Na-ijlende gevolgen steenkolenwinning Zuid-Limburg

Final report
on the results of the working group
5.2.6 - risk from mine gas

by

Projectgroup
"Na-ijlende gevolgen van de steenkolenwinning in Zuid-Limburg"
(projectgroup GS-ZL)

on behalf of

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WG 5.2.6 - risk from mine gas -
Final report

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1 Objectives

Coal mining activities in South Limburg have been ceased by the end of the 1960s. The mine water drainage stations, except the Beerenbosch II shaft, have stepwise been decommissioned until the mid-1970s, accompanied by backfilling of the respective shafts. The industrial shafts have been backfilled with plugs from certain depths to the ground surface. In the Beerenbosch II shaft, mine water management ceased to exist in 1994 and the shaft has been backfilled in the following period.

The historical shafts in the southern part of the Domaniale and Neu Prick concessions have been decommissioned long ago in the early 20th century. It is assumed that for the backfilling waste rock was used at that time.

After stopping the mine water management, the mine water level in the northwestern part rose up into the overburden.

In the course of mine water level rise various impacts have been registered at the surface, like subsidences and sudden gas releases, containing among others the mine gas methane.

The following technical paper lines out the degassing characteristics of abandoned coal mines. In conclusion, the potential hazards from methane or other mine gas components will be assessed.

Finally protective measures against the potential hazard from mine gases and their incidence at the surface around abandoned coal mines will be qualified and recommendations as well as a proposal for monitoring are presented.

2 Theoretical considerations about degassing in abandoned coal mines

The seams of coal mines tend to have various gas contents in advance to mining. Extracting operations disaggregate the top and floor rocks of mined areas, and, as a consequence methane (mine gas) is released as well from the mined seams as from the adjacent seams. After discharge the (volatile) methane (mine gas) will find its way to the shafts and along the way charge the mine air of all mine workings with a possibly harmful methane-air mixture. Mine layout and technical measures (dimensioning of mine ventilators, ventilation layout, mine air monitoring, control of methane concentration) provide the compliance with safety regulations regarding methane limits in the mine air.

After a mine closure, a portion of residual gas as a part of the natural gas content will remain in the workings (the content depending on the mining intensity). Consequently further gas is released over a period of up to several decades. In the unventilated abandoned workings the gas of certain concentration may be enriched.

Abandoned mine workings nearby coal seams with high natural gas content may thus contain high residual methane concentrations, and vice versa.

Due to the fact that methane oxidation (chemical reaction of methane, CH_4 and oxygen, O_2), generates carbon dioxide (CO_2), there is a certain amount of carbon dioxide in old mine workings. These chemical processes entail a low oxygen concentration in abandoned mine workings.

Barometric changes cause on one hand the release of gas mixtures from abandoned mines to the surface at low air pressure or, on the other hand, air influx into abandoned mine workings at high air pressure. This air flow is enabled only when flow paths connect the former workings with the surface. The flux of air or gas mixtures is often provided in vugs inside backfilling columns of closed shafts or by joints between shafts and the surrounding rock formations. Furthermore remaining pipeworks are often appropriate paths for gas escape from mine workings of abandoned mines. Additionally, mining induced faulty zones in combination with low thickness of overburden may facilitate the flow.

Unflooded abandoned mine workings are ideal stores and transit spaces for mine gas mixtures. With the rise of the mine water level the cavity volume will be reduced. In case of isolated mine workings with overpressure caused by mine water rise diffuse gas release at the surface may result. Excess pressure in isolated workings can even force sudden gas discharge at the surface.

The mine water rise stops the methane release from coal seams once the hydrostatic pressure exceeds the remaining desorption pressure of methane. Methane discharge is completely finished when the mine water level finally has surpassed all seams and all mine workings (e.g. when the mine water level reaches the top of the Carboniferous bedrock).

Gas release from the overburden can, however, not be excluded in case of gas enrichment in cavities, permeable formations or cracks under pressure by the mine water rise.

3 Geology and gas content

3.1 Geological and mining conditions

The area of interest in terms of structural geology of the Upper Carboniferous is the northwestern part of the Wurm syncline and its continuation to the Waubach-anticline. The sequence of strata is ascending northwestward which implies the occurrence of Westfal A strata at top Carboniferous, while the southeastern (syncline) part of the deposit is dominated by rocks of Westfal B age.

Within the flank of the Wurm syncline special folding and thrust faults parallel to the strike direction is known.

Folding and thrust faulting of the deposit represent the compressional forces and these are followed chronologically by stress relief resulting in normal faults. Faults of this type cross the structure perpendicular in NW – SE direction and are characterised by normal and oblique faults. They show great dislocation variations and subdivide the deposit into horst and graben structures. Due to activities in recent geologic history such cross faults cause significant dislocations even of the top of the Carboniferous bedrock and in the overburden.

The most important fault is the Feldbiß fault with a dislocation of the Carboniferous formation approximately 250 to 300 m and the top of the Carboniferous bedrock approximately 150 m.

The upper western part of the Feldbiß fault will consequently later be submerged by the mine water rise than the sunken eastern part.

3.2 Gas content of the coal seams

Coal mining in South Limburg has been decommissioned in the late 1960s. Gas content of the coal seams has not been measured due to the missing of related measurement procedures which were developed not before the early 1970s.

For the assessment of gas distribution, gas content data of the nearby Aachen coalfield were transferred since this coal district was operating until the early 1990s, yielding gas content data for comparison purposes. From the gas content data of the Aachen coalfield, a gas content (methane) vs. depth (distance from top of Carboniferous) chart has been derived (Fig. 1).

The corresponding data point out a gas free horizon with an extension of 100 to 150 m below the overburden with a rapid increase of gas contents up to 11 m^3/t.

3.3 Microbial methane generation

In recent years the processes involved in gas generation have often been discussed by experts. In particular the possibility of significant microbial gas generation aside from the gas generation associated with the coalification was argued.

To clarify the matter several research projects were launched by DMT GmbH & Co. KG, partnering with the Federal Institute of Geosciences and Natural Resources as well as Deutsche Steinkohle AG (German Hard Coal Mines). During the research experiments on three abandoned mines have been performed. Additionally subsurface and laboratory tests comprising degassing processes of mining timber, coal and mine water have been executed.

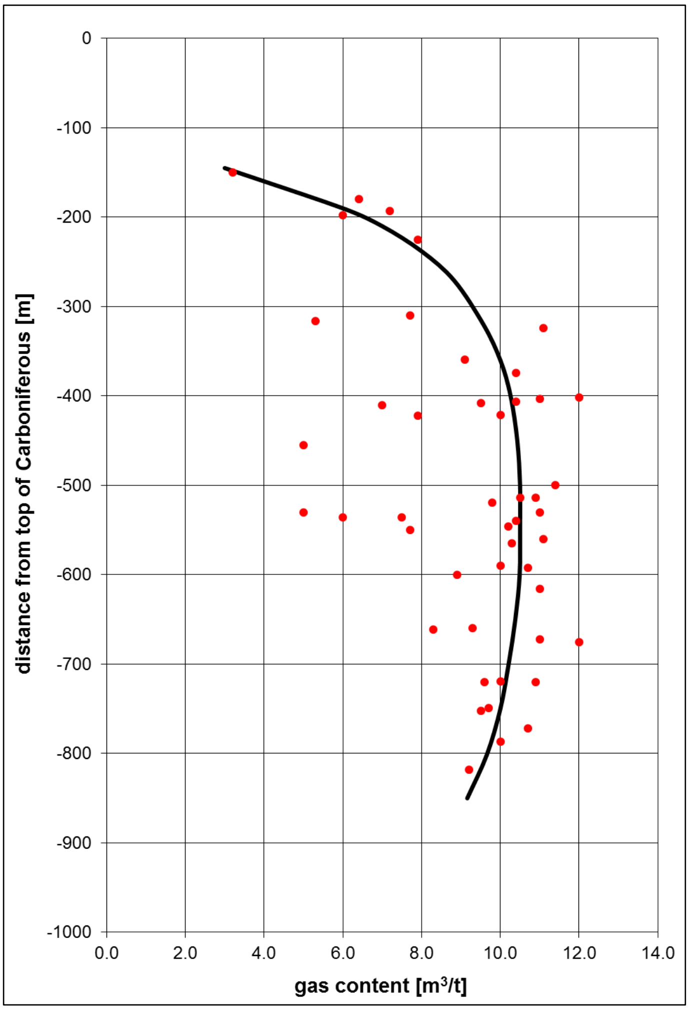

Fig. 1: Gas content (methane) vs. depth trend of the Aachen coal district

The investigations resulted in the detection of a certain methane generation from mining timber and coal while the coal produced less gas than the timber. On the other hand no methane generation from mine water was identified.

Even if at that time no results were achieved for an undisputed quantification, it could be elaborated that microbial gas generation has negligible relevance compared with the gas of thermal origin (coalification).

Scientific research substantiated the empirical knowledge that flooded subsurface structures do not show noticeable methane production, a fact confirmed by measurements at the South Limburg shafts.

3.4 Methane concentrations in abandoned mines

Methane concentrations in abandoned mines of the South Limburg coal district depend on the initial gas content of the respective coal seams. Considering the gas content vs. depth trend (Fig. 1), high methane concentrations were assumed for mine workings deeper than 300 m below the overburden. High methane concentrations in mine openings have probably been existent only several months after the abandonment of a mine while the deep levels were not yet submerged with mine water.

In the meantime large parts of the South Limburg coal deposit are drowned up to or partly into the overburden (see Fig. 2). Therefore methane desorption from flooded coal seams in the northwestern and the middle part of the coal district has ceased.

