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The role of gas volume on the advective movement of gas through an engineered barrier system

Robert J. Cuss

British Geological Survey (BGS), London, UK (corresponding author: rjcu@bgs.ac.uk)

Jon F. Harrington

British Geological Survey (BGS), London, UK

Patrik Sellin

Svensk Kärnbränslehantering AB (SKB), Stockholm, Sweden

Matti Nord

Svensk Kärnbränslehantering AB (SKB), Stockholm, Sweden

The final experiment (full canister test, FCT) of the large-scale gas injection test (LASGIT) aimed to explore the impact of gas volume on gas transport behaviour. Unlike previous tests, the FCT involved pressurising a full-scale KBS-3 canister up to ~7100 kPa when pressure was held, allowing excess water to drain and to establish gas entry. Once drained, pressure gradually decreased by 220 kPa, indicating gas moving into the fully saturated clay buffer. Observations showed different pore pressure and total stress behaviour compared with earlier tests, but no major changes were seen in the buffer's response, suggesting gas migration was unaffected by gas volume. The slow pressure decay shows gas travelled through a limited number of narrow pathways, which were not formed through tensile fracturing. A gas leak early in the FCT led to depressurisation and later pressurisation of the canister, causing a 50 μm expansion in its radius. This mechanical loading on the buffer, greater than the bentonite's drainage capacity, caused pore pressure and radial stress changes. The expansion of the canister by pressurisation or thermal effects should therefore be considered in performance assessments.

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

Notation

K_w	bulk modulus of water
P	pressure
P_s	starting gas pressure
V	volume
V_p	pathway volume
V_s	starting volume of gas
V_w	volume of water surrounding the canister
ΔP_c	change in canister pressure
ΔP_e	change in gas pressure since entry
ΔV	change in volume

Introduction

In the Swedish KBS-3 (Kärnbränslesäkerhet version 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 (Figure 1(a)). Pre-compacted bentonite blocks (Figure 1(b)) will surround the canister, swelling in the presence of groundwater, filling construction gaps, and creating stress within the deposition hole. Bentonite pellets will be used between the deposition hole and the outer diameter of the bentonite blocks, while the gap between the canister and the bentonite blocks will be closed by the swelling of the bentonite blocks (Figure 1(b)). Once hydrated, the buffer (bentonite blocks and pellets) will act as a low-

permeability diffusional barrier, severely limiting the migration of any radionuclides released from the canister after closure of the repository. Should groundwater penetrate the canister through some form of defect, the anoxic corrosion of the ferrous insert will lead to the formation of hydrogen, with additional gas generated by radiolysis of the water. If the rate of gas generation is higher than the diffusive properties of the buffer, it is possible that gas will accumulate in the void spaces of the canister (Horseman, 1996; Horseman *et al.*, 1997, 1999; Ortiz *et al.*, 2002; SKB, 2011; Wikramaratna *et al.*, 1993; Weetjens and Sillen, 2006). Laboratory experiments performed prior to the start of Lasgit showed that gas would enter the buffer at a critical gas pressure related to the specific conditions of the bentonite (Harrington and Horseman, 2003). This has been confirmed in the laboratory during the lifetime of the Lasgit experiment (e.g. Graham *et al.*, 2016). While laboratory experiments increased our understanding of buffer performance, several uncertainties were identified (Horseman *et al.*, 2004), notably the sensitivity of the gas migration process to experimental boundary conditions and possible scale dependency of the measured responses. It was therefore decided that a full-scale KBS-3 demonstration was necessary, and so Lasgit was devised (Sellin and Harrington, 2006).

Several field-scale experiments have been conducted examining specific aspects of advective gas migration in clay-rich host rocks

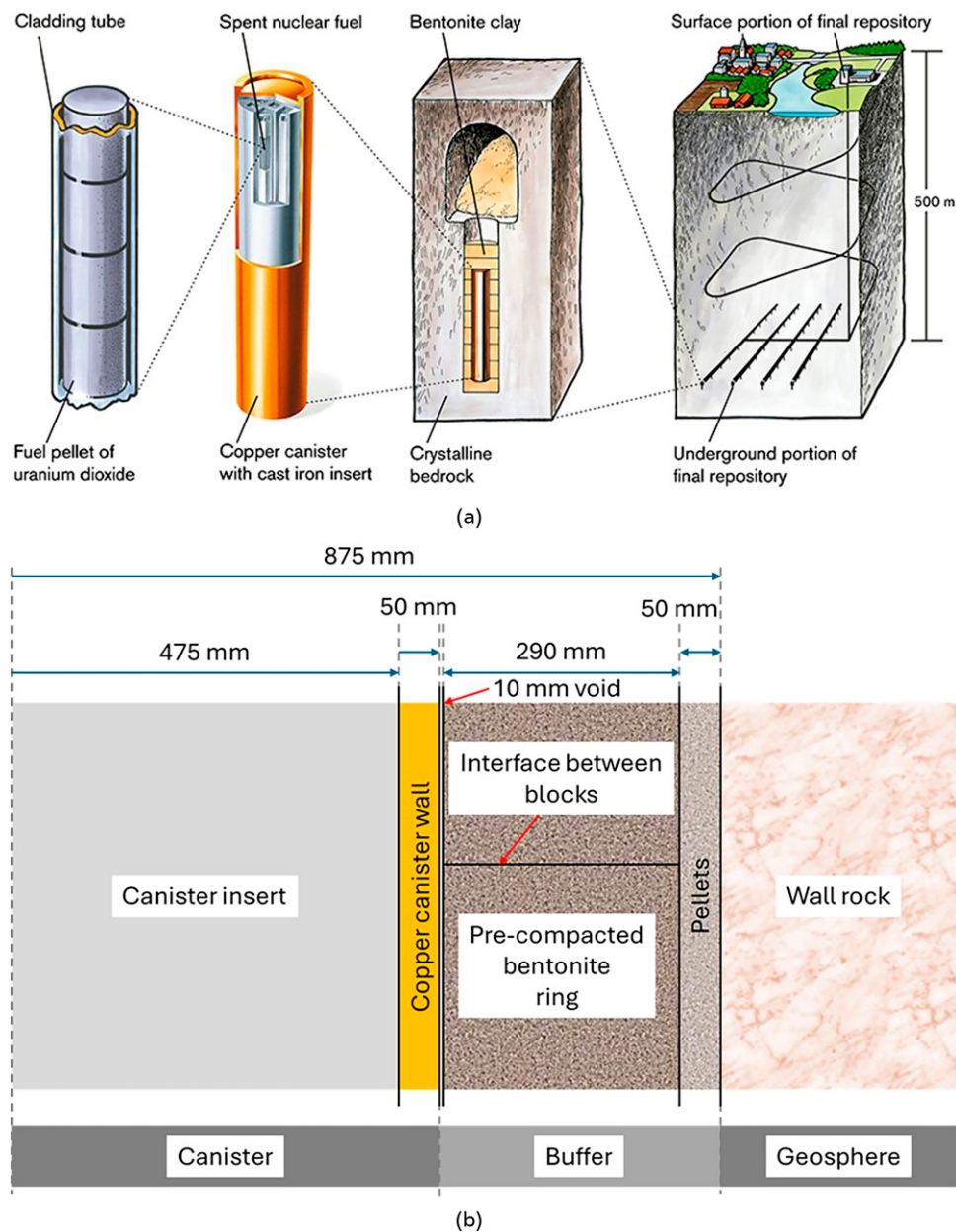


Figure 1. The KBS-3 disposal concept. (a) Diagram of the disposal system from fuel pellet up to the deep geological repository. (b) Cross-section sketch through the Lasgit deposition hole showing the canister, engineered void, pre-compacted bentonite ring, pellets, and wall rock. The bentonite ring and pellets make up the buffer, isolating the canister from the geosphere

and barriers. At the Mont Terri underground research laboratory (URL) in Switzerland, the GP/GS (Marschall *et al.*, 2003, 2005), HG-A (Lanyon *et al.*, 2009), HG-B (Xu *et al.*, 2013), and GT (Zhang, 2024) experiments have examined gas transport issues in Opalinus Clay. At the Meuse/Haute-Marne URL in France, the PGZ (de La Vaissiere *et al.*, 2014) and GTPT (Senger *et al.*, 2006) experiments examined gas transport in Callovo-Oxfordian claystone. At the Hades URL in Belgium, the MEGAS E4/E5

(Volckaert *et al.*, 1995), RESEAL (Van Geet *et al.*, 2009), and BACCHUS 2 (Jacops *et al.*, 2023) experiments examined advective gas transport in Boom Clay. Few gas tests have been conducted on bentonite seals at the field scale. The RESEAL experiment looked at advective gas movement of bentonite blocks used to seal Boom Clay (Van Geet *et al.*, 2007), while the GAST experiment (Teodori *et al.*, 2013) at the Grimsel Test Site in Switzerland looks at gas movement in sand/bentonite mixtures used as tunnel backfill. Therefore, Lasgit

is a unique experiment looking at corrosion-derived advective gas movement in a bentonite buffer.

