Appendix 1: Chemicals of low concern per the National Chemicals Assessment

A-1.1 National Chemicals Assessment

	CAS RN	CAS Chemical Name	Common Name
1	10377-60-3	Nitric acid, magnesium salt (2:1)	Magnesium nitrate
2	11138-66-2	Xanthan gum	
3	124-38-9	Carbon dioxide	
4	127-09-3	Acetic acid, sodium salt (1:1)	Sodium acetate
5	1302-78-9	Bentonite	Bentonite clay
6	1317-65-3	Limestone	Limestone
7	144-55-8	Carbonic acid sodium salt (1:1)	Sodium bicarbonate, baking soda
8	14807-96-6	Talc (Mg ₃ H ₂ (SiO ₃) ₄)	Talc
9	25038-72-6	2-Propenoic acid, methyl ester, polymer with 1,1-dichloroethene	Vinylidene chloride, methyl acrylate polymer
10	463-79-6	Carbonic acid	Carbonated water
11	533-96-0	Carbonic acid, sodium salt (2:3)	Sodium sesquicarbonate
12	56-81-5	1,2,3-Propanetriol	Glycerol
13	6381-77-7	D-erythro-Hex-2-enonic acid, γ-lactone, sodium salt (1:1)	Sodium erythorbate
14	67-48-1	Ethanaminium, 2-hydroxy-N,N,N- trimethyl-, chloride (1:1)	Choline chloride
15	68130-15-4	Guar gum, carboxymethyl 2- hydroxypropyl ether, sodium salt	Sodium carboxymethyl hydroxypropyl guar
16	7447-40-7	Potassium chloride (KCI)	Sylvite
17	7647-14-5	Sodium chloride (NaCl)	Common salt
18	7727-37-9	Nitrogen	Nitrogen
19	7727-43-7	Sulfuric acid, barium salt (1:1)	Barium sulfate
20	7732-18-5	Water	Water
21	7757-82-6	Sulfuric acid sodium salt (1:2)	Sodium sulfate

Table A1- 1 Chemicals identified as of low concern for human health (NICNAS 2016c)

	CAS RN	CAS Chemical Name	Common Name
22	7758-16-9	Diphosphoric acid, sodium salt (1:2)	Sodium pyrophosphate
23	7778-80-5	Sulfuric acid potassium salt (1:2)	Potassium sulfate
24	7783-20-2	Sulfuric acid ammonium salt (1:2)	Ammonium sulfate
25	7786-30-3	Magnesium chloride (MgCl ₂)	
26	77-92-9	1,2,3-Propanetricarboxylic acid, 2-hydroxy-	Citric acid
27	9000-30-0	Guar gum	Guar gum
28	9000-70-8	Gelatins	Gelatins
29	9003-05-8	2-Propenamide, homopolymer	
30	9003-06-9	2-Propenoic acid, polymer with 2-propenamide	Polyacrylamide
31	9004-62-0	Cellulose, 2-hydroxyethyl ether	Hydroxyethyl cellulose
32	n.s.	Natural fibres I	
33	n.s.	Natural fibres II	
34	CBI	Natural fibres III	
35	n.s.	Nut hulls	
36	CBI	Polyacrylamide/polyacrylate copolymer	
37	n.s.	Polyanionic cellulose PAC	
38	n.s.	Polyesters	
39	CBI	Polymer I	
40	CBI	Polymer II	
41	СВІ	Polysaccharide	
42	n.s.	Walnut hulls	
43	n.s.	Wood dust	
44	n.s.	Wood fibre	

n.s. = not specified; CBI = confidential business information

A1-2 IMAP Tier I assessment

For chemicals not considered to pose an unreasonable risk to the health of workers and public health per the IMAP Tier I assessment see EXCEL database (IMAP Human Health Tier-1 tab)

For chemicals not considered to pose an unreasonable risk to the environment from their industrial use per the IMAP Tier I assessment see EXCEL database (Tier-1 Environment tab and Tier-1 Environment Provision tab).

Appendix 2: Hydraulic head gradients at the Narrabri Gas Project



Figure A2 - 1 Hydraulic head gradients 100 years after commencement of CSG production for cells of the Santos Narrabri Gas Project. CSG production lasted for 26 years.



Figure A2 - 2 Hydraulic head gradients 200 years after commencement of CSG production for cells of the Santos Narrabri Gas Project. CSG production lasted for 26 years.

Appendix 3: Summary of Gunnedah Basin model particle tracking v01

A budget output file ('SS_BC_2.CBB') containing flow velocity vectors was obtained from the steady state Gunnedah Basin model.

- As Modflow–Surfact cannot write compact budget output files (which are required for Modpath simulations), a Python script ('Convert_full_CBB_to_compact_v1_150215.py') was written to convert SS_BC_2.CBB to compact format ('SS_BC_2.CBB_compact').
- To undertake Modpath simulation, the files SS_BC_2.MPNAM, SS_BC_2.MPSIM, SS_BC_2.DIS, SS_BC_2.MPBAS were created or copied from the original steady state model files.
- In order to identify particle starting locations, the following analyses were undertaken using ArcMap. The 2-D steady state model grid was exported from the Groundwater Vistas GUI in ESRI shapefile format. As projection information was not provided, through trial and error it was found that the projection used was GDA 1994 MGA Zone 55. Also exported from the Groundwater Vistas GUI was an outline of a polygon describing the Narrabri Gas Project (NGP) area; this feature was exported as a '.map' file, which is a text file containing the vertices of the polygon. These data were imported into and saved as a comma delimited file, from which a point shapefile was created in an ArcMap document. Polyline and polygon shapefiles were subsequently created from these point data. Using the polygon representation of the NGP area, another three polygons were created by buffering at 10, 20 and 30 kilometre distances. These may be used in future particle tracking analyses. In order to identify model cells located on the NGP area boundary, the 'Selection by Location' tool was used; this identified a total of 260 cells. A subset of 20 cells was then manually selected, which mostly consisted of the vertices of the NGP area polygon.
- A Modpath input text file was created using the row and column identifiers of the 20 particle locations and by specifying the initial model layer as #6 (i.e. the Pilliga Sandstone aquifer). Within each cell, the starting location was set to the cell centroid. Particle tracking simulation was set to continue until each particle exited the model. Unfortunately, for 8 of the 20 particles, this resulted in non-convergence of the Modpath simulation. This is likely because these particles could not exit the model, due to capture by a sink in layer 6, or due to repeated oscillation between two neighbouring cells. Using the remaining 12 particles however, Modpath simulation was successful; particle tracking results were subsequently visualised using ArcMap (Figure 1).
- Each of the 12 particles moves in a north-westerly direction and exits the model at one of four possible locations (all located in the upper layer of the model). Three possible boundary conditions may serve as particle exit locations: river package cells, evapotranspiration package cells, or (negative flux) recharge package cells. River cells are not present in this region of the model. The presence of evapotranspiration or recharge package cells will be investigated. The time elapsed until particle exit ranged from ~2000 years to ~230 000 years. None of the 12 particles travelled more than 7 cells (i.e. 7 km) from the NGP area boundary.

Appendix 4 Spatial analysis species distribution and bore information

Table A4 - 1 Surat Basin – Habitat (potential species distribution) types within 30km of a CSG well.

Habitat (potential species distribution)	Distance (m)
Acacia harpophylla and/or Casuarina cristata open forest on fine-grained sedimentary rocks Endangered Regional Ecosystem (as dominant component)	0
Weeping Myall Woodlands Threatened Ecological Community	0
potential distribution of Jalmenus eubulus	0
Brigalow (Acacia harpophylla dominant and co-dominant) Threatened Ecological Community	0
potential distribution of Grantiella picta	0
potential distribution of Star Finch (eastern) (Neochmia ruficauda ruficauda)	0
potential distribution of Great Egret (Ardea alba)	0
potential distribution of Calyptorhynchus lathami	0
Semi-evergreen vine thickets of the Brigalow Belt (North and South) and Nandewar Bioregions	0
Threatened Ecological Community	
potential distribution of Cyperus clarus	0
potential distribution of Micromyrtus carinata	0
potential distribution of Fork-tailed Swift (Apus pacificus)	0
potential distribution of Nyctophilus corbeni	0
potential distribution of Acacia wardellii	0
potential distribution of Ooline (Cadellia pentastylis)	0
potential distribution of Eucalyptus taurina	0
potential distribution of Paradelma orientalis	0
potential distribution of Chalinolobus dwyeri	0
potential distribution of Rutidosis lanata	0
potential distribution of Geophaps scripta scripta	0
potential distribution of Squatter Pigeon (southern) (Geophaps scripta scripta)	0
Eucalyptus populnea, Acacia harpophylla open forest on fine-grained sedimentary rocks	
Endangered Regional Ecosystem (as dominant component)	51
potential distribution of Solanum stenopterum	54
potential distribution of Solanum elachophyllum	84
potential distribution of Picris barbarorum	105
Semi-evergreen vine thicket or Acacia harpophylla with a semi-evergreen vine thicket	
understorey on fine-grained sedimentary rocks Endangered Regional Ecosystem	156
	326
Eucalyptus populnea woodland with Acacia harpophylla and/or Casuarina cristata on alluvial	642
potential distribution of Red Goshawk (Erythrotriorchis radiatus)	1020
potential distribution of Hemiasnis damelii	1020
potential distribution of Koala (combined populations of Queensland (Phascolarctos cinereus	2111
(combined populations of QLD, NSW and the ACT))	8305
potential distribution of Melaleuca irbyana	9490
potential distribution of White-bellied Sea-Eagle (Haliaeetus leucogaster)	13471
Acacia harpophylla and/or Casuarina cristata shrubby open forest on Cainozoic clay plains	
Endangered Regional Ecosystem (as dominant component)	14261
Acacia harpophylla-Eucalyptus cambageana woodland to open forest on fine-grained	
sedimentary rocks Endangered Regional Ecosystem (as dominant component)	14347
potential distribution of Cattle Egret (Ardea IDIS)	18760
potential distribution of Phascolarctos cinereus	21557
Bioregions Threatened Ecological Community	22441

Table A4 - 2 Surat Basin – Basic Right Groundwater Bores within 500m of a CSG well.	

Bore Reg. Number	Distance (m)
Purpose	
RN10986	
Stock	31
RN43550	
Stock	102
RN17948	
Stock	118
RN30087	
Stock	121
RN14376	
Stock	148
RN123063	
Stock	197
RN13367	
Stock	219
RN15895	
Stock	223
RN36485	
Domestic Supply; Stock	233
RN31934	
Stock	299
RN17947	
Stock	314
RN14375	
Stock	358
RN43720	
Stock	366
RN36486	
Domestic Supply; Stock	387
RN26170	
Stock	415
RN14374	
Stock	416
RN14378	
Stock	461

Table A4 - 3 Surat Basin – Water Access Right Groundwater Bores within 30km of a CSG well.