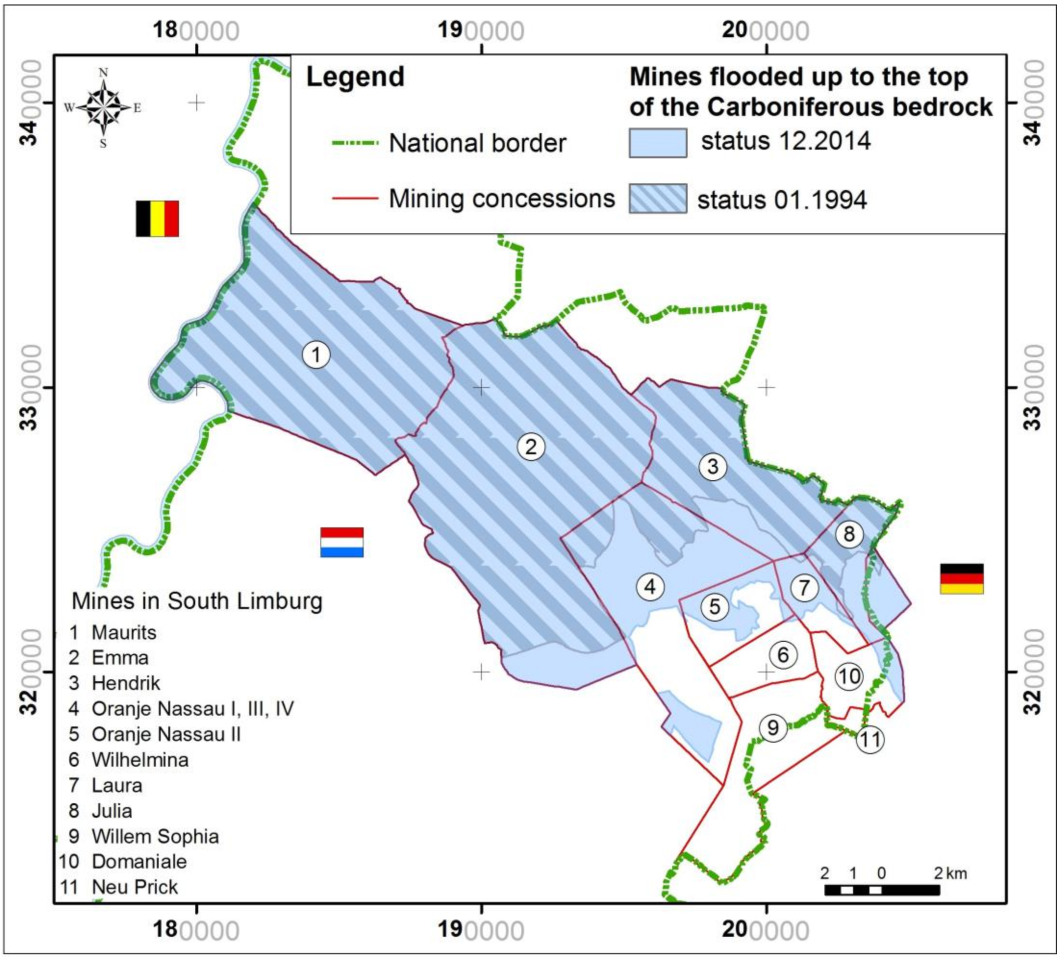

Fig. 2: Flooded mines of the South Limburg coal district

In the southeastern part of the deposit the mine water level has not yet reached the overburden. However, the deeper mine workings are flooded, e.g. the mine water at the Beerenbosch II shaft was retained at a maximum level of -214 m NAP (approximately 314 m below the overburden) until 1994. Below that depth no gas release took place due to flooding.

With further rise of the mine water the actual water level at the Beerenbosch II shaft was measured at 39 mNAP (status of July 2015).

3.4.1 Measurement of gas concentrations in mine gauge pipes

In the course of two inspection visits measurements of the gas composition were executed at several abandoned shaft locations in the South Limburg mining district. These were the Beerenbosch II and Willem II shafts (Domaniale) in Kerkrade, shaft II of Julia mine in Eygelshoven, shaft I of Wilhelmina mine in Kerkrade and shaft II of Oranje Nassau I mine in Heerlen; all shafts are equipped with water gauge pipes (for the sounding of the mine water level). During the measurements dated 29.04.2015 and 07.07.2015 a low outflow of mine gas could be expected due to the low or decreasing atmospheric pressure.

In the gauge pipes of those shafts (Julia mine, shaft II and Oranje Nassau I mine, shaft II), in which the mine water level was determined in the overburden, no methane was detected. The carbon dioxide concentration was low and the oxygen concentration was at a high level correlating to atmospheric conditions.

The mine water level of Wilhelmina, shaft I was below the baseline of the overburden formations. Regardless of that fact, no methane was detected in the gauge pipe. The carbon dioxide concentration was low and the concentration of oxygen at 17,7 vol.-% was close to atmospheric values. These facts are not surprising as all mining levels connected to the shaft have already been flooded and the gauge pipe running down to the deepest mining level ends in the mine water (see Fig. 3).

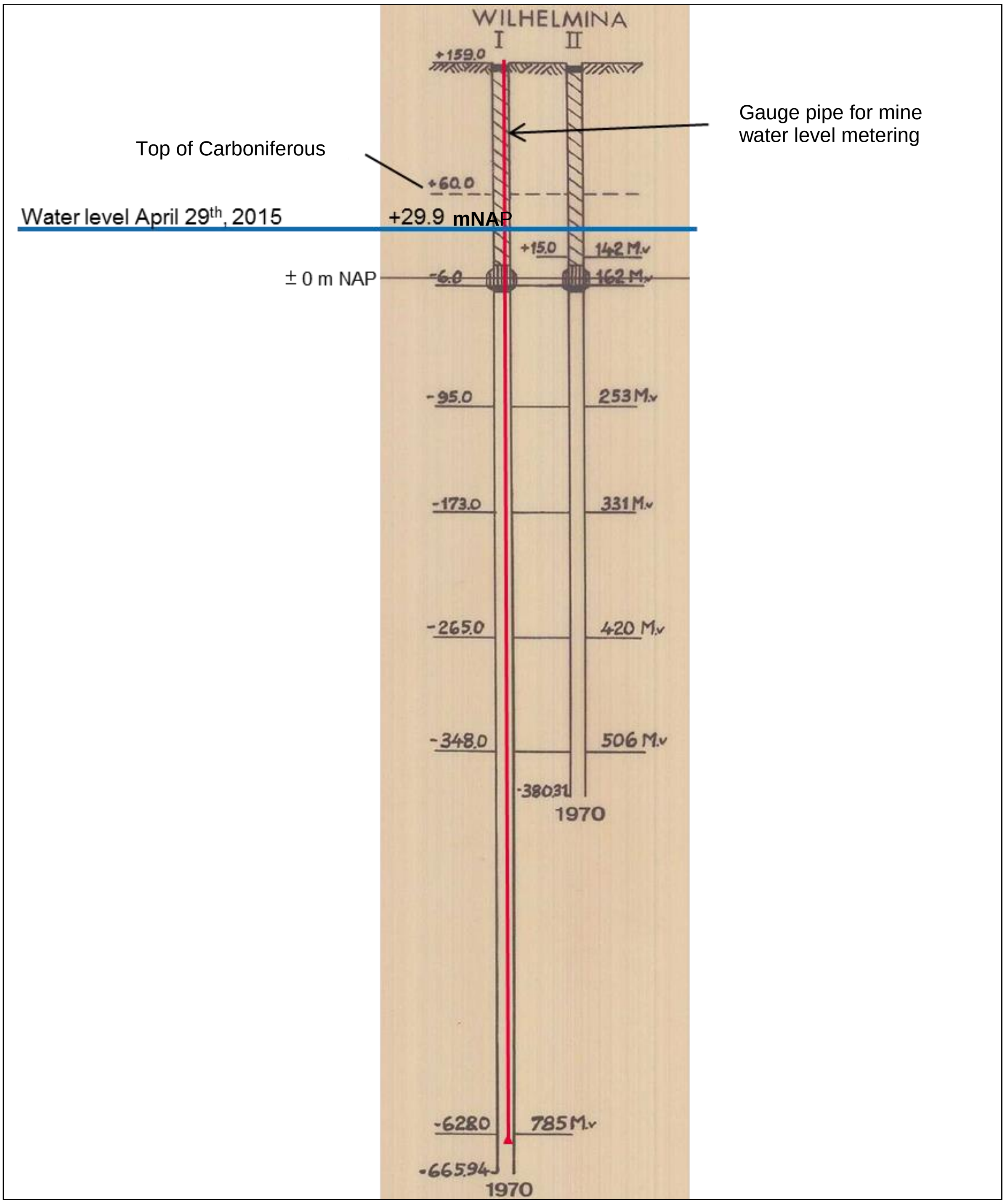

Fig. 3: Wilhelmina mine, shafts I and II

The mine water level in the Beerenbosch II shaft was measured below the overburden baseline and even the 75 m level as topmost mining level was above the mine water level. No methane was detected in the shaft gauge pipe. Concentrations of carbon dioxide (0,06 vol.-%) as well as oxygen (19,9 vol.-%) corresponded with natural atmospheric conditions.

Gas composition measurements of subsurface workings were not feasible due to the submersion of the gauge pipe (Fig. 4).

