

Hydraulic Testing of Compacted Bentonite Used for Plug and Abandonment Operations

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Abstract

The University of Queensland Centre for Coal Seam Gas (UQ CCSG) has investigated plugging wells with bentonite through laboratory experiments and with field trials. This paper presents the laboratory tests, which were used to investigate the stability range of plugged sections for later well plug and abandonment operation designs. The plugs were tested on a specially built well simulator facility at The University of Queensland (UQ), School of Chemical Engineering. The bentonite material used for the plug production was treated with water and 1 weight% polyvinylpyrrolidone (PVP) which acted as a binder to allow the bentonite to be pressed into a cylindrical shape suitable for dropping into vertical wells. The experiments have shown that the best performing plug/casing size combination is able to hold pressure gradients of up to 5.9 bar/m (25.9 psi/ft) after 296 days of hydration before failing. Open hole simulations on the testing facility showed surprisingly high failure pressure gradients of 21.1 bar/m (93.3 psi/ft) after 146 days of hydration. The findings of this research indicate that the use of compressed bentonite is a viable method for sealing wells, whether they can be coal seam gas wells, conventional oil and gas wells, water wells, or coal exploration wells.

Keywords

Bentonite Plugs, Hydraulic Testing, Failure Pressure Prediction, Well Abandonment

1. Introduction

Compacted bentonite is used in variable forms for the abandonment of wells in industry for different well types [1] [2] [3] [4] [5]. Towler *et al.* (2015) [6] summarizes previous research about the use of bentonite to plug and abandon wellbores. This project aimed originally to develop a novel, more reliable, lower-cost

plugging and abandonment (P & A) technology initially for the coal seam gas (CSG) industry. Coal exploration wells, water wells and conventional oil and gas wells were added to the primary scope. The laboratory program aimed to fully characterize the bentonite, undertake detailed technical assessments of plug performance under different sub-surface conditions, and provide the technical evidence to support the use of plugs in “non-ideal” conditions e.g. uncased bores and wells. The mineralogical composition of the bentonite used in this study and its geomechanical properties are reported in detail by Holl & Scheuermann (2018) [5].

A customized well simulator facility was built at the University of Queensland/School of Chemical Engineering, which was designed to test different diameters of plugs in various pipe geometries and length of plugged sections by pressuring the vessels up to a maximum of 6.7 MPa (1000 psi) while testing.

2. Materials and Plug Production

Amcol Australia Pty Ltd supplied three of their mined raw bentonite materials from its Queensland Bentonite Mine (Gurulmundi, Australia). The three different bentonite materials were tested during the project to identify the most suitable material based on the comparison of mineralogical, geochemical, geomechanical properties and finally their plugging performance, tested with the well simulator. The best performing material was the Amcol 5D bentonite, followed by the 5A bentonite. They were used after PVP treatment (5D PVP/5A PVP) or as untreated material (5D raw/5A raw) for further testing.

Bentonite plugs with an outer diameter (OD) of 88.9 mm (3.5")/190 mm length (7.5") (**Figure 1**) and 139.7 mm (5.5")/215 mm length (8.5") are produced in the laboratory of the School of Chemical Engineering/UQ using a custom built hydraulic bentonite plug press.



Figure 1. Bentonite plug with a diameter of 88.9 mm (3.5") and 190 mm length (7.5"). The central hole is 19 mm (0.75") wide.

Raw bentonite treated with potable water and 1 weight% polyvinylpyrrolidone (PVP) is pressed into a bullet geometry with a cone shaped tip and a center hole that allows fluid to pass through the plug and stabilize the fall through a water column to the final setting depth [5] [7]. A hydraulic pressure of 16.5 MPa (2400 psi) is applied during the production process, which is equal to 25.8 metric tons compression weight for the 139.7 mm (5.5") plugs. 15.2 MPa (2200 psi) was used for the 88.9 mm (3.5") plugs, which translates to 9.6 metric tons compression weight.

3. First Hydraulic Tests Using the Well Simulator Facility

The Well Simulator Facility consists of one meter long pipe sections of 97.2, 139.8 and 173.1 mm internal diameter (ID) (red, blue and green pipes in **Figure 2**). These were stacked and flanged to each other to create taller test sections. First trials were commenced in July 2017 after calibrating the digital pressure transducers, using the pre-set proportional pressure relief valve with a nominal set pressure of 6.9 MPa (1000 psi).

Spacers were plunged into the pipe sections to ensure that the pressure transducers in the lowermost flanges are still operational, even after filling the pipes up to 20 cm below the top flanges with hydrating bentonite plugs. The pipe section was loaded with bentonite plugs by dropping them from the top into a casing partly filled with potable water. The pipe section was filled with water to the top after installing the plugs. The first trials were commenced without installing blind flanges on the top to allow visual inspection of the failure that occurred during pressuring the plugged pipes up while pumping potable water into the bottom flange.



Figure 2. The Well Simulator Facility at the University of Queensland. Three different pipe sizes can be installed and tested up to a maximum pressure of 6.9 MPa (1000 psi). Sections of up to 5 m height can be installed. One pressure transducer is installed at the flange of each pipe and allow pressure monitoring while pumping.

The first hydraulic test delivered promising results. **Figure 3** shows the pressure progression over time while testing ten 88.9 mm OD 5D PVP plugs (each 190 mm long) installed in a 2 m long pipe section (2 joints, 97.2 mm ID) after 78 days of hydration using potable water. The constant pump rate during the test was 4.8 l/h (1.3 ml/s). We expected to see a very similar result to those provided by the mechanical dislodgement tests using a loading frame [5].

We could not identify the same stepwise geometry due to gradual shear failure of each single plug. We registered a first distinct signal caused by slip related pressure loss after 150 seconds (10.8 bar/157psi). There was no water production visible on top of the plugged section. Pressure was building again slowly and a couple of smaller peaks could be recorded. After 810 seconds final failure occurred at a maximum pressure of 19 bar (275 psi) and water production was detected at the top of the plugged section. The smaller peaks between 150 and 800 seconds are believed to be triggered by stick-slip phenomena of multiple or single bentonite plugs at different times within the plugged section. Material heterogeneities within the compacted bentonite plugs might be responsible for the “masked” dislodgment patterns compared to the patterns detected in the mechanical loading frame tests [5]. The pump was running a further 460 seconds after failure of the plugged section before being shut down. The shut-in pressure readings stabilized finally at 11.1 bar (161 psi), which are very close to the pressure peak, which was detected at the beginning of the test.

