GT-190300
10 Dec 2020

Quantifying leakage from underground pipelines

Phase 1

Trust
Quality
Progress

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Phase 1

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1 Summary

Methane is a greenhouse gas that, when released into the atmosphere, contributes to climate change. The most important component in natural gas is methane. It is therefore important that the emissions of the gas sector are accurately and traceably quantified.
The estimation of the emission of underground pipelines is typically a process of two stages. One stage is executing a leak survey that identifies the location and number of leaks in the piping system. Secondly a number of reference leaks is selected of which the amount of leakage is quantified.
One of the methods available for quantification is the 'suction method', which is the topic of this report.
The uncertainty of the estimate of the total emission is determined by various factors, of which arguably the two most importance ones are the accuracy (systematic and statistic uncertainty) of the suction measurement and the statistical uncertainty in the average leaks flow rate (due to the limited sample size and the inherent variation of leaks flow rates occurring in the piping system).

This research describes the results of a set of suction measurements under controlled conditions, (i.e. known leak flow rate). The main findings are that a random error of less than +/- 5% is achievable and that the systematic error is possibly +/- 15%. A possible source of the systematic error in this set of measurements is the long time to reach equilibrium suction condition. This leads to an overestimation of the leakage. It is expected that this systematic error can be reduced by carefully extraction gas out of the soil at larger distances around the leak. A suction measurement protocol is included in the report, taking this aspect, among others, into account. Other systematic errors are not yet fully excluded.

Suction measurement data set
From analysis of a historic Dutch dataset of suction measurements it appears that the standard deviation of each leak flow rate in the population of all leaks is about as large as the average. Further analysis (as well as a rule of thumb) suggests that about 20 measurements would be required to achieve a relative uncertainty of +/- 25% (with a relatively low confidence level of ca 0.8) in the estimate of the average leak flow rate.

Campaign advice
With regard to a measurement campaign the following recommendations are given:
- Use the suction measurement method according to protocol (annex II) to quantify the methane emission of selected leaks;
- The protocol must include removal of gas in a wide area around the leak;
- Expect to need about 20 leak flow rate measurements for each subcategory of leak type, in order to expect an accuracy in average leak flow rate estimate of 25%.

As the statistical uncertainty due to the variance of leaks flow rates in the field is larger than the uncertainty of the suction measurement, further development of the suction method is not urgently required. The suction measurement with a strict protocol to remove gas at larger distances from the leak is fit for its purpose. A direct way of improving the accuracy of the estimate of the amount of fugitive methane emission from buried gas distribution pipelines is to increase the number of suction measurements.

The suction method is inherently a relatively time consuming and thus expensive measurement. This precludes its application to all of the detected fugitive leaks. A

cost/benefit analysis could be used to determine the optimum number of leaks to be quantified, if more information on the variance in flow rate becomes available.

Therefore it is advised to implement a continuous measurement program, gradually covering all situations and gradually reducing the statistical uncertainties.
An additional advantage of a continuous program is that any change in the leak population (e.g. due to the aging of the network) is monitored and will become apparent. Also the attention to certain subcategories of leak types can be prioritized as warranted by intermediate results and for optimizing the measurement program. Analysis of the intermediate results should be part of the continuous program.

2 Project description

2.1 Introduction

Methane is a greenhouse gas that, when released into the atmosphere, contributes to climate change. The most important component in natural gas is methane. The GERG report "Analysing the Methods for Determination of Methane Emissions of the Gas Distribution Grid" contains an overview of European registration methods. Based on this overview, the development of a pan-European method is being conducted in a follow-up project "Development of an Accurate and Consistent Method for Methane Emission Estimation from the Gas Distribution Grid". In this GERG project various methods for the determination of methane emissions from, among other, underground pipelines have been identified and investigated.

Suction measurements to quantify underground leaks

For the quantification of the emission of methane from underground pipelines the method by suction sampling has been identified as widely used and effective. The measurement procedure consists of extracting a mixture of gas and air from the soil surrounding a leak using a high flow sampling technique and analysing the mixture to determine the leak flow rate of the underground leak. The measurement does not move any soil in the immediate neighbourhood of the leak and therefore has minimal influence on the leak flow rate.

A number of countries combine the results of a limited number of suction measurements with data of leak surveys to calculate an overall emission of the underground network of the mains.

Uncertainties in the current measurements

Current measurements show a large variation in leak flow rates. In high flow sampling techniques, variable soil conditions (e.g. cracks) and weather conditions (e.g. precipitation) potentially have a significant influence on the measurements. Also the factors Material, Pressure Level, Diameter and Age (or cause of the leak) and Soil Type (grain size) will have an influence.

As a result of these uncertainties, the latest GERG project on the development of a methane emission estimation method recommends to gain more knowledge and insight into underground leaks to get a more accurate estimate of the total emissions. This should lead to an European measurement program to quantify the underground leakages of pipes.

Objective

The main objective of the project of this report is to develop an European set of measurements of underground leakages to be used in a methane emission quantification method.

In order to reach that objective the following process with two phases is proposed: First the current set of measurements and the measurement method will be further analysed. Using this analysis a recommendation for a coordinated measurement program will be given which can be executed in a next phase. This report is about the first phase after which a Go/No Go decision is to be made.

2.2 Research questions

In this report - that covers phase 1 - the following research questions are addressed:

1. What is the accuracy of the suction method and how is this influenced by changes in the measurement protocol?
2. What is the influence of external conditions (wind, rainfall, soil) on the amount of leakage and the suction measurements?

3. What is the overall uncertainty in the average leak flow rate as expected from a given a set of well documented, suction measurements?

2.3 Approach of phase 1: Analysing, planning and recommendation

Statistics (analysis)

Describing the influencing factors by analysing the currently available set of measurements. The statistics will reveal the influence of factors such as pressure, material etc. The current uncertainty is identified by fitting the measurements to some parametrised statistical distribution functions.

Kiwa Technology has already developed a suitable statistical analysis method. A preliminary application of this method shows that the uncertainty in the population average of the estimated leak flow rate is significant (up to a factor 2).

As a consequence the calculated emission estimate also bears a significant uncertainty.

The effect of variations in the suction measurement method (such as the amount of air flow and position of sampling rods and wait time to steady state) will also be included in the analysis e.g. by means of computer modelling (see annex).

Limited number of suction measurements (validation)

In order to ascertain the validity of the model assumptions a limited number of suctions measurement under controlled and carefully documented (weather and soil) conditions will be performed. For this part of the project two controlled leaks in two different types of soil will be constructed on the premises of Kiwa Technology. The pressure of the leaks was initially planned to be varied between 100 mbar and 4 bar as does the leak flow through the hole. Due to experimental issues only measurements with a fixed pressure of approximately 100 mbar have been done.

During the measurement period the influence of wind and rain was recorded.

The initial plan was to measure every two weeks both leaks using the suction method until a total of 10 measurements per leak had been conducted. However, during the execution of the program, it became apparent that the distances over which the leakage was dispersed in the soil was larger than expected and it was impossible to operate both leaks simultaneously, Eventually 14 measurements were done.

The results provide a limited validation of the effect of variations in measurement conditions and an accuracy assessment.

Also the reproducibility of the suction measurement method is identified and a detailed suction measurement procedure is given. This procedure can be used in the coordinated measurement program in phase 2(see annex).

3 Measurements

3.1 Set-up

3.1.1 Site

The site for the measurements is located at the premises of Kiwa Apeldoorn (Figure 1, Figure 2, Figure 3). The distance to the nearest building is ca 10 m. The building is single storey 5m high.
Adjacent to the site are some low scrubs (2.5 m) and at larger distance (20 m) there a trees and a multi-story building (10 m height).

Figure 1 Site location, top view (red rectangle) Situation date ca. 2015. Source: Google Maps.

Figure 2 Site location, side view (red rectangle).

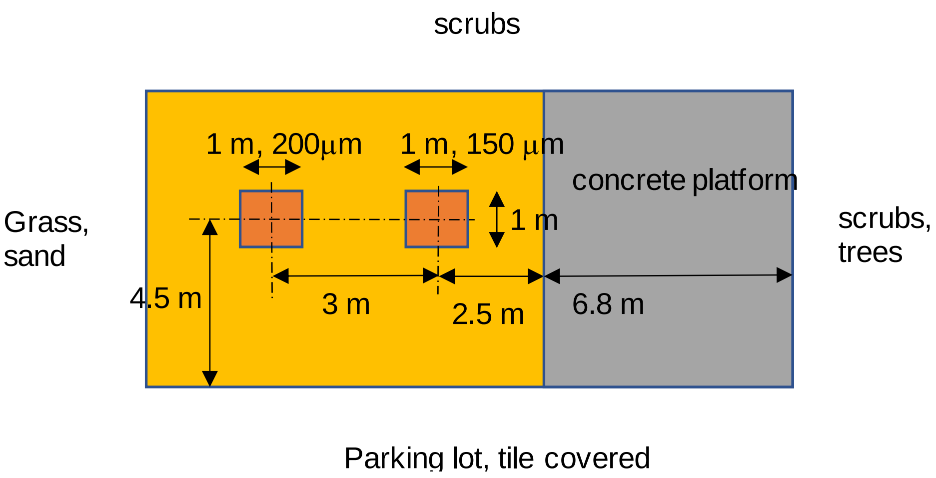


Figure 3 Site dimensions.

3.1.2 Soil

Two separate leak locations were prepared at the site. Each location comprises an area of approximate 1m x 1m filled to a depth of 1.5 m with sand of known and specified quality (see annex). The location was filled with 200 µm respectively 150 µm sand.
The sand was compacted in several stages during filling of the locations.

Several weeks after the initial filling of the locations, two small holes were dug, in which the leakage tubes were placed (Figure 8). The holes were filled again with the original sand and compacted manually in several stages.

3.1.3 Leaks

The leaks are constructed from copper tubing in which holes of various size are drilled (Figure 4, Figure 5, Figure 6). The tubes are made of 28mm copper pipes and are 30 cm long. A hole was selected in each of the four pipes that provided the desired approximate leakage at internal pressures between 30 and 200 mbar.
The other holes were closed by soldering.

Figure 4 Set of pipes with various holes.

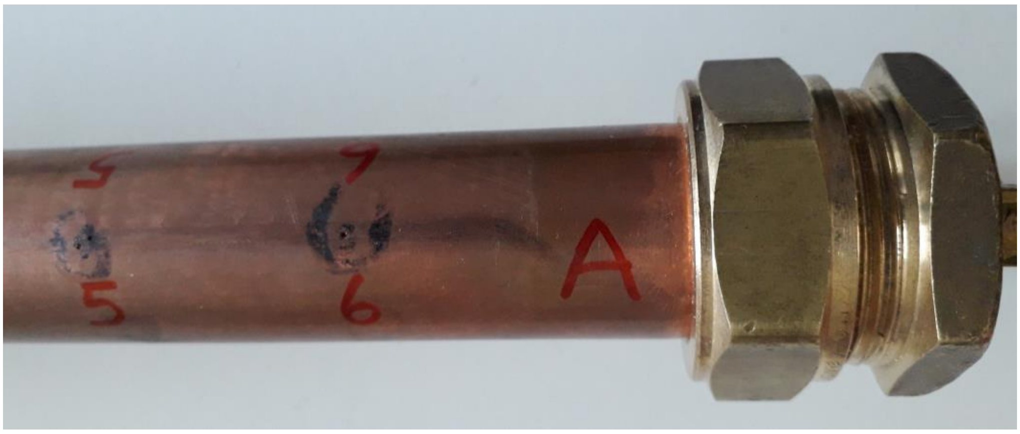


Figure 5 Detail of the pipe and a leak.

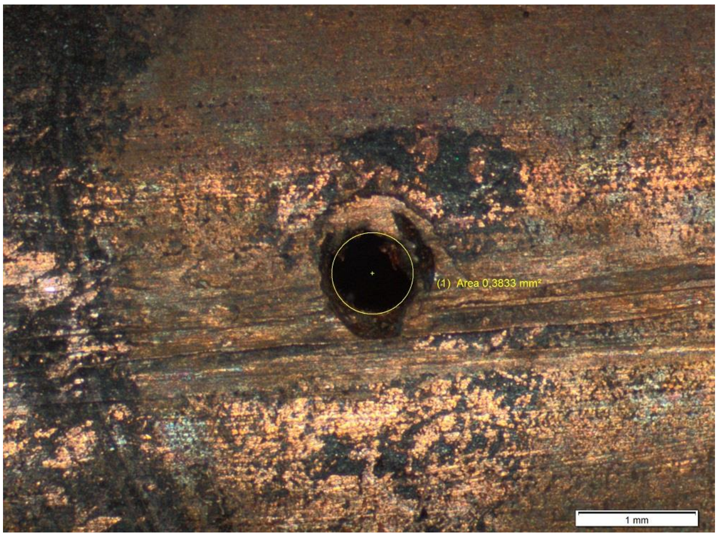


Figure 6 Detail of a leak hole. Macro photo with size indication (1 mm).

