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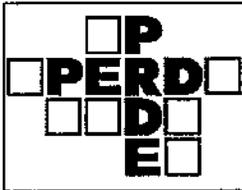
Migration of Methane into Groundwater

**from
leaking production wells
near Lloydminster**

March 1995

CAPP Pub. #1995-0001

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Migration of Methane into
Groundwater from Leaking
Production Wells near
Lloydminster

Report for Phase 2 (1995)

March 1996
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B. Schreiner and M. Millard (SRC) conducted geological logging of the test holes at the new research sites; the cuttings were examined and interpreted by M. Millard. The gas and inorganic concentration analyses were conducted by the SRC Analytical Laboratory. Existing soil gas data were provided by Saskatchewan Energy and Mines and Husky Oil; further analyses* for final site selection were conducted by Husky Oil.

1.0 INTRODUCTION

In 1995 the Saskatchewan Research Council continued an investigation of gas migration in groundwater in the Lloydminster area. This report documents the 1995 research program, which followed the initial (1994) program (Van Stempvoort and Jaworski, 1995; Schmitz, 1995).

The research project has the following objectives:

- to investigate the occurrence of methane in groundwater near leaking production wells in the Lloydminster study area,
- to determine whether the methane is derived from the leaking well or occurs naturally in the aquifer,
- to determine the concentration gradients and approximate flux rates of methane from leaking wells to shallow aquifers, and
- to predict the migration rate of methane in aquifers under various scenarios of time and physicochemical conditions (e.g., aquifer properties).

This project is funded by the Canadian Association of Petroleum Producers (CAPP), the Lloydminster Area Operators Gas Migration Team (LAOGMT), the Panel for Energy Research and Development (PERD) and the Saskatchewan Research Council (SRC). In 1995, the steering committee for this program included Ron Schmitz (Husky Oil, CAPP), Garry Lorenz (LAOGMT), Les Bernier (Saskatchewan Energy and Mines), David Blume (Provost Area Surface Rights), Tom Cook (Alberta Energy Utilities Board), Garry Ericson (Saskatchewan Energy and Mines), Margaret Klebek (Alberta Environmental Protection), Kennedy Kohlman (Koch Exploration), Brian Moneta (Elan Energy), Don Roberts (Alberta Energy Utilities Board), Scott Robinson (Saskatchewan Environment and Resources Management), Harold Seitz (Wascana Energy), Kurt Uhrich (Amoco) and Gary Webster (CAPP).

The 1995 program included five components as indicated in the following sections:

- expansion of monitoring at the Lindbergh site,
- selection of five new sites; installation of monitoring wells at two of these sites,
- investigation of dissolved methane and other hydrochemical species,
- development of modelling for simulation of methane migration in groundwater,
- survey of methane in 23 water supply wells in the Lloydminster area.

2.0 BACKGROUND

2.1 Definition of the Study Area

In this investigation, the Lloydminster study area (referred to subsequently as the "study area") refers to portions of Saskatchewan and Alberta as follows: Townships 36 through 63, Ranges 1 through 13, west of the 4th Meridian in Alberta; Townships 44 through 52, Ranges 17 through 28 and Townships 38 through 43, Ranges 24 through 28, west of the 3rd Meridian in Saskatchewan (Figure 1).

2.2 Vertical Gas Migration



Erno and Schmitz (1994) and others have documented leakage of natural gas (mainly methane) from oil and gas production well to soils in the Lloydminster area. The gas appears to be leaking from relatively deep geological units that have been intersected by the production wells: evidently the Cretaceous Mannville Group (production zones) and/or the Lea Park Formation (Rich et al., 1994, E. Jensen and K. Muelenbachs, personal comm., 1995; see Figure 2). The vertical pathways that transport methane from the deep sources to the soil horizons appear to be within the annuli of the production wells (Figure 3; cf. Chafin, 1994). Apparently there are permeable zones, referred to as "microannuli", within or adjacent to the cemented annuli, which allow upward migration of gas phase methane. This leaking gas apparently disperses readily along the ubiquitous networks of fractures and other pores in soil.

