Field assessment of decommissioned well integrity in England

Chief Scientist's Group report

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Professor Doug Wilson
Chief Scientist

Executive summary

Wellbore integrity failure at decommissioned petroleum wells is a historic and ongoing challenge for industry and regulators. Unfortunately, decommissioned wells sometimes develop integrity failure which can result in releases of methane to the surrounding soils and atmosphere. Currently, the incidence and environmental risks associated with decommissioned well integrity failure are not well understood. As the number of decommissioned wells grows and as wells age during the transition to net zero, it is essential that effective monitoring and detection strategies are developed to confirm their true integrity status.

In order to understand more about the integrity of decommissioned onshore wells in England, field investigations were carried out at 6 decommissioned well sites in the East Midlands, 4 of which were previously identified as suffering integrity failure. The investigations involved 2 field campaigns where decommissioned well sites were examined using surficial methane measurements, shallow auger drilling, and sub-surface sampling of soil gas and sediment with subsequent laboratory analysis. Dynamic flux chambers were also used with a greenhouse gas analyser to collect continuous measurements of any methane fluxes to atmosphere.

The monitoring of methane concentrations and fluxes during field investigations identified no anomalous measurements (measurements exceeding typical natural baseline concentrations) at the ground surface or in the shallow soils around the decommissioned wellheads. However, the surficial geology at all 6 sites was found to be dominated by low permeability glacigenic clays, which will act as robust barriers to capillary flow barriers and will severely limit, if not totally inhibit, any gas migration from the wellbore to the surface and atmosphere.

Overall, our results suggest that none of the wells investigated are showing signs of integrity failure, as indicated by releases of hydrocarbon gases into shallow overlying soils or the atmosphere. These results contrast with a previous investigation done as part of the ReFINE project, which reported that 4 of the decommissioned well sites visited in this study showed signs of integrity failure. The discrepancy may be attributed to: (i) the complexity and spatiotemporal variation that occurs with subsurface fugitive gas migration; (ii) false positives associated with land use; and/or (iii) limitations with the previously used methods of investigation and interpretation. However, while we detected no signs of well leakage, we cannot deduce that the decommissioned wells visited in this or the previous study are not, or will not be, subject to integrity failure. In the present study, we showed that the surficial geology was dominated by very low permeability clays (that is, all < 0.05 mD in permeability), which would limit any fugitive gas migration away from the wellbore. Consequently, any gas migration would be potentially undetectable, particularly with the measurement methods that were used previously by the ReFINE project. Consequently, any inferences regarding decommissioned well integrity in England based on the measurements taken to date should be viewed with caution, as these data are likely to be inadequate to draw accurate conclusions. In order to effectively and authoritatively assess decommissioned well integrity in England, further investigations are needed at a range of wells. This includes more characterisation of surficial geology and the use of more intrusive, robust and continuous hydrocarbon gas measurement methods.

Introduction

Wellbore integrity failure is recognised as a critical environmental risk associated with petroleum resource development[1]. It has been suggested that it can occur in 0.1 to 75% of energy wells[2]. It results in hydrocarbon fluid migrating within and/or outside a wellbore structure into the environment[3]. Migrating hydrocarbon fluids can impact groundwater[4-6], pose an explosion hazard[7] and contribute to greenhouse gas emissions upon reaching the atmosphere[8-10]. Once released, methane (CH_4) has a global warming potential 86 times greater than carbon dioxide (CO_2) over 20 years, and 25 times greater over 100 years[11,12]. Consequently, CH_4 emissions are a significant contributor to short-term global warming and their role in climate change is becoming increasingly recognised as scientists observe atmospheric concentrations continually rising[13,14].

Wellbore integrity failure is a complex and multifaceted phenomenon[2,15,16] that involves a combination of environmental (for example, geography/geology) and human (for example, engineering or regulatory) factors that play a role in how it develops[3]. Integrity failure can occur in any 'demographic' of energy wells, for example, whether wells are shallow, deep, producing, abandoned, conventional or unconventional. However, it is of particular concern with decommissioned wells (as opposed to active or suspended wells) where plug and abandonment have sought to seal and prevent fluids migrating within or outside the well in perpetuity[17,18]. After decommissioning, there is clearly a benefit in monitoring, measuring and verifying the containment of fluids in order to ensure that wells are sealed effectively and safely and that no environmental impacts are occurring[19]. However, there are currently no such stewardship programmes for decommissioned wells in any country. Consequently, containment performance, or the presence and nature of actual or potential environmental impacts, remains uncertain and a point of debate.

Although the UK does not have as extensive an onshore oil and gas industry as some countries, such as North America, it has approximately 2,150 onshore energy wells; the majority of which are decommissioned[2]. A field investigation was carried out as part of the ReFINE project (http://www.refine.or.uk/) to assess the integrity of a subset of 102 of these decommissioned wells across England, and to identify if hydrocarbon fluids might be leaking. It was reported that approximately 30 of the well sites assessed had potentially elevated levels of methane at the soil surface around the abandoned wellhead location, compared to a paired control site. These potentially elevated levels were considered to indicate well integrity failure[20]. However, the results and conclusions from this study should be viewed cautiously in light of more recent research, which has shown that leakage from energy wellbores is a highly complex phenomenon that varies in time and space[8,9,21,22]. These and other studies show that surficial monitoring methods, (such as those used previously in the ReFINE project) are limited in their potential to conclusively detect or quantify leakage associated with well integrity failure. For example, a leakage signal from a buried well may be suppressed by geologic materials (for example, rock, clay, soil) between the wellhead and the monitoring point. So, the signal may depend on the permeability of these materials, which may vary with moisture content, and on many other variables, such as precipitation and barometric pressure variation.

Since this initial study by the ReFINE project, no other research has sought to: (i) further understand the status of decommissioned wells in the UK, (ii) further assess if and to what extent integrity failure may be occurring at those identified as potentially leaking or (iii) characterise what the resultant levels of leakage into the environment may be.

Consequently, the present project was initiated as a collaboration between Heriot-Watt University and the Environment Agency, in order to build on previous work and to advance understanding of the status of decommissioned wells in England. The project comprises 3 related tasks:

1) A literature review of decommissioning guidance/regulations over the past 100 years in England as well as other factors which may potentially influence long-term well integrity.
2) An assessment of the potential long-term integrity of decommissioned onshore wells in England, based on factors of importance identified in task 1.
3) Field investigations to further assess the integrity of selected decommissioned wells, focusing on wells that the ReFINE project suggested, based on its fieldwork, were showing integrity failure.

This technical report summarises the findings of task 3, for which fieldwork was done at previously investigated decommissioned wells and at newly investigated sites in the East Midlands, in order to more confidently assess decommissioned well integrity. In this report, we revisit data previously acquired by the ReFINE project. Next, we describe methods used in the current study and present new data collected during 2 field campaigns carried out in 2020. The new data include: (i) surficial methane measurements, (ii) shallow soil auger drilling, (iii) soil gas and sediment sampling (with subsequent laboratory testing) and (iv) the use of dynamic flux chambers to collect continuous measurements of methane fluxes to the atmosphere. Previously and newly collected data are discussed and conclusions drawn about the likely integrity of investigated decommissioned wells in England. Finally, recommendations are made for potential next steps to increase understanding on decommissioned well integrity in England, as part of ongoing stewardship of our legacy of petroleum resource development.

ReFINE project field investigations

The current investigation was partly motivated by a previous research project that was carried out across England in 2015 by the Researching Fracking in Europe consortium (ReFINE). The ReFINE project investigated 102 onshore energy wells in England that were considered to have been properly decommissioned according to UK's regulations, that is, plugged, cut, capped, buried and reclaimed. Specifically, it undertook field investigations which measured methane in surficial soil gas at these 102 wells. For these investigations, the decommissioned wellhead was located using coordinate records and GPS (generally attaining ~10m accuracy). Seven equidistant measurements of surficial methane concentrations were made along 60m transects that were centered directly above the assumed wellhead location. In addition, equivalent measurements were also taken at a nearby control site, comprising an adjacent field of similar land use where there was no energy well.