Due to imperfections of the drilling the leakage did not exactly correlate with bore diameter. The leakage was measured in a test box filled with the same soil as used at the test site. Leakage was measured as function of the pressure (for a typical result see Figure 7).

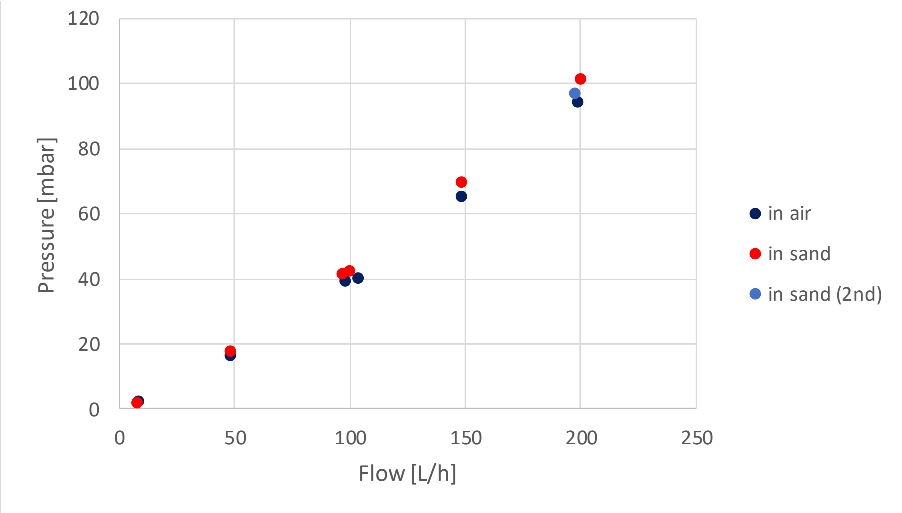


Figure 7 Typical relation between leak flow and pipe pressure. One measurement series of tube in open air (dark blue), a measurement series in sand (red) and a repeated experiment in san with same tube buried and sand compacted again (light blue).

Care was taken to compactify the sand by applying pressure and adding and removing water. The repeatability of the effect of the sand burying the same leak several times was found to be limited. Most of the pressure loss occurs in the leak hole. The pressure loss in the sand is less than 10% of that value and varies with about a factor of 2 when repeating the experiment, as is apparent from comparison of the two typical measurement series in sand in figure 7. For example: at 200 L/h the leak pressure in open air the sand is 93 mbar and the two experiment with the buried leak show 97 and 102 mbar, a difference of 5 mbar respectively 10 mbar with the measurement in open air.
The relation between pressure and leakage is nearly linear, indicating that the flow through the leak behaves as laminar flow. This is a bit surprising, as the estimate Reynolds number at 200 L/h is about 7 000 (diameter 0.7 mm), which is well above the transition from laminar to turbulent in pipe flow as cited in the literature (Re = 2900). Possibly the length of the hole is not long enough to let the flow develop into turbulent flow.

The selected pipes are connected (Swagelok) to long flexible tubes (Ø ¼", 5 – 10 m). Two tubes are used for each pipe: one for the leak flow and one for pressure measurement.
At each leak site two pipes are buried side by side (Figure 8).

Figure 8 Positioning the leaking pipes in the soil (only a single one at a time was used).

3.1.4 Installation and instrumentation

For a detailed specification of the instruments used see table 1. A schematic of the installation is given in annex IV.

Instrument	**Manufacturer**	**Type**	**Id.**
Mass flow controller	Bronkhorst	FG-201CV-RAD-22-V-DA-000	M19213219B
Mass flow controller	Bronkhorst	FG-201CV-RAD-22-V-DA-000	M19213219A
Mass flow meter	Bronkhorst	F-106AZ-RAD-01-V	M19213219C
MFC control unit	Bronkhorst	E-8101-A-20-10-00	
Pressure regulator	Unknown	IR4015253 4PMX	330258
Pressure regulator	Unknown	IR4015250 4PMM	330268
Weather station (wind, temperature, precipitation, pressure)	Renkforce	WH2315	Not available
Suction pump	Esders	Vakumobil	156 – 07/13
Manifold + 9 valves	Kiwa		
Datalogger/PC	HP		
Methane monitor 1	Inficon	Irwin	
Methane monitor 2	Edinburg Sensors	Guardian NG	
Gas chromatograph	Interscience	Thermo Scientific Trace 1300 + TCD-detector	714530067

Table 1 Equipment used during the experiments.

The main measuring instruments are Bronkhorst mass flow controllers used in the monitoring mode. Two mass flow controllers (MFC) are used in the leak injection lines, continuously monitoring the gas flow in each of the leaks.
The leak gas flow is controlled by two pressure regulators.

Flow and pressure data was logged continuously during the duration of the experiments (sept – dec 2019) every 3 seconds.

Another high volume, low pressure drop mass flow controller was used to measure the total suction flow. Its data is logged during the actual measurement only.

The trend of the methane concentration in the suction mixture is measured using a Inficon Irwin methane detector. For the final measurement a Guardian NG of

Edinburg Sensors was used. The final sample in all the measurements is analysed with a gas chromatograph.

3.2 Results

The suction method was intended to be validated by measurements on two different leaks, emitting a known amount of methane, under a variety of weather conditions. During the validation of the suction method it became apparent at the first measurements that there was an unexplained excess of methane. Thus the planned set of measurements was changed to first identify the cause of the discrepancy. This was done by looking carefully at the possible source of systematic error and eliminating them as well as positively identifying the error.

Because the uncertainty of the suction method is largest with smaller leaks, the tests to identify the error were performed using the larger leak. The initial hypothesis was that an unknown leak source interfered with the measurements. No such source was detected. Another hypothesis was zero-drift of the methane sensor. Cross check with gas samples with a gas chromatograph did not indicate a zero-drift error. The final hypothesis was that gas that injected earlier contributed to the measurements, even after 6 h of suction and seemingly equilibrium conditions. Especially test 2810 indicated a very slow removal (> 48 h) of gas in the soil at distances larger than 2 m.

A final test provided the example picture of the situation (see Figure 9.

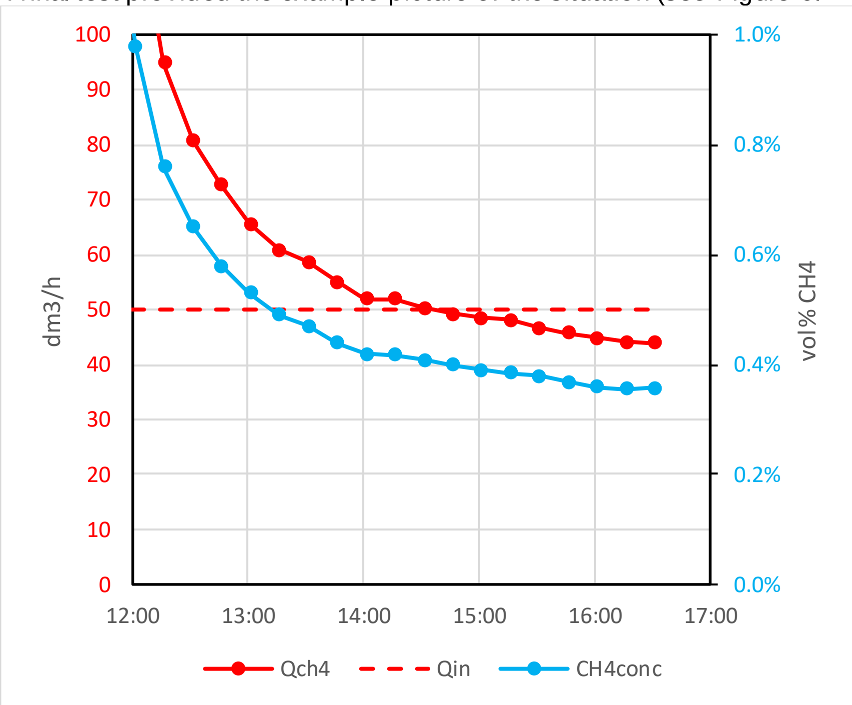


Figure 9 Suction flow as measured between begin and end of the measurement. Suction is terminated, according to protocol, at 16:30 when at two consecutive readings at 15 minutes interval no further decrease in concentration is registered. The suction was constant at 12 m^3/h during the period.
Qch4: calculated leak flow rate from suction flow rate x CH4conc,
CH4conc: volume concentration methane in suction air

The number of measurements is necessarily limited and therefore it is hard to quantify all the effects, but the following observations summarize the tests:

- Weather conditions (rain, temperature) during the measurements or in the days before the measurement appear not to influence the detected leakage, indicating that any residual influence is less than 20%;
- Throttling the suction from 13 m^3/h to 5 m^3/h appears to decrease the detected leakage by 10%. Apparently a suction rate of 5 m3/h is not sufficient to capture all the leakage;
- Displacing all the 9 suction rods by 0.5 m from the leak appears to decrease the detected leakage by 10%;
- Suction for a significantly lower period than 6 h appears to decrease the detected leakage;
- Changing the suction depth from 0.5 m to 0.8 appears not to influence the detected leakage;
- The detected leakage appears (in most tests) to be systematically higher than the injected flow (10 – 20%), possibly indicating that equilibrium is not reached after nominal suction of 6 h;
- Initially the two leaks separated at 3m distance were operated simultaneously. After the first test the larger one was shut down. It cannot be excluded that the reservoir of that leak influenced the next few tests.

Measurement code	Protocol	Deviation $Q_{suction}/Q_{in}$ %	uncert. ±	Remark
2009	Standard conf., no zero point correction conc. measurement	164.2	23.7	First measurement leak A, test of equipment (no GC measurement)
2509	Standard conf.	126.7	3.2	Check of repeatability leak A
2609	Standard conf, small leak	280.3	15.5	First measurement leak B
3009	Standard conf, small leak	268.0	18.5	Check of repeatability leak B
0210	Five rods only	133.0	3.6	Check for presence of additional gas source around leak A (influence of leak B)
0710	Five rods only, small leak	269.2	7.3	Check for presence of additional gas source around leak B (influence of leak A)
0910	Standard conf, 8 x 0.8 m depth, central rod at 0.5 m	121.3	2.7	Check of effect of suction depth (leak A)
1410	Standard conf, long measurement. Two samples: 0.74% after 6 h and 0.70% after 18h. Qin fluctuates: 85 L/h at 6h, 92 L/h at 18h	93.5	2.0	Check of effect of long duration suction (leak A)
1710	Nine rods in circle at 0.7 m	111.4	2.4	Check for effect of different suction pattern (leak A)
2210	Standard pattern 0.5 m displaced, actual measurement only the 5 central rods used	95.6	13.8	Check for mispositioning of standard suction pattern (leak A) (no GC measurement)
2410	Standard conf (other leak closed). Nb conc fluctuated ca 10% and peaked around sampling	84.8	1.8	Standard suction measurement of leak A followed by check leak A closed and leak B physically closed. Inc carpet probe measurement (8 x 0 ppm, 1 x 6 ppm)
2810	Control measurement with only 4 outside rods. Remark: after measurement the leak was closed and 24h later central rod sampled: 0.2% CH4 in sample during 1h!	7.2	0.2	Check for background around leak A (all leaks closed)
3110	Standard conf., reduced suction	108.2	4.7	Check for effect of reduced suction (leak A)
0611	Standard conf., reduced suction repeat measurement	98.6	4.4	Check of repeatability of measurement with reduced suction (leak A)
2204	Standard conf, fixed flow	88.6	2.0	Reference test with fixed flow (50 L/s) and new methane monitor

Table 2 Summary of measurement results (for standard configuration see Figure 29.(annex IV)

3.3 Analysis

In the next paragraphs the potential sources of error are listed. Conclusions are presented in 3.3.4.