Along the vertical flow paths from deep formations to soil, methane may also migrate laterally into permeable sediments intersected by the production wells. Plumes of dissolved methane may spread by advection and dispersion into aquifers (Figure 3). In some cases, methane may also migrate laterally as a gas phase within these aquifers.

Studies conducted in the United States have documented the effects of large-scale invasion of natural gas from exploration holes or defective production wells to shallow aquifers and surface water bodies (Rose and Alexander, 1945; Preston, 1980; Kelly et al., 1985). In these cases, the gas apparently migrated along uncemented annuli, whereas the wells in the Lloydminster area generally have cement to surface. Kelly et al. (1985) examined changes in groundwater chemistry following a massive influx of gas from a "blow-out". The concentrations of reduced species (Fe, Mn and sulfide) increased, while concentrations of oxidized species (dissolved oxygen, nitrate and sulfate) decreased due to oxidation of the methane, which is consistent with the results from this program to date.

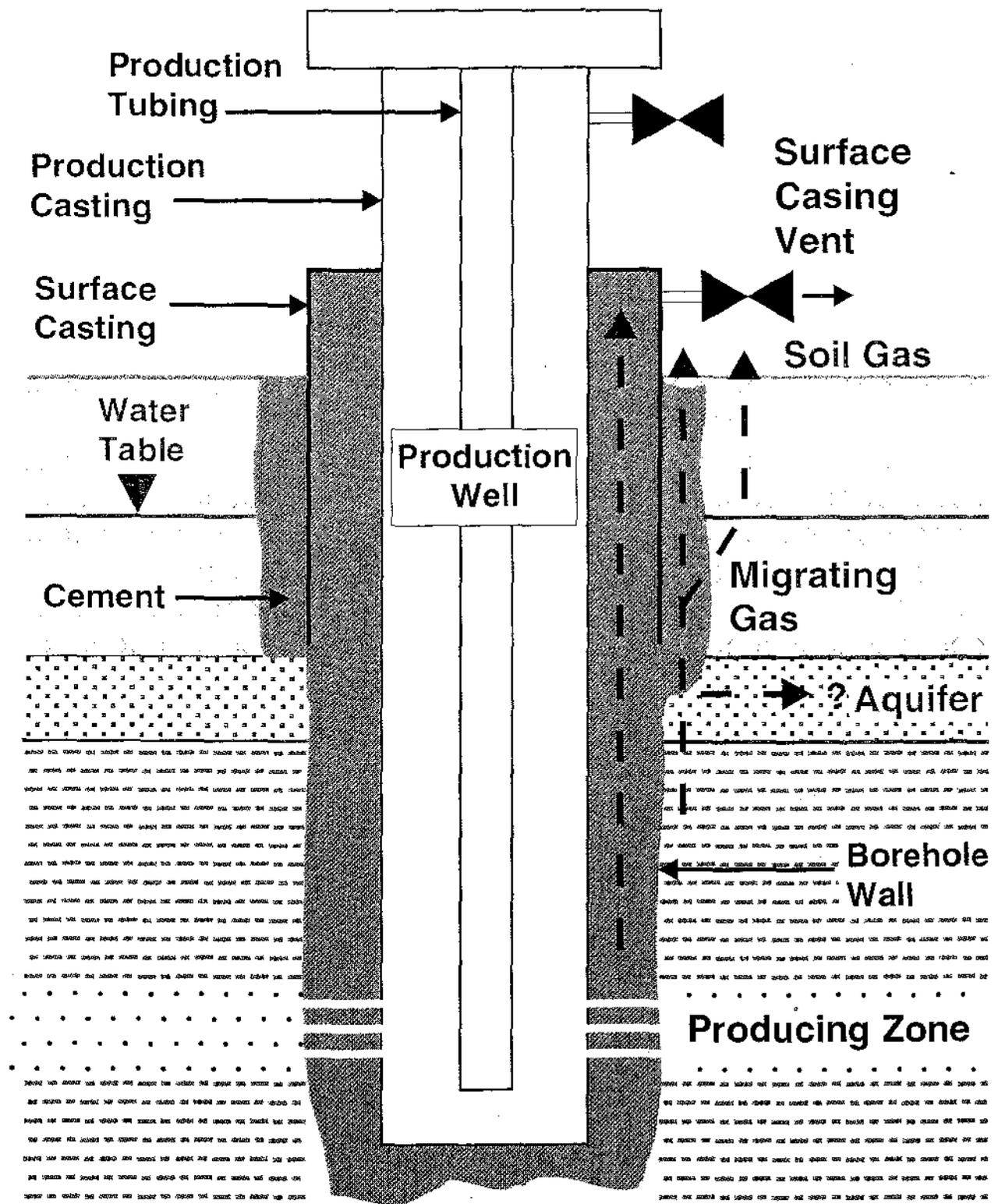


Figure 3 Schematic of gas migration, modified after Schmitz et al (1994).