Bore Reg. Number	Distance (m)
Purpose	
RN26169	
Stock; Stock Intensive	605
RN11414	
Town Water Supply	640
RN14358	
Stock Intensive	15796
RN58124	
Town Water Supply	17163
RN123245	
Stock; Stock Intensive	24485
RN123244	
Stock; Stock Intensive	24811
RN123247	
Stock; Stock Intensive	24877
RN123246	
Stock; Stock Intensive	24880
RN58133	
Stock; Stock Intensive	25882
RN123146	
Stock Intensive	26984
RN123158	
Stock Intensive	27777
RN58484	
Group Domestic; Stock	27983
RN58023	
Town Water Supply	29167
RN123104	
Stock; Stock Intensive	29361
RN123297	
Stock Intensive	29467

Appendix 5: Attenuation data for organic substances

Table A5 - 1 Properties of organic substances. 1 = Horowitz et al. (1982); 2 = Lyman et al. (1990); 3 = Podoll et al. (1989); 4 = Yediler et al. (1991); 5 = Mihelcic et al. (1988); 6 = Dellesite (2001); 7 = Howard et al. (1991) [cited in ATSDR 1998]; 8 = Monteil-Rivera et al. (2003); 9 = Jacobson and Williams (2000); 10 = US EPA 1998b Pesticides reregistration status (https://archive.epa.gov/pesticides/reregistration/web/html/status.html); 11 = WHO - International Programme on Chemical Safety Concise International Chemical Assessment Document No. 5. Limonene (1998b); 12 = Muller (1981); 13 = Malik and Letey (1991); 14 = TOXNET (https://toxnet.nlm.nih.gov/); 15 = US EPA 811-F-95-004a-T; 16 = Hawari et al. (2001); 17 = EPI suite (US EPA 2012b); 18 = Aronson and Howard (1997); 19 = Brannon et al. 2005; 20 = Boyd et al. 1982; 21 = Koplinke et al. 1995; 22 = Kollig 1993; 23 = Loehr 1989; 24 = Herbes and Schwall 1978 (cited in Howard (1989)); 25 = Park et al. (1990); 26 = Van Aken et al. (2004); 27 = Harris (1990); 28 = US EPA (1995b); 29 = Cui et al. (2011); 30 = Kahrilas et al. (2014); 31 = US EPA (2009); 33 = Caulfield et al. (2002); 34 = Sharma et al. (2013); 35 = ECHA Registration dossier (https://echa.europa.eu); 36 = Hale et al. (2015); n.r. = not reported; n.d. = not applicable; nbd = not biodegradable.

Name	CAS Number	Solubility (mg/L)	Log K _{ow}	рК _а	Log K _{oc} (K _{oc} [L/kg])	Anaerobic biogedradation balf-life (d)	Aerobic biodegradation balf-life (d)	Hydrolysis half-life (d)	Comments
2-methylphenol (o- cresol)	95-48-7	25,900	1.95	10.3 (acid)	1.34 (21.9) ²⁰ 1.7 (50) ²¹ 1.76 (57.5) ²² 2.39 (246) ⁴	20 - 1386 ¹⁸	1.6 – 5.1 ²³	n.a. ²	
Naphthalene	91-20-3	31	3.3	n.d.	1.23 – 4.43 (17-26915) ⁶	96 - nbd ¹⁷	2.1-2.2 ²⁵ 8.67 ¹⁷ (0.21) - 88 ²⁴	n.a. ²	⁶ Adsorption on soil decreases with increasing temperature (15-50°C) ³ ¹⁷ BIOWIN4 (EPIv3.12) estimation was days-weeks which resulted in a 8.67 d half-life based on Table 4-3. ²⁴ The 0.21 d half-life from Herbes and Schwall (1978) is removed from the data set as it was derived for oil- contaminated sediment

									which is not representative for this analysis. ² Naphthalene will not hydrolyze in water because it does not contain a hydrolyzable group (Montgommery 2007).
НМХ	2691-41-0	5	0.16	n.d.	1.5-2.3 (32-200) ⁸ 2.7 – 3.1 (450-1250) ³⁴	2.3 ¹⁶	15 ²⁶	31.2 (fresh) ¹⁹ 21.1 (saline) ¹⁹	⁸ Based on measured K_d values and $f_{oc} = 0.084$ and 0.0033 for an agricultural topsoil and sandy loam, respectively. ³⁴ B horizons ¹⁶ The anaerobic half-life value of 2.3 d was obtained hereby fitting a first-order degradation model to the published data of Hawari et al. (2001). The aerobic half- life value of 15 d was obtained here by fitting a first-order degradation model to the published data of Van Aken et al. (2004).
2-butoxyethanol	111-76-2	1x10 ⁷	0.83	n.d.	0.88 (7.6) ¹⁷ 0.46 – 0.9 (2.9 - 8) ¹⁷	28 - 112 ⁷	7 – 28 ⁷ 14 - 56 ⁷ 17.3 ¹⁷	n.a. ²⁷	⁷ surface water (7-28) and groundwater (14-56) values ${}^{17}K_{oc}$ estimated from Log K_{ow} (=0.83)

									 ²⁷Hydrolysis of 2- butoxyethanol is unlikely, as it contains both alcohol and ether functional groups, which are generally resistant to hydrolysis (Harris 1990).
Bronopol	52-51-7	250,000	-0.64	n.d.	1.6-3.15 (36.8-1416) ³⁵ -0.031 – 0.42 (0.9-2.6) ¹⁷	n.d. ³⁰	n.d. ³⁰	At 20 °C: 18y (pH4), 1.5y (pH6), 2 months (pH8) ²⁸ At 60°C: 4 days (pH4), 3h (pH8) ²⁸ 0.094-0.13 ²⁹	 ³⁵Batch equilibrium sorption data on soil (sand, loamy sand, loam, clay loam) ²⁹Data from Cui et al. (2011) is for hydrolysis tests in natural surface waters with pH of 7.4 – 7.7 and oxidation-reduction potential of -27 – - 49 mV
Methyl-chloro- isothiazolinone	26172-55- 4	No limit	0.4	n.d.	1.48-2.16 (30-144) ¹⁰	5 (water/ sediment) ⁹	0.21 ¹⁰	22 ¹⁰	¹⁰ adsorption/desorption: aerobic soil metabolism study in sandy loam (K_{oc} = 91), silt loam (K_{oc} = 30), clay loam (K_{oc} = 105), and sand (K_{oc} = 144) soils (based on Wang 1991) ¹⁰ Hydrolysis at pH9 (25°C)
d-Limonene	138-86-3	7.6	4.57	n.d.	3-3.8 (1120-6324) ¹⁷ 4.44-4.77 (27542- 58884) ³⁶	n.a. ¹¹	2.3 - 18 ³²	n.a. ³¹	¹⁷ K_{oc} estimated from Molecular Connectivity Index (MCI = 4.698) and Log K_{ow} (= 4.38), respectively.

									 ³⁶sorption on peat and bituminous coal ³²Aerobic biodegradation half-lives derived here using 41% and 98% degradation in 14 days. ³¹Limonene does not have functional groups for hydrolysis and its cyclohexene ring and ethylene group are known to be resistent to hydrolysis.
Acrylamide polymer (Acrylamide)	9003-05-8 79-06-1	High ¹⁴ (2.2kg/L) ¹⁵	(n.a.; high mobility ¹⁵)	n.d.	1.4-2.6 (25-398) ¹³	n.d. ¹⁴	n.d. ¹⁴	Likely inert ¹⁴	Most literature focuses on acrylamide (minor impurity) ¹³ based on three soils (coarse-loamy, mixed thermic Haplic Durixeralf; fine, montmorillonitic, thermic Chromic Pelloxerert; fine-loamy, mixed, thermic, Typic Haploxeralf) and three polyacrylamides ¹⁴ Under acidic conditions (pH <4), hydrolysis rate increases with temp (100°C) and decreasing pH ³³ Polymer is inert ¹⁴

Appendix 6: Analytical solutions for solute transport in groundwater systems

Table A6 - 1 Selected analytical solutions for solute transport in porous media.

Analytical solution	Characteristics of solution: geometry, chemical source description, single or multiple chemicals, degradation	Reference
$c(x, y, z, t) = \frac{M}{\theta} \frac{1}{8\pi^{3/2}} \frac{1}{\sqrt{D_x D_y D_z / R}} \frac{1}{(t - t')^{3/2}} \exp[-\lambda(t - t')]$ $\cdot \exp\left[-\frac{\{(x - x') - v(t - t') / R\}^2}{4D_x(t - t') / R}\right] \cdot \exp\left[-\frac{(y - y')^2}{4D_y(t - t') / R}\right]$ $\cdot \exp\left[-\frac{(z - z')^2}{4D_z(t - t') / R}\right]$	Infinite and semi-infinite medium; single chemical; degradation; point source, cube source, line source, plane source.	Lenda and Zuber 1970 (and further in Guyonnet and Nevill 2007)
$C(x,y,z,t) = (C_0/8) \{ erf [x - vt + (X/2)/2(D_x t)^{\frac{1}{2}}] $ - erf [x - vt - (X/2)/2(D_x t)^{\frac{1}{2}}] } $\{ erf [y + (Y/2)/2(D_y t)^{\frac{1}{2}}] - erf [y - (Y/2)/2(D_y t)^{\frac{1}{2}}] \} $ $\{ erf [z + (Z/2)/2(D_z t)^{\frac{1}{2}}] - erf [z - (Z/2)/2(D_z t)^{\frac{1}{2}}] \}$	Parallelepid instantaneous pulse source, assumption of infinite aquifer thickness, aquifer is homogeneous and isotropic; single chemical.	Hunt 1983

$C_{c} = \frac{M_{o} \exp\left(\frac{1}{2} \frac{V^{*}_{x}}{D_{x}}\right)}{8\pi \Theta R \sqrt{D_{y} D_{z}}} \left(\exp\left(\frac{1}{2} \frac{RU}{D_{x}}\right) \operatorname{erfc}\left(\frac{1}{2} \frac{R_{d} R + Ut}{\sqrt{R_{d} D_{x}^{*} t}}\right) \right)$	PLUME3D: transient and steady-state concentration distributions arising from a continuous point source in an infinite aquifer with uniform ground- water flow. The model includes both linear adsorption and first-order reactions; single chemical.	Wagner et al. 1985
+ exp $\left(-\frac{1}{2}\frac{RU}{D_{x}^{*}}\right)$ erfc $\left(\frac{1}{2}\frac{R_{d}R - Ut}{\sqrt{R_{d}D_{x}^{*}t}}\right)$		
$R = x^{2} + \frac{D_{x}^{*}}{D_{y}^{*}}y^{2} + \frac{D_{x}^{*}}{D_{z}^{*}}z^{2} $ 1/2		
$U = V^{\star} \left(1 + \frac{4 D_{X}^{\star} R_{d} \lambda}{V^{\star} 2} \right)^{1/2}$		
$C(x,y,z,t) = (C_0/8) \operatorname{erfc} [(x - vt)/2(D_x t)^{\frac{1}{2}}]$ $\{\operatorname{erf}[(y+Y/2)/2(D_y x/v)^{\frac{1}{2}}] - \operatorname{erf}[(y-Y/2)/2(D_y x/v)^{\frac{1}{2}}]\}$ $\{\operatorname{erf}[(z+Z/2)/2(D_z x/v)^{\frac{1}{2}}] - \operatorname{erf}[(z-Z/2)/2(D_z x/v)^{\frac{1}{2}}]\}$	Single-species one-dimensional advective transport, three-dimensional dispersion, without linear sorption and without first-order decay, assumption of infinite aquifer thickness, aquifer is homogeneous and isotropic; continuous finite source (finite patch).	Domenico and Robbins 1986



$$c(x,y,z,t) = \frac{c_o}{8} f_x(x,t) f_y(y,x) f_z(z,x),$$
where $f_x(x,t) = \left(\exp\left\{ \frac{x}{2\alpha_x} \left[1 - \left(1 + \frac{4k\alpha_x}{v} \right)^{1/2} \right] \right\}$

$$\times \operatorname{erfc} \left\{ \frac{x - vt \left(1 + \frac{4k\alpha_x}{v} \right)^{1/2} \right\} \right\}$$

$$f_y(y,x) = \left[\operatorname{erf} \left\{ \frac{y + \frac{Y}{2}}{2(\alpha_x vt)^{1/2}} \right\} - \operatorname{erf} \left\{ \frac{y - \frac{Y}{2}}{2(\alpha_x x)^{1/2}} \right\} \right]$$

$$f_z(z,x) = \left[\operatorname{erf} \left\{ \frac{z + \frac{Z}{2}}{2(\alpha_z x)^{1/2}} \right\} - \operatorname{erf} \left\{ \frac{z - \frac{Z}{2}}{2(\alpha_z x)^{1/2}} \right\} \right]$$
Domenico 1987