The measurements from the wellhead transect and from the control site were directly compared in order to infer any relative anomaly, the magnitude of which was used to draw conclusions on decommissioned well integrity. Single, one time methane concentrations were measured at each transect position using a telescopic rod with a suction cup connected to a calibrated portable tunable diode laser (TDL-500, Geotechnical Instruments Ltd.; accuracy 1ppm), which was placed on the ground surface at each measurement location. Land use was noted and some weather conditions were measured, but no soil gas samples were taken for laboratory analyses; nor was surficial geology delineated or subsurface soil gas composition determined.

Following data collection, the single methane concentration from above the assumed decommissioned well centre was normalised to the overall average of its respective field control. Subsequent interpretations used these normalised values rather than the absolute measurements of CH_4 concentration. The normalisation process assumed that the average from the control site represented ambient conditions without a decommissioned well, and that any anomaly associated with the decommissioned well position could be identified by comparing the central decommissioned well value with this ambient value. Specifically, the central decommissioned well value was divided by the ambient average, to give a relative concentration, that is, a normalised value. On this basis, a normalised value of 1 would indicate an amount of CH_4 above the wellhead that equalled the control. A normalised value below 1 would indicate less CH_4 above the wellhead than at the control. A normalised value above 1 would indicate more CH_4 above the wellhead than at the control. From the 102 surveyed wells, 50 had relative concentrations above their wellhead that exceeded 1, and statistical tests) were carried out to analyse variance and to assess the significance of the excess concentrations. The analysis of variance tests were reported to show that 31 out of the 102 well sites exhibited statistically significant elevated CH_4 concentrations at the ground surface. These were attributed to well integrity failure. Conversely, 39 of the 102 sites investigated presented statistically significant lower surficial CH_4 concentrations than their control sites and therefore were concluded to be acting as net CH_4 sinks.

Although no direct measurements of CH_4 efflux were made in the ReFINE investigations, Fick's first law was used to estimate the flux of CH_4 (in mg methane/m^2/s) from the soil surface to atmosphere at each decommissioned well. This was achieved by using the concentration of methane at the soil surface (mg CH_4/m^3) and the diffusion coefficient (m^2/s) at steady state over time in 2D (using an explicit finite difference method); also by considering other specific parameters for the well location (temperature, porosities and clay-sized particles in the soil). Using this method, a flux of 3,256kg CO_{2eq}/well/year was estimated for the largest relative CH_4 concentration anomaly observed, and a net negative flux (uptake or net sink of CH_4) of -563kg CO_{2eq}/well/year was estimated for the lowest CH_4

relative concentration observed. Overall, estimated fluxes for the least squares mean relative (not absolute) concentrations for each well showed a normal distribution with a mean fugitive CH_4 emission of 364 ± 677kg CO_{2eq}/well/year. Until now, no follow up research has been carried out at these decommissioned wells to confirm or further constrain these observations.

Table 1 shows the relative concentrations obtained by the ReFINE project for the 10 decommissioned well sites where CH_4 anomalies were most elevated compared to their control locations. It also shows the absolute CH_4 concentrations measured above the decommissioned wells at these sites, which have not been previously reported. Table 2 shows an example of the CH_4 concentrations and weather parameters measured by ReFINE at an individual site; the example shown is for Old Hills-1, which had the greatest decommissioned well anomaly of the 102 sites measured. Figure 1 shows the distribution of all the absolute CH_4 measurements taken during the ReFINE investigations for both control and decommissioned well sites. Table 3 shows the descriptive statistics for the measurements from all 102 sites. These results and their implications for well integrity and the current study are discussed in more detail in section 7.3.

Table 1: Decommissioned well sites with the 10 most elevated CH_4 anomalies according to the ReFINE investigations, based on the methods described. For each well the Table shows important attributes that are relevant to integrity. The attributes comprise: intent (E: exploratory, A: appraisal and D: development or production wells); spud date (that is, commencement of drilling) and age; and land use/type. The final 2 columns show the CH_4 concentrations measured in the ReFINE project, as absolute concentrations and as relative concentrations (that is normalized to the concentration at the adjacent control site).

Anomaly rank	Site	Basin	Intent	Spud date (age years)	Vegetation /land use	Absolute CH_4 @ assumed well head (ppm)	Relative CH_4
1	Old Hills 1	E.Mid	E	2004 (16)	Grazing field	0.9	3.71
2	Rogate 1	Weald	E	1985 (35)	Woodland	1.6	2.04
3	Eakring 159	E .Mid	D	1944 (76)	Forest detritus	1.6	1.93
4	Osmington 1	Wessex	E	1970 (50)	Grazing field	1.8	1.77
5	Torksey 4	E.Mid	A	1975 (45)	Grazing field	1.8	1.73

6	Lewes 1	Weald	E	1936 (84)	Grazing field	1.8	1.59
7	Halton Holegate 2	E.Mid	E	2001 (19)	Ploughed field	1.8	1.56
8	Hellingly 1	Weald	E	1937 (83)	Grazing field	2.3	1.53
9	Kirby G7	N.Ykshr	A	1939 (81)	Grazing field	1.8	1.50
10	Cliffe at Hoo 2	Weald	E	1960 (60)	Crop field edge	2.2	1.50

Table 2: Example of absolute CH_4 concentration field measurements from the ReFINE investigations for Old Hills 1, which was reported as exhibiting the greatest elevated CH_4 anomaly relative to its control site (3.7 times greater). The results show the absolute surface methane concentration measured at various distances along the survey transect over the assumed decommissioned wellhead location, and at an adjacent control area. Relative (normalised) CH_4 was determined by dividing the observed CH_4 value at the assumed wellhead location (decommissioned well distance 0) by the average CH_4 for 7 measurements taken along the control area transect (for example, for Old Hills-1: 0.9ppm/0.242ppm gives 3.7).

Sample location	Distance from assumed well head location	Surficial CH_4 (ppm)	Temp (˚C)	RH (%)
Decommissioned well (DW)	30	0.6	14	63.3
DW	20	0.7	13.9	63.4
DW	10	0.9	14.1	63.1
DW	0	0.9	14	63.9
DW	10	0.4	13.4	66.6

DW	20	0.3	13.7	64.8
DW	30	0.4	13.6	64.4
Control	30	0.2	13.1	66.1
Control	20	0.2	13.4	66.2
Control	10	0.2	13.4	62.9
Control	0	0.3	13.4	66.9
Control	10	0.3	13.6	65.1
Control	20	0.3	13.6	65.4
Control	30	0.2	13.4	66.4

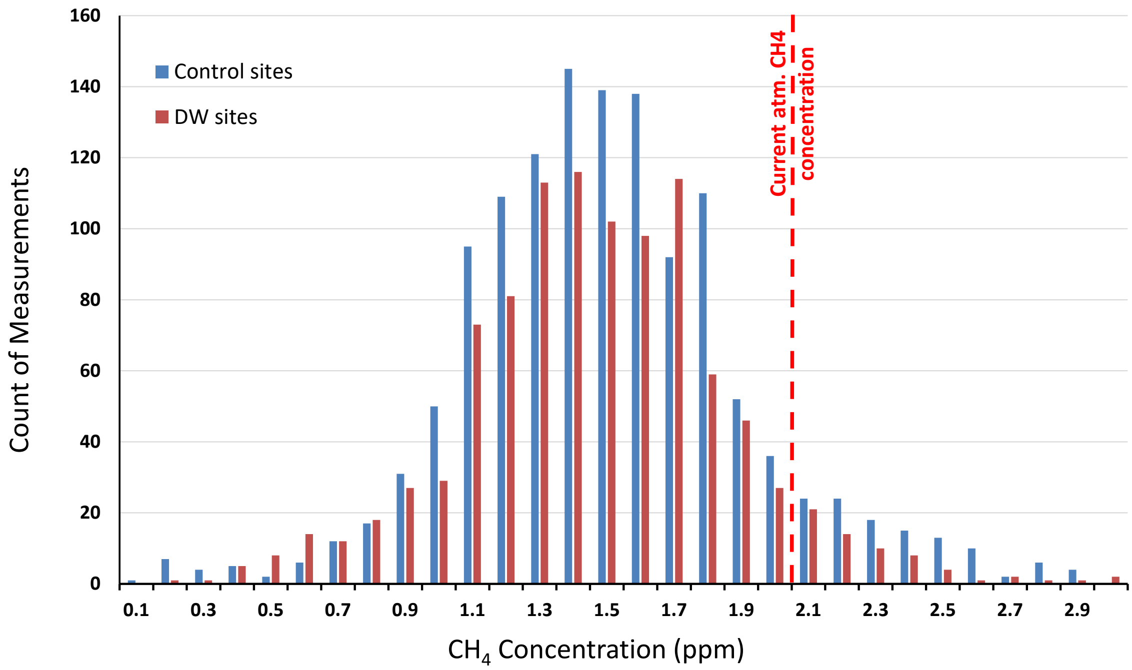

Figure 1: Histogram showing the distribution of all absolute CH_4 measurements taken during the ReFINE investigations (n=2296) at: decommissioned well sites (blue bars; n=1031) and adjacent control sites (red bars; n=1287). The red dashed line shows the current typical baseline concentration of CH_4 near ground level in the atmosphere, which is 2ppm.

