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Published in:
Safety Science

Link to article, DOI:
10.1016/j.ssci.2011.10.004

Publication date:
2012

Document Version
Early version, also known as pre-print

Citation (APA):
Hedlund, F. H. (2012). The extreme carbon dioxide outburst at the Menzengraben potash mine 7 July 1953. *Safety Science*, *50*(3), 537-553. https://doi.org/10.1016/j.ssci.2011.10.004

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Project No.	
Document no.	Menzen-53
Version	
Date of issue	20 October 2011
Prepared	FHHE
Checked	

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Abstract

Carbon dioxide is an asphyxiant and an irritant gas. An extreme outburst of carbon dioxide took place 7 July 1953 in a potash mine in the former East Germany. During 25 minutes, a large amount of CO_2 *was blown out of the mine shaft with great force. It was wind still and concentrated* CO_2 *accumulated in a valley leading to multiple asphyxiation casualties. Based on a review of concentration-response relationships, the location of victims, and other information, it is concluded that concentrations of 10-30% carbon dioxide may have occurred 450 m from the point of release for at least 45 minutes. It is concluded that 1,100-3,900 tonnes of* CO_2 *were blown out of the mine shaft, possibly with intensities around 4 tonnes per second. It is also concluded that the large majority of the gas escaped as a near-vertical high-velocity jet with only little loss of momentum due to impingement. The release was modelled using PHAST. Output from the model is inconsistent with the asphyxiation harm observed. The high-momentum release is predicted to disperse safely and never reach the ground. Carbon dioxide capture and storage (CCS) schemes will involve handling and transportation of unprecedented quantities of* CO_2*. Case histories to date include sudden releases of* CO_2 *of up to 50 tonnes only, far too small to provide a suitable empirical perspective on predicted hazard distances for CCS projects. The 1953 outburst contributes to filling this gap.*

Keywords: Carbon dioxide accident, toxicology, asphyxiation fatality, jet dispersion modelling

Research highlights

- *A forceful accidental outburst of 1,100-3,900 tonnes of* CO_2 *is analyzed*
- *The* CO_2 *accumulated in a valley and led to asphyxiation fatalities*
- *Dispersion modelling predicts that the high-momentum release would dilute safely*
- *Predicted concentration contours cannot explain the asphyxiation harm observed*

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1 Introduction

1.1 Carbon dioxide

Carbon dioxide can exist as a gas, liquid, solid (dry ice) or supercritical fluid, depending on its temperature and pressure. The expression *dense phase* CO_2 is often used as a collective term for describing supercritical or liquid phase CO_2. (DNV 2008).

Gaseous carbon dioxide is odourless, colourless and often regarded as non-toxic and inert. It may act as a simple asphyxiant displacing the oxygen required to sustain life. It can accumulate in low-lying areas since it is 1.6 times denser than regular air.

Because of its extensive use and production, the hazards of CO_2 are well known and routinely managed (Benson et al. 2002)

The supply chain handles high purity commercial liquid CO_2 in refrigerated and pressurized tanks, typically at -30 °C and 15 barg. To give a sense of magnitude and scale, the North-European market is supplied by ships with capacities of 900-1,200 tonnes (Berger et al. 2004). Market participants inform us that the standard storage tank capacity is 330 tonnes and that terminals typically have 3-5 tanks, i.e. a storage capacity of about 1,000-1,500 tonnes. Very few consumer sites have storage capacities in excess of 50 tonnes, often much less.

1.2 Accident history

Pressurized storage vessels holding liquid carbon dioxide have been a source of several major accidents (Table 1). Clayton and Griffin (1995) did extensive research to obtain information on CO_2 vessels that had ruptured. They concluded that while the overall safety record of carbon steel storage vessels had been good, some accidents had been caused by low-temperature damage due to auto-refrigeration.

Lampe and Schattka (2010) report a 2008 incident involving the malfunction of an industrial fire suppression system in a large warehouse with flammable paints and solvents located in a mixed industrial/residential area in Mönchengladbach (Germany). The fire suppression system released about 50 tonnes of carbon dioxide inside the warehouse. The release took place Saturday in the early morning hours, under a meteorological inversion condition. There were no employees present on the premises and fire fighters who entered the building did so with self-contained breathing apparatus due to the asphyxiation risk. Outside the warehouse however, several fire fighters collapsed due to oxygen deficiency and 14 citizens collapsed on the nearby public road, including one motorcyclist who fell off his bike.

A natural disaster involving a large release of carbon dioxide took place in Lake Nyos (Cameroon) in 1986. Due to an unusual combination of factors it is possible for carbon dioxide of volcanic origins to accumulate slowly as a dissolved gas in the dense saline lower strata of the lake, eventually leading to a highly unstable situation. In 1986 a sudden eruption of carbon dioxide from the lower strata took place. The amount released may have been up to 1.5 million tonnes. The denser than air plume of carbon dioxide followed the natural topographic depressions of the land, travelling up to 25 km and killing an estimated 1,700 people and large numbers of livestock.

Location	Year	CO_2 amount	Release type	Hazard	Fatalities	Source
Ireland	1986	15 tonnes	High-momentum	Pressure vessel failure (brewery)	0	Clayton and Griffin (1995)
Sweden	1960	25 tonnes	High-momentum	Pressure vessel failure	unknown	Clayton and Griffin (1995)
Worms (Germany)	1988	30 tonnes	High-momentum	Pressure vessel failure, (foods/drinks industry), blast damage, tank fragments hurled more than 300 m	3	Clayton and Griffin (1995)
Italy	unknown	50 tonnes	High-momentum	Pressure vessel failure	unknown	Clayton and Griffin (1995)
Mönchengladbach (Germany)	2008	50 tonnes, fire extinguishing system	Low-momentum	Asphyxiation. Citizens collapse on nearby public road, probably 50-100 m	0	Lampe and Schattka, (2010)
Lake Nyos, (Cameroon)	1986	up to 1.5 million tonnes	Low-momentum	Asphyxiation, plume travels up to 25 km	1,700	Kling et al. (1987)

Table 1 Examples of accidents involving major releases of carbon dioxide. The extreme Lake Nyos disaster, is the only recorded instance of a sudden release of carbon dioxide above 50 tonnes.

1.3 New technologies involving large amounts of CO_2

Carbon (dioxide) capture and storage (CCS) schemes aim to store CO_2 permanently in deep geological formations due to concerns over greenhouse gas emissions. Natural gas from the Snøhvit gas field in Norway contains 5-8 % CO_2, which is separated and injected into a formation below the gas field. Injection began in 2008 and will eventually amount to 2,000 tonnes per day (NPD 2010). The proposed Barendrecht project in The Netherlands involves injecting about 1,100 tonnes of CO_2 per day from a nearby refinery into a depleted gas reservoir (Molag 2009). The amount handled per day in these projects is roughly similar to the storage capacity of an existing large CO_2 terminal. Significantly larger quantities may be handled if, or when, CCS expands into power generation. The planned FutureGen project in the USA involves injection of up to 6,800 tonnes per day from a 275 MW coal gasification power station (DoE 2007). Capturing emissions from a single standard 1,000 MW coal-fired power plant will require handling of 30,000 tonnes CO_2 per day (Price et al. 2007). In any case, CCS schemes will involve handling and transportation of CO_2 on a hitherto unprecedented scale and magnitude.

Transmission pipeline risk studies have assumed that block valves would close in the event of pipeline damage and limit the released quantity to the inventory of a single pipeline section. To give a sense of magnitude and scale a severed 19” pipeline section 8 km long may release 1,300 tonnes of carbon dioxide in about 3-4 minutes. A worst-case hazard analysis for the FutureGen project suggests that acute life threatening concentrations, defined as exceeding 7% CO_2, may occur within 70 m of the point of release and that no serious threat to human health exists beyond 200 m, see Table 2. The predictions of other studies are more optimistic. Molag (2009) defines concentrations in excess of 10% harmful, and states that it is highly unlikely that such high concentrations will occur in the event of a pipeline accident. A photo of a Dutch residential area in the vicinity of an existing CO_2 pipeline is included, presumably to underline the suggestion that an accidental release is unable to cause harm. Indeed, proponents of the Dutch Barendrecht project argue that it is safe; CO_2 is not poisonous and cannot explode (WSJ 20090421).

Planned pipeline				**Release**		**CO_2 hazard range (m)** [a]		
Name	Diameter (inch)	Section length (km)	Inventory (tonnes)	rate (tonnes per second)	duration (seconds)	Fatality likely (>7 vol%)	No life threat (<4 vol%)	No serious effect (< 3 vol%)
Mattoon	14.4”	0.8	72.3	4.4	16	<1	< 1	< 1
Tuscola	14.4”	8	723	4.4	162	47	96	140
Jewett	19.3”	8	1,290	8.0	162	66	136	202
Odessa	12.8”	8	568	3.5	162	41	82	121

Table 2 Transmission pipeline risk study considers the sudden releases of up to 1,300 tonnes of carbon dioxide. No life threat exists beyond 140 m. Source: DoE (2007)

[a] *Worst case estimated distance to “no life threatening effects” (4 vol% CO_2 (TEEL-3) and “no serious or irreversible effects “ 3 vol% CO_2 (TEEL-2). The gas was assumed to escape as a horizontal jet at ground level and modelled in SLAB, a hazardous air dispersion model approved by the U.S. EPA.*

These predictions are largely based on expected jet dilution effects. CO_2 released from a high-pressure source would develop a velocity up to the speed of sound and entrain a quantity of air of many tens of times its own weight. Mazzoldi et al. (2009) report a theoretical study in which computational fluid dynamics (CFD) tools were used. Their study case on the release of 1,800 kg/s CO_2 perpendicular to the wind direction for 10 minutes is particularly instructive. If no jet dilution takes place, i.e. the release velocity is 0 m/s, the maximum downwind distance to 10 vol% is estimated at about 850 m. For a near-horizontal jet with a relatively modest release speed of 49 m/s, just about one fifth of the sonic velocity, the maximum downwind distance to 10 vol% is estimated to be only 50 m.