3.3.1 Systematic errors

Systematic errors are the effects unaccounted for that compromise the accuracy of the measurement. The following potential sources of systematic error are identified:

1. Leakage between point of measurement of injected gas flow and leakage point in the soil. This would cause less gas to be extracted than assumed to be injected.
2. Methane content of the injected gas. The source of the gas is bottles of > 99.5% purity non-odorized methane.
3. Non-equilibrium between suction and injection. Before the actual measurement of the amount of leakage is taken, equilibrium between suction and injection must be established. Equilibrium is only reached asymptotically and the time constant depends on the amount of gas present in the soil and the amount of suction applied (see annex II).
4. Methane content of the extracted gas. The flow meter of the suction is calibrated with air. The methane content of the mixture causes an error (< 0.2% relative, see annex I).
5. Long and medium term drift of the sensors. The zero point of the flow and methane concentration measurement equipment is checked before and after each test and found to be negligible.

Any leakage between the tip of the suction rod and the suction flow measurement point will only be external air, due to the underpressure of the tubing and manifold. Therefore it has no effect on the calculated total amount of extracted methane.

3.3.2 Uncertainty

The measurement uncertainty is due to three main sources:

1. Uncertainty of the actual leak flow. The flow is measured using a mass flow controller (see annex)
2. Uncertainty of the methane concentration. The methane concentration is measured using a gas chromatograph (see annex I)
3. Uncertainty of the suction flow. The total suction flow is measured using a mass flow controller (see annex I)

For all instruments a calibration curve is available. The cited accuracy is treated a random uncertainty and assumed to include the effect of temperature, variations in gas mixture (e.g. humidity) and other influences.

3.3.3 Impact of external conditions (weather)

The impact of external conditions is potentially twofold:

1. The flow resistance of the soil changes. As the leakage is pressure controlled this influences the leakage flow
2. The flow pattern changes, due to changes in ground water level and local saturation. On a somewhat larger time scale bacterial activity can block the gas flow locally and can even convert some methane in not measure carbon dioxide. This possibly influences the amount of not-extracted gas.

3.3.4 Discussion

During the suction procedure carpet probe measurements at the surface above the leaks and connection lines were occasionally performed. They showed no methane emission (<10 ppm), from which it is concluded that systematic error 1 (as listed in 3.3.1) is negligible at nominal suction.

The errors 2 and 4 contribute at most about 1% systematic uncertainty. For the systematic error 3 (non-equilibrium condition) there is no direct assessment, but simulations (see annex) indicate the possibility of an effect of more than 10%. Systematic drift of the instrumentation (error 5) is excluded.
Ad 3.3.2: The formulas used for calculation of the random uncertainty are well known and conventional (see annex I). These are used to obtain the uncertainties given in table 2. They are much smaller than the observed errors.
Ad 3.3.3: The injected volume of gas is measured during the suctions tests. No variation in flow that correlated with actions (e.g. starting or stopping the suction, hammering the tubes in the soil, walking around the site) were observed, beside some incidental changes in pressure setting of the pressure regulators. This was random and apparently due to vibration and movement of the mechanical regulators. These changes were minor (<5%) and occurred only in the preparation phase of the measurement.

The major source of systematic error, and the one that can explain a measurement that is too high in the order of 10 – 20%, is that the suction process did not yet reach its equilibrium at the end of the test (after 5 – 6 h). This possibility is further confirmed by simulation (see annex).

It is observed that the error decreases during the months over which the test are taken. This is not fully explained, but could be due to the fact that the duration of gas injection prior to the actual test did vary per test, so the size of the 'gas reservoir' was not the same at the start of the various suction operations.

Based on this experience is it recommended to include in the test protocol a check to ensure that gas at a larger distances from the leak (between 3 – 5 m) is indeed removed.

Although it is plausible that the slow approach to equilibrium condition was the main cause of systematic error in these experiments, the tests do not prove the absence of other sources of systematic error. Further testing using a impermeably closed container with soil could give a more definitive proof.

4 Campaign analysis

4.1 Dutch data set

In the previous decades Kiwa has undertaken several small measurement campaigns with suction measurements on behalf of Netbeheer Nederland. These measurements are partly the basis for the estimate of average leak flow rate (as currently used as emission factor for the various types of .leak in the reported methane emission[1]).

This is a dataset of 67 suction measurements, on nominal gas pressures between 30 mbar to 8 bar and various pipeline materials. Additionally concentration measurements with carpet probe are available. Generally no information of pipeline diameter or cause of the leak is available. Also location, soil and weather conditions are not directly available, although possibly to be retrieved when archived data sources are consulted.

As simple analysis provides the average leak flow rate of the various materials at the pressure stages of the Dutch network. As the number of measurements is very limited the standard deviation of the set of measurements can only be used as a rough indication of the uncertainty in the average leak flow rate.

It appears that the standard deviation is about as large as the average. As a rule of thumb this suggests that about 20 measurements would be required to achieve an relative uncertainty of +/- 25% (with a relatively low confidence level of ca 0.8) in the estimate of the average leak flow rate.

See Annex III for some more detailed analysis of how many measurements would be required to obtain a typical uncertainty, using a hypothetical leak flow rate distribution.

Nom.Pressure/Material	#	Avg (dm^3_n/h)	Stdev (dm^3_n/h)
30 mbar	**18**	**123**	**128**
AC	1	205	-
GCI	14	110	140
Nod. CI	3	161	67
70 mbar	**1**	**46**	**-**
GCI	1	46	-
100 mbar	**29**	**60**	**116**
AC	2	142	87
GCI	11	28	36
HPE	1	231	-
PE	2	49	69
u-PVC	4	172	275
m- PVC	6	15	12
Steell	3	19	11
1 bar	**2**	**16**	**22**
Nod CI	1	0	-
Nod CI (300mm)	1	31	-
3 bar	**3**	**28**	**20**
PE 63	1	49	-
PE80	2	17	11

[1] See e.g.: Methaanemissie door gasdistributie 2018 Netbeheer Nederland

4 bar	**6**	**263**	**341**
Nod CI	1	6	-
PE	3	268	367
PE 80	1	713	-
Steel	1	58	-
8 bar	**8**	**451**	**730**
Nod CI	1	581	-
PE100	1	0	-
Steel	6	504	836

Table 3 Analysis of data set suction measurements. Leak size in dm^3_n/h methane. 'Stdev' is the sample standard deviation.

4.2 General data sets

The analysis in annex III is valid for any European data set that is to be collected. And the results of the Dutch dataset might set a realistic expectation for the variability of leaks flow rates that occur.
Without introducing some physical and mechanical context it is fairly useless to speculate about the distribution of leak flow rates in a particular network. At least one should try and make a separation between various leak categories by cause (such as leak in a joint, corrosion or point load). The purpose of such a split is to provide a statistically homogeneous dataset for each of the various types of leaks. This would allow for a more smart combination of data from various networks and thus potentially improves the statistical uncertainty.
With sufficient empirical verification one could argue that the average leak flow rate is proportional to the (nominal) overpressure to a power of 0.5 or 1 (or a value in between). This would then allow to classify measurements of various pressures into the same category and to obtain a smaller confidence interval than using the separate data sets.

4.3 Measurement campaign advice

Based on the experience with the current experiments, the Dutch data set of suction measurement and the analysis presented in annex III, the following recommendations are given:

- Use the suction measurement according to protocol (annex II) to quantify the methane emission of selected leaks
- The protocol must include removal of gas in a wide area around leak
- Expect to need about 20 quantitative leak measurements for each subcategory of leak type, in order to expect an accuracy in average leak flow rate estimate of 25%

Considering the large variation in expected leak flow rates and the relative small contribution of the uncertainty of the individual suction measurement, further development of the suction method (although welcome) is not urgently required. A more direct way of improving the accuracy of the estimate of the amount of fugitive methane emission from buried gas distribution pipelines is to extend the dataset of suction measurements.

As the above recommendations implies a significant effort, it is advised to implement a continuous measurement program, gradually covering all situations and gradually reducing the statistical uncertainties.
An additional advantage of a continuous program is that any change in the leak population (e.g. due to the aging of the network) is monitored and will become apparent. Also the attention to certain subclasses of leak types can be prioritized as warranted by intermediate results and for optimizing the measurement program. Analysis of the intermediate results should be part of the continuous program.

5 Conclusions

5.1 Measurements

The uncertainty of the suction method is to be separated in a random and in a systematic component.

The random component consists of the uncertainties in the suction flow measurement and the concentration measurement and possibly intrinsic random variation of leakage during the measurement. Based on the specification of the equipment used and the calibration, the random uncertainty is estimated to be less than +/- 5%.

The systematic uncertainty is dominant. An important source of systematic error is stopping the suction before equilibrium is reached. Simulations, extrapolation of measurement time series and comparison with known leakage suggest possible systematic errors in the order of 10% – 20%.

From the measurements no indication of influence of weather and soil condition could be seen. Obviously, winter conditions with frozen soil are expected to compromise the measurement, but such condition were not part of this measurement program and are rather easily recognized and thus avoided in practice.

The measurement protocol has proven to be workable in its original form, although in hindsight a better control of the removal of gas in the soil at larger distance from the leak site appears to be required in order to reduce (the chance of) systematic error. The protocol (annex II) is adapted in this respect. With this protocol the suction method is fit for its purpose.

5.2 Dutch leak data set

It appears that the standard deviation of the leak flow rate in the population of all leaks is about as large as the average. As a rule of thumb this suggests that about 20 measurements would be required to achieve a relative uncertainty of +/- 25% (with a relatively low confidence level of ca 0.8) in the estimate of the average leak flow rate.

5.3 Campaign advice

With regard to a measurement campaign the following recommendations are given:

- Use the suction measurement method according to protocol (annex II) to quantify the methane emission of selected leaks;
- The protocol must include removal of gas in a wide area around leak;
- Expect to need about 20 quantitative leak measurements for each subcategory of leak type, in order to expect an accuracy in average leak size estimate of 25%.

As the statistical uncertainty due to the variance of leaks flow rates in the field is (much) larger than the uncertainty of the suction measurement, further development of the suction method is not urgently required. The suction measurement with a strict protocol to remove gas at larger distances from the leak is fit for purpose. A direct way of improving the accuracy of the estimate of the amount of fugitive methane emission from buried gas distribution pipelines is to increase the number of suction measurements.

The suction method is inherently a relatively time consuming and thus expensive measurement. This precludes its application to all of the detected fugitive leaks. A cost/benefit analysis could be used to determine the optimum number of leaks to be quantified, if more information on the variance in flow rate becomes available.

It is advised to implement a continuous measurement program, gradually covering all situations and gradually reducing the statistical uncertainties.
An additional advantage of a continuous program is that any change in the leak population (e.g. due to the aging of the network) is monitored and will become apparent. Also the attention to certain subclasses of leak types can be prioritized as warranted by intermediate results and for optimizing the measurement program .
Analysis of the intermediate results should be part of the continuous program..

6 References

Cornelia, B. (2000). Retrieved from diffusion_in_porous_media__111209.pdf: http://www.fhi-berlin.mpg.de/acnew/department/pages/teaching/pages/teaching__wintersemester__2011_2012/cornelia_breitkopf__diffusion_in_porous_media__111209.pdf

Lee, P. M. (2004). *Bayesian Statistics 3rd ed.* New York: Arnold.

WG_ME. (2019). *Assessment of methane emissions for Gas Transmission & Distribution System Operators.* Brussels: Marcogaz.

I. Calibration

Methane concentration (Gas chromatograph)

The GC used for the analysis of the gas is checked regularly and part of the calibration program of the chemical lab of Kiwa Technology.
The GC is calibrated using certified calibration gas mixture (example NG858: 0.8979 +/- 0.0045 mol% methane in air).
Correction for deviation of absolute pressure from reference conditions (1013.25 mbar) is applied.

For a mixture of 1 mol% methane in air a relative uncertainty of 1.3% is quoted (Bert Gerritsen personal communication 15 Oct 2019)

Suction flow (MFC)
F-106AI Mass Flow Meter
Model Key : F-106AZ-RAD-01-V
Productserie : IN-FLOW
Medium : Air (Lucht)
Range : 0.4...20 m3n/h
Accuracy : ±1% full scale (at calibration conditions)

Methane injection (MFC)
Each leak is monitored by a mass flow controller.
The specification of the two MFC's is as follows:

MFC A
Model key : FG-201CV-RAD-22-V-DA-000
Serial number: M19213219A
Productserie : EL-FLOW Prestige
Medium : Mix: 81.3% CH4 (Methaan) + 2.87% C2H6 (Ethaan) +
0.39% C3H8 (Propane) + 0.16% C4H10 #1 (Butane) +
0.05% C5H12 #3 (Pentane) + 14.33% N2 (Stikstof) + 0.01%
O2 (Zuurstof) + 0.89% CO2 (Koolstof dioxide)
(mol %)
Range : 0.004...0.2 m3n/h mixture = 0.005…0.2481 m3n/h methane
Accuracy : ±(0.5% of measureant plus 0.1% v.d. full scale)(at calibration conditions)
Calibration certificate : 3-points calibratioin

The conversion factor from this gas mixture to pure methane is calculated using the conversion tool "Fluidat" provided by the manufacturer.