Table 3: Descriptive statistics for all absolute CH_4 measurements (in ppm) taken during the ReFINE investigations.

Descriptive statistic	DW sites (n=1031)	Control sites (n=1287)	All measurements (n=2296)
Mean	1.46	1.50	1.48
Median	1.50	1.50	1.50
Mode	1.40	1.40	1.40
Standard deviation	0.39	0.42	0.41
Sample variance	0.16	0.17	0.17
Kurtosis	0.92	1.02	1.01
Range	2.80	2.70	2.80
Minimum	0.20	0.20	0.20
Maximum	3.00	2.90	3.00
Sum	1505	1932	3437

Method

Decommissioned well site selection

Six decommissioned well sites in the East Midlands were selected for investigation in the current study. Four sites were selected from the 102 sites that were previously investigated by the ReFINE project. They were chosen because they had been reported as showing statistically significant amounts of excess surficial CH_4, based on their normalised relative concentrations. Specifically, they had been ranked 1st, 3rd, 5th and 28th out of 102 sites for elevated relative CH_4 anomaly. Two additional sites were selected, which had not been investigated by ReFINE, but which were identified in the current project as having a potentially heightened relative risk of integrity failure. Their heightened risk was shown by the fact that Cahill and others[23] had assigned them to risk tiers 3 and 4, based on decommissioned well attributes related to integrity failure risk. The 6 decommissioned well sites investigated in this study are summarised in Table 4.

Table 4: Decommissioned well sites investigated during the current study. Attributes relevant to integrity are shown for each site, comprising: intent (E = exploratory, A = appraisal, and D = development or production); spud date (and age); land use/vegetation type; absolute and relative CH_4 concentrations (as measured by the ReFINE project); and risk tier (tiered from 1 to 6 in line with decreasing likely long term integrity, as described in Cahill and others[23]).

ReFINE anomaly rank	Site	Intent	Spud date (age years)	Land-use/ vegetation	Absolute CH_4 @ assumed well head (ppm)	Relative CH_4	Risk tier
1	Old Hills 1	E	2004 (16)	Grazing field	0.9	3.71	1
3	Eakring 159	D	1944 (76)	Forest detritus	1.6	1.93	4
5	Torksey 4	A	1975 (45)	Grazing field	1.8	1.73	3
28	Long Clawson 1	E	1943 (77)	Winter wheat	1.3	1.2	4
NA	Bottesford 1	E	1943 (77)	Crop field	N/A	N/A	4
NA	Plungar 9	D	1955 (65)	Crop field	N/A	N/A	3

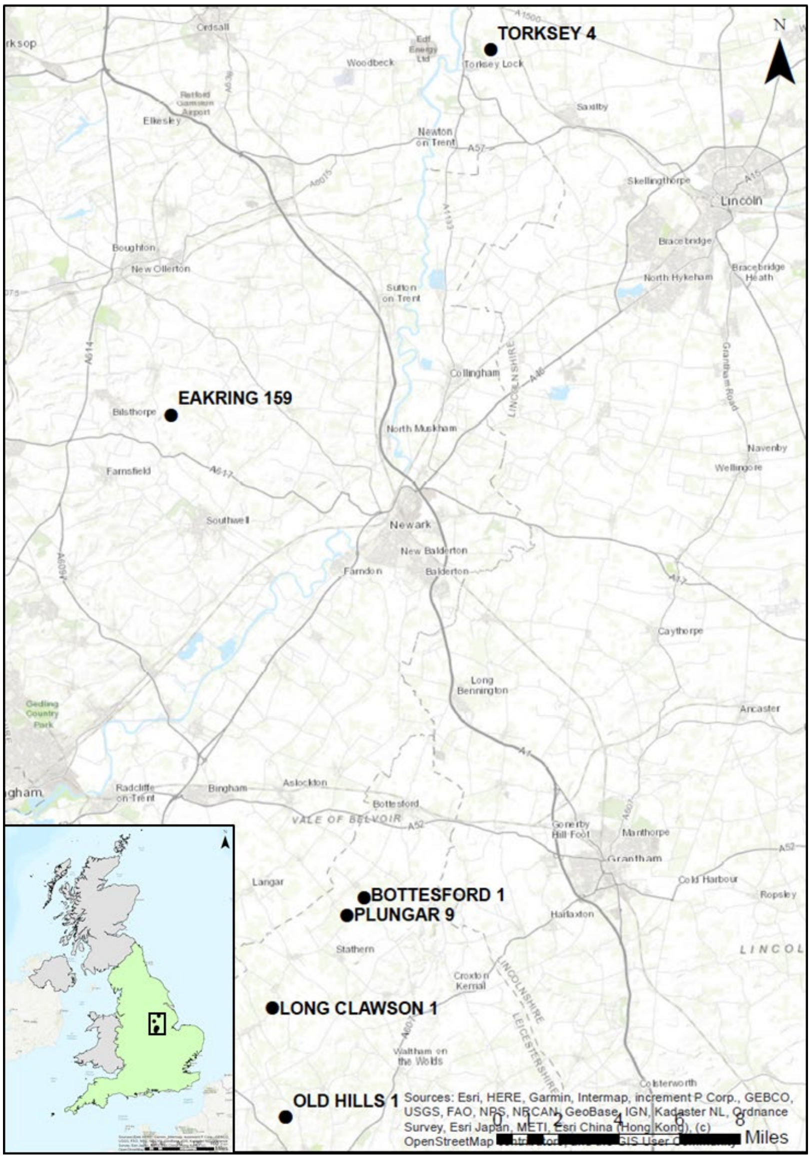

Figure 2: Map of East Midlands showing decommissioned well sites investigated in the current study.

Field methods

Site location, surficial geology characterisation and sediment sampling

Decommissioned wellheads were located by coordinates to within 1m using a GPS device. CH_4 concentrations were then measured at the located ground surface using a field portable greenhouse gas analyser (GA5000 or IRwin® Methane Leak Detector) and integrated pump system. Volumetric concentrations of CH_4, CO_2, O_2, H_2S and CO were measured in ppm, with a sensitivity of 0.1ppm and an accuracy of 1ppm for all these gases. Subsequently, a series of shallow holes were advanced to an average depth of 2m (ranging from 1 to 3m dependent on geology) at and around the assumed decommissioned wellhead location using a hand auger. The geology was logged during augering and soil samples were taken for laboratory analyses (see Laboratory analyses section below).

Soil gas sampling

After advancing auger holes to depth, a hollow stainless steel drive point soil vapour probe was pushed down the hole, and advanced several cm further into the soils before being sealed in place with hydrated clay. The greenhouse gas analyser and pump system was then attached to the vapour probe and soil gas was sampled from the bottom of the auger hole continuously for at least 5 minutes while monitoring CH_4, CO_2, O_2, H_2S and CO.

After initial measurements with a hand-held greenhouse analyser, physical soil gas samples were taken from auger holes at selected locations by peristaltic pump using a 25ml gas-tight Syringe with Luer Lock Valve. The syringe was placed 2 inches into the flowing soil gas effluent tube, which was purged several times before taking a gas sample and locking the syringe system. Soil gases were then transferred into a 12ml pre-evacuated sampling tube and sent for analyses at either the Isotope Science Laboratory at the University of Calgary or at the NERC Isotope Geoscience Laboratory at BGS Nottingham.