The second hydraulic test in the Well Simulator was conducted using the same material (5D PVP) and the same test geometry/height as used in the first trial, but with a lower constant pump rate of 2.4 l/h (0.7 ml/s). The results are presented in **Figure 4** and show a lot more similarity to the data derived from the mechanical dislodgement tests using a loading frame [5]. Again, we can't assign single pressure peaks to single plugs. Failure of the plugged section caused a water leakage at 5 bar (72 psi) after pumping 1920 seconds. The water flow was detectable at the interface plug/steel pipe. The central hole within the plug was

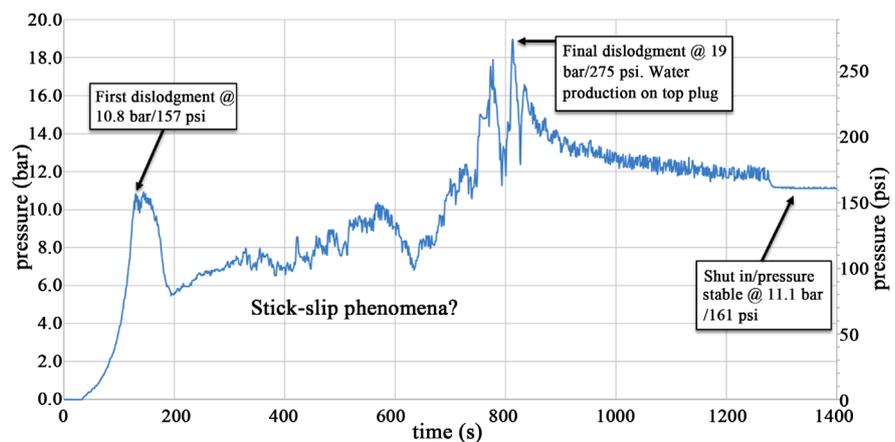


Figure 3. First hydraulic test using the Well Simulator Facility. Ten 88.9 mm OD 5D PVP treated plugs installed in 2 m of 97.2 mm ID pipe are tested after 78 days of hydration using a constant pump rate of 4.8 l/h (1.3 ml/s).

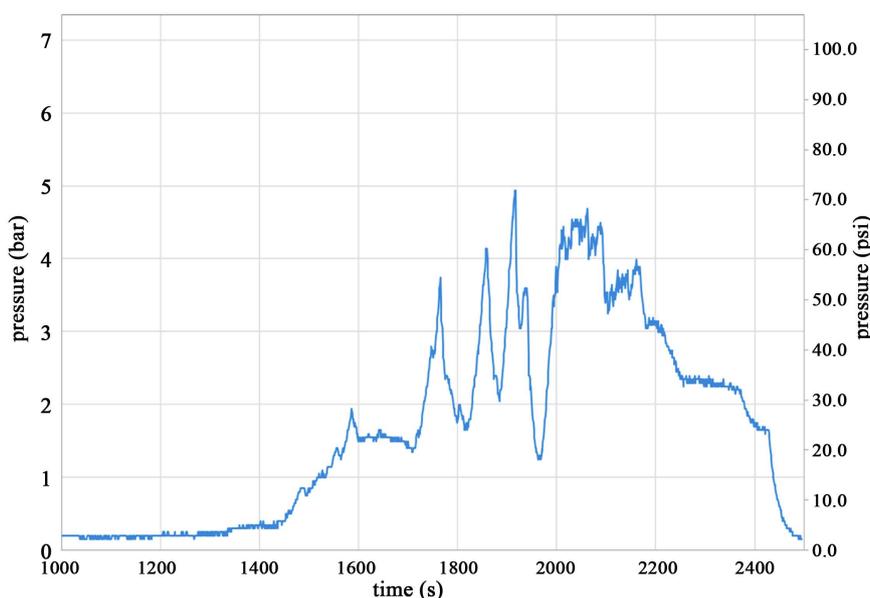


Figure 4. Second hydraulic test using the Well Simulator Facility. Ten 88.9 mm OD 5D PVP treated plugs installed in 2 m of 97.2 mm ID pipe are tested after 51 days of hydration using a constant pump rate of 2.4 l/h (0.7 ml/s).

filled/cured with expanded bentonite after 51 days of hydration. Water flow through the center of the plugged section of this sample was detected earlier. This occurred after 25 days of hydration time and failure happened during a trial test at a substantially lower pressure of 2.2 bar (32 psi).

We decided to keep the tested plug interval in the simulator and tested it again a week later after further hydration (58 days), but this time with a much higher constant pump rate of 36 l/h (10 ml/s). The results are shown in **Figure 5**. The rig pump was operated at 80 percent of its pumping capacity and the pressure data readings are quite noisy because of vibrations of the pump, which is directly installed beneath the rig table in contact with the metal structure. Final failure happened after a pumping period of 125 seconds at a pressure of 39.8 bar (577 psi). There was no visible water production at the top of the plugged section, instead the hydrated bentonite failed in shear mode (frictional failure) and was pushed out of the casing. The pump was shut down after 225 seconds. At this stage, 400 mm of hydrated bentonite plug material (two of the ten loaded plugs) was already pushed out of the pipe and was still moving until we depressurized the system using a manual pressure relief valve and the plug movement stopped.

