CATO-2 Deliverable WP 3.6-D04
Development of an atmospheric pipeline monitoring strategy

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1 Executive Summary (restricted)

In the safety study included in the Environmental Effects Report (MER) of the Barendrecht CO_2 storage site it is concluded that monitoring of a stretch of the transport pipeline located in the vicinity of vulnerable objects is desirable from the perspective of safety management. This would also show that public concerns regarding safety issues are taken into consideration seriously. Therefore, a simulation study is performed that examines the feasibility of the detection of small leaks by means of the simultaneous monitoring of:

- atmospheric CO_2 concentrations at a distance of some tens of meters from the pipeline,
- local wind direction and
- wind-force.

Points of leakage would be detected by correlating the CO_2 concentrations that would be caused by a leak with the actually observed concentrations. If a correlation exists, a leak may be present and the location applies for inspection. The study concludes that there is sufficient cause to perform a field test of the method.

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Document Change Record

(this section shows the historical versions, with a short description of the updates)

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2 Applicable/Reference documents and Abbreviations

2.1 Applicable Documents

(Applicable Documents, including their version, are documents that are the “legal” basis to the work performed)

	Title	**Doc nr**	**Version date**
AD-01	Beschikking (Subsidieverlening CATO-2 programma verplichtingnummer 1-6843	ET/ED/9078040	2009.07.09
AD-02	Consortium Agreement	CATO-2-CA	2009.09.07
AD-03	Program Plan	CATO2-WP0.A-D.03	2009.09.29

2.2 Reference Documents

(Reference Documents are referred to in the document)

	Title	**Doc nr**	**Issue/version**	**date**
	Veiligheidsanalyse Ondergrondse Opslag van CO_2 in Barendrecht, revisie 4, Tebodin, 2008	3800784	4	2008.10.20

2.3 Abbreviations

(this refers to abbreviations used in this document)

ppm	Parts per million, by volume

3 Introduction

The safety of long-term CO_2 storage is, without any doubt, a very important issue of this technique for society. In other studies, much attention is given to the geological stability of the location, geophysical monitoring techniques and the monitoring and inspection of the injection locations. Evaluation of the safety of the transport from the production site to the storage, however, is not trivial either. Although the potential total mass that may be emitted is much smaller than the potential total emission form the storage itself, the local effects of a breakout may be considerable, especially in the vicinity of residential areas, schools, sports fields etc.

This is made clear in the safety analysis that is included in the Environmental Effect Report (MER)[1] of the Barendrecht carbon storage facility. In this report, risk analyses are performed for several scenarios in connection with the failure of the pipeline, the compressors at the injection location, the injection duct and the injection well. Scenarios exist in which the 5% concentration level (below which no acute danger is supposed to be present) extends over 50 m from the location of the failure. Among those is the evaluation of a total severance of the pipeline at an underground stretch. This evaluation concludes that concentrations > 5% can occur exist at distances > 400 m, but, according to the report, almost exclusively at heights > 15 m. The authors state that at ground level dangerous concentrations will exist only within 2 m of a leak.

Apart from the impact of an undesired event, the probability of its occurrence is important. The aforementioned safety study computes location bound risk contours around objects for which an accepted assessment method is available, such as the compressor stations at the source and at the injection location, aboveground stretches of the pipeline and the injection wells. However the method used for the computation of the risk contours is reported not to be designed for underground stretches of a pipeline. A table is included that states the probability of the occurrence of a rupture of an underground stretch ($m^{-1}y^{-1}$), not being part of a pipeline street, to be two orders of magnitude larger than the corresponding probability for a stretch in a pipeline tunnel or pipeline street. The probability of the occurrence a leak in such a stretch is reported to be one order of magnitude larger than the corresponding chance for a stretch in a pipeline tunnel or pipeline street. In other words: the MER study states that there is a very small risk of exposure to dangerous concentrations due to a leak in either the pipeline or the rest of the installation.

