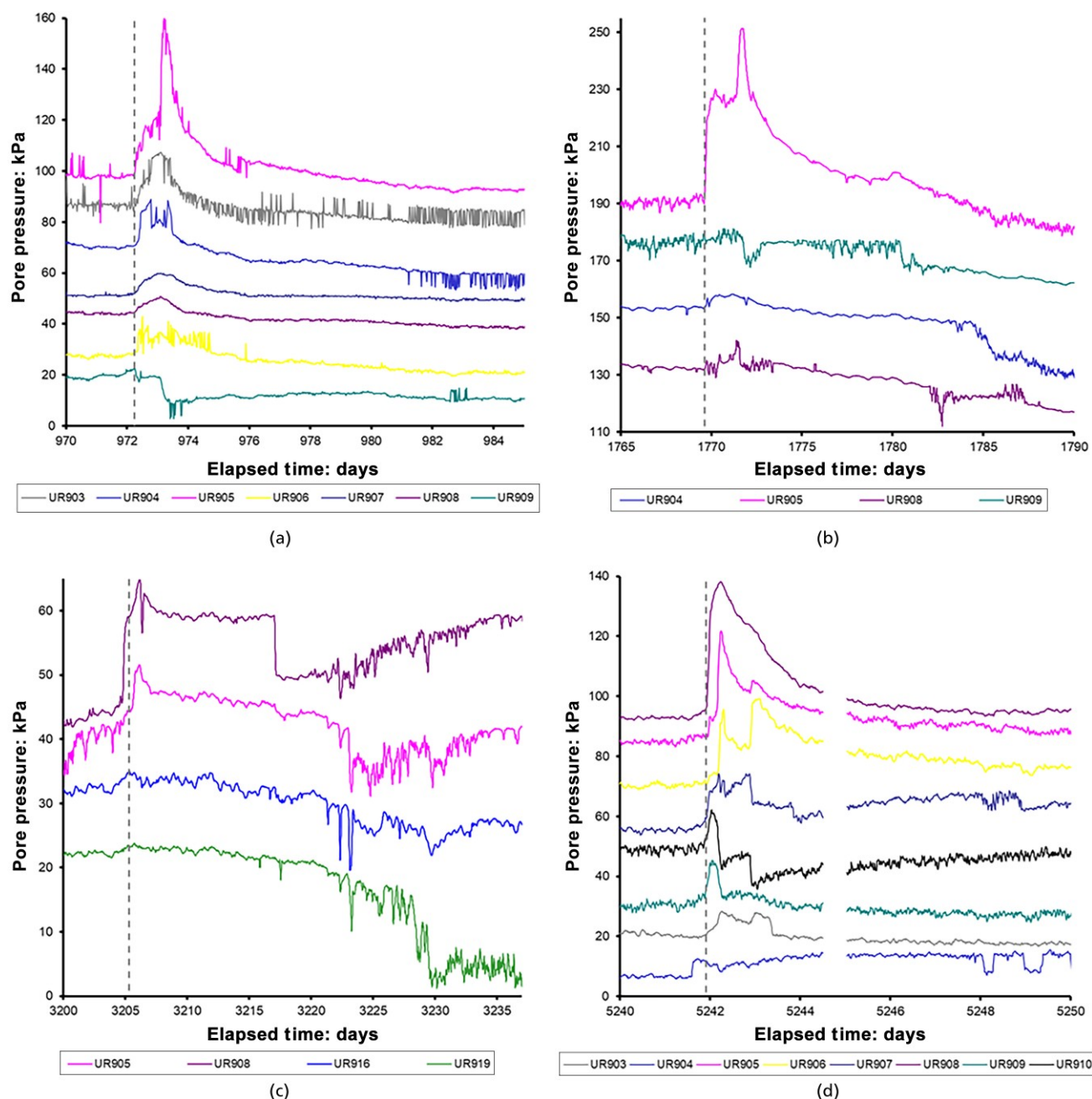


Figure 7. Comparing the pore pressure response for four gas injection tests in filter FL903: (a) Gas Test 1; (b) Gas Test 2; (c) Gas Test 4; (d) Gas Test 6. Gas peak pressure is highlighted as a dashed event line. Note: For display purposes each sensor has undergone translation along the y-axis

degree and may show that sealed pathways formed in the earlier tests were re-established.

Comparing tests in FU910

Two tests were conducted in canister filter FU910 on the upper array of canister filters at a height of 4124 mm in the deposition

hole; GT3 and GT5. The data relating to the tests are summarised in Table 4.