	$c = c_0 e^{-(y^2/2\sigma^2)}$	Huyakorn et al. 1987
	Fig. 1. Schematic description showing a Gaussian strip source in a uniform ground-water flow field within a finite thickness aquifer.	
	Three-dimensional analytical solution for transient and steady-state	
	concentration distributions resulting from a partially penetrating strip	
	distribution in the lateral direction (along the y-axis) and a uniform	
	distribution over the vertical mixing or penetration depth	
	Single-species one-dimensional advective transport, three-dimensional	Martin-Hayden
$C(x, y, z, t) = \frac{C_0}{C_0} f_z f_z f_z$	dispersion, linear adsorption and first-order decay; assumption of infinite	and Robbins
$f_{x} = \exp\left(\frac{x\left[1 - \left(1 + 4\lambda\alpha_{x}/v_{s}\right)^{0.5}\right]}{2\alpha_{x}}\right) * erfc\left(\frac{x - vt\left(1 + 4\lambda\alpha_{x}/v_{s}\right)^{0.5}}{2(\alpha_{x}vt)^{0.5}}\right) +$		
$\exp\left(\frac{x\left[1+\left(1+4\lambda\alpha_{x}/v_{s}\right)^{0.5}\right]}{2\alpha_{x}}\right)*erfc\left(\frac{x+vt\left(1+4\lambda\alpha_{x}/v_{s}\right)^{0.5}}{2(\alpha_{x}vt)^{0.5}}\right)$		
$f_{y} = erf\left(\frac{(y+Y/2)}{2(\alpha_{y}x)^{0.5}}\right) - erf\left(\frac{(y-Y/2)}{2(\alpha_{y}x)^{0.5}}\right) \qquad f_{z} = erf\left(\frac{z+Z}{2(\alpha_{z}x)^{0.5}}\right) - erf\left(\frac{(z-Z)}{2(\alpha_{z}x)^{0.5}}\right)$		



0	Sequential first order, coupled reactive transport model for multiple	Aziz at al. 2000
$C(x, y, z, t) = \frac{C_0}{8} f_x f_y f_z$	species one-dimensional advective transport three-dimensional	(hased on Sun et
$\left(x \left[1 - (1 + 4) \alpha / y \right]^{0.5} \right)$ ((1 - 4) - ((1 - 4))^{0.5} \right)	dispersion linear adsorption Biotransformation is assumed to occur only	al 1000a
$f_{x} = \exp\left[\frac{x \left[1 + 4\lambda \alpha_{x} / v_{s}\right]}{2\alpha}\right] + erfc\left[\frac{x - v(1 + 4\lambda \alpha_{x} / v_{s})}{2(x - v)^{0.5}}\right] +$	in the aqueous phase (which is a conservative assumption): assumption of	1999b: Sun and
$\begin{pmatrix} 2\alpha_x \end{pmatrix} \begin{pmatrix} 2(\alpha_x \nabla t) \end{pmatrix}$	infinite aquifer thickness, aquifer is homogeneous and isotronic	Clomont 1999)
$\left(\mathbf{x}\left[1+\left(1+4\lambda\alpha_{x}/v_{s}\right)^{0.5}\right]\right)$ $\left(\mathbf{x}+\mathbf{vt}\left(1+4\lambda\alpha_{x}/v_{s}\right)^{0.5}\right)$	RIOCHLOR version 1.0. Multiple species Spatially-varying constant source	clement, 1999)
$\exp\left[\frac{1}{2\alpha_{x}}\right] * erfc\left[\frac{1}{2(\alpha, vt)}\right]^{0.5}$	by superimposing multiple fully penetrating vertical plane sources	
	arianted perpendicular to ground water flow	
	oriented perpendicular to ground-water now.	
$f_{y} = \operatorname{erf}\left(\frac{(y+Y/2)}{2(\alpha_{y}x)^{0.5}}\right) - \operatorname{erf}\left(\frac{(y-Y/2)}{2(\alpha_{y}x)^{0.5}}\right) \qquad f_{z} = \operatorname{erf}\left(\frac{z+Z}{2(\alpha_{z}x)^{0.5}}\right) - \operatorname{erf}\left(\frac{(z-Z)}{2(\alpha_{z}x)^{0.5}}\right)$	SURFACE TOP OF WATER-BEARING UNIT Source Thickness BOTTOM OF WATER-BEARING UNIT	
	BIOCHLOR version 2.2. Modification from version 1.0: the source decays	Aziz et al. 2002
	exponentially via a first order expression.	
	General method is developed to derive analytical solutions in one, two, or	Sun et al. 1999a
	three dimensions of any number of species with first-order sequential	
	degradation in multiple dimensions (limited to serial networks);	
	assumption of infinite aquifer thickness, aquifer is homogeneous and	
	isotropic. Various boundary conditions; retardation factor identical for	
	each species, degradation is limited to the liquid phase.	
	Analytical solutions in one, two, or three dimensions of serial-parallel	Sun et al. 1999b
	reaction networks that are needed to describe the transport of	

multispecies coupled by linear reaction networks with different stoichiometric yields; assumption of infinite aquifer thickness; aquifer is homogeneous and isotropic; degradation is limited to the liquid phase.	
STANMOD: Analytical solutions in one, two, or three dimensions accounting for sorption, degradation, and production.	Lei et al. 1994

Appendix 7: Hazard screening risk assessment tool for deep groundwater contamination risks from hydraulic fracturing

James Kear and Zuorong Chen – CSIRO - Energy

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1. Introduction

Hydraulic fracturing for coal seam gas production has a 40 year history, with more than 20 years of commercial experience in North America prior to the recent development of the Australian CSG industry. There has been a commensurate development of modelling approaches and relevant experimental and field data to understand and predict hydraulic fracture growth. In CSG hydraulic fracturing design, one of the most important considerations for the effectiveness of the treatment is preventing unwanted vertical hydraulic fracture growth out of the CSG production interval into the overburden geological layer. Such height growth is ineffective and inefficient from a production viewpoint and therefore the topic has received much attention as highlighted in Fisher and Warpinski (2012).

This topic is also pertinent from a groundwater contamination viewpoint as vertical hydraulic fracture growth is often highlighted as a potential contaminant transport pathway to water bearing aquifers. Generalisations of the risk of vertical fracture growth through interlying aquitards into an overlying aquifer are difficult as fracture growth characteristics are site specific. Campin (2013) identifies that although there is broad agreement that the risk is related to the vertical physical separation of the aquifer and the hydraulically fractured formation (the risk is higher for cases where the physical separation is smaller). Post-treatment analysis studies such as King and King (2013) consider this potential contaminant transport pathway unlikely, however accurate generalisations are extremely difficult as hydraulic fracture growth is highly dependent on local in-situ conditions.

This initial hazard screening tool introduces multiple lines of evidence and a demonstration of the modelling approaches which could be used to inform an assessment of the hazards to deep ground water presented by hydraulic fracturing stimulation of CSG wells in the Gunnedah and Surat Basins. Specifically these lines of evidence concentrate on estimating the vertical extent of a hydraulic fracture and any other plausible pathways that may be stimulated or reactivated during a CSG hydraulic fracturing treatment.

There are a number of commercial and research numerical simulators that are highly sophisticated and for which there is a long track record of use by the industry. However, even with this sophistication, commercial numerical simulators do not yet handle the three dimensional nature of hydraulic fracture growth nor do they well account for the mechanics of hydraulic fracture interaction with natural fractures and lithological contacts. For CSG, this limitation is particularly relevant where hydraulic fracture grown has been observed to occur not only vertically in the seam, but also with horizontal branches that grow along the contact between the coal and roof/floor rock formations. The present state of the art typically entails treatment design to ensure appropriate containment, length, and proppant placement using a planar, pseudo-3D numerical model as described in Annex C: Pseudo-3D hydraulic fracture height growth models.

A range of methods are available for monitoring and diagnosis of hydraulic fracture growth. These include well pressure analysis, tracers, micro seismic monitoring, and tilt meter monitoring. Such monitoring is typically only deployed early in the development of an area due to the high associated costs.

Hydraulic fracture stimulations of CSG wells are designed to maximise productivity while minimising the potential risk of fracture fluid contamination of sensitive strata. Factors that affect hydraulic fracture growth fall into two broad categories; (i) in-situ properties of the geological layers and (ii) design characteristics of the hydraulic fracture treatment.

Key in-situ properties and their influence on hydraulic fracture growth include:

- Permeability of the CSG production interval, overlying aquitard, basement rock and (to a lesser extent) the water bearing aquifer. Permeability of the rock matrix and propensity of fracture sets within each geological later will have an impact on the fracture propagation and leakoff of hydraulic fracture fluid into each of the geological layers.
- Orientation of the in-situ rock stress is the principal determinant of the macro-scale orientation of the hydraulic fracture growth, that is, hydraulic fractures preferentially grow perpendicular to the minimum principal in-situ stress direction. If known, this preferred hydraulic fracture orientation provides a key

indicator of a fracture directly intersecting a natural fault or a water bore within the CSG production interval.

- The magnitude of the in-situ stresses in each geological layer influence the hydraulic fracture shape and treatment pressure (pressure required to open and grow the hydraulic fracture is related to the minimum principal in-situ stress). The stress contrasts between the different layers is the principal controller of fracture height growth as it determines the propensity of a hydraulic fracture to grow preferentially in one geological layer over another. The magnitude of the in-situ stresses also impacts the propensity for hydraulic fractures to cross or blunt when intersecting faults and natural fractures.
- Mechanical properties of each of the geological layers can impact hydraulic fracture growth. Hydraulic fractures will grow preferably in a layer with a lower fracture toughness while a layer with a higher stiffness will tend to have higher in-situ stresses which serves to restrict fracture opening.
- Highly permeable large faults and structures in a rock mass can have a major impact on the growth of hydraulic fractures and care should be taken to map the location and to estimate the permeability of such features.