Lasgit was a full-scale demonstration experiment operated by Svensk Kärnbränslehantering AB (SKB) at the Äspö Hard Rock Laboratory (HRL) at a depth of 420 m. The installation phase was undertaken from 2003 to early 2005, with the experiment starting on 1 February 2005. The experiment logged data for a total of 5782 days (15.8 years) and was decommissioned by mid-February 2021 (Cuss *et al.*, 2022).

The original aim of the Lasgit experiment was to perform a series of gas injection tests through water-saturated clay 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 first six gas injection tests have been reported previously (Cuss *et al.*, 2011, 2014, 2022, 2026). Modelling has been performed on one of the gas injection tests (GT4) as part of the DECOVALEX-23 project (Radeisen *et al.*, 2023; Rutqvist, 2025; Noghretab *et al.*, 2024; Tamayo-Mas *et al.*, 2025) to better understand the physics of advective gas flow in the KBS-3 disposal concept.

In this paper, we introduce the final gas injection test, the full canister test (FCT). One specific aim of the experiment was to investigate the role played by the upstream volume of gas on the performance of the barrier. The first six gas injection tests used a limited volume of gas, utilising a 5-litre gas/water interface vessel. This limited volume meant that at gas entry, a pressure drop was seen as a network of pathways was formed. The volume of this pathway network compared with the total volume of gas was sufficient to result in a pressure decrease. If the volume of injected gas was much larger and the same volume of pathway network was formed, no pressure decrease would occur. By using the void space of the canister ($>1\text{ m}^3$), it would be possible to see if any changes in gas flow occurred if a larger volume of gas existed. One possible scenario would be a run-away process that could result in damage to the buffer system. Therefore, the FCT directly addressed this issue.

Experimental setup

The Lasgit experiment (Table 1) consisted of three operational phases: an installation phase, a hydration phase, and a gas injection phase. The initial hydration phase began on 1 February 2005 with the closure of the deposition hole. The primary aim of this phase was to fully saturate and equilibrate the buffer. A series of detailed gas injection tests was then planned to follow.

Experimental geometry

The Lasgit experiment was commissioned in deposition hole DA3147G01, which was the first deposition hole to be drilled at the Äspö HRL. The deposition hole was vertical, with a length of 8.5 m and a diameter of $\sim 1.75\text{ m}$. Prior to the emplacement of Lasgit, the deposition hole was fully mapped (see Cuss *et al.*, 2022). A full-scale

Table 1. List of test stages during the complete test history of Lasgit

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+

KBS-3 copper canister with an iron insert was modified for the Lasgit experiment with 12 circular filters of varying dimensions located on its surface in three separate arrays (see Figure 2) to provide point sources for gas injection simulating potential canister defects. The 12 filters could also be used to inject water during the hydration stages to help locally saturate the buffer around each test filter. High water saturations in bentonite $>95\%$ can take a considerable time to achieve in field-scale tests (Huertas *et al.*, 2005). Therefore, filter mats were placed in strategic positions both within the buffer and on the rock wall to aid hydration. The FCT was conducted using an additional filter (the FCT filter) at the base of the canister (Figures 2 and 3(a)). This comprised an air-actuated valve in contact with a sintered disc on the surface of the canister. The canister was surrounded by specially manufactured pre-compacted Mx-80 (Johannesson, 2003) bentonite blocks, all of which had initial water saturations $>95\%$ (Cuss *et al.*, 2022). Bulk density of the blocks ranged between 2018 and $2061\text{ kg}\cdot\text{m}^{-3}$, achieving a predicted swelling pressure of between 3970 and 4368 kPa within the Lasgit depositional hole. Bentonite pellets manufactured by Saut-Concreursin in France were used in the engineering void between the pre-compacted bentonite rings and the rock wall. Each pellet was pressed from bentonite and had dimensions of $16.3 \times 16.3\text{ mm} \times 8.3\text{ mm}$, a water content of about 17%, and an expected density of a single pellet of about $2050\text{ kg}\cdot\text{m}^{-3}$. As the bentonite system began to saturate, these swelled to fill the construction gaps and form 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 of force.

The deposition hole, buffer, and canister were equipped with instrumentation to measure the total stress (PR, PB, and PC), pore water pressure (UR and UB), and relative humidity (WR) in 32, 26, and 7 positions, respectively (see Figure 2). 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, air-conditioned gas laboratory that allowed

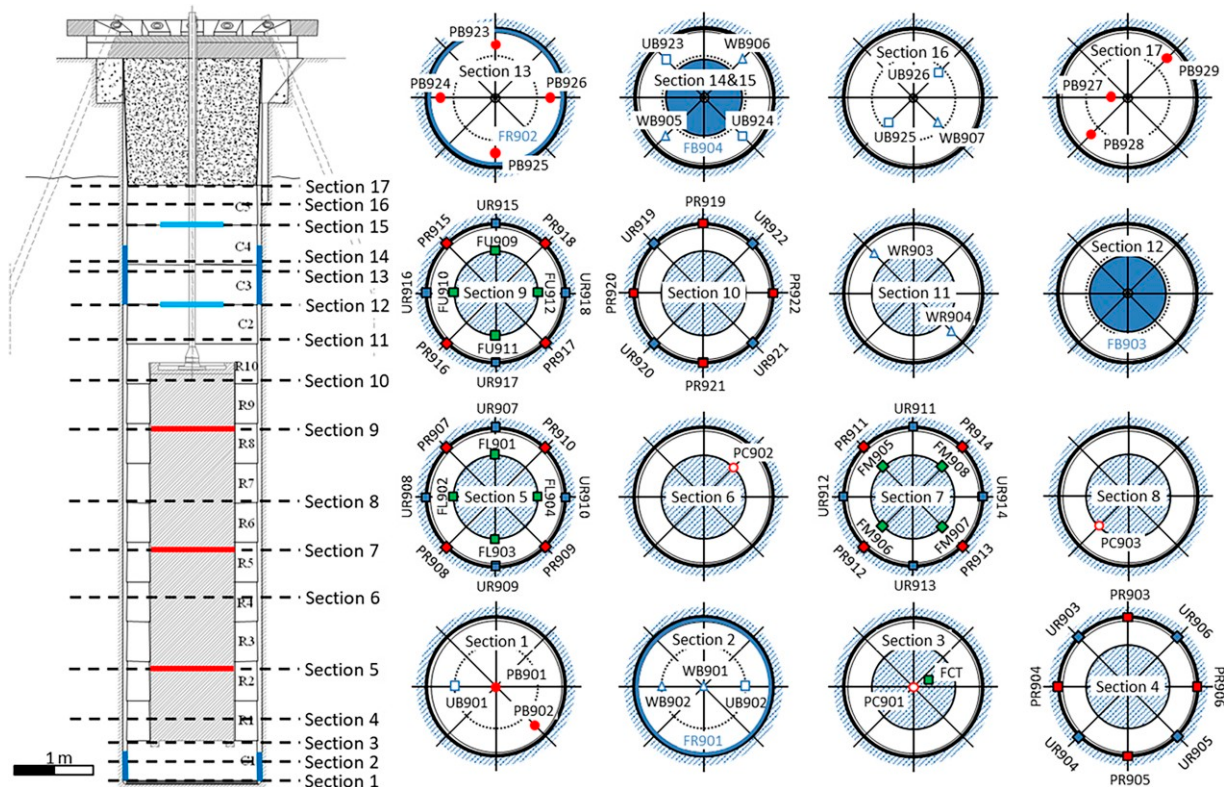


Figure 2. Location of all sensors at 17 intervals in the deposition hole. Note: FCT, full canister test filter; PC, total stress sensor on canister surface; PR, total stress sensor at rock wall; PB, total stress sensor within the buffer; UR, pore water pressure at the rock wall; UB, pore water pressure within the buffer; WR, relative humidity; FB, filter mat between bentonite segments; FR, filter mat at the rock wall; Can, position of the canister. See Cuss *et al.* (2022) for a detailed map of sensor locations

remote control and monitoring of the test. All sensors were calibrated prior to emplacement within the deposition hole, with all sensors having additional thermocouples allowing temperature compensation.

The boundary conditions of the experiment were those dictated by the pressures and stresses built up naturally within the bentonite buffer during rehydration. The canister lid had been pre-stressed to 1300 kN to impose a similar force comparable with that which would be generated by the backfill placed within the gallery above each deposition hole in a geological disposal facility. The experiment was conducted at ambient temperatures, which did not vary significantly during the FCT. The full test history is summarised in Table 1.