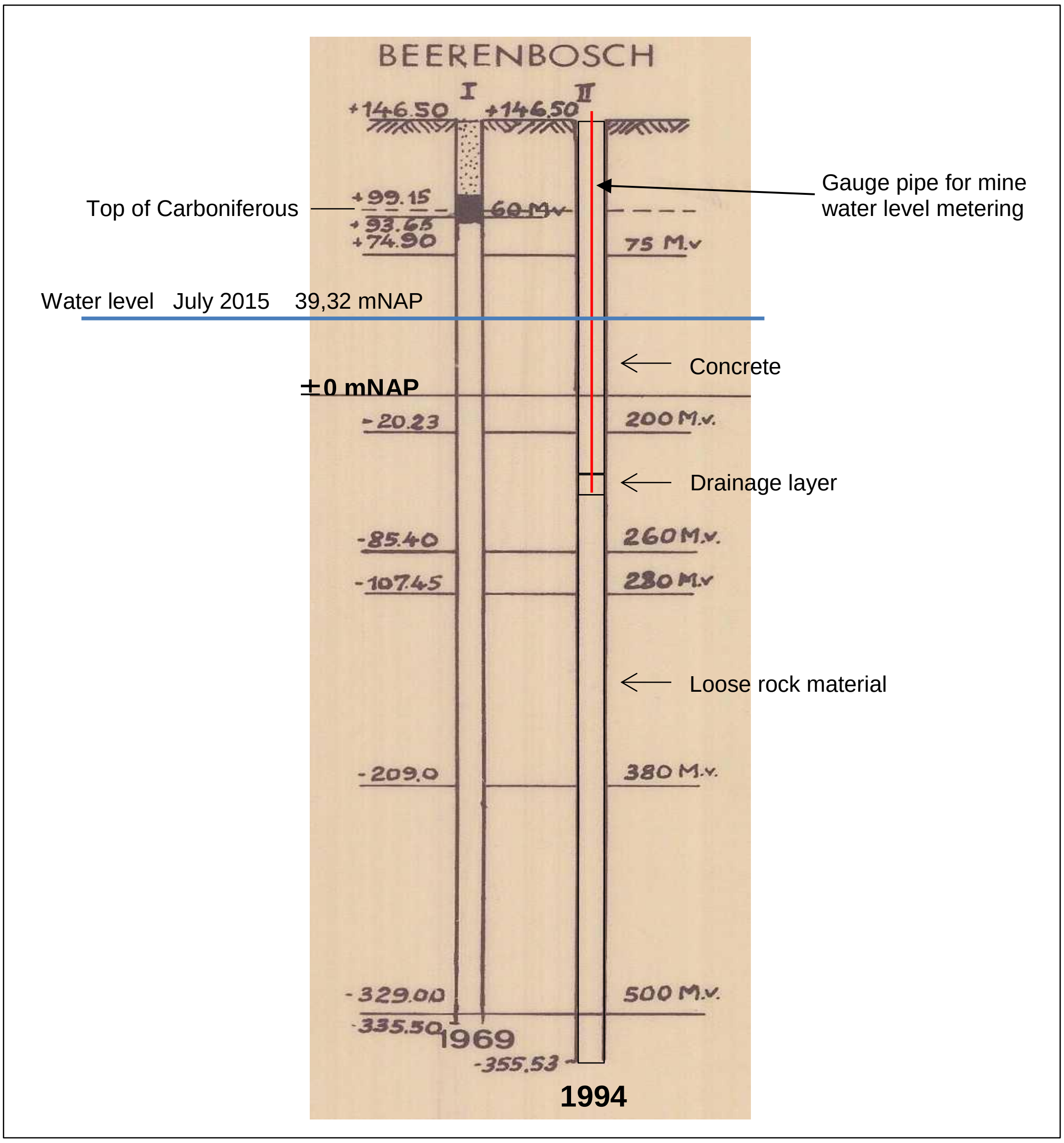

Fig. 4: Domaniale mine, Beerenbosch I and Beerenbosch II shafts

A different configuration was encountered at the Willem II shaft of the abandoned Domaniale mine with three mining levels still above the mine water level and the gauge pipe ending at the basis of the backfill plug (Fig. 5).

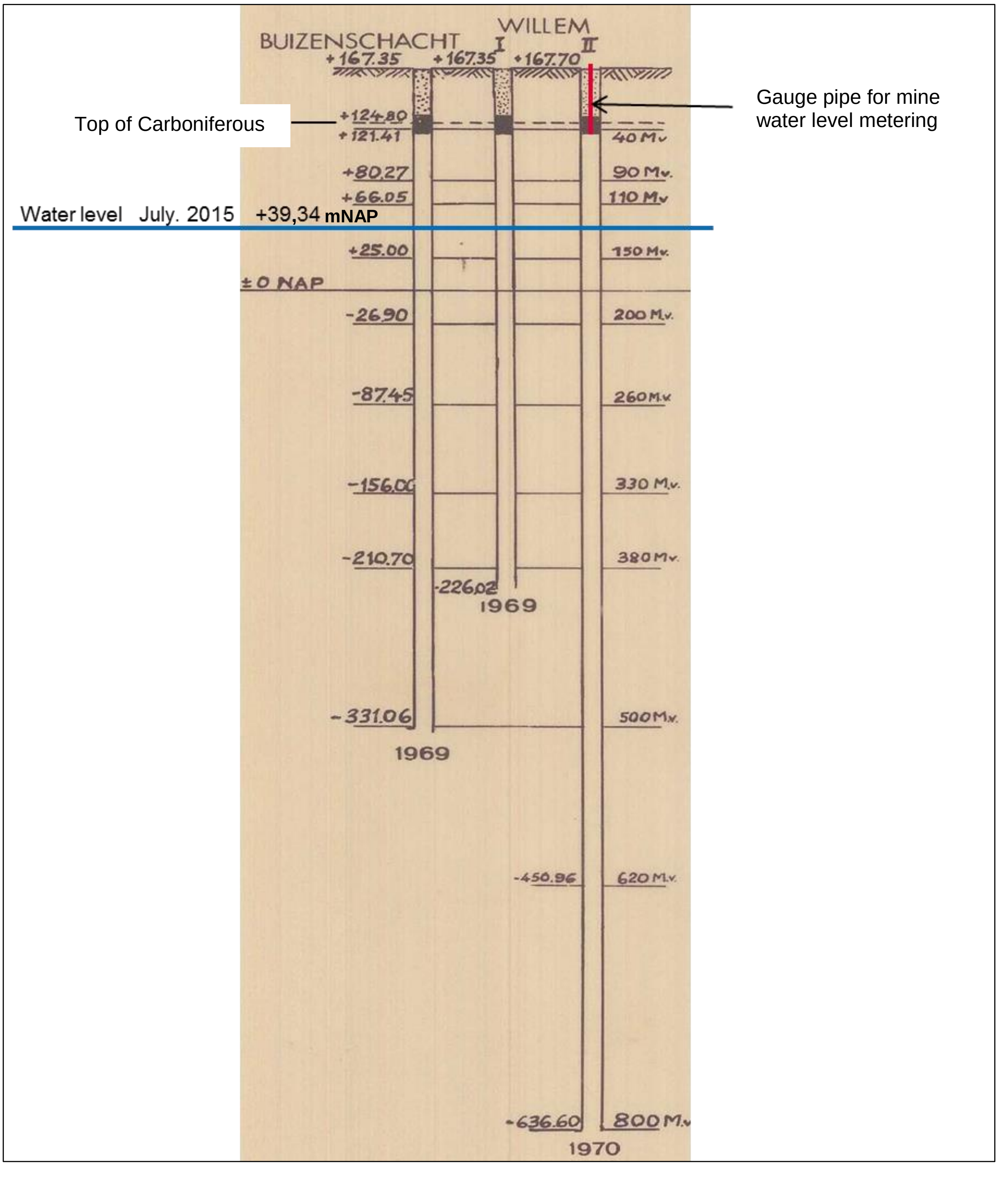

Fig. 5: Domaniale mine, Willem I, Willem II and Buizenschacht shafts

The measurements dated 29.04.2015 identified the discharge of a gas mixture from the gauge pipe with a methane concentration of 0,03 vol.-%. A repeated inspection dated 07.07.2015 showed a methane concentration of 0,08 vol.-% in the outflow. Additional compounds of the gas mixture were each time carbon dioxide (10,3 or 10,6 vol.-%) and oxygen (1,0 or 1,3 vol.-%).

Mine gas outflow takes place at low atmospheric pressure whereas high atmospheric pressure causes air influx into the unflooded mine workings.

The unflooded mine structure represents quite a large volume where over a long period the gas pressure corresponds with the average air pressure. However, there will certainly exist discrete flow paths to the surface apart from the backfilled Willem I, Willem II, and Buizenschacht shafts, establishing pressure compensation between the atmospheric surface conditions and the subsurface gas pressure. The high flow resistance delays the surface-to-mine pressure compensation up to several days. The average gas mixture (subsurface) pressure thus permanently lags behind the average atmospheric pressure.

During the inspection on 07.07.2015 a gas pressure of approximately 7,8 hPa was metered in the gauge pipe which met the pressure difference between the average atmospheric pressure of 997,8 hPa for the 6 previous days and the actual air pressure of 990 hPa during the measurement.

The layout of the gauge pipes, the length of the backfilling and the mine water levels in the specified shafts limited measurements of gas concentration and pressure in the gauge pipe of the Willem II shaft only.

The most relevant measurement data of the April and July inspections are clearly organised in Tab. 1.

Tab. 1: Gas concentrations in the mine gauge pipes

Shaft	Inspection-date	CH_4 [vol.-%]	CO_2 [vol.-%]	O_2 [vol.-%]	Water level [mNAP]
Julia II (Laura-Julia)	29.04.2015	------	0,12	20,8	13,5 (overburden)
Shaft II (Oranje Nassau I)	29.04.2015	------	0,04	20,9	22,0 (overburden)
Shaft I (Wilhelmina)	29.04.2015	------	0,22	17,7	29,9 (overburden)
Beerenbosch II (Domaniale)	07.07.2015	------	0,06	19,9	39,3 (Carboniferous)
Willem II (Domaniale)	29.04.2015 07.07.2015	0,03 0,08	10,3 10,6	1,0 1,3	39,3 (Carboniferous)

3.4.2 The Beerenbosch II shaft after mining period

The Beerenbosch II shaft of the former Domaniale mine remained operating after the mine closure in 1969 and was in service for the mine water management until 1994. The mine water level was controlled at a depth of approximately -214 mNAP. The mine water level rose after the abandonment of the water management and the backfilling of the shaft. Consequently in further areas of the South Limburg deposit the mine water level rose into the overburden (see Fig. 2). In July 2015 the mine water level was located at 39,3 mNAP in the shaft Beerenbosch II (see Fig. 4).

Already during the period of water management low oxygen gas mixtures were discharged containing an essential carbon dioxide component. The methane concentration was negligible at that time which is proved by a measurement in the unventilated and covered shaft dated 27.08.1992 which showed concentrations of methane (0,05 vol.-%), carbon dioxide (9,4 vol.-%) and oxygen (7,0 vol.-%).

3.4.3 Result

The determination of the gas composition in the Willem II shaft, Domaniale results in very low and harmless methane concentrations (between 0,03 and 0,08 vol.-%) in the unflooded workings of the former Domaniale mine.

Similar data (0,05 vol.-%) were identified at the open Beerenbosch II shaft in 1992. At that time the major part of the South Limburg mines was not filled with water up to the overburden and the mine water level of Domaninale mine was registered at -214 mNAP.

In the meantime the mine water level has risen to 39 mNAP (07.2015). As a consequence nearly all coals seams are submerged and hence are unable to release methane. There is a low probability of future advanced methane concentrations above the recent values. This assessment is very likely for the further abandoned mines of the coal district.

The mine gas component carbon dioxide behaves different to these considerations. At the Willem II shaft, Domaniale the carbon dioxide recently was registered with concentrations of 10,3 and 10,6 vol.-% after 9,4 vol.-% in 1992.

In the abandoned workings oxygen was measured with low concentrations of 1,0 and 1,3 vol.-% (measurements from April and July, 2015) which corresponds with the data acquired in 1992 in the unventilated Beerenbosch II shaft.

4 Specification of hazardous degassing areas

The South Limburg coal district can be divided into three areas with a view to potential hazards from mine gases. These are:

(a) areas with rise of the mine water level into the overburden strata;

(b) areas with flooding of all mine workings, although the mine water level is still below the overburden;

(c) areas with unflooded mine workings.

