

Stimulation of Gas Flows Using Nitrogen Injection

— ACARP C24019



The image shows two workers in a dark, underground tunnel. They are wearing orange high-visibility vests, blue hard hats, and safety glasses. One worker is holding a clipboard and a pen, while the other is looking at it. They are standing next to a large blue gas cylinder. In the background, there are two metal racks, each containing four white gas cylinders. The racks are labeled with numbers 1, 2, 3, and 4. The tunnel walls are made of concrete and there are large pipes overhead.

Ting Ren
University of Wollongong
Wollongong. 28th June 2017

Contents

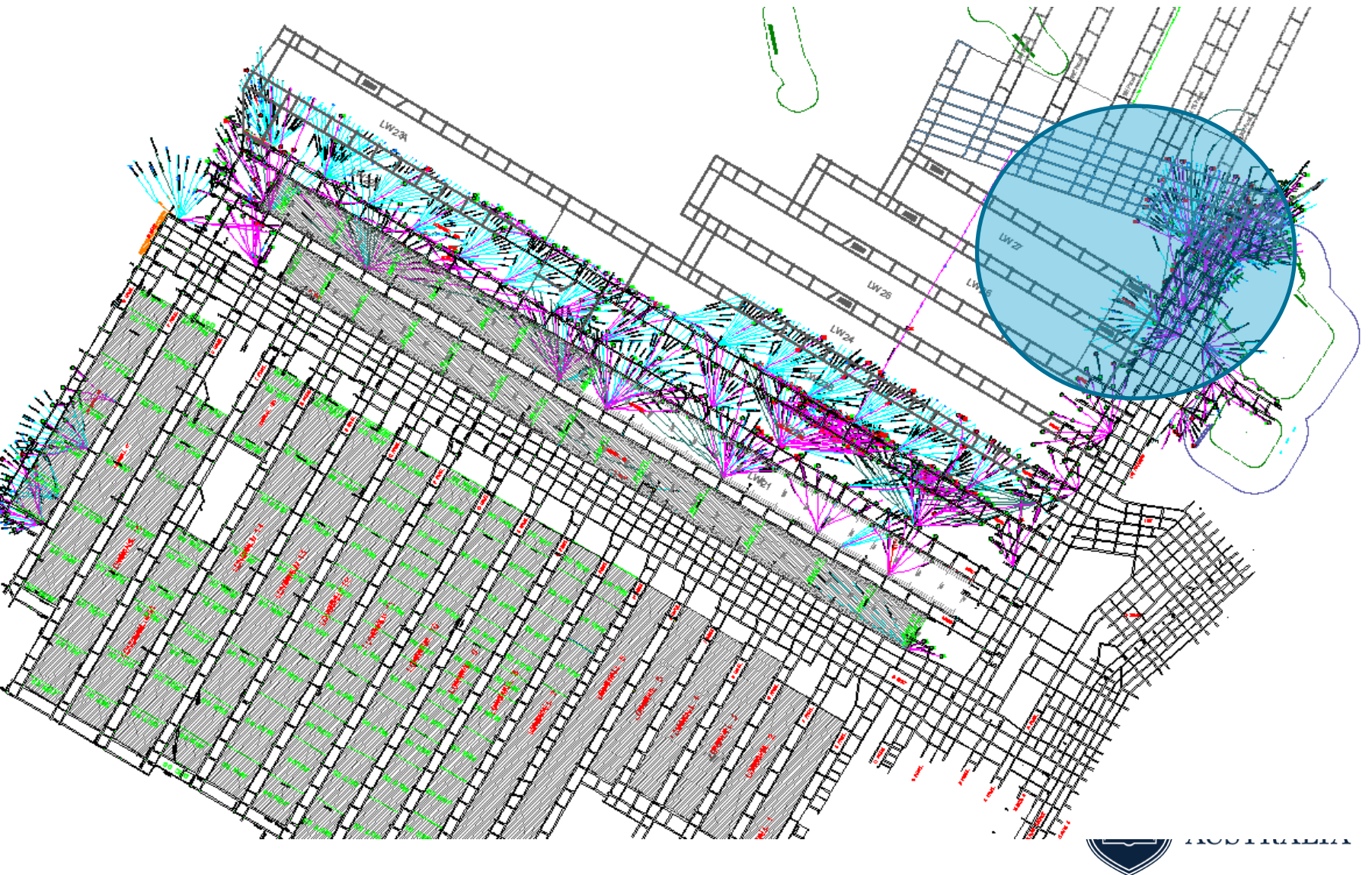
- Brief Background
- Field Trials and Results
- Laboratory Studies
- Numerical Simulations
- Summary

1. Project objectives

- ACARP Project C21019
- conduct field trials of nitrogen (N_2) flushing using UIS directional boreholes to demonstrate the effectiveness of such technology for enhanced gas recovery in hard-to-drain and low permeability seams.