Design characteristics of a hydraulic fracture treatment allow the fracture engineers some control over the nature and location of the generated hydraulic fracture network. Major items under the control of the hydraulic fracture engineer include:

- Borehole orientation, if the minimum stress direction is oriented perpendicular to the vertical borehole (as is typical in Australian CSG), the hydraulic fracture will grow parallel from the borehole in a "wing" shape.
- Boreholes can either be lined with a cemented steel casing or left open in the CSG production interval (uncased). The casing of boreholes provides strength and control over the site of fracture initiation, however the area of exposed production interval is restricted to areas where the casing is deliberately perforated, potentially reducing well performance. Uncased boreholes are, however more likely to degrade with time since the wall of the borehole is not strengthened by the cemented steel casing and therefore may need an earlier workover.
- Length of borehole pressurised in each fracturing "stage" is controllable. It is possible to attempt to grow
 multiple hydraulic fractures simultaneously by pressurising a length of borehole that contains multiple
 perforations through the borehole casing or a large uncased section. The benefit of attempting
 simultaneous growth may be in cost savings through reduced time to stimulate a borehole, but the trade-off
 is reduced control over individual fracture growth and a reduced certainty about the volume of fracturing
 fluid (and proppant, such as sand, used to keep the induced hydraulic fracture open) used in each fracture.
- Proppant (such as graded sand) is added to hydraulic fracture fluid to hold open the created hydraulic fracture after fracturing pressure has been relieved. This will maximise the retained permeability of the hydraulic fracture.
- Viscosity of the hydraulic fracturing fluid has a strong effect on fracture growth. A more viscous fracture fluid will carry proppant more effectively and would tend to preferentially create a larger single main fracture channel. A less viscous fluid would flow more freely into, and perhaps stimulate, intersected natural fractures.
- Hydraulic fracturing fluid injection rate is related directly to treatment pressure and has many effects on fracture growth. Some effects include: a larger fracture opening, increased likelihood of fractures crossing intersected natural fractures and a larger maximum fracture radius.

The analysis of these in-situ mechanical properties and design characteristics specific to an individual hydraulic fracture treatment is required to accurately simulate hydraulic fracture growth in a research or industrial numerical model. The modelled results would provide a likely estimate of fracture orientation, extent and conductivity. However, the modelled output would only be relevant to the specific well stimulated.

Modelling is not the only line of evidence of hydraulic fracture growth, hydraulic fractures can be monitored with microseismic and tiltmeter instruments, the fracture fluid pressure record can be analysed and key environmental receptors and local wells can be monitored. For the purposes of this hazard risk screening tool, a largely qualitative approach has been taken to the assessment of hydraulic fracturing stimulation of plausible transport release pathways complimented by basic numerical modelling using properties from a conceptual geomechanical model of the Gunnedah Basin.

2. Evidence to inform an assessment of the hazards to deep ground water presented by hydraulic fracturing

To accurately assess the risks to deep ground water presented by hydraulic fracturing of Australian CSG wells, multiple lines of evidence must be gathered and reviewed for each of the plausible transport release pathways. The most appropriate lines of evidence identified in the creation of this hazard risk screening tool are as follows:

- 1. Basic hydraulic fracture growth models to provide bounding data points;
- 2. Industry standard numerical modelling of hydraulic fracture growth;
- 3. Analysis of samples from monitoring / water wells;
- 4. Remote hydraulic fracture growth monitoring;
- 5. Interpretation of injection pressure data;
- 6. Observation of key environmental receptors.

2.1. Line of evidence 1: Basic hydraulic fracture growth and fluid

transport models to provide bounding data points

The most basic hydraulic fracture growth models consider single planar fracture growth in a pre-determined configuration. Two common configurations are KGD (named after Khristianovic, Zheltov, Geertsma and de Klerk) and PKN (named after Perkins, Kern and Nordgren) that respectively consider simple forms of plane strain and constant height fracture configurations (Figure A7 - 1).



Figure A7 - 1 Sketches of PKN and KGD hydraulic fracture configurations from Adachi et al. (2007).

In both these configurations, the hydraulic fracture height is constrained to be limited to the height of the CSG production interval with the assumption that in-situ mechanical properties suppress hydraulic fracture growth in either the overlying aquitard or the underlying basement rock. The PKN fracture model assumes that there is no slip along interfaces between the CSG production interval and the bounding geological layers and therefore the hydraulic fracture width is zero along these planes. In contrast, the KGD model assumes that the growing hydraulic fracture causes slip along the interface between the CSG production interval and the bounding geological layers and the hydraulic fracture opening is constant along the thickness of the CSG production interval. These classical hydraulic fracture analytical models are effective in providing bounding data points for a reasonable maximum horizontal extent of hydraulic fracture growth using (a more description of these models is provided in Annex B: Classical hydraulic fracture growth models).

2.2. Line of evidence 2: Industry standard numerical modelling of

hydraulic fracture growth and fluid transport

Industry standard hydraulic fracture growth models use a variety of approaches to expand beyond the limitations of the basic hydraulic fracture models. Such industry standard models are less constrained to a pre-determined configuration and are able to consider more complex scenarios such as the effects of geological layers with different stresses and mechanical properties on hydraulic fracture growth.

In this report, the pseudo-3D (P3D) approach as described in Adachi et al. (2010) and the equilibrium height pseudo-3D model as described in (Fung et al. 1987; Mack et al. 1992) are used to generate modelling outputs considered to be analogous to current industry standard products. More information on these models is contained in Annex C: Pseudo-3D hydraulic fracture height growth models. Figure A7 - 2 shows a schematic of the layout of a hydraulic fracture model in a P3D environment. In the P3D configuration, the hydraulic fracture is allowed to grow in height beyond the central dark grey geological layer which represents the CSG production interval and into the light grey layers which represent the overlying aquitard and underlying basement rock.



Figure A7 - 2 Schematic of the fracture geometry as considered by the pseudo-3D (P3D) approach from Adachi et al. (2010).

The extent of the vertical hydraulic fracture growth is determined by the in-situ mechanical properties of the geological layers and the design characteristics of the hydraulic fracture treatment. Although less geometrically constrained than the PKN and KGD fracture models, this P3D modelling approach is still not able to consider many complex aspects of hydraulic fracture growth such as T-Shaped fracture growth and network fracture growth as the geometry is still confined to a single plane. The P3D model is useful as it provides a closer representation of hydraulic fracture growth than the PKN or KGD models however it should not be the only line of evidence considered when determining fracture growth behaviour.

2.3. Line of evidence 3: Analysis of samples from monitoring

wells / water bores

Each plausible transport release pathway ends with water extraction production from a monitoring well or water bore. Analysis of water samples from these wells forms would form an important line of evidence in determining if contaminants have been transported from the coal seam gas well to the water bore.

Although analysis of data from wells in close proximity to CSG production wells is not within the scope of this report, identification of hydraulic fracturing chemicals (or lack thereof) provides an important line of likelihood evidence that is valuable when considering the hazards associated with hydraulic fracturing in the development of a CSG asset.

2.4. Line of evidence 4: Remote hydraulic fracture growth

monitoring

Hydraulic fracture growth is impossible to observe directly in the field, however, methods exist to remotely monitor aspects of the orientation and extent of the stimulated hydraulic fracture network.

Four of these methods to monitor fractures are fracture fluid tracers, micro-seismic instrumentation, tilt-meter instrumentation, and monitoring for intersections with offset boreholes. Monitoring of fracture growth is important during early phases of development of new areas. This monitoring serves to calibrate modelling and verify designs are producing the fractures intended.

Although monitoring of hydraulic fracture growth beyond early phases of development is not common in the Australian CSG industry (primarily due to the added cost), the results of such monitoring, where available, would be a valuable line of evidence when evaluating the likelihood associated with each plausible transport release pathway.

2.5. Line of evidence 5: Interpretation of injection pressure data

Hydraulic fracturing pressure records provide operators critical information on the growth of the hydraulic fracture. For each of the plausible pathways analysed in this report, a hydraulic fracturing pressure abnormality could reasonably be expected. The analysis of pressure records in themselves should not be used as a sole price of evidence in a hazard screening exercise. However, interpretation of treatment pressure data for highly sensitive wells or analysis of cases where operators abandoned a hydraulic fracturing treatment due to a pressure abnormality could conceivably be used as a useful line of evidence to inform a risk screening exercise.

2.6. Line of evidence 6: Observation of key environmental

receptors

Suitably selected environmental receptors should provide a line of evidence if contaminants contained within a hydraulic fracturing fluid have been transported to sensitive strata. The identification of such key environmental receptors for the purpose of monitoring is not within the scope of this report however if data from monitoring these receptors was available, it would be a valuable line of evidence for each of the plausible transport release pathways.

3. Plausible transport release pathways



The four plausible transport release pathways addressed in this report are depicted in Figure A7 - 3 below.

Figure A7 - 3 Four plausible transport release pathways addressed in this report.

In this section of the report, firstly each plausible transport release pathway is discussed with reference to current industry practice. Secondly, the hazard to the deep groundwater is reviewed with reference to the appropriate lines of evidence and finally simulations depicting hydraulic fracture growth in a conceptual geomechanical model of the Gunnedah Basin are presented in relation to plausible Pathways A, B and D. The resultant contaminant transport details will inform the next stage of this hazard assessment.

3.1. Plausible Pathway A: fracture growth into an aquifer

In plausible Pathway A, the vertical extent of the hydraulic fracture is such that is connects the CSG production interval to the water bearing aquifer through the overlying aquitard (Figure A7 - 4). The vertical and horizontal extent of the hydraulic fracture growth are governed by the injected fracture fluid volume and the leak-off into the formation. While hydraulic fracturing engineers have some control over fracture size though selection of fluid viscosity and injection rate, variations from designed fracture extent may come from inaccurate knowledge of the geology or from screen out where proppant becomes blocked and halts hydraulic fracture growth.



Figure A7 - 4 Sketch of plausible fate and transport release Pathway A. A water bore is shown as typical receptor.

It is well known that a thick, unfractured aquitard that is highly stressed, strong, and stiff relative to the coal seam will lead to an extremely small likelihood that the hydraulic fractures will grow out of zone as hydraulic fractures favour growth in lower stress layers, while higher stress layers act as barriers to fracture growth (Bunger 2015). It is also clear that growth out of the zone is likely if the bounding geological layers possess none of the known attributes that comprise a barrier to hydraulic fracture growth.

Maxwell (2011) demonstrated that industry fracture models can be prone to over estimation of height growth compared to the results of microseismic fracture monitoring. Industry fracture models currently also are unable to predict complex fracture geometry such as T-Shaped growth as seen in (Rodvelt 2014; Rogers 1994) or three dimensional forms of multiple fractures (Kear et al. 2013). The disconnect between the modelled fracture growth predations and post-treatment analysis has led to a range of estimates of the likelihood of out of zone hydraulic fracture growth creating a conductive pathway between the production interval and an overlying water bearing aquifer (Broomfield 2012; Fisher and Warpinski 2012; King 2012; Maxwell 2011).

Table A7 - 1 below reviews the applicability of each line of evidence to plausible Pathway A.

Table A7 1 Lines	ofouidanca	rolovant to	nlaucibla	Dathua	
TUDIE A7 - I LINES	of evidence	relevant to	pluusible	ruuwu	γн.