Flux monitoring

To obtain methane efflux measurements, a dynamic flux chamber system was deployed at select sites for periods of up to 24 hours. The system comprised an Eosense® eosAC Multi-Species Soil Flux Chamber coupled with a tunable diode CH_4 laser and Campbell Scientific CR1000 data logger (Figure 3). Prior to deployment, cylindrical collars were positioned around hand auger holes and pushed 3 to 5cm into the soils to create an effective seal. Dynamic flux chambers were then deployed over the top of the auger holes and either operated in manual or programmed mode, so they opened and closed at predefined times, while continuously measuring chamber air CH_4 concentrations with the laser. A regression line was derived from any rate of change in CH_4 concentration observed during chamber closure. The regression line gradient was combined with the ideal gas volume (derived from ambient temperature and pressure), the chamber volume ($0.0021m^3$) and the cross-sectional area ($0.0182m^2$) to yield a CH_4 flux value (in mass/area/time).

Figure 3: Testing of CH_4 dynamic flux chamber system prior to field campaign 2.

Laboratory analyses

Gas chromatography and mass spectrometry

Specialist isotope laboratories (University of Calgary and NERC Geoscience Laboratory) processed physical soil gas samples from select decommissioned well sites for analysis of molecular composition and stable carbon isotopes. In the case of the University of Calgary, gas compositional analysis (H_2, He, N_2, O_2, Ar, CO_2 and alkanes C_1 to C_6) is completed by injecting a 5ml aliquot of a gas sample into a Scion 450/456 gas chromatograph (GC). The GC uses 4 separate analytical columns connected to 3 thermal conductivity detectors and a flame-ionisation detector for gas separation and quantification. The lower detection limit for hydrocarbons is 1ppm (compared to a typical natural atmospheric baseline CH_4 of 2ppm) and for non-hydrocarbon gases is 50ppm.

Certified gas standards (Praxair Distributors Inc.) are used to calibrate the GC immediately prior to the analysis. Analytical drift is monitored by injecting the appropriate gas standards after every 10 samples analysed. Analytical precision and accuracy for gas composition analysis is typically better than ± 2.5% of the reported concentrations.

Carbon isotope ratios of CO_2 and CH_4 (after conversion to CO_2 and cryo-focusing) were determined with a ThermoFisher MAT 253 isotope ratio mass spectrometer (IRMS) coupled to a Trace GC Ultra + GC Isolink (ThermoFisher). Carbon isotope ratio measurements of CO_2 were bracketed and normalised using 2 calibration gases with widely different $\delta^{13}C$ values (Oztech −3.6 and −48‰) that were anchored against international reference materials. For CH_4, additional reference gases from Scott ($\delta^{13}C$ of−69 and−25‰) and Isometric ($\delta^{13}C$ of −67, −38 and −24‰) were used to ensure complete conversion of CH_4 to CO_2 prior to mass spectrometric analyses and accurate $\delta^{13}C$ values for CH_4. Results are reported in the internationally accepted delta ($\delta^{13}C$) notation (in ‰) relative to Vienna Standard (that is, Vienna Pee Dee Belemnite) with a precision better than ±0.5‰ and ± 0.3‰ for $\delta^{13}C$ values of CH_4 and CO_2, respectively.

Porosity, pore size distribution and permeability

Selected soil samples from the shallow auger holes at investigated decommissioned well sites were subjected to Mercury Intrusion Capillary Pressure Analysis (MICP). MICP characterisation provides quantitative information on a porous material (that is: pore volume, pore size, pore area, surface area, bulk density and total porosity) from which other important fluid-flow parameters such as permeability can be estimated. Three clay samples from the Torksey-4, Eakring-159 and Old Hills-1 sites were processed by MCA Services laboratories (Cambridge, UK) and analysed using a Micromeritics AutoPore V instrument.

MICP uses mercury as a non-wetting fluid with a contact angle >90º that requires applied pressure to enter a porous medium. The applied pressure is inversely proportional to the size of the pore structures, which make it possible to correlate pressure increments to volume (displacement) of mercury in a sample at a range of pressures, thereby deriving density and porosity [24,25]. Using Washburn's relationship between capillary pressure and pore radius[26], a pore size diameter can be estimated as follows:

$$D = \frac{-4\gamma cos\theta}{P}$$

Where D is pore diameter (nm), ɣ is the surface tension of mercury (usually around 480 dynes/cm^2), Ɵ is the contact angle of mercury (usually is about 140°) and P is the controlled applied pressure (kPa). MICP can delineate pore sizes ranging from 3 -to 600,000 nm with pressures up to 60,000 psi. Data obtained from MICP can be used to estimate a theoretical permeability using several different approaches, for example, Winland (1980), Katz and Thompson (1987) or Di & Jensen (2015)[27]. It is important to note that permeability values obtained from such empirical methods may vary somewhat from the true value (that is, as derived directly from field or laboratory measurements). This is because such empirical permeability models were formulated based on a specific rock type (for example, porous sandstones, tight mudstones) under specific conditions (for example, tight reservoirs, karstic environments). We estimated permeability using all 3 previously mentioned models, but report only values obtained from Winland (1980), which is an empirical model derived for tight rocks based on the Klinkenberg air permeability of various lithologies [28]. Consequently, permeability was estimated using the following equation:

$$k = (494)(r_{35}^{1.7})(\emptyset^{1.47})$$

where R_{35} is the pore throat radius (µm) that corresponds to a mercury saturation from the MICP of 35%, and Ø is the porosity obtained from MICP.

Results

Field campaign and sampling overview

An initial 5-day reconnaissance campaign was carried out in January 2020, followed by a second 5-day campaign in July 2020. During each campaign, in-field surficial measurements for CH_4 were taken using a portable greenhouse gas analyser as previously described. In addition, a series of shallow auger holes were drilled at and around the assumed decommissioned wellhead locations from which sediment samples, soil gas samples (and controls) and flux chamber measurements were attained. A summary of measurements and samples taken during the field campaigns is provided in table 5. Figure 4 shows field activities, including flux measurements using the dynamic flux chamber. Figure 5 shows the low permeability surficial clays encountered at Old Hills-1 and Plungar-9, which were also encountered at all the other decommissioned well sites investigated.

Table 5: Summary of field campaign activities, including auger holes drilled, samples/measurements taken and geology encountered.

Decommissioned wellsite	No. of shallow auger holes (deepest in m)	Sediment samples (MICP analyses in Brackets)	GC Soil-Gas Samples	GC control gas samples	Dynamic flux chamber monitoring locations (total duration)	Prevalent surficial soil lithology
Old-Hills-1	6 (2.28 m)	11 (1)	10	2	4 (24 hrs.)	Clay
Eakring	5 (1.02 m)	5 (1)	-	-	-	Clay
Torksey -4	3 (1 m)	7 (1)	-	-	-	Clay
Plungar-9	1 (0.7 m)	1	-	-	1 (10 min)	Clay
Bottlesford-1	1 (1.2 m)	1	-	-	1 (10 min)	Clay
Long Clawson-1	3 (3.27 m)	2	4	1	2 (7 hrs.)	Clay

Figure 4 a) Shallow auger drilling at Long Clawson-1. **b)** CH_4 flux measurements being attained over a shallow auger hole (>2m deep) at the assumed decommissioned wellhead at Old Hills-1.