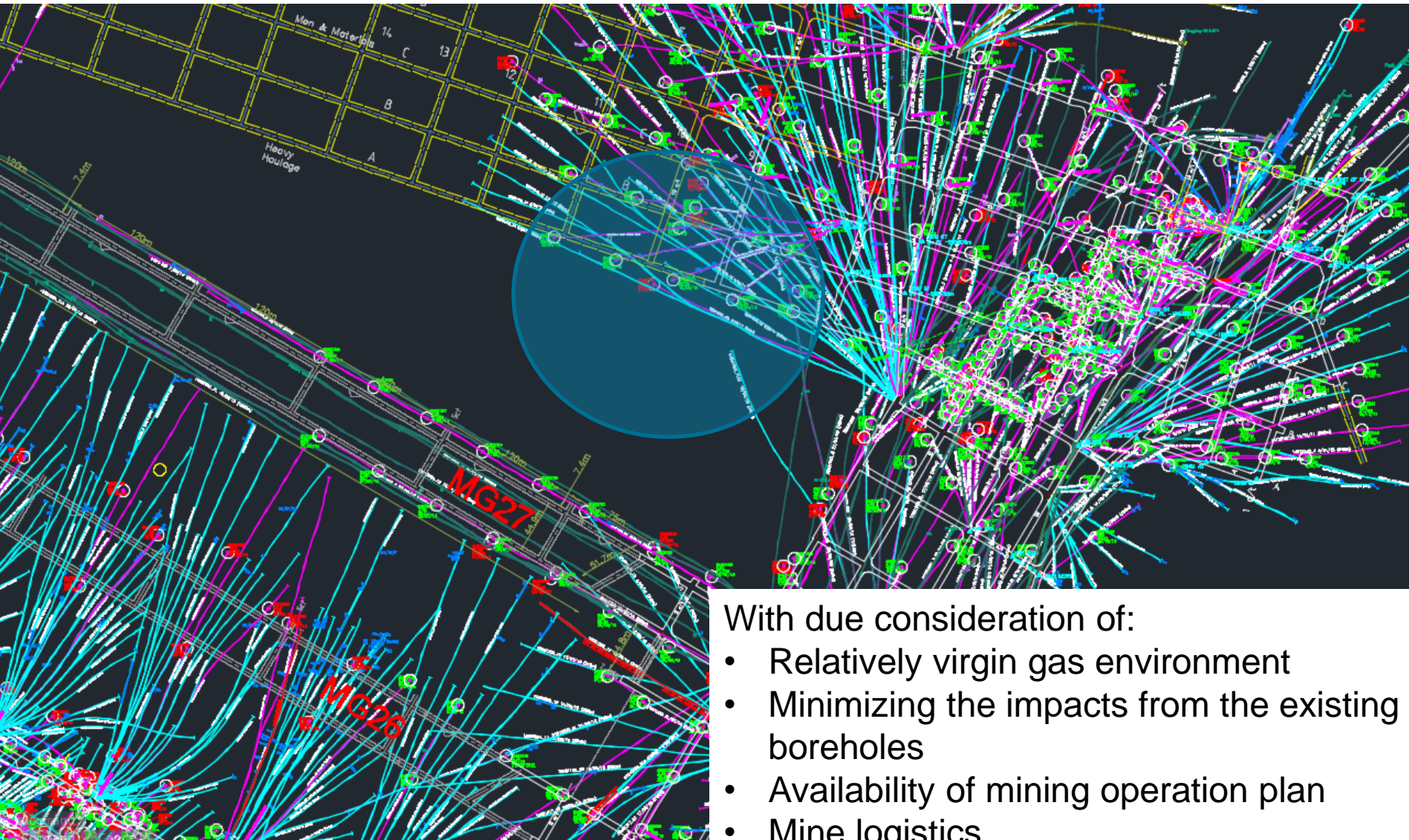
Field Trials - Site selection

Metropolitan Colliery



Field Trials - Site selection

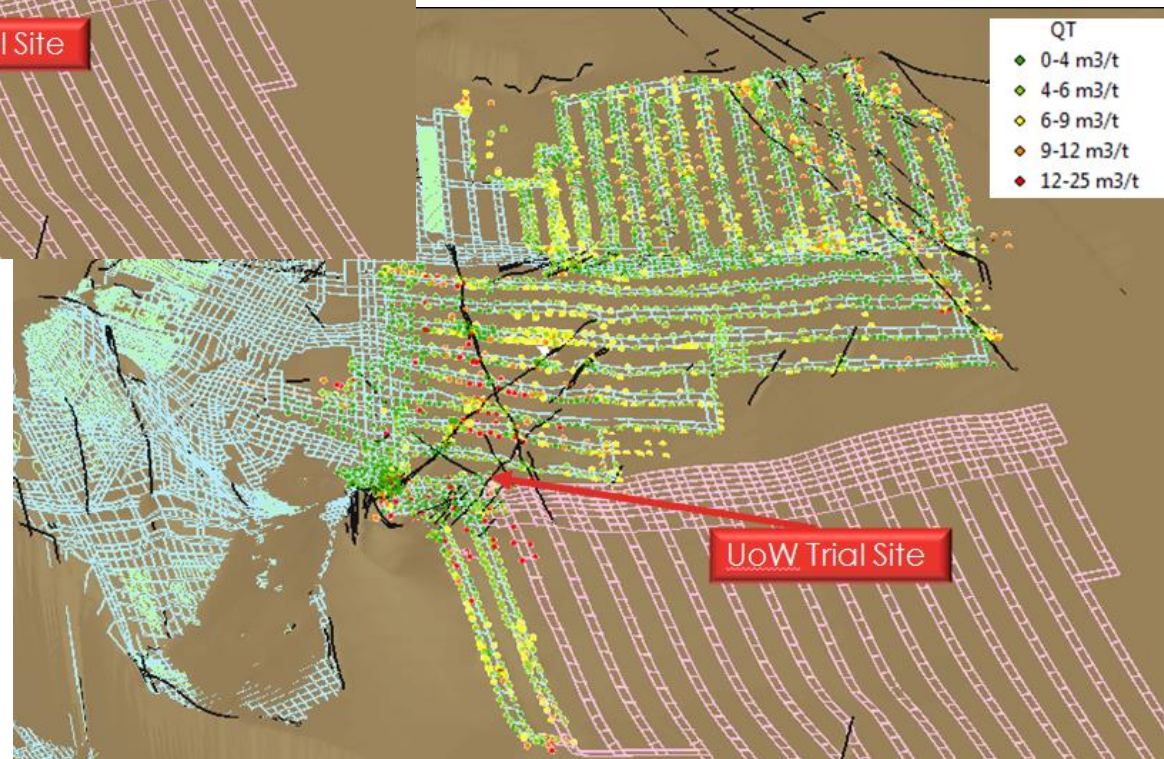
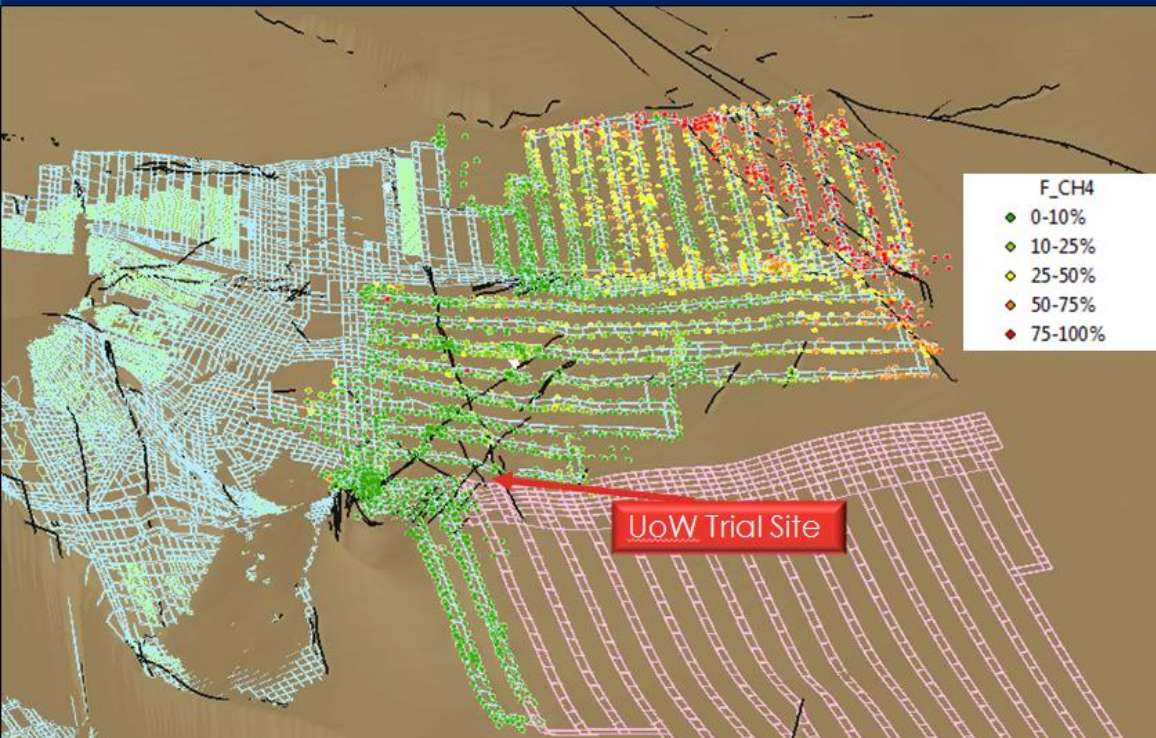
Metropolitan Colliery



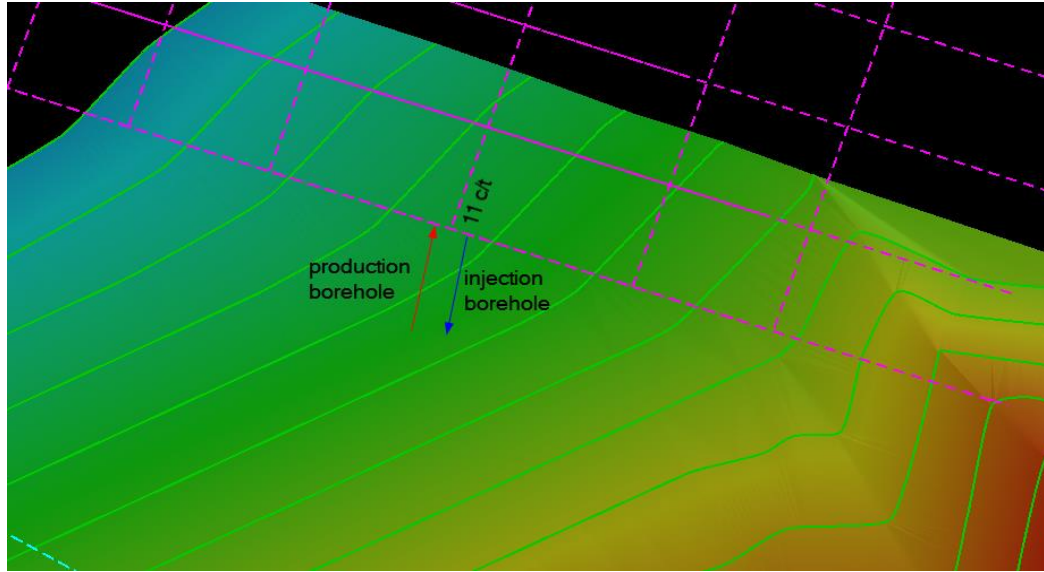
With due consideration of:

- Relatively virgin gas environment
- Minimizing the impacts from the existing boreholes
- Availability of mining operation plan
- Mine logistics