Line of evidence	Applicability to hazard assessment of plausible Pathway A
1: Basic hydraulic fracture growth and fluid transport.models to provide bounding data points	Moderately applicable. Basic hydraulic fracture growth models provide bounding data points for a simplistic estimate of extent of vertical hydraulic fracure growth. The output of basic hydraulic fracture growth models can be compared to the vertical separation of the water bearing aquifer will provide a useful line of evidence for plausible Pathway A.
2: Industry standard numerical modelling of hydraulic fracture growth and fluid transport	Moderately applicable. Industry standard numerical modelling provides a more accurate estimate of the extent of the vertical hydraulic fracture growth. The output of industry standard numerical models can be compared to the vertical separation of the water bearing aquifer will provide a key line of evidence for plausible Pathway A.
3: Analysis of samples from monitoring / water well	Highly applicable. Contaminants transported to the water bearing aquifer along plausible Pathway A should conceivably be detected in samples from monitoring or water wells.
4: Remote hydraulic fracture growth monitoring	Highly applicable. Remote monitoring of hydraulic fracture growth would provide an estimate of vertical fracture extent to compare to the vertical separation of the water bearing aquifer and provide a useful line of evidence for plausible Pathway A.
5: Interpretation of injection pressure data	Loosely applicable. Vertical out of seam hydraulic fracture growth may produce an injection pressure plot that is different to hydraulic fracture growth contained in the CSG production interval but it is unlikely that this difference would be able to be accurately identified.
6: Observation of key environmental receptors	Currently not data available

3.2. Plausible Pathway B: fracture growth into a well

In plausible Pathway B, a hydraulic fracture grown in a CSG production interval directly intersects a water bore in the same geological interval (Figure A7 - 5). When assessing the likelihood of plausible Pathway B, it is important to have a useful estimate of the horizontal extent of the hydraulic fracture.



Figure A7 - 5 Sketch of plausible fate and transport release Pathway B. Water bores are shown as typical receptors.

Obtaining such an estimate is not straightforward as fluid transport and crack propagation behaviour in coal is often badly predicted by linear theories. Additionally, any height growth will also directly reduce the horizontal extent of hydraulic fracture growth. As a result, simple, tractable solutions can give very poor estimates of hydraulic fracture length and therefore must be applied only with caution and in a manner that is cognizant of their limitations. In this case these simple models are used to provide a bounding data points on for the maximum possible horizontal extent of fracture growth.

Table A7 - 2 Lines of evidence relevant to plausible Pathway B.

Line of evidence	Applicability to hazard assessment of plausible Pathway B
1: Basic hydraulic fracture growth and fluid transport models to provide bounding data points	Highly applicable. Basic hydraulic fracture growth models provide bounding data points for the maximum potential extent of hydraulic fracture growth. Plausible pathway B involves the intersection of the growing hydraulic fracture and a water bore that draws from the CSG production interval. The maximum potential extent of the hydraulic fracture is relevant when reviewing the proximity of the water bore to the production borehole.
2: Industry standard numerical modelling of hydraulic fracture growth and fluid transport.	Highly applicable. Industry standard numerical modelling provides a more accurate estimate of the extent of the hydraulic fracture growth. The output of industry standard numerical models can be compared to the horizontal and vertical location of water bores in relation to the production borehole.
3: Analysis of samples from monitoring / water well	Highly applicable. Contaminants transported to the water bore plausible Pathway B should conceivably be detected in samples from the water bore.
4: Remote hydraulic fracture growth monitoring	Highly applicable. Remote monitoring of hydraulic fracture growth is especially applicable for assessing this plausible pathway. If the water bore that draws from the CSG production interval is monitored for hydraulic fracture intersection then this would provide direct evidence of a the establishment of a plausible transport pathway.
5: Interpretation of injection pressure data	Moderately applicable. An intersection between the growing hydraulic fracture and a water bore may cause an abnormality in the injection pressure plot. However the cause of this abnormality may not be clearly distinguishable from a fracture intersection with a highly permeable zone.
6: Observation of key environmental receptors	Currently no data available

3.1. Plausible Pathway C: well rupture during injection

Plausible Pathway C describes a scenario where migration of hydraulic fracturing fluid occurs along the annulus of a poorly completed well. Like hydraulic fracturing, well completion technology has a long history (Figure A7 - 6). Best practice begins during the drilling process by ensuring the drilling fluid is appropriately designed so that breakout of the wellbore, which can lead to cementing difficulties, is minimised. Casing and cementing technology is also well-established, and historically wells that leak are often, if not invariably, the product of well construction that is below best practice.



Figure A7 - 6 Sketch of plausible fate and transport release Pathway C. A water bore is shown as typical receptor.

A number of factors can impact on well integrity. Poor hole conditions resulting from wellbore breakouts during drilling, casing that is not centred in the hole, and cement that does not perform well under physio-chemical conditions encountered in a given well all can lead to a poor cement seal. A review of the likelihoods of onshore petroleum well failure in a North American context is presented in (King and King 2013). However, Wu et al. (2016) identify that, to date there have not been any estimates made of failure rates for CSG wellbores in Australia and further that due to the differences in completion practises, data on Australian water bore life expectancies should not be extrapolated to CSG wells.

As a full review of failure rates for CSG wellbores in Australia is beyond the scope of this report, this hazard risk screening tool will be limited to identification and discussion of applicable lines of evidence in Table A7 - 3 below.

Table A7 - 3 Lines	of evidence	relevant to	plausible	Pathwav C.
	-,		p	

Line of evidence	Applicability to hazard assessment of plausible Pathway C
1: Basic hydraulic fracture growth and fluid transport models to provide bounding data points	Highly applicable. While hydraulic fracture growth models are only limited in applicability due to the nature of plausible Pathway C, fluid transport models could assist in determining the propensity of hydraulic fracture fluid to migrate up a poorly sealed cement well annulus.
2: Industry standard numerical modelling of hydraulic fracture growth and fluid transport.	Highly applicable. Hydraulic fracture growth models are only limited in applicability due to the nature of plausible Pathway C. Industry standard fluid transport models could provide additional insight into the flow of hydraulic fracture fluid up a poorly sealed cement well annulus and into a highly permeable formation.
3: Analysis of samples from monitoring / water well	Highly applicable. Contaminants in the water bearing aquifer should conceivably be detected in samples from monitoring or water wells.
4: Remote hydraulic fracture growth monitoring	Moderately applicable. Monitoring of hydraulic fracture growth should provide evidence if the hydraulic fracturing stimulation was rendered ineffective by a highly conductive loss of wellbore integrity or if the loss of wellbore integrity was exacerbated by attempted hydraulic fracturing stimulation.
5: Interpretation of injection pressure data	Loosely applicable. Hydraulic fracturing fluid flowing up the annulus of a wellbore should have a different injection pressure response to a normal hydraulic fracture treatment. However the cause of this abnormality may not be clearly identifiable.
6: Observation of key environmental receptors	Currently no data available

If the best well completion practises are followed and the lines of evidence from Table A7 - 3 above and the lack of reported cases are considered then the risk of hydraulic fracturing contaminants being transported up the wellbore annulus in plausible Pathway C could be considered exceptionally unlikely (medium confidence) (Mastrandrea et al. 2010) for the purposes of this hazard screening tool.

3.2. Plausible Pathway D: fracture growth into a fault

In plausible contaminant transport Pathway scenario D, an unidentified natural fault spanning the water bearing aquifer, the aquitard and the CSG production interval exists either (Figure A7 - 7):

- In the path of the growing hydraulic fracture in the CSG production interval, or
- Directly intersects the specific section of the borehole in the CSG production interval which is isolated and pressurised to grow a hydraulic fracture.



Figure A7 - 7 Sketch of plausible fate and transport release Pathway D. A water bore is shown as typical receptor.

In either scenario, during fracture growth the pre-existing fault is pressurised, reopened and acts as a preferential pathway for the fracture fluid. Hydraulic fracture intersection of natural faults has been suggested as the mechanism that causes larger than expected fracture height growth events in the Barnett and Jonah fields in the USA (Fisher and Warpinski 2012; Warpinski 2009; Wolhart et al. 2006).

Often a "step-rate" or a "step-down" test is conducted at the start of a treatment where injection pressure is recorded for different flow rates. Either of these tests should identify a highly conductive fault that directly intersects the borehole in the CSG production interval by a marked discrepancy in the test results compared to similar wells in the field.

The volume of hydraulic fracture fluid and proppant pumped for the fracture treatment is believed to limit the height growth in the same way as a typical hydraulic fracture (Fisher and Warpinski 2012). Therefore the likelihood of the fracture extending through the aquitard to the water bearing aquifer is minimal. In fact, logically a highly conductive fault would more likely cause the fluid to preferentially flow downwards due to gravitational effects rather than towards the surface.

During the fracturing treatment, a highly conductive fault either intersecting the borehole or intersecting the growing hydraulic fracture in the CSG production interval would likely cause a corresponding abnormality in the treatment pressure. The hydraulic fracture engineers could identify this abnormality in the treatment pressure and abandon the fracturing operation. If the engineers did not notice the discrepancy they would pump the planned volume of fracturing fluid and proppant.

A worst case scenario exists where a critically stressed fault could be pressurised and reactivated by a growing hydraulic fracture. In this scenario it is theoretically possible that the conductivity of the fault could be enhanced between the water bearing aquifer and the CSG production interval. The reactivated fault would not retain much permeability as proppant would tend to travel downwards in a highly conductive channel rather than upwards towards the aquifer and the fracture would not continue to grow once it reached the aquifer as all the fluid pressure would be released. It is assumed that such a significant geological structure would be mapped and well understood by the operator prior to conducting any facture treatment and therefore this worst case scenario is excluded from consideration in this report.

Line of evidence	Applicability to hazard assessment of plausible Pathway D
1: Basic hydraulic fracture growth and fluid transport models to provide bounding data points	Highly applicable. Basic hydraulic fracture growth models provide bounding data points for the maximum potential extent of hydraulic fracure growth. Plausible Pathway D involves the intersection of the growing hydraulic fracture and a natural fault. The maximum potential extent of the hydraulic fracture is relevant when reviewing the proximity of natural fault systems to the production borehole.
2: Industry standard numerical modelling of hydraulic fracture growth and fluid transport	Highly applicable. Industry standard numerical modelling provides a more accurate estimate of the extent of the hydraulic fracture growth. The output of industry standard numerical models can be compared to the horizontal and vertical location of natural faults in relation to the production borehole.
3: Analysis of samples from monitoring / water well	Highly applicable. Contaminants transported to the water bearing aquifer along plausible pathway should conceivably be detected in samples from monitoring or water wells.
4: Remote hydraulic fracture growth monitoring	Highly applicable. Tilt-meter or micro-seismic monitoring of hydraulic fracture growth would likely identify growth into or re-activation of a significant natural feature.
5: Interpretation of injection pressure data	Moderately applicable. An intersection between the growing hydraulic fracture and a natural fault may cause an abnormality in the injection pressure plot. However the cause of this abnormality may not be clearly distinguishable from a fracture intersection with another highly permeable zone.
6: Observation of key environmental receptors	Currently no data available

Figure A7 - 8 Lines of evidence relevant to plausible Pathway D.