Figure 9 compares the gas pressure and flow data. In GT3, flow into the buffer was low, up until the sudden increase in flow around peak pressure. There were no pre-cursor flows and a single

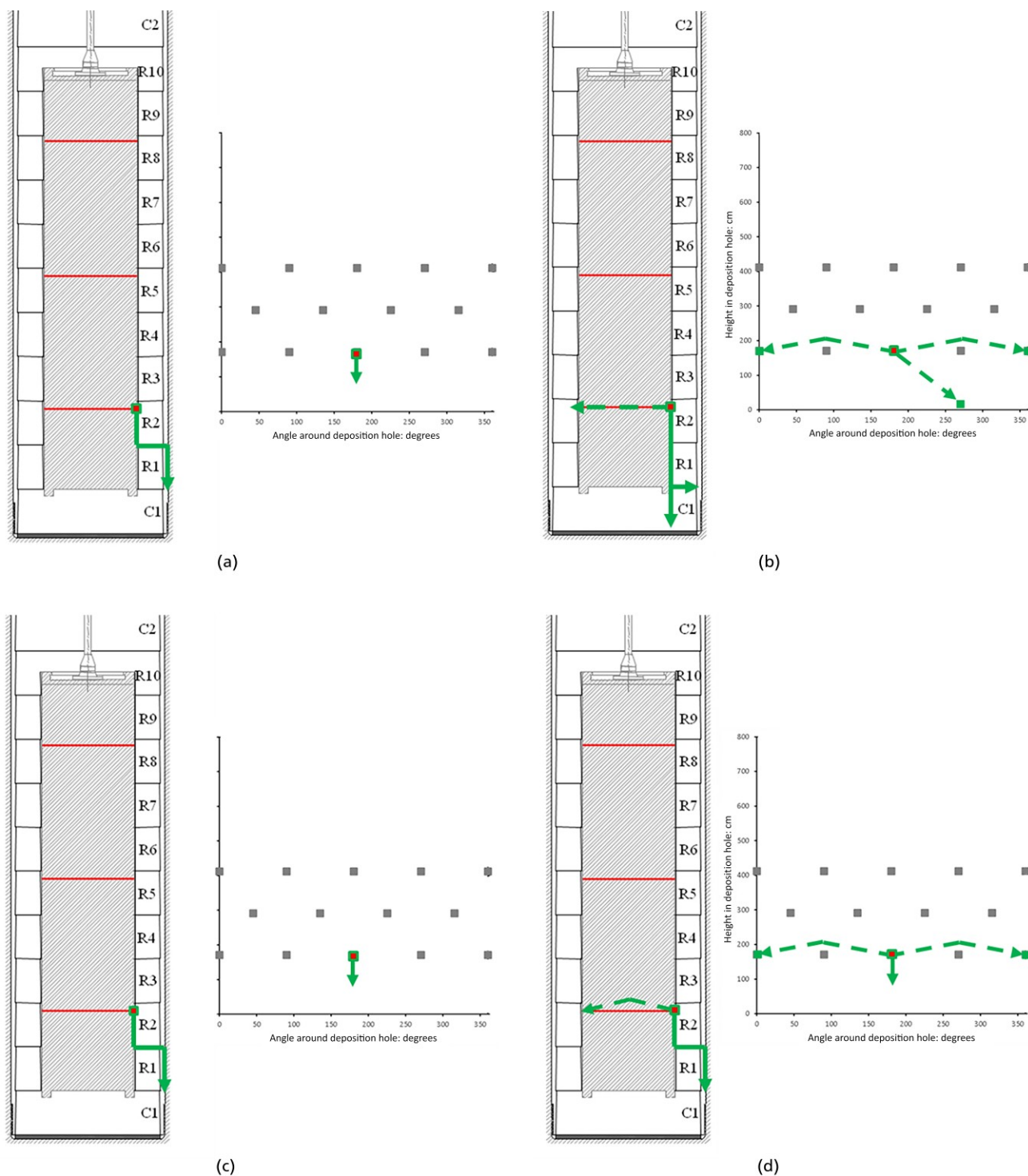


Figure 8. Schematic diagram of the direction of gas flow during gas testing in lower canister filter FL903: (a) Gas Test 1; (b) Gas Test 2; (c) Gas Test 4; (d) Gas Test 6