Still, preventive measures would be sensible to detect cases in which a leakage starts at a small but detectable size and gradually evolves into an unacceptable situation. The safety report points to external causes / third party interference as the dominant class of causes of pipeline failure (98 … 99%). This still leaves other causes such as welding and assembly faults at a relevant level. Moreover, external causes may result in small damage that gradually deteriorates by corrosion, too. For instance, soil drilling by interested but unauthorized parties, an earth moving machine causing damage subsequently covered up, or a stroke of lightning may all cause this type of failure. Also, local residents and users of office buildings may require that measures be taken to create an early warning in case of an imminent failure – even if they would have been informed that the location bound risk had been assessed to be too small to justify the deployment of such a system.

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[1] Veiligheidsanalyse Ondergrondse Opslag van CO2 in Barendrecht, revisie 4, Tebodin, 2008, document nr 3800784

The goal of the present study is to assess if a method based on atmospheric measurements could fulfil such an early warning function. To that end the system is simulated using various operating conditions. The output of the study is a recommendation whether to proceed or not with a field test.

4 Principle of operation

Low-cost CO_2 concentration sensors are located on both sides of the pipeline, in two parallel rows and at regular distances. At distances of about 1 km simple meteorological sensors are placed that monitor wind speed and wind direction. CO_2 concentrations, wind speed and wind direction are recorded over a period of time. In a computer program a grid of imagined source locations is created that covers the pipeline and the adjacent ground strips. The software places a virtual CO_2 source at one of the grid points and computes the virtual CO_2 concentration it would have created at the adjacent sensors for every point of time within the recording period. The correlation is computed between the real concentrations and the virtual concentrations. This is constantly repeated for every grid point. Grid points that yield a correlation that is raised compared with the surrounding grid points, apply for inspection (e.g. with a hand-held CO_2 monitor). The usage of multiple sensors makes it possible to distinguish sources that are close to the pipeline transect (within 20-30 m) from common sources like a ploughed field, groups of cows, cars or heating systems.

5 Simulation study (proof of principle)

5.1 Design

Before testing the concept in the field, it had to be established that it could work. To that end, a study was set up in which the real CO_2 concentration time series were simulated as well as the virtual CO_2 concentration time series. Both series were obtained using meteo data and CO_2 background concentrations from the Cabauw tall tower (KNMI, Lopik) in January, 1995 and a simple Gaussian plume model. Random noise was added to the real series; noise would also have been present if real sensors would have been used. Because the background concentration would have to be obtained locally (it varies not only in time but also over space) the background concentration was equated to the lowest sensor reading, which differs from the background concentration because of the presence of noise. Correlations were computed for various combinations of source strength, noise amplitude and distance of separation between the real source and the virtual source. Estimations were made of the time needed to detect a source, either by its direct effect on a downwind sensor or by the gradually increasing correlation between the real data and the virtual data on all adjacent sensors.

5.2 Execution

5.2.1 Detectabilty

Five sensors are placed at mutual distances of 100 m, in two rows divided by 100 m. The pipeline – which does not appear as such in the simulation – may be imagined to be located halfway both rows. A source is located at coordinates (0,0) (fig.1).

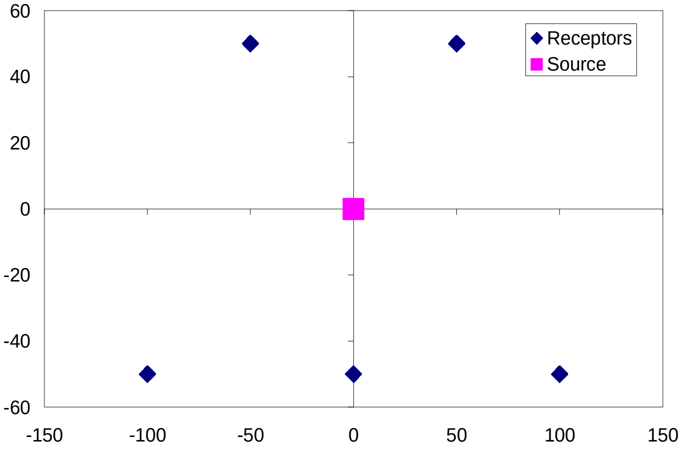

Figure 1 Spatial design of the simulation.