To conduct the FCT, several modifications were needed to the existing Lasgit laboratory. (i) A large supply of gas was needed, and this was achieved by adding a pallet of 12 cylinders of nitrogen to the system (see Figure 3(b)). This was a sufficient volume of gas to raise the pressure in the canister more than 20 MPa, beyond the expected gas entry pressure. (ii) A reliable supply of water was needed to use the existing interface vessels to get an accurate estimate of gas pumped into the canister. (iii) An

additional pressure sensor in the interface vessel circuit to measure the pressure of the interface vessels. (iv) Re-plumbing of the system to facilitate the test, giving interface vessels with a total volume of 10 litres. (v) The addition of two one-way valves to add safety in the Lasgit laboratory.

Experimental procedure

The following describes how the FCT was conducted:

- The gas supply was used to directly fill the canister to a starting pressure of around 5000 kPa; this took nearly 24 h, as filling was slow, being limited by the small diameter of the pressure lines.
- The interface vessels were drained using the remaining volume of gas within. It took around 20–25 min to drain the interface vessel, depending on the pressure and volume of the remaining gas.
- The interface vessel was then fully filled with gas; the pressure was monitored so that it was approximately equal to the pressure in the canister.
- The interface vessel valve was opened, reconnecting the interface vessel with the canister. The pressure of the interface vessel and canister was noted.

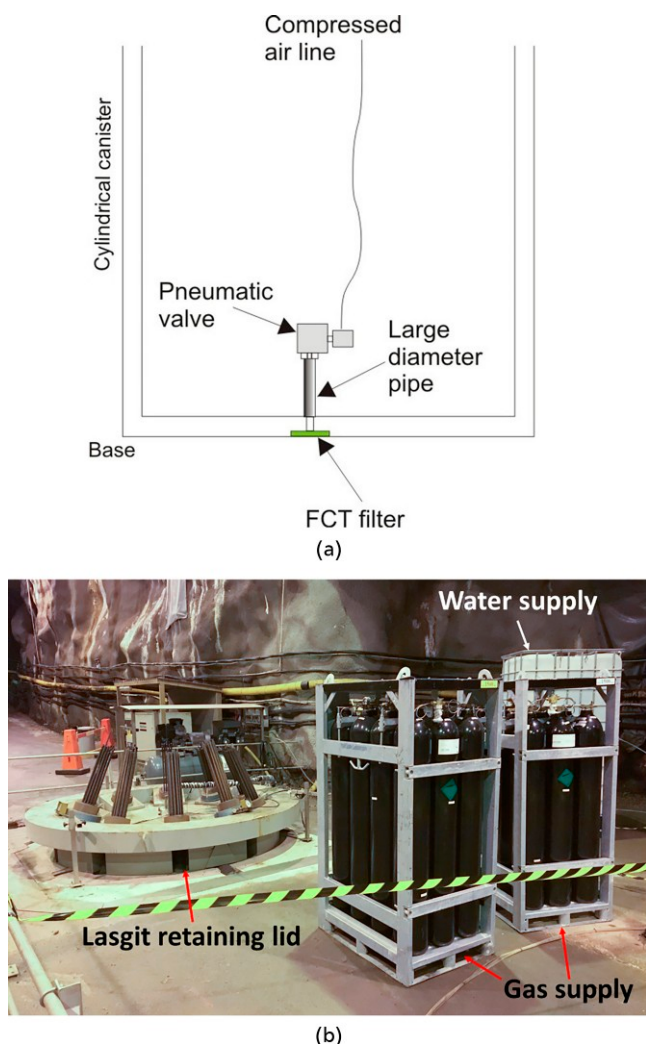


Figure 3. The full canister test arrangement. (a) Schematic diagram showing the filter assembly located in the base of the canister, and (b) the addition of a pallet of 12 gas cylinders of nitrogen and a water bowser was necessary to perform the full canister test

- The syringe pumps (Teledyne/ISCO 500D) were started in reciprocating mode, pumping water into the base of the interface vessels at a constant rate. A total of 20 refills of the pumps were needed to fully empty the interface vessels of gas, as each pump's volume was 0.5 litres.
- The procedure was repeated by performing Stages 2–5. For each refill procedure, the total volume of water pumped into the interface vessel was calculated.

The procedure was timed so that refilling occurred at 12–24 h intervals, as the refill process required manual operation of the experiment using remote access to the logging PC. Most refills occurred on a 12-h interval. Throughout the pressure ramp, a total of 55 refills were performed.

It was necessary to reduce the pressure of the canister at the end of the experiment in a controlled and safe manner. This was done in a similar way to filling. The interface vessels were filled with gas from the canister and isolated, allowing 10 litres of pressurised gas to be drained over a 15–50 min interval, depending on the pressure of the canister. It took 55 emptying cycles until the pressure was such that the remaining volume of gas could be directly vented.

Results

Initial canister pressurisation

The boundary conditions of the FCT were substantially modified by the pressurisation of the canister. This was compounded by a leak, which resulted in a second fill of the canister. Figure 4 shows the initial pressurisation of the canister during the site visit on Day 5266 (Event 1, Figure 4). The filling of the canister directly from the pallet of gas cylinders was controlled by a regulator. As shown, it took around 5 h before a stable fill was established, and the system was left to fill overnight. It took nearly 24 h to bring the pressure in the canister up to the starting pressure of ~5000 kPa. The system was left with the canister in direct communication with the gas supply and was left to equilibrate. Following the lab visit and filling of the canister, local staff of the Äspö HRL inspected the system on Day 5268. This showed that the cylinder side of the regulator on the cylinder pallet had significantly reduced in pressure over the weekend, that is, the volume of gas in the pallet was significantly reduced. The canister was isolated at Day 5268.56 (Event 1a, Figure 4) to observe pressure. It was expected that an initial loss of pressure would happen as the gas cooled in the canister and as the gas went into solution with the available water in the system. However, pressure was reducing at 10 kPa/h, which was significant. The gas supply was re-established to the canister at Day 5269.14 (Event 1b, Figure 4) to see if re-pressurisation would change the rate of pressure decay. The canister was isolated for a second time at Day 5269.44 (Event 1c, Figure 4), this time giving a pressure reduction rate of around 7 kPa/h. This was lower than the previous but still a substantial rate, confirming the presence of a leak in the system.

A site visit on Day 5277 (Event 2, Figure 4) quickly established that the leak was not occurring within the Lasgit laboratory, meaning that it was either occurring in the pressure line to the canister or from one or more of the connections to the canister. It was established that the cable leading to the canister stress sensors was pressure sealed and that one of these was a source of leaking gas, as detected by a leak solution with a slow but steady release of gas. It was decided to sever all three stress sensor cables and to pressure seal the lines transporting the cables. Unfortunately, cutting the cables greatly increased the rate of gas flow with a high-pressure discharge of gas that was too high to cap in a safe manner. Therefore, gas was allowed to drain from the canister until it was safe to cap the lines. This resulted in a reduction in canister pressure to ~750 kPa before the lines were capped and sealed.

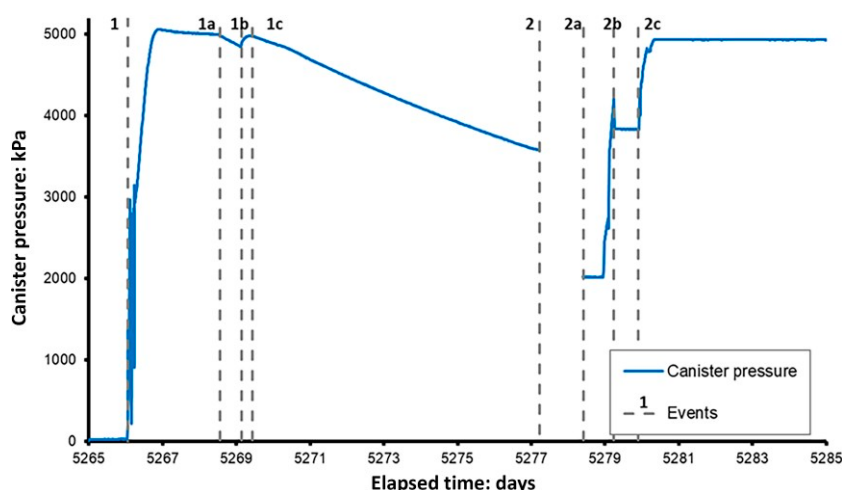


Figure 4. Pressure of the canister during the initial pressurisation, showing the leak in pressure and the re-establishment of canister pressure

Pressure monitoring at Day 5277.96 showed that the canister pressure was no longer reducing and that the leak was sealed, assuming that it was not a pressure-dependent feature. The amount of gas lost from the system was sufficient to mean that not enough gas was available in the gas pallet to enable a full gas ramp. Therefore, a second pallet was added.