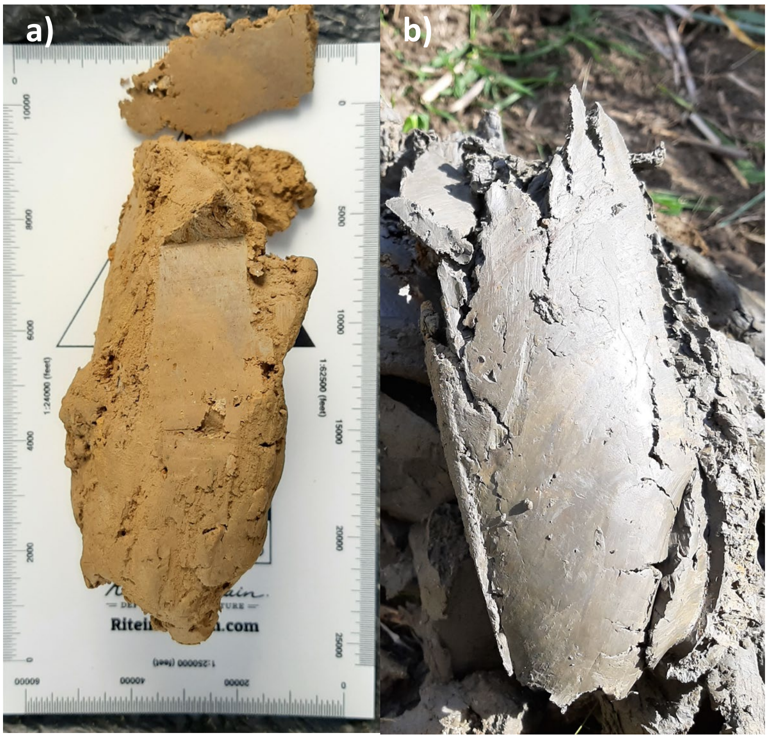

Figure 5: Clays were revealed to dominate the surficial geology at all decommissioned well sites investigated, including; **a)** Old Hills-1 and **b)** Plungar-9.

In-field surficial and soil gas measurements

During both field campaigns, CH_4 field measurements taken with the hand-held greenhouse gas analyser at both ground surface and up to 3m depth below ground surface (that is, within the shallow auger holes). These measurements showed little to no signs of elevated methane, that is, measured values were not above the typical atmospheric baseline level of ~2ppm. Exceptionally, one subsurface location at Old Hills-1 exhibited a measurement minimally elevated above background (6ppm) during field campaign 1. However, this measurement was not repeatable during field campaign 2. Table 6 shows a summary of soil gas compositions measured in shallow auger holes as determined in the field.

Table 6: Summary of in-field measurements for CH_4, CO_2 and O_2 showing that all the investigated decommissioned well sites exhibited levels at or around the natural baseline for CH_4 (2 to 3ppm). Only one location at one site showed CH_4 levels above ambient (that is, a single auger hole at Old Hills-1 exhibiting 6ppm of CH_4). The composition of typical natural gas is also shown for comparative purposes, together with the typical concentration in background air.

DW site	CH_4 range (ppm)	Mean CO_2 (%)	Mean O_2 (%)
Torksey-4	1-2	0.43	21.7

Eakring	1-2	0.52	21.2
Old Hills-1	1-6	0.7	20.5
Long Clawson-1	1-2	0.7	20.25
Plungar-9	1-2	-	-
Bottesford-1	1-2	-	-
Atm. air	~2	0.3	~21
Typical natural gas	>850,000	2	0

CH_4 efflux

A dynamic flux chamber and laser CH_4 detector system were deployed during field campaign 2 at 4 decommissioned well sites (as stated in table 5), and collected more than 13 hours of closed chamber flux measurements. Due to the potential signs (indicated by in-field measurements and laboratory physical soil gas analyses) of elevated CH_4 in the soils around the decommissioned well Old Hills-1 during field campaign 1, flux chamber measurements were focused at this decommissioned well site. Average flux measurements for each decommissioned well site are given in table 7. Figure 6 shows an example of CH_4 measurements collected during flux chamber deployment over 3 shallow auger holes advanced at decommissioned well Old Hills-1. Overall flux chamber CH_4 measurements at all decommissioned wells showed values that remained stable at or around atmospheric CH_4 levels (between 2-3ppm). These stable and low concentrations fluctuated only slightly, resulting in either very small positive or negative fluxes (for example, -2.0E-10 μmol/m^2/s at Plungar-9 and 2.4E-09 μmol/m^2/s at Bottesford-1). Overall, all fluxes measured at investigated decommissioned well sites were very small and within a range that would be considered normal for soils in a summer period[29]. A livestock feces CH_4 emissions test was also performed at decommissioned well Old Hills-1 (described in more detail in section 7.2). The feces showed the greatest CH_4 flux to atmosphere by a significant margin.

Table 7: Summary of CH_4 flux measurements for 4 decommissioned well sites investigated, including the livestock feces test. Results show CH_4 efflux at each decommissioned well is for most part negligible, fluctuating between very small negative or positive fluxes associated with natural processes. By contrast, the livestock feces have by far the largest CH_4 flux.

DW site	Number of flux measurements	Total duration of flux measurements (minutes)	Average CH_4 flux (μmol/m²/s)	Average CH_4 flux (g/m²/d)	Average CH_4 flux (kg/m²/y)	Average flux in kg CO_2-e/m²/yr (100 yr GWP)
Old Hills-1	80	743	-0.010	-0.014	-0.005	-0.131
Long Clawson-1	8	258	-0.044	-0.060	-0.022	-0.551
Plungar-9	2	12.5	0.014	0.019	0.007	0.175
Bottesford-1	1	17	-0.003	-0.004	-0.001	-0.037
Livestock feces test	1	7	0.786	1.089	0.398	9.939

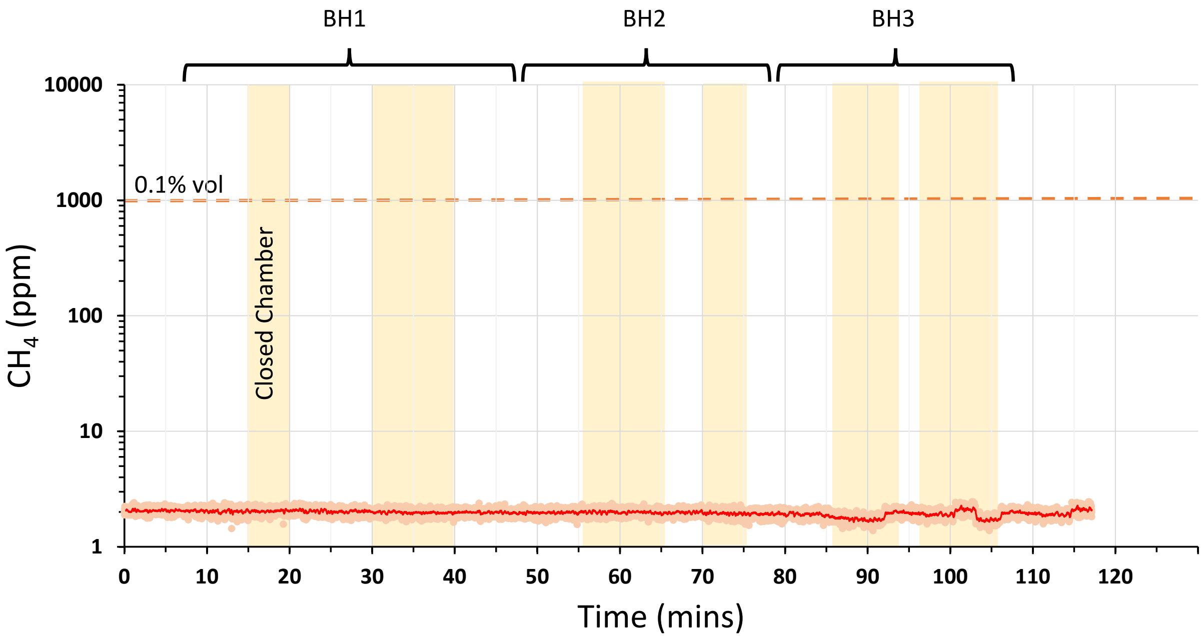

Figure 6: Example of CH_4 flux chamber laser data over approximately 2-hour period of monitoring at Old Hills-1 decommissioned well site. The red time series is a 10 second moving average over this period. The chamber was deployed on 3 shallow auger holes advanced up to 2.7m depth below ground around the assumed decommissioned well head. Orange shaded time sub-periods show when the chamber was closed and measuring CH_4 concentration from the auger hole; unshaded sub-periods show when the chamber is opened to equilibrate the system and is measuring atmospheric air. Measurements were observed to be very stable at around 2ppm, regardless of the chamber being open or closed. Consequently, calculated CH_4 flux measurements were either very small positive or negative flux estimates around zero; it was inferred from this that the decommissioned well has maintained integrity.