The real dataset was simulated as follows:

1. The background CO_2 time series was obtained from measurements at Cabauw tall tower in January, 1995. The instruments at Cabauw are designed for background concentration levels. Therefore, the Cabauw series is assumed not to contain instrumental noise at a level relevant for this application.
2. Uncorrelated noise (also called “white noise”) is added to the Cabauw series to represent instrument noise. This series is called “background series”.
3. The Gaussian plume model is applied to compute the CO_2 concentration increase at all five sensors caused by the plume using the given source strength and using the Cabauw meteo data. Those five time series are called “model series”.
4. The background series and the model series are added up to obtain the “simulation series”. This represents the five series of CO_2 readings that would be really obtained (figs 2 and 3).

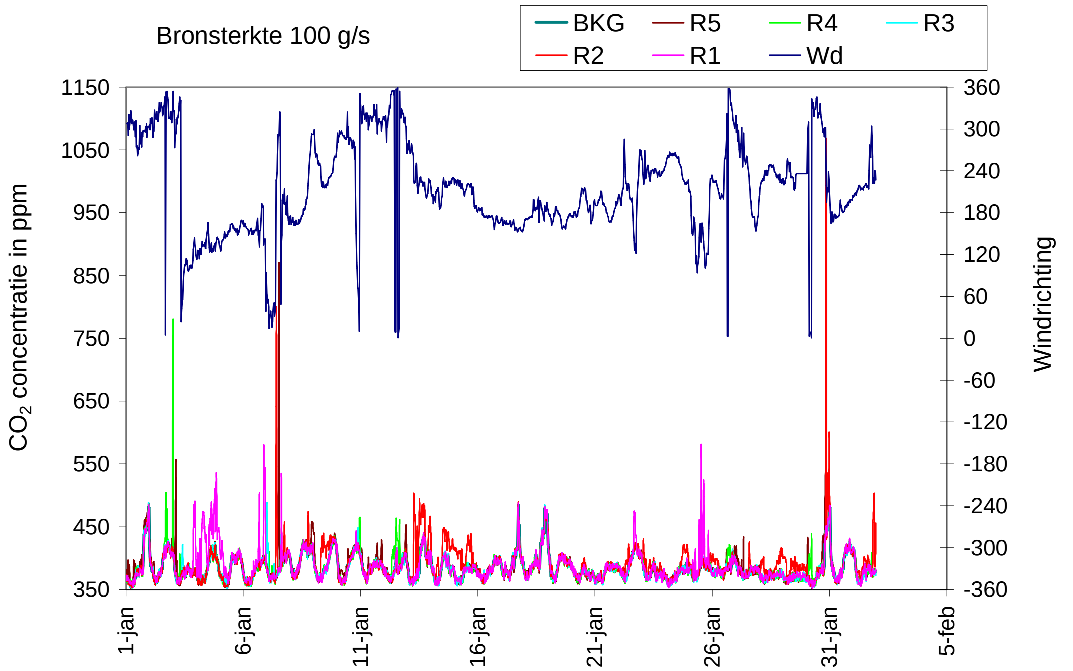

Figure 2 Simulation series with a source of 100 g s^{-1}in the centre of the grid ([0,0]in figure 1). A noise level of 20 ppm was added to the background signal.