The canister was refilled from the cylinder pallet carefully to make sure the canister was leak-tight. Initially, gas pressure was raised to ~ 2000 kPa on Day 5278 (Event 2a, Figure 4) to determine the leakage rate, which was found to be negligible. Pressure was increased to ~ 4000 kPa at Day 5279.24 (Event 2b, Figure 4) and finally 4950 kPa at Day 5279.90 (Event 2c, Figure 4), with no leaks detected. Therefore, the experiment could progress, and the system was set up to allow a gas ramp to occur.

In establishing a leak-tight pressurised system, the canister was pressurised, slowly depressurised, rapidly depressurised, and then re-pressurised in steps. Figure 5 shows that this complex history had a profound impact on the entire Lasgit system. The change in radial stress (PR) is shown in Figure 5(a). The initial pressurisation of the canister resulted in an increase in all PR sensors. The change ranged between 344 and 675 kPa, with PR912 showing the greatest change and PR904 showing the least. Radial stress increased while the canister was being pressurised, and once the canister had reached pressure, the radial stresses started to decay. By the time of lowering the pressure in the canister at Day 5277.36 (Event 2, Figure 4), the increase in stress because of pressurisation had decayed to a range between 21 and 145 kPa.

Figure 5(b) shows the change in pore pressure at the deposition hole wall (UR) because of canister pressurisation. This shows that the pressurisation of the canister had a profound influence on all UR sensors. However, unlike in the PR sensors, there were

differences in the general form of the change. Some sensors, such as UR910, reacted very quickly to the pressurisation, while others, such as UR921, took much more time to react or reacted more gradually. At the end of initial pressurisation, the UR sensors changed between 6 and 814 kPa, with UR910 showing the greatest change and UR919 showing the least. Prior to the depressurisation of the canister (Event 2, Figure 4), the change in pore pressure had decayed to a range between -70 and 463 kPa.

The sensors all showed considerable change when the pressure in the canister was reduced to fix the leaking canister (Event 2, Figure 4). Figure 5 shows that all sensors greatly decreased in reading at this time. For both radial stress and pore pressure, most sensors reduced considerably to be lower than when the canister was first pressurised. The only exceptions were UR907 and UR910, which were still at an elevated level. Re-pressurisation then increased pore pressure and stress, although not to the same magnitude as during the initial pressurisation.

Figure 5(c) compares the average change in pore pressure and radial stress at the deposition hole wall. In general, the two compare well, with pore pressure showing a lower magnitude change. There were differences when the canister was re-pressurised in steps.

Figure 6(a) shows the distribution of the change in radial stress distribution because of canister pressurisation. It shows that the greatest increase occurred at the mid-height of the canister, while the least change occurred at the top and the bottom of the sensor array. This was not unexpected, as the greatest mechanical deformation of the canister will have occurred at its centre (barrelling). Figure 6(b) shows the change in stress when the canister was depressurised. This shows the inverse of pressurisation, with the centre decreasing the most and the top and bottom of the array showing only a minor reduction in stress compared with the

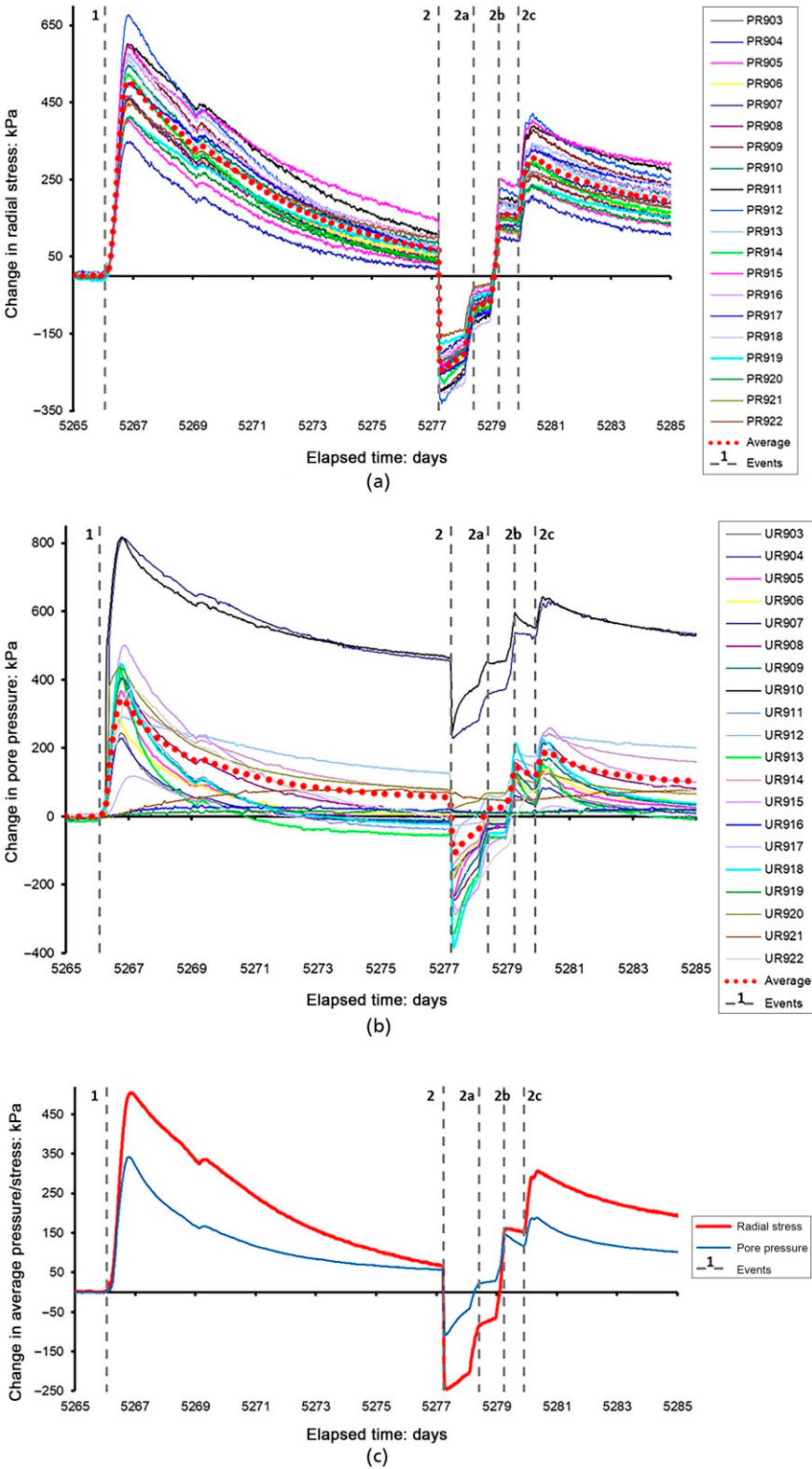


Figure 5. Change in stress and pore pressure at the deposition hole normalised to Day 5266.00. (a) radial stress, (b) pore pressure, and (c) average change