The full scale for pure methane of this MFC is 0.2481 m3n/h.

MFC B
Model key : FG-201CV-RAD-22-V-DA-000
Serial number: M19213219B
Productserie : EL-FLOW Prestige
Medium : H2 (hydrogen)
Range: 0.012...0.6 m3n/h h2 = 0.010…0.527 m3n/h methane
Accuracy : ±(0.5% of measureant plus 0.1% v.d. full scale)(at calibration conditions)
Calibration certificate : 3-points calibratioin

The full scale for pure methane of this MFC is 0.527 m3n/h.

For both MFCs the sensitivity for temperature and pressure is specified as zero:
< 0,02% FS/°C; span: < 0,025% Rd/°C and < 0,15% Rd/bar typical N2; with pressure correction: < 0,02% Rd typical N2

Formulas used for uncertainty estimation.
The relative accuracy A of a measurement is expressed as the ratio between the difference of the measured emission minus the applied injection divided by the applied injection:

$$A = \frac{Q_{suction}\ C_{methane}}{Q_{leak}} - 1$$

Therefore the uncertainty in the relative accuracy δA is related to the uncertainty in the primary measurements $\delta Q_{suction}$, $\delta C_{methane}$ and δQ_{leak} as:

$$\left(\frac{\delta A}{A+1}\right)^2 = \left(\frac{\delta Q_{suction}}{Q_{suction}}\right)^2 + \left(\frac{\delta Q_{leak}}{Q_{leak}}\right)^2 + \left(\frac{\delta C_{methane}}{C_{methane}}\right)^2$$

According to the information from the calibration, we take the uncertainties as:

$$\delta C_{methane} = 0.013\ C_{methane,rd}$$

$$\delta Q_{suction} = 0.01\ Q_{suction,fs} = 0.2\ m_n^3/h$$

$$\delta Q_{leak} = 0.005\ Q_{leak,rd} + 0.001\ Q_{leak,fs}$$

Where:

For MFC A: $Q_{leak,fs} = 0.2\ m^3{}_{nCH4}/h$
For MFC B: $Q_{leak,fs} = 0.8\ m^3{}_{nCH4}/h$

Note: the suction flow measurement is based on the calibration of air. No correction is made for the methane content. This introduces a systematic error. According to the manufacturer the relative error at 1 vol% methane is 0.2%, due to the different thermal properties of methane versus air.

Sand.
The grain size distribution of the sand used in the experiments is specified in the two reports below.

KREMER ZAND EN GRIND

Winning "De Beetse"

Beetserwijk 10 9551VN Sellingen tel. 0599-324201 fax. 0599-324471

Korrelgrootte verdeling zeefmethode EN 933-1

Openings-grootte zeef	Massa achtergebleven materiaal	Percentage achtergebleven materiaal	Cumulatief % achtergebleven materiaal	Cumulatief % doorgelaten materiaal
2 mm	0	0,00	0	100
1,4 mm	0	0,00	0	100
1 mm	0,3	0,22	0	100
710 µm	0,7	0,52	1	99
500 µm	2,1	1,55	2	98
355 µm	5,1	3,77	6	94
250 µm	14,3	10,57	17	83
180 µm	33,2	24,54	41	59
125 µm	63	46,56	88	12
90 µm	11,1	8,20	96	4
53 µm	5	3,70	100	0
Pan	0,5	0,37	100	0

Methode : wassen en zeven

Product : 0/1

Recept nr : vulzand depot

fm : 1,07

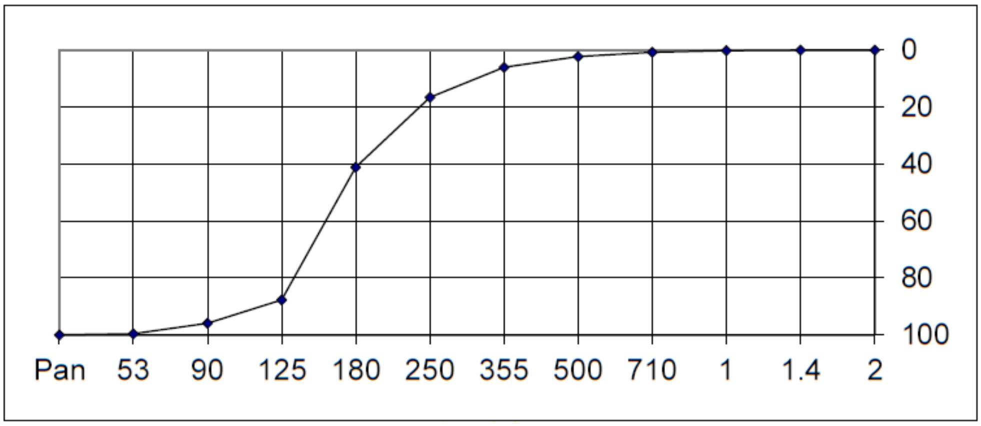
Datum : 05-nov-18

Analist : B.Meems

Perc. fijn : 2,7

Humuszuur :

Grafiek van de zeef resten op de zeef



Percentage fijn materiaal (f) dat door de 63 µm-zeef gaat = $\frac{(M_1 - M_2) + P}{M_1}$ x 100 = 2,7

Figure 10 Specification of the batch of 150 um grained sand

KREMER ZAND EN GRIND

Winning "De Beetse"

Beetserwijk 10 9551VN Sellingen tel. 0599-324201 fax. 0599-324471

Korrelgrootte verdeling zeefmethode EN 933-1

Openings-grootte zeef	Massa achtergebleven materiaal	Percentage achtergebleven materiaal	Cumulatief % achtergebleven materiaal	Cumulatief % doorgelaten materiaal
4 mm	0	0,00	0	100
2,8 mm	0	0,00	0	100
2 mm	0	0,00	0	100
1 mm	0	0,00	0	100
500 µm	1,3	0,82	1	99
250 µm	67,5	42,72	44	56
125 µm	86,6	54,81	98	2
63 µm	2,5	1,58	100	0
Pan	0,1	0,06	100	0

Methode : droog zeven

Product : M3c zand

Recept nr : cycldepot

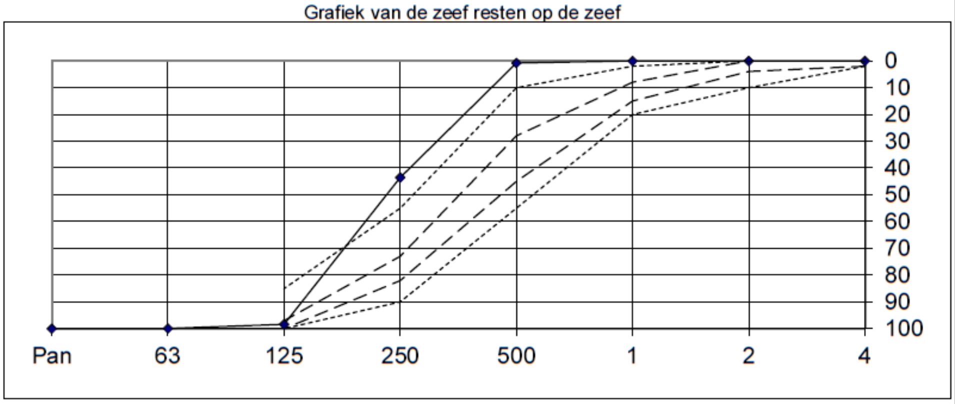
fm : 1,43

datum : 26-mrt-19

Analist : B.Meems

opm

Grafiek van de zeef resten op de zeef



zeef openingsgrootte

Figure 11 Specification of the 200 μm grained sand

Soil cone resistance test.
At 25 February Fugro B.V has performed a set of 11 manual sounding tests in the neighborhood of the leaks on the premises of the Kiwa test site. One of the 11 soundings did not return useful results, due to instability of the soil. In two soundings (nr 4 and 9) very small soil resistance was encountered in the top 1½ m of the soil. Debris in the soil was found in tests nr 3, 6, 7, 8 and 10, resulting in gaps in de measure profiles as the debris has to be removed to allow the deeper sounding to proceed.

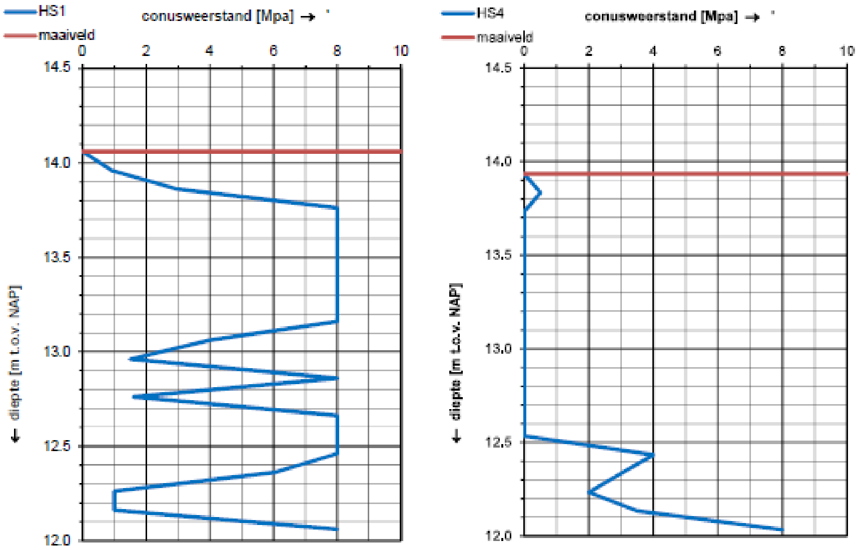


Figure 12 Typical cone resistance measurement (2 out of 10 available tests)

The soil was found to be variably compacted in layers. Resistance varied between 0 – 8 MPa as measured using a cone size of 1 cm^2.

Reference: Kiwa NL Monitoring terrein Apeldoorn, Rapportage Grondonderzoek Fugro Report 1420-162976, 3-3-2020

II. Simulation by particle diffusion

In a typical suction measurement, gas/air mixture is extracted from to soil at a constant rate until an equilibrium concentration is perceived to be reached. The value at the end of the suction process is used in the estimate of the leak rate. Some reasonable choice must be made, weighing the cost and duration of the measurement against a further reduction of error. There is some concern that a long tail of slowly decreasing gas concentration occurs during the extraction process, and that this masks, to the eyes of the experimenters, the real, lower equilibrium.
In order to study the potential influence of a large reservoir of leaked gas around the leak that is being sampled in the course of the suction process, a numerical simulation was performed.
The simulation comprises a three-dimensional, time dependent simulation of gas flowing in a infinite disk of soil of 2 m thickness.
The leak is a point source of 0.108 m^3/h in the centre of the disc at a depth of 0.8 m.
The leaks fills the initially gas-free soil during 10 days (240 h). After this period the suction starts, using one suction tube near the leak and four tubes around the leak (see figure). The suction points are located at 0.5 m depth and each tube evacuates 0.22 m^3/h.

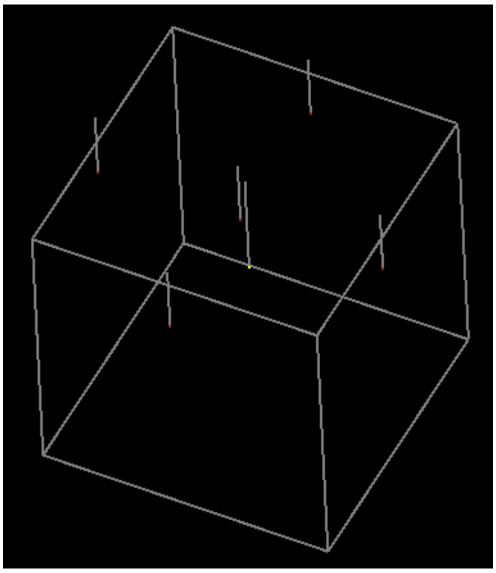


Figure 13 Schematic drawing of the location of the leak (0.8m depth, yellow dot) and the five suction points (0.5 m depth, red dots). The box is 2m x 2m x 2m (l x w x h) The box and vertical white lines are for reference only.