The high failure pressure was not triggered by the extended hydration time of 1 week. The results of the long-term tests presented later in this paper clearly show that maximum strength of the plugs is reached after much longer lasting hydration periods. The fact that the bentonite plug was pushed out of the casing shows that we are dealing with a different failure mode than observed in the two tests mentioned before. Hydrated bentonite seems to show a similar behavior like non-Newtonian Fluids while failing (shear thickening effect). High pressure/flow rate will trigger shear failure at the complete circumference of the

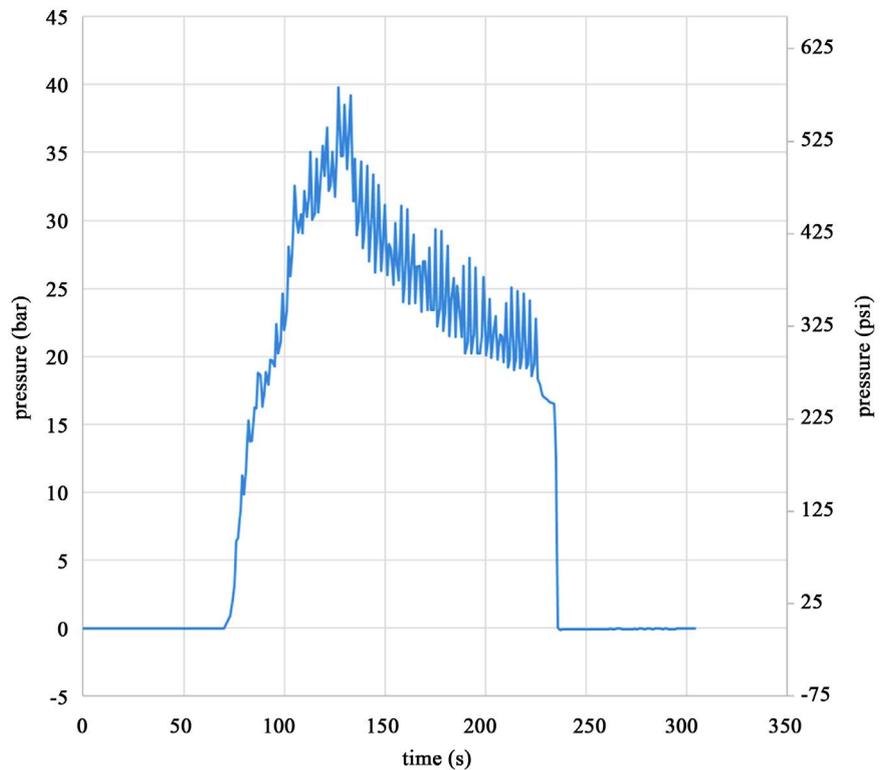


Figure 5. Second hydraulic test continued. Ten 88.9 mm OD 5D PVP treated plugs installed in 2 m of 97.2 mm ID pipe are tested after 58 days of hydration using a constant pump rate of 36 l/h (10 ml/s).

hydrated plug at a high failure pressure, whereas low flow rates creating single micro channels at the interface plug/steel pipe at much lower applied pressures, as shown in the following tests.

The third and fourth hydraulic test have been done using single 1 m pipe sections (97.2 mm ID) with pre-hydrated bentonite. Single pipes were loaded with bentonite plugs, hydrated in the laboratory and later installed on the simulator to optimize the testing capacity of the rig. **Figure 6** shows a comparison of the 5A bentonite as PVP blend and in its untreated form. They were tested after 48 days of hydration using a constant pump rate of 2.4 l/h (0.7 ml/s). The recorded curve geometries are quite different compared to the test results using water (blue curve in the background of **Figure 6**). There was a small volume of air (0.5 l) at the bottom of the plugged section above the water level within the installed pipe, because of the pre-hydration procedure. This air was used to test failure in presence of gas flow. The gas volume was compressed while pumping water. The plugged section finally failed as in the second hydraulic test with water, after the complete air volume escaped through the micro channels at the interface plug/steel pipe.

Both materials were tested after 48 days of hydration. Failure was observed when air bubbles were detected at the interface plug/steel pipe (**Figure 7**, left side) in the 5A PVP sample after 2300 seconds at a failure pressure of 1 bar (14.5

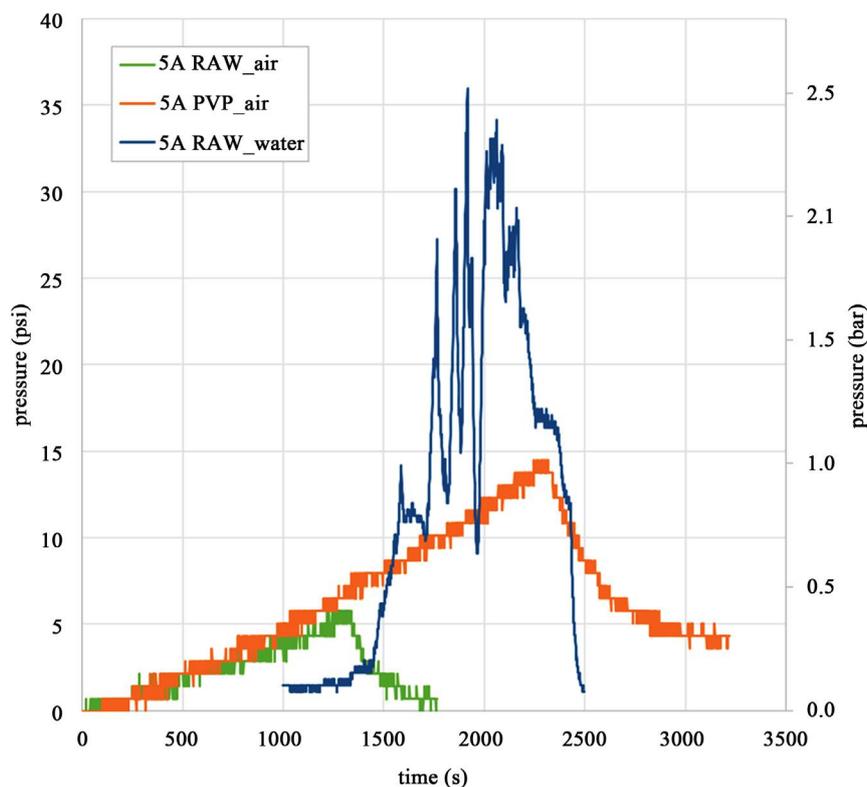


Figure 6. Third and fourth hydraulic test. Five 88.9 mm OD plugs (5A raw/5A PVP) installed in 1 m of 97.2 mm ID pipe are tested after 48 days of hydration using a constant pump rate of 2.4 l/h (0.7 ml/s). The blue curve in the background represents 1 m equivalent of 5D PVP tested after 51 days using water.