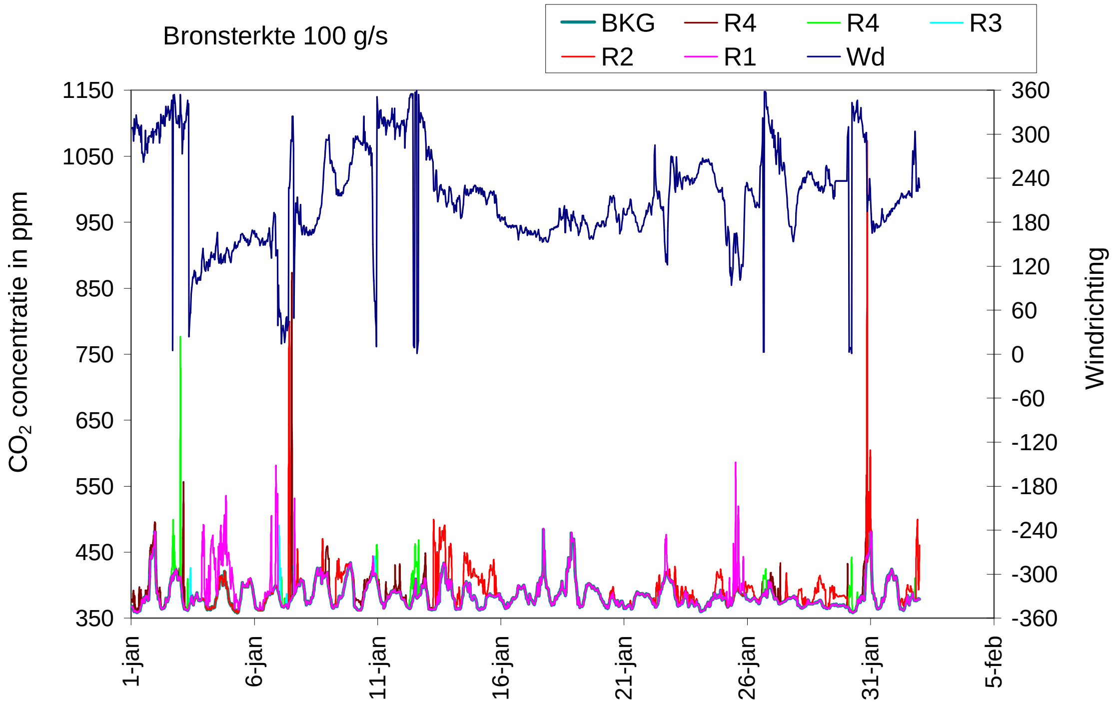

Figure 3 As Figure 2, no noise.

The figures 2 and 3 show the colored peaks in the concentration on top of the background concentration line. The latter shows a typical diurnal pattern with higher concentrations during the night, which are a result of natural CO_2 respiration from the soil in combination with a generally more stable atmosphere (less mixing). In the daytime the enhanced mixing in combination with the uptake of CO_2 by vegetation (even in January) leads to lower concentration levels. The peaks that originate from the 100g/s source clearly stick out on top of the background data. The comparison of figure 2 and 3 shows that even a noise level of 20 ppm (which would be extremely high for the type of instruments that are proposed) would not obscure these peaks.

The correlation is performed as follows:

1. The background concentration level is set to match the lowest reading of the sensors that are upwind relative to the pipeline (provided that this sensor is not in error). This is the “simulation background”.
2. Subtract the simulation background from the simulation series (equivalent to the measurements for a real setup). Five time series remain which are the “analysis series”. Those represent the fingerprint of the real source on the five sensors. This dataset has two sources of noise:
   - The selection of the sensor with the lowest reading to obtain the simulation background. This results in a noise amplitude slightly larger than the input noise amplitude, because of the selection of the minimum value.
   - The noise output by the other four sensors.
3. Compute the response series for the virtual source at a selected grid point and for the nearest sensors – in this study, all five sensors. This is called the “virtual series”. For the purpose of this simulation the source strength used in the model for the virtual emission is not important because it has no effect on the correlation. The virtual series represent the fingerprint of the virtual source that it would cause on the five sensors.
4. Compute the correlation between the analysis series and the virtual series using all five sensors.

		Position of virtual source				
Flow (g s^{-1})	Noise (ppm)	@ real source	10 m east	25 m east	200 m north	Max conc. increase @ any sensor
100	0	1.000	0.875	0.393	0.071	660
100	5	0.996	0.871	0.391	0.071	660
100	10	0.985	0.861	0.388	0.069	660
100	20	0.945	0.827	0.374	0.062	660
10	5	0.731	0.692	0.313	0.054	70
5	5	0.456	0.462	0.215	0.047	30
3	5	0.274	0.301	0.142	0.018	20
2	5	0.152	0.202	0.104	0.004	13
1	5	0.0490	0.1051	0.0388	0.0192	6

Table 1 Correlations (r) as a function of source strength, noise amplitude and displacement of the virtual source relative to the real source.

Results are reported in table 1. The first column indicates the source strength of the model series (based upon the real source at 0,0). The second column represents the noise amplitude a (the noise is uniformly distributed over [-0.5a; +0.5a]). The third column represents correlations between the analysis series and the virtual series if the virtual source coincides with the real source (coordinates 0,0). The fourth and fifth columns represent correlations if the virtual source were displaced by 10 m (coordinates 10,0) and 25 m (coordinates 25,0) along the pipeline to the east. The sixth column represents correlations if the virtual source is displaced 200 m to the north (coordinates 0,200), a position that lies north of the northern row of sensors.