Methodological choices and assumptions abound in hazard analysis. Koornneef et al. (2009) examine nine published risk studies and report a considerable variation in computed hazard distances; they conclude that further validation of release and dispersion models is necessary.

Comparison with observed consequences of actual large-scale energetic releases of CO_2 may provide an empirical perspective on model predictions. There is a gap however, as reported accident cases comprise releases in the range of tens of tonnes only, none in the range of hundreds or thousands of tonnes. The 7 July 1953 outburst in Menzengraben contributes to filling this gap.

1.4 CO_2 dangers in potash mining

Carbon dioxide is a well known mining hazard and responsible for the lives of countless miners. For example, in Lower Silesia, major carbon dioxide disasters took place in the Wenzeslaus coal mine near Jugów (Hausdorf) 9 July 1930 with the loss of 151 lives, and 10 May 1941 in the Ruben coal mine near Nowa Ruda (Neurode) with 187 miners killed (Farrenkopf 2002); both locations now in Poland, then in Germany. Outbursts of carbon dioxide have been reported in evaporite (potash) mines worldwide. The salt mines of the Werra district of the former German Democratic Republic (DDR) are unique for the presence of large quantities of CO_2 (Müller 1958). The most frequent and largest CO_2 outbursts on record have taken place there (Ehgartner et al. 1998).

Potash is extracted for its content of potassium, an important plant nutrient. The evaporite deposits of the Werra district are thought to have formed some 200 million years ago when the land was closer to equator. Sections of the sea were cut off from the ocean and evaporation exceeded inflow. Over time, the increasingly concentrated brine receded to smaller basins within natural depressions in the terrain and salts would eventually begin to precipitate according to their inability to stay in solution, known as a precipitation sequence. Because potassium salts are generally highly soluble they would be naturally concentrated and precipitate last in relatively small areas with respect to the size of the original seas. Finally, the deposits were overlaid with other material, protecting them from weathering and taken to their present location by tectonic forces (Fite 1951). Selected important evaporite minerals are: NaCl (halite), KCl (sylvite) and $KCl{\cdot}MgCl_2{\cdot}6H_2O$ (carnallite).

A period of basaltic volcanism took place 14-25 million years ago shaping the appearance of the Werra district today with ridges and cone-shaped mountains of volcanic origins. Volcanic basalt rose through the mantle through local fault lines and basalt pipes, penetrating the evaporite deposits. The rising basalt created pathways for volcanic carbon dioxide and water, to impregnate nearby evaporite deposits and leading to complex local re-dissolution processes that can transform and redistribute salts. For example, magnesium chloride is thought to leach out of carnallite (Hoppe 1960), possibly with a volume loss of up to 50% (Zapp and Lindloff 2003), leading to pore formation where other salts subsequently may precipitate or CO_2 be trapped. This particular leaching process increases the potassium content of the original carnallite and may eventually transform it into a bluish secondary sylvite mineral, in German known as *Umwandlungssylvinit*, potentially with abundant gas inclusions. Seams of Umwandlungssylvinit have been a source of extreme carbon dioxide outbursts (Gimm 1954, Marggraf 1971).

Due to the lithostatic pressure of the overburden, entrapped carbon dioxide will be in its dense phase. Liquid carbon dioxide has seeped into mine tunnels forming flakes of dry ice or has escaped violently, producing sounds compared to machine gun fire (Müller 1958). An outburst is a sudden violent expulsion of gas and salt leading to cavity formation. The likely outburst mechanism is shown in Figure 1. The sudden explosive depressurization of entrapped CO_2 is thought to lead to a chain reaction expelling a mixture of gas and fractured salt from an inward-moving expulsion front. The cavity may branch out and expelled salt from upper cavities may bury and hide the existence of lower cavities (Duchrow 1959; Duchrow et al. 1988). As reported by Marggraf (1971) the resulting temperature drop is modest, only about 4 °C, and the carbon dioxide gas may attain velocities in excess of 200 m/s and the expelled salt approx 50 m/s. An outburst can unleash forces with great destructive potential. A four tonnes salt boulder has been moved 60 m down a tunnel and a heavy duty drilling vehicle weighing 11.3 tonnes has been overturned and displaced 145 m (Duchrow 1997). Blasting work was known to be able to trigger major outbursts. Consequently, gas-tight safety chambers were built where miners preemptively took refuge during blasting. In 1938, two miners in a safety chamber overheard the completion of the blasting sequence. Upon leaving "*they suddenly heard howling and roaring winds, like the most severe storm, and the noise of overturned conveyor cars coming tumbling down the tunnels. They immediate returned to the chamber.*" (Müller 1958:66).

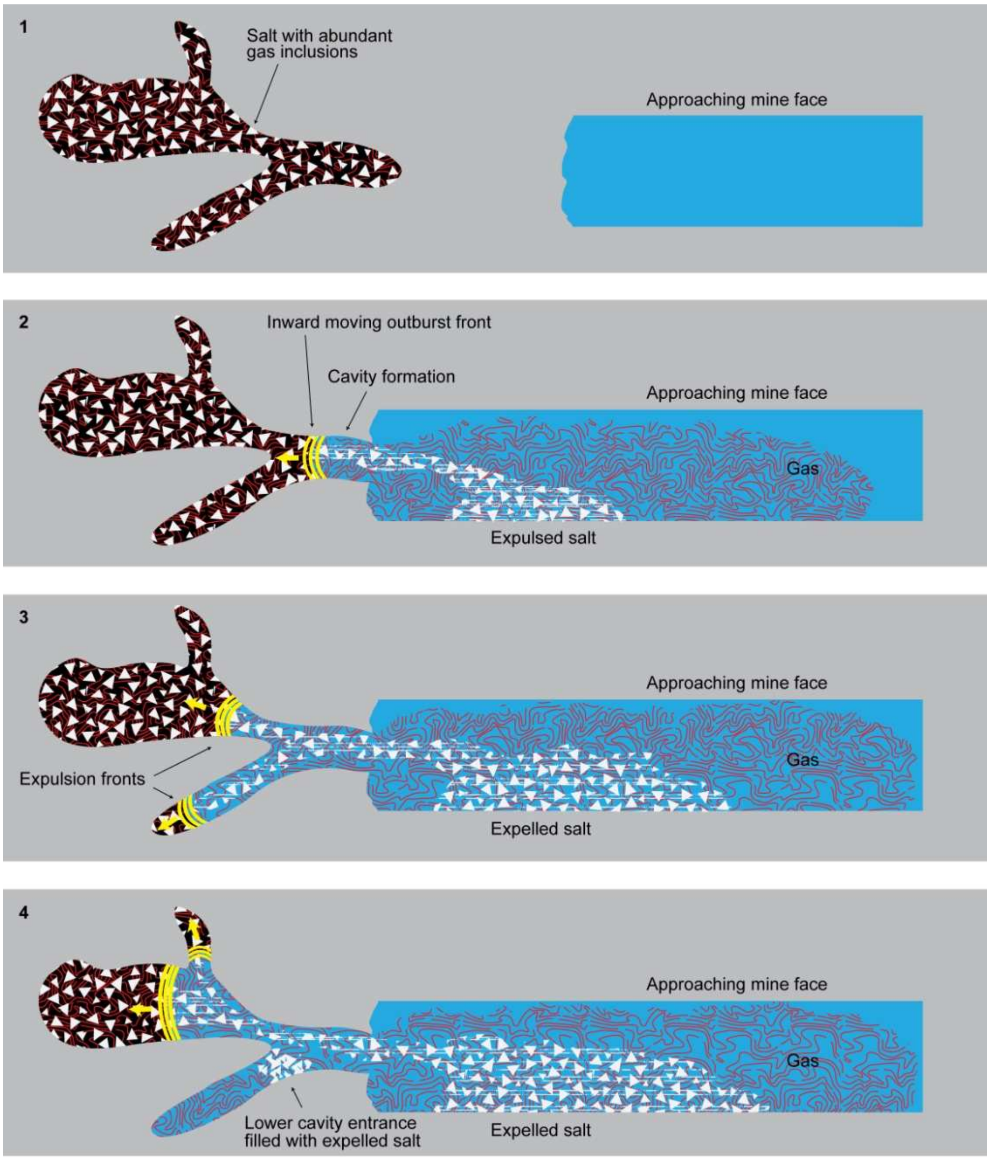

Figure 1 *Suggested CO_2 outburst mechanism when a potash seam excavation face approaches a CO_2-rich deposit. Based on: Duchrow et al. 1988*

To give a sense of magnitude and scale, selected outbursts are presented in Table 3. While major outbursts took place in most mines, the Menzengraben mine was particularly affected. The consequences were also more severe because the Menzengraben mine had a relatively small volume with respect to the outburst size, much smaller than other mines (Junghans 1953b).