Laboratory analyses

Soil gas composition and stable carbon isotopes

Physical soil gas samples were obtained from the decommissioned well sites at Old Hills-1 and Long Clawson-1, as well as from control samples of ambient atmospheric air (taken from 1.5m above ground level at field sites) and of laboratory air. The samples were analysed for hydrocarbon gas composition and stable carbon isotopes ($\delta^{13}C$-CH_4), and the results are shown in Table 8 and Figure 7. Soil gas samples (shaded green) are concurrent with measurements taken in the field with the greenhouse gas analyser, showing that all samples (with the exception of one sample taken from Old Hills-1 auger hole 2) are at or around background atmospheric in terms of CH_4 concentrations (2 to 3ppm) with $\delta^{13}C$-CH_4 values varying from -25 to -50 ‰. Meanwhile, atmospheric air controls and lab controls (shaded grey) exhibited similar levels of CH_4 to the soil gas samples, that is, at or around 2 to 3ppm and revealed $\delta^{13}C$-CH_4 values of -28.9 to -40.3 ‰. In effect, the decommissioned well site soil gas samples show no difference from the control samples suggesting, as shown with in-field measurements, that no leakage from the decommissioned wells is occurring. The only samples to show elevated CH_4 above what might be considered normal were attained from Old Hills-1, auger hole 2 during campaign 1. Here, the in-field greenhouse gas analyser measurements detected CH_4 levels around 2 to 4ppm in excess of expected baseline conditions (5 to 7ppm). Physical soil gas samples analysed by GC in the laboratory support these field values exhibiting slightly elevated CH_4 concentrations of 7 and ~14ppm, with corresponding $\delta^{13}C$-CH_4 values of -45 to -50 ‰. However, no ethane or propane were detected in these or any other samples. Interestingly, very small traces of hexane (nC6; ~12ppm) were found in samples from Old Hills-1 auger hole 2, which potentially indicates that some oil or other hydrocarbon liquid may have been spilled here in the past and degraded (see Discussion and conclusions section below).

Table 8: CH_4 concentration (ppm) and stable carbon isotope ratios for CH_4 (‰) for soil gases and control air, attained from 2 different laboratories.

DW site	Uni. of Calgary Lab Methane ppm	NERC Lab Methane ppm	$\delta^{13}C$ – CH_4 (‰)
Old Hills-1.1	3	6	-45.8
Old Hills-1.2	7	13.9	-50.7
Old Hills atm. air control	2	3.4	-40.3
Lab control	2	3.4	-41
Long Clawson-1.1	-	2.5	-25

Long Clawson-1.2	-	2.5	-25.8
Long Clawson-1.3	-	2.9	-23.3
Long Clawson-1.4	-	2.6	-25.7
Long Clawson atm. air control 1	-	2.7	-29.6
Long Clawson atm. air control 2	-	2.4	-28.9
Lab air	-	2	-34.6

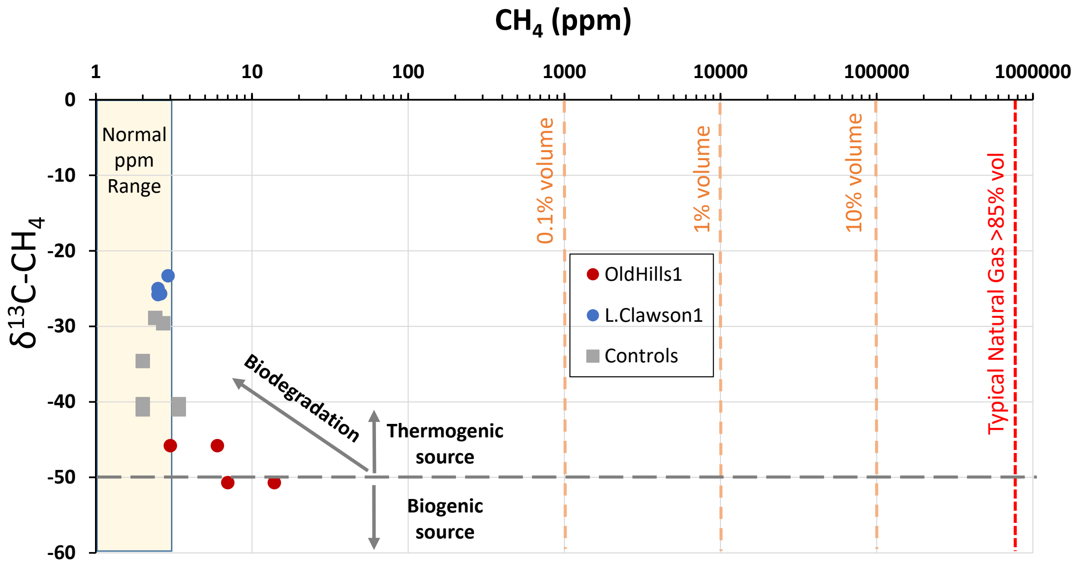

Figure 7: Decommissioned well site physical soil gas sample CH_4 concentrations (ppm) versus $\delta^{13}C\text{-}CH_4$ (‰) for all samples collected and measured during the investigation. Yellow shaded region shows the normal concentration range of CH_4 expected in atmospheric air, while dashed lines show key concentrations of CH_4 with the typical natural gas composition of >85% delineated by red.

Porosity, pore size distribution and permeability

Table 9 shows the results from the 3 clay samples analysed by MICP, including estimated permeabilities. Figure 8 shows intrusion data (as % total) and associated pore size distribution. The results show that 70%, 80% and 94% of the pores within the clay samples are < 10μm in diameter (that is, only 30%, 20% and 6% are >10μm and considered macropores) at Eakring, Torksey and Old Hills respectively. Consequently, all 3 samples are of very low permeability (all < 0.05 mD), with the clay at Torksey-4 in particular being very low permeability (< 0.001 mD). For comparison, MICP results for a permeable sandstone (attained from an area of petroleum resource development in British Columbia, Canada) are also shown. In this case it can be seen that, in contrast to the decommissioned well site clays, 75% of the pore structures are >10μm in diameter and considered macropores, resulting in a much greater permeability of >259 mD. These results imply that the clays encountered at the investigated decommissioned well sites will act as robust capillary barriers, which severely limit, and most likely fully prevent, the flow of fluids (including gases) within or through the clays - as has recently been shown[30].

Table 9: Summary of mercury intrusion porosimetry data for surficial clays encountered at investigated decommissioned well sites, including estimated permeabilities. A more permeable sandstone from British Columbia Canada is included for comparative purposes.

Pore parameter	Torksey 4	Eakring 159	Old Hills 1	BC SS
Total intrusion volume at 60k psia (mL/g)	0.13	0.159	0.17	0.14
Total pore area at 60k psia (m^2/g)	19.14	15.07	14.32	1.4
Median pore diameter at 3k psia (μm)	0.071	0.577	0.20	14.8
Median pore diameter at 23k psia (μm)	0.009	0.008	0.01	0.009
Average pore diameter (μm)	0.027	0.042	0.04	0.4
Bulk density at 0.33 psia (g/ml)	1.68	1.62	1.59	1.7
Apparent (skeletal) density at 60k psia (g/ml)	2.16	2.19	2.18	2.2
Porosity (%)	22.1	25.9	27.2	23.7
Permeability* (mD) (Winland, 1980)	0.001	0.041	0.006	259.1