3.3. **Overview of applicability of lines of evidence to each**

plausible pathway

An overview of the applicability of each of the lines of evidence to the four plausible pathways is presented in Table A7 - 4.

Line of evidence	2	Plausible Pathway A: Fracture growth into an aquifer	Plausible Pathway B: fracture growth into a well	Plausible Pathway C: well rupture during injection	Plausible Pathway D: fracture growth into a fault
Plausible pathw conceptualisatio	ay on	Compared and the second and the seco	Contraction of the second seco	 Image: A state of the state of	Construction of the second sec
Line of evidence hydraulic fractu fluid transport r	e 1: Basic re growth and nodels	Moderately applicable	Highly applicable	Highly applicable	Highly applicable
Line of evidence standard numer fracture and flui models	2: Industry rical hydraulic id transport	Highly applicable	Highly applicable	Highly applicable	Highly applicable
Line of evidence samples from m water bores	e 3: Analysis of nonitoring /	Highly applicable	Highly applicable	Highly applicable	Highly applicable
Line of evidence fracture monito	e 4: Remote ring	Highly applicable	Highly applicable	Moderately applicable	Highly applicable
Line of evidence Interpretation o pressure data	95: f injection	Loosely applicable	Moderately applicable	Loosely applicable	Moderately applicable
Final assesment for Gunnadah Basin (terminology as defined in Mastrandrea et al. (2010))	High agreement across experts and robust evidence support a "level of confidence" or "quantified measure of uncertainty"?	Yes, multiple, consistent an independent lines of high-quality evidence to support a quantified measure of uncertainty	Yes, multiple, consistent an independent lines of high-quality evidence to support a quantified measure of uncertainty	Yes, multiple, consistent an independent lines of high-quality evidence to support a level of confidence	Yes, multiple, consistent an independent lines of high-quality evidence to support a quantified measure of uncertainty

Table A7 - 4 Applicability of lines of evidence to each plausible pathway.

Level of	Extremely unlikely	Extremely unlikely	High to very	Extremely unlikely
confidence or	(<5% probability)	(<5% probability)	confidence that	(<5% probability)
quantified	with high	with high	this pathway	with high
measure of	confidence to	confidence to	would be unlikely	confidence to
uncertainty	extend vertically	extend		extend
(likelihood)	beyond 100m with	horizontally		horizontally
	parameters as	beyond 300m with		beyond 300m with
	defined in	parameters as		parameters as
	Appendix 7	defined in		defined in
		Appendix 7		Appendix 7
		Appendix 7		Appendix 7

4. Hydraulic fracturing stimulation of plausible transport release pathways in a conceptual geomechanical model of the Gunnedah Basin

In order to address lines of evidence 1 and 2 (modelling of hydraulic fracture growth), a conceptual geomechanical model is required. In this case the conceptual geomechanical model has been constructed from information from the CDM Smith (2014) report on Wilga Park well No.5. Table A7 - 5 describes each of the geological layers.

Formation	Depth	Depth to	Thickness	Geomechanical	Hydrostratigraphic	Lithology	
Layers	(m)	(m)	(111)	woder Layer	unit		
Surficial sediments	0	30	30	1	aquitard	Sand, silt and clay	
Pilliga Sandstone	30	230	200	2	aquifer	Quartzose sandstone	
Purlawaugh	230	320	90	3		Lithic labile sandstone	
Deriah	320	400	80	4		sandstone	
Napperby	400	460	60	5		mudstone	
Digby	460	490	30	6	aquitard	conglomerate	
Trinky,	490	590	100	7		sandstone	
Wallala,,							
Benelabri							
Hoskissons	590	620	30	8	CSG Reservoir	coal	
Watermark	620	640	20	9		Siltstone, claystone	
Porcupine	640	750	110	10		Sandstone, siltstone.	
. er eupine	0.0				aquitard	conglomerate	
Maules Creek Upper	750	770	20	11		Sandstone, siltstone	
Maules Creek	770	800	30	12	CSC Posonuoir	coal	
Coal					C3G Reservoir		
Maules Creek	800	850	50	13		Conglomerate,	
Lower / Leard					Inter-burden	sandstone, siltstone	
Basement	850	1000	150	14		sandstone	

Table A7 - 5 A conceptual geomechanical model of layers represented in Gunnedah Basin (Ref: Wilga Park well No.5).

4.1. **Synthetic in situ stress in each layer of the conceptual**

geomechanical model

The vertical stress is induced by the weight of the overlaying rock, and can be obtained with the known bulk density of the overlaying formation using the equation:

$$\sigma_V(z) = g \int_0^z \rho(z) dz$$
 (Equation A7-1)

where g is the gravitational acceleration, z is the depth, and $\rho(z)$ is the density as a function of depth.

The horizontal stress components in rock layers are induced by gravitational loading and tectonic stress. The minimum horizontal stress is estimated as (Gale et al. 2014; Gidley 1989).

$$\sigma_h = \frac{\nu}{1-\nu} \sigma_V + \frac{E}{1-\nu^2} \varepsilon_{\text{tect}}$$
(Equation A7-2)

where $\varepsilon_{\text{tect}}$ is the horizontal tectonic strain and is assumed to be uniform with depth, *E* and *v* are Young's modulus and Poisson's ratio, respectively as detailed in Table A7 - 6 below.



Figure A7 - 9 Synthetic in-situ stresses in the conceptual geomechanical model layers.

The synthetic stresses in each layers of the conceptual geomechanical model are calculated using the physical properties listed in Table A7 - 6. Figure A7 - 9 shows the distribution of the synthetic stress as function of the depth. Note pore fluid pressure is not considered here.

Table A7 - 6 - Physical properties of the Conceptual Geomechanical Model Layers (CGML) and the synthetic stresses in each layer.

CGML	Depth to (m)		Thickness	Density	E	ν	σ_V (MPa) at		σ_h (MPa) at		Layer
	Тор	Bottom	(m)	(kg/m³)	(GPa)		Тор	Bottom	Тор	Bottom	
1	0	30	30	2000	2.8	0.2	0.00	0.59	0	1.02	Sand/clay
2	30	230	200	2200	13	0.2	0.59	4.90	4.21	5.29	Sandstone
3	230	320	90	2600	20	0.22	4.90	7.19	7.69	8.33	Sandstone
4	320	400	80	2700	28	0.1	7.19	9.31	9.28	9.52	Sandstone
5	400	460	60	2350	0.55	0.28	9.31	10.69	3.80	4.34	Mudstone
6	460	490	30	2500	10	0.22	10.69	11.43	6.17	6.38	Conglomerate

7	490	590	100	2600	19	0.13	11.43	13.97	7.51	7.89	Sandstone
8	590	620	30	1200	2	0.3	13.97	14.33	6.65	6.80	Coal
9	620	640	20	2200	2.83	0.3	14.33	14.76	7.07	7.26	Claystone
10	640	750	110	2700	28	0.1	14.76	17.67	10.12	10.45	Sandstone
11	750	770	20	2760	20	0.2	17.67	18.21	10.67	10.80	Siltstone
12	770	800	30	1500	3	0.34	18.21	18.65	10.40	10.63	Coal
13	800	850	50	2700	28	0.08	18.65	19.97	13.41	13.74	Sandstone
14	850	1000	150	2700	28	0.08	19.97	23.94	13.74	14.74	Sandstone

The conceptual mechanical properties and synthetic in-situ stresses of geological layers from the Gunnedah Basin conceptual geomechanical model have been used to produce a number of analytical and numerical modelling outputs relevant to plausible Pathways A, B and D.

4.1.1.Plausible Pathways B and D

In plausible Pathways B and D, a growing hydraulic fracture directly intersects either a water bore (plausible Pathway B) or a highly conductive natural fault (plausible Pathway D). In both of these plausible pathways, the horizontal extent of the fracture is the critical parameter. PKN and KGD models from line of evidence 1 provide a theoretical upper bound (>99% confidence) for horizontal extent of hydraulic fracture growth and the P3D model from line of evidence 2 provides a more likely horizontal extent of hydraulic fracture growth (>50% confidence).



Figure A7 - 10 Line of evidence 1 for plausible Pathways B and D.

A nominal hydraulic fracturing fluid injection rate of $Q_0 = 0.05 \ m^3/s$ for 60 minutes for a total of 180,000L was selected for analysis. For the purposes of this hazard risk screening tool, a leakoff coefficient of $C_L = 0 \ m/_{s0.5}$ was selected to represent the most conservative case where no hydraulic fracturing fluid was lost into the CSG production interval. Figure A7 - 10 shows the horizontal extent of hydraulic fractures calculated using both PKN and KGD models for two different scenarios. The two scenarios have identical injection and hydraulic fluid viscosity conditions however they differ in the leakoff coefficient parameter. Figure A7 - 10 shows that the PKN geometry in the zero leakoff coefficient scenario (red line in Figure A7 - 10) provides the estimate of the upper bound of horizontal hydraulic fracture growth of approximately 300m after 60 minutes of injection time. For this set of fracture treatment parameters, a fracture would be considered extremely unlikely (high confidence) to extend further than this distance from the well.

4.1.2.Hydraulic Fracture Height Growth in Plausible Pathway A

Plausible Pathway A considers a case where the vertical hydraulic fracture growth extends from the CSG production interval, through the overlying aquitard into a water-bearing aquifer. In this plausible pathway the contaminant transport hazard relates to the extent of vertical hydraulic fracture growth. Results from the equilibrium height model provide a conservative estimate for maximum hydraulic fracture height growth a case where the fracture toughness (K_{IC}) is highest in the basement rock, lowest in the production interval and intermediate in the overlying aquifer. Figure A7 - 11 provides the relationship between fracture height growth and treatment pressure above the closure stress (Δp). As can be seen, up to approximately $\Delta p = 2.0$ MPa very little height growth is predicted by the model.



Figure A7 - 11 The fracture height growth map shows the relation between the fracture height and the treatment pressure above the closure stress using the equilibrium height model.

In the absence of information on in-situ stresses, pore pressures and typical hydraulic fracturing treatment pressures a hydraulic fracturing fluid pressure that is higher than the minimin in-situ pressure magnitude by (Δp) 3.75 MPa has been selected for the purposes of providing data to this hazard risk screening tool. As can be seen in Figure A7 - 11, for this set of fracture treatment parameters, a fracture would be considered extremely unlikely (high confidence) to extend vertically further approximately 100m from the centre of the CSG production interval (labelled coal seam in Figure A7 - 11).

5. Data Gaps

The following data gaps have been identified:

- Identification of individual water bores or other wells that intersect the CSG production interval;
- Detailed individual well completion reports;
- Identification of key environmental receptors ;
- Information on individual hydraulic fracturing treatments including:
 - In-situ properties of the geological layers;
 - Hydraulic fracturing pressure data;
 - Pre-fracture calibration test results;
 - Fracture fluid injection rate, volume, duration and viscosity;
 - Tiltmeter or microseismic monitoring records.

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Annex A : Hydraulic fracture design overview

Hydraulic fracture growth is difficult to simulate especially in a complex rock mass such as a coal seam that contains joints and cleats, as well as bedding planes and over and under-lying formations with significantly different mechanical properties. A good fracture design in a CSG scenario will take into account all available details of each geological layer including fracture density and orientation as well as mechanical properties such as fracture toughness, stiffness, Poisson's ratio and permeability and in-situ conditions such as stress orientation and magnitude and pore pressure.