Plan 1 shows the different areas that were defined based on the findings of WG 5.2.2/5.2.3 and WG 5.2.4/5.2.5.

In category (a) no methane desorption will take place.

In the areas categorised (b) (see shafts Wilhelmina I and II (Fig. 3)), un-flooded coal seams may be found which can still release methane. Due to the flooding of the underground workings, however, no more voids for a possible gas storage will exist.

Category (c) concerns the areas with open, unflooded underground structures. In these areas certain gas mixtures exist. Their pressure corresponds with barometric conditions. The gas mixture generally consists of nitrogen as a consequence of the low oxygen concentration. Methane is represented only in low and non-hazardous concentration. Nevertheless, low oxygen/high carbon dioxide gas mixtures indicate the risk of suffocation.

5 Assessment of shaft remediation regarding degassing issues

Backfilled shafts can serve as path for mine gas from unflooded underground voids to the surface. Cracks and communicating pores in the backfill columns as well as residual voids or joints between shaft lining and rock formations form the flow paths. Furthermore the backfill with hydraulically setting compounds may allow for certain gas flow, which in the past was identified at safely closed abandoned and backfilled shafts of German mines. A proper backfill column facilitates only low gas escape, but the drop or run out of a backfill column may enable major gas flux to the surface.

The industrial shafts of the South Limburg coal district (see Plan 1) have been closed with a technology where drops or run outs are unlikely to be the case. Gas escape may occur but at low flow rates only.

In the Neu Prick and in the southern Domaniale coalfields with historical shafts, however, backfill was executed using waste rock from mining. Differing grade of compaction of this material may enable more or less gas escape. As already mentioned above, high flow rates can succeed a drop or run out of such a backfill column.

It should once again be pointed out that the gas escape out of backfilled shafts is possible only if the shafts are connected to open, unflooded mine workings (see category (c) in chap. 4).

In Tab. 2 the industrial shafts with connection to mine workings above the mine water level are organised (category (c), chap. 4).

Tab. 2: Industrial shafts with unflooded levels, status July 2015

Shafts	Mine	Water level	Unflooded levels
Willem I, Willem II, Buizenschacht	Domaniale	31 mNAP	40 m-level 90 m-level 110 m-level
Beerenbosch I	Domaniale	31 mNAP	60 m-level 75 m-level
Beerenbosch II	Domaniale	31 mNAP	75 m-level
Nulland	Domaniale	31 mNAP	60 m-level
Baamstraat	Domaniale	~ 31 mNAP	Access at 105 mNAP
Neuland	Domaniale	~ 31 mNAP	Access via shaft possible?
Louise	Domaniale	~ 31 mNAP	Access via shaft possible?
Catharina	Neu Prick	~ 31 mNAP	Access via shaft possible?
Willem II	Willem Sophia	~ 31 mNAP	105 m-level
Melanie	Willem Sophia	~ 31 mNAP	100 m-level
Ham II	Willem Sophia	~ 31 mNAP	Access at 95 mNAP Access at 55 mNAP

At all shaft locations specified in Tab. 2 mine gases may leak out at the surface.

Moreover most probably the historical shafts of Domaniale and Neu Prick coalfields are connected above the mine water level to old workings and therefore mine gases may leak out at the surface.

For the shafts

- Willem I, Sophia (both Willem Sophia mine)
- Shaft I, Shaft II (both Wilhelmina)

applies the statement that mine gas outflow is negligible due to the complete flooding of all mine voids although the mine water level is still below the overburden (but above all mining installations, see category (b) in chap. 4).

6 Identification of potential degassing paths

It was already mentioned above that flow paths in backfilled or abandoned shafts connect gas filled old workings with the surface. So there is always the potential for gas leakage if mine workings have access to a shaft above the mine water level (see category (c)).

This includes both the industrial mine shafts listed in Tab. 2 and all historical mine shafts (see report of WG 5.2.2/5.2.3). One must consider that emission of mine gas from backfilled mine shafts is not limited to the direct vicinity of a shaft head. In fact, emission of mine gas may occur all over a protection-zone that is relevant for the emission of mine gas. According to the German (NRW)-regularities this so called “Gas-emission-protection-zone” should have a radius of 25 m. For the definition of the “Gas-emission-protection-zone” of the historical mine shafts, the respective position accuracy has to be added (see report of WG 5.2.2/5.2.3).

A further option for gas escape from underground may occur near active mining induced zones of discontinuity (“Drempels”) or along old boreholes (“Downward drillings”). This pertains only to areas that have not been submerged by mine water yet (category (c)).

Supplemental gas flow from underground voids into the overburden may also take place in the context of sinkhole events. This pertains only to areas that have not been submerged by mine water yet (category (c)).

Finally, gas may migrate into the overburden. Depending on the permeability of the surrounding rocks high gas volumes can be enriched and covered by impermeable cap rocks. These “gas stores” might be incidentally tapped by boreholes or pillar foundations which then would cause sudden gas releases.

7 Cases of recent gas leakage incidence

7.1 Oranje Nassau I, shaft II

7.1.1 Incident and measurements

In September 1979 gas samples were taken from the long-term degassing gauge pipe in order to determine the gas composition. Some time before gas concentrations of CH_4 > 7 vol.-% and of CO_2 > 6 vol.-% were measured with a Dräger device. In 1979 two series of 3 samples each were taken and handed out to the central laboratory of D.S.M. Limburg B.V. for an analysis.

These were the results for CH_4, CO_2, O_2 und N_2:

CH_4 6,0 to 10,8 vol.-%

CO_2 5,3 to 9,3 vol.-%

O_2 9,3 to 0,7 vol.-%

N_2 76,4 to 76,5 vol.-%

Additional carbon monoxide (CO) analysis showed concentrations less than 0,05 vol.-%. Furthermore, hydrogensulfide (H_2S) odor was stated from the 2nd sample series. The occurrence of CO was seen in relation to a previous self-ignition in the N-coalfield of Emma mine. The lack of respective documents made it an open ended question.

Analysis results of 4 additional gas samples dated 27.05.1980 were sent from the D.S.M laboratory to the mining authority. The maxima for CH_4, CO_2, O_2 and N_2 were:

CH_4 = 10,1 vol.-%

CO_2 = 9,5 vol.-%

O_2 = 0,1 vol.-%

N_2 = 78,6 vol.-%.

Further measurements comprised pressure and volume flow at the open valve of the gauge pipe under low atmospheric pressure conditions. The measurements were conducted between 20.05.1980 and 02.06.1980.

On the start date (20.05.1980) the gauge pipe was opened from 12:30 to 14:00 pm and showed continuous outflow.

The pipe was opened again on 21.05.1980 from 9:15 am till the next morning (22.05.1980, 9:00 am) for gas outlet. At 10:00 am of the same day, a gas meter was mounted in order to meter the gas volume until the next day at 9:00 am. The volume amounted to 192 m^3.

A following flow velocity metering was executed in a pipe (length 3 m, diameter 80 mm) which was connected to the gauge pipe. The determined flow velocity was 5.580 m/h (1,55 m/s) which corresponds to a volume flow of 28 m^3/h. The measurement was repeated (26.05.1980) under lower barometric conditions and then a volume flow of 56 m^3/h was determined.

Due to an air pressure increase, the gauge pipe showed an influx at 02.06.1980.

7.1.2 Result

In the period 1979/1980 the mine water level was located at approximately -210 and -190 mNAP. Unfortunately, exact information is missing due to a suspension of data observation between 19.12.1977 and 26.07.1982. The gauge pipe is installed down to approximately -330 mNAP and ends in the mine water (Fig. 6).

Above the mine water level the 136 m-, the 166 m-, the 210 m- and the 250 m-level were free of water. The backfilling plug ended at a depth of -27 mNAP which is equal to the 136 m-level.

The connection to the shaft enabled gas release from 4 levels. Corresponding to the actual atmospheric pressure, an overpressure up to 116 mm H_2O (approximately 11,4 hPa) or a negative pressure of -20 mm H_2O (approximately -2 hPa) was determined.

From the fact of consistent volume flow of gas mixtures from the pipe over a longer period can be concluded that the gauge pipe had leakages below the backfill plug and above the mine water level (in the water free section of about 170 m).

CH_4-concentrations of approximately 10 vol.-% appear quite realistic. In 1980 the mine water level of the abandoned mines was still about 214 m below the level in the year 2015. Several coal seams were unflooded. Pursuant to the gas content - vs. - depth characteristic (Fig. 1) the registration of considerable (higher) methane concentrations was plausible.