Date	Mine	salt burst (tonnes)	CO_2 released (m^3)	Source
1908.11.27	Dietlas	2,700	18,000	(a)
1938.04.15	"Marx-Engels"	7,000	not stated	(a)
1938.12.31	"Ernst Thälmann"	15,000	200,000	(a)
1942.01.29	Menzengraben	5,000	75,000	(a)
1943.06.03	Menzengraben	18,000	450,000	(a)
1950.05.10	"Marx-Engels"	20,000	not stated	(a)
1951.10.13	Menzengraben	13,000	200,000	(a)
1953.07.07	Menzengraben	65,000	700,000	(a)
1957.10.15	Menzengraben	22,000	400,000	(a)
1981.08.21	not stated	6,000	1,000,000	(b)
1984.5.25	not stated	110,000	2,300,000	(b)

Table 3 *Selected reported carbon dioxide outbursts in the Werra district. As discussed later in text, early CO_2 amounts are probably not based on measurements. Sources: (a) Hoppe 1960:109, (b) Duchrow et al. 1988:247*

The outburst hazard was eventually controlled using a combination of pre-emptive evacuations prior to blasting, automatically closing heavy duty drop doors to retard depressurization and attenuate destructive gas velocities in the tunnels, powerful ventilation equipment, communication devices, safety chambers and prognosis drilling resulting in little loss of life.

The 1953 outburst in the Menzengraben mine may be the world's largest in terms of cavity size (Ehgartner et al. 1998). The largest outburst on record known to the author took place in 25 May 1988 and lead to the expulsion 2.3 mio. m^3 CO_2 (Duchrow et al. 1988). The mine is not named but can be inferred to be in the Werra district.

The 1953 outburst led to high concentrations of CO_2 in the valley. The actual extent of the gas cloud and the concentrations involved are unknown but may be inferred from the location of victims, the observed harm and concentration-response relationships. Because rescue parties were deterred from approaching the scene it is also relevant to review warning properties and possible means of detecting dangerous concentrations.

2 Carbon dioxide toxicity

2.1 Acute CO_2 toxicity thresholds

Generally accepted concentration-effect relationships can be found in the recommended standards for occupational exposure to carbon dioxide (e.g. NIOSH 1976). Exposure to 4–5% CO_2 for a few minutes leads to headache, dizziness, and unpleasant dyspnoea (difficulty of breathing). Exposure to 7-10% for several minutes to an hour results in headache, increased heart rate, shortness of breath, dizziness, sweating, rapid breathing, and near or full unconsciousness. Dizziness, drowsiness, severe muscle twitching, and unconsciousness occur after one to several minutes exposure to 10–15%. Above 15%, loss of consciousness occurs in less than one minute. Death occurs within minutes at 30%. Carbon dioxide acts as a potent cerebral vasodilator, which may explain many of the symptoms associated with carbon dioxide toxicity, including headache, dizziness and narcosis (Benson et al. 2002).

The CO_2 concentration endpoints used in earlier risk studies wary. Mazzoldi et al. (2008) take 0.2% and 1.5% as “levels of concern”, and 7% as the limit above which “human fatality is likely to occur”. A US study (DoE 2007) cites Temporary Emergency Exposure Limits (TEEL) defined by the US DoE of which TEEL-1 = 3% (adverse), TEEL-2 = 3% (irreversible adverse), and TEEL-3 = 4% (life threatening). Aines et al. (2009) also use TEEL-2 and TEEL-3 values.

The Immediately Dangerous to Life or Health (IDLH) value defined by US NIOSH is currently 4%, i.e. similar to TEEL-3 (NIOSH 1994). . The TEEL and IDLH values appear to be cautiously defined; or more precisely: they may attempt to define protection from harm rather than harm itself, based on unstated safety factors. Risk studies from The Netherlands use so-called probit functions based on the assumption that 4 hours exposure to 10% results in 1% lethality and 5 minutes exposure to 20% results in 99% lethality (Koornneef et al. 2009).

Studies on long-term exposure to elevated levels of CO_2 for submarine, aircraft and manned spacecraft operations provide an illuminating perspective on TEEL and IDLH values. Healthy individuals can tolerate continuous inhalation of 3% (i.e. TEEL-2 “irreversible adverse”) for at least one month and 4% (i.e. IDLH “immediately dangerous”) for over a week (Glatte et al. 1967, Lambertsen 1971). When exposed to 6% for 16 minutes, many test subjects reported a subjective feeling of difficulty in doing a card sorting exercise but objectively there was no deterioration in their performance, and more than two-thirds believed the CO_2 would not influence their ability to drive a car or pilot a plane safely (White et al. 1952). Above 7 % both objective and subjective effects (dyspnoea and mental impairment) become progressively more pronounced (Lambertsen 1971).

Unconsciousness inevitably occurs at 15% or higher. 20 or 30% induces uncoordinated neuromuscular response and generalized epileptiform convulsions. Exposure to 30 % can lead to unconsciousness in less than 30 seconds and convulsions within one minute (Lambertsen 1971).

2.2 Warning properties and means of detection

While the US NIOSH confined space hazard classification system defines carbon dioxide as a nontoxic, inert gas that displaces oxygen required to sustain life, exposure to elevated concentrations has significant physiological effects before oxygen dilution could be significant (Benson et al. 2002). One such effect is respiratory compensation as carbon dioxide dissolved in the blood stimulates the breathing control centre in the brain. Respiratory stimulation becomes particularly marked when the concentration exceeds 3%, which is considered the threshold at which most individuals become aware of the effect. The average volume breathed during one minute increases from 7 litres at 0.03% carbon dioxide to 9 litres at 2%, 11 litres at 3%, 26 litres at 5%, and 77 litres, i.e. a ten-fold increase, at 10% (Benson et al. 2002, Lambertsen 1971). Simple calculation yields that a concentration of 10% carbon dioxide in regular air corresponds to an oxygen concentration of about 19%, i.e. well above the lower limit for oxygen deficit (hypoxia) effects, which is 16% oxygen (NIOSH 2004). Severe symptoms of laboured breathing will thus be experienced before effects of oxygen deprivation set in.

Carbon dioxide dissolves in the moisture of the mucous membranes of the eyes and the respiratory tract producing carbonic acid, a membrane irritant. Because carbon dioxide is only modestly soluble in water, relatively high concentrations are required to produce irritation. The upper airways are innervated by both the first cranial (olfactory) and fifth cranial (trigeminal) nerves, mediating the sensations of olfaction and mucous membrane irritation, respectively. Trigeminally mediated sensations, notably nose and throat irritation, are important in the study of air-pollution-related health complaints (Shusterman et al. 2001). Carbon dioxide, being both odourless and a membrane irritant, is useful in tests of nasal trigeminal chemoreception sensitivity because it provides no olfactory cue to the test subjects. The lower detection threshold seems to be about 15% (Shusterman et al. 2001) with a median value of 28 % (Shusterman and Balmes 1997). Severe CO_2 poisoning effects, including laboured breathing, will therefore occur before sensory warning from mucous membrane irritation becomes apparent.

Talks with retired miners from the Menzengraben area revealed an unexpected means of detection. When asked how they would know if they accidentally ventured into mine tunnels with high concentrations of CO_2, invariably their first response was that CO_2 was odourless. However, because it is denser than air, concentrations at ground level could be very high while still being breathable for an individual standing upright. Independently, miners said that this produced a distinct feeling of warmth around the lower extremities. A miner told of the horror of walking "in hot water", whilst rushing to safe higher levels after a sudden carbon dioxide outburst. No literature has been identified, describing the phenomenon. In the Lake Nyos disaster, survivors reported a sensation of warmth before losing consciousness, which the investigators dismissed as hallucinatory (Kling et al. 1987). In old medical literature, there is sporadic mention of an atmosphere of carbon dioxide surrounding an area of skin giving a sensation of warmth (e.g. Howell and Bowditch 1901)[1]. Because CO_2 gas has a lower thermal conductivity than air it could be speculated simply to act as an insulator.[2]

Retired miners also recalled that they had a burning lamp on a line. On suspecting the presence of CO_2, e.g. upon experiencing laboured breathing or a sensation of warmth, they would lower the lamp near to the ground. If the flame flickered or went out concentrations would be dangerously high. The theoretical minimum carbon dioxide concentration for extinguishment of higher paraffins is 28% (NFPA 12, 2005). The lamp test is thus only capable of detecting of very high concentrations that would cause rapid loss of consciousness.[3] Miners believed that a single breath of concentrated CO_2 could lead to collapse, and once down, death would ensue rapidly.

2.3 Exposure to extreme concentrations

Severe irritation of the mucous membrane may trigger reflex nerve arcs, which act protectively against respiratory tract irritation. The reflex is produced 700-800 ms after inhaling a critical concentration of CO_2 i.e. before the stimulus reaches the lungs (Dunn et al. 1982). The primitive Kratschmer reflex is mediated through the trigeminal nerve and may result in life threatening reflex changes in autonomic, cardiovascular, and respiratory systems. Effects include laryngospasm, bronchospam, respiratory arrest and depressed heart rate. It is a known possible complication during surgery resulting from severe mucous

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[1] Literature from the field of balneotherapy offer related mention, observing that therapeutic baths in carbon dioxide enriched water also produces a subjective feeling of warmth. Schmidt (1989) studies indifference temperatures and reports that a 32 °C carbon dioxide bath is experienced as a 35 °C fresh water bath. Hartmann et al. (1997) show that immersion in CO_2 enriched water produces local vasodilatation and increased cutaneous blood flow. Schmidt (1989) argues however, that the subjective feeling of warmth cannot be explained by vasodilatation alone, but must be caused by sensory nerve stimulation.