Assuming a zero flow boundary condition at the bottom of the domain (the 'ground water table'), and a zero pressure at the top of the domain (the surface), incompressible flow and a uniform porous soil, the average streamlines can readily be calculated, using a set of positive and negative point sources, at suitably reflected positions with regard to the upper and lower domain boundaries that induces a potential (Darcy) flow. Additional to that deterministic flow, diffusion is simulated with a random walk Monte Carlo process of test particles, each representing a small volume of gas (typically 10^{-4} m^3).

As diffusion coefficient is taken the value of dilute methane in air. A correction is made for the effects of porosity and tortuosity of the soil. Typically the effective diffusion D_{eff} is calculated as:

$$D_{eff} = \frac{\epsilon}{\tau} D$$

Where ε is the porosity and τ the tortuosity. Both depend on the shape and sizes of the grains in the soil. For a porous bed of approximately spherical particles $\varepsilon = 0.416$ and $\tau = 1.56$, D = 0.21 10^{-4} m/s^2 (Cornelia, 2000). This implies that the effective diffusion is about one quarter of the diffusion of the gas in air.

Distribution of gas in soil

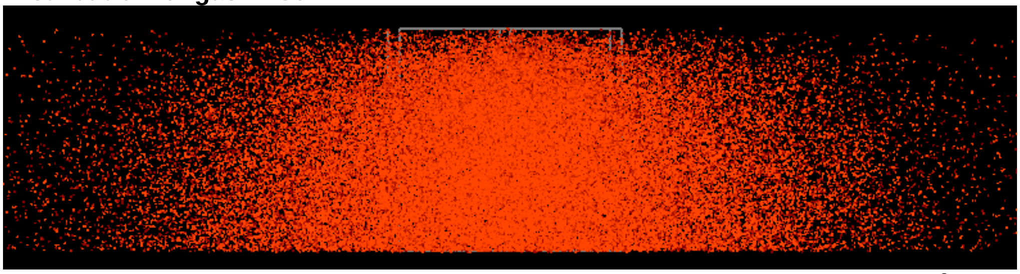


Figure 14 Distribution of gas in soil after 192 h continuous injection of 0.108 m^3/h. Side view of simulation of ca 92.000 particles. Box size is 2 m x 2 m x 2 m.

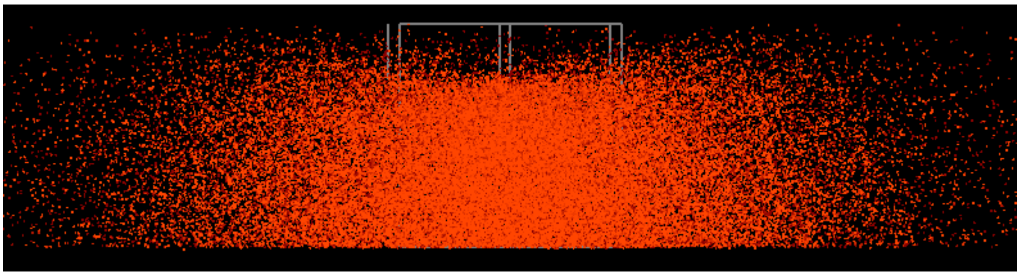


Figure 15 Distribution of gas in soil 0.5 h after start of suction (5 x 2.88 m^3/h)

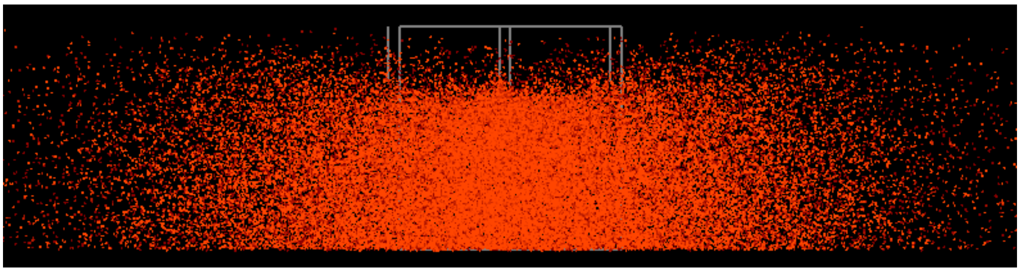


Figure 16 Distribution of gas in soil 1 h after start of suction (5 x 2.88 m^3/h)

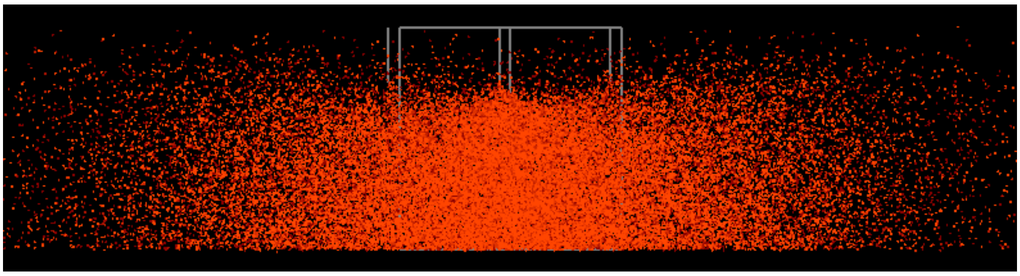


Figure 17 Distribution of gas in soil 2 h after start of suction (5 x 2.88 m^3/h)

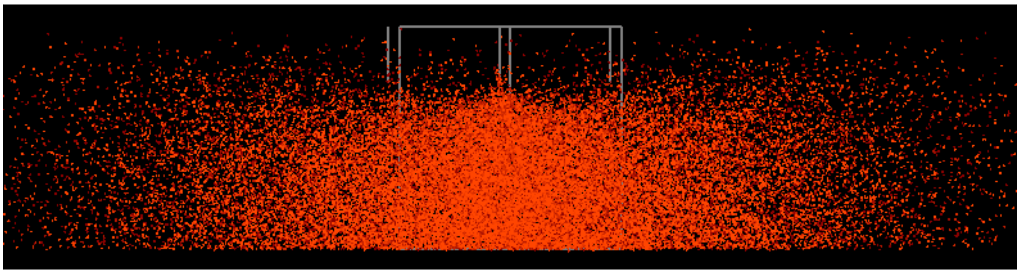


Figure 18 Distribution of gas in soil 3 h after start of suction (5 x 2.88 m^3/h)

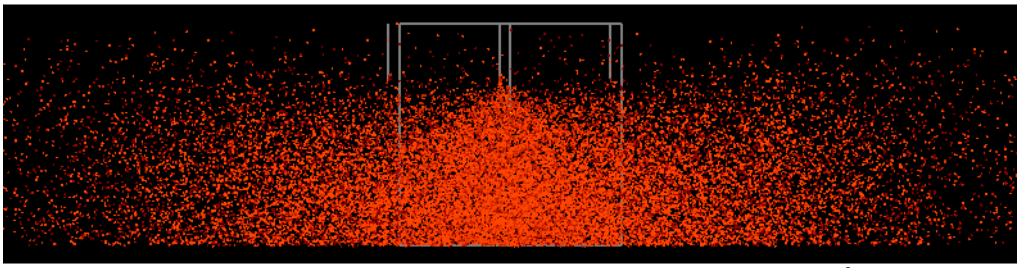


Figure 19 Distribution of gas in soil 6 h after start of suction (5 x 2.88 m^3/h)

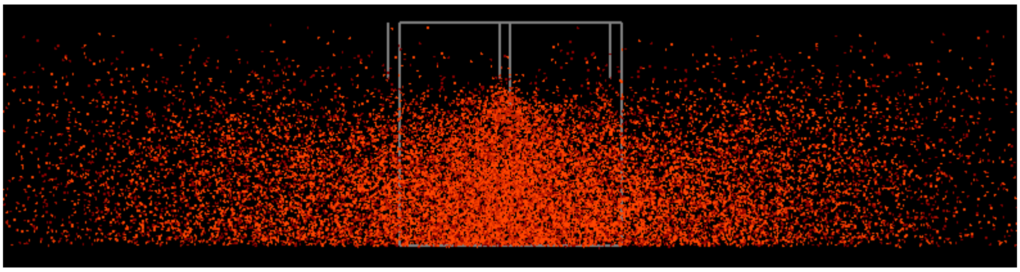


Figure 20 Distribution of gas in soil 9 h after start of suction (5 x 2.88 m^3/h)

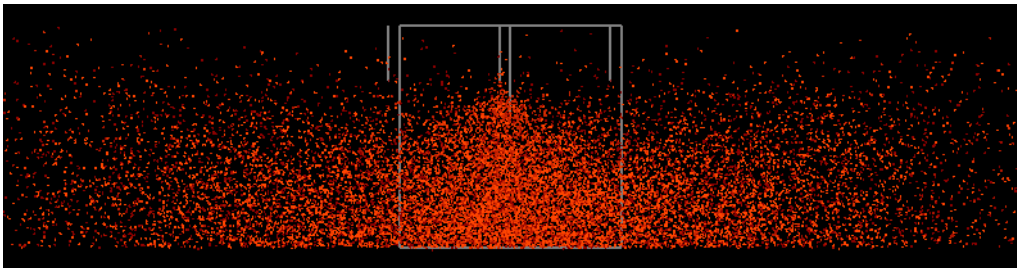


Figure 21 Distribution of gas in soil 12 h after start of suction (5 x 2.88 m^3/h)

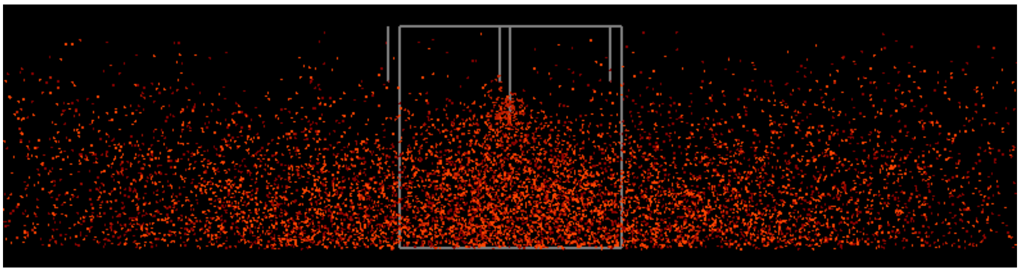


Figure 22 Distribution of gas in soil 21 h after start of suction (5 x 2.88 m^3/h)

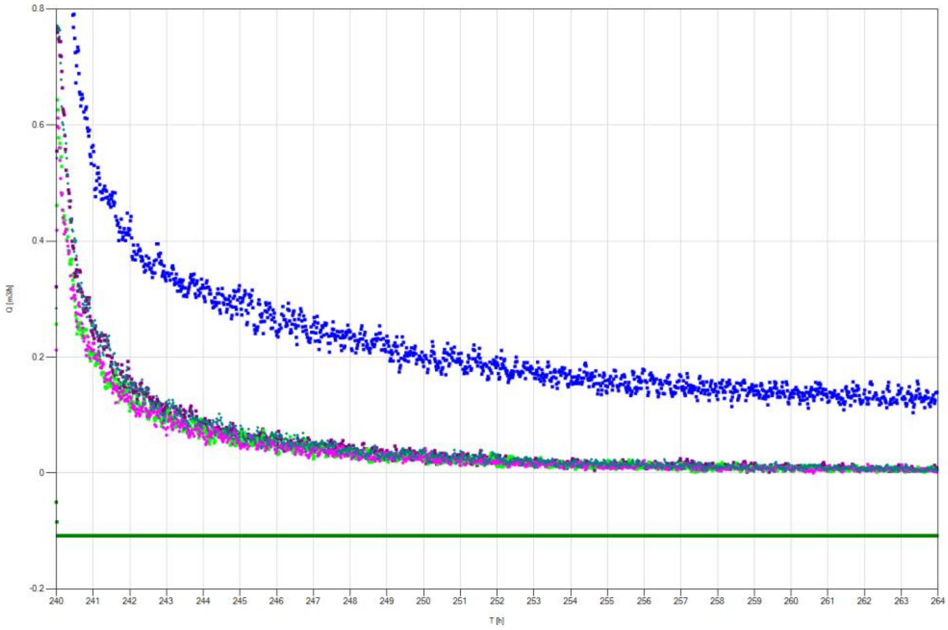


Figure 23 Injected gas flow (green line) and evacuated gas flow (blue and 4 other coloured markers). At equilibrium the sum of the blue + purple + violet + light green + sea green emission is equal to the negative value of the green line. A approximately 40% accuracy appears to be reached after about 24 h (see also next figure).
Note T=0 h is start of injection (leak), T = 240 h is start of suction. Simulation ends at T=264 h.