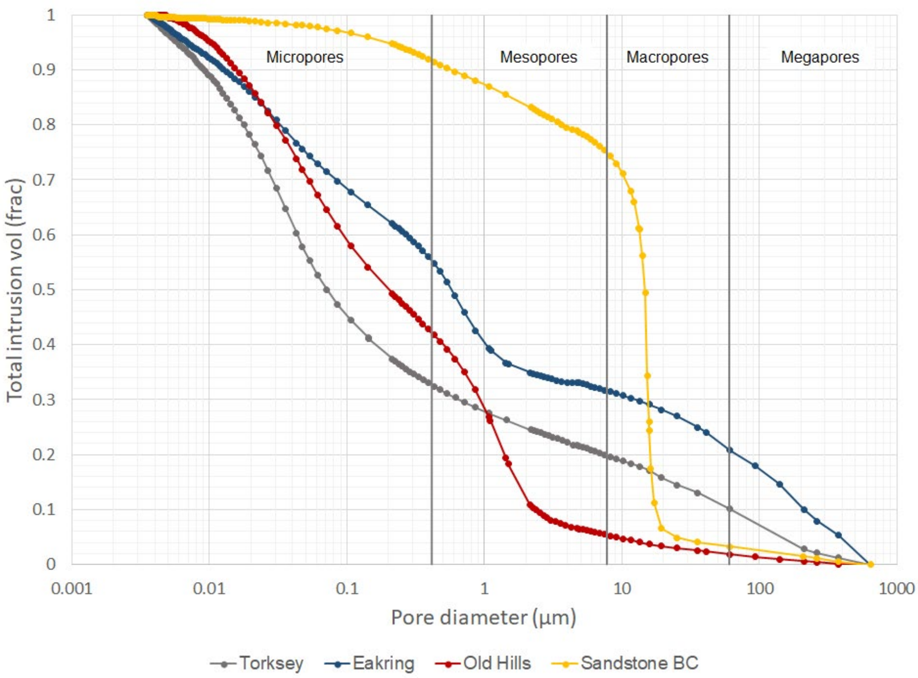

Figure 8: Intrusion volume (% total intrusion) - pore diameter curves from decommissioned well sites, including generalised porosity size classification[31]. Data corresponding to a permeable sandstone from British Columbia, Canada (Sandstone BC) is included to show the difference between low permeability surficial clays and more permeable rock properties.

Discussion and conclusions

Field measurements and decommissioned well integrity

In this study, we performed the most intrusive and comprehensive field assessment of integrity for 6 decommissioned well sites in England ever conducted. Our intrusive investigations, which included attainment of soil gas samples at depths of up to 3m below ground level and the deployment of a dynamic flux chamber for a total of 13.4 hours of closed chamber measurements (during 50 hours of deployment) around the 6 decommissioned wellheads, found no evidence of elevated hydrocarbon gases (that is, above natural levels).

Exceptionally, one decommissioned well location (Old Hills-1) and one sample (auger hole 2) exhibited levels of CH_4 which might be considered slightly anomalous (that is, up to ~14ppm as determined by laboratory methods). This value is far in excess of any previously measured during the ReFINE investigations, but was not repeated during follow up monitoring which did not detect any anomaly, including when a dynamic flux chamber was deployed for 12 hours of closed chamber flux measurements around the decommissioned well. Traces of hexane (nC6; ~12ppm) were found associated with this soil gas sample, but other intermediate hydrocarbon gases such as ethane and propane were not detected. The presence of hexane, but not ethane and/or propane, is likely a result of soil contamination from the surface with oil or petroleum products spilled during surface activities (for example, during drilling and abandonment of the decommissioned well) and their subsequent degradation. Overall, we conclude that all decommissioned wells investigated, including Old Hills-1, show no signs of integrity failure.

It should be noted that petroleum wells (active, suspended or decommissioned) can and do suffer integrity failure[2,3,32]. When they do, natural gas and/or other petroleum fluids migrate within the subsurface and to the surface with significant concentrations of CH_4, ethane and propane presenting (that is, typical source gas % compositions of ~80%, ~15% and ~3% respectively). In such cases, these hydrocarbon gases are typically 'obvious' at the surface and/or in the soils around the wellhead, with concentrations of CH_4 detected, ranging from several thousand ppm (that is, 0.1 to 1% volume) to several hundred thousand ppm (that is, 10 to 90%). For example, Lyman and others[22,33] reported soil gas concentrations of CH_4 ranging from 20% to 80% volume (that is, 200,000 to 800,000ppm) in soils around energy wells in the Rocky Mountains and Gulf Coast regions of the US. In terms of CH_4 flux, the current study measured very low positive and negative levels (+/- 0.01μmol/m^2/s), commensurate with the low concentrations of CH_4 detected in the soils. Wells suffering integrity failure would be expected to present much higher flux rates than those seen here. For example, Forde and others[21] investigated the integrity of 17 energy wells in British Columbia, Canada, some of which had been identified as having integrity failure. More than 350 flux measurements were attained, where it was reported that CH_4 flux measurements were consistently positive and averaging 1.6μmol/m^2/s, and reaching as high as 180μmol/m^2/s; this compares with a highest positive flux measured in the current study of 0.014μmol/m^2/s at Plungar-9 (Table 7). All measurements of CH_4 concentration and flux in the current study (and in the previous ReFINE study) are far lower than those reported elsewhere for energy wells with failed integrity. Consequently, the observations made around decommissioned wells in England are not indicative of well integrity failure as it is known to occur and observed in North America and elsewhere.

That being said, while our intrusive investigations found no evidence that the 6 decommissioned wells visited were suffering any form of integrity failure, we also reaffirmed that the surficial geology at a decommissioned well site must be considered when attempting to asses integrity in the field, as was recently shown[30]. Shallow auger holes at all 6 decommissioned well sites revealed glacigenic Quaternary clay tills dominating the surficial geology, and laboratory tests confirmed these materials to be of very low permeability (all had an estimated permeability of < 0.05mD). Such materials, in which the decommissioned wells are embedded, would severely inhibit, if not prevent, the flow of any fugitive gases away from the well structure so that any flows would be undetectable at the surface and potentially in the subsurface. Consequently, while we detected no signs of integrity failure in this study, the Quaternary geology in which the decommissioned wells are embedded prevents us from concluding that the decommissioned wells investigated are absolutely not leaking.

Livestock feces test

In order to better understand the potential for false positives and to constrain the magnitude of natural CH_4 from soils around decommissioned well sites (particularly those reclaimed for agriculture), we enclosed a small amount of livestock feces (found within metres of the Old Hills-1 decommissioned well) in the flux chamber system and monitored emissions. During this rudimentary field test, CH_4 concentrations increased almost immediately (as would be expected), climbing from baseline to 6ppm within 7 minutes (Figure 9). Based on these measurements, CH_4 flux was calculated to be 0.78μmol/m^2/s, far in excess of any other measurements made at any of the decommissioned wells investigated in this or the ReFINE study. This field trial shows that land use and type could potentially elicit false positive results when investigating decommissioned wells, particularly if leakage is marginal or only manifesting at very low levels at the surface.

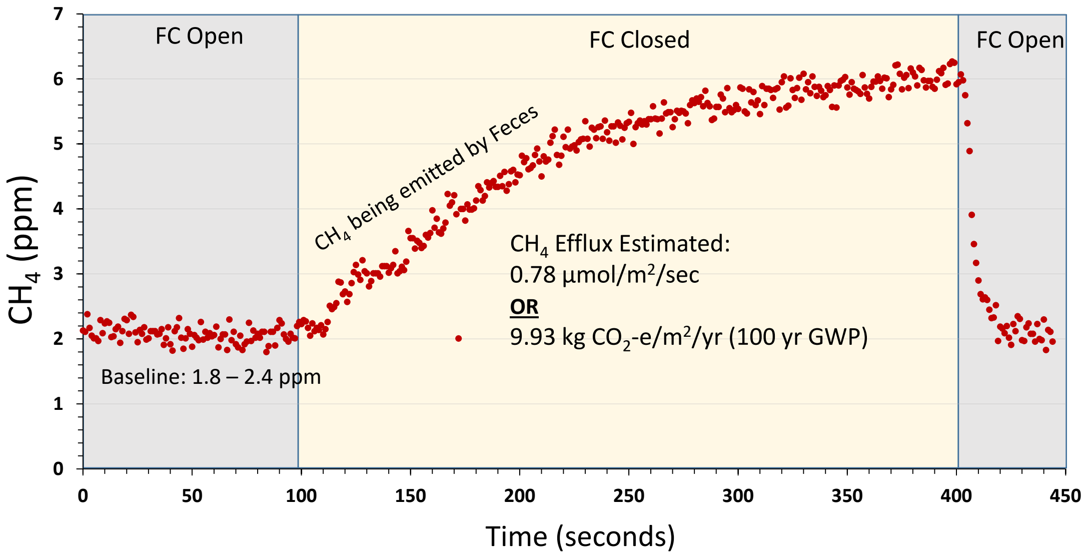

Figure 9: Livestock feces flux chamber test showing clear CH_4 emissions and concentrations of CH_4 reaching 6ppm, which is in excess of nearly all measurements made in this or the ReFINE investigations. This increase in CH_4 concentration with time resulted in a determined flux of 0.78μmol/m^2/sec or nearly 10kg CO_2-e/m^2/yr (100 yr GWP). This shows that integrity failure is inferred from very low CH_4 values that are only marginally elevated above baseline conditions, therefore, there is a strong risk for false positives due to livestock.