[2] The thermal conductivity of air and CO_2 is 0.0262 and 0.0166 respectively, i.e. the value of CO_2 is 63% that of air. Both properties are at 300 °K and atmospheric pressure, unit is W/m/°K. Source: Perry and Green (1984) Table 3-314

[3] Later tests revealed that the lamp was capable of detecting CO_2 levels "above 15%" CO_2 only, and its use was discontinued (Pickert et al. 1980). The source refers to a gasoline lamp, while retired miners informed they had carbide lamps.

membrane irritation caused by packing of the nasal passage (Nirmala et al. 2006). Early animal experiments exposing rabbits to 60-80% CO_2 reported instant powerful respiratory effects, combined with general extensor spasms of the greatest intensity, attributed to the Kratschmer reflex. When the animals were allowed to breathe air again, recovery took place rapidly, first with spontaneous powerful movements of cramp-like nature (Hill and Flack 1908).

The use of CO_2 in abattoirs has been studied extensively. Slaughtering is a process of bleeding an animal to death and it is a statutory requirement in many countries that animals be stunned prior to exsanguination (Becerril-Herrera et al. 2009). CO_2 stunning of pigs is popular since it requires less handling and allows higher throughput of animals compared with other methods (Hartung et al. 2008). Pigs are typically guided into a gondola, which is lowered into a CO_2 pit. When stunning in 80–90% CO_2, loss of sensitivity and consciousness is said to be induced within about 30 seconds. Pigs typically exhibit agitation with forced breathing, stretching the head upwards and vocalizing loudly at the beginning of gas stunning (Nowak et al. 2007). Exposure time in the pit and the time lapse between stun and sticking (bleeding) are critical parameters as the animals can regain consciousness after exhalation of CO_2. For example, if stunned in 83% CO_2 for 92 seconds and allowed a recovery period of 58 seconds before sticking, more than a third of the pigs showed either a sensibility to pain or a righting reflex (Velarde et al. 2000).

Accident case stories suggest that humans may also recover from exposure to extreme concentrations. Many survivors of the Lake Nyos disaster, who awoke 6 to 36 hours after losing consciousness, found that their oil lamps had gone out, although they still contained oil, and that their animals and family members were dead (Kling et al. 1987). Concentrations must at least briefly have exceeded 28% to extinguish the lamps. Halpern et al. (2004) report a confined space industrial accident in an ice-making factory where impact damage to a discharge valve led to a sudden major CO_2 discharge. 25 persons were exposed to almost 100 percent CO_2 for a few seconds up to 1 minute before successfully reaching open air. Within seconds, many of the exposed persons were incapacitated and needed to be evacuated by co-workers. All victims recovered fully.

For the purposes of evaluating the consequences of the 1953 Menzengraben outburst concentration-effect relationships have been defined in Table 4. It is clear that the effects cannot be explained from oxygen deficiency alone.

Concentration (vol%)		Effect
CO_2	O_2 [a]	
3		50 percent increase of breathing volume, threshold for laboured breathing to become conscious
5		Four-fold increase of breathing volume, most individuals will retreat fearing for their lives
7	19.5 [b]	Discomfort, dizziness and other effects of mental impairment become progressively more pronounced above this level
10	18.9	Ten-fold increase of breathing volume, terror induced by laboured breathing will urge even the most determined individuals to retreat. Ability to attempt to escape not seriously impaired. Possible loss of consciousness after prolonged exposure.
15	17.9	Loss of consciousness occurs in less than one minute. Lower threshold for experiencing mucous membrane irritation. Confusion and possible membrane irritation may impede escape
20	16.8[c]	Confusion or mucous membrane irritation will likely incapacitate victims making escape unlikely. Death may ensue.
30	14.7	Instant incapacitation. Loss of consciousness occurs in less than 30 seconds, convulsions within one minute. Death may ensue. 50 percent of individuals will experience mucous membrane irritation. Flames extinguished, combustion engines stall
>30		Unconsciousness and death; depending on exposure profile, some individuals may recover

Table 4 *CO_2 concentration thresholds used as a basis for evaluating the consequences of the 1953 Menzengraben outburst.*

[a] *Selected corresponding oxygen concentrations in regular air, computed as $(100-C_{CO2})*0.21$, where C_{CO2} is vol% CO_2.*

[b] *For a workplace, 19.5 vol% oxygen is the lower limit defining an oxygen-deficient atmosphere, the limit includes a safety factor (NIOSH 2004)*

[c] *Value above 16 vol% oxygen, the lower limit for oxygen deficit (hypoxia) effects (NIOSH 2004)*

3 The 1953 outburst

3.1 The Menzengraben mine, surroundings and topography

The Menzengraben mine, GPS 50°47’34” N, 10°05’59”E (#2 Shaft), is located in the Wartburgkreis of the state Thuringia (Thüringen) in the central part of Germany, in the Werra mining district. At the time of the accident the area was part of the German Democratic Republic (DDR). The mine is now closed.

The Menzengraben mine is located on the western ridge of a valley roughly midway between the towns Stadtlengsfeld (distance 2.2 km) to the southeast and Dietlas (distance 2.8 km) to the northwest. The NW-SE ridges rise some 100-150 m to both sides and the valley lowlands slope gently from Stadtlengsfeld towards Dietlas. In the lowlands, the river Felda, a tributary to the Werra river, winds from SE to NW, never far away from the main road connecting Dorndorf-Dietlas-Stadtlengsfeld and a railroad line which connected Dorndorf and Kaltennordheim.

In 1953 the mine was part of the Heiligenroda mining conglomerate. Originally it was part of the Großherzog von Sachsen mines, with #1 Shaft sunk in Dietlas and #2 and #3 Shafts sunk in Menzengraben. The Menzengraben shafts are located about 225 m apart, both have an internal diameter of 5.0 m. The #2 Shaft was used for ore hoisting and incoming ventilation, #3 Shaft for the personnel hoist and outgoing ventilation.

Due to the history of serious CO_2 outburst in the Menzengraben mine, the mining authority (TBBI) in Erfurt had passed an order in 1949 forbidding blasting when personnel were below ground. The order effectively mandated the use of electric detonators remotely controlled from above ground. The blaster monitored his work using a closed circuit microphone-loudspeaker system.

Salt hoisted at Menzengraben was loaded onto rail cars for processing at the Dorndorf factory. The local salt processing facilities known as the Old Factory were no longer in use. Near the mine access road, two two-storey factory buildings had been converted to homes for employees, henceforth referred to as the *Factory Settlement*. The majority of the miners lived in a settlement on the eastern side of the Felda, henceforth: the *Menzengraben Settlement*. A bridge across the Felda connected the mine with the main road. From the road junction a steep footpath lead up to the Menzengraben Settlement. A forest house was located on the western side in the direction Dietlas (Figure 2 and Figure 3).