5.0 METHANE, ETHANE & OTHER ANALYSES FOR RESEARCH SITES, 1995

5.1 Sampling and Analytical Methods for Dissolved Species

Water samples were collected from all monitoring wells and analysed for the following components: concentrations of dissolved methane and ethane, major ions, pH, Eh, Fe, Mn, and $\text{NO}_3 + \text{NO}_2$. The methane and ethane data are essential for modelling the fluxes of these gases from leaking wells into shallow aquifers. The redox species concentrations give a general indication of the potential for bio-oxidation of methane within the aquifers.

Improvements were made to methane (and ethane) sampling and extraction techniques, based on the methods and experience of the 1994 program (Van Stempvoort and Jaworski, 1995). Instead of using an in-line sampler above-ground in a back-pressured system, as in 1994, a modified system was designed for down-hole placement of samplers. The in-line samplers used in this system were very similar to the stainless steel and Teflon® samplers used in 1994, but narrower in construction so that they could be lowered down the monitoring wells. At the Marshall and Wildmere sites, groundwater was sampled with a bladder pump, but in the 1995 system the pump was located above rather than below the sampler. At the Lindbergh and Swimming sites, where water levels were relatively high, the samplers were placed downhole below peristaltic pumps. The low pumping rates during purging (~10 L) and sampling for methane (~100 to 200 mL/min) were chosen to maximize lateral flow from the formations to the samplers (Kearl et al., 1994), with negligible contamination from the overlying stagnant water column. Thus, inflatable packers were not used, as in 1994, to isolate the well screen interval. The above described modified sampling system was used for sampling all monitoring wells in 1995, and at the Lindbergh site and Swimming sites for up to two or three occasions.

For laboratory extraction of dissolved methane from the samplers, a modified system was tested and implemented. A small glass headspace vessel was designed (~20 mL), with a vacuum-tight fitting for attaching a sampler. For evolving methane into the evacuated headspace, each sample was agitated in an ultrasonic water bath at room temperature. The headspace was adjusted to 1 atm pressure with He injected from a gas reservoir through a septum. A subsample was then collected with a microsyringe via the same septum for injection into the gas chromatograph.

As anticipated, the above proposed changes in extraction procedures reduced the time required for each analysis, and eliminated the problem of some incomplete sample transfers, as occurred in 1994 (Van Stempvoort and Jaworski, 1995).

For analyses of methane, excepting those near the detection limit (at least one result of 0.003 mg/L or less, where detection limit = 0.001 mg/L), duplicates generally deviated by less

Analyses for MGN-95-01A changed dramatically between September 28 and November 22, increasing from 0.002 to 2.6 mg/L (means of duplicate analyses). This increase in methane concentration was probably caused by the purging of more than 5000 L from this well during hydraulic testing on October 18 to 19, which may have drawn contaminated water from near the production well, located 3.4 m from this monitoring well.

Table 9. Dissolved methane and ethane concentrations in groundwater at the Wildmere site.

Monitoring Well	Sample Date	methane mg/L	ethane mg/L
WDM-95-01	Oct 17/95	0.06	0.006
	Oct 17/95	0.046	0.003
WDM-95-02	Oct 18/95	0.016	ND
	Oct 18/95	0.031	ND
WDM-95-03	no analyses due to pump stuck in well screen		
WDM-95-04	Oct 17/95	0.054	ND
	Oct 17/95	0.068	ND
WDM-95-05	Oct 18/95	0.013	ND
	Oct 18/95	0.012	ND

ND = not detectable. Detection limit is 0.001 mg/L

For samples collected on December 15 from nests MGN-95-04, -05 and -07, the methane concentrations increased from bottom to top of the aquifer (Figures 14, 15, 17). For nest MGN-95-06, the methane concentrations were low, but slightly higher in the deepest well than the other two (Figure 16). As a group, the samples taken from all wells at this site indicate relatively low concentrations of sulfate down gradient of the production well, and near the top of the aquifer (Figures 13 to 17, Table 12).