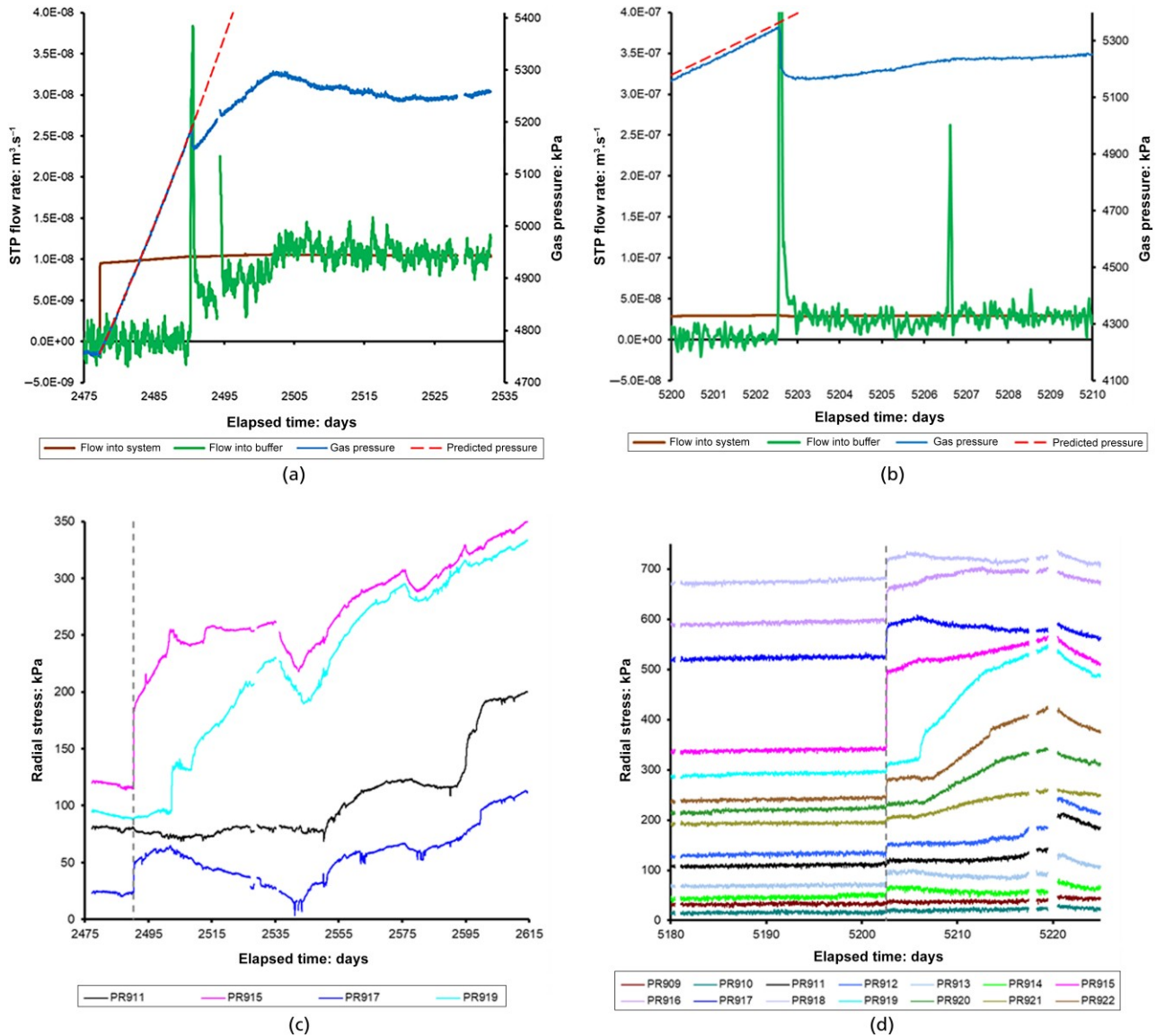


Figure 9. Comparison of gas entry behaviour for the two tests conducted in canister filter FU910: (a) gas entry behaviour for Gas Test 3; (b) gas entry behaviour for Gas Injection Test 5; (c) radial stresses observed in Gas Test 3; (d) radial stresses observed in Gas Test 5. Note: For display purposes in (c) and (d) each sensor has undergone translation along the y-axis

peak in flow was seen, reducing gas pressure rapidly. This suggests that the pre-cursor flow seen in GT1 at filter FL903 was related to the saturation of the buffer. The peak in flow was short lived and flow into the buffer quickly reduced to below that of flow into the system and as a result gas pressure started to rise again. Similar behaviour was seen in GT5; no pre-cursor flow and a rapid increase in flow with a single short-lived spike. In both tests, flow into the buffer did not reduce below the flowrate into the system for some time so gas pressure slowly increased. Therefore, gas entry saw a rapid propagation of pathways, lowering gas pressure. These pathways either became unstable or the

gas flow encountered a “baffle” in the buffer, resulting in an increase in gas pressure. In both tests, gas pressure had a secondary peak, which this time was broader compared with the instantaneous pressure drop seen at initial peak pressure. In both tests pressure increased above, or very close to, the initial peak pressure. This contrasts with what was seen in FL903, with peak pressure being followed by reducing gas pressure. At FU910, this suggests that continued propagation of pathways was more difficult higher on the canister or that an easy route out of the system was not achieved. In both tests, during the initial recovery of gas pressure there was a change of slope, suggesting that pathway

propagation increased. This change in slope was more obvious in GT5 but is present in GT3. In both tests, this event also corresponded with a short-lived spike in flow, although in GT3 there was a break in data recording that may have masked the feature.

At peak pressure, the gas pressure rapidly reduced. In GT3 a reduction of ~ 40 kPa was seen, with GT5 reducing ~ 180 kPa. This may suggest that GT5 re-activated existing pathways in the system quite easily or that a pathway of higher transport capacity had formed. In GT3 pressure recovered to create a secondary, broad, peak, while in GT5 a second instantaneous pressure drop was seen at a gas pressure like the initial peak gas pressure (see Figure 4(a)). This behaviour suggests that gas pathways were continuing to grow, and that gas had not been able to exit the deposition hole, at least until the secondary peak occurred. The rapid loss of more pressure in GT5 suggests that the repeat test exploited features formed during GT3 and that the buffer had not fully self-healed following the first gas test. The qualitative gas flow behaviour shown in Figure 9 shows a similar behaviour and form for both gas pressure and flow, with short lived spike in flow resulting in steady-state movement of gas as flow into the buffer matched flow into the system.