If no noise is present and the virtual source coincides with the real source, the correlation equals 1 by definition. A source of 100 g s^{-1} is detectable even in the presence of 20 ppm noise, which is unrealistically high for modern instruments. A source of 3 g s^{-1} is detectable but the correlation remains at the same level if the virtual source is displaced by 10 m, which implies that an inspection should cover an area of ~ 100 m^2 to find the source. When the model source location is displaced by 25 m as compared to the true source location, the correlation for this source strength is clearly significantly lower. This implies that the method will be able to determine the source location within 10 or 20 m from the actual location. Virtual sources outside the area between the two rows of sensors never cause any correlation between the analysis series and the virtual series, because they would mostly give a virtual response on two detectors at once or on none of the detectors at all.

5.2.2 Speed of response

In the next simulation a source of 100 g s^{-1} was switched on 50 times during the interval of used meteo data, at random points in time. The real source and the virtual source coincide in all cases. In 35 cases the correlation sharply increased within 6 h. In one case it lasted 110 h. A histogram is presented in fig 4, a typical response in fig 5.

In fig 6 it is shown why it may take some time before detection will take place, and why even a correlation that is already at an increased level because a source was switched on, may temporarily vanish. The source is switched on at the start and the correlation rapidly rises to about 1.0. After ~16 days the wind turns south. The plume becomes located between the two northern sensors, and is detected by none of those. At that moment the correlation plummets until the wind shifts to a different direction. This is also visible in fig. 3: between January 16 and 21, all sensors give the same readings.

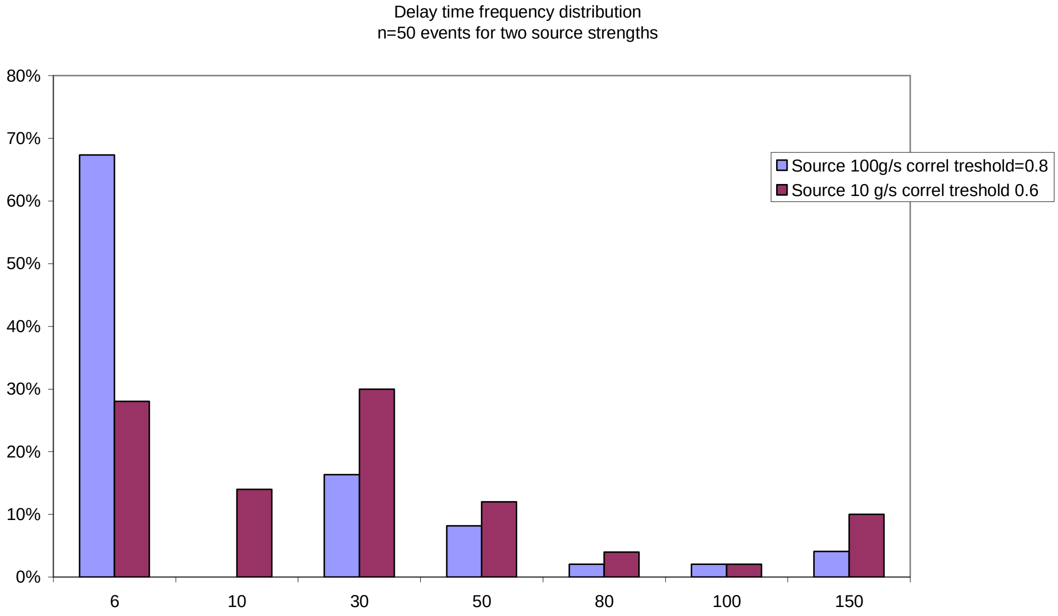

*Figure 4 Histogram of delay times before a source of 10 or 100 g s^{-1} is detected (at a noise amplitude 5 ppm) and a 100*100 m detector grid (fig 1) .*