As for the Lindbergh site, collectively the methane and sulfate data are consistent with gas phase migration of methane, focused along the top of the aquifer (cf. Section 6.3), combined with biodegradation of the methane that involves sulfate as a terminal electron-acceptor.

To simulate air flow during sparging, Marley et al. (1992) developed a model called SPARG1. This model focusses on air flow, and assumes that flow of water is negligible.

TETRAD (Vinsome, V10.4 Users Manual, 1994; Vinsome and Shook, 1993; Shook, 1995) is a 3-dimensional, multi-phase (water/gas/oil) numerical model which accounts for partitioning of contaminants between all phases, transport, sorption and decay. This model calculates the pressure-dependent compressibility of liquids and gas phases. A modified version of TETRAD has been used to simulate the flow of air into an initially water-saturated aquifer during sparging (Lundegard and Anderson, 1993), and similar applications are ongoing (Arnold, 1995). The TETRAD model appears to be a promising tool for future application in the methane migration program.

A number of other complex numerical models have been designed to simulate multi-phase fluid flow and contaminant transport in aquifers (e.g., MOTRANS, Kaluarachchi and Parker, 1990; FEMWATER, G.T. Yeh et al., 1992). MOTRANS is a finite-element, 2-dimensional model developed to simulate the flow of water, dense or light nonaqueous phase liquid (NAPL) and/or gas (air), and partitioning of up to five chemical components between these phases. This model simulates the volatilization and flow of oil derived gases in the vadose zone. For conventional simulations, it ignores the flow of gas below the water table in order to improve run-time performance.

FEMWATER is a finite element model that, in conjunction with LEWASTE is capable of being used to model LNAPL and DNAPL flow (Yeh et al., 1992). The FEMWATER model is gaining acceptance for groundwater flow modelling. Unfortunately, this model does not yet consider the flow of a compressible gas below the watertable.

Further review of relevant mathematical models is ongoing.

7.0 METHANE IN WATER SUPPLY WELLS IN THE STUDY AREA

To provide a context for the data collected at the research sites, the following information was obtained:

- historical data on presence of "gas" in water supply wells in the study area,
- a survey of methane concentrations in 23 supply wells in the study area,
- published data on dissolved methane in supply wells in other gas and oil producing areas.

7.1 Historical Data on Presence of Gas in Supply Wells

Alberta Environmental Protection (AEP) has provided a summary of their records of water wells in the study area that indicated that "gas" was present. Of ~24,000 water well records, presence of gas was reported for 58 wells (Table 13). These records do not provide chemical analyses of the gas.

Fifteen of the AEP records of gas in wells were observations made during the Federal water well survey of 1935-36. Gas was reported for two other wells prior to oil and gas exploration and development in the area: in 1949 and 1953 (Table 13). Generally, the early AEP records (1935-53) indicated presence of gas in wells completed at depths > 40 m BGS. Although the gas was not identified, these records suggest that methane was present in some aquifers in the study area prior to oil and gas exploration.

Of the 41 later AEP records that report presence of gas (1960-95), most were observations made by drillers' at the time the wells were installed. These wells tended to be relatively deep (mean completion depth of 123 m BGS, range of 51 to 238 m BGS) compared to the average well in the region (< 50 m BGS based on AEP records).

A study by the Prairie Farm Rehabilitation Administration (1993) indicated occurrence of dissolved methane in eight monitoring wells completed in Judith (Belly) River Fm aquifers in the Special areas in Alberta. Methane was the dominant dissolved gas observed, but absolute concentrations were not determined. The source of the methane (intrinsic vs. oil & gas activities) was unknown. This area investigated by the PFRA overlaps with and includes the southernmost portion of the Lloydminster study area.

Currently there is no provincial database that provides historical information on the presence of gas in water wells for the Saskatchewan portion of the study area. Unlike the AEP records, the equivalent water well database provided by the Saskatchewan Water Corporation contains no information on the occurrence of gases in wells.