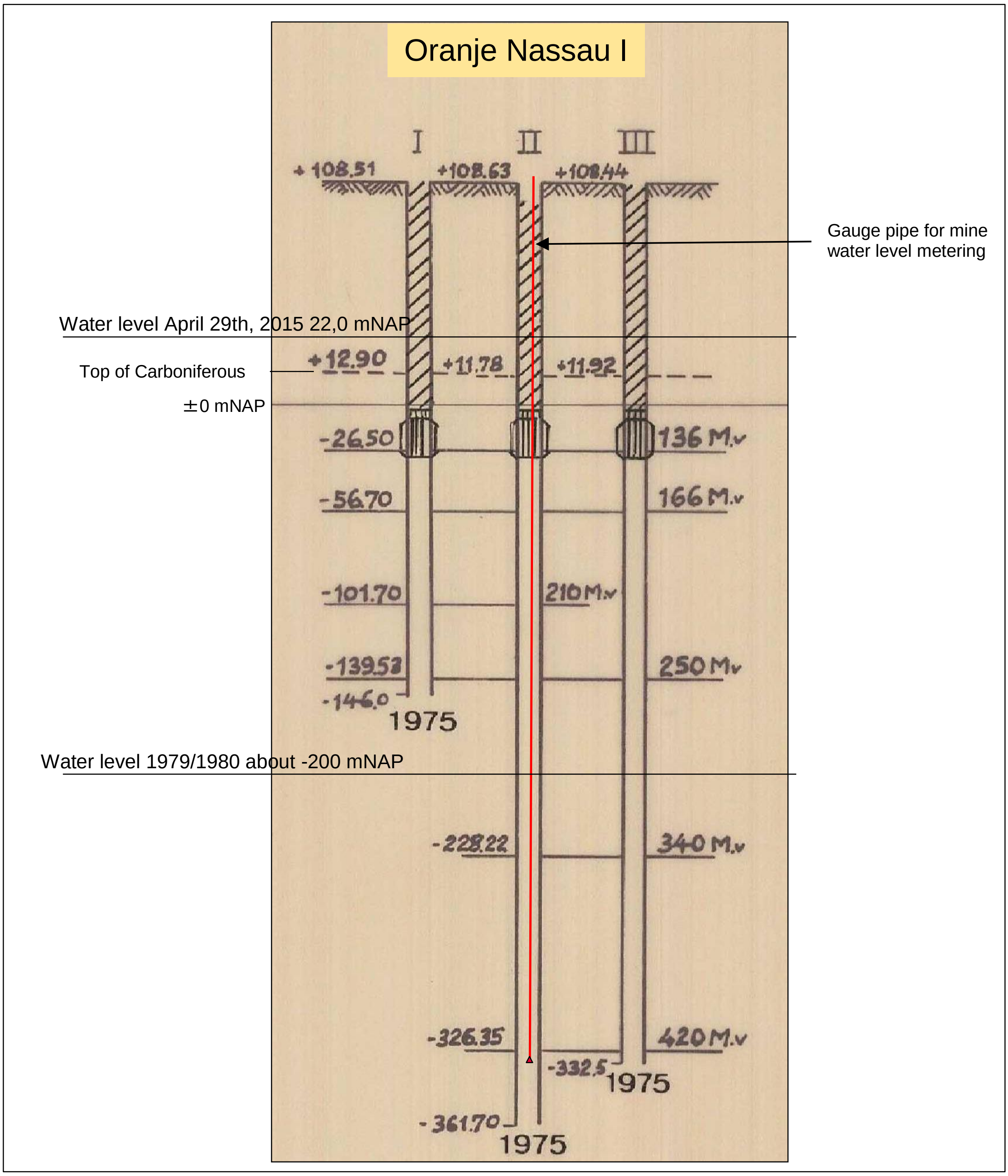

Fig. 6: Oranje Nassau I mine, shafts I, II and III

In the meantime the mine water level has risen into the overburden in the former Oranje Nassau mines (Fig. 6).

7.2 Heerlen Theatre

7.2.1 Incident and measurements

There are a few documents available which describe that on Friday, 09.09.2005, there was an ignition during the pillar foundation for the construction of the new Heerlen Theatre. A worker of the construction company was injured. Measurements of the fire brigade led to the result that no methane could be substantiated, but carbon monoxide was detected instead; the documents submitted to DMT did not figure the concentration.

Continued measurements dated Monday, 12.09.2005, gave no indication to the existence of gas mixtures.

On Tuesday, 13.09.2005, further measurements were executed after drilling the next hole for the pillar foundation. Supposedly a considerable concentration of carbon monoxide was detected, which had not been registered in the submitted documents. The existence of further gases, especially methane, is not stated. It is quite possible that the presence of methane could not be verified.

After the measurements was decided to ventilate the boreholes in advance to further operations (e.g. welding work).

No further incidents were reported.

7.2.2 Result

At the time of the incident all involved parties (authorities, construction companies, engineering firms) supposed that methane discharge from an abandoned mine had triggered the ignition.

There are several facts to be considered for the interpretation of the incident and the measurements:

On 09.09.2005 a CO-concentration was registered. Methane (CH_4) was not identified and was not necessarily to be expected due to the fact that during a CH_4-ignition an oxidation of CH_4 to CO_2 and CO takes place.

With the measurement of 12.09.2005 neither CH_4 nor CO was identified.

After drilling the next borehole on 13.09.2005 an „increased" carbon monoxide concentration was registered but no methane. While the CO-gas from the ignition of 09.09.2005 was removed since long, the matter was about the source of the recent CO-gas, which occurs not naturally in the substrate. These facts have been noticed in the documents about the incident.

Generally it is arguable if the measured gas was CO, because the applied measurement technology of portable measuring device consists of electrochemical measuring cells with cross sensitivity to hydrogen. Hydrogen (H_2), however, is inter alia a by-product of chemical reactions during concreting work, if the aggregates contain aluminium as a remainder of incineration plants. This reaction has often been observed in mines and during shaft backfilling operations. This is an explanation why the „measured" CO might have actually been H_2 instead.

Back to the existence of methane on the construction site, there has to be remarked that the thickness of the overburden below the Heerlen theatre amounts to approximately 80 to 90 m. The mine water level according to measurements in the gauge pipe of Oranje Nassau I shaft II was located at approximately -3 mNAP which means that the mine water level had not yet risen up to the overburden but all underground workings were submerged.

A methane migration from mine workings up to the theatre construction site is quite improbable. If methane was involved in the incident, it must have been discharged from overburden cavities. Yet it has to be noted that the methane concentration in all unflooded subsurface workings was below 0,1 vol.-% which was confirmed by measurements of the Beerenbosch II water management in 1992 and recent measurements in the Willem II shaft (Domaniale) in Kerkrade. An ignition of methane is not feasible at such a low concentration.

Considering the aforementioned statements it is arguable if the ignition must be traced back to methane. The linkage between the ignition and the presence of methane appears to be quite speculative. On the other hand, the ignition of H_2 starts with a concentration of 4 vol.-%.

7.3 Shopping centre „Winkelcentrum 't Loon“ in Heerlen

7.3.1 Incident and measurement

In the autumn of 2011 a sinkhole occurred in the area of a shopping centre (Winkelcentrum ’t Loon) in Heerlen. Subsequently to the filling with hydraulic setting material, two control boreholes were drilled. DMT was provided with a brief protocol and two e-mails concerning the drilling operations at the peripheral zone of the sinkhole.

The submitted documents make evident that the drilling period lasted from 26.04.2012 until 10.05.2012. Starting on 08.05.2012, gas was registered from a drilling depth of more than 66,5 m. The gas composition analysis performed by the fire department and by IHS proved the low oxygen concentration (approximately 5 vol.-%). There was no explosive atmosphere at that time.

The analysis of a gas sample taken on 09.05.2012 had a measurement reading of 10 % LEL (lower explosive limit) according to a methane concentration of 0,44 vol.-%. Apart from methane, according to the document, the gas sample contained hydrogen (H_2).

Further gas release was detected between drilling depth of 70 and 78 m. No further gas measurements were reported.

Top Carboniferous was reached on 10.05.2012 at a drilling depth of 80 m.

7.3.2 Result

At the above mentioned period the mine water level in Oranje Nassau I, shaft II was located at 16 mNAP, which corresponds to a water level approximately 3 m above the top of the Carboniferous bedrock. At the shopping centre in a southern distance of approximately 1,5 km to the shaft II, Oranje Nassau I the Carboniferous bedrock has probably not been completely flooded, but all mine workings are believed to be submerged.

It can be concluded that the gas release must have originated from the overburden.

In congruence with the foundation operations at Heerlen Theatre it cannot be excluded that in some cases the analysed hydrogen may be a side effect of a chemical reaction during the sinkhole backfilling operations as the submitted documents state grouting materials (Dämmer) discovered at 10 m drilling depth.

8 Risk assessment for mine gas

8.1 Bow-Tie-Analysis as general method for risk assessment

As defined in the project proposal, the so called Bow-Tie-Analysis is applied for risk assessment. Initially, the report in hand describes an individual Bow-Tie-Analysis assessing the risk that is related to mine gas.

The individual analysis will be combined to an integrated Bow-Tie-Analysis for all working groups afterwards. The results of this integrated Bow-Tie-Analysis will be published separately.

The Bow-Tie-method is an effective risk assessment technique that assists the identification and management of risks. Furthermore, the comprehensive layout makes this method a suitable tool for communicating risks. In the following, an outline of the method is presented. A simplified Bow-Tie-diagram is given by Fig. 7.

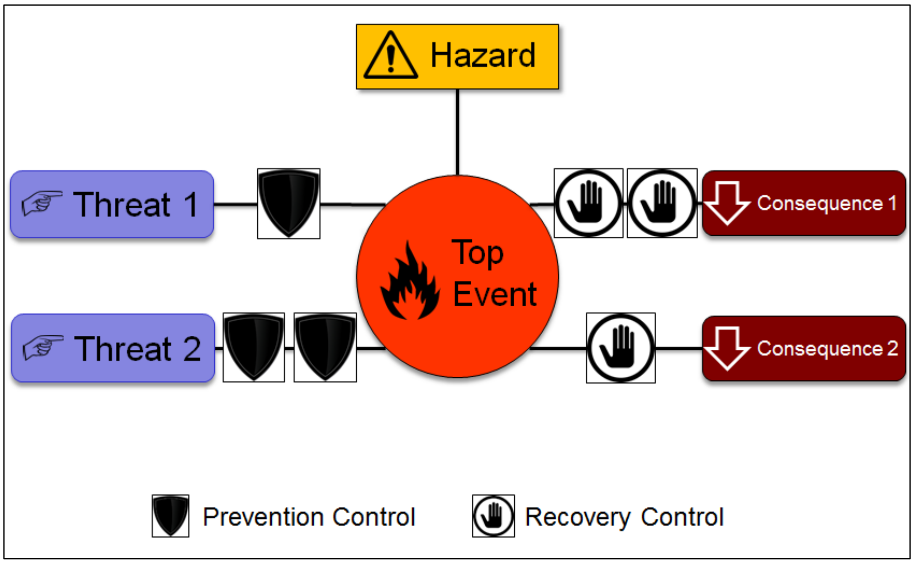

Fig. 7: Simplified Bow-Tie-diagram (Escalation Factors and Escalation Factor Controls not depicted)

A Bow-Tie-model revolves around a certain Hazard. When released/activated, an undesired event (Top Event) may arise from this Hazard. Modelled after a chronology, triggers (Threats) that may release the Hazard, i.e. that may cause the Top Event, are placed on the left-hand side. Following the chronology, the Top Event may result in actual impacts (so called Consequences) that are placed on the right-hand side of the model. Threats, Top Event and Consequences are interconnected with lines with each line representing a different potential incident related to the Hazard.

In order to control the Top Event, i.e. both prevent the Top Event from occurring and stop the Top Event from occurring and limit the severity of a Top Event, respectively, the Bow-Tie-method includes so called Controls (Prevention Controls and Recovery Controls, respectively). In the model, the Controls are arranged between a Threat and the Top Event and between the Top Event and the Consequence, respectively. If there is more than one Control, the Controls usually are sequential.

The efficacy of Controls can be reduced by so called Escalation Factors. Escalation Factors themselves cannot cause a Top Event, but they can increase a risk by increasing the likelihood of a certain incident. To prevent these Factors the Bow-Tie might also include so called Escalation Controls.