Comparison with ReFINE results

Firstly, it should be noted that the ReFINE investigations were conducted as a 'first pass' scoping exercise, in order to provide an initial indication of potential decommissioned well integrity in England across a large number of wells. Consequently, the methods used were, by design and necessity, minimally intrusive and for reconnaissance purposes. Consequently, there were always limits on the conclusions that could be drawn from them (as acknowledged by the research team involved) and more work would be needed to better constrain the true status of decommissioned wells in England. Nonetheless, it was concluded that 30 out of the 102 wells investigated were suffering integrity failure, including 4 investigated in this study (hence their selection for re-investigation). Torksey-4, Eakring-159, Old Hills-1 and Long Clawson-1 were all suggested as exhibiting signs of well integrity failure, on the basis of anomalously elevated methane levels that were detected at the ground surface and were reported as statistically significant (based on the methods described under 'ReFINE Project Field Investigations' above). Moreover, these 4 wells were reported as exhibiting some of the greatest relatively anomalous CH_4 concentrations found during the ReFINE study (that is, ranked 1st, 3rd, 5th and 28th for relative elevated CH_4 anomaly). Consequently, they were anticipated to present easily measureable levels of hydrocarbon gases at the surface and more so at depth in the surrounding soils. Consequently, the findings of this investigation (that is, no signs of integrity failure as stated above) are somewhat surprising and warrant a more detailed review of ReFINE results to better understand this inconsistency.

As part of this investigation, the ReFINE results, including previously unreported absolute surficial CH_4 concentrations, were kindly provided by the University of Durham (some of the unreported data are shown in Tables 1 and 2). These results demonstrate several important insights that must be considered when attempting to assess decommissioned well integrity. Firstly, the ReFINE investigation identified those decommissioned wells that might be suffering integrity failure by considering relative concentrations that had been normalised against nearby control sites, and not by considering absolute observed CH_4 concentrations. If the absolute concentrations (Table 2) are considered, it is clear that even the most anomalous decommissioned well site identified by the ReFINE project (Old Hills-1, where CH_4 was reported to be 3.7 times higher than the control) had absolute concentrations that were only ~0.9ppm. Although this value may have been elevated compared to the control site by a factor of 3.7 (Table 1), it is comfortably within what would be considered a normal and natural range for surficial and soil gas CH_4. If anything, it might be considered to be anomalously low compared to atmospheric concentrations of CH_4 of ~2ppm. For example, Schout and others[19], who investigated the integrity of 29 decommissioned wells in the Netherlands, only considered surficial CH_4 measurements around decommissioned wellheads as potentially anomalous if they exceeded 2.5ppm. Even then, nearly all the measurements exceeding 2.5ppm were found to be non-repeatable and not associated with well integrity failure, based on follow-up measurements with a flux chamber. In the case of the ReFINE investigations, the vast majority of measurements at both control and decommissioned well sites fall below the typical atmospheric baseline value of 2ppm. Furthermore, nearly all ReFINE measurements (n=2227/2296 or 97%) are within 2 standard deviations of the mean (that is, <2.3ppm for a mean of 1.5ppm and SD of 0.4) and so would not be considered outliers. In addition, all the measurements are constrained by the accuracy (+/- 1ppm) of the tunable diode laser used, and when this accuracy constraint is taken into account, they would be considered relatively normal. Also, measurements that are greater than 2 standard deviations from the mean (n=69/2296 or 3% of all measurements) are still within, or very close to, ranges that would be considered normal for soils. Moreover, 50 of the 69 measurements, which could potentially be considered elevated outliers, were made at control sites and not at decommissioned well sites. If the ReFINE investigations had considered absolute concentrations, instead of relative concentrations normalised against control sites, it is likely that they would have concluded that none of the decommissioned wells investigated was suffering integrity failure – in agreement with this study. However, it must be acknowledged that the low permeability of the surficial geology (clay), which was not considered in the ReFINE investigations, would preclude any conclusions about the integrity of buried decommissioned well structures being made with full confidence either way.

Summary

Well integrity is a complex issue associated with all petroleum wells. It is of particular concern with respect to abandoned and decommissioned wells which are required and assumed to be sealed in perpetuity. A complex combination of environmental, engineering, regulatory and geopolitical factors can interact and compound to determine if a well suffers integrity failure in the long term. England has a modest, but still significant, onshore population of decommissioned energy wells (>2,000). The current status of these wells and their potential long-term integrity are poorly constrained. However, it was recently suggested that the integrity of 30% of a subset of 102 decommissioned wells investigated may have failed, resulting in CH_4 being released into surrounding soils and subsequently the atmosphere. Here, we carried out a series of intrusive field investigations at 6 decommissioned wells, 4 of which were members of the subset previously identified as suffering integrity failure. These new investigations revealed no signs of integrity failure, with CH_4 levels around all decommissioned wells being near to natural baseline levels. However, it was determined that all the decommissioned wells investigated in this study were embedded in low permeability glacigenic Quaternary clays (with estimated permeabilities of < 0.05mD), which would act as robust capillary flow barriers that would severely limit, if not totally inhibit, any gas migration from the wellbore to the surface and the atmosphere. The discrepancy between our results and those reported previously may be attributed to the complexity and spatiotemporal variation that has been shown to occur with subsurface fugitive gas migration. These complexities include false positives associated with land use (for example, by livestock) and/or limitations in previously used methods of investigation and interpretation. In the previous investigation, a method of normalising decommissioned well CH_4 measurements to a nearby control field was used before wells were assessed for integrity. Also, assessments did not consider observed absolute CH_4 values. When the observed absolute values are reviewed, it is apparent that nearly all the measurements obtained previously were within the natural ranges for atmospheric and soil, and that no measurements were at the levels typical for wells with integrity failure. Specifically, the absolute values were 1 to 3ppm, in contrast to values of 1,000 to 100,000s for ppm for failing wells. If the previous investigation had considered absolute values, it is unlikely that it would have been suggested that 30% of the 102 wells investigated were suffering integrity failure. However, any conclusion about decommissioned well integrity in England that is based on the measurements to date (from both the ReFINE investigations and this study) should be viewed with caution, because the low permeability of surface geology may mean that the methods used so far are inadequate to accurately detect or quantify leakage into the sub-surface from wells that are buried below that surface geology.

Recommendations

The following recommendations are made based on the findings of this investigation:

- More intrusive and continuous investigation methods are needed to accurately and authoritatively assess decommissioned well integrity in England.
- Surficial geology must be considered and better characterised in order to robustly assess decommissioned well integrity using surface and/or sub-surface measurements, especially consideration should be given to how soil type influences fluid flow and transport.
- Absolute values for CH_4 observed around decommissioned wells must be considered when assessing integrity.
- More understanding is needed of natural CH_4 source and sink processes, and of how decommissioned well integrity failure can become evident, distinct and measurable in local environments.
- Land use must be considered when assessing decommissioned well integrity, and in particular the possibility of false positives due to livestock feces or residues from hydrocarbon spills that occurred when wells were operating. It is particularly important to consider false positives if CH_4 is only marginally above typical baseline conditions (that is, < 100ppm).

Information from the above suggested activities may be used in predictive and scenario–based modelling of source-pathway-receptor processes at decommissioned wells, in order to better understand how a failed decommissioned well would present and the risks it poses to receptors.

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