Figure 9 compares the response observed in selected radial stress (PR) sensors around the time of peak stress and gas entry. Peak pressure occurred in GT3 at Day 2490.37 (Figure 9(a)). At this time, PR915 and PR917 increased in stress, with PR919 increasing around five days later (Figure 9(c)). This suggests that gas moved in this general direction along the canister surface. Radial stress increased at PR911 some 100 days later. This suggests that gas movement was transient throughout this test. For GT5 (Figure 9(b)), gas peak pressure occurred at Day 5202.57 and this was accompanied by an increase in almost all PR sensors (Figure 9(d)). A stepped response was seen, with some sensors showing a delayed response. The radial stress data suggest the slow formation of pathways in GT3, which were reactivated rapidly in GT5. In sensor PR917 the form of the response was similar between tests, with PR915 also superficially similar, although the response was more complex in GT3 and the amplitude of variation in GT5 was significantly greater. In both tests, PR919 saw a delayed increase of stress as gas moved.

The radial stress responses show that GT3 saw the slow formation of virgin pathways in the buffer. Certain features of GT5 suggest that gas pathway propagation was in a similar direction, possibly re-opening sealed pathways extant from the earlier gas injection test. This suggests that pathways had not fully self-healed and were easily reactivated, but near the injection filter the system had self-sealed, probably because of the two-step hydraulic tests conducted and local re-hydration of the buffer.

In both gas injection tests, pathways were seen to directly propagate to other sensors within the deposition hole, as shown in

Figure 10. In GT3 gas first moved to FU909 in a series of events, later gas arrived at FU911 in a series of pressure increases, albeit over a longer time. Next, gas reached PC903, and finally reached FL904 towards the bottom of the canister. For GT5 at peak gas pressure, FU909 and PC903 increased instantaneously. This suggests that pathways created during GT3 were re-opened at peak pressure during GT5 and shows that limited sealing of the existing pathway network occurred in the ~ 2500 days between the two tests. Gas did not reach FU911 or FL904, showing that at least some of the pathway network was not reactivated and had self-sealed. It should be noted that both FU911 and FL904 were hydraulically tested between the two gas injection tests, and this may have aided self-sealing. However, FU909 was also hydraulically tested and this had not experienced full self-sealing. It is not certain whether gas managed to escape the deposition hole as pathways were still forming or developing in GT3. However, pathways are only able to store a limited amount of gas and it is expected that gas had escaped the deposition hole.

Discussion

Inferring gas pathway movement

The formation of dilatant pathways results in the compression of clay around the pathway, resulting in an increase in stress, reduction in porosity, and an increase in pore pressure. Careful examination of all available data, be these in graph form or 3D contour maps, can show where changes in pore pressure and stress are occurring. This indicates the direction of gas movement, as shown experimentally by Harrington *et al.* (2017) and Graham and Harrington (2024) and numerically by Kim *et al.* (2021). However, it must be noted that the distribution of sensors was relatively crude and that contour plotting can result in artefacts that can be suggestive of variations. Therefore, all available ways of plotting the data were examined to infer a direction of gas movement. These observations can be supplemented by observations where gas had directly migrated to sensors within the deposition hole, be these canister filters (FL901, FL903, FL904, FU909, FU911), pore pressure sensors within the buffer (UB902), and/or stress sensor on the canister surface (PC903). The absence of gas intercepting sensors could also aid interpretation, for instance, in GT3 gas reached the lower array of canister filters without intercepting the mid-plane filters and contour maps showed where gas had moved between these filters. Therefore, although the distribution of sensors means that exact location of gas pathways is difficult, a general direction of propagation can be determined that is confirmed by the migration of gas to individual sensor locations within the deposition hole. Confidence can therefore be given to the interpretation of migration direction.

Gas peak pressure with time and stress

Gas injection tests were conducted using canister filters FL903 or FU910. In all tests, gas movement occurred around the peak pressure, and gas found a pathway out of the deposition hole. This resulted in the careful venting of pressurised gas in a controlled