8.2 Bow-Tie-Analysis on gas in the subsurface

In both, the German Ruhr and the Saar coalfield, a variety of buildings with gaseous pollutions is reported. Gas emissions at the surface use to strike particular buildings, streets of houses or even whole city quarters. According to the selection of buildings, their structure and existing substance or buildings under construction different measures might be effected.

This report characterises the low probability of methane emissions at the surface in the South Limburg coal district. Control measures are not crucial in this region against potential hazard from methane, but as well appropriate for the protection against the access of carbon dioxide emissions. Various measures are explained below.

In the report in hand, “gas in subsurface” is regarded to be the general Hazard; the related Bow-Tie-diagram is shown in Appendix 1. In general, diffuse gas emission in open areas is not harmful to humans and animals nor to the environment. A potential hazard only occurs when gas is allowed to accumulate, e.g. by gas access into residential buildings, commercial installations and sewage systems. In terms of the Bow-Tie-Analysis, the accumulation of gas in the aforementioned (underground) structures is defined to be the Top Event; in the Bow-Tie-diagram in Appendix 1, this Top Event is summarised as “Gas trapping in building”.

In terms of the Bow-Tie-Analysis, potential Threats are related to the flow paths of mine gas. One can differentiate between:

- A flow path that enables mine gas to enter an (underground) structure; and
- A flow path that enables a spatially concentrated degassing of mine gas.

In the following, the most important Threats are outlined:

- Existing flow paths entering enclosed area: In general, any gap in the structure of a building/foundation might serve as a potential flow path for mine gas that allows it to enter an enclosed area. As wall ducts are the most common gaps in foundations, they are listed as a single Threat. Other gaps might be joints or cracks in the foundation.
- Pipe ducts: Wall ducts for service pipes (e.g. water, gas) are natural weak points for gas entering (underground) structures such as basements.

- Drill/bore or pillar creating flow path: As mentioned before, degassing is taking place diffusively when there are undisturbed underground conditions. However, man-made drillholes might serve as preferential flow paths for gas and thus might facilitate a spatially concentrated degassing.
- Sinkhole/Drempel: In general, Sinkholes and Drempels might facilitate the upward migration of mine gas. For further details, reference is made to chap. 9.3.3 and chap. 9.3.4.

Once mine gas has accumulated in an (underground) structure, there are, in general, two potential Consequences. These Consequences are depending on the gas mixture. One can differentiate:

- Explosion: The presence of an explosible gas mixture is a necessary condition for an explosion. There are different explosive limits for the typical constituents of mine gas (CO, CH_4, H_2S); CO_2 does never form an explosible gas mixture. The explosion limits are given by Tab. 3

Tab. 3: Lower and upper explosive limits for typical constituents of mine gas

Constituent	Lower explosive limit [vol-%]	Upper explosive limit [vol-%]
CO	12,5	75
CH_4	4,4	16,5
H_2S	4,3	46

- Damage to persons/injuries: On the one hand, the presence of increased concentrations of the different constituents of mine gas can have different damaging effects to persons. At this point, reference is made to the respective specialist literature. On the other hand, decreasing oxygen levels of the breathing air can also cause serious damage to life and limb. The effects range from temporary performance limitations to faint and brain damage.

In the Bow-Tie-Analysis, the most important Consequences are exemplary outlined as follows:

- Explosion injuries: Damage to life and limb that is caused by an explosion of an explosible gas mixture.
- Damage to persons injuries: Damage to life and limb that is caused by higher concentrations of mine gas (or single constituents) and/or low oxygen concentrations.
- Explosion damage: Damage to property in the broadest sense.
- Social unrest: Social unrest is regarded to be an indirect Consequence from the Top Event. As the Top Event might affect personal property and might as well impair the personal sense of protection the Top Event might lead to social unrest. Social unrest might even get worse if no action is taken by the authorities.

However, there are several Prevention Controls as well as Recovery Controls/Escalation Controls for the Top Event. In the Ruhr and Saar area, control measures are focused on gas mixtures consisting of low oxygen and carbon dioxide plus the explosive constituent methane. For the potential impact areas in the South Limburg mining district, the following Controls are discussed:

Prevention Controls:

- New buildings: regulations spatial planning: Prior to construction projects in potential impact areas, the builder has to be aware of the potential Hazard “gas in subsurface”. Building regulations as well as an appropriate regional development planning are considered to be useful Prevention Controls, i.e. the respective authorities have to notify whether there is a potential danger of degassing in a to-be developed building area or not. As the case may be, it will be necessary to comply with certain building regulations. Some common safeguarding measures for construction projects in potential impact areas are given in chap. 8.3.1. Further reference is made to chap. 9.2.2.

- Gas-tight / sealed ducts: Recommendation for sealing leaking wall ducts are made in chap. 8.3.2.2.
- Awareness-raising drilling companies: Any drilling company has to be aware of the dangers that are related to drilling work in the potential impact areas.
- Measurements: Some recommendations for measuring the gas content during constructional measures are made in chap. 9.2.2 and chap. 9.3.2.
- Monitoring mine water level: As described in chap. 9.1, rising mine water diminishes the area that is potentially affected by degassing. Hence, monitoring the mine water level is a useful way to keep track of the area that is currently affected by degassing.

Recovery Controls/Escalation Controls:

- Concentration measurements: As mentioned before, an altered composition of the breathing air can cause different dangers to life and limb. Measuring the composition of the breathing air is a useful measure to encounter these dangers. There are portable measuring devices available for measuring the composition of the breathing air.
- Avoidance of ignition sources: As mine gas might form explosible gas mixtures, any ignition sources have to be avoided when staying in a hazardous area. Furthermore, in special cases, one must use explosion-proof measuring device and tools.
- Ventilation: Some common ventilation techniques that can be applied in existing buildings are presented in chap. 8.3.2.
- Locking of enclosed areas: Locking a hazardous area is regarded to be a useful immediate measure to prevent persons from entering it.
- Evacuation: Evacuation is another immediate measure.

- Awareness-raising and Communication: In general, all persons who live inside the potential impact areas should be informed about the potential dangers of mine gas, and should be able to act properly when encountering a hazardous area.

8.3 Potential practical Control measures

8.3.1 Safeguarding measures for buildings under construction

8.3.1.1 Gravel-bed drainage below bottom slabs

For the gas protection of buildings under construction a gravel bed with a vertical drain layer (filtration ditch) along the exterior wall may be placed below the bottom slab (Fig. 8).

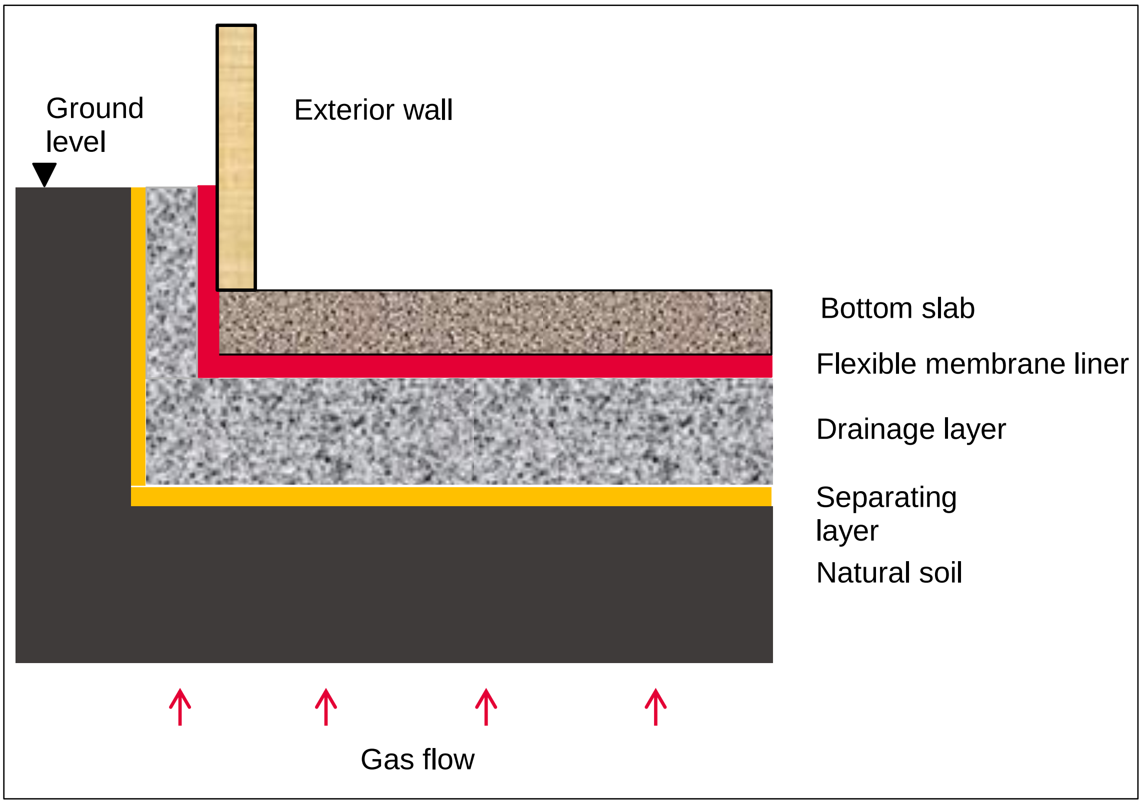

Fig. 8: Gravel-bed drainage below bottom slabs

The drainage ensures

- a two-dimensional distribution of potential gas emissions
- a gas discharge via the vertical drainlayer

in order to avoid to a large degree a potential gas overpressure below the bottom slab.

Additionally, bottom slabs and wall cable/pipe routings have to be designed as impermeable as possible.

8.3.1.2 Gravel-bed drainage with embedded drainage pipes

If necessary, for a certain gas flow auxiliary drain pipes may be embedded in the gravel bed (Fig. 9). These pipes can either end in the vertical drain layer or be joined in a collector pipe running upward along the building and ending above the roof.

All bottom slabs and wall openings below ground surface must be designed as impermeable as possible.

8.3.1.3 Design of an impermeable bottom slab

Alternatively the bottom and wall structure up to the ground surface may be build out of watertight concrete, which is supposed to seal water access as well as gas access.

All bottom slab and earth-covered wall openings must be realised using high quality sealings.