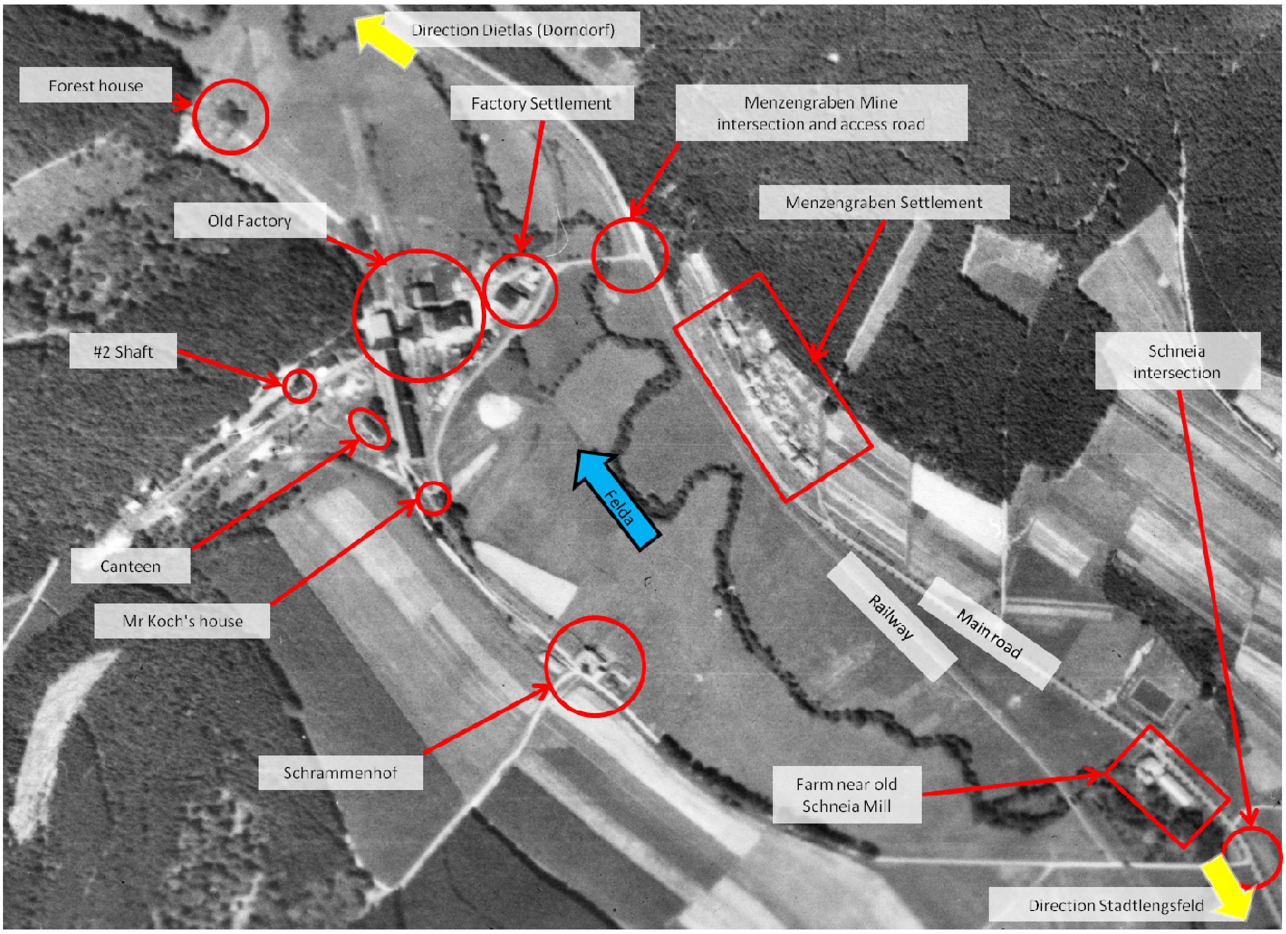

Figure 2 *Excerpt of high altitude USAF aerial photo, dated 22.7.1945. North is up. Source: Photo mrk 4518(4135-22), original scale 1:40,000. (Courtesy: Landesamt für Vermessung und Geoinformation, Erfurt - © GeoBasisDE / TLVermGeo, Gen.-Nr.:21/2011)*

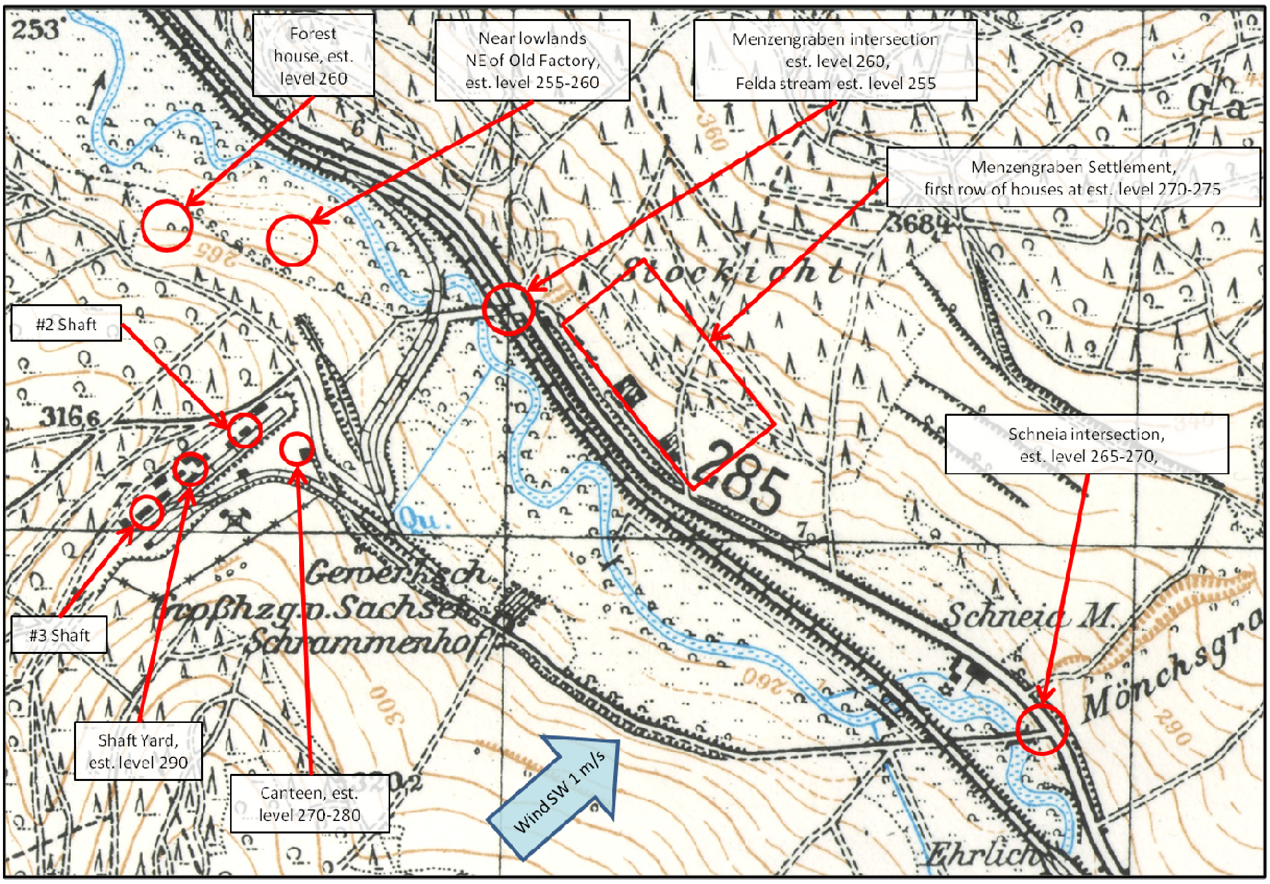

Figure 3 *Excerpt of old topographical map of the Menzengraben mine and surrounding area. North is up, grid lines are 1,000x1,000 m. Level indications for locations of interest are estimates only, read from map, supplemented with observations from field visit in Aug. 2010, and compared with Google Earth, which appears to be slightly imprecise for some locations. Source: Map 5226. Edition 1955, Hessischen Landesvermessungsamt, (Based on original from 1907) Original scale 1:25,000. (Courtesy: Landesamt für Vermessung und Geoinformation, Erfurt - © GeoBasisDE / TLVermGeo, Gen.-Nr.:21/2011)*

3.2 Primary sources

Primary sources on the 7 July 1953 outburst are sparse. The key primary source is a previously unpublished four-page company document written by the Heiligenroda mine manager Rudolf Junghans, dated 8th July 1953, i.e. the day after the accident, which relates the sequence of events, the emergency response and an early damage assessment (Junghans 1953a). An extensive account was later published in the mining journal Bergbautechnik as a two-part article (Junghans 1953b). The emphasis of the article however, is on the damage, the considerable difficulties in bringing the mine back into operation and the nature of the potash seams considered responsible for the outburst. The article holds little information on the extent of the gas cloud and the chronology of events is often opaque. The state-controlled newspapers covered the accident and provide fragments of additional information. The local edition of Das Freie Wort (DFW 19530709) covered the event under the headline of a “natural disaster" with a list of victims and which hospitals they were taken to. The regional edition brought the mine accident on the front page the following day (DFW 19530710) as did Thüringisches Landeszeitung (TL 19530710). The descriptions appear to be based on Junghans' first account and praise the emergency response. The local edition of Das Freie Wort carried death notices (DFW 19530716) and later reported a formal celebration of the emergency responders and awards given to individuals for outstanding performance and bravery (DFW 19530814).

Except when otherwise indicated, the description below is based on Junghans' accounts. He also reported the weather conditions (Table 5).

	23:30	01:00	04:00	07:00
Wind speed	SW 1 m/s	SW 2 m/s	WSW 7 m/s	WSW 7 m/s
Temperature (°C)	18	17.7	16.8	16.6
Barometric pressure (mbar)	1014	1014.1	1013.9	1014
Humidity (%rel)	73%	75%	77%	81%

Table 5 Meteorological conditions at the Kaltennordheim weather station, 22 km south of Menzengraben, the night between 7 and 8 July 1953. The sky was overcast and the weather dry. Source: Junghans 1953b

3.3 Sequence of events

On the 7th July 1953 at 23:35, after having confirmed that everybody had left the mine, the blaster, Mr DK detonated the explosive charges in two rooms. He duly monitored the blasting sequence over the microphone-loudspeaker system. "Immediately afterwards", he heard an unusually large outburst.

Interviewees stated that the blaster was located in the mine safety office. Mr DK likely ran towards the porter's lodge[4], a distance of about 100 m, and alerted the porter, Ms AW, of an imminent gas danger. On his way, he would be passing the #2 Shaft House, the building erected above #2 Shaft. There is no further mention of Mr DK but he probably ran about 30 m north, up a steep incline, and escaped unharmed. Ms AW sounded the factory siren. The siren hardly wailed one cycle, however, before being silenced by a power failure due to a short circuit caused by impact damage to electrical installations below ground. With the sky overcast the power failure left the mine and the two nearby settlements in complete darkness. Gas then "*came rushing up #2 Shaft with unprecedented force and blew a 10 m^2 hole in the iron reinforced concrete ceiling of the #2 Shaft House. The escaping gas sounded like four to five large*

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[4] Drawings show two possible porter lodges, one near the entrance to the mine premises (AG Kali 1950), and one located immediately east of the #2 Shaft House (VEB 1950). According to interviewees the porter lodge near the entrance was not used, and a drawing (VEB 1950) indicates it may have served for residential purposes by 1953.

locomotives blowing steam at the same time accompanied by a deep rumbling undertone. The sound lasted for about 25 minutes." It was wind still and "*in a relatively short time the entire valley from Stadtlengsfeld to Dietlas was completely filled with concentrated carbon dioxide".*

The inhabitants of the two settlements were initially bewildered by the wailing and then silenced siren, the electrical blackout and the noise of the escaping gas. As soon as they realized the gas danger however, the people at the Factory Settlement fled across the bridge over the Felda and retreated to the safety of the heights of the eastern ridge.