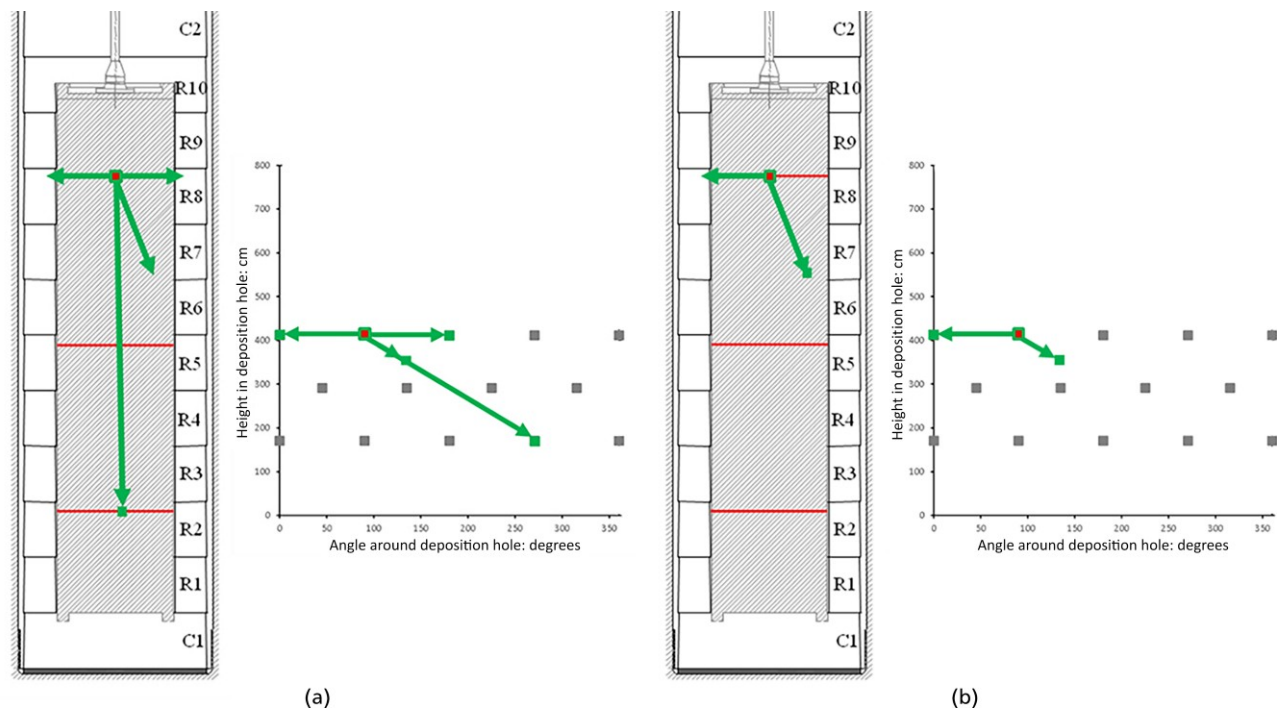


Figure 10. Schematic diagram of the direction of gas flow during gas testing in upper filter FU910: (a) flow in Gas Test 3; (b) flow in Gas Test 5

manner that had little to no long-term effect on the physical properties of the buffer. Repeat gas testing suggested that pathways were extant for prolonged periods and were sometimes reactivated by subsequent tests in the same filter. Moreover, testing in FU910 may have intercepted pathways created in previous tests from filter FL903.

Figure 11(a) shows gas peak pressure for the six gas injection tests. In filter FL903, gas peak pressure increased throughout the

experiment and is shown with a best fit described by a logarithmic function, as labelled. Peak pressure at FU910 was at a lower pressure and is also shown with a logarithmic fit for consistency with FL903. The grey areas displayed on Figure 11(a) show when artificial hydration was not occurring. As the Lasgit equipment aged beyond its designed operation lifetime, failures of the air actuated valve system in the Lasgit gas laboratory increased. The on/off nature of artificial hydration was making interpretation of data difficult, and it was decided to stop artificial hydration at Day 3745.

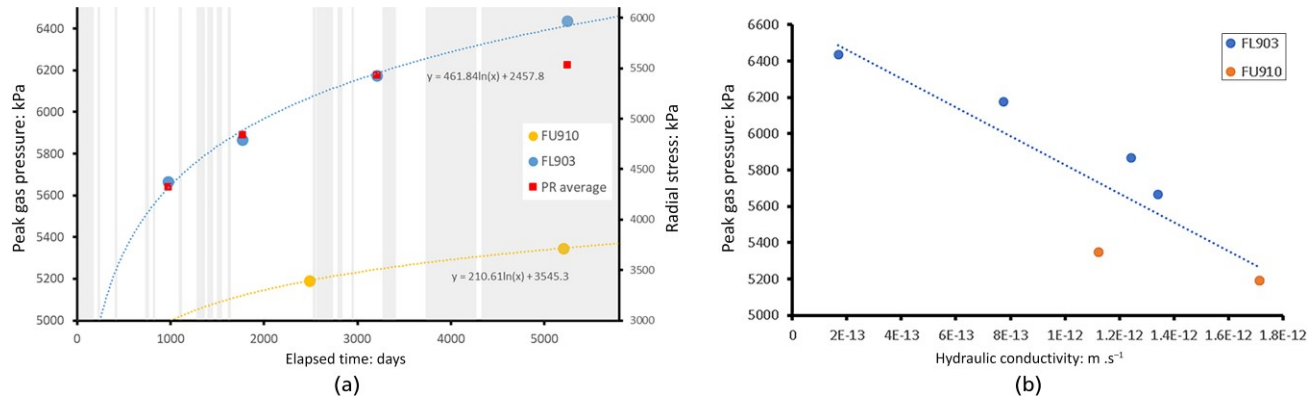


Figure 11. Gas peak pressure evolution for six gas injection tests in Lasgit: (a) evolution with time. The grey regions show when the system was not artificially hydrated; (b) the relationship between gas peak pressure and hydraulic conductivity

This had a direct influence on the evolution of pore pressure and radial stress in the system (see Cuss *et al.*, 2022), with many sensors reaching plateau as a result.

Filter FL903 was located on Section 5 (Figure 1) with UR909 directly opposite and between radial stress sensors PR908 and PR909. The average of radial stress sensors PR908 and PR909 is displayed in Figure 11(a). This clearly shows that radial stress near to FL903 increased in a manner like gas entry pressure. However, it had reached a plateau because of the cessation of artificial hydration, yet peak gas pressure continued to increase. It appears that peak gas pressure was independent of this boundary condition. Figure 11(b) shows the relationship between hydraulic conductivity determined from two-stage constant head tests (Cuss *et al.*, 2022) with peak gas pressure. This suggests that peak gas pressure scales with hydraulic conductivity and as the buffer evolved, peak pressure increased as hydraulic conductivity reduced. This isn't surprising as both hydraulic and gas properties will be dependent on the swelling of the buffer and the geometry of the pore network, and as the buffer matured, water and gas flow would become more difficult. The progress of hydraulic properties appears independent of, or at most affected only very slightly by the ending of artificial hydration.