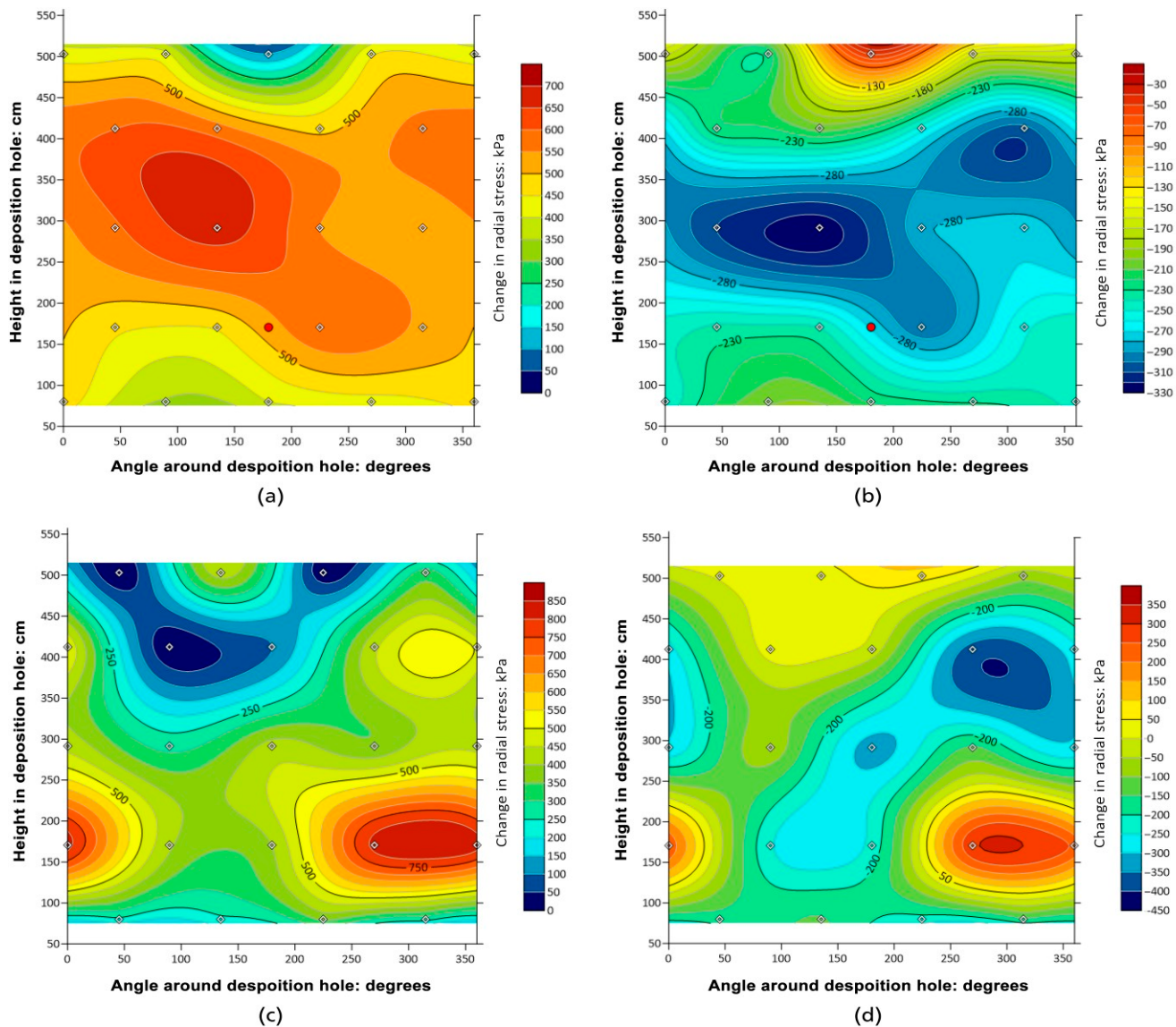


Figure 6. Change in stress and pore pressure distribution because of initial canister pressurisation. (a) Radial stress change during pressurisation (Day 5266.81), (b) radial stress change during depressurisation (Day 5277.36), (c) pore pressure change during pressurisation (Day 5266.81), and (d) pore pressure change during depressurisation (Day 5277.36)

starting condition. Figure 6(c) shows the distribution of the change of pore pressure at the end of initial pressurisation. This shows an increase in pore pressure towards the bottom of the canister and the least change towards the top of the sensor array. When the canister was depressurised (Figure 6(d)), the largest reduction occurred towards the top of the canister, with the high-pressure region that formed at the base of the canister still prevailing.

The behaviour seen can be explained by the drainage characteristics of the buffer. The expansion of the canister in response to internal pressurisation was estimated from the pressure change

(~500 kPa) and the compressibility of water. Assuming no water drained from the buffer during expansion, the change in volume of the canister can be estimated from Equation 1:

$$1. \quad \Delta V = \frac{\Delta P_c}{K_w} \times V_w$$

where ΔV is the change in volume, ΔP_c is the change in canister pressure, K_w is the bulk modulus of water (2.2 GPa), and V_w is the volume of water surrounding the canister, assuming a porosity of

45% (3.46 m^3). This gives a change in volume of $7.87 \times 10^{-4} \text{ m}^3$, or an expansion of the canister in the radial direction of $4.77 \times 10^{-5} \text{ m}$ ($\sim 50 \mu\text{m}$). Soils, including Mx-80 bentonite, are influenced by the strain rate that they are subjected to (Zhang *et al.*, 2025). The mechanical loading of the buffer was at such a rate that it could not drain and, therefore, started to react as an undrained medium. This raised pore pressure as the pore network contracted. Radial stress increased because of the mechanical deformation as well as the swelling of the buffer in response to an increased pore pressure. The raising of pore pressure will have initiated hydraulic flow, and, therefore, pore pressure then decayed as fluid was expelled from the buffer into the surrounding wall rock. The canister was deflated at a rapid rate to fix the gas leak. Again, this occurred at a rate greater than the hydraulic properties of the buffer, and, therefore, the buffer went into suction as the pore network expanded because of mechanical heave as the canister contracted and the buffer volume increased. Re-loading occurred at a relatively rapid rate as well, increasing radial stress and pore pressure in the same way as before. However, as the system had drained and then went into suction, the increase in stress was not as dramatic.

The response to mechanical loading is likely to be rate-dependent. A rapid increase in pressure greater than the drainage properties of the buffer resulted in an increase in pore pressure and stress. The scenario of interest with gas generated by corrosion will result in a much slower increase in gas pressure, one which is likely to mean that the buffer is able to drain because of canister expansion, and therefore excess pore pressure and radial stress are unlikely.

Gas injection test

The FCT was conducted as a two-stage gas ramp, as shown in Figure 7. However, the means for increasing pressure were different compared with previous gas injection tests. Previously, a fixed amount of gas was compressed within an interface vessel (Cuss *et al.*, 2022), with water pumped into the bottom of the vessel at a constant rate to reduce the volume of the gas and thus increase pressure. In the FCT, the volume of gas within the canister was constant, with more gas added from two interface vessels by pumping water into the base of the vessels. Therefore, the volume of the system varied by ~ 10 litres while gas was being added. For each of the 55 refills of the interface vessel, the starting pressure, end pressure, and volume of water pumped into the vessels were recorded so that the amount of gas added to the canister could be determined. The gas pressure of the canister was estimated from Boyle's law (Equation 2):

$$2. \quad P_1 V_1 = P_2 V_2$$

where P is pressure, and V is volume. Each refill of the interface vessels increased the volume of the system by ~ 10 litres at a constant pressure. Injection of water into the interface vessels decreased the volume of the system by a known amount, resulting in an increase in pressure. The changes in volume and pressure are known, and the volume of the canister was estimated from the first injection step, meaning that the predicted pressure could be estimated. This calculation assumed no change in temperature and no

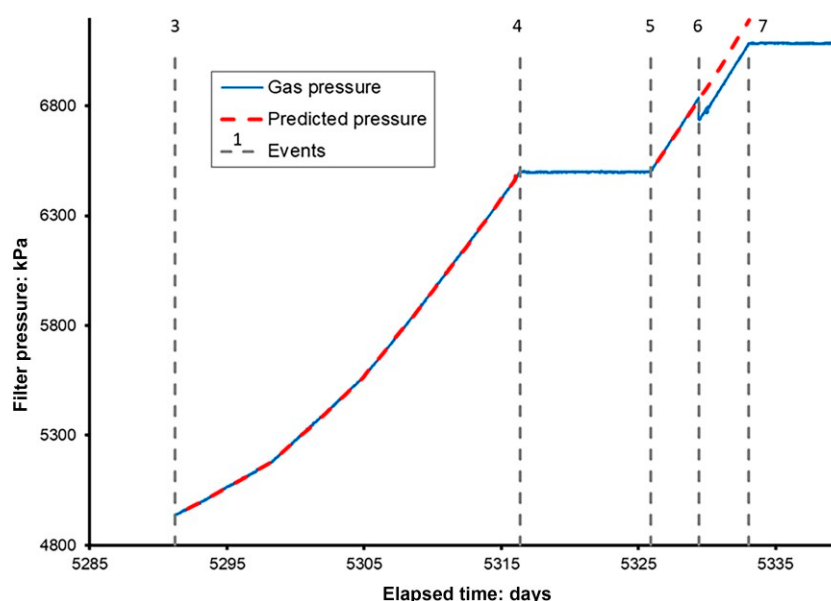


Figure 7. Recorded and predicted gas pressure during the full canister test

loss of gas in solution. Figure 7 shows the predicted pressure with a very good correlation with the observed pressure. The first seven refills were performed over 24-h periods using one syringe pump. The next ten refills were conducted over 18 h using a single syringe pump. It was decided to switch to reciprocating pumps and to refill on a 12-h basis for the remaining 38 refills. The first gas ramp started on Day 5291 (29 July 2019; Event 3, Figure 7) and raised the pressure from 4934 to 6499 kPa in 25 days (Day 5316; Event 4, Figure 7). Pressure was held constant for around 10 days, when a second gas ramp was started on Day 5326 (Event 5, Figure 7), which lasted for nearly 7 days and took pressure from 6550 to 7085 kPa.