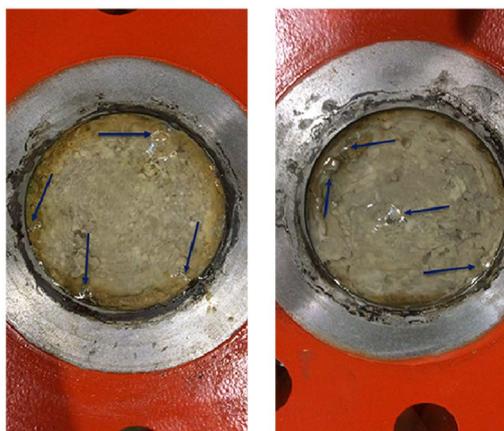


Figure 7. Failure behaviour of PVP treated 5A and raw 5A bentonite after 48 days of hydration. Left: 5A-PVP in a 97.2 mm ID pipe (third hydraulic test). Air bubbles (arrows) occur at the interface plug/steel pipe using micro channels as pathways, generated at failure pressure. Right: 5A-raw in a 97.2 mm ID pipe (fourth hydraulic test). Air bubbles (arrows) occur at the center of the plug and at the interface plug/steel pipe at failure pressure.

psi). The 5A raw bentonite failed in the center and at the plug/steel pipe interface after 1265 seconds and 0.4 bar (5.8 psi) failure pressure (**Figure 7**, right

side). The center of the 5A raw plug was not cured with expanded bentonite after 48 days of hydration. Direct comparison of PVP blended bentonite with the raw material confirms that the polymer blend is 60% stronger than the raw material and the failure pressures are roughly 50% higher using water than failure pressures using air.

The decision was made to pre-hydrate plugs in single pipe sections for the long-term testing to complete the planned experimental program in the two year project time frame. The 97.2 mm ID pipe sections were loaded with 5A PVP and 5D PVP bentonite plugs and stored in the laboratory with a 20 cm long PVC pipe extension on top of the pipe to guarantee a continuous hydraulic head on top of the plugged section. The PVC pipes were filled to the top with potable water and covered with a lid. The water level was checked 3 times per week and topped up if necessary. The pipes were installed on the rig after 3, 6 and 9 months hydration time and tested.

4. Hydraulic Long-Term Testing

The two most promising bentonite materials to be tested in the long term test program are the 5D and the 5A bentonite of Amcol Australia Pty Ltd. Pre-hydrated plugs in single pipe sections were prepared and stored with a PVC pipe extension on top of the pipe to guarantee a continuous hydraulic head on top of the plugged section. The total number of tests was limited by the amount of pipe segments available. The 97.2 mm ID pipes, loaded with 88.9 mm OD plugs of 5D PVP and 5A PVP were chosen for a testing program including three measurements per material, after each 3, 6 and 9 month hydration time. A 4 m high 139.8 mm ID pipe section was loaded with seventeen 127 mm OD plugs of 5D PVP as a permanent setup, which was tested after 2, 4, 6 and 8 months of hydration. This experimental design was also chosen to test the re-healing performance of already dislodged bentonite plug sections. This test is ongoing and the plugged section will stay installed on the Well Simulator Facility beyond the end of the project for further long-term testing. The 173.1 mm ID pipes were loaded with 139.7 mm OD plugs of the 5D PVP material. A sandstone cylinder was installed in an 173.1 mm ID steel pipe to simulate open hole conditions at the Well Simulator Facility.

4.1. Results of the 97.2 mm ID Pipe Sections

Three 97.2 mm ID pipe sections were loaded with five 5A PVP and 5D PVP bentonite plugs each and pre hydrated in the laboratory. The results of the six hydraulic tests of the 97.2 mm ID pipe long term testing are shown in **Figure 8** and **Figure 9**. The samples were tested after hydrating for 99, 183, and 296 days. After all three tests the 5D PVP bentonite performed significantly better than the 5A PVP. The failure pressure of 5D PVP is nearly double as high after 296 days as the one from the 5A PVP material. Water production on top of the plugged sections could be detected in all tests.

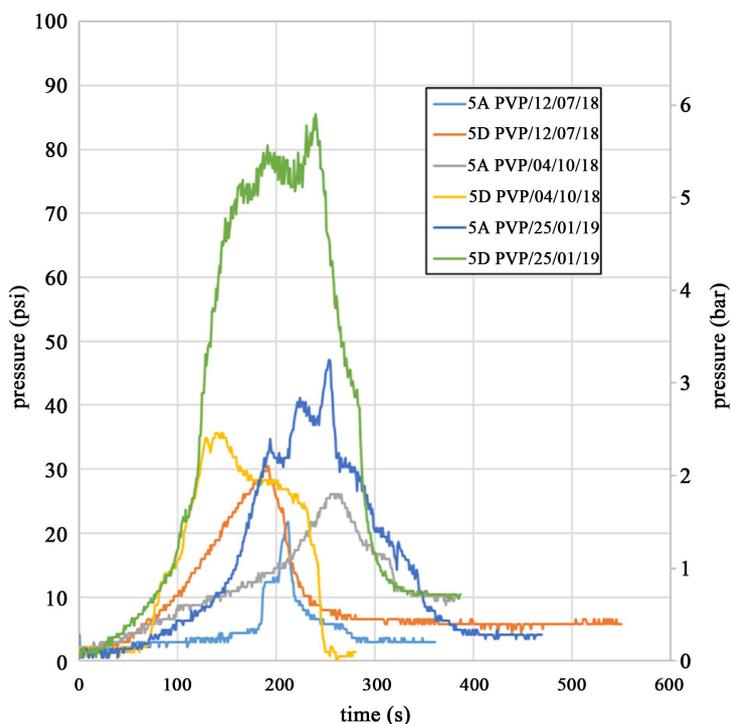


Figure 8. The six hydraulic tests of the 97.2 mm ID pipe long term testing series: Five 88.9 mm OD plugs (5D PVP/5A PVP) installed in 1 m of 97.2 mm ID pipe are tested after 99, 183 and 296 days of pre-hydration using a constant pump rate of 2.4 l/h (0.7 ml/s).