Previously, it had been suggested that stress was the primary controller of gas peak pressure (Graham *et al.*, 2016; Cuss *et al.*, 2014; Levasseur *et al.*, 2021, 2024). Figure 12 shows the relationship between gas peak pressure and stress for the tests in Lasgit and for laboratory tests reported in Graham *et al.* (2016). The dashed line represents when stress on the canister equals gas peak

pressure. One test in FU910 and the Full Canister Test (Cuss *et al.*, 2026) were close to this condition. However, most tests in FL903 occurred at a pressure up to 600 kPa above local stress. This may be because of inaccurate estimates of stress at the filter but may represent a need for a slight excess pressure to cause peak conditions. It should be noted that gas peak pressure was not below local stress, highlighting that the anticipated variability in physical properties of the bentonite at the full-scale did not result in weaknesses that gas could exploit. Also, gas peak pressure was not significantly above local stress, as had been seen in a limited number of laboratory-scale experiments (Cuss *et al.*, 2022). Therefore, stress was the primary control on gas migration, with hydraulic conductivity evolution a secondary control. Hydraulic conductivity is a proxy for the maturity of the buffer. Hydraulic conductivity was continuing to decrease even though post-test geotechnics showed that the average saturation of the buffer was 0.999 (Cuss *et al.*, 2022). Therefore, while stress, pore pressure, and buffer saturation in the system appeared to have stabilised, hydraulic behaviour had not equilibrated. This requires further experimentation to determine the exact controls of gas peak pressure.

Conceptual model of gas flow

The following conceptual model of gas movement has been devised from all observations from the gas injection tests in Lasgit, laboratory tests (e.g. Graham *et al.*, 2016; Graham & Harrington, 2024), and analogue visualisation tests (Jacobs & Kolditz, 2024). In an unsaturated or partially saturated bentonite there is a linear dependence between gas flow rate and pressure gradient, which indicates that two-phase flow would be the

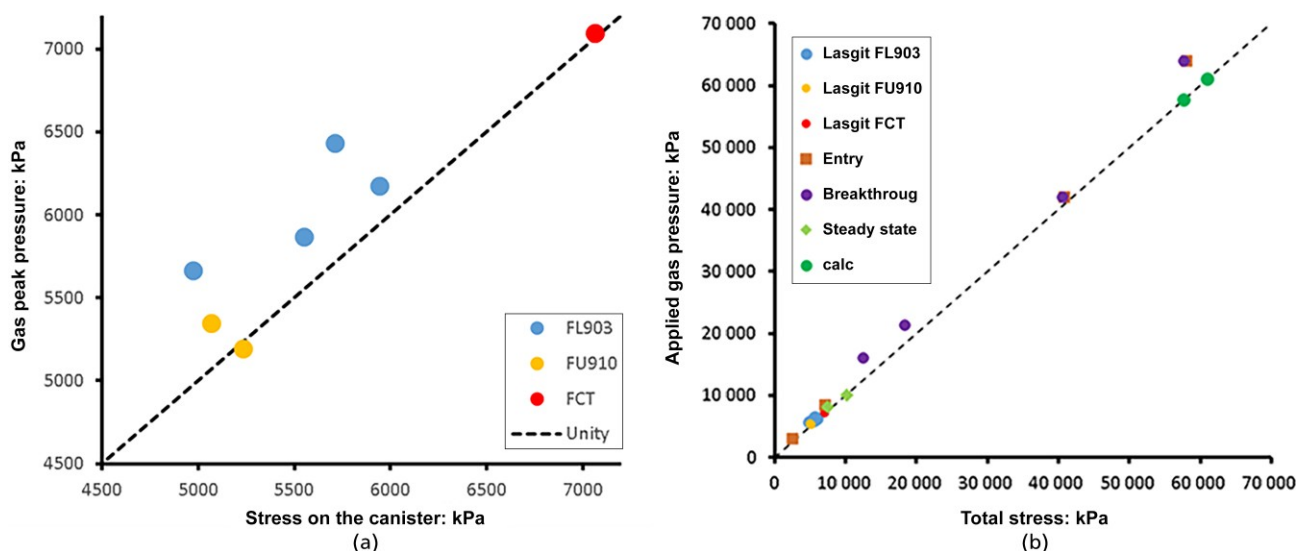


Figure 12. The relationship between gas peak pressure and radial stress on the canister for all gas injection tests in Lasgit: (a) data from Lasgit; (b) compilation of data from tests in bentonite, adapted from Graham *et al.* (2016)