Early in the test history, a volume of water was unintentionally pumped into the canister. The exact volume was unknown, but it was not sufficient to fill the available void space of the canister. Water entering the canister had been anticipated at the outset of the experiment, and the valve in the base of the canister had a snorkel so that water could pool in the base of the canister and, therefore, not all of it would need to be expelled before gas could enter the buffer during the FCT. However, this snorkel was limited and was estimated to be around 300–400 mm in height. It was uncertain whether the water level was above the snorkel or not. A second potential issue was whether the air-actuated FCT valve was still working. This valve had sat submerged in water for around 14 years, and it had not been operated. Fortunately, the valve had been set to be open, so as long as the air supply was active, the valve was open throughout the test history. There was no way of testing that the valve worked, and its operational status was unknown. In all previous tests, the gas entry pressure was approximately equal to the local stress state. The FCT valve was close to stress sensor PC901, and this meant an estimate of local stress could be made. However, the canister stress sensors had to be severed to achieve a gas-tight canister, and stress had to be estimated from when the sensor had been active. At Day 5266.13, stress at PC901 was 7063 kPa, and this gave an estimate of what gas entry pressure would be. Therefore, there was a limit to how high canister pressure should be raised. If pressure were raised too high and water were in contact with the bentonite, then there would be a risk of hydrofracture, something that was not of interest. Gas pressure was therefore held when it reached the estimate of local stress, and when at 7085 kPa (Event 7, Figure 7), the pressure was held at this value by stopping the addition of gas to the canister.

Figure 7 also shows that an issue was experienced during the second gas ramp (Event 6, Figure 7). During refill 47, a valve was unintentionally left open, and gas was able to vent through the refill system, lowering the canister pressure as gas leaked. Fortunately, only a small amount of gas was lost, and the pressure was still able to be raised to the target value. The volume of gas added during each refill was known accurately, meaning the start

pressure, end pressure, and change of volume were known. From this, the volume of the canister could be determined, assuming there was no loss of gas from the system. This gave a canister volume of 1313 litres.

Figure 8(a) shows the canister pressure for the remainder of the period. Two event lines (Table 2) are shown. The first of these (Event 8, Figure 8) occurred at Day 5410.86 and represents the first evidence of gas entry, with pressure increasing in UB902. The second event line (Event 9, Figure 8) at Day 5420.25 highlights when pressure in canister filter FL901 started to increase. Following Event 9, the pressure reduced in the canister from 7100 kPa to a final pressure of 6878 kPa at Day 5688.92, a loss of 220 kPa.

Figure 8(b) shows a crude estimate of the volume of gas pathways. As the volume of the canister was static, the reduction in pressure could be converted to a change in volume (i.e. pathway volume) assuming no loss of gas (Equation 3):

$$P_1 V_1 = P_2 V_2 \text{ where } P_2 = P_1 + \Delta P \text{ and } V_2 = V_1 + \Delta V$$

$$3. \quad \text{Therefore: } V_p = P_s \left(\frac{V_s}{1 + \Delta P_e} \right) - V_s$$

Where V_p is the change of volume (pathway volume), V_s is the starting volume (1380 litres), P_s is the starting pressure (7085 kPa), and ΔP_e is the change in pressure since entry. This was a crude calculation, as it assumed no loss of pressure along the pathway or temperature variation but gave an estimate of the minimum volume that the pathways would be occupying. Figure 8(b) shows that the reduction in canister pressure would occur if there were a total of 41.5 litres of pathway. This volume of pathway is highly unlikely to have formed within the buffer or for the gas to have found a sink of this size, as stresses and pore pressure within the system would have increased significantly if this were the case. Therefore, gas had escaped the system. This may have started at the point where the slope changed around Day 5440.

Figure 9(a) shows the pore water response at the deposition hole wall (UR) around the time of gas entry. As shown, most sensors towards the bottom of the sensor array showed a response. Location UR905 showed the first response at Day 5410.86 (Event 8, Figure 9), with a minor peak in pore pressure. This was followed at Day 5412.49 by a slow increase in pressure of UR906, with UR905 increasing again a short time after, as did UR904. At Day 5420.25 (Event 9, Figure 9), pore pressure in UR903–UR906 and UR908 peaked and then instantaneously reduced. In order of pressure increase, UR905, UR906, UR904, UR903, and UR908 increased by 99.2, 91.1, 43.6, 27.9, and 10.9 kPa, respectively, at

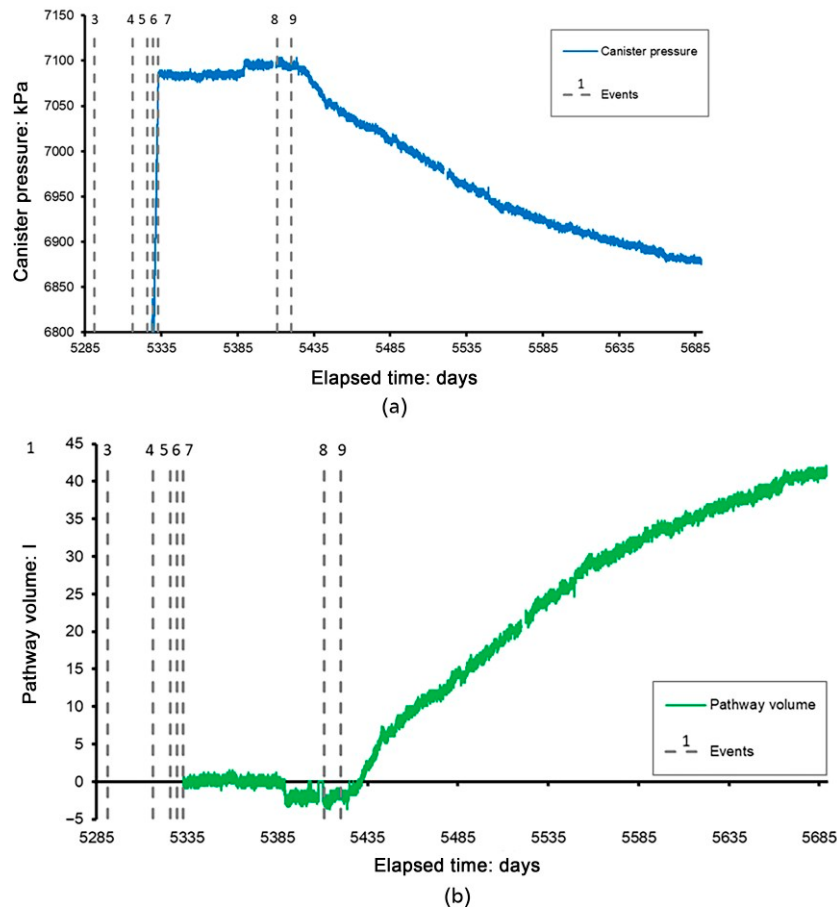


Figure 8. Response of canister pressure around the time of gas entry during the full canister test. (a) Pressure of the canister and (b) estimate of the volume of pathways

Table 2. Description of events highlighted in figures

Event	Elapsed time: days	Description
1	5266.07	Start of pressurisation of canister
1a	5268.56	Isolation of canister
1b	5269.14	Gas reconnected to canister
1c	5269.44	Isolation of canister
2	5277.23	Depressurisation of canister to fix leak
2a	5278.41	Canister pressure increased to 2000 kPa
2b	5279.24	Canister pressure increased to 4000 kPa
2c	5279.90	Canister pressure increased to 4950 kPa
3	5291.18	Start of gas ramp 1
4	5316.39	End of gas ramp 1
5	5325.91	Start of gas ramp 2
6	5329.40	Accidental leakage of gas from injection system
7	5333.07	End of gas injection
8	5410.86	First evidence of gas entry (pressure increase in UB902)
9	5420.25	Stress relief and pressure increase in FL901