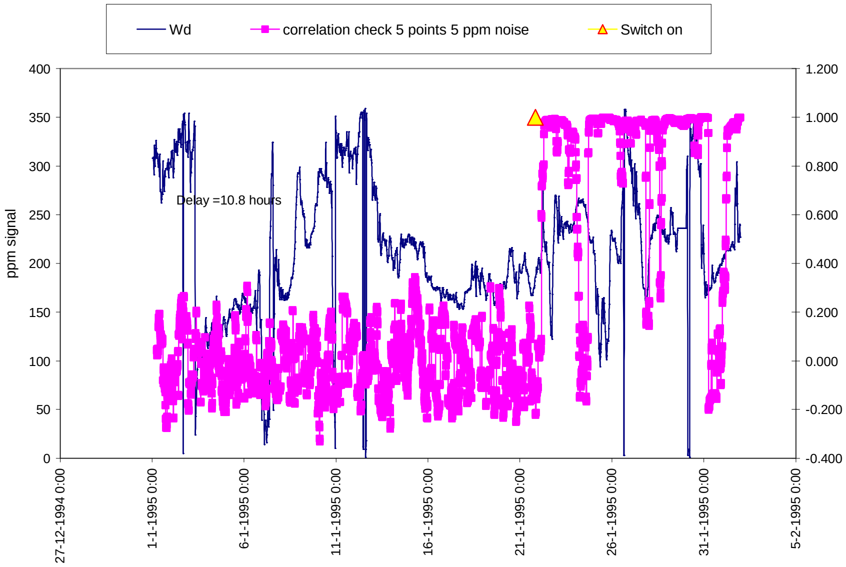

Figure 5 Effect of switching on a source of 100 g s^{-1}, noise amplitude 5 ppm.

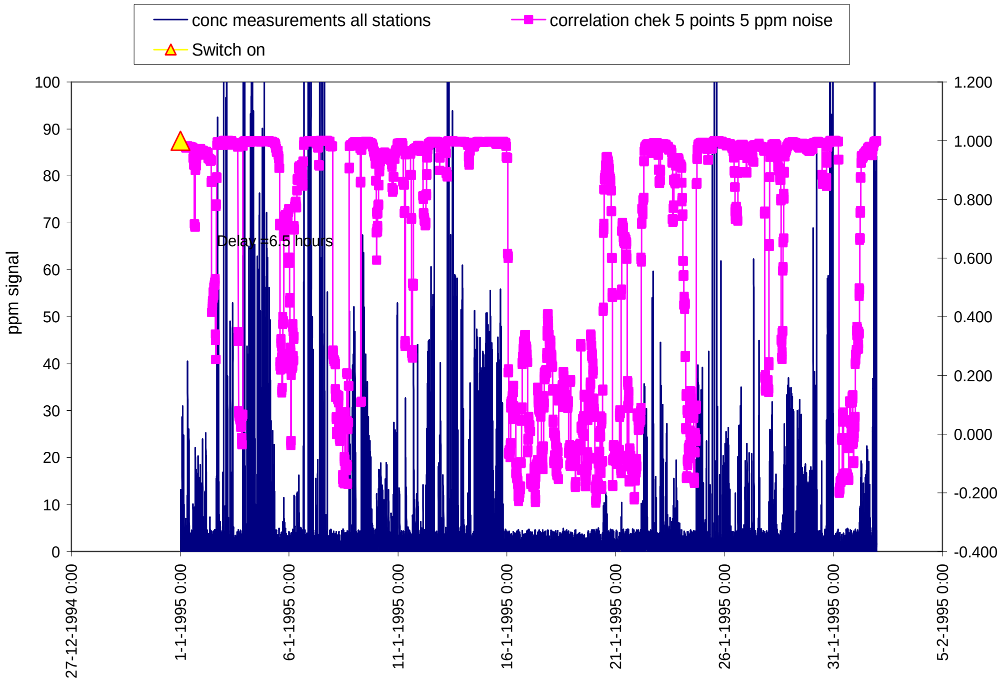

Figure 6 Effect of an extended period of unfavourable wind direction.

6 Conclusions

6.1 Power of detection

We did not try to evaluate whether correlations are statistically significant. We only judged if the correlation of a virtual source that coincides with the real source can be discriminated from the correlation of a virtual source that is at a different location. A source of 3 g s^{-1} with a noise amplitude of 5 ppm yields a correlation < 0.3. If the virtual source is shifted 25 m along the pipeline, the correlation drops to a value that is appreciably smaller. This leads to the conclusion that under these conditions the source may be detected and located within 10 to 20 m.