Table 13. Water wells in study area in which gas was noted to be present (Alberta Environmental Protection waterwell database).

Q or LSD	Sec	T	R W4	Well Owner	Depth (m)	Year Reported	Q or LSD	Sec	T	R W4	Well Owner	Depth (m)	Year Reported
Reported between 1935 and 1953						Reported between 1960 and 1995							
NE	32	41	2	Feero	117.3	1935	NE	29	36	5	Provo Gas Prod.	237.7	1960
SW	4	42	2	McMann	114.3	1935	NE	31	37	9	G. Hewitt	42.7	1960
NW	6	42	7	S. McLaughlin	19.8	1935	NW	28	41	13	D. Bowmes	73.2	1979
SW	3	43	4	S.V. Snyder	3.0	1935		34	37	8	S. Twa	160.0	1988
SW	11	44	3	A. Cooper	97.5	1935	NW	23	37	13	R. Holloway	142.0	1964*
12	3	48	12	F. Ploc	45.4	1935	SW	15	50	2	W. Ulan	87.8	1964*
8	35	49	1		6.1	1935	SE	24	36	12	H. Plenbert	132.6	1965*
14	36	49	1		38.7	1935	SW	22	37	13	H. Wideman	189.0	1965*
1	3	50	1	Blackwell	50.6	1935	14	20	46	2	J. W. Gordon	106.7	1966*
15	23	50	1	K. Parr	34.1	1935	NW	30	43	9	Mon-Max Services	67.1	1967*
SE	34	50	2		28.3	1935	SW	4	39	13	D. Coppack	106.7	1968*
15	34	52	4	Hodgson	47.2	1935	NE	32	36	12	S. Mereski	82.3	1969*
4	36	52	4	R. Seville	102.4	1935	9	25	42	10	Hardisty Storage	125.3	1969*
SE	4	53	4	G. Brett	71.9	1935	SE	14	36	12	A. McRae	118.9	1970*
NE	16	45	11	G.F. Albrecht	115.8	1936	NW	4	57	3	North School (Frog L. IR)	56.4	1970*
SW	14	50	2	Plater	63.4	1949	SE	19	43	2	R. Morrison	71.9	1971*
4	7	45	12	Seman Engin.	54.9	1953	NE	3	40	5	H. Tennant	167.6	1972*
							11	25	50	5	Water Res.	51.8	1972*
								19	36	11	D.&E. Dennis	173.7	1973*
							NE	8	48	11	J. Veenstra	106.7	1973*
							SE	36	36	12	A. Bye	137.2	1974*
							NW	20	40	8	L. Crone	192.0	1974*
							SW	9	39	8	R. Gilbertson	152.4	1975*
							SE	18	51	2	General Crude Oil	91.4	1975*
							SE	6	36	3	R. Worobo	184.1	1976*
							NW	8	36	6	K. Gilmer	160.3	1976*
							NE	22	36	12	C. Plehnert	137.2	1976*
							SE	28	37	8	J. Ekroi	177.4	1977*
							SW	36	41	9	B. Cullen	169.5	1977*
							SW	16	38	13	A. Engel	117.7	1978*
							NW	11	59	9	A. Severin	68.3	1978*
							NW	25	36	2	J. Scheck	142.0	1979*
							10	28	60	3	World Wide Energy	109.7	1982*
							SW	6	41	12	P. Spady	125.6	1986*
							NW	26	50	2	L. Gnyra	109.7	1989*
							NW	2	53	12	E. Horon	103.6	1989*
							NE	19	53	7	Jacula Farms	85.3	1990*
							4	21	38	1	Pan Cdn.	218.8	1992*
							8	33	42	11	C. Davidson	65.5	1994*
							NE	17	42	13	B. Kuefler	76.2	1994*
							SW	33	52	2	M. Hames	97.5	1995*

*reported by driller at time of well installation

7.2 1995 Survey of Methane in Water Supply Wells in Study Area

Samples were also collected from 23 domestic water supply wells in the Saskatchewan portion of the Lloydminster study area and analyzed for methane concentrations (Table 14). These methane data are not directly comparable to the research site data (Section 2.3), due to differences in the collection methods. However, this supply well survey provides useful data on dissolved methane in groundwater as used in the region (cf. Chafin, 1994).