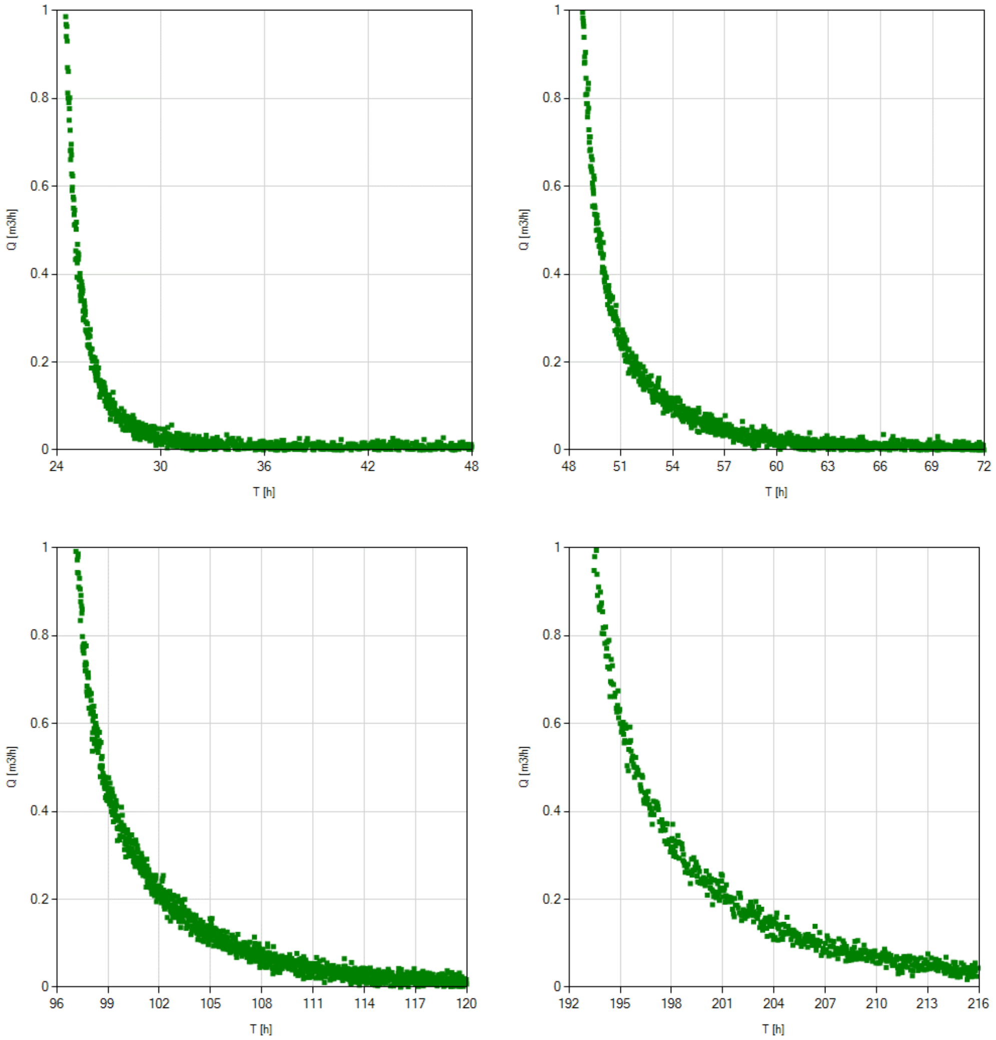


Figure 24 Imbalance between injection and suction (same scale as previous figure, but filtered over 5 minutes). Injection time before suction start: 24 h, 48 h, 96 h and 192 h.

Conclusion.
For the condition of the calculation, it appears that in this model even after a suction period of 24 h there is still a significant imbalance between injected and evacuated gas flow. The imbalance depends on the duration of injection before the suction starts and is apparently due to the reservoir of gas in the soil created during the injection period. In the case of an injection period of 8 days (192h) the imbalance after 24 h of total suction of 14.4 m^3/h is still approximately 0.04 m^3/h. This is 40% of the injection (0.108 m^3/h)

III. Sample size

Two sources of uncertainty are of relevance for the determination of the average leak flow rate (WG_ME, 2019). These are:

- the uncertainty of the leak flow rate measurement itself
- the (unknown) distribution of the leak flow rates in the field.

Both uncertainties can be broken up in multiple parts. For the leak flow rate distribution in the field one would preferably distinguish between leaks of various causes, materials, diameters, gas pressure and environmental conditions (e.g. soil grain size, moisture content). The relevant assumption is that the set of leak data are a statistically homogenous group a data. Establishing and proving statistically homogeneity, however, is a challenge in itself and is not addressed here.

The uncertainty in average leak flow rate is reduced by increasing the number of independent samples. In principle, with the exclusion of the effect of systematic errors, the uncertainty in the average leak flow rate reduces, when a sufficient large number of samples is available, with the square root of the number of samples taken.

The detailed strategy of collecting an optimal variety of samples is the topic of phase 2 of the project. But to indicate the magnitude of this task we include in this annex some calculations of distributions and sample sizes with the associated uncertainty.

In these examples the measurement uncertainty is set to zero and only the effect of the shape and width of the distribution of leak flow rates is taken in consideration. With a non-zero measurement uncertainty the total uncertainty in the average leaks size is always larger.

Method.
A distribution of leak flow rates is specified. (e.g. a lognormal distribution with an average of 1 kg_{CO2eq}/h and a standard deviation of 50%).
A specified, relatively small amount, of samples (e.g. 10) is taken randomly from this distribution and their average is calculated. This procedure is repeated a large number of times (e.g. 100000)[2]. This set of averages is in itself another distribution, of which the statistical properties (e.g. mean, median and 5percentile bounds) are taken. These properties reflect the uncertainty in experimental determination of the average leak flow rate using a given sample size and assuming a given leak flow rate distribution.

This is a theoretical exercise. If we knew the leak flow rate distribution there would be no need to perform measurements in the first place. If we would have physical and theoretical reasons to assume a certain family of distributions (e.g. lognormal), we could try a best fit of the parameters of this family (mean and standard deviation) to the measurements and reconstruct the expected mean leak flow rate. This would introduce additional uncertainty. For such a procedure the paradigm of Bayesian Statistics. (Lee, 2004) provides a suitable framework.

Example 1. Lognormal distribution (unimodal)
As leaks typically have only positive outflow, it make sense to assume a distribution with a positive support (0, +∞) only. A suitable distribution is a lognormal distribution. In this example we assume a lognormal distribution of a mean of 1 kg_{CO2eq}/h and a relative standard deviation of 50%. The PDF and CDF of this distribution are shown in the figure below.

[2] A similar method is also suggested in the annex of the Marcogaz report (WG_ME, 2019)

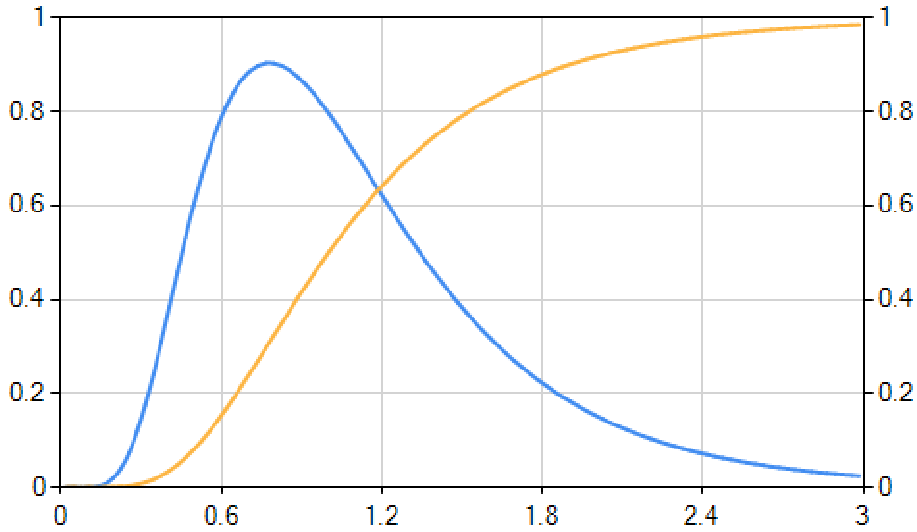


Figure 25 Assumed probability density function (blue) and cumulative distribution function of leak flow rates in a particular, statistically homogeneous set of leaks. Horizontals scale in kg/h.

Using this distribution the uncertainties in the estimate of the leak flow rate (which is 1.13 kg/h) for various samples sizes is given in the table below.

#Samples	1	3	10	30
<Average>	1.13	1.13	1.13	1.13
<Median>	1.00	1.08	1.12	1.13
<-5perc>	0.44	0.66	0.85	0.96
<+5perc>	2.28	1.78	1.47	1.32

Table 4. Statistics of the estimate of average leaks flow rate in kg_{CO2eq}/h using #Samples, assuming the leak flow rate distribution of Figure 25 and 1 000 000 trials.

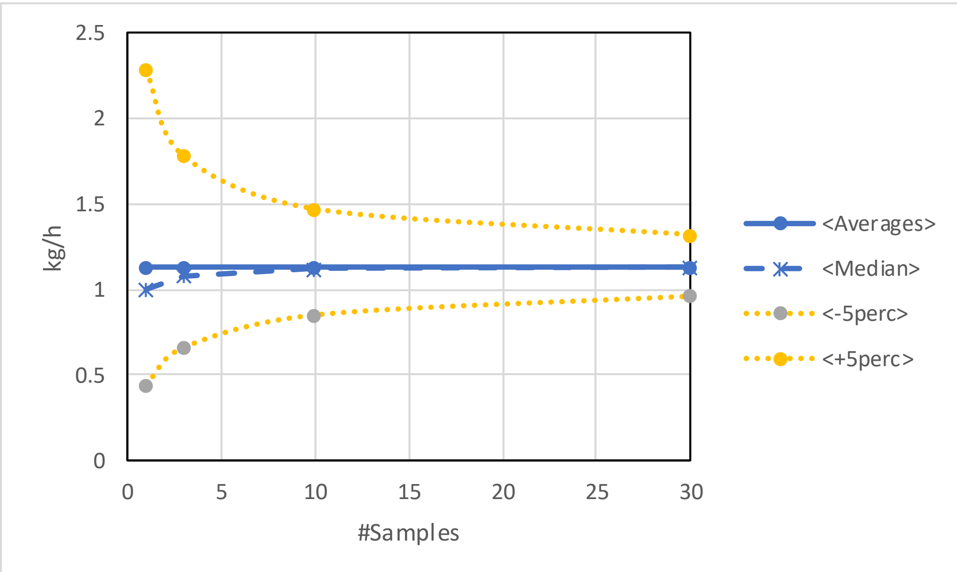


Figure 26 Statistics of the estimate of average leaks flow rate using #Samples, assuming the leak flow rate distribution of Figure 25.

The table and figure show that, with this assumed distribution, there are approximately 30 samples needed to obtain an estimate of the average leak flow rate with an uncertainty of about 15% and a confidence level of 90%.