6.2 Speed of detection

In a sample of 50 cases in which a leak of 10 g s^{-1} was randomly switched on, it was detected within 6 h in 30% of the cases. For a bigger leak (100g/s) this level increases to 70%. A "beginning" 10 g/sec leak would be detected within max 150 hours. A leak of this magnitude leads to a maximum concentration of 550 ppm at 100m distance (480 ppm background + 70 ppm from the source). This seems to be satisfactory under the assumption that the speed at which such a leak would deteriorate would be much longer.

If the wind direction persistently locates the plume between two sensors or straight along the pipeline, detection may be delayed for a prolonged time (in fact this leads to the maximum of 150 hour delay time mentioned above). The probability of this condition may be decreased only at the cost of increasing the detection threshold (moving the rows of sensors away from the pipeline) or cost (using more sensors per unit pipeline stretch). Placing some sensors close to the pipeline could also help but would increase the detection threshold for leaks in their close vicinity because for such locations the number of available sensors would effectively be decreased by one.

6.3 Validity of the model

A simple Gaussian plume model is used which is designed for usage in a non disturbed wind field and for the dispersion of trace constituents that do not change the properties of the medium. Conditions may exist under which this model is not valid. For this exercise however the model is considered sufficiently accurate. More complex models require a lot more input data both in terms of terrain characteristics and meteorology.

6.3.1 Disturbance of the wind field by large objects

In the vicinity of a large object such as an apartment building or an elevated road the wind field could be disturbed, causing differences between the wind direction and speed output by the meteo station and elsewhere in the grid of virtual source locations. Also the dispersion of the plume could be enlarged by turbulence. Both effects will raise the detection threshold and the time needed for detection. In most cases however wind directions would exist in which the object would not disturb the wind field. Because such conditions would occur in the course of time detection would take place eventually. Furthermore the problem could be alleviated by increasing the density of meteo stations along stretches known to suffer from this phenomenon.

6.3.2 Disturbance of the properties of the air by the outflow

An emission of 3 g s^{-1} corresponds with 1.7 l s^{-1} at a temperature of 25°C and an air pressure of 1013 hPa. The density of carbon dioxide under these conditions is about 150% of the density of air. Because atmospheric conditions very close to the ground level will be turbulent under all except windless conditions, we assume that the plume near the source will be rapidly dispersed and diluted. If the emission has been taken place for a prolonged period of time, the Joule-Thomson effect should be considered. Carbon dioxide that expands from 40 Bar to 1 Bar will drop in temperature by about 28°. Its density will by consequence increase, to about 175% of air density at a temperature of about -15°C. This is well above the critical temperature at which dry ice would be formed. Therefore we assume that under those conditions as well rapid mixing would take place after which the plume would behave as the air in which it travels.

At higher flow rates of e.g. 100 g s^{-1} the assumptions may not hold. On the other hand, predicted detection power and speed at this rate are more than adequate so some degradation will be acceptable.

The dispersion in the vertical direction may be affected by the difference between the density of the outflow and air density. This may result in a decrease of the optimum height for the sensors.

6.3.3 Representativeness of the noise used for simulation

Real instrument noise, in most cases, has a Gaussian probability distribution and a power spectrum that is dominated by the low frequencies (so-called pink noise). In the simulation uniformly distributed uncorrelated noise was used. We think this is allowable because:

- The low frequencies are mainly caused by environmental factors such as changes in temperature, air pressure and humidity. Because those will be the same for a group of adjacent sensors and because those will all respond in the same way, the low frequency components of the instrument noise will largely be cancelled out.
- The probability density function of the parent data used for correlation does not affect the probability density function of the resulting correlation (only its standard deviation does).