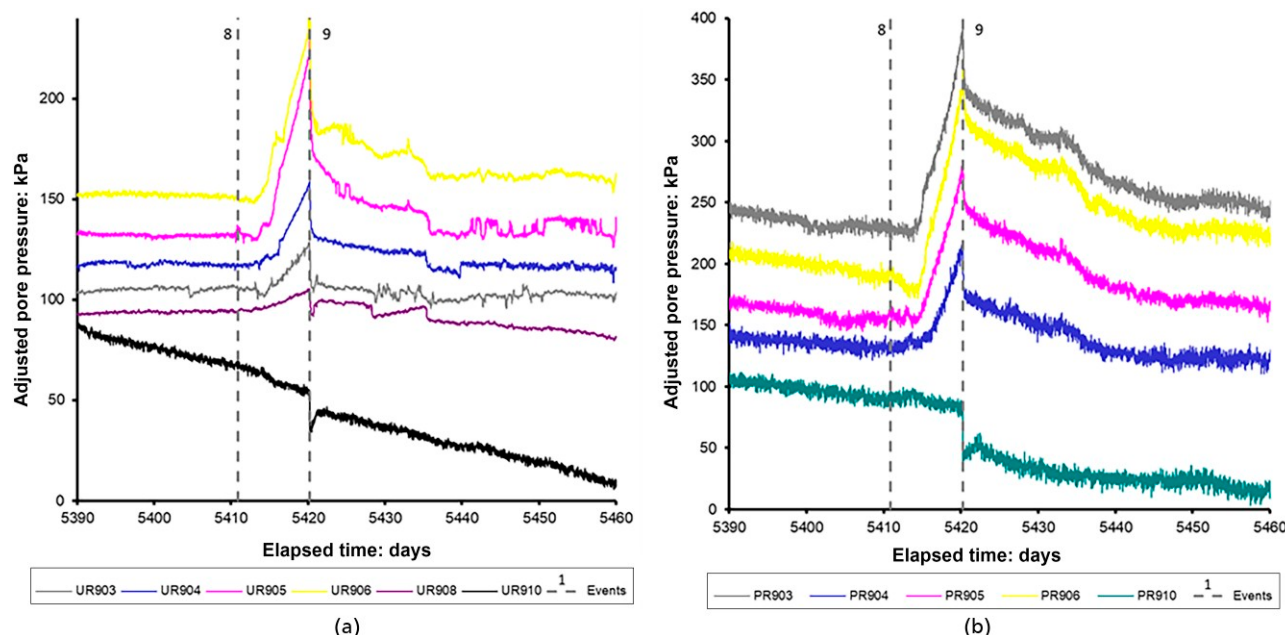


Figure 9. Details of radial stress and pore fluid pressure at the rock wall around the time of gas entry. (a) Pore pressure at the deposition wall, and (b) radial stress on the deposition wall

the peak in pressure. This was followed by a rapid reduction of 59.3, 48.5, 26.3, 26.7, and 13.4 kPa, respectively. UR910 showed slightly different behaviour in that there was no pressure increase, but it showed a decrease of 23.3 kPa. Multiple events can be identified in the data, such as pressure reductions that occurred in UR904–UR906 and UR908 at Day 5436.15. The multiple events seen in the pore pressure data are a strong indication that the gas was moving within the deposition hole.

Radial stress at the deposition hole wall (PR) is shown in Figure 9(b). As shown, radial stress was still recovering from the pressurisation of the canister. As with pore pressure, radial stress started to increase around Day 5414.21. At Day 5420.25, pore pressure in PR903–UR906 peaked (Event 9, Figure 9) and then instantaneously reduced. In order of stress increase, PR906, PR903, PR905, and PR904 increased by 195, 168, 118, and 84 kPa, respectively, at the peak in pressure. This was followed by a rapid reduction of 49, 54, 34, and 39 kPa, respectively. The reduction in stress post-peak was not as dramatic as seen in the pore pressure results. PR910 showed slightly different behaviour in that there was no pressure increase but showed a decrease of 39 kPa. Little other stress changes occurred for the rest of the FCT.

Figure 10(a) shows sensor locations that recorded the direct movement of gas. Gas reached pore water sensor UB902 within the buffer first. At Day 5410.86 (Event 8, Figure 10(a)), UB902 instantaneously increased by 68 kPa. This was followed by stepped

increases in UB902 until Day 5412.49, when the rate of pressure change increased. The stepped increase shows that gas movement initially was not continuous, suggesting that movement was like that seen in capillary snap-off (Amann-Hildenbrand *et al.*, 2015) or like fault-valve behaviour (Sibson, 1990). The episodic movement of the gas suggests that pathway growth was occurring in multiple pathways, with movement progressing past some form of baffle until an open pathway was formed. Pressure at UB902 peaked at Day 5420.25 (Event 9, Figure 10(a)), reducing by around 120 kPa. At this time (Day 5420.25), pressure at FL901 also started to increase; after a short time, the pressure in FL901 matched that in UB902, some 1380 kPa below the pressure in the canister. This shows the decrease in pressure along the newly formed pathways. FL901 and UB902 approximately matched one another for the rest of the test and showed the same general reduction in pressure as seen in the pressure of the canister. No other sensors showed evidence of direct gas movement. While the sensors that directly received gas show locations where gas had moved to, the careful examination of interpolated maps of stress and pore pressure (such as those shown in Figure 6) can give insight into the movement of gas within the deposition hole. From this, Figures 10(b) and 10(c) show a schematic diagram of the continued gas flow, with gas reaching FL901 before finding a way out of the deposition hole.

Discussion

The FCT reached gas entry in a different manner than for the previous six gas injection tests reported in Cuss *et al.* (2011, 2014, 2022, 2026).

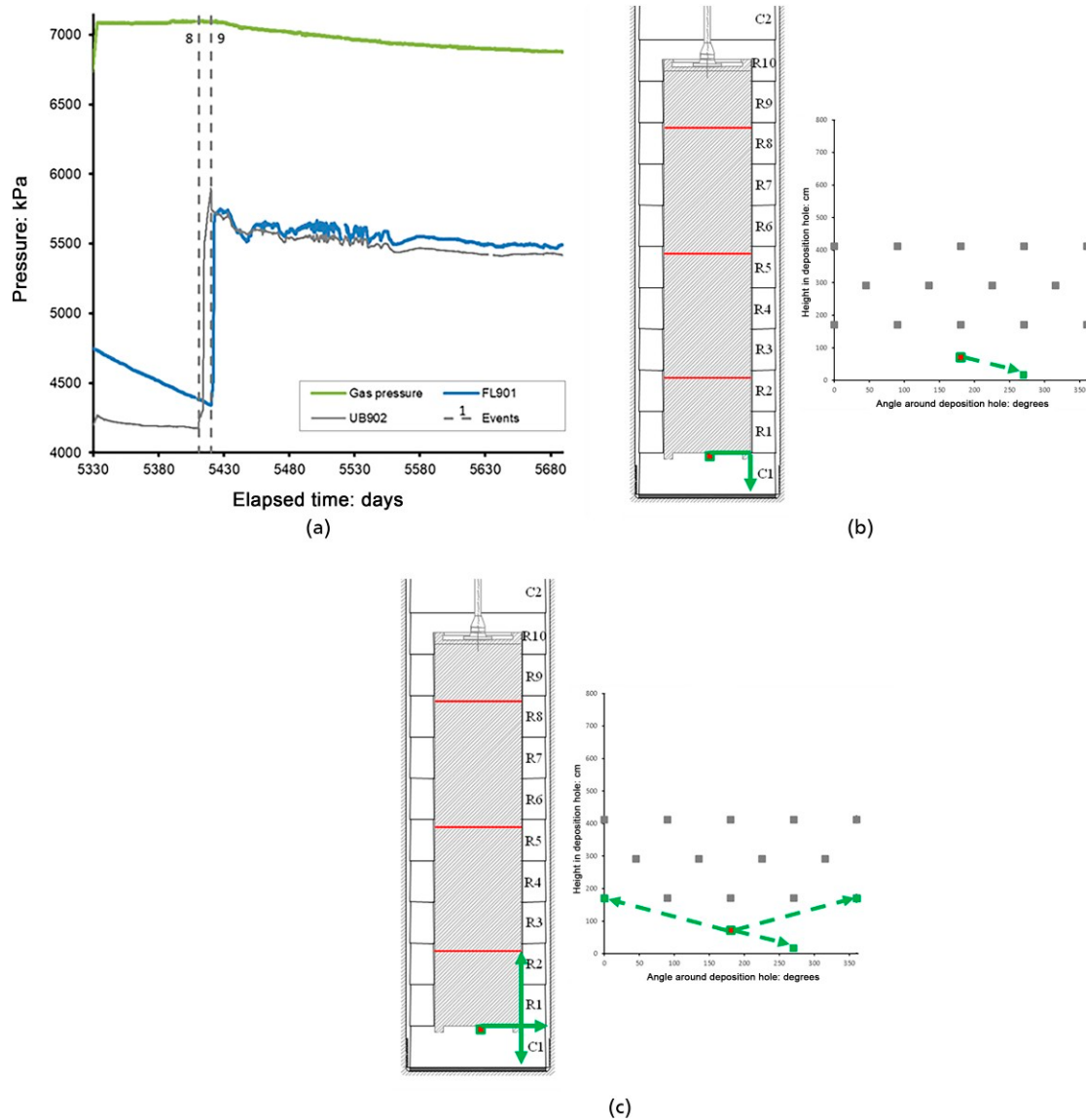


Figure 10. The movement of gas during the full canister test. (a) Details of sensors that showed evidence of gas pressurisation during the full canister test, (b) gas movement to UB902, and (c) gas movement to FL901

Gas pressure was held constant at a magnitude a little higher than gas entry was expected, while water in the canister slowly drained through the FCT filter. Had the gas ramp been increased, it was likely that the buffer would have been hydrofractured by the water in the filter, something that was of no interest. All previous tests had gas entry at a pressure close to the local stress. The FCT filter was located close to the axial stress sensor on the bottom of the canister, PC901. This meant that gas entry was expected to be ~ 7000 kPa. When pressure reached 7100 kPa, it was kept constant to allow the FCT filter to drain of water and to wait until gas entry occurred. It was estimated that 7100 kPa was sufficient for gas entry

to occur but would not be high enough that the bentonite would be hydro/gas fractured. Although the FCT was conducted in a slightly different manner from the previous tests, it is concluded that the course of action taken was justified and would not result in a significant change in gas transport behaviour.