At the Menzengraben Settlement responses were quick and multiple. Upon realizing the gravity of the situation, Mr H cycled to the nearest telephone in Stadtlengsfeld to alert the authorities in Dorndorf of the accident. Mr N, the operations manager, discovered that the power failure had not disabled his home telephone line. He sounded the disaster alarm, mobilized rescue teams of neighbour mines and alerted nearby hospitals and doctors. Unaware that Mr H had already biked to Stadtlengsfeld, the operations manager dispatched a team of two messengers on foot to Stadtlengsfeld. The inhabitants fled their homes up the eastern ridge. Junghans praises the exemplary cold-headed behaviour of the people there "*though many, clad only in nightgowns, barely saved their lives*".

The police blocked the main road in Dietlas and in Stadtlengsfeld to stop unsuspecting traffic entering the valley, and the Kaltennordheim passenger train in Dorndorf scheduled for departure 00:16 was halted. *"During the first 45 minutes it was impossible to cross [from eastern heights] to the other side".* Several attempts by miners to cross over to the mine works had to be aborted. Just when a team was about to make a detour over the Schrammenhof in order to circumvent the Menzengraben intersection and the nearby lowlands, they met with the first recue vehicles arriving from the potash mine Heiligenroda I/III (located in Springen) and the gas emergency team from the Dorndorf factory. Wearing breathing apparatus, the teams searched the vicinity of the Factory Settlement for victims. "Shortly thereafter", the mine manager, the party secretary, the factory doctor and the police arrived at the scene. "At the same time", Dr Klug of Stadtlengsfeld had set up a makeshift medical aid station at the main hotel, where he attended several casualties. Dr Klug arrived "40 minutes later" at the provisional command centre, set up on a hill "west of Mr Koch's house" and "southeast of the shaft yard". "Some 20 minutes later" two additional rescue teams from the potash mine Kaiseroda II/III arrived. The teams searched the buildings of the Factory Settlement for victims. At search team was also dispatched to the forest house. Casualties were taken to nearby hospitals in Dermbach, Vacha and Bad Salzungen. Three casualties were found in the canteen and taken to hospital. "Meanwhile", a rescue team wearing breathing apparatus carried out a systematic search of the Menzengraben shaft yard. It was found to be almost gas free and additional victims were found. The power supply was restored and at 02:30 the command centre had been relocated to the mine's dining room. More rescue teams arrived at the scene, a second team from Heiligenroda, a team from Kaiseroda I in Merkers and a team from the Sachsen-Weimar works in Unterbreizbach. They searched the entire lowlands and located the last victim.

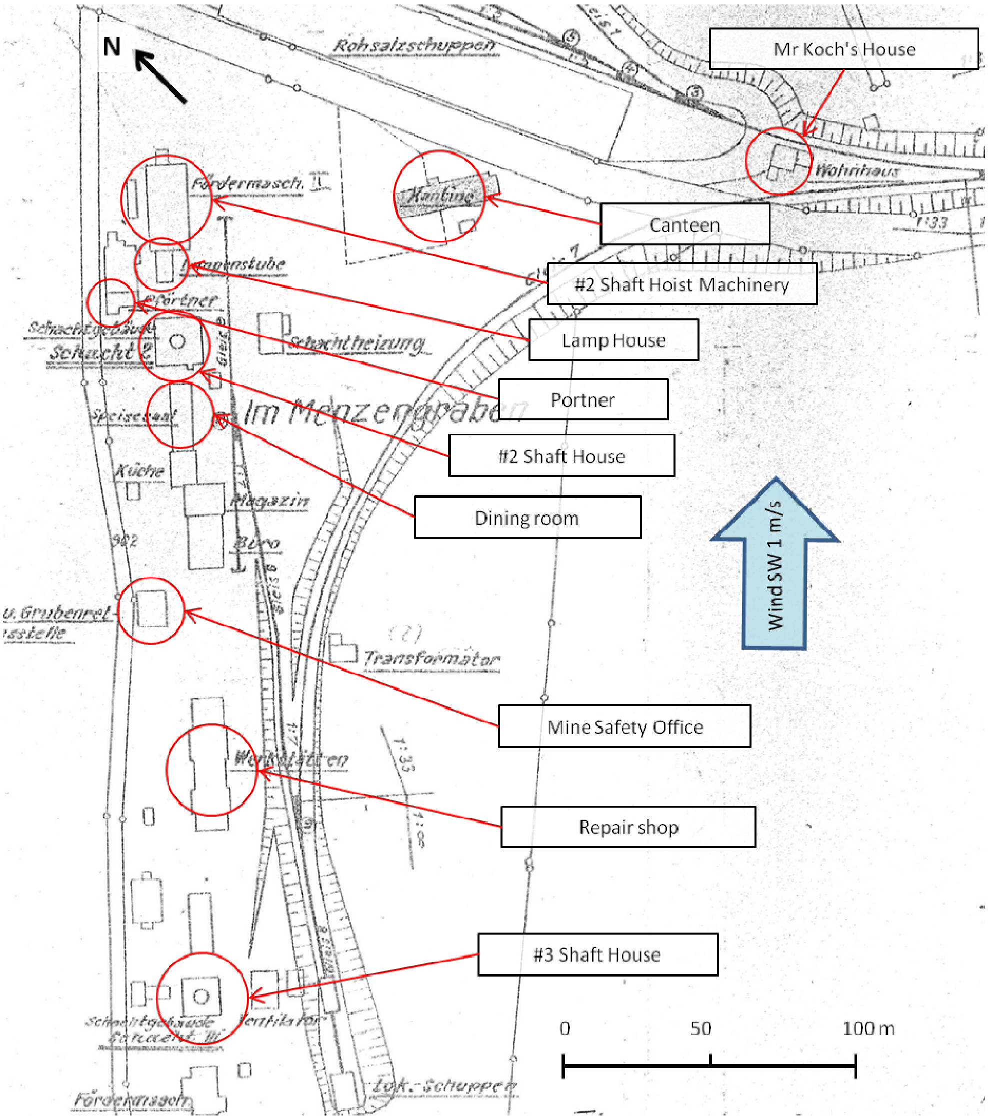

Figure 4 *Details of the Shaft Yard with locations of interest marked. Source: VEB 1950. (Courtesy: Thüringisches Staatsarchiv Meinigen) NO PERMISSION YET*

All sources praise the rescue efforts for being swift, efficient and altruistic, but precise indications of time are mostly absent and the available information is insufficient for a firm reconstruction of the timeline. What is clear is that blasting took place at 23:35 and the command centre was set up in the dining room three hours later, at 02:30.

The miners at the Menzengraben Settlement wanted to reach the mine safety office, where breathing apparatus were stored. Their last aborted attempt to cross the main road likely took place 45 minutes after the outburst began, i.e. at

00:20. They then retreated uphill and contemplated alternatives. In the meantime the wind was picking up slightly. The road may have been passable when they met with the first recue vehicles arriving from the direction of Dietlas. .

The rescue team from Springen and the gas emergency team from the Dorndorf factory likely met at 00:25 in Dietlas and were held back for briefing and instructions. Junghans says that the recue teams were instructed to wear breathing apparatus while advancing on the main road and that the western lowlands were considered dangerous. They likely advanced cautiously, mindful of the gas danger. They may have arrived at the Menzengraben intersection at 00:55, met with the miners of the Menzengraben Settlement and ventured over the bridge at 01:00. Management may have arrived 01:05 and set up the first command centre on the hill perhaps at 01:30. The victims in the forest house and the canteen may have been reached at about the same time, about two hours after the onset of the gas release.

In all there were three fatalities. Debris from the shattered concrete ceiling had struck the repair shop superintendent, Mr LS. He was found dead in the yard west of the #2 Shaft House with serious head trauma. The location is probably 20-40 m from the #2 Shaft House The last victim to be located, Mr PP, a craftsman, was found dead “northeast of the old factory” due to asphyxiation. The location is probably 275-300 m from the #2 Shaft House. He had been dead for at least one hour when found. Mrs ErS, the wife of a worker, was one of three victims found “in the canteen”. When found, her breathing was very troubled and she later died in hospital. The two other victims there survived. One victim, Mr EuS, may have been her husband judging from the uncommon surname that they shared (DFW 19530709). According to a newspaper account, Mrs ErS had been overcome by gas “in her home” (DFW 19530710). Interviewees stated that a family was living in the canteen building. It is therefore concluded that Mrs ErS was indeed fatally affected by gas in the canteen about 100 m from #2 Shaft House, ruling out her having been in one of the buildings of the Factory Settlement, at a distance of 300 m. Two workers, Mr OK and Mr GS were overcome by gas “near the Lamp House”, they both survived. The Lamp House is 10-15 m from #2 Shaft House.