Analyses of major ions, Fe, Mn, and nitrate for samples from the same wells were conducted to indicate any correlation of dissolved methane and other hydrochemical parameters. The supply wells to be sampled were selected by members of the steering committee. Each well supply system chosen had:

- a lithologic log,
- an e-log,
- a well completion record (depth, screen interval),
- well casing < 30 cm (12") diameter,
- a submersible pump,
- an outdoor hydrant or tap for sampling of untreated water (i.e., no chlorine).

A single sample was taken from each well, using the supply pump. The stainless steel samplers that were used at the research sites (Section 5.1) were also used in this survey. These samplers were connected with 1.64 cm dia. vinyl (PVC reinforced) tubing to the well hydrant or tap, similar to the in-line, down-flow configuration used by Van Stempvoort and Jaworski (1995). A length of 0.82 cm dia. stainless steel tubing was attached to the down-flow end of each sampler to restrict the flow and produce back-pressure, in order to prevent formation of gas bubbles in the system. Each system was purged for 10 to 20 min prior to sampling.

Methane was detected in most of the supply wells (20 of 23 wells, see Table 14). The concentrations were generally low: all but three were < 0.05 mg/L. **The two highest concentrations measured were slightly above 1 mg/L. In these two cases, there may be a risk of an explosion,** if the water supplies pass through poorly ventilated air spaces (Harder et al., 1965).

Overall, there is no significant correlation between the methane concentrations and the completion depths of the supply wells, or methane and other hydrochemical parameters as shown in Table 14 (Pearson product moment correlation, 0.05 level of significance). However, it appears that methane concentrations are strongly dependent on geographic locations and aquifer

Table 14. Survey of methane concentrations in water supply wells in the Saskatchewan portion of the study area.

LOCATION				-----Completion-----																untreated water sampling point
Q	Sec	T	R W3	Well Owner	Depth (m)	Year Drilled	Aquifer Unit	Methane (mg/L)	Na	Ca	Mg	K	HCO	SO ₄	Cl	NO ₂ +NO ₃	Fe	Mn		
Aberfeldy																				
NE	13	49	26	J. Phipps	29.6	1978	drift	0.002	278	120	49	6.5	599	578	17	< 0.01	2.0	0.12	remote hydrant	
SW	15	49	26	G. Pierce	20.7	1981	Judith R.	0.005	402	87	46	5.8	631	692	34	1.2	0.31	0.04	wellhead hydrant	
NE	18	49	26	M. Napper	27.4	1986	intertill	0.002	351	124	42	5.7	612	658	48	0.04	1.1	0.5	wellhead hydrant	
NW	23	49	26	T. McDougall	40.2	1984	Judith R.	0.001	367	121	59	7.8	715	725	13	0.02	4.4	0.09	house tap	
SE	28	49	26	S. Rolfheiser	23.5	1987	Judith R.	0.008	226	190	84	8.8	692	718	8	0.02	1.4	0.03	remote hydrant	
Golden Lake																				
SE	8	47	23	H. Tuplin	23.5	1976	intertill	0.002	158	268	97	8.7	598	932	23	< 0.01	4.2	1.1	wellhead hydrant	
NW	30	47	23	R. Stevenson	55.5	1986	Judith R.	0.469	470	111	64	8.7	709	815	127	0.01	7.1	0.14	house tap	
SE	35	47	23	C. Ballan	30.8	1994	Judith R.	0.015	747	37	18	6.8	494	1130	158	0.17	0.19	0.01	quonset tap	
Lone Rock																				
SE	30	47	26	P. Mihalich	22.6	1993	Judith R.	0.01	365	91	43	8.0	601	643	29	0.06	1.2	0.05	wellhead hydrant	
SW	10	47	27	G. Lamb	65.5	1986	Judith R.	0.007	620	37	18	5.5	619	928	15	0.06	0.32	0	wellhead hydrant	
SW	15	47	27	J. Lamb	36.0	1976	Judith R.	1.308	609	30	15	4.1	633	885	14	0.05	1.3	0.02	house tap	
SE	17	47	27	D. Graham	39.0	1984	Judith R.	1.071	441	67	36	6.6	694	668	9	0.16	0.72	0	wellhead hydrant	
SW	30	47	27	J.W. Anderson	49.7	1987	Judith R.	0.006	210	132	66	7.1	698	480	7	0.08	2.0	0.01	wellhead hydrant	
SE	33	47	27	M. Martin	68.9	1987	Judith R.	0.003	330	14	7.1	2.9	592	261	7	0.03	0.17	0	remote hydrant	
Neilburg																				
SE	2	45	25	G. Hall	108.2	1977	Judith R.	0.032	900	18	6	5.7	464	1280	220	0.04	0.34	0.02	remote hydrant	
SE	23	45	25	N. Hallet	118.9	1976	Judith R.	0.044	508	213	104	12.0	483	1440	124	< 0.01	5.6	0.11	wellhead hydrant	
SW	8	45	26	N. Koch	27.4	1988	intertill	0.003	83	240	124	7.5	671	738	11	0.03	3.0	0.98	wellhead hydrant	
SE	25	45	26	L. Watson	124.7	1980	Judith R.	0.006	898	86	31	6.9	468	1650	145	0.71	0.17	0.09	remote hydrant, leaking	
NW	30	45	26	G. McGladdrey	26.2	1988	intertill	0.003	170	389	189	8.2	543	1520	26	< 0.01	2.8	1.3	wellhead hydrant	
Celtic, Tangleflags																				
SE	23	51	25	L. Bright	20.4	1985	intertill	< 0.001	163	91	36	4.2	517	232	44	1.0	0.15	0.08	wellhead pressure tank	
NE	5	51	23	K. Jarret	29.3	1977	Empress	< 0.001	107	119	48	7.8	465	294	28	0.89	0	0	remote hydrant	
SE	34	52	22	L. Hoffman	29.9	1984	intertill	0.001	206	168	62	6.3	688	532	20	0.02	2.0	0.62	wellhead hydrant	
SW	27	53	22	S. Schneider	43.9	1992	intertill	< 0.001	50	183	65	6.2	595	338	2	0.01	1.7	1.4	wellhead hydrant	