In a homogeneous and isotropic medium, simple planar hydraulic fractures will grow oriented normal to the minimum principal stress direction. In the production interval of Australian CSG wells, the minimum principal stress direction is typically horizontal therefore fractures will preferentially grow oriented vertically as depicted in Figure A7 - 12 below. In this respect the hydraulic fracture growth in the Australian CSG industry is similar to a number of other hydraulic fracturing applications including stimulation of shale gas wells in the USA (vertical maximum principal stress therefore vertical hydraulic fractures).

One of the key differences between the current CSG industry practice in Australia and the shale gas in the USA is the orientation of the production borehole. In USA shale gas developments, horizontal drilling is used to create a borehole with a long horizontal section through the production interval (Rahim and Al-Anazi 2012; Soliman et al. 1990). In contrast, in most hydraulically fractured Australian CSG applications, a straight vertical borehole is used.



Figure A7 - 12 - Sketches of hydraulic fracture growth from a horizontal well (left) and a vertical well (right).

The second key difference between the USA shale gas industry and the Australian CSG industry is the height of the production interval. The size of a hydraulic fracture is designed by controlling the volume of injected fracture fluid. In the USA shale gas industry, the production interval is often relatively large compared to the designed extent of the hydraulic fracture. Fractures in shale gas formations are often designed such that the tip of the fracture will approximately reach the vertical interface between the production interval and the underlying aquitard. A radial fracture growth model (such as

depicted in Figure A7 - 15) is often a sound basis for fracture design for shale reservoirs were the hydraulic fracture is designed extend to match reach the vertical extent of the production interval.

In contrast, fracture treatments for Australian coal seams are designed and pumped to promote a fracture that will have a length much greater than the height. Such a slender fracture is best depicted initially by the KGD model and then the PKN model as shown in Figure A7 - 15 below. These analytical models presume that the fracture is entirely contained within the coal seam and the height of the hydraulic fracture grows to match the height of the production interval



Figure A7 - 13 Sketches of PKN and KGD hydraulic fracture configurations from Adachi et al. 2007.

Some of the fracture fluid is lost as leak-off into the formation matrix or natural fracture network, this is related to the viscosity and pumping rate of the fracture fluid (designed by hydraulic fracturing engineers) and the permeability of the formation (typically estimated during pre-fracture calibration tests).

Once fluid leak-off has been estimated, an effective fracture volume (V_f) can be established.

Using the following equation, an approximation for the average fracture width can be obtained for fractures expected to be height-constrained in the shale geological layer as depicted in Figure A7 - 13 above (similar equations exist for penny-shaped or circular fractures):

$$\overline{w} = 2\left(\frac{\mu q_i x_f}{r'}\right)^{0.25}$$
 (Equation A7-3)

The average width \overline{w} is related to the fracture fluid viscosity (μ), injected volume into fracture wing (q_i) (half of the fracture), the length of the fracture wing (x_f) and the formation plane-strain modulus (E'). Dividing the effective fracture volume by the average fracture width gives an estimate of the fracture surface area.

The designed length of the fracture is estimated as the calculated fracture surface area divided by the height of the formation (obviously this assumes that the fracture will not grow out of the CSG production interval into the bounding geological layers).

If the geological conditions are such that it is anticipated that the fracture will grow out of the shale gas seam, a numerical model (typically a P3D model) is run to give the same information on the fracture extent, width profile etc.

The design elements that the fracture engineer has in his/her control are:

- Pumping Rate;
- Fluid viscosity;
- Well spacing / orientation;
- Proppant;

- Distance between fracture stages;
- Number of perforations per fracture stage (number of hydraulic fractures to attempt to grow simultaneously).

The critical parameters outside of the fracture engineer's control are:

- Stiffness and young's ratio of the formation and surrounding geological layers;
- Orientation and magnitude of the principal stresses in the formation and surrounding geological layers;
- Permeability of the formation and surrounding geological layers (including natural fracture network).

Annex B : Classical hydraulic fracture growth models

Classical hydraulic fracture models provide a method of determining end members for possible extent of hydraulic fracture growth. Three models are introduced and relate to different hydraulic fracture growth conditions: the PKN hydraulic fracture model, the Penny-shaped hydraulic fracture model, and the KGD model (Figure A7 - 13).

PKN hydraulic fracture model

The PKN model is applicable to for conditions when the vertical hydraulic fracture remains confined within the horizontal CSG production interval, on account of a sufficiently high contrast in horizontal stress between the reservoir layer and the adjacent impermeable layers (Kovalyshen and Detournay 2010; Nordgren 1972; Perkins and Kern 1961). In other words, the PKN model is based on the assumption that the hydraulic fracture propagates laterally with a constant height H corresponding to the thickness of the reservoir (Figure A7 - 14).



Figure A7 - 14 PKN hydraulic fracture geometry

The solution to a PKN hydraulic fracture can be expressed as:

$$w(x,t) = W(t)\Omega[\xi,P(t)]$$

$$L(t) = l(t)\gamma[P(t)]$$
(Equation A7-4)

Here, w(x, t) and L(t) are the average crack width and crack length, W(t) and l(t) are power law of time functions, respectively, and Ω and γ are dimensionless crack opening and length, the variable $\xi = x/L(t)$ ($0 \le \xi \le 1$) defines a stretching system of coordinates.

The viscosity-dominated solution is as follows:

$$W_m = \left(\frac{\overline{\mu}}{\overline{E}}\frac{Q_0^2}{H}\right)^{1/5} t^{1/5}$$

$$l_m = \left(\frac{\bar{\mu}}{\bar{\mu}}\frac{Q_0^3}{H^4}\right)^{1/5} t^{4/5}$$

$$\bar{\Omega}_{m0} = \left(\frac{12}{5}\right)^{1/3} (1-\xi)^{1/3} \left[1 - \frac{1-\xi}{96} + \frac{23(1-\xi)^2}{64512} - \frac{7(1-\xi)^3}{1327104} + \cdots\right]$$

$$\gamma_{m0} = 0.660422$$

$$\bar{\Omega}_m = \gamma_m^{-2/3} \Omega_m$$
(Equation A7-5)

The average crack width is related to the local net pressure $p(x, t) = p_f - \sigma_0$, the difference between the fracturing fluid pressure p_f and the confining stress σ_0 as

$$w(x,t) = \frac{H}{E}p(x,t)$$
 (Equation A7-6)

Eqs. (A7-4) - (A7-6) predict the crack length L, width w, and the fluid pressure p_f as functions of time t and position x. The PKN hydraulic fracture model input parameters are as follows:

- geometric parameters (thickness of formation layer);
- mechanical parameters (Young's modulus and Poisson's ratio of formation layer, viscosity of the fracturing fluid);
- the minimum horizontal principal stress;
- injection rate.

Penny-shaped hydraulic fracture model



Figure A7 - 15 Penny-shaped hydraulic fracture geometry (Detournay 2004).

The solution to a penny-shaped hydraulic fracture (Figure A7 - 15) can be expressed as:

$$w = \varepsilon L \Omega, p = \varepsilon E' \Pi$$
, and $R = \gamma L$ (Equation A7-7)

For the toughness dominated solution, we have

$$\varepsilon_{K} = \left(\frac{{K'}^{6}}{{E'}^{6}Q_{0}t}\right)^{1/5}, L_{K} = \left(\frac{{E'}Q_{0}t}{K'}\right)^{2/5}, \Omega_{K} = \left(\frac{3}{8\pi}\right)^{1/5} (1-\rho^{2})^{1/2}, \Pi_{K} \cong 0.3004, \gamma_{K} \cong 0.8546 \text{ (Equation A7-8)}$$

where $\rho = r/R(t)$.

For the viscosity dominated solution, we have:

$$\varepsilon_{M} = \left(\frac{\mu'}{E't}\right)^{1/3}, L_{M} = \left(\frac{E'Q_{0}^{2}t^{4}}{\mu'}\right)^{1/9},$$

$$\Omega_{M0} \approx (C_{1} + C_{2}\rho)(1-\rho)^{2/3} + B_{1}\left[(1-\rho^{2})^{1/2} - \rho\cos^{-1}\rho\right],$$

$$\Pi_{M0} \approx A_{1}\left[\omega_{1} - \frac{2}{3(1-\rho)^{1/3}}\right] - B_{2}\left(\ln\frac{\rho}{2} + 1\right),$$

$$\gamma_{M0} \approx 0.6955$$
(Equation A7-9)

where $A_1 \approx 0.3581, B_1 \approx 0.1642, B_2 \approx 0.09269, C_1 \approx 1.034, C_2 = 0.6378, \omega_1 = 2.479.$

The Penny-shaped hydraulic fracture model input parameters are as follows:

- mechanical parameters (Fracture toughness, Young's modulus and Poisson's ratio of rock formation, viscosity of the fracturing fluid);
- the minimum vertical principal stress;
- injection rate.

Annex C : Pseudo-3D hydraulic fracture height growth models

The present state of the art typically entails treatment design to ensure appropriate containment, length, and proppant placement using a planar, pseudo-3D numerical model.

The equilibrium height pseudo-3D model

For hydraulic fracture treatment of a multi-layered formation shown in Figure A7 - 17, fracture height, h, pressure, p_{cp} , and the width distribution, w(z), in a cross-section can be determined using (Fung et al. 1987; Mack et al. 1992)

$$\begin{split} K_{IU} &= \sqrt{\frac{\pi h}{2}} \Big[p_{cp} - \sigma_n + \rho_f g \left(h_{cp} - \frac{3}{4} h \right) \Big] + \sqrt{\frac{2}{\pi h}} \sum_{i=1}^{n-1} (\sigma_{i+1} - \sigma_i) \left[\frac{h}{2} \cos^{-1} \left(\frac{h-2h_i}{h} \right) - \sqrt{h_i (h-h_i)} \right] \text{(Equation A7-10)} \\ K_{IL} &= \sqrt{\frac{\pi h}{2}} \Big[p_{cp} - \sigma_n + \rho_f g \left(h_{cp} - \frac{3}{4} h \right) \Big] + \sqrt{\frac{2}{\pi h}} \sum_{i=1}^{n-1} (\sigma_{i+1} - \sigma_i) \left[\frac{h}{2} \cos^{-1} \left(\frac{h-2h_i}{h} \right) + \sqrt{h_i (h-h_i)} \right] \text{(Equation A7-11)} \\ w(z) &= \frac{4}{E^*} \Big[p_{cp} - \sigma_n + \rho_f g \left(h_{cp} - z \right) \Big] \sqrt{z(h-z)} + \frac{4}{\pi E^*} \sum_{i=1}^{n-1} (\sigma_{i+1} - \sigma_i) \left[(h_i - z) \cosh^{-1} \left(\frac{z}{|z-h_i|} + \frac{h_i}{h} + \frac{h_i}{|z-h_i|} \right) + \sqrt{z(h-z)} \cos^{-1} \left(\frac{h-2h_i}{h} \right) \Big] \end{aligned}$$

Here, K_{IU} and K_{IL} are the fracture toughnesses of the layers containing the upper and lower tips of the fracture, h_{cp} and h are the positions of the centre of the perforations and the top of layer i both measured from the bottom tip of the fracture, σ_n is the minimum horizontal principal stress in layer n, ρ_f is the density of the fluid, g is gravitational acceleration, and E^* is the plane-strain Young's modulus of the section.