The local newspaper brought a list of nine victims taken to hospital with asphyxiation symptoms, three women and six men. (DFW 19530709). They all recovered. The fatally affected Mrs ErS who died in hospital is not on the list. The porter, Ms AW, who activated the factory siren was overcome by gas and lost consciousness. Her name is on the list but there is no mention of when or where she was located. The porter’s lodge is located about 10 m from #2 Shaft House. She was later rewarded for bravery for having alerted the downhill settlements of the gas danger (DFW 19530814). The number of asphyxiation victims in the forest house, about 530 m from #2 Shaft House, is not stated but must amount to four. A worker, Mr WS, suffered a broken leg while fleeing uphill in darkness. There is no information on whether he was at work or if he fled from his home and he is not on the list. There is no information about the people who received medical attention by Mr Klug at the main hotel in Stadtlengsfeld. They may have included Mr H who came by bike and the messenger team on foot from the Menzengraben Settlement, and it may have been medical examination rather than medical treatment.

It is remarkable that victims located in the immediate vicinity of the #2 Shaft House survived, while a victim succumbed hundreds of metres away. A newspaper account praises the actions of miners who at great personal risk retrieved unconscious victims and brought them to higher ground, "saving many lives" (DFW 19530709). As described above, the rescue teams would have located the victims about two hours after the outburst began. Medical attention given at such a late stage is unlikely to have much effect on a victim of asphyxiation, It is more plausible that the timely action by miners, accustomed to the dangers of carbon dioxide when working below ground, may have been decisive.

An interviewee (born 1941) recalled that geese were found dead in the lowlands near the old Schneia Mill, where there was a farm. From the main road there is a steep decline of about 4-5 m to the nearby Felda and the lowlands. The dead geese indicate that concentrations in the lowlands, more than 1.2 km upstream of Menzengraben, had exceeded 20 percent. It has not been possible to confirm or refute this observation independently. Duchrow (1997) says that rescue vehicles advancing from Dietlas were troubled by high concentrations of gas, which at times made the engines stall. This would be a highly significant observation, as the concentration at road level would have been in excess of 28 percent; concentrations that are instantly incapacitating and fatal. Duchrow's stated source is Junghans (1953b) but there is no mention of stalled engines in this source. Interviewees stated that engine stalling was rare; it had happened below ground on certain diesel vehicles with low air-intake points[5], but they had no knowledge of this happening above ground. Duchrow has since passed away, and as it stands, his comment is unverifiable. Apart from the casualties at the forest house, there are no reports of effects of gas downstream of Menzengraben, towards Dietlas, possibly because nobody lived in that part of the valley.

To summarize, the carbon dioxide concentration likely exceeded 20 percent at the canteen 100 m away, where Mrs ErS was fatally affected and northeast of the old factory where Mr PP died 275-300 m away. Asphyxiation victims were located in the forest house 530 m away, indicating that concentrations there exceeded 15 percent. High concentrations of gas made it impossible to cross the main road intersection 450 m away, but there is no information on how miners determined that the concentrations were dangerous. Assuming that the terror induced by laboured breathing discouraged them, the carbon dioxide concentration would have been 5-10 percent. However, bearing in mind that asphyxiation victims were located in the forest house, at roughly the same elevation but further away and cross-wind, it is conceivable that concentrations were higher, possibly 30 percent, capable of extinguishing an oil lamp. An overview is provided in Table 6.

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[5] There is very little mention of engines stalling in the literature. Gimm (1954) reports that a moped stalled below ground, which provided the first warning of an impeding outburst.

Location	Distance (m)	Elevation [a] (m)	Victims	Concentration vol% CO_2	Comment
#2 Shaft House	0	290			Main source of CO_2, near-vertical jet from roof
Porter's lodge	10	290	Ms AW	>15%	Unconscious, survived
Lamp house	10-15	290	Mr OK Mr GS	>15%	Unconscious, survived
#2 Shaft Yard	20-40	290	Mr LS	unknown	Died from head trauma, struck by debris from roof
Canteen building	100	270-280	Mrs ErS Mr EuS A victim	>20%	Died from asphyxiation Unconscious, survived Unconscious, survived
Northeast of the old factory	275-300	255-260	Mr PP	>20%	Died from asphyxiation
Forrest house	530[b]	260	Four victims	Probably >15%	"Asphyxiation victims", survived
Main road near the Menzengraben intersection	450	260	None	Likely >10% Possibly > 30%	"Impossible to pass "
Menzengraben Settlement	575	270-275	None	Unknown	People fled uphill, "barely saving their lives"
Valley	2.5 km	Potentially 250-265 -	None	Unknown	"Entire valley from Stadtlengsfeld to Dietlas" completely filled with "concentrated CO_2. "

Table 6 *Overview of locations, distance and reported CO_2 effects.*
a) Elevations are approximate only
b) Estimated distance of cloud following terrain, direct path over a hill is only 400 m. Location is cross-wind

3.4 Material damage

The gas came rushing up #2 Shaft with unprecedented force and shattered the roof before exiting "into the open air". Large amounts of splintered construction timber was scattered over "the entire area" up to 150 m from the #2 Shaft House. "There is no doubt" that the main pathway of the gas to the surface was through #2 Shaft. The other shaft only suffered "minor damage"; with some unspecified damage to the roof of the #3 Shaft House and the roof of the adjacent ventilation building.

There was extensive damage to #2 Shaft House. The shaft opening was partly covered by a 8-10 mm steel deck plate, of which the entire eastern section over the ventilation compartment was torn and bent upwards. Above, there was a 10 m^2 hole in the iron reinforced roof (Figure 5).

The eastern elevator cage was at the bottom, and the western cage at surface level. Gas coming up the cage compartment deformed various U and T-steel beams of the hoist frame and then continued straight up where it blew out the wooden cladding of the hoist frame. Figure 6 shows the wooden cladding, with at least one side blown out, and the hole in the roof in the foreground. Gas also impinged on the underside of the western cage and severed the tail cable.

Figure 7 shows the damage inside the #2 Shaft House. Large pieces of construction timber, parts from the ventilation and the cage compartments, lumps of concrete and iron beams are scattered around. The window frames and perhaps even some windows appear intact, indicative that the overpressure inside the building was minimal.

The most plausible interpretation of the damage is that the gas stream coming up the ventilation compartment continued straight up, destroyed the roof, stayed clear of the hoist frame and exited freely into the open air. A plot plan (Figure 4) shows that the hoist machinery was located east of the shaft house. It could therefore be speculated that gas impinged on the inclined back leg, most likely an open truss girder structure. Junghans says specifically, that there was no damage to the outdoor parts of the hoist frame, indicating that impingement may have been minimal, if it happened at all. The gas stream coming up the cage compartment clearly impinged but had sufficient force to continue straight up, blow out the wooden cladding and exit vertically into open air.

Based on a low-detail drawing[6], the cross-sectional area of the ventilation compartment is estimated to be 5.77 m^2. The cage footprint was 2.31 m^2. Assuming that the gas could not push the western cage upwards (empty weight 2.5 tonnes), and allowing 10% for clearances, the maximum free cross sectional area at ground level available for the gas jet can be estimated at $5.77+1.1*2.31 = 8.31\ m^2$.

In conclusion, the primary pathway of the gas stream was an almost vertical mostly unobstructed jet through the hole in the roof of the #2 Shaft House, with secondary venting up through the blown out wooden panel(s) of the hoist frame partly obstructed by structural steel members, and probably some minor tertiary diffuse venting through shattered windows. Additional venting took place through the #3 Shaft House, the damage there was light suggesting that the venting was of minor magnitude.

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[6] Drawing and other technical data are taken from a summary technical data sheet for several mines, marked “W 1.3 02 00 002” (ZM40500) kindly provided by Dipl. Ing. Hartmut Ruck.

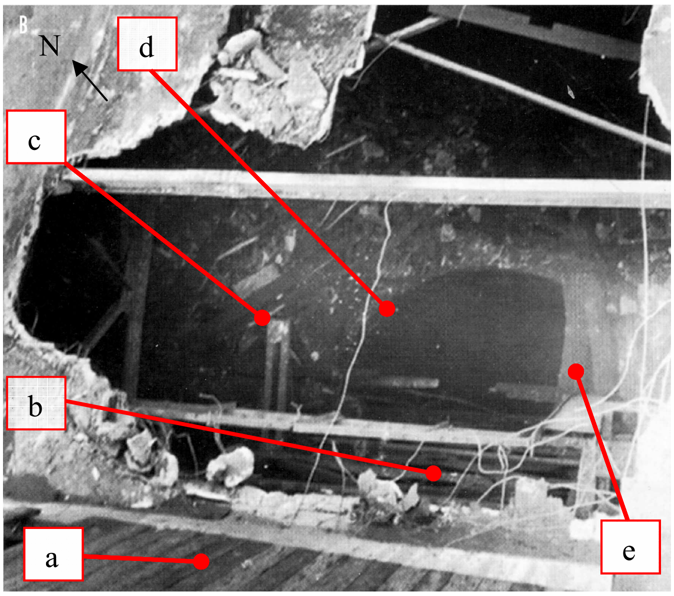

Figure 5 Looking down the shattered concrete roof of #2 Shaft House into the completely destroyed ventilation compartment. Legend: a) wooden cladding of the hoist frame; b) hoist frame lattice steel structure; c) ground level with debris; d) large deck plate, bent vertically upwards; e) intact deck plate; (photo from Hohmann and Mehnert 2004).