dominating transport mechanism (Villar *et al.*, 2012). At a degree of saturation of $\sim 80\%$ – 90% or higher the behaviour changes entirely (Graham *et al.*, 2002; Villar *et al.*, 2012; FORGE, 2014). No advection of gas will take place in the bentonite unless the applied pressure is equal to or higher than the total stress. The only transport mechanism is the omnipresent diffusion of dissolved gas and the movement of dissolved gas by advection under the prevailing hydraulic gradient. If the gas pressure reaches a higher value than the total stress within the bentonite, a mechanical interaction will occur (Birgersson *et al.*, 2008; Graham *et al.*, 2012). This will lead to either (1) consolidation of the bentonite, and/or 2) formation of dilatant pathways. When the pressure reaches this value, a transport pathway is formed through the buffer and gas is released. Laboratory results (e.g. Horseman *et al.*, 1999; Harrington & Horseman, 1999, 2003; Graham *et al.*, 2012; Harrington *et al.*, 2017; Harrington *et al.*, 2019) suggest a system of microfractures is formed due to rupturing of the clay. Gas pressure then falls and the gas production rate determines the further course of events. If the pressure falls to a sufficiently low value, the transport pathway(s) begin to close.

The interface between the canister and buffer played an integral role in gas movement (Figure 13). In several gas injection tests, the gas reached isolated points within the deposition hole (various sensors/filters). In GT2 gas moved 180° around the canister surface from filter FL903 to FL901 while no pressure change was

observed in filters FL902 or FL904. This demonstrated that the entire interface was not conductive and that the engineering gap present at the start of the test had closed and self-sealed. Geotechnical analysis of the buffer during decommissioning (Cuss *et al.*, 2022) showed that the dry density of the buffer did reduce towards the canister, which means that gas migration will be easier in the interface between the canister and the buffer. Rutqvist (2025) modelled GT4 as part of the DECOVALEX-2023 project. It was necessary to include a zone close to the canister to reproduce the response seen, similar to the conceptual model shown in Figure 13 including modified gas transport parameters along the interface between blocks. It is possible that gas entered the buffer. However, it is unlikely that while migrating within the buffer that it managed to intercept FL901 on the opposite side of the canister. Therefore, it is suggested that localised gas pathways formed that moved around the canister surface intercepting a limited number of sensors. This is consistent with Gutiérrez-Rodrigo *et al.* (2021), who showed preferential channels can form along interfaces or heterogeneities where conditions differ slightly from the surrounding matrix in experiments performed in FEBEX bentonite, with localised gas flow episodes (instantaneous or gradual) occur along small-diameter stable pathways.

In test GT3, the gas injection stage was prolonged. This showed that movement occurred on multiple pathways. A single pathway could not have seen the pressurisation of sensors over a series of

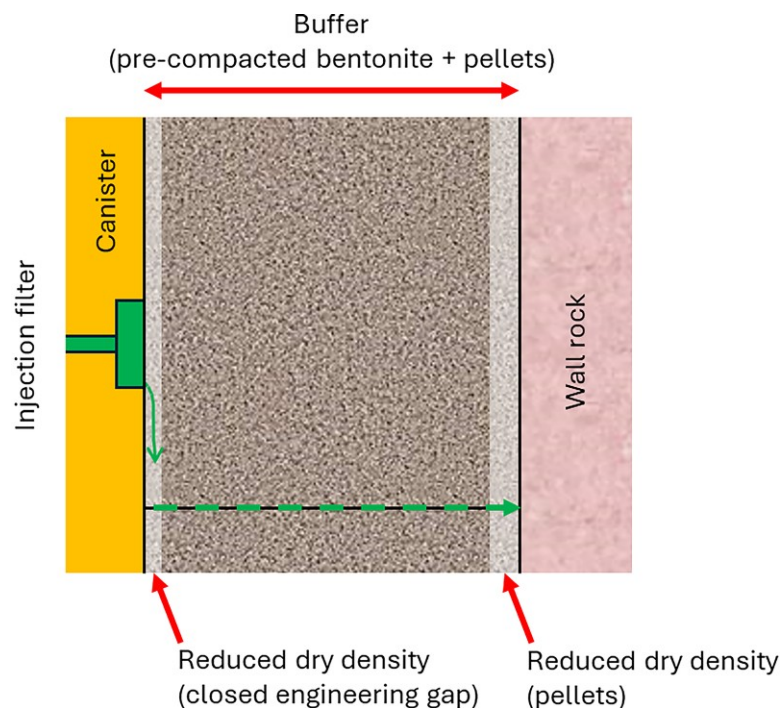


Figure 13. Sketch showing inferred gas pathway along the low-density zone formed as a result of the closure of the engineered gap. See text for full description

pressure increase events. Therefore, multiple pathways were forming at the same time, even once a dominant pathway had formed allowing gas to exit the deposition hole. Test GT3 also showed behaviour of episodic flow. Many sensors increased to the gas injection pressure through a series of pressure increases. This shows that the pathways that formed were not continuously open, and that gas movement was like the propagation of bubbles. This may suggest that pathways became unstable as they grew, that is as they lengthened there wasn't sufficient energy to keep the pathway open. Therefore, pathways were not simple tensile fractures in the bentonite.