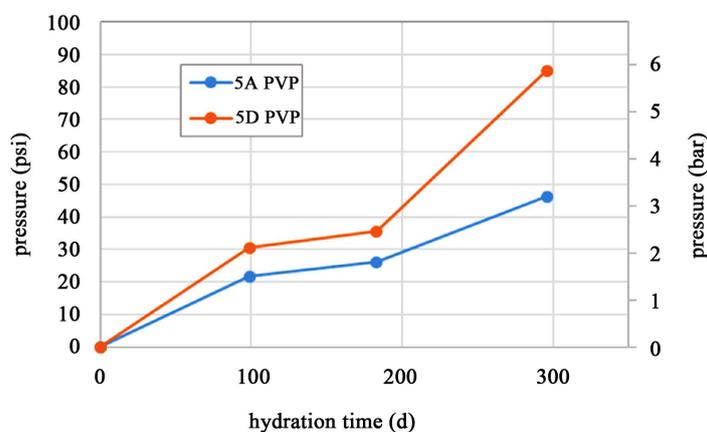


Figure 9. Time dependent failure pressures of 1 m of 97.2 mm ID pipe sections filled with hydrated 5A PVP and 5D PVP bentonite. The 5D PVP material shows significantly higher pressures than the 5A Bentonite.

4.2. Results of the 139.8 mm ID Pipe Sections

127 mm OD diameter plugs were prepared by stripping 12.7 mm from the originally produced 139.7 mm OD plugs (**Figure 10**). A section of 4 m was filled with the plugs and hydrated. Water was refilled weekly at the top to assure a constant water head on the installed bentonite. This experiment was designed for two purposes: to test the long term failure behavior of the plugs and to examine the “self-healing” ability of the plugged section after being dislodged [7].



Figure 10. Originally 139.7 mm OD, stripped to 127 mm OD for the long term testing in the 139.8 mm ID pipe sections.

It was expected that the sealing performance of the bentonite plug during/after the healing process would actually increase.

The pump rates were increased during the third and fourth test, because no water production could be detected at the top of the plugged section after the first pressure drops (black arrows in **Figure 11**). The massive increase of pressure at final failure seems to be impacted by the effect similar to non-Newtonian fluid behavior, as already described in Chapter 3 (second hydraulic test, continued, **Figure 5**).

Figure 12 shows two curves, representing the pressures at maximum failure pressure (5D PVP high flow) and the pressure readings after the first pressure drops at constant flow rate of 2.4 l/h (0.7 ml/s) (5D PVP min flow). The 5D PVP high flow readings of the third and fourth tests are most likely as high because of the pump rate triggered effect mentioned above and are not used for further interpretation.

4.3. Results of the 173.1 mm ID Pipe Sections

A 1 m plugged section of 139.7 mm OD plugs was installed in a 173.1 mm ID pipe and tested after 85 days of hydration, using a constant pump rate of 2.4 l/h (0.7 ml/s). Final failure pressure was measured to be 0.7 bar (10.2 psi) after 545 seconds of flow when water production was detected on top of the plugged section (**Figure 13**).

The hydrated plugs slipped out of the casing when the pipe was removed from the rig. This is an example for the limitations of the bentonite plugging technology as it stands at the time of the reporting. The 139.7 mm OD plugs were not

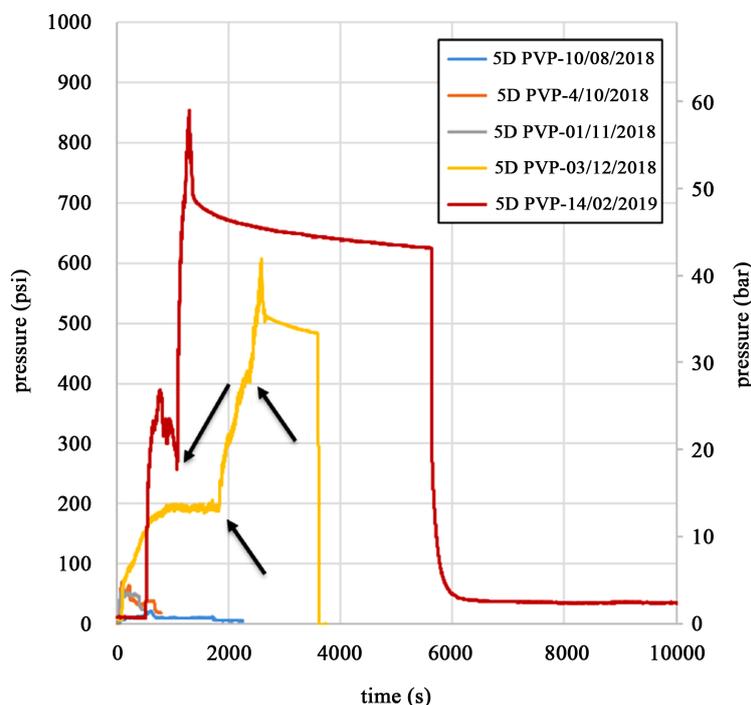


Figure 11. The four hydraulic tests of the 139.8 mm ID long term testing series: seventeen 127 mm OD plugs (5D PVP) installed in 4 m of 139.8 mm ID pipe are tested after 65, 120, 148 and 253 days of hydration using a constant pump rate of 2.4 l/h (0.7 ml/s) during the first two tests. The pump rates were increased to a maximum of 7.2 l/h, 2.1 ml/s during the third and fourth test, because no water production could be detected after the first pressure drops (black arrows in the graph).

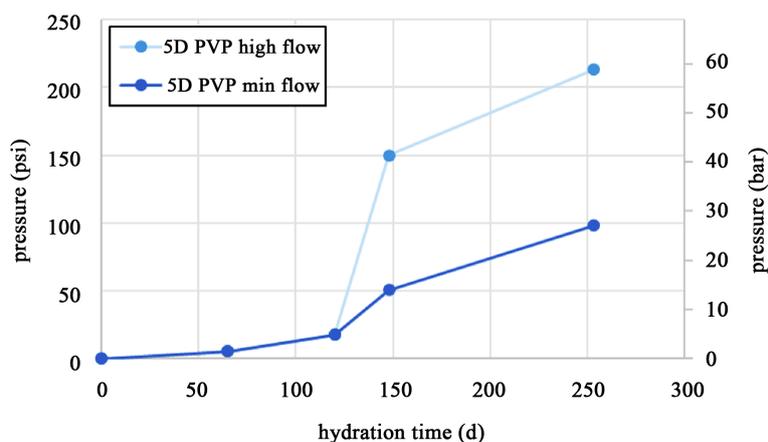


Figure 12. Time dependent failure pressures of a 1 m high 139.8 mm ID pipe section filled with hydrated 5D PVP bentonite. The original data were height converted for better comparability with the 97.2 mm ID pipe long term test results, assuming that the failure pressure is directly proportional to the height of the plug [6].

able to expand enough to create a proper seal in the 173.1 mm ID pipe section. The decision was made not to proceed with this testing geometry combination because the moisture content of the hydrated plugs was simply too high to create a proper seal.