Figure 9 shows the radial stress and pore pressure results for the FCT test for selected sensors. It should be noted that the sensor array was optimised for testing in the canister filters and that the coverage at the base of the canister was limited. However, gas entry was observed. The form of the pore pressure (Figure 9(a))

profile was different from that seen in all the other gas injection tests. Pore pressure increased and then, when it peaked, quickly dropped. This is almost the opposite behaviour to that seen in the previous tests, where pore pressure tended to rise instantaneously and take time to decay. The rapid decrease in pore pressure suggests that gas moved into the buffer and relieved the loading of the deposition hole wall. Radial stress had a similar form to pore pressure (Figure 9(b)), which had similarities to that seen in Gas Test 2 (Cuss *et al.*, 2011). The data may suggest that the buffer was loaded by inflating gas pathways and that the reduction in pore pressure and stress was this ‘balloon’ being deflated as a pathway reached the outside of the deposition hole and gas could exit the system.

Figure 10(a) shows that gas migrated within the KBS-3 system and directly intercepted the canister filter FL901 and pore pressure sensor UB902 within the bentonite, near to the FCT filter. The gas took at least two pressure events to fully pressurise UB902. Once both sensors were fully pressurised, they had similar pore pressure, and both decayed for the remainder of the test period at a similar rate to that of the FCT gas pressure. This pressure decay showed chaotic response, before eventually resulting in a slow and steady reduction in pressure. Both FL901 and UB902 were clearly in direct, open communication with one another. However, the pressures recorded at UB902 and FL901 were considerably lower than the canister pressure, which suggests that the connection between the canister and sensors was through a narrow pathway. The slow pressure decay of the canister pressure at FL901 and UB902 is thought to have occurred as gas exited the deposition hole. It should be noted that FL901 was pressurised in both Gas Test 2 (Cuss *et al.*, 2011) and Gas Test 4 (Cuss *et al.*, 2022, 2026), and UB902 was pressurised in Gas Test 2 when testing from canister filter FL903. It is probable that the FCT test exploited the same pre-existing weaknesses in the buffer as were exploited in earlier gas injection tests. Variations in the geotechnical properties of the buffer were seen (Cuss *et al.*, 2022), and it has been interpreted that gas exploited the interface between the canister and the buffer (Cuss *et al.*, 2026). It is evident that the significantly larger volume of gas used in the FCT had not altered the gas propagation behaviour, except that an initial gas pressure reduction was not seen in the FCT test as gas entered the bentonite buffer.

In total, seven gas injection tests were performed in the Lasgit experiment, with tests GT1, GT2, GT4, and GT6 performed near the base of the canister in filter FL903 and tests GT3 and GT5 undertaken in filter FU910 towards the top of the canister. The FCT reported in this paper was the seventh test and was performed through a filter located at the base of the canister. In the early tests (GT1 and GT2) performed while the buffer was in a poor state of maturity (i.e. the bentonite was in a state of pore water pressure and stress disequilibrium), small precursor gas flows into the

bentonite were thought to have occurred, based on an assumption of the starting gas volume (Cuss *et al.*, 2022). However, when gas pressure was held constant, the rates of inflow massively reduced, suggesting a hiatus in (or very limited) pathway growth. In all tests, injection led to the continued pressurisation of the gas and an increase in gas pressure. Similar to laboratory tests, peak gas pressure was always equal to, or, in most cases, slightly in excess of, local total stress. In the FCT, the pressure reduced at a slow rate, which appeared to be decreasing with time. The rate of pressure drop in the FCT was much lower compared with the other tests, because of the much larger upstream gas volume. This clearly demonstrated that a slow energy release can be expected, even if the volume of gas is large. It also suggests that the number and volume of gas pathways were gas-volume invariant and were more sensitive to gas pressure than gas volume. This is an important observation from the Lasgit experiment. The pressure decay in the FCT indicated sudden changes in pressure at certain times. This could be interpreted as closure or reduction in the size of the pathways. The slow pressure decay in the FCT also suggests that the gas was transported in pathways of more limited size to those observed in GT1 through GT6, even when the buffer was exposed to a large volume of gas. This contradicts, at least to some extent, the mechanism of rapid macroscopic tensile fracturing.

The FCT offered a unique opportunity to investigate whether the volume of gas would alter the physics of advective gas movement. The experimental procedure had to be modified because of the presence of water within the canister, which was unintentionally pumped into the canister early in the test history. While this meant that the test was not operated as originally planned, it did show that gas escape from the system was controlled and no ‘run-away’ affects were seen. This gives confidence that the buffer will perform its intended function in the KBS-3 disposal concept. Further experimentation could be conducted on laboratory-scale samples to confirm that the volume of gas has no influence on advective gas movement. The use of large interface vessels could be used to simulate large gas volumes.

Conclusions

The FCT was the final gas injection test conducted as part of the LASGIT and offered a unique opportunity to investigate the role of gas volume in the movement of gas within a full-scale KBS-3 disposal mock-up. Two clear conclusions can be taken from the test:

- Pressurising the copper/iron canister resulted in expansion of the canister of $\sim 50 \mu\text{m}$, even though the initial pressurisation target was less than the stress acting on the canister. This small expansion of the canister resulted in the buffer compressing, leading to an increase in pore water pressure and total stress. The buffer behaved as if it were undrained, as the loading rate was much higher than the drainage rate of the clay. Once the pore pressure and stress peaked, they slowly

decreased back to close to the starting condition. However, it should be noted that as the canister had a leak, the pressure within the canister was reducing as well, and therefore the expansion of the canister would have been reducing. The leak of the canister required a site visit, where it was necessary to further reduce the gas pressure to safely cap the leaking line and make the canister gas-tight. This rapid reduction in gas pressure resulted in the buffer going into suction, and pore pressure and radial stress were greatly reduced.

Re-pressurisation of the canister in steps resulted in raised pore pressure and stress once again, but this time of a lower magnitude. The response can be explained by the drainage characteristics of the buffer, and in the real-world scenario of interest, inflation of the canister at such a rapid rate is unlikely. However, expansion of the canister through pressurisation and/or thermal expansion should be considered as part of the performance assessment.

- The primary aim of the FCT was to observe whether a large volume of gas would change the physics of gas transport seen in the previous six gas injection tests in Lasgit. The canister was found to have 1313 litres of volume, compared with the 5-litre maximum used in GT1–GT6. In the previous tests, the formation of a gas pathway network increased the effective volume of the gas and resulted in the lowering of gas pressure. If the same volume of gas pathway formed in the FCT, no detectable reduction in gas pressure would occur, and this potentially could lead to a change in gas migration behaviour. The rapid reduction in gas pressure seen in GT1–GT6 eliminates the possibility of detecting additional (time-dependent) pathway formation after gas breakthrough. The results from the FCT clearly demonstrate that no additional pathways are formed after the first breakthrough.

Because of a volume of water injected into the canister early in the experiment, the two-stage gas ramp employed was paused at 7100 kPa, which was just above the estimated total stress at the FCT filter. This allowed the water from the canister to drain until gas was able to escape. A slow and gradual reduction in pressure was seen once the water had drained. A pressure reduction of 220 kPa was observed during the FCT, which, if converted to a pathway volume, would equate to 45 litres of pathway. It is not feasible that such a large volume could be accommodated without a significant increase in pore pressure and total stress; therefore, it can be concluded that gas had escaped the deposition hole. The behaviour of pore pressure and total stress was different from that seen in previous gas tests. However, no significant change was seen in the behaviour of the buffer, and the formation of pathways and migration of gas can therefore be seen to be gas volume invariant. The slow pressure decay in the FCT also suggests that the gas was transported in pathways of more limited size than those observed in GT1 through GT6, even when the buffer was exposed to a large volume of gas. This contradicts the mechanism of rapid macroscopic tensile fracturing.

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