Field Trials - Site selection

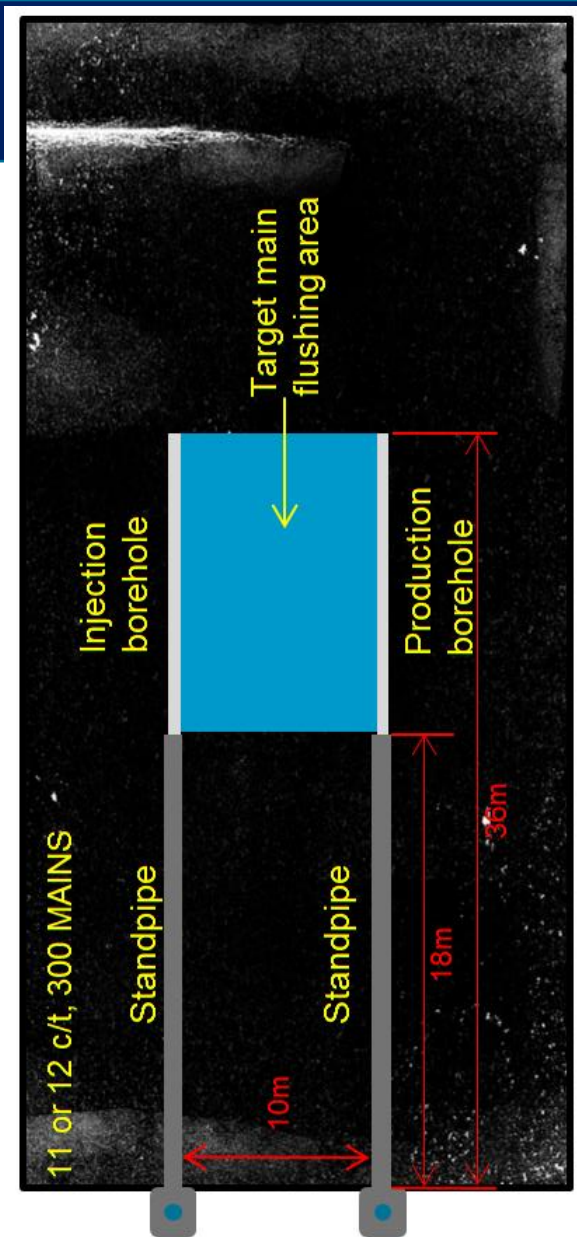


Field Trials - Borehole design



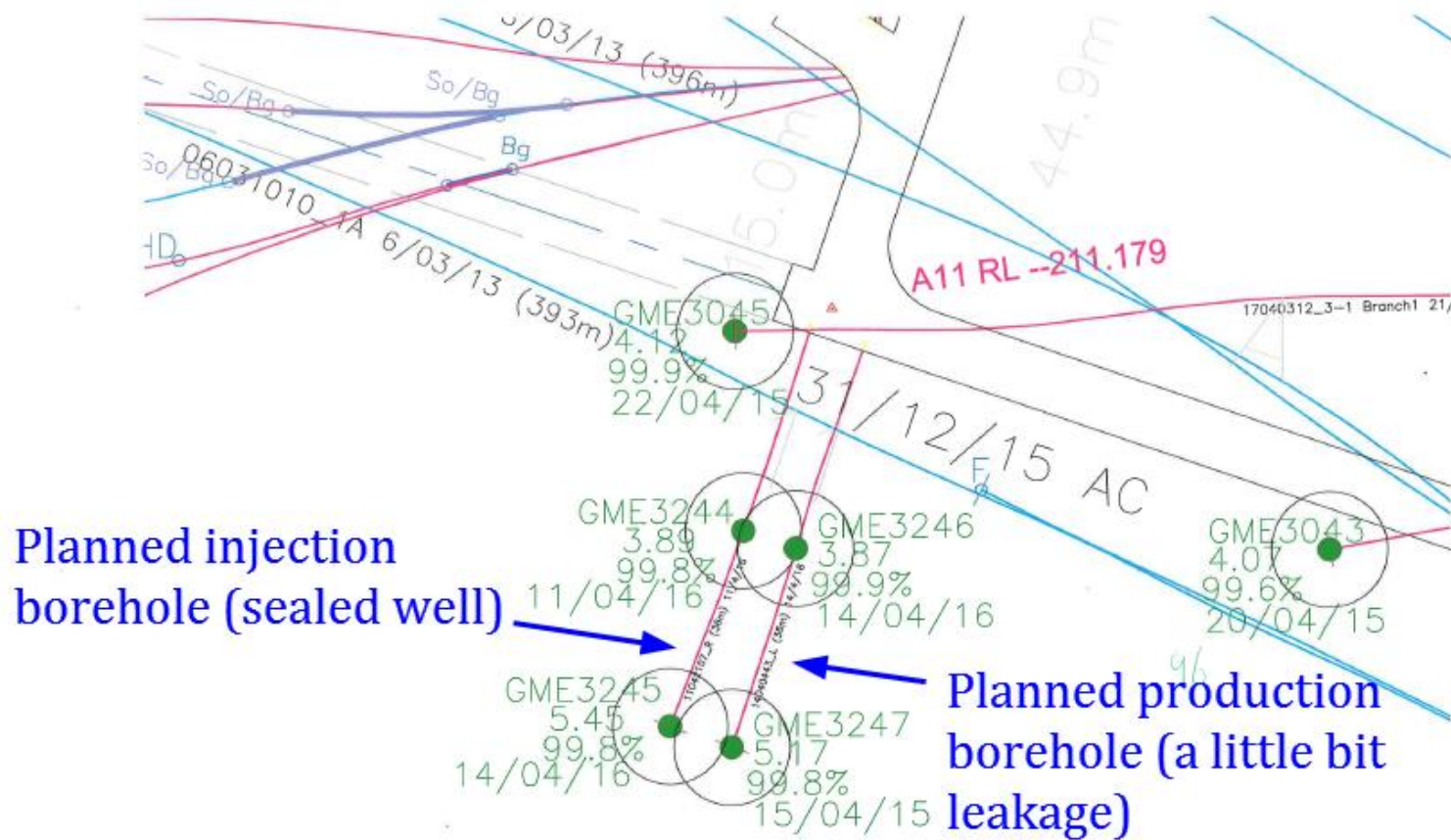
Borehole configuration:

- Two boreholes with spacing of 10m
- Borehole Length: 36m
- Borehole orientation and angle: vertical to rib
- Standpipe length: 18m
- Drilling method: Rotary or directional



Field Trials - Borehole drilling

- Two boreholes were drilled at 11c/t, 300 Mains
- Gas contents measured.



Field Trials - Borehole drilling

- Two boreholes were drilled at 11c/t, 300 Mains
- Gas contents measured.

ILLAWARRACOAL
Pride, passion, performance.

Gas Laboratory
Illawarra Coal Holdings
Coal
South32

TOTAL GAS CONTENT REPORT - INSEAM CORE

Report Number: GME3247	Issue Number: 1	Date of Issue: 18/04/2016
To: METROPOLITAN COLLIERY Helensburgh NSW 2508	Attention: Peter Jandzio	

Sample Location:

Colliery: METROPOLITAN	Seam: BULLI	Hole No: 14040443	Depth: 36.0 to 37.2 m
Collier Location: 300 MAINS AHDG 11C/T 198.8DEG LH SIDE 36M			
Time Cored: 01:18 - 01:26 hrs	Date Cored: 15 Apr 2016	Cored by: C. ROWE	
Comments:			

Gas Content (at 10% NCM):

Q1: 0.111 m³/t

Q2: 0.719 m³/t

Q3: 4.34 m³/t

QT: 5.17 m³/t

Desorption Rate: 35.7 mL/min*0.5/kg

IDR 30 Index: 0.217 m³/t



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Field Trials - Borehole drilling



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Field Trials - Borehole drilling



Field Trials - Nitrogen source

➤ initially we plan to use the TANKS.....

- a) Liquid nitrogen tank handling and transport induction was presented for UOW researchers and Metrop mine workers at the mine site on 06/07/2016;
- b) 3 tanks of liquid nitrogen were delivered to the mine and a trial of transport was conducted on 27/07/2016;
- c) Due to the concerns of safety issue from the mine workers, the selection of nitrogen sources was re-discussed and nitrogen gas bottle packs were decided to use instead of liquid nitrogen tank on 07/09/2016;



Field Trials - Nitrogen source

➤ Nitrogen Bottle from CoreGas:

- a) 8 Packs of 12-bottle nitrogen were delivered
- b) Corresponding accessories were prepared and inspected by the mine mechanical engineers.

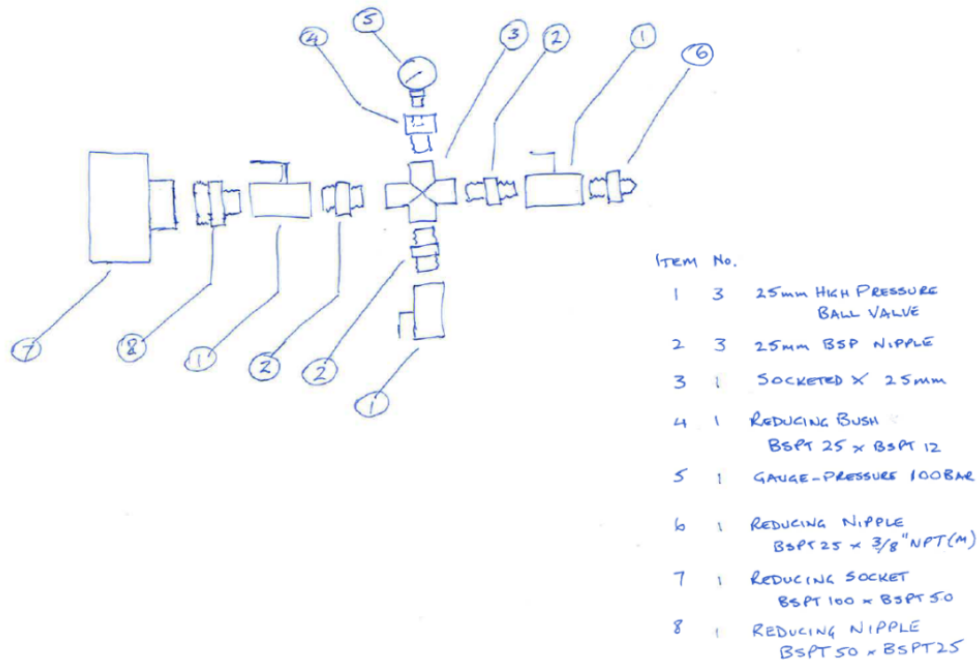
Size	6 pack	12 pack
Pressure, MPa	30	30
Contents, m ³	80	161
Weight (full), kg	607.92	1,180
Weight (empty), kg	515.0	995
Dimensions(Height), mm	1985	1985
Dimensions(Diam/Width), mm	709 X 510	1020 X 800



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Field Trials - Nitrogen injection pipes

Injection accessory was designed to conduct the nitrogen injection and match the standpipe on site at Metro



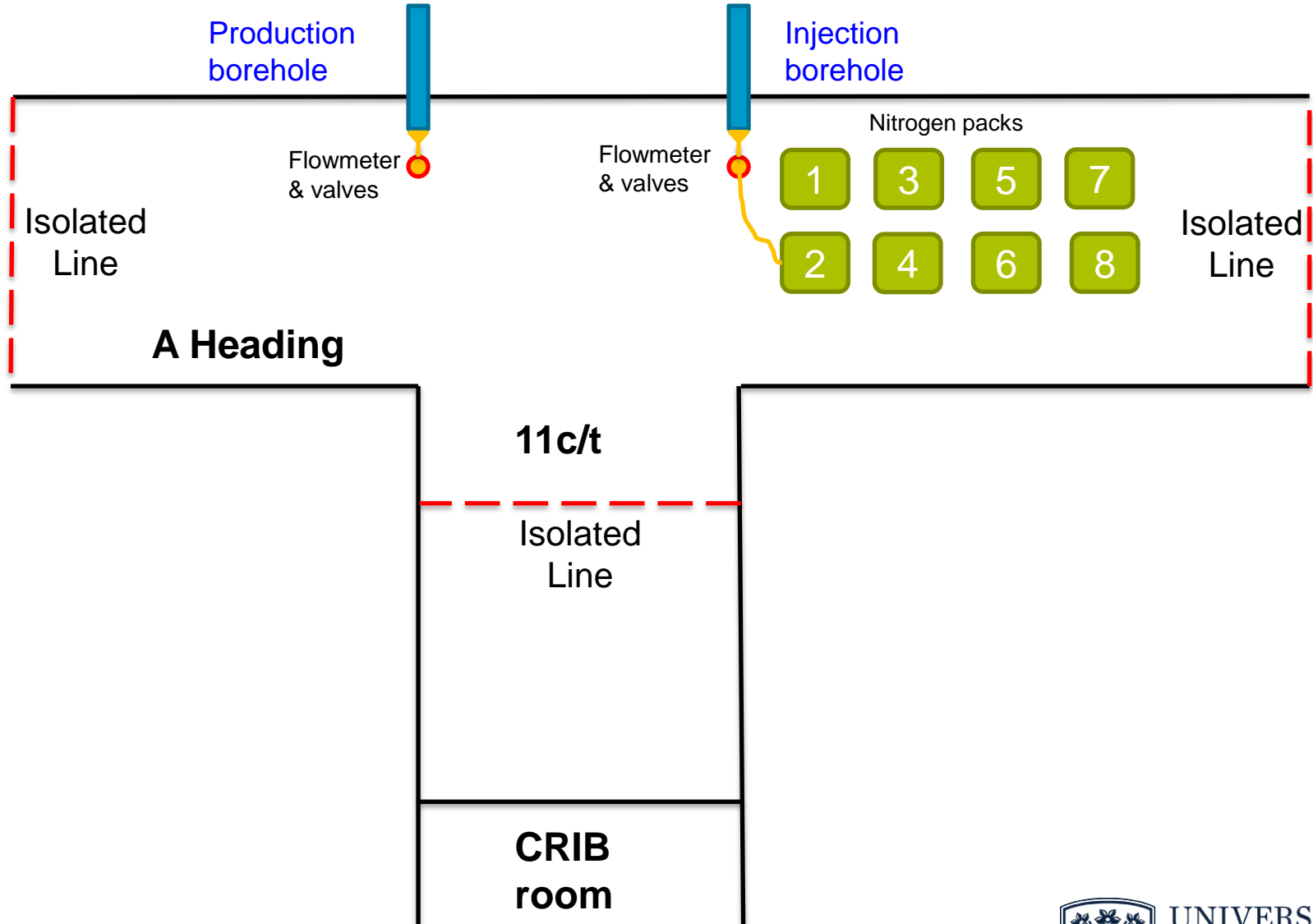
Field Trials - Nitrogen injection borehole sealing