Example 2. Sum of two lognormal distributions (bimodal)
Usually unimodal distributions are used and they are often intuitively preferred for reason of simplicity ('Occam razor').
Nevertheless, if there is more than a single physical mechanism that produces leaks, multi modal distributions become plausible. One can e.g. consider leaks due to corrosion and leaks at joints due to soil movement. A specific distribution can be associated with each cause (and there can exist some interaction too).
We therefore introduce an example where 80% of the, typically smaller, leaks follow one, relatively wide, lognormal distribution and 20%, typically larger leaks, follow another more narrow lognormal distribution (see figure),

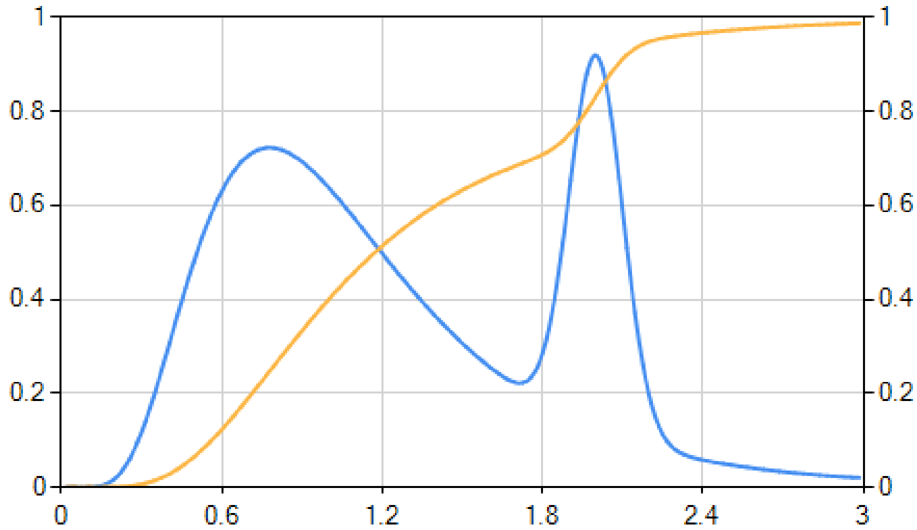


Figure 27 Assumed probability density function (blue) and cumulative distribution function leak flow rates in a particular statistically homogeneous set of leaks.

Using this distribution the uncertainties in the estimate of the leak flow rate (which is 1.31 kg/h) for various sample sizes as given in the table below.

#Samples	1	3	10	30
<Averages>	1.31	1.31	1.31	1.31
<Median>	1.17	1.28	1.30	1.30
<-5perc>	0.46	0.74	0.99	1.12
<+5perc>	2.20	1.95	1.65	1.50

Table 5 Estimates of the statistics for average leaks flow rate using #Samples, assuming the leaks flow rate distribution of Figure 27 and 1 000 000 trials.

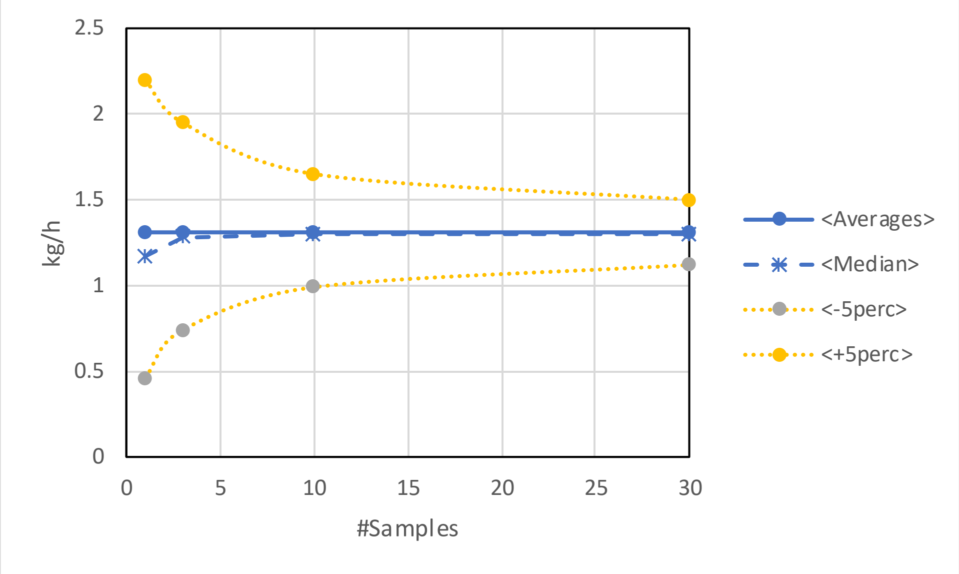


Figure 28 Statistics of the estimate of average leaks flow rate using #Samples, assuming the leak flow rate distribution of Figure 27.

The table and figure show that, with this assumed distribution, there are approximately 30 samples needed to obtain an estimate of the average leak flow rate with an uncertainty of about 20% and a confidence level of 90%. Because of the additional leak cause that introduces, on the average, larger leaks, obviously the average leak flow rate increases and also the estimate of the average leak flow rate increases. Also the uncertainty increases, compared to the previous example.

Cost benefit analysis.
There is as yet no direct financial incentive to report lower methane emission, so any financial cost benefit analysis is slightly arbitrary. However, here we sketch a possible quantified approach.

Assume:

- The cost per reported estimated emitted kg $_{CO2eq}$ is 0.02 €/kg.
- Estimation has to be reported with a 95percentile uncertainty interval.
- A single reference measurement costs 2000 €
- The leak emergence rate of a pipeline (of a given category) is 0.01 km/y
- The total length of that particular category pipeline is 5000 km.
- The occurring leak flow rates are distributed according Figure 27 and we may use figure 26 to assess the uncertainties that are due to the spread of the distribution and the uncertainty in the reference measurements
- A leak survey costs 50 €/km
- There is no explicit cost of lost methane

If 5 reference measurements are available, we have to base our reporting on the assumption that the average leak flow rate is 1.8 kg/h. If 10 reference measurement are available we are allowed to use a value of 1.6 kg/h.

If we perform a leak survey once every 5 yr, we expect to locate 250 leaks. We assume that we are allowed to calculate with 50% of that number as the average number of leaks present on average of the last 5 years. So we report 125 leaks

If we perform a leak survey once every 2 yr, we expect to locate 100 leaks. We assume that we are allowed to calculate with 50% of that number as the average number of leaks present average of the last 2 years. So we report 50 leaks.

A comparison of the costs of the 4 options (5 or 10 reference measurements, 2 or 5 year interval leak survey) is shown in the table below.

Option	Cost ref meas [€]	Cost survey [€/y]	Cost emission [€/y]	Payback time [yr]
5 ref meas + 5 yr interval	€ 10,000	€ 50,000	€ 39,420	
10 ref meas + 5 yr interval	€ 20,000	€ 50,000	€ 35,040	
Difference	€ 10,000	€ 0	-€ 4,380	2.28
5 ref meas + 2 yr interval	€ 10,000	€ 125,000	€ 15,768	
10 ref meas + 2 yr interval	€ 20,000	€ 125,000	€ 14,016	
Difference	€ 10,000	€ 0	-€ 1,752	5.71

Table 6 Calculate payback time for (additional) reference measurements

It is perhaps worth pointing out that leak repair costs are independent of which option is chosen. Leak emergence is always the same and each leak that occurs has to be repaired sooner or later.
Another observation is, that (when not calculating with NPV, net present value), any expenses in reference measurements are eventually profitable.
Finally, obviously, the payback time of any expenses for reference measurement is inverse proportional to the average flow rate of the leak and the number of leaks actually occurring.

IV. Proposed measurement protocol

Equipment.
The complete list of equipment needed for field measurements is:
1. Suction rod
2. Flexible tubing
3. Header with valves
4. Filter
5. Flow measurement device incl. read-out
6. Methane concentration monitor incl. read-out
7. Suction pump
8. Manometer (underpressure)

(Minimum) auxiliary equipment is:
1 Hammer
2 Measuring tape
3 Sample bags
4 Calibration gas (1% methane in dry air)
5 Calibration gas (10% methane in dry air)
6

Conditions
- The location of the leak (xy) must be known within reasonable tolerance (better than 0.3 m)
- The location of the leak (z) must be known with reasonable certainty to be between 0.3 and 1 m below surface
- The source of the leakage must be known beyond reasonable doubt to be a specific gas pipeline
- The soil must be sufficiently dry to avoid clogging of the suction tubes, tubing and filter
- The methane concentration of the gas in the pipeline must be known or determined

Procedure

Set up
1. Suction tubes
   a. The suction tubes are pressed or hammered into the soil to a depth of 50 cm (see indicator ring around the tube)
   b. The default pattern is shown in the figure below. The central tube is positioned on top of the leak

   Note for Kiwa site: variations on the default pattern are part of the experiments

   Note: If possible, check for the presence of gas in the soil at larger distance (2 – 5 m) around the leak location. If such gas is present, additional suction tubes at larger distances around the leak location are recommended for use in the initial phase of suction in order to reduce the time needed to reach a equilibrium between suction an leakage.

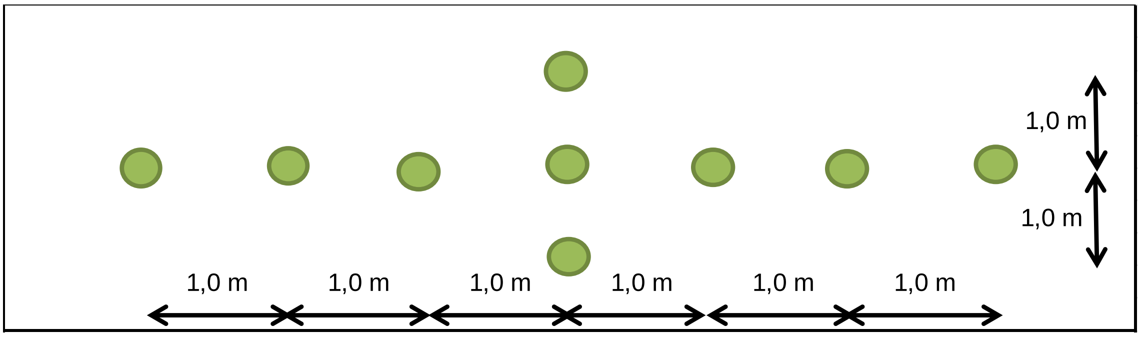


Figure 29 Schematic drawing of the pattern of suction locations. The central rod is located on top of the leak..

2. Header. All suction tubes are to be connected individually to the central header. Connect the header to the suction pump using a single line.
3. Suction pump. The suction pump has an input filter. Check for the presence of moisture in the filter and remove water and droplets before starting the pump (check again and remove any water direct after the measurements).
4. Flow meter. Connect the outlet of the suction pump to the inlet of the flow meter. Also connect the electronic control/read out-unit to the flow meter. The read-out is in $m^3{}_n$/h (air).
5. Gas concentration monitor. Use the side branch of the T-joint to connect the outlet of the flow meter to the inlet of the gas (methane) concentration monitor.
   Note for Kiwa: The use mode of the Irwin Inficon gas concentration monitor is the setting “bovengronds lekzoeken”.
6. Suction blow off. Connect the main branch of the T-joint to the blow off pipe.

Measurement process

1. Take a photo of the measurement site, showing the configuration of the suction tubes.
2. For this, the box containing the mass flow controllers need to be opened. Wear an operational personal methane detector when doing this.
   For Kiwa site only: close the supply to the other leaks.
3. Disconnect the line between the suction pump and the flow meter and connect it to the blow-of. Start the pump and check during 5 minutes that no water collects in the lines between the suction rods and the pump and in the filter. If all remains dry then reconnect the line, otherwise postpone the measurement (and inform the project leader / customer)
4. Start the pump. Check all connections for (audible) suction of external air.
5. Check if data logging is operational (computer program running), and mark the start time in the report
6. Mark the flow and concentration every 15 minutes.
7. For Kiwa site only: close each of the valves of the suction tubes on the header one by one. If the total leak flow (concentration x flow) increases, keep the valve closed, otherwise reopen it. Do this until the flow becomes too small (< 6 m^3/h).
   Remark: the methane concentration will start to decrease. The reading of the Irwin methane meter is problematic. It will be 3 figures when below 1000 ppm. Above 1000 ppm it switches to a reading in percent, using a resolution of 0.1 %. This resolution is hardly sufficient to discern a decreasing trend.
8. Start doing, after three hours and if the gas concentration is between 0.1 and 0.9 vol%, the following actions every 15 minutes:
   - Register the values of flow and concentration at full suction capacity.
   - Throttle the flow using the slider on the header to 1 m^3/h and wait 2 minutes
   - Register the flow and concentration in this situation.
   - Reopen the slider to nominal (full) suction capacity.