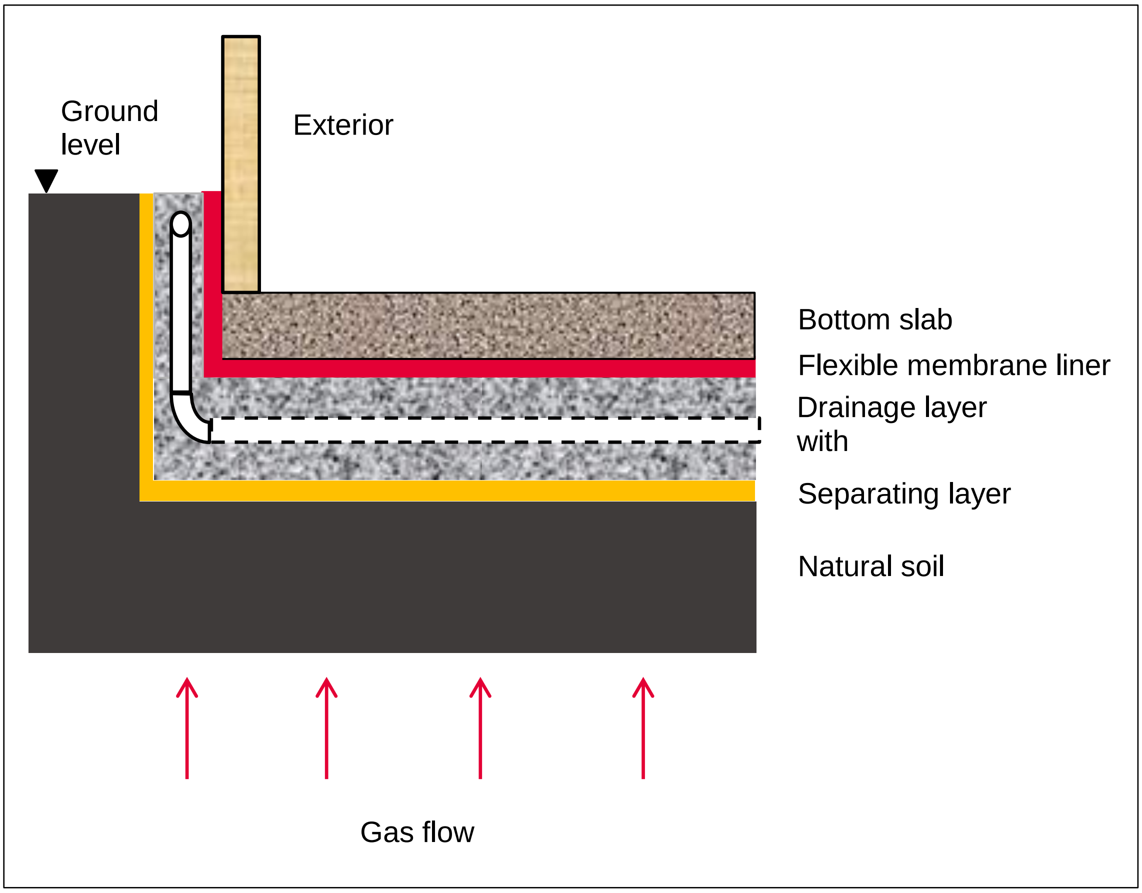

Fig. 9: Gravel-bed drainage with embedded drainage pipes

8.3.2 Control measures for existing buildings

Contrary to new constructions for existing structures measures are more difficult and require solutions other than standard methods. Methods for a specific or a potential hazard have to be adapted to the number and the condition of polluted structures/buildings.

8.3.2.1 Natural cross ventilation

For low gas emissions a natural cross ventilation may be sufficient depending on the gas volume, the building structure, indoor layout and the options for natural ventilation (number of windows). Natural ventilation must be maintained permanently (even in winter times).

8.3.2.2 Sealing of gas access points

Detected gas access points should be sealed durable with non-shrinking material. But sealing only makes sense if it does not provoke leakages for further gas access. All protective procedures are depending on the building structure.

8.3.2.3 Forced ventilation

A forced ventilation (fan) may be installed if higher gas flow cannot be avoided with sealings or diluted to a harmless atmosphere using natural cross ventilation. One single or various fans in the outside wall of a building provide the air exchange between indoor and outdoor atmosphere. The fans may run perpetually or automatically, controlled by a stationary gas monitor with a concentration sensor.

8.3.2.4 Passive degassing applying gas drainages and gas wells

It will probably not be useful to apply sealings or ventilation installations in every unit if a great number of buildings or a sewage system is affected by gas. In such a case the entire polluted area should be the target of degassing measures.

Horizontal drainage layout or vertical gas wells are appropriate methods for the gas drainage from the substrate or at least a reduction of gas under pressure.

8.3.2.5 Active drainage systems

Depending on the substrate, the building foundation and the size, a passive gas drainage may not be the satisfactory solution. An active gas drainage based on the vacuum principle will in such a case be the successful version. It is advantageous that no operations at the building structure are necessary and gas can be kept off from areas in which sealing options are impossible. It is disadvantageous that permanent follow-up costs (energy, maintenance) are to be expected.

8.4 Result

Based on existing evidence in combination with recent measurements of degassing in the South Limburg coal district, no significant methane discharge can be identified at the surface. A hazard from potential explosion based on combustible gas mixtures, is therefore reduced to a minimum.

However, potential hazard by embroidering components (carbon dioxide, oxygen depletion) remains. Practical safeguarding measures against uncontrolled gas access into buildings, transferred from practical experience in the German Ruhr and Saar coal districts, are specified.

Gravel beds below bottom slabs and vertical drainlayers or impermeable bottom slabs of building constructions, in combination with sealings of pipe and cable ducts, are suggested as an adequate practice against gas access.

For existing buildings particular constructive modifications can be designed and in a lot of cases additional sealings of ground and wall openings as well as natural ventilation may provide the safety requirements.

9 Recommendations and proposals for Monitoring

9.1 General remarks

In the German Ruhr and Saar coal districts all buildings that are affected by mine gas (here methane) are subject to a monitoring programme. For this purpose, measurements of gas concentrations are executed in regular intervals (1 or 2 times per year). Particular buildings with a high level of pollution are perpetually monitored with stationary gas monitors. Monitoring of that intensity is not deemed necessary based on the recent evidence in South Limburg.

As mentioned in chap. 6, the area that is related to Category (c) (see Plan 1) was identified to be decisive when it is to specify the areas that are potentially threatened by the emission of mine gas. To be more specific, mine shafts within or close to that area were considered to be the preferential pathways for mine gas. Further paths for the migration of mine gas might be associated with sinkhole events, “Drempels” or “Downward drillings” (see chap. 6).

Hence, the recommendations and the proposals for monitoring measures that will be discussed below focus on the “Gas-emission-protection-zones” around the relevant shafts (see chap. 6). Some remarks are given for sinkhole events and “Drempels” as well as “Downward drillings” in areas of Category (c).

In general, the rise of mine water gradually diminishes the area that is potentially threatened by the emission of mine gas (see Plan 1). According to the findings of WG 5.2.4/5.2.5 mine water is going to rise to a level of 80 mNAP (‘average case’) in the respective area. However, the shafts that were identified to be a present-day hazard will still be a hazard in this final state of mine water rise because in the surroundings of the shafts the Carboniferous bedrock will not be submerged completely.

9.2 Gas-emission-protection-zones

9.2.1 Existing buildings

Existing buildings and present land use within “Gas-emission-protection-zones” usually should have something like a “right for continuance”. Therefore, the actual approach related to existing buildings should be concentrated on monitoring. Furthermore, administrative tools aiming at general awareness-raising should be implemented with respect to the Dutch legislation.

Monitoring may focus on buildings or enclosed spaces that, at least partially, cover the “Gas-emission-protection-zones” of the relevant shafts. In the first place, reference is made to both the historical mine shafts of Domaniale and Neu Prick as well as to the industrial shafts listed in Tab. 2. On the other hand in these coal fields less methane and rather carbon dioxide and low oxygen concentration is to be expected.

For buildings that are situated above the aforementioned shaft heads and in their „Gas-emission-protection-zones“ respectively, an exterior assessment (from outside the building) of the structural conditions of the building has to be conducted first. If relevant cracks or fissures in the walls or the bottom slabs of some buildings are noticed, these partly damaged buildings are the main target point for monitoring measures.

In such buildings semi-annual gas measurements should be performed using portable measurement device able to detect the constituents methane, oxygen and carbon dioxide. Measurements should be executed at low or decreasing air pressure conditions for optimum capture of gas influx. It is recommended to perform measuring campaigns in spring or autumn due to most distinct air pressure fluctuations.

The measuring intervals should be intensified to quarterly intervals if structural modifications like crack initiation or subsidence effects appear. It is of great importance to not only register the room air but in particular the air in cracks, bottom drains, cable and pipe ducts and empty conduits etc.

If increased gas concentrations (CH_4 > 5 % LEL[1], CO_2 > 0,5 vol.-%) or low oxygen concentrations (O_2 < 19 vol.-%) are noticed, measures for buildings or ventilation measures, as mentioned in chap. 8.3, have to be carried out.

9.2.2 Construction projects

To handle the risks from mine gas effectively, the principle of urban development should be not to increase the risk.

Therefore, in the context of construction projects within the „Gas-emission-protection-zones“ of the relevant shafts, in general, appropriate safeguarding measures according to chap. 8.2.1 have to be implemented. Furthermore, a monitoring has to be carried out during the whole construction phase. This monitoring can be carried out with portable measuring device and should include the measurement of both the CO_2- and the O_2-concentration. During all construction work that takes place in the excavation, the measurements have to be performed continuously.

[1] LEL Lower explosion limit; 4,4 vol.-% methane corresponds with 100 % LEL

For constructions that are equipped with safeguarding measures according to chap. 8, monitoring is not required.

9.3 Unflooded mine workings (category (c))

9.3.1 Sewage system

If not already required, portable measuring device that are able to detect the aforementioned gas components have to be carried along on any regular inspection of sewage systems within the threatened area (area c).

Sewage systems that cross areas of category (c) and in which noticeably high CO_2-concentrations were detected during a regular inspection have to be integrated into the monitoring measures. In this case, annual measurements of the CO_2- and O_2-concentrations should be performed at any entry to that particular sewage system.

For new sewer constructions within the threatened area (area c), appropriate safeguarding measures according to chap. 8 are recommended. In the special case of sewage systems this means that the pipes have to be designed as impermeable as possible. For worker protection during construction work in excavations see the recommendations in chap. 9.2.2.