An inflation packer was used to provide a better seal of the production hole before nitrogen flushing



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Field Trials - Site layout



Field Trials - Site layout



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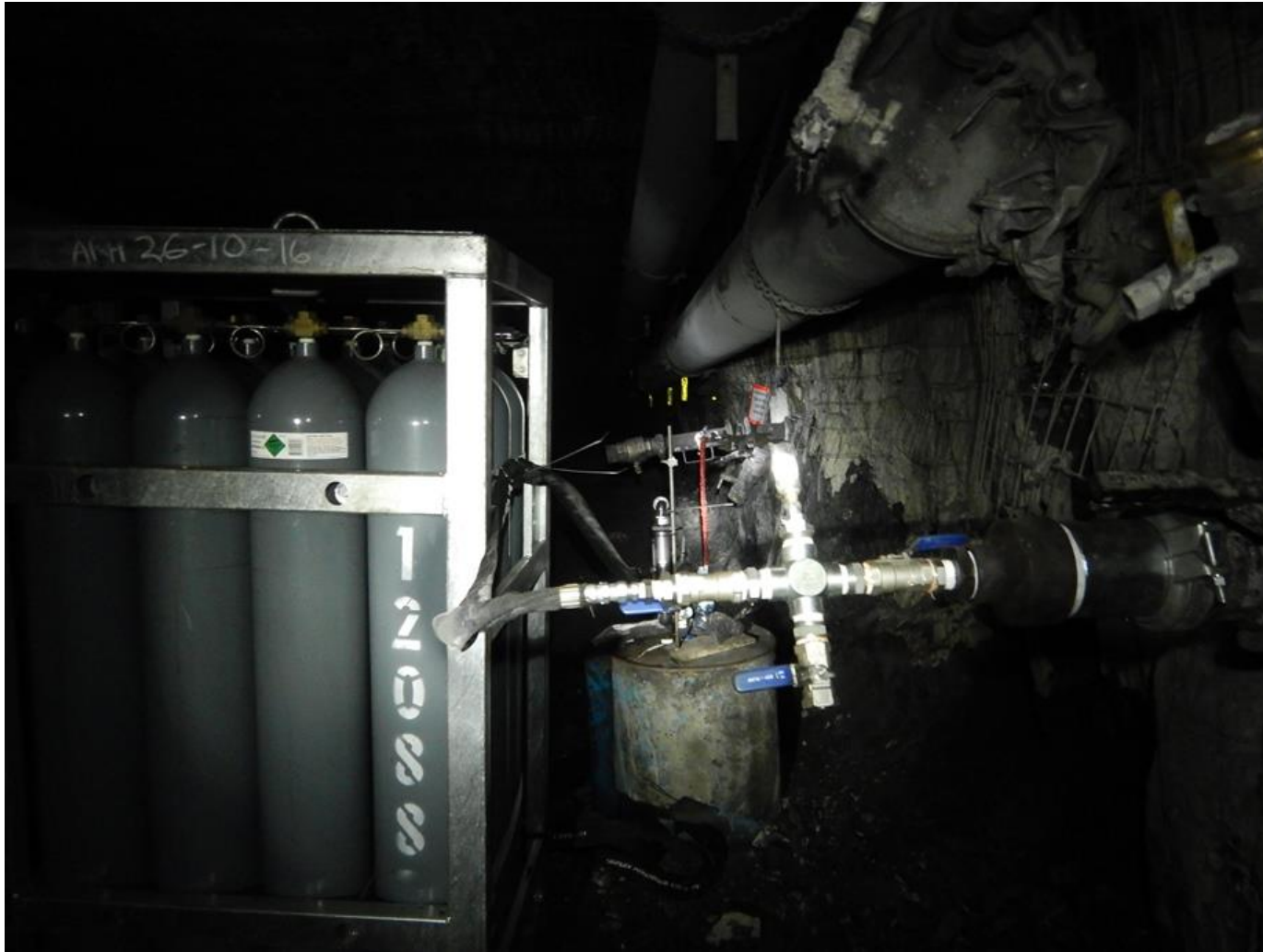
Field Trials - Site layout



Field Trials - Site layout



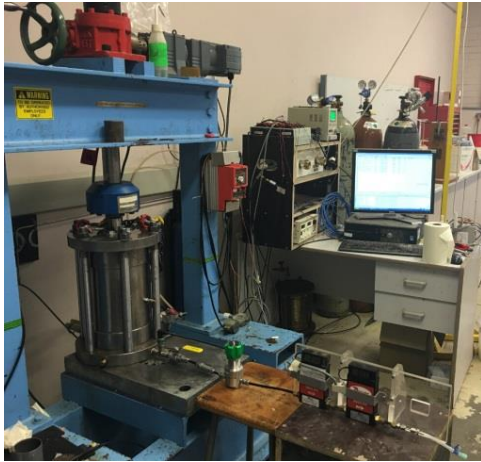
Field Trials - Site layout



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3. Summary of completed works

- ✓ **Laboratory nitrogen flushing tests:** Laboratory nitrogen flushing tests on cores were conducted to prove the effectiveness of such technology and to help optimize the design of field trial. Work included studied:
 - Different permeability scenarios
 - Nitrogen injection pressure
 - The replacement ratio of nitrogen to CO₂
 - The best involving time of nitrogen injection



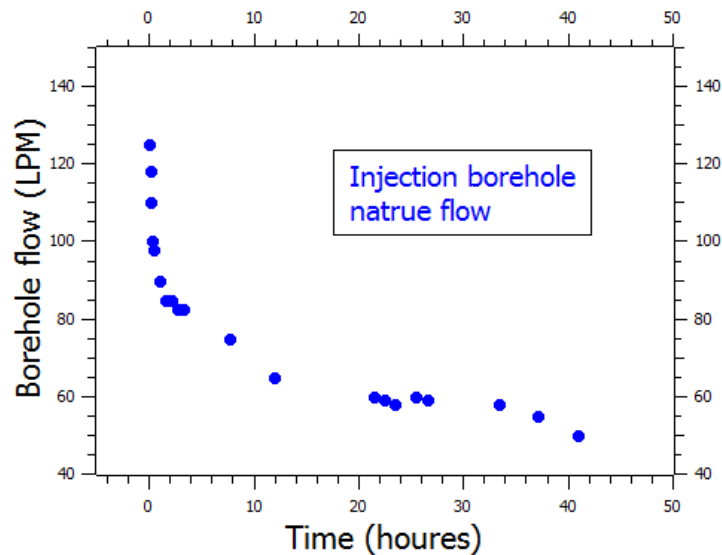
Setup of core flushing test apparatus with back pressure regulator and combined flow meter

Setup of syringe-GC gas composition analysis apparatus



Field Trials - before flushing

- a) No gas flow was observed from production borehole, indicating the gas around production hole had been leaked through fractures during the period of shut-in, or the borehole was blocked;
- b) Gas flow was observed from injection hole, the flow rate was recorded and gas samples were collected.