6.4 Cost

6.4.1 Cost of installation

A breakdown of the installation costs for 1 km, based on the conditions assumed in this study, would be:

Item	Quantity	Cost per item	Total cost
Sensor (e.g. Vaisala GMP 343)	20	2300	46000
Weather station (e.g. Vaisala WXT 520)	1	1500	1500
Instrument boxes	20	500	10000
Power supply (connected to power grid)	20	100	2000
Industrial Process PC	1	2500	2500
Local wireless communication	19	200	3800
GPRS wireless communication	1	300	300
Supporting parts & materials	20	100	2000
Working hours	200	70	14000
Total			**82100**

6.4.2 Cost of operation (y^{-1})

A breakdown of the operating costs for one stretch of 1 km, based on experience with other measurement stations, would be:

Item	Quantity	Cost per item	Total cost
Visits à 8 h	2	600	1200
Cal gas bottle	1	1000	1000
Replacement of a sensor	1	2300	2300
Other replacements	1	500	500
Depreciation	20%		16500
Total			**21500**

7 Go / no go decision for phase 2 (field test)

Arguments in favour of proceeding with a field test are:

- The method could work down to detection of a leak of 3 g s^{-1}. If the noise level of the sensors could be decreased compared with this study (the maker of the most obvious

candidate reports a repeatability of 1 ppm with 30 s measurement intervals) and if a longer observation time is chosen (4 months instead of 1 would theoretically yield a 2-fold improvement of the detection limit) detection of leaks < 0.5 g s^{-1} appears to be possible.
- Detection of a leak of 10 g s^{-1} appears to be possible within 6 h in 30% of the cases (N = 50); the longest delay in the period of the test data was 150 h. This seems to be adequate.
- The costs of installation and operation do not appear to be prohibitive, especially if public concern is among the motives for deployment.
- The method may also be applied to monitor the injection well, the injection site or the surrounding terrain.

Points of doubt with regard to proceeding with a field test are:

- The speed of deterioration of a leakage was not taken into account. If a small leak would be expected to develop into a major rupture within 6 h, the method would not be adequate. This would be the case if a small damage would quickly degrade the mechanical integrity of the pipeline. We assume that the mere fact that it was permitted to be constructed rules this out.
- Leaks may become observable by phenomena that may be visually observed, such as growth or withering of vegetation, an ice plume due mixing of air with CO_2 that has been cooled down by the Joule Thomson effect or visible disturbance of the soil. Because the utilization of such phenomena would necessitate inspection, this would be much less cost efficient and reliability would be questionable.
- The simulation was performed with uncorrelated noise. In reality the noise will be auto-correlated (“pink noise”). If low frequency noise dominates and if it is not cross-correlated between sensors, spurious detections of non-existing sources may ensue. However, such noise usually originates from environmental sources common to all sensors, so this is not to be expected.
- Near large objects such as buildings and elevated roads the wind field may be disturbed. This would make the computations of the plumes of virtual sources invalid. However, large buildings near the pipeline are not to be expected (in case of the Barendrecht pipeline they are reported to be absent). If relevant at all, this problem could be further alleviated by installing more weather stations, up to one station per sensor.
- Large stationary point sources of CO_2 close to the sensors may increase the minimum detectable leakage and / or increase the expected time needed for detection. This problem could not be tackled within the possibilities of the method itself. However, such sources are expected to be rare – installations for district heating or for the heating of greenhouses being the most probable ones. Even if those were present there would be prolonged periods in summer during which they would not be in operation.

We believe the advantages of the method to be straightforward and the points of doubt to be surmountable or not decisive. Therefore we recommend to proceed with the field test.

8 Consequences of the simulation results for the field test

The findings have some consequences for the design of the field test:

- Sensors should be used with a reading-to-reading repeatability of < 5 ppm.
- Careful consideration should be given to the requirements to the operating conditions of the instruments. The outputs of the weather station should be used to apply corrections for air pressure, temperature and relative humidity.
- The optimal measurement height should be examined. If feasible, an experiment should be done with a CO_2 emission at -15℃ to simulate the Joule-Thomson effect.
- The optimal geometry for the sensor configuration should be assessed.
- It may be practical to use existing locations to mount the sensors such as lamp posts and fences. The consequences of an unevenly spaced grid should be examined.
- Significance levels of the correlation between the analysis series and the virtual series should be computed using real noise spectra. This would improve the detection of diffuse or very small emissions.
- The choice of the sensor from which the background level is obtained should be reconsidered. Choosing the upwind sensor that is closest to a linear trajectory in the wind direction should yield a smaller standard deviation of the analysis series.