In most tests it was evident that gas had found a way out of the deposition hole, most notably GT2 when the injection of neon was detected in the near-by pressure-relief holes (Cuss *et al.*, 2011). Localised pathway movement to various sensors and geotechnical properties (Cuss *et al.*, 2022) suggests that the interface between the canister and buffer was exploited as the interface was likely to have properties favourable to gas movement compared with the internal body of each bentonite block/ring. Gas will always exploit regions of the buffer that are easiest for gas flow, with lower dry-density bentonite having a lower gas entry pressure (e.g. Gutiérrez-Rodrigo *et al.*, 2015). It would be difficult for gas to leave the low-density interface zone and enter the higher-density buffer to propagate to the deposition hole wall. Therefore, it was interpreted that gas probably moved along the interface between two blocks/rings in the deposition hole. However, the interfaces between blocks would also have better access to water, making these zones a better gas seal because of raised swelling pressures.

Figure 14 shows a conceptual model of gas pathway formation that incorporates the observation above. (1) Dilatant pathways form from the injection filter. As the pathway grows, it branches to form two distinct pathways (2). These grow at different rates (3) and certain pathways can become unstable and stop growing

(4). This promotes other pathways, that may also branch as the grow creating more pathways. A dominant pathway may form (5), which dependent on variable buffer properties, may become unstable and stop growing. The elastic energy of the clay surrounding the pathway results in partial closure of the unstable pathway, creating an isolated pocket of gas (6). Continued gas injection results in new pathway growth (7), until a time when the closed section of gas pathway re-opens (8). Pathways continue to grow until an exit from the system is found (9), relieving gas pressure in some pathways and resulting in isolated pockets of gas once more.

Conclusions

Several conclusions can be made from the six gas injection tests conducted in the Lasgit experiment:

1. The primary control of gas peak pressure was local stress, with gas peak pressure not being less than total stress and being a maximum of 600 kPa above. This indicates that very little or no consolidation of the clay occurs during the pressure build-up.
2. A secondary control on gas peak pressure was the maturity of the buffer (hydraulic conductivity), which was linked to the development of stress. The ending of artificial hydration resulted in stresses in the system being reduced, yet gas peak pressure continued to increase. The buffer continued to mature even though stress had reduced. As hydraulic conductivity decreased with time, gas peak pressure increased.
3. The first test conducted in FL903 showed pre-cursor flow, which was not seen in subsequent tests. Pre-cursor flow is likely to have resulted from the buffer not being fully water saturated. Most tests in FL903 saw one or more spikes in flow, showing that pathway formation was progressing in stages. After the short-lived spike in flow, the flow into the buffer decreased to be lower than the flow into the system and pressure started to increase. This continued until a secondary peak in pressure was seen and the flow into the buffer was then marginally greater than flow into the system and pressure slowly decreased. A similar flow response was seen at FU910.

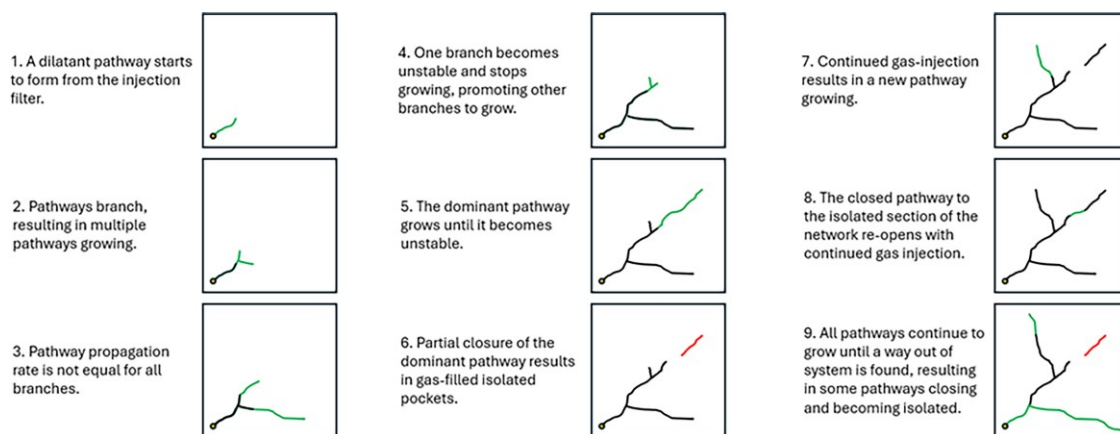


Figure 14. Conceptual model of gas flow. See text for full description

4. Localised flow paths were observed, as inferred from pore water pressure, radial stress changes, and the migration of gas to induvial sensor locations. This showed that gas moved down the deposition hole as dictated by the stress field, most probably within a zone of lower dry-density bentonite formed by the closure of the buffer rings early in the test close to the buffer/canister interface. Gas found a passage out of the deposition hole, possibly along a zone of locally reduced dry density caused by the interfaces between blocks.
5. Subsequent gas injection testing re-opened sealed pathways from previous tests. Not all pathways were re-activated and new pathways did form. Therefore, pathway sealing is variable and may be related to the limited time between gas injection tests.
6. The growth of pathways was transient. A conceptual model has been described where multiple pathways form, with some growing faster than others. As pathways become unstable, other pathways become dominant and grow until a pathway escaping the deposition hole is created.
7. Gas movement did not weaken the KBS-3 engineered barrier system, with gas release being controlled at a pressure close to the local stress.

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