Gas composition of nature gas flow (AF=airfree)
from injection borehole:

Sample/date	N2(AF) %	CO ₂ (AF) %	CH ₄ (AF) %
01-25/10	0	99.8088804	0.191119552
02-25/10	0	99.8129021	0.187097904
03-25/10	0	99.8149599	0.185040056
01-26/10	0	99.8040786	0.195921372



Field Trials - Nitrogen flushing

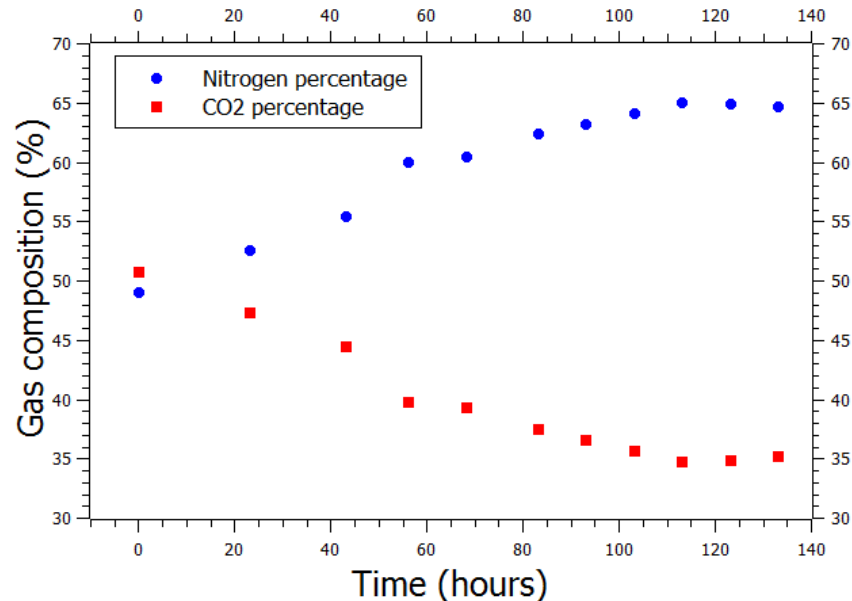
- **Four stages of nitrogen injection were carried out from 27 Oct to 21 Nov:**
 - ❖ **27 Oct:** *stage one*, 2 packs (around 300m³) of nitrogen were injected, gas samples from production borehole were collected during and after injection;
 - ❖ **07 Nov:** *stage two*, one and half packs (around 225m³) of nitrogen were injected, gas samples from production borehole were collected during and after injection;
 - ❖ **15 Nov:** *stage three*, water inflation packer was used to seal the borehole, five and half packs (around 825m³) of nitrogen were injected, gas flow from production borehole was measured and gas samples were collected during and after injection;
 - ❖ **21 Nov:** *stage four*, water inflation packer was used to seal the borehole, 1 pack (around 150 m³) of nitrogen was injected, gas flow from production borehole was measured and gas samples were collected during and after injection.



Field Trials - Results

1st Flushing :

- The production borehole has **0 flow** before injection
- Gas flow was observed at 400KPa of injection, indicating [UIS nitrogen injection can stimulate and activate gas desorption and subsequent gas flow ;](#)
- **35%~60%** CO₂ concentration was found in the produced gas.
- Under the current reservoir conditions and injection pressure (400KPa), the injected nitrogen can breakthrough in **45 mins**.



Field Trials - Results

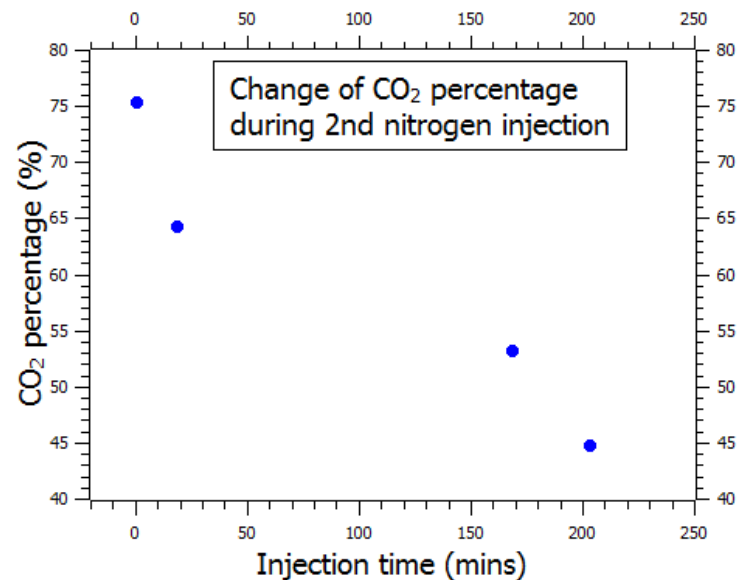
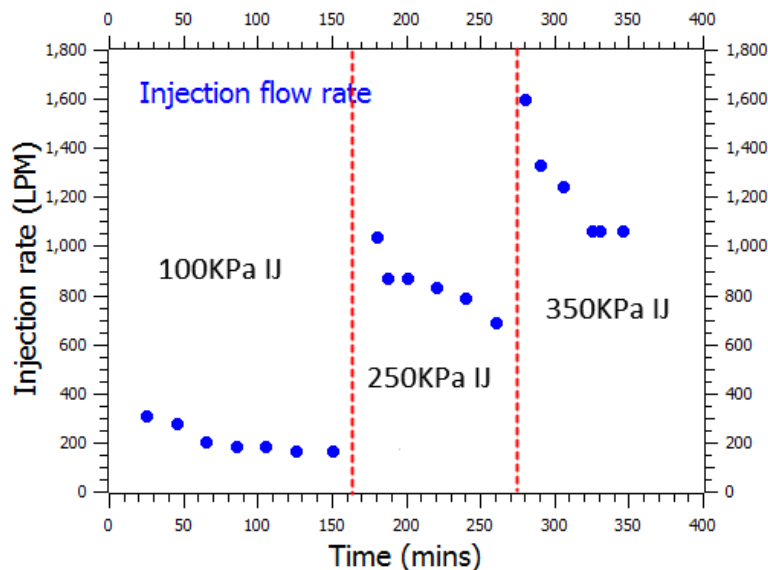
2nd Flushing :

Injection pressure at 100KPa, 250KPa and 350KPa were used, the injection rate and response of production borehole were recorded.

Note	Time (real)	Time (min)	Production flow	Pack regulator pressure	Borehole pressure	Flowmeter pressure	Flowmeter reading	Injection flow (corrected)	Pack pressure	Injection flow (back-calculated from pack)
Start	8:00	0	-						29	
	8:25	25	-	3	1.1	2.575	190	311.46	28	213.3333333
	8:45	45	-	2.5	1.3	2.6	170	280.02	27	266.6666667
	9:05	65	-	2	1.2	2.4	130	205.73	25	533.3333333
	9:25	85	-	2	1.2	2.4	120	189.91	23.5	400
	9:45	105	-	1.5	1.2	2.275	120	184.9	22.7	213.3333333
	10:05	125	-	1.5	1.2	2.275	110	169.49	21.5	320
	10:30	150	-	1.5	1.2	2.275	110	169.49	21	106.6666667
	11:00	180	0.6	10	2.7	5.525	-	-	16	1066.666667
	11:07	187	1	10	2.47	5.3525	370	874.47	14.5	1142.857143
	11:20	200	1.5	10	2.8	5.6	360	870.29	12.5	820.5128205
	11:40	220	out of range	9.5	2.81	5.4825	350	837.19	9.5	800
	12:00	240	out of range	9.5	2.8	5.475	330	788.81	6.5	800
	12:20	260	out of range	8	2.8	5.1	300	692.1	3.5	800
Stop to set up Q1 Kit										
Restart	13:20	0							32	
	13:30	10	1	10	2.4	5.3	-	-	29.5	1333.333333
Try to use Q1 kit	13:45	25	1.2	10	2.8	5.6	360	894.46?	26	1244.444444
take off flow meter	14:05	45	No response	12	3	6.25	-	-	22	1066.666667
	14:10	50	No response	12	3.2	6.4	-	-	21	1066.666667
	14:25	65	No response	12.5	3.35	6.6375	-	-	18	1066.666667

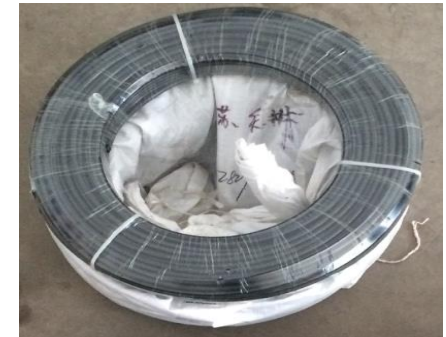
Field Trials - Results

- No gas was produced with 100KPa injection, indicating the effect of nitrogen injection may require a 'kickoff' pressure. Nitrogen injection rate drops quickly in each injection cycle
- Gas production at 250KPa injection exceeded the upper limit of small flow meter (1.5LPM), indicating the production rate increases quickly with continued injecting.
- At 350KPa injection, the 5L gas sample bag can be fully filled in around 20s, illustrating the produced gas flow was approximately 15LPM
- CO₂ percentage drops with continuing injection. that free CO₂ in fractures can be flushed out efficiently, CO₂ desorption rate dictates overall flushing effect.
- Higher injection pressure may not always be a better option.



Field Trials - Results

3rd Flushing: Water inflation packer was used to seal the borehole at 24m location (leaving 12m open borehole).



* ② means pack number 2 was used

* OOR means out of range

* GS1 means gas sample 1, the following time (Min:Sec) indicates the period of filling full sample bag (4.5L)

Time	Action	Nitrogen pack outlet pressure (KPa)	Nitrogen pack pressure (MPa)	Flow meter Reading (injection) (LPM)	Gauge pressure on Injection borehole (KPa)	Production flow (LPM)
08:00	Installation of water injection packer, the packer (1.5m) was pushed to 24m position from the drilling collar, left 12.5m open borehole	-	-	-	-	None
09:10	Start injection		②14		-	None
09:13	Step 1 1Kpa injection	400	-	270	80	None
09:17		400	-	200	110	None
09:24		300	-	185	120	None
09:39		250	-	160	120	None
10:00		200	②11	150	120	None
10:20		200	-	130	120	None
10:40		200	②10	110	120	None
11:00	Increase injection pressure	1000	-	OOO	200	None
11:10	Step 2 250KPa injection	1000	②8	360	220	None
11:15		800	-	320	230	None
11:20		1000 (increased)	②5.5	360	230	None
11:30		700 (pack pressure low)	②3	290	230	0.2
11:40		600(pack pressure low)	②2	230	210	
11:45		1000 (new pack change over)	③31	OOO	220	0.3
12:00		1000	③27.5	OOO	280	1.0
12:20		800 (reduced)	③24	330	260	1.5 (GS1)
12:43		800	③19	320	270	OOO
13:02		800	③17	320	270	OOO
13:25		800	③14	320	280	GS2 (sample bag method used) 1:15 1:18
13:45		800	③11	310	280	GS3 1:15 1:05
14:00		800	③9.5	310	280	GS4 1:10 1:05
14:12	Increase pressure	1300	③8.2	get rid of flow meter	300	-
14:28		1100 (pack	③3.8	-	300	GS5