9. Terminate the measurement when over three consecutive readings (1/2 hour) show less than 5% relative decrease in methane suction flow.
10. Fill a sample bag directly after the last reading. Deliver the bag to the lab for analysis by GC.
11. Tidy up the site. Remove all plastic carpets on and around the leak site. .
12. For Kiwa site only: Reopen any closed other leaks (if relevant).
13. Store the measurement data on file/disk (and backup)

Additional notes for field situation[3]

1. It is assumed that the leak has previously been identified and located during the DSO's leak survey. Therefore typically some drilling holes are already in place for leaks in an urban environment (pavement, street, etc.). Also the DSO is responsible for providing barriers and warning sings to secure the measurement site.
2. At arrival at the site of the leak a quick leak survey is to be performed along the existing holes and in the area specified by the DSO with standard leak survey equipment (bell or carpet probe with semiconductor or FID concentration measurement) to make sure that there is (still) a leak indication on the surface (sometimes leaks cannot be found anymore, as a period of time has elapsed between the leak survey and the date of the measurement).
3. Concentration readings from the drilling holes via FID are then taken and documented. The pipeline documentation is checked for an understanding of the (supposed) location of the pipeline. Drilling holes are added to left and right of the pipeline (existing ones from locating tasks are usually only on top of the pipeline) to generate a symmetric field of probes. For this the holes with most significant concentrations are chosen as central area. It is checked that sufficient area is covered by using further holes in all directions to prove that at some distances no more (relevant) concentration can be found.
4. If the leak is located in the vicinity of a house service connection add probes in that direction, as it is typically unclear if the leak actually stems from the distribution line or service line. Drilling holes are usually in the depth of 30 – 50 cm, depending on the laying depth of the gas pipes and presence other infrastructure such as electricity cables, water pipes and fiber cables.
5. When placing the probes make sure to seal the annular gap between probe and hole as much as possible. According to German experience O-rings are suitable on concrete/pavement. If the leak is located below a grass/soil/field it is sufficient to just compact the excavated material from the drilling around the probe.
6. Document the starting concentrations of all probes before coupling the suction pumps (not the measurement case yet as parts of it are not EX-secure), then start the suction.
7. After a couple of minutes check all probes for underpressure and concentration individually using the "quick-release couplings on the top of the probes. Check for congestions if one or more probes don't show any underpressure. It may happen that the air flow resistance at some location is to high due to soil conditions (especially if very inhomogeneous soil is present, which is typical for old pipes buried after WW2) – then very little or no methane concentration will be observed for long time. In this case these probes can be relocated or removed as no leaking gas will escape via these paths.
8. From time to time the overall concentration in the accumulation hose is measured. When the concentration here is below 2.5 % the measurement logging is started and the measurement software will provide a timeline of methane leak rates t0 be used to check if the stable state has been reached.
9. Continue with the suction and periodical checking underpressure and concentration from the probes individually and deciding whether to remove

[3] Derived from notes from Stefan Gollanek, describing German experience.

probes with none or very low concentrations while underpressure is available. Through this procedure the probing field around the actual centre of the leak can be decreased, as the original centre might well not be where the highest concentration has originally been observed! Also, by removing probes on the outskirts of the measurement field that show no more (or only marginal) concentrations most of our suction power is used for the area of soil that is still (partly) saturated by methane. Using an initially larger area speeds up the time it takes to create an area free of gas that has escaped the leak in the past around the actual leak[4].

10. When the overall concentration measurement is stable for a longer period of time (this is not exactly defined, but the rate of concentration change should typically be pretty small for at least half an hour to an hour or so), check the surface within the measurement area for any gas concentrations via carpet/bell probe again. This proves that all the gas leaking from the pipe finds its way through the suction device and none escapes to the surface. If this check is ok, the actual measurement taken as the average value of concentration (and suction flow) over a period of roughly five minutes.
11. The typical volume flow during suction is about 20 m^3/h and the FID is calibrated for 100 ppm of Methane, as this is the typical measurement range for leaks.

This completes the description of the German procedure. It is also recommended to check other details, depending on the situation (e.g. introduction of water to the air flow, weather conditions etc.). In their experience the reduction of gas concentration (gas suction rate) that is seen in the measurement equipment is very rarely “smooth” in time. Often step like changes are observed over time. It is also quite common, that in the beginning leak rates remain rather stable on a high level and only at some point rates start decreasing. It is speculated that this happens due to (sometimes extensive) “lakes” of natural gas forming right underneath the surface if it is mostly air tight, thus forcing the gas to creep along the sealed barrier. When the suction is started, this “lake” is emptied first and a rather continuous flow of natural gas is delivered to the probes from this reservoir.

Results and uncertainty

Results should be reported in kg_{CH4}/y (WG_ME, 2019) for each leak measurement separately.
Uncertainty should be explicitly stated and preferable based on 1 s (63% confidence interval).

Set-up

[4] This is different from the protocol used in the suction experiments in this report.

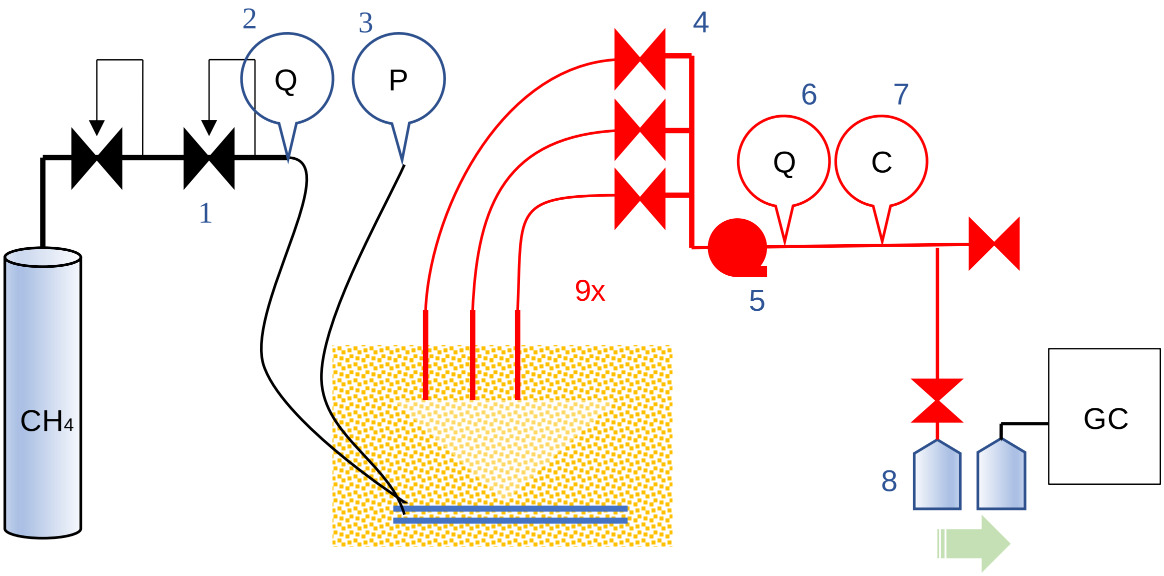


Figure 30 Layout of the installation and test equipment. Red parts are components of the suction measurement

1	pressure regulator (ca 100 mbar)
2	methane flow measurement
3	leak pressure measurement
4	manifold with valves
5	suction pump (ca 10 m^3/h)
6	air methane mixture flow measurement
7	methane concentration measurement
8	sample bag for off line concentration measurement

V. Historic Dutch suction measurements dataset

Nr	Jaar	Materiaal	Drukklasse	Concentratie max. (ppm)	Lekgrootte (l/h)	Id	Comment
1	2005	PVC	100 mbar	150	11.2	2005-1	150 ppm
2	2005	Staal	8 bar	8000	65.7	2005-2	8000 ppm
3	2005	PVC	100 mbar	800	94.6	2005-3	800 ppm
4	2005	Staal	100 mbar	1000	14.9	2005-4	1000 ppm
5	2005	GGY	100 mbar	150	8.5	2005-5	150 ppm
6	2005	GGY	100 mbar	1000	4.6	2005-6	1000 ppm
7	2005	PVC	100 mbar	-	580.2	2005-7	- ppm
8	2005	PVC	100 mbar	-	1.6	2005-8	- ppm
9	2005	Staal	100 mbar	3000	32.1	2005-9	3000 ppm
10	2005	Staal	100 mbar	-	10.9	2005-10	- ppm
11	2005	Staal	8 bar	300000	460.9	2005-11	300000 ppm
12	2005	Staal	8 bar	400000	104.6	2005-12	400000 ppm
13	2005	Staal	4 bar	15000	58.4	2005-13	15000 ppm
14	2005	GGY	30 mbar	800	170	2005-14	800 ppm
15	2005	GGY	30 mbar	3000	15.9	2005-15	3000 ppm
16	2005	GGY	30 mbar	1000	169.3	2005-16	1000 ppm
17	2005	HPE	100 mbar	300	231.4	2005-17	300 ppm
18	2005	PE	4 bar	100	690.1	2005-18	100 ppm
19	2005	PE	4 bar	500	22.1	2005-19	500 ppm
20	2005	PE	4 bar	60	91.4	2005-20	60 ppm
21	2005	GGY	70 mbar	1000	46.1	2005-21	1000 ppm
22	2005	GGY	30 mbar	3000	350.2	2005-22	3000 ppm
23	2005	Nod. GY	30 mbar	800	230.5	2005-23	800 ppm
24	2005	Nod. GY	30 mbar	100	156.7	2005-24	100 ppm
25	2005	Nod. GY	30 mbar	800	96.1	2005-25	800 ppm
26	2006	GGY	30 mbar	1800	167	2006-26	1800 ppm
27	2006	GGY	30 mbar	740	10	2006-27	740 ppm
28	2006	GGY	30 mbar	350	18	2006-28	350 ppm
29	2006	GGY	30 mbar	780	9	2006-29	780 ppm
30	2006	GGY	30 mbar	130	452	2006-30	130 ppm
31	2006	GGY	30 mbar	370	48	2006-31	370 ppm
32	2006	GGY	30 mbar	5600	31	2006-32	5600 ppm
33	2006	GGY	30 mbar	180	15	2006-33	180 ppm
34	2006	GGY	30 mbar	6700	72	2006-34	6700 ppm
35	2006	GGY	30 mbar	240	7	2006-35	240 ppm
36	2006	GGY	100 mbar	2500	24	2006-36	2500 ppm
37	2006	GGY	100 mbar	10000	32	2006-37	10000 ppm
38	2006	GGY	100 mbar	1560	9	2006-38	1560 ppm
39	2006	GGY	100 mbar	1300	15	2006-39	1300 ppm
40	2006	GGY	100 mbar	1300	4.5	2006-40	1300 ppm
41	2006	GGY	100 mbar	1000	12	2006-41	1000 ppm
42	2006	GGY	100 mbar	15000	117	2006-42	15000 ppm
43	2006	GGY	100 mbar	15000	76	2006-43	15000 ppm
44	2006	GGY	100 mbar	460	4	2006-44	460 ppm
45	2006	Slagvast PVC	100 mbar	3400	13	2006-45	3400 ppm
46	2006	Slagvast PVC	100 mbar	150	6	2006-46	150 ppm
47	2006	Slagvast PVC	100 mbar	7700	35	2006-47	7700 ppm
48	2006	Slagvast PVC	100 mbar	9100	20	2006-48	9100 ppm
49	2006	Slagvast PVC	100 mbar	1220	3	2006-49	1220 ppm
50	2006	Slagvast PVC	100 mbar	700	10	2006-50	700 ppm
51	2014	AC	100mbar	114	80.6	2014-51	114 ppm
52	2014	AC	100mbar	170	203.9	2014-52	170 ppm
53	2014	PE	100mbar	50	98.5	2014-53	50 ppm
54	2014	AC	30mbar	150	205.1	2014-54	150 ppm
55	2014	Staal	8 bar	Tussen 600 en 700	2179.5	2014-55	Tussen 600
56	2014	PE	100 mbar	300	0.3	2014-56	300 ppm
57	2014	Staal	8 bar	100	0	2014-57	100 ppm
58	2014	Nod GY	8 bar	80	581	2014-58	80 ppm
59	2014	Nod GY (300mm)	1 bar	240000	31.1	2014-59	240000 ppm
60	2014	PE80	3 bar	800	24.9	2014-60	800 ppm
61	2014	PE100	8 bar	50	0	2014-61	50 ppm
62	2014	PE80	3 bar	44	9.4	2014-62	44 ppm
63	2014	Nod GY	1 bar	Tussen 150 en 250	0.2	2014-63	Tussen 150
64	2014	PE 63	3 bar	7000	48.8	2014-64	7000 ppm
65	2014	PE 80	4 bar	700	712.6	2014-65	700 ppm
66	2014	Staal	8 bar	1600	215.9	2014-66	1600 ppm
67	2014	Nod GY	4 bar	7000	6.1	2014-67	7000 ppm