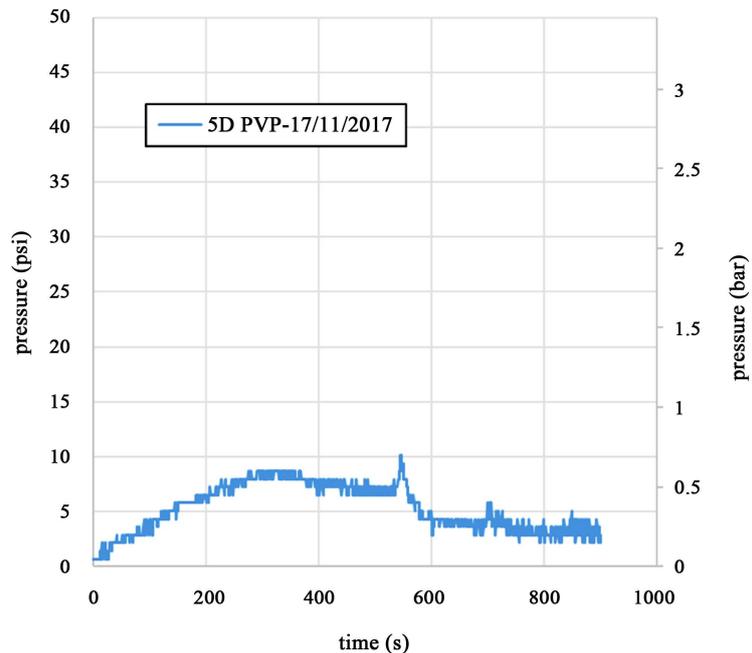


Figure 13. 1 m plugged section of 139.7 mm OD plugs (5D PVP) in a 173.1 mm ID pipe, tested after 85 days of hydration using a constant pump rate of 2.4 l/h (0.7 ml/s).

4.4. Simulation of Testing Bentonite Plugs in Uncased Holes

An 80 cm long sandstone cylinder with an ID of 94 mm was drilled out of a block of Helidon Sandstone out of the Ipswich-Moreton Basin (Figure 14). This geometry is close to HQ size (96 mm), which is the usual size of continuously cored boreholes in the coal exploration industry in Queensland. The sandstone pipe was glued into one of the 173.1 mm ID steel casings of the Well Simulator Facility, using a high tensile and flexural strength, low viscosity epoxy resin to mimic open hole conditions (Figure 15). The Helidon Sandstone is an equivalent to the Lower Jurassic Precipice Sandstone, which is the basal sedimentary deposit within the coal bearing Surat Basin succession in Queensland, Australia. This was the only trial using a natural rock as containment for the hydrated plugs in the Well Simulator. Different lithologies like claystones or even coal would be desirable to cover most of the existing rock types in the Surat Basin to understand the sealing performance of bentonite plugged sections in diverse lithological sequences. Unfortunately, they would not survive primary drilling, the gluing process and finally the hydraulic test program, because of their swelling abilities and brittle failure behavior.

The cylinder was loaded with four 190 mm long 76.2 mm OD 5D PVP bentonite plugs (stripped down from 88.9 mm OD originally plug size). It was tested after 98, 122 and 146 days of hydration. The results of the hydraulic tests are shown in Figure 16. A constant pump rate of 2.4 l/h (0.7 ml/s) was used for sample 17-07-water (grey curve) and the maximum failure pressure reading was 8.4 bar (122.5 psi) when water production was detected on top of the plug. Samples 10-08-water and 03-09-water did not show any water production after

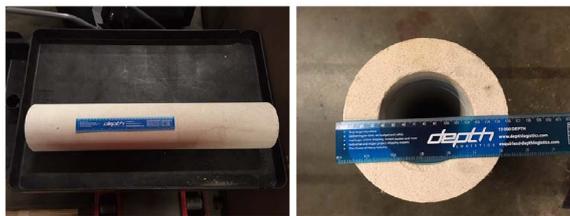


Figure 14. 80 cm long Helidon Sandstone cylinder (left), 94 mm internal diameter (right).



Figure 15. Helidon Sandstone cylinder (94 mm ID) within a 173.1 mm ID pipe after hydraulic testing. The sandstone cylinder was installed using a high tensile and flexural strength, low viscosity epoxy resin.

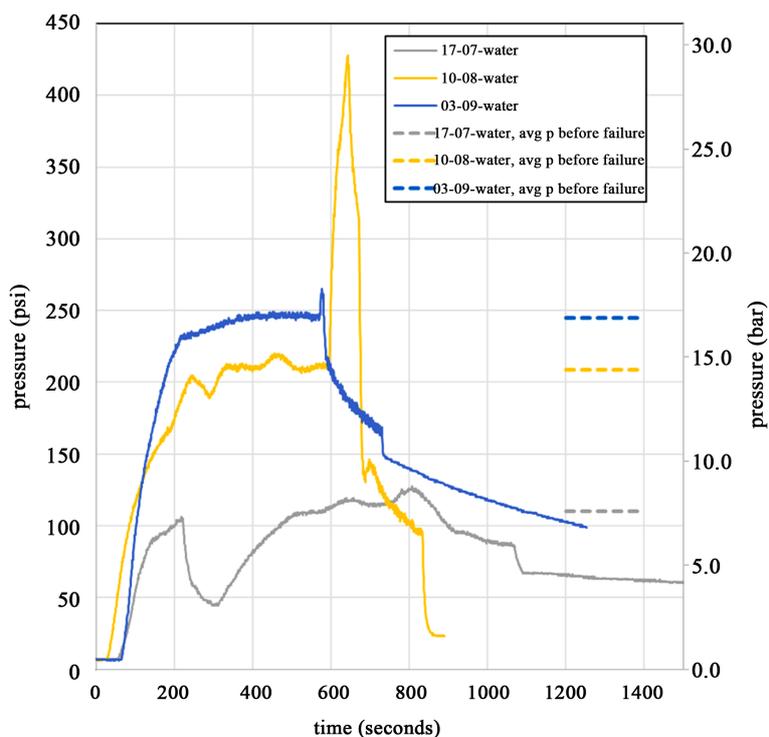


Figure 16. The three hydraulic tests of the Helidon Sandstone cylinder installed in an 173.1 mm ID steel pipe: four 19 cm high 76.2 mm OD 5D PVP bentonite plugs (stripped down from 88.9 mm OD originally plug size) were hydrated and tested in two month intervals. The presented failure pressures are measured for the 0.8 m plugged section.