Event logs of third step of UIS nitrogen injection

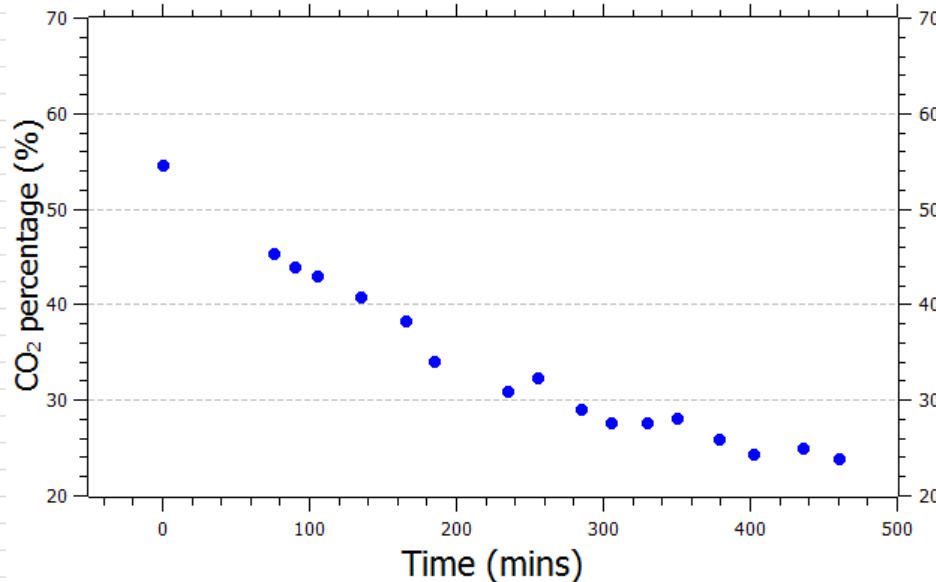
		pressure low)				1:00 0:55
14:43	Step 3 400KPa injection	700	②1.8	-	260	
14:46		1600 (change over new pack)	④30.5	-	300	
15:00		1700	④24	-	380	GS6 1:00 0:55
15:20		1800	④19	-	400	GS7 0:50 0:53
15:47		1600	④11	-	400	
16:12		1000 (pack pressure low)	④7	-	350	GS8 0:25 0:27
16:31		700(pack pressure low)	④5	-	300	GS9 0:27 0:27
16:36	Increase pressure	1800(change over new pack)	⑤31	-		
17:01	Maximum flow injection	1800	⑤21	-	430	GS10 0:25 0:20 0:26
17:23		1800	⑤15.5	-	440	GS11 0:20 0:20
17:45		1400(pack pressure low)	⑤10	-	390	GS12 0:22 & 0:22
18:05		1000(pack pressure low)	⑤7	-	340	GS13 0:23 & 0:23
18:13		2000(change over new pack)	⑥30.5	-	-	-
18:33		2000	⑥20.5	-	440	30 (biggest flow meter used)
18:46		2000	⑥16.5	-	460	33
19:00		2000	⑥13	-	460	GS15 35
19:06		change over new pack found leakage of pack ⑦	-	-	-	-
19:11		1600 (change over new pack)	⑥31	-	-	-
19:25		1800	⑥26	-	430	GS16 31
19:40		1800	⑥20	-	440	33
20:00	Stop injection	1800	⑥14	-	440	GS17 31



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Field Trials - Results

Time(actual)	Time	External standard				Normalized & Air free				AVE			
		O2	N2	CO2	Methane	N2	CO2	Methane		N2	CO2	Methane	
	12-15sample1	2.363	47.42	46.87	0.061	38.65327	45.16399	54.76474	0.071275	0	45.31498	54.61341	0.071607
		2.344	47.249	46.181	0.061	38.55276	45.46597	54.46209	0.071938				
	13-30sample2	2.051	54.933	39.17	0.048	47.32379	54.68317	45.26137	0.055465	75	54.60434	45.34027	0.055391
		2.037	54.87	39.411	0.048	47.31273	54.52551	45.41917	0.055318				
	13-45sample3	2.628	56.433	36.957	0.045	46.68312	55.78425	44.16197	0.053773	90	55.90482	44.04137	0.053815
		2.638	56.599	36.698	0.045	46.81202	56.02538	43.92076	0.053857				
	14-00sample 4	1.30	55.18	38.038	0.045	51.3041	55.80318	43.14508	0.05084	105	56.83514	43.11402	0.050847
			0	100	200	300	400	500					
	14-30 sample5									135	59.12456	40.82919	0.04625
	15-00sample6									165	61.68681	38.27115	0.042036
	15-20 sample7									185	65.84169	34.12407	0.034245
	16-10sample8									235	68.947	31.02261	0.030382
	16-30sample9									255	67.63877	32.32718	0.034044
	17-00sample10									285	70.85524	29.11719	0.027577
	17-20sample11									305	72.36482	27.60977	0.025413
	17-45sample12									330	72.28862	27.68608	0.025302
	18-05sample13									350	71.82691	28.1457	0.027391
	18-34sample14									379	73.99285	25.9839	0.02325
	18-57sample15									402	75.56788	24.40946	0.022658
		3	74.525	20.442	0.019	63.395	75.59984	24.3175	0.022658				
	19-31sample16	2.746	73.849	21.317	0.02	63.66134	74.89716	25.07931	0.02353	436	74.88665	25.0898	0.023545
		2.774	73.852	21.307	0.02	63.56046	74.87615	25.10029	0.023561				
	19-55sample17	2.95	74.912	20.167	0.019	63.9675	76.01288	23.96454	0.022578	460	76.00481	23.97321	0.021971
		2.952	74.98	20.205	0.018	64.02808	75.99675	23.98189	0.021365				

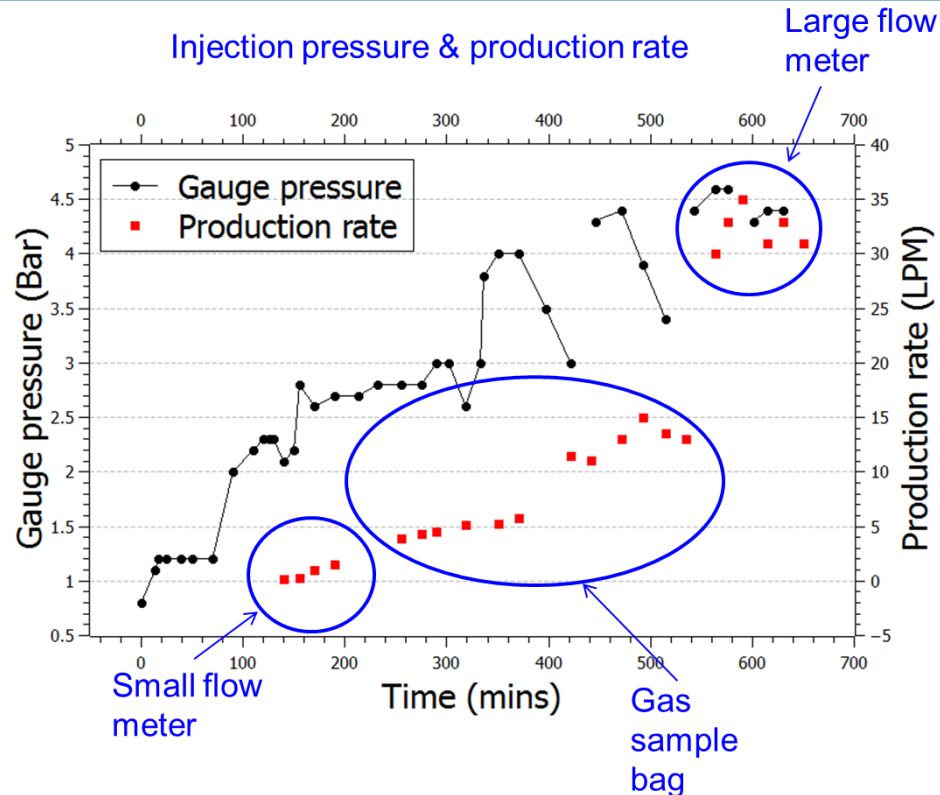


Change of CO₂ percentage during nitrogen injection



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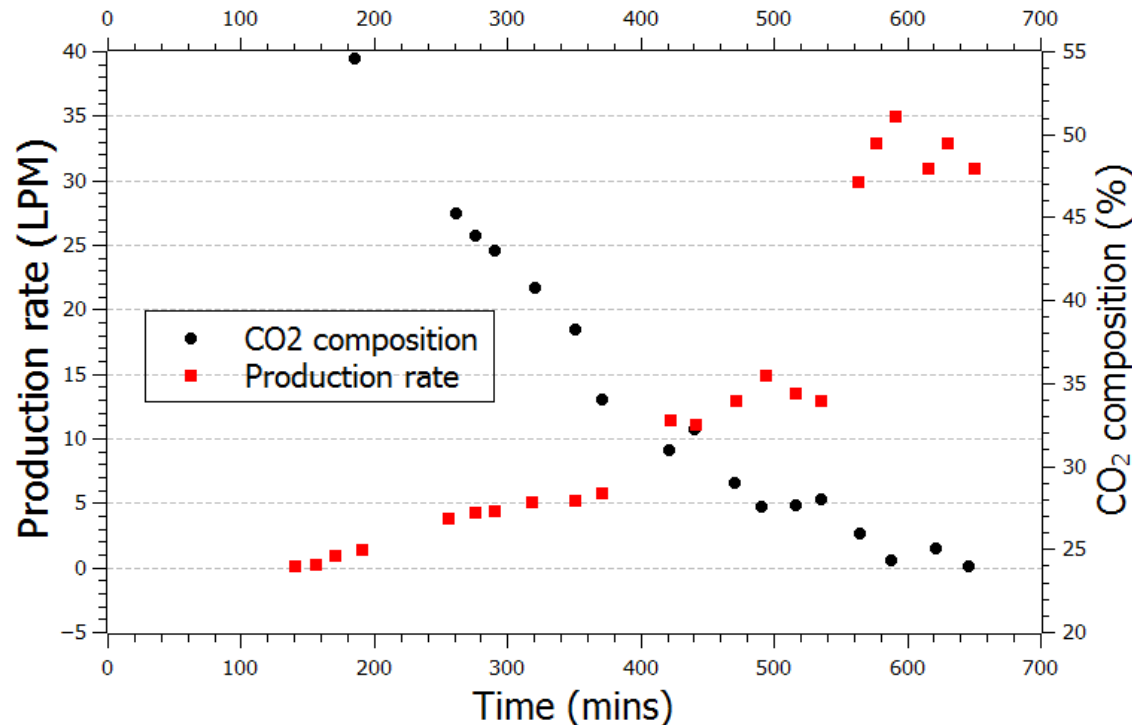
Field Trials - Results



Injection pressure & production rate

- Production gas flow was measured by flow meters and gas sample bags;
- No gas production was observed with 100KPA injection, which confirms the 'kickoff' pressure assumption;
- The higher the injection pressure was, the greater the production flow was.