The difference between upper and lower stress intensity factors at equilibrium can be computed as

$$K_{IL} - K_{IU} = 2\sqrt{\frac{2}{\pi h}} \sum_{i=1}^{n-1} (\sigma_{i+1} - \sigma_i) \sqrt{h_i (h - h_i)}$$
(Equation A7-13)

For a specific lower tip location, the height of the fracture and corresponding upper tip position can be found by an iterative scheme. Once the fracture height that satisfies Eq. (A7-13) is obtained, Eq. (A7-10) or (A7-11) can be used to solve for the pressure, p_{cp} , that will create the fracture of height *h*. Then, the fracture width distribution can be obtained using Eq. (A7-12).



Figure A7 - 16 Fracture height growth in a multi-layered formation.

The equilibrium height pseudo-3D model can provide a complete fracture height map (height-pressure map). The equilibrium height pseudo-3D input parameters are as follows:

- geometric parameters (thickness of each layer);
- mechanical parameters (fracture toughness, Young's modulus and Poisson's ratio of each layer);
- the minimum horizontal principal stress in each layer.

The classical pseudo-3D hydraulic fracture model





The pseudo-3D hydraulic fracture model predicts the crack width, height and length growth, crack footprint, and fluid pressure (Adachi et al. 2010) (Figure A7 - 17). The classical pseudo-3D input parameters are as follows:

- geometric parameters (thickness of each formation layer);
- mechanical parameters (fracture toughness, Young's modulus and Poisson's ratio of each formation layer, viscosity of the fracturing fluid);
- the minimum horizontal principal stress;
- injection rate.

Annex D : Hydraulic fracture growth numerical research models

Hydraulic fracturing modelling involves the coupling of at least three processes: (i) the mechanical deformation of rocks induced by the fluid pressure on the fracture surfaces, (ii) the flow of fluid within the fracture, and (iii) the fracture propagation. A typical coupling of rock deformation and fluid flow has been presented by Adachi et al. (2007).

Mathematically, rock deformation is modelled using the theory of linear elasticity, represented by an integral equation that determines the non-local relationship between the fracture width and the fluid pressure. Fluid flow is modelled using lubrication theory, represented by a non-linear partial differential equation that relates the fluid flow velocity, the fracture width and the pressure gradient. The criterion for fracture propagation is usually given by the conventional energy-release rate approach of linear elastic fracture mechanics (LEFM) theory, in terms of rock toughness.

Many numerical methods have been proposed for solving the above initial and boundary value problems with moving boundaries, including fracture tip and fluid front. Common numerical methods include finite element methods (FEM), including extended FEM; boundary element methods (BEM), including displacement discontinuity methods and symmetric Galerkin BEM, and coupled finite/discrete element methods. Many simplified models avoid solving the coupling hydraulic fracturing problems directly, these models play an important role in fracture design as their simplicity and implied assumptions allow rapid computation.

Physically, fracture growth within a natural fracture network is complicated not only by fracture growth acceleration and arrest, but also by fracture nucleation, connection and crossing. Conductive channels follow the newly-created fracture path, normally perpendicular to the least compressive normal stress and the pre-existing fracture segments. To break through a natural fracture network commonly incurs a relatively higher fluid pressure. In addition, shear slip-dominated fracture growth may replace open-mode fracture growth under some circumstances and the pre-existing hydraulic conductivity can play a significant role in fracture path selection.

The computational difficulty in modelling hydraulic fracture growth in a fracture network forces rigorous models to use a finite number of fractures (Zhang et al. 2014; Zhang et al. 2009). Research studies have focused mainly on mechanisms associated with fracture nucleation, connection and crossing. The stochastic feature of the fracture network can only be considered through the rearrangement of fracture size, orientation and residual conductivity.

An understanding of the role of hydraulic fracture in modelling in efficient hydraulic fracture design for CSG wells, especially for situations that lack accurate mapping of subsurface fracture networks

Annex E : Out of plane hydraulic fracture growth

All hydraulic fracturing models described in Annex B: Classical hydraulic fracture growth models, Annex C: Pseudo-3D hydraulic fracture height growth models and Annex D: Hydraulic fracture growth numerical research models consider hydraulic fractures that are constrained to growth in a single plane. This assumption is particularly tenuous for the case of hydraulic fracture stimulation of Australian CSG wells as two situations occur where out of plane growth is plausible.

Firstly, coal seams contain networks of joints and cleats that can provide a growing hydraulic fracture an energetically preferential pathway that is not orientated with the maximum stress direction. Such a set of natural weaknesses can lead to a hydraulic fracture that "steps" into or out of plane as it grows or even bifurcates in some scenarios into multiple fracture growth. Direct observations of this behaviour are presented in (Jeffrey et al. 2009).

Secondly, at the interfaces between the coal seam and over/under-lying geological formations, a situation occurs that often can strongly promote what is known as T-shaped growth. If the over/under-lying formations are significantly tougher and/or under significantly higher horizontal stress, the hydraulic fracture can preferentially grow into the interface between the coal and the over/under-lying formation. This T-shaped growth has been directly observed in mine-back experiments (Jeffrey and Settari 1998), studied in the laboratory context (Llanos et al. 2006) and simulated in 3D finite element modelling (Chen et al. 2015). The formation of T-shaped fractures at the roof/floor of a CSG production interval has a lot to do with the in-situ stresses in each of the geological layers.

An example of two basic scenarios can be used to highlight the effect of stress contrasts:

First scenario: The intermediate/maximum principal stress is >120% of the minimum principal stress i.e. there is a significant difference between the maximum and minimum stress magnitudes:

- Fractures will align strongly with the maximum/intermediate principal stresses
- A significant interaction it an interface, stress change or toughens change in the rock mass is required to achieve fracture growth out of this plane in this scenario.
- Examples significant interactions required for out-of-plane could be:
 - A weak and conductive natural fault slightly deviated from the preferential fracture plane;
 - Encountering a geological layer that has significantly higher toughness or is under significantly higher stress;
 - Depletion of the pore pressure in the surrounding rock matrix (such as for shale gas re-fracturing after a few months of production);
 - Major and non-reversible displacement/deformation of the rock mass as caused by large width hydraulic fracture opening.

Second scenario: The intermediate/maximum principal stresses are approximately equal to the minimum principal stress

- Fractures will not align strongly in any direction and tend to follow local weaknesses in the rock fabric;
- Natural fractures and minor interactions with different geological layers will strongly influence hydraulic fracture growth;
- Out of plane hydraulic fracture will be more easily achieved (through re-fracturing, changing the fluid composition, varying the proppant etc.).

Complex multiple hydraulic fracture modelling

Out of plane hydraulic fracture growth is difficult to numerically model as models must take into account many complexities including the perturbations on stress fields induced by fracture interaction and pre-existing structural heterogeneities. Recently, many models have been proposed to represent a naturally fractured rock mass using a method known as discrete fracture network (DFN) modelling (Figure A7 - 18). In DFN models, fractures are defined explicitly by their location, orientation and conductivity in contrast to homogenization methods such as dual-porosity models (Dershowitz 2011; Weng 2015).

Although a DFN approach could in theory be used to represent the complexity of joints and cleats in a CSG coal seam, this is not believed to be common practice amongst Australian CSG industry currently. One major limitation of this approach is the availability of good quality representative data on the structural heterogeneities in a specific coal seam. As with any modelling approach the accuracy of the output is directly related to the extent to which the system is understood.

Approaches such as the T-shaped hydraulic fracture model (Chen et al. 2015) are able to consider simple out of plane hydraulic fracture geometries but are computationally intensive and require a large number of input parameters. As such they have not been commonly adopted by industry in fracture design are more suited to research investigations into the mechanics of hydraulic fracture growth.



Figure A7 - 18 3D T-shaped hydraulic fracture geometry.

The 3D T-shaped hydraulic fracture model predicts the crack width, height and length growth, crack footprint for both the horizontal and vertical fracture branches, and fluid pressure.

The 3D T-shaped hydraulic fracture model input parameters are as follows:

- geometric parameters (thickness of each formation layer);
- mechanical parameters (fracture toughness, Young's modulus and Poisson's ratio of each formation layer, viscosity of the fracturing fluid);
- the minimum horizontal principal stress and vertical principal stress;
- injection rate;
- Cohesion (tensile strength) and fracture toughness of the interface between geological layers.

Annex F : Estimation and measurement of in-situ rock stresses

As the orientation and shape of hydraulic fracture growth is determined by the in-situ stress field, an understanding of the in-situ rock stress is critical for hydraulic fracture treatment design.

The orientation and magnitude of in-situ rock stress can be difficult and expensive to directly measure and in difficult mediums such as some coal seams, traditional methods such as USBM Overcoring Torpedo and the CSIRO Overcoring Gauge can be unsuitable.

As scientific understanding and technology has developed over time, the International Society of Rock Mechanics (ISRM) has endorsed a series of informative "Suggested Methods" for rock stress estimation. The latest of these suggested methods (Stephansson and Zang 2012) gives an overarching guide to establishing a model for the in-situ rock stress at a given site and suggests a structured approach where data from geological and world stress map databases is combined with borehole and drillcore analysis and more direct methods to achieve a final rock stress model.

An initial estimate of vertical stress magnitude can be obtained using a typical lithostatic gradient of 25 MPa/km and this can be used to make an initial estimate of horizontal stresses magnitude via Poisson's ratio of the rock matrix. This initial estimate can be refined using data from the world stress map and regional stress maps and through analysis of local geological data. Additional refinement can be made thorough analysis of core data.

An instrumented and monitored small hydraulic fracture can be used to determine a number of properties of the CSG production interval. A number of variations and names exist for hydraulic fracture injection/pressure fall-off methods. However, essentially the magnitude of the minimum in-situ stress can be indirectly measured and if the fracture is monitored using tiltmeter and/or microseismic instrumentation, the orientation of the minimum in-situ stress can also be determined. The test will also provide information on the required energy to propagate a hydraulic fracture and the permeability of the production interval. An excellent overview of the method can be found in Appendix A of (Martin et al. 2013).

In the case of CSG developments, direct stress measurement methods will often not be applicable and full hydraulic fracture injection/pressure fall-off tests are cost prohibitive. Many companies favour an easier and faster step-rate test (Cardinal Surveys Company 2009; Schlumberger 2016) at the beginning of their hydraulic fracturing stimulation to provide basic data on the production interval.

CONTACT US

- t 1300 363 400
- +61 3 9545 2176
- e enquiries@csiro.au
- w www.csiro.au

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FOR FURTHER INFORMATION

- Land & Water
- Dirk Mallants
- t +61 8 8303 8595
- e Dirk.Mallants@csiro.au
- w www.csiro.au/en/Research/Environment/Water

Land & Water

- Simon Apte
- t +61 2 9710 6838
- e Simon.Apte@csiro.au
- w www.csiro.au/en/Research/Environment/Water

Energy

- James Kear
- t +61 3 9545 8347
- e James.Kear@csiro.au
- w www.csiro.au/en/Research/Energy/Hydraulic-fracturing