reaching an average plateau pressure. The decision was made to double the pump rate for sample 10-08-water and the final failure seems to be impacted again by the effect similar to non-Newtonian fluids behavior, as already described above. The pump rate was only increased to 2.8 l/h (0.8 ml/s) for sample 03-09-water, which triggered immediate failure after a small pressure increase of 1 bar (15 psi), showing a sharp pressure peak in the blue curve. The average pressures before failure were used for the failure pressure comparison because of the flow rate variations at the end of the two later tests.

The presented failure pressures at observed water production are measured using the 0.8 m plugged section (Figure 16), but later converted to a 1 m plugged section to make them comparable to the other presented failure pressure results (Figure 17), assuming that the failure pressure is directly proportional to the height of the plug [6]. The failure pressures are substantially higher than in comparable plug/pipe ratio sizes. This is most likely caused by the roughness of the sandstone cylinder surface. Higher frictional forces have to be overcome to create failure of the bentonite plugged section in the sandstone compared to a plugged section in a steel casing with relatively smooth surface.

This result has also implication for the design of abandonment operations of older wells with casing corrosion. Corroded steel pipes with rough surfaces might withstand significantly higher pressures while plugged with bentonite than new casings. We cannot quantify this effect to date. Research on the influence of surface roughness to failure pressures of bentonite plugs was not manageable within the limited timeframe of the project, but might become a focal point for a successor project.

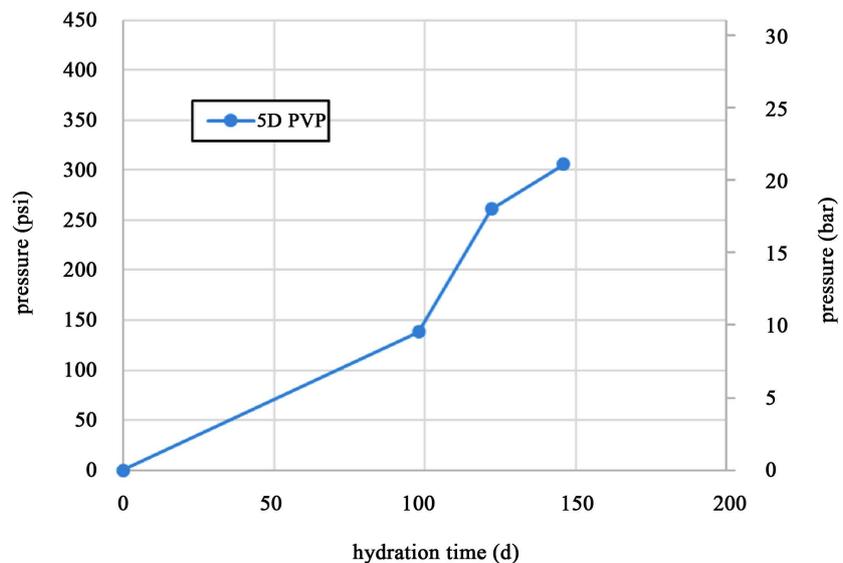


Figure 17. Time dependent average failure pressures of a 1 m high sandstone cylinder section filled with hydrated 5D PVP bentonite. The average failure pressures are converted to a 1 m plugged section assuming that the failure pressure is directly proportional to the height of the plug [6] to make them comparable to the other presented failure pressure results.

4.5. Summary of the Results of the Hydraulic Long-Term Testing

A summary of the failure pressures of all long-term hydraulic test results is given in **Table 1** and **Figure 18**. The erroneous results of the experiment “139.8 mm ID pipe, 5D PVP, high flow” are also included in the table and figure to show the pitfalls arising in this kind of experiments.

The comparison of the two best performing bentonite materials show a clear result: the best performing material is the 5D PVP blend that is able to hold pressure gradients up to 5.9 bar/m (25.9 psi/ft) (**Table 1**) after 296 days of hydration in a 97.2 mm ID pipe. The pressure gradients are used to design the

Table 1. Summary of all long term hydraulic test results commenced during the project time.

experiment	time and results						
	date	test	failure pressure (bar)	failure pressure (psi)	days of hydration	failure gradient (bar/m)	failure gradient (psi/ft)
97.2 mm ID pipe, 5A PVP	05/04/2018	start	0	0	0	0	0
	12/07/2018	1st	1.5	21.8	99	1.5	6.6
	4/10/2018	2nd	1.8	26.1	183	1.8	8.0
	25/01/2019	3rd	3.2	46.3	296	3.2	14.1
97.2 mm ID pipe, 5D PVP	5/04/2018	start	0	0	0	0	0
	12/07/2018	1st	2.1	30.5	99	2.1	9.3
	4/10/2018	2nd	2.5	35.6	183	2.5	10.8
	25/01/2019	3rd	5.9	85	296	5.9	25.9
139.8 mm ID pipe, 5D PVP min flow	07/06/2018	start	0	0	0	0	0
	10/08/2018	1st	0.4	5.5	65	0.4	1.7
	4/10/2018	2nd	1.2	17.6	120	1.2	5.4
	1/11/2018	3rd	3.5	50.5	148	3.5	15.4
139.8 mm ID pipe, 5D PVP high flow	14/02/2019	4th	6.8	98	253	6.8	29.9
	7/06/2018	start	0	0	0	0	0
	10/08/2018	1st	0.4	5.5	65	0.4	1.7
	4/10/2018	2nd	1.2	17.6	120	1.2	5.4
173.1 mm ID pipe, 5D PVP	1/11/2018	3rd	10.3	150.1	148	10.3	45.8
	14/02/2019	4th	14.7	213.1	253	14.7	65
	25/08/2017	start	0	0	0	0	0
sandstone cylinder, 5D PVP	17/11/2017	1st	0.7	10.2	85	0.7	3.1
	10/04/2018	start	0	0	0	0	0
	17/07/2018	1st	9.5	138	98	9.5	42.1
	10/08/2018	2nd	18	261	122	18	79.6
	3/09/2018	3rd	21.1	306	146	21.1	93.3