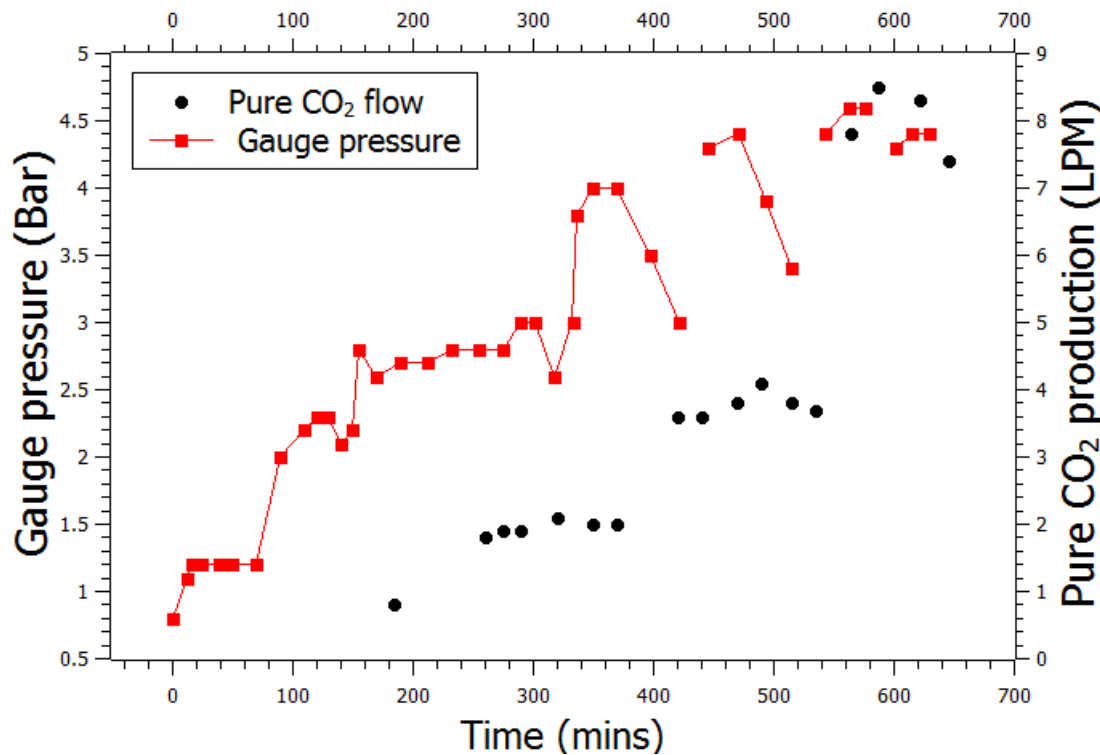
Field Trials - Results



Production rate
& CO₂ composition

- CO₂ percentage continued to drop during the entire injection process (from 55% to 25%), the desorption rate again became the constraint of flushing effect;
- CO₂ production became stable at the late injection stage, even the production rate increased sharply.

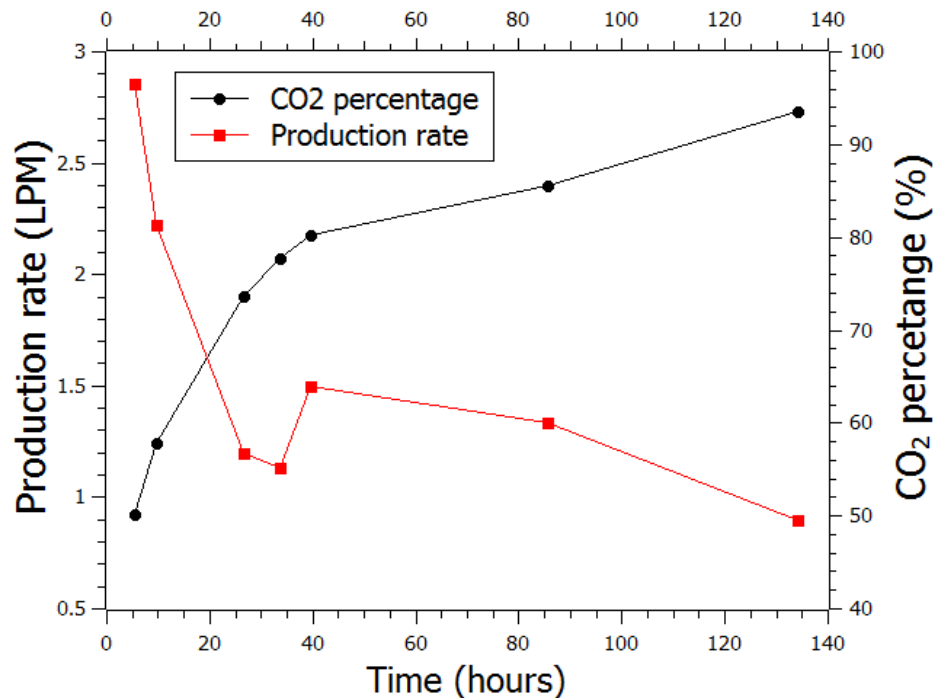
Field Trials - Results



Injection pressure &
pure CO₂ production rate

- i) Although the CO₂ percentage of the produced gas kept dropping, the pure CO₂ flow was almost stable at each injection pressure step;
- j) The higher the injection pressure was, the greater the pure CO₂ production flow was;

Field Trials - Results



Subsequent flow rate & composition after stopping injection

- k) After stopping injection, production flow continued to flow for 5 days and apparent flow was still observed before injection stage four. Comparing to the injection time (10 hours), strong post flushing effect was observed!
- l) The production rate dropped by 2/3 in these 5 days, however the CO₂ percentage of the production gas recovered to 90%.

Field Trials - Results

4th Flushing: Pulse injection.

* ② means pack number 2 was used

* OOR means out of range

* GS1 means gas sample 1

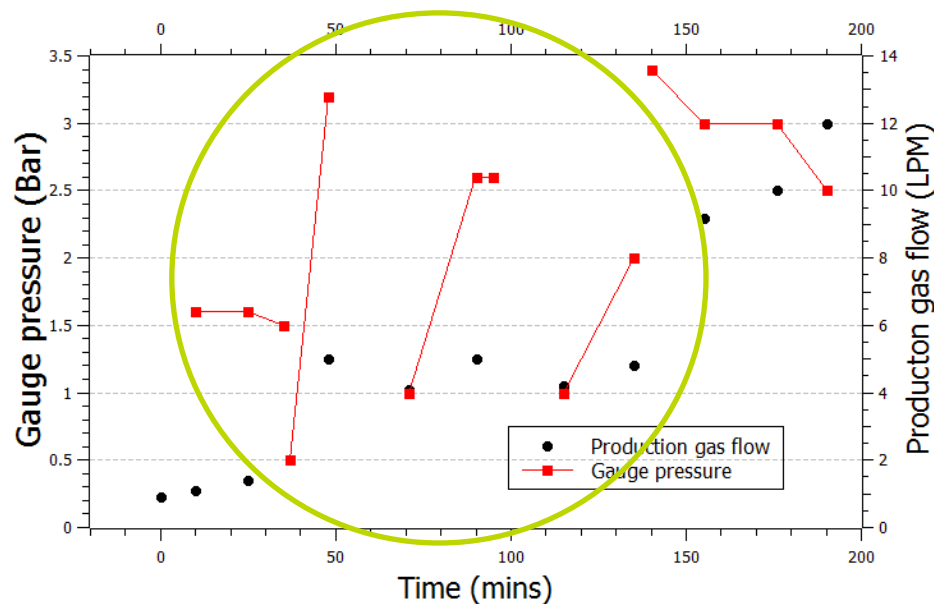
Time	Action	Nitrogen pack outlet pressure (KPa)	Nitrogen pack pressure (MPa)	Gauge pressure on Injection borehole (KPa)	Production flow (LPM)
10:13	Arrive site, get the first sample before injection	-	-	-	GS1 3min 2.7L
10:15	Start injection	1000	⑤6.7	-	
10:25		800	⑤6	160	GS2 3min 3.24L
10:40		600	⑤4.5	160	GS3 3min 4.1L
10:50		400	⑤3.5	150	
10:52	Pack change over	1500	⑥12	-	
11:03	Stop injection for pulse test		⑥9.5	320	GS4 1min 5L
11:26	Resume injection	1300	⑥6	100	GS5 1min 4.1L
11:45		1000	⑥6	260	GS6 1min 5L
11:50	Stop injection for pulse test	-	⑥5.5	260	
12:10		-	⑥5.5	100	GS7 1min 4.2L
12:30		-	⑥4	200	GS8 1min 4.8L
12:35	Change over to pack 8	1500	⑧15.5	-	
12:50		1500	⑧10.5	340	GS9 30s 4.6L
13:11		1000	⑧7	300	GS10 30s 5L
13:25	Stop injection	700	⑧5	270	GS10 20s 4L