9.3.2 Drill holes and foundation piles

For drill holes and foundation piles in areas associated to category (c) that are sunk through the uppermost aquiclude, the influx of oxygen-deficient gases with increased CO_2-concentrations cannot be excluded. There, the occurrence of flammable gases cannot be excluded as well.

Measurements of the CO_2- and O_2-concentration as well as the concentration of flammable gases have to be performed during the construction work using appropriate portable device. In this context, the use of explosimeters with catalytic bead sensors is recommended.

9.3.3 Sinkhole events

In case of a sinkhole event within the threatened area of category (c), the influx of oxygen-deficient gas with increased CO_2-concentration cannot be excluded. There, the occurrence of flammable gases cannot be excluded as well.

Measurements of the CO_2- and O_2-concentration as well as the concentration of flammable gases have to be performed on a periodic basis using appropriate portable device. In this context, the use of explosimeters with catalytic bead sensors is recommended. During construction work within or in the vicinity of sinkholes, continuous gas measurements have to be performed.

9.3.4 “Drempels” and “Downward drillings”

“Drempels” and “Downward drillings” were identified as further options for gas escape in areas of category (c).

Regarding the large number of “Drempels” and “Downward drillings” and the low probability of gas emission the benefit-cost ratio has to be taken into consideration (see ALARP-principle). Therefore, neither monitoring nor other measures are recommended as long as there is no definite evidence for gas emissions in a zone of former “Drempels” or old “Downward drillings”.

Essen, 31. August 2016/02. December 2016

DMT

Dr. Heribert Meiners | Michael Opahle

Gerhard Hölscher | Dr. Erwin Kunz

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Appendix 1

Na-ijlende gevolgen steenkolenwinning Zuid-Limburg

Final report on the results of the working group
5.2.6 - risk from mine gas

Bow-Tie-diagram: Mine gas

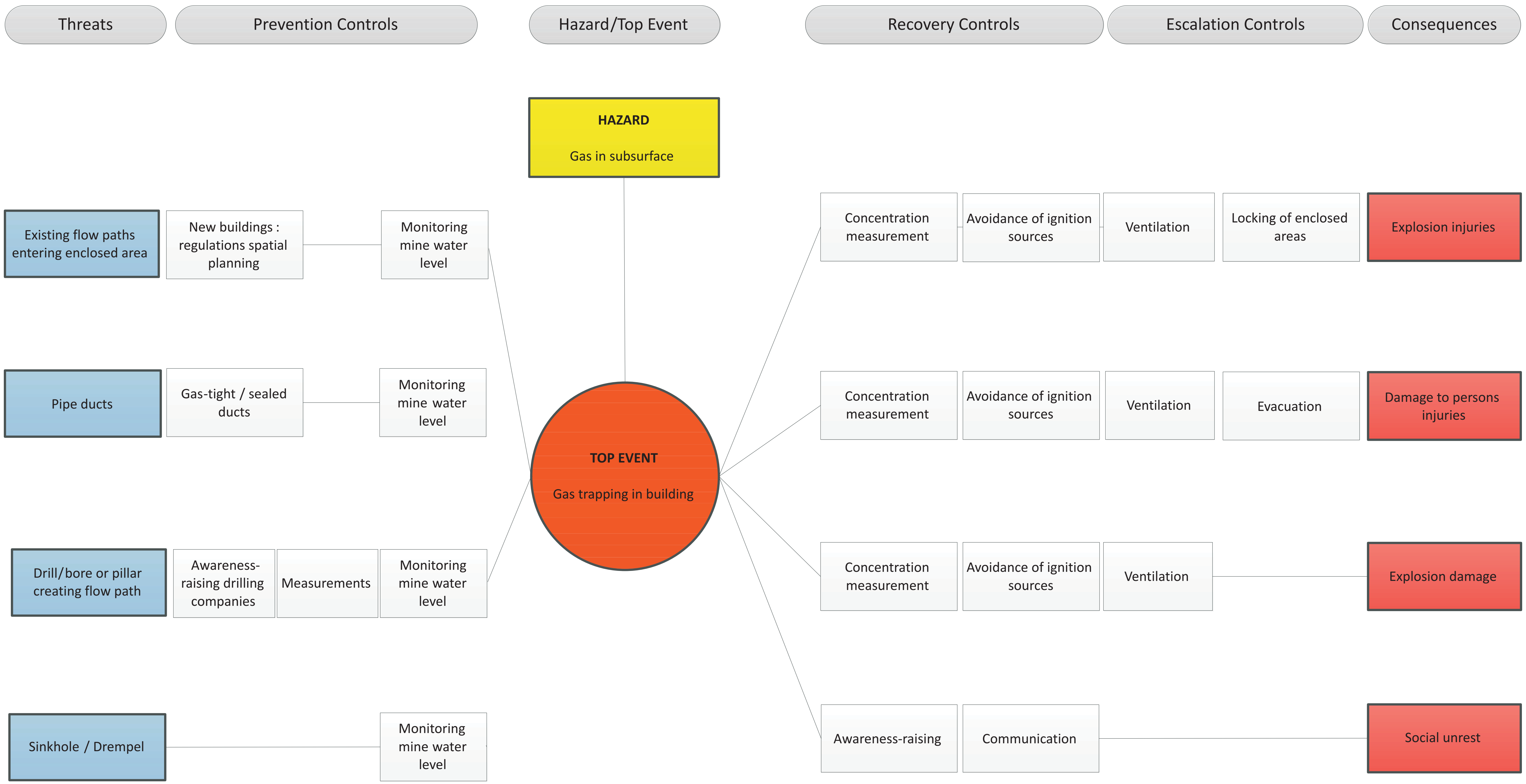
by

Projectgroup
"Na-ijlende gevolgen van de steenkolenwinning in Zuid-Limburg"
(projectgroup GS-ZL)

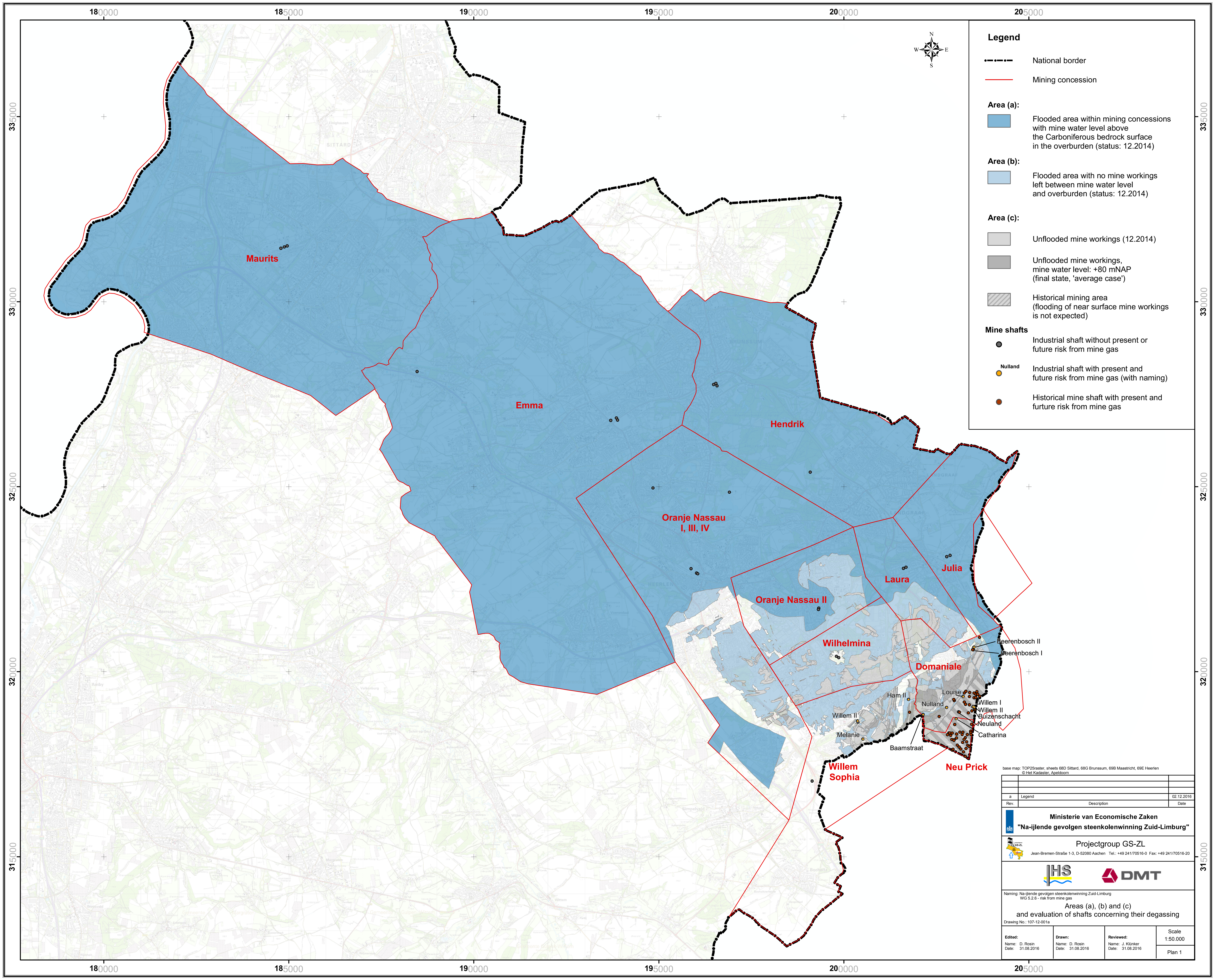
on behalf of
Ministerie van Economische Zaken - The Netherlands

Essen, 31. August 2016
(Rev. a: 02. December 2016)

5.2.6 Mine gas



Threats
Prevention Controls
Hazard/Top Event
Recovery Controls
Escalation Controls
Consequences
HAZARD
Gas in subsurface
Existing flow paths entering enclosed area
New buildings : regulations spatial planning
Monitoring mine water level
Pipe ducts
Gas-tight / sealed ducts
Monitoring mine water level
Drill/bore or pillar creating flow path
Awareness-raising drilling companies
Measurements
Monitoring mine water level
Sinkhole / Drempel
Monitoring mine water level
TOP EVENT
Gas trapping in building
Concentration measurement
Avoidance of ignition sources
Ventilation
Locking of enclosed areas
Explosion injuries
Concentration measurement
Avoidance of ignition sources
Ventilation
Evacuation
Damage to persons injuries
Concentration measurement
Avoidance of ignition sources
Ventilation
Explosion damage
Awareness-raising
Communication
Social unrest



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