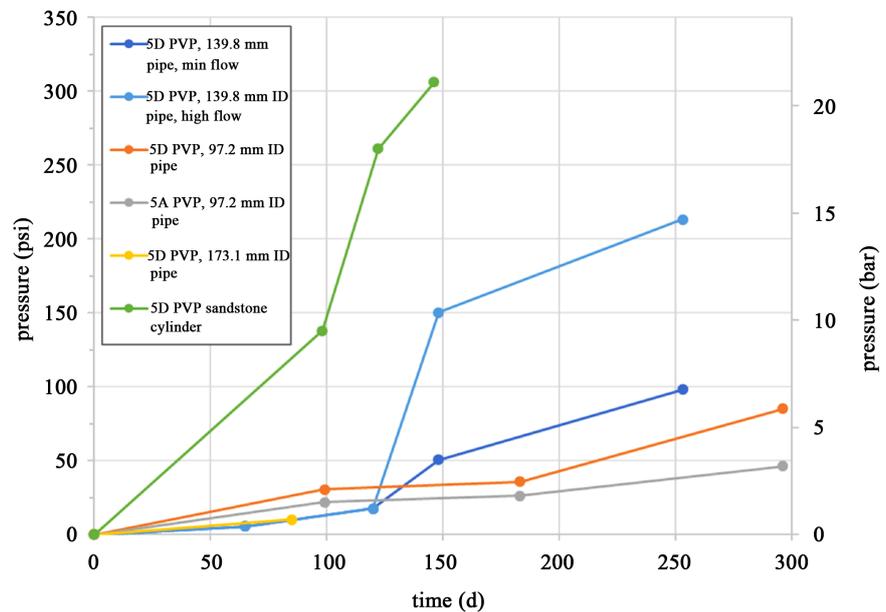


Figure 18. Results of all hydraulic long term tests commenced during the project time, using PVP treated bentonite in different pipe sizes. Hydration time dependent failure pressures of 1 m high plugged sections (tested with potable water).

height of a plugged section for a given maximum reservoir pressure. The results of the 139.8 mm pipe testing are not as conclusive. **Figure 18** shows two blue curves for the 139.8 mm pipe 5D PVP plugs: The bright blue curve with the abnormally high pressure readings for the two last data points, is impacted by the effect similar to non-Newtonian fluid behavior triggered by increased pump rates. The dark blue curve (5D PVP, 139.8 mm pipe, min flow) represents failure after using a constant pump rate of 2.4 l/h (0.7 ml/s).

It was expected that the dark blue curve would plot below the grey curve representing a pipe/plug combination with a smaller diameter. Bentonite is more stable in its plugging performance if it has to fill smaller “voids” after hydration which is directly related to the in situ moisture content [6]. The higher the final moisture content, the weaker the plugged section. The increased pressure volumes of the two last readings of the dark blue curve (alternative interpretation) are well above the 97.2 mm pipe results. This is caused by re-healing of the bentonite plugged section. The plug increases in strength after being disturbed due to the testing and later rehydration [6].

The most surprising result is the performance of the 5D PVP blend in the open hole simulation. The influence of high frictional forces associated with the rough surface area of the sandstone cylinder seems to be the dominant factor influencing the final failure. More research is needed to explain the observed high failure pressure gradient of this specific experiment.

5. Conclusions

Different failure modes depending on flow rates were identified during the hy-

draulic testing of the plugs using the Well Simulator Facility in the School of Chemical Engineering at UQ.

Frictional failure happens at the interface of the casing wall and bentonite plug and the entire plug is pushed out of the pipe. This happens only at high flow rates. Hydrated bentonite behaves similarly like a non-Newtonian Fluid while failing. A rapid pressure increase will trigger shear failure at the complete circumference of the plug at a high failure pressure.

Slow pumping creates single micro channels at the interface of the plug/steel pipe at much lower applied pressures. At low flow rates, failure modes are more complex and material/hydration time-dependent. The 5D bentonite hydrates more quickly than the 5A material. The hole in the center of the plugs is sealed earlier when using the 5D material.

The identification of the micro channeling effect influences the design for well abandonment planning. The lower failure pressure levels for gas compared to water detected in this study have to be taken into account for the abandonment planning of different well/reservoir types.

Failure pressures are roughly 50% higher for the bentonite/PVP blend plugs while using water than failure pressures using air. The failure gradients reported in **Table 2** are based on failure using water as the pumping medium. They have to be corrected to 50% lower pressure gradients for free gas containing wells.

The failure gradients shown in **Table 2** can be used for the design of abandonment operations using comparable plug/pipe diameters. The 5D PVP blend is easily able to withstand 69 bar (1000 psi) reservoir pressure in a 97.2 mm casing after installing a 30 m high plugged section, even after reducing the reported gradient by a 50% safety/contingency margin for the basis of design.

Nuclear magnetic resonance (NMR) experiments might help to create a better understanding of the process of the micro channeling generation. A future project should use this or an alternative suitable detection technique to try to map/visualize the growth of these channels at the interface of the plug/steel pipe during a hydraulic test.

Table 2. Failure gradients and calculated failure pressures for 30 m plugged sections for the tested plug/pipe combinations. 30 m of plugged pipe section is a standard height for abandonment operations in the drilling industry using cement.

experiment	failure pressure for a 30 m plugged section			
	failure gradient (bar/m)	failure gradient (psi/ft)	(bar)	(psi)
97.2 mm ID pipe, 5A PVP	3.2	14.1	96	1389
97.2 mm ID pipe, 5D PVP	5.9	25.9	176	2549
139.8 mm ID pipe, 5D PVP, min flow	6.8	29.9	811	2959
173.1 mm ID pipe, 5D PVP	0.7	3.1	21	306
sandstone cylinder, 5D PVP	21.1	93.3	633	9180

The reported results of this study allow detailed abandonment planning of different well types. This technology is suitable to be used securely for open hole or fully cased water, water monitoring, CSG wells and coal exploration wells.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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