Event logs of fourth step of UIS nitrogen injection

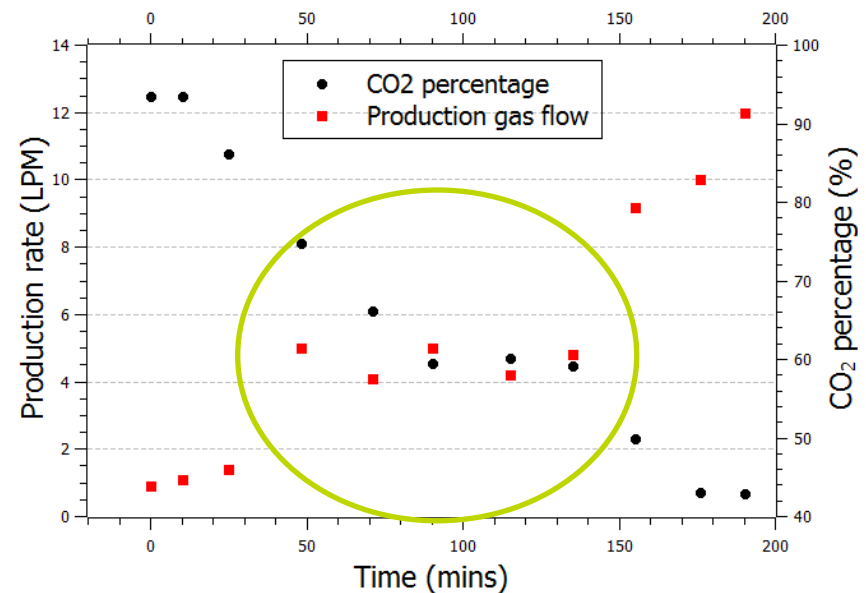


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Field Trials - Results



Injection pressure
& production rate



Production rate & CO₂ percentage

- A relatively high and stable CO₂ percentage & flow can be obtained by using pulse injection;
- Pulse injection provides extra desorption time for the coal seam, also effective use of nitrogen and improves overall flushing efficiency.

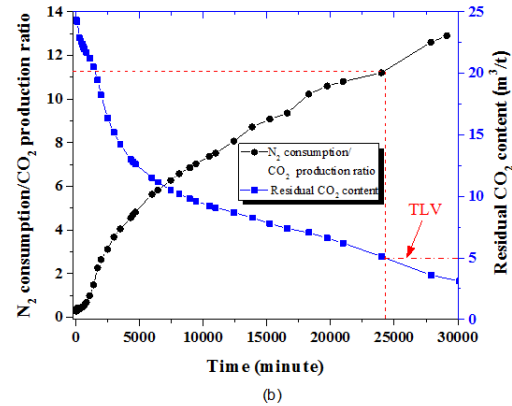
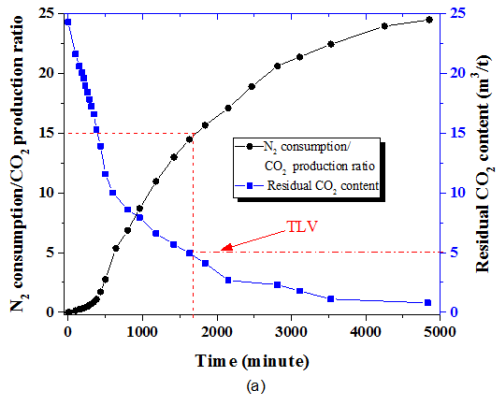
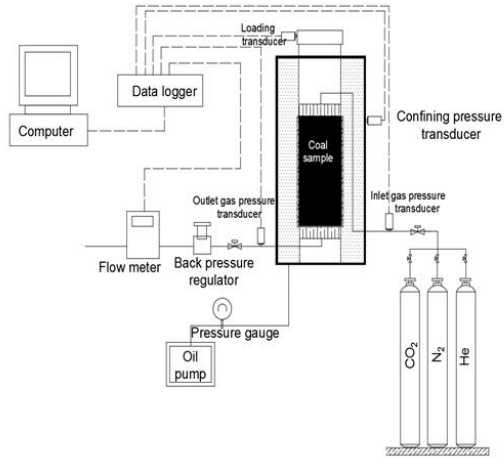
Field Trials - Summary

- Nitrogen flushing can accelerate the gas flow between the injection and production boreholes;
- Production flow is in proportion to the injection pressure. A 'kickoff' pressure may be required to active the flushing effect (100~250KPa in this case);
- Borehole quality may have great impacts on the flushing result;
- The produced gas contains a large percentage of CO₂, indicating the coal seam gas can be successfully flushed out;
- CO₂ percentage in the produced gas drops with continuing injection, showing desorption rate may become a constraint of flushing effect when gas content is low;
- The pulse injection method could enhance the flushing efficiency, the best injection mode (pressure & pulse interval) requires further studies.

Other studies

Lab testing and reservoir simulations

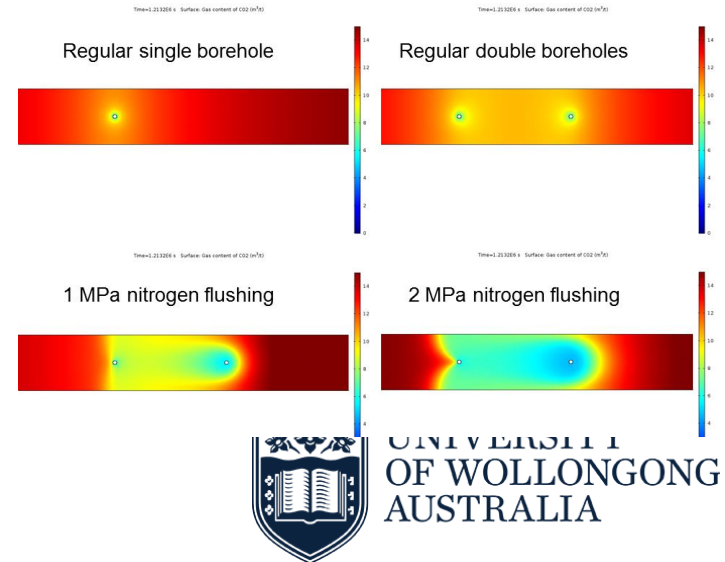
- **N₂ flushing CO₂ test**



$$\begin{aligned} 1 \quad & \left[\phi_m \frac{M_1}{RT} + \rho_c \rho_{gs1} \frac{V_{L1} b_1 (1 + b_2 P_{m2})}{(1 + b_1 P_{m1} + b_2 P_{m2})^2} \right] \frac{\partial P_{m1}}{\partial t} - \rho_c \rho_{gs1} \frac{V_{L1} b_1 b_2 P_{m1}}{(1 + b_1 P_{m1} + b_2 P_{m2})^2} \frac{\partial P_{m2}}{\partial t} \\ & = -D_1 \frac{3\pi^2 M_1}{l^2} \frac{1}{RT} (P_{m1} - P_{f1}) \end{aligned}$$

$$\begin{aligned} 2 \quad & \left[\phi_m \frac{M_2}{RT} + \rho_c \rho_{gs} \frac{V_{L2} b_2 (1 + b_1 P_{m1})}{(1 + b_1 P_{m1} + b_2 P_{m2})^2} \right] \frac{\partial P_{m2}}{\partial t} - \rho_c \rho_{gs} \frac{V_{L2} b_1 b_2 P_{m2}}{(1 + b_1 P_{m1} + b_2 P_{m2})^2} \frac{\partial P_{m1}}{\partial t} \\ & = -D_2 \frac{3\pi^2}{L^2} \frac{M_2}{RT} (P_{m2} - P_{f2}) \end{aligned}$$

$$\begin{aligned} 3 \quad & (\phi_f + P_{f1} \frac{1}{K}) \frac{\partial P_{f1}}{\partial t} + P_{f1} \frac{1}{K} \frac{\partial P_{f2}}{\partial t} + P_{f1} (\beta - 1) \frac{\varepsilon_{L1} b_1 + (\varepsilon_{L1} - \varepsilon_{L2}) b_1 b_2 P_{m2}}{(1 + b_1 P_{m1} + b_2 P_{m2})^2} \frac{\partial P_{m1}}{\partial t} + \\ & P_{f1} (\beta - 1) \frac{\varepsilon_{L2} b_2 + (\varepsilon_{L2} - \varepsilon_{L1}) b_1 b_2 P_{m1}}{(1 + b_1 P_{m1} + b_2 P_{m2})^2} \frac{\partial P_{m2}}{\partial t} = -\nabla \left(\frac{P_{f1}^k}{\mu_1} \nabla P_{f1} \right) + D_1 \frac{3\pi^2}{L^2} (P_{m1} - P_{f1}) \\ 4 \quad & P_{f2} \frac{1}{K} \frac{\partial P_{f1}}{\partial t} + (\phi_f + P_{f2} \frac{1}{K}) \frac{\partial P_{f2}}{\partial t} + P_{f2} (\beta - 1) \frac{\varepsilon_{L1} b_1 + (\varepsilon_{L1} - \varepsilon_{L2}) b_1 b_2 P_{m2}}{(1 + b_1 P_{m1} + b_2 P_{m2})^2} \frac{\partial P_{m1}}{\partial t} + \\ & P_{f2} (\beta - 1) \frac{\varepsilon_{L2} b_2 + (\varepsilon_{L2} - \varepsilon_{L1}) b_1 b_2 P_{m1}}{(1 + b_1 P_{m1} + b_2 P_{m2})^2} \frac{\partial P_{m2}}{\partial t} = -\nabla \left(\frac{P_{f2}^k}{\mu_2} \nabla P_{f2} \right) + D_1 \frac{3\pi^2}{L^2} (P_{m2} - P_{f2}) \end{aligned}$$



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