Table 14) have very low concentrations, at or less than the detection limit of 0.001 mg/L. The range in concentrations (mg/L) of methane for all wells completed in Judith River sands is 0.001 to 1.3, and the mean is 0.21. In contrast, the concentrations in wells completed in drift aquifers range from non-detectable to 0.003, and their mean is < 0.002.

The relationship between methane concentrations in water supply wells and presence of gas-leaking oil exploration and production holes (active, inactive, decommissioned) is unknown.

7.3 Methane in Groundwater in Other Oil and Gas Producing Areas

Dyck and Dunn (1986) found methane (and helium) anomalies associated with oil and gas fields in southwestern Saskatchewan. In their 1976 survey of 939 domestic wells and springs, they found that methane concentrations tended to be highest in areas where exploration drill hole density increased, and also had a weak positive correlation with depth of sampling. They suggested that the anomalies could be due to either leakage of methane from the exploration drillholes into aquifers tapped by the domestic wells, or due to "natural" migration from the oil and gas fields along faults and fracture zones. Overall, they found that 88% of the samples had methane concentrations below detection (< 0.014 mg/L), 95% were < 0.3 mg/L, and the maximum concentration was 94.5 mg/L.

Chafin et al. (1993) and Chafin (1994) documented a 1990-91 survey of 203 water supply wells and 2 springs in the Animas River Valley of Colorado and New Mexico. Gas has been produced from various formations in this area for decades. Recent expansion of the development of a coal-bed gas field in this area has led to public concern about "the possibility of increasing concentrations of natural gas in domestic water supplies". The survey indicated that the methane concentrations were below the reporting limit of 0.005 mg/L in 66% of the cases. Twelve percent of the sites had methane concentrations of 1 mg/L or more. The mean concentration was 1.3 mg/L, and the maximum was 39 mg/L. Wells completed in bedrock tended to have higher methane concentrations than those completed in surficial alluvium. Presence of methane was often associated with presence of H₂S. A concurrent survey of soil gas concentrations was conducted, at the groundwater collection sites and adjacent to 352 gas wells in the area. The carbon isotopic composition of methane in a few of the groundwater samples was analysed and compared to data for gas from production wells, cathodic-protection wells and soil adjacent to gas wells in the area. Chafin (1994) concluded that most "shallow" gas in the area is probably

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entire

derived from deep, thermogenic sources. Chafin did not find evidence for substantial vertical migration of methane by natural processes, including diffusion and fracture transport. He stated that the soil gas data "indicate that gas-well annuli are more important than natural fractures for the upward migration of gas". Chafin concluded that "manmade migration pathways probably introduced most near-surface gas to the study area".

8.0 SUMMARY AND RECOMMENDATIONS

Five new research sites with leaking production wells were investigated in the 1995 program. At two of these sites (Wildmere, Swimming), monitoring wells were installed in aquifers, at depths of ~70 and 10 m BGS respectively. At one site (Sedgewick), there were no aquifers in a deep zone targeted for monitoring (210 to 230 m BGS). At the other two new sites (Golden Lake, Lone Rock) there are no significant aquifers.

The Lindbergh (1994) and Swimming sites were selected for detailed investigations. Additional nests of monitoring wells were installed at both sites in 1995 to provide vertical profiles of the aquifer hydrochemistries. Pumping tests conducted at these two sites provide important information on hydraulic properties that can be used in future modelling.

Samples were collected from all available monitoring wells and analysed for methane concentrations and other selected hydrochemical parameters. Elevated concentrations of methane were detected in the aquifers at each site. The levels were typically highest within several m of the production wells. The highest concentrations (1995; mg/L) at the research sites were: 0.06 at Marshall, 0.068 at Wildmere, 3.1 at Swimming and 19.1 at Lindbergh.

In the well nests at the Swimming and Lindbergh sites, the levels of methane generally increased towards the top of the aquifer. These vertical gradients indicate that lateral gas phase migration of methane may be occurring along the top of the aquifers.

Gradients of sulfate concentrations at all four sites indicate that sulfate reduction is probably linked to biodegradation of methane in the aquifers.

An analytical model, PATCH3D, had been used for preliminary simulation of 1994 methane data. On the basis of the 1995 findings, this model is not suitable for the ongoing research program. A revised modeling approach is being developed that will take into account lateral gas phase migration. The focus during 1995 was examination of the gas phase migration process.

A survey was conducted of dissolved methane concentrations in 23 supply wells in the Saskatchewan portion of the study area. The methane concentrations were generally low (< 0.05 mg/L); two were slightly higher than 1 mg/L which is the minimum explosion hazard level (Harder et al., 1965). The concentrations appear to be strongly related to geographic locations and completion zones of the wells. Samples from the Judith River sands (mean = 0.21 mg/L) tended to be higher than from drift aquifers (mean < 0.002 mg/L). More study is required to establish the reasons for these higher concentrations.

8.1 Recommendations

1. It will be valuable to continue monitoring the methane concentrations in the monitoring wells at four research sites through 1997, with a focus on the Lindbergh and Swimming sites. These two sites have relatively large monitoring well networks (14 or 15 wells each), including vertical "nests" of wells. The networks may have to be expanded in the future, depending on further analytical results and modeling of the methane plumes at these sites. It is anticipated that members of the steering committee for this study will have the opportunity to review any specific proposals for expansion of the monitoring networks.

2. The development of quantitative models of methane migration should continue, in conjunction with an ongoing monitoring program. The modeling should focus on the Lindbergh and Swimming sites. Part of this modeling will be conducted as a graduate thesis project (M. Rieser, Masters student, U. of Montana).

3. The survey of dissolved methane in water supply wells in the Lloydminster study area (and selected other hydrochemical parameters) should be expanded. At least 50 to 100 additional analyses should be conducted to provide a database that will contain statistically significant information on the geographic and stratigraphic distribution of dissolved methane in groundwater in the study area. It will also be useful to review the protocol for sampling from these supply wells.

4. Selected analyses of the isotopic compositions of dissolved methane and sulfate should be conducted (research sites, supply wells). These data will provide additional information on the source and fate (e.g., biodegradation) of methane, and the significance of microbial reduction of sulfate.

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