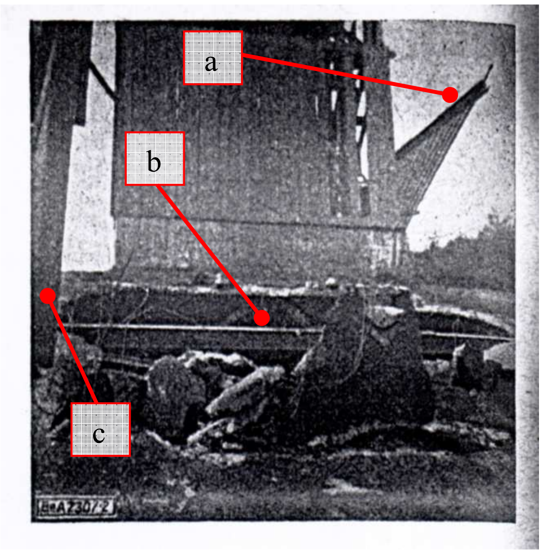

Figure 6 Photo taken from the roof of #2 Shaft House, facing southwest. Legend: a) hoist frame with at least one side (north) of the wooden cladding blown out; b) hole in the concrete roof where the gas jet exited into the open air; c) possibly part of the inclined back leg, (photo from Junghans 1953b)

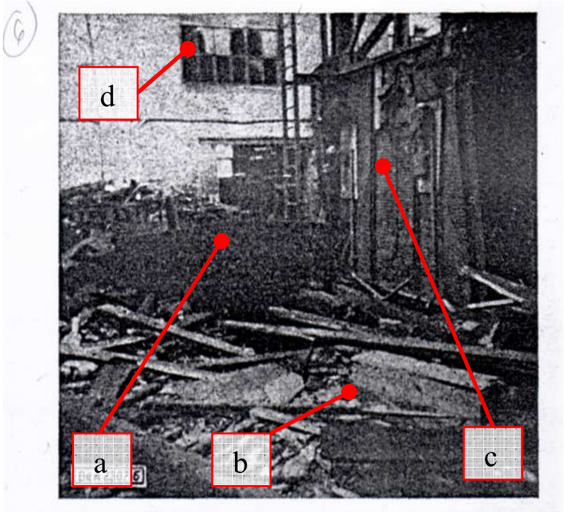

Figure 7 *The inside of #2 Shaft House, facing south. Legend: a) steel deck plate bent upwards; b) snapped construction timber; c) side of the cage structure; d) intact window frames (photo from Junghans 1953b).*

There was extensive damage below ground. The compartment dividers in #2 Shaft were destroyed and about two-thirds of the cross-sectional beams anchored in the shaft wall were torn out. Destruction in the tunnel system comprised overturned and deformed conveyor cars, rail tracks twisted and bent upwards with the sleepers (ties) torn off, and extensive destruction of electrical cabling and ventilation equipment. Excerpts from the damage description reads: 50% of the conveyor cars destroyed, 2.5 km of twin-track rails to be laid, and three wire-drawn ore scraper units entirely destroyed. It took 12 weeks to bring the mine back into production.

3.5 Outburst cavity size and salt burst amount

Early inspections revealed a cavity about 60 m long, 12-15 m wide and 6-12 m high, but measurements were hindered by the presence of pockets of concentrated CO_2. The salt burst was estimated to be 18,000 tonnes (Junghans 1953b). The outburst initiated in a transition zone between carnallite and sylvite, with a seam of secondary sylvite (Umwandlungssylvinit), the cavity extending into the sylvite. Later, Junghans (1955) provided revised estimates, a detailed survey showed that the cavity length was 140 m with an average width of 10 m, and the salt burst amounted to 65,000 tonnes. Duchrow (1959) argues that the cavity may have been larger and speculates that the likely salt burst was 100,000 tonnes, perhaps even multiples of that.

3.6 Determination of amount of CO_2 released

3.6.1 Direct estimation of the outburst size

Junghans (1953b) says that the exact outburst size escapes precise estimation and “can only be based on conjecture”. The outburst intensity clearly exceeded the normal mine ventilation rate of about 2,500-3,500 m^3/min and, at this flow rate, he observes, there is hardly any noise from the diffuser of the mine ventilator. “*It can therefore safely be presumed that at least 12,000 m^3/min of gas flowed to the surface during the outburst* […*therefore*….] *about 300,000 m^3 of CO_2 were vented during the first 25 minutes. In addition, the entire mine, with a volume of about 480,000 m^3, was left flooded with concentrated CO_2. The outburst size can therefore be estimated to about 700,000 m^3*” (Junghans 1953b:461-462).

Without going into detail, Junghans’ account reveals the extremely approximate nature of assessing the outburst size in the absence of instrument readings.

3.6.2 Estimation based on key ratios derived from other outbursts

For some outbursts (Table 3), estimates of gas volumes and salt burst amounts are available, which permits computation of a key ratio of cubic metres of CO_2 per tonne of salt. Hoppe (1960:109) provides a range of 11-45 m^3/t for the Werra district, based on data from Müller (1958). Bearing in mind the difficulties and uncertainties in estimating both the salt burst and the gas volume for the 1953 outburst, such ratios should be viewed with caution.

Only one source has been identified, which reports actual measurements of outbursts. Mr Hubert Wolf followed the blasting teams in three mines and set up instruments in the tunnel system to record gas velocity and overpressure profiles, should blasting trigger an outburst. He documented the results in a doctoral dissertation (Wolf 1965). Wolf’s measurements confirm the hypothesis, that an outburst is the superimposition of numerous smaller outbursts, the result of a chain reaction over time, not a single massive release of CO_2. His results for the Menzengraben mine are presented in Table 7.

Date	Salt	CO_2	Ratio	Duration	Intensity		Pressure	
					avg	max	avg	max
	tonnes	Nm^3	Nm^3/ton	sec	Nm^3/sec	Nm^3/sec	Pa	Pa
14 Jan 1962	8,000	122,000	15.3	165	740	1,390	2,300	35,500
18 Mar 1962	300	2,750	9.2	17	165	430	540	1,560
1 Oct 1962	300	5,880	19.6	30	197	385	130	360
10 Oct 1962	600	12,100	20.2	41	300	580	270	730
22 Nov 1962	2,000	24,800	12.4	52	477	1,220	2,900	7,600
29 Jan 1963	600	4,950	8.3	15	330	700	670	3,150
2 Mar 1963	900	8,850	9.8	25	354	540	1,700	2,180
22 Mar 1963	5,500	74,900	13.6	150	500	1,230	3,350	7,600
23 Apr 1963	20,000	300,000	15.0	150	2,000	- [a]	- [a]	86,500

Table 7 *Measurements of major carbon dioxide outbursts in the Menzengraben mine provoked by blasting work. Pressure readings are included to give an idea of orders of magnitude only, as they are influenced by the specifics of instrument location, tunnel geometry, etc. (Nm^3 refers to normal cubic metres). Source: Wolf 1965:54.*

[a] *Not available due to instruments damaged by outburst.*

The outburst 23 Apr 1963 is remarkable for its magnitude and severity, which unfortunately destroyed many of Wolf's instruments. Gas came up both shafts for several minutes. Large boulders of salt took down 10 mm steel doors. A ventilation lock 900 m away was destroyed, instruments behind the lock were blown 50 m down the tunnel and destroyed, and damage to electrical installations caused a power failure. Instruments located behind a protective door that withstood the overpressure survived (Wolf 1965).

For lack of better data it may be assumed, that the 23 Apr 1963 outburst was similar in nature to the 7 Jul 1953 outburst. Both outbursts cavities extended into a sylvite deposit. Drop doors were installed after the 1953 outburst (Junghans 1958) and by 1963 the mine volume had increased four-fold to 2 mio. m^3 (Wolf 1965). These factors plus the much shorter outburst duration may explain the less severe damage. Using Junghans' original salt burst amount of 65,000 ton, and the 23 Apr 1963 outburst ratio of 15 Nm^3/t, the 1953 outburst computes to 0.975 mio. Nm^3. Using Duchrow's revised salt amount of 100,000 ton, the 1953 outburst computes to 1.5 mio. Nm^3.

Wolf's measurements introduce a new parameter, the average outburst intensity in normal cubic metres of CO_2 per second. This parameter is useful, because it allows estimation of the outburst size directly from the outburst duration, i.e. eliminating uncertainties associated with the estimation of the amount of expelled salt. For the 23 Apr 1963 outburst, the average intensity was 2,000 Nm^3/s. Junghans (1953b) says the escaping gas could be heard for 25 minutes. It would take some time for the mine to depressurize after the outburst has terminated and until escaping gas can no longer be heard. Assuming a duration of 20 minutes the outburst computes to 2.4 mio. Nm^3.

The outburst volume relates to the amount of CO_2 liberated from the evaporite minerals. Some of the CO_2 will remain below ground. Three days after the outburst, the #3 Shaft bottom CO_2 concentration was measured to be 86% (Junghans 1953b). Assuming homogeneous mixing, adjusting for static head and temperature of the mine (17-19 °C), some 436,000 Nm^3 of CO_2 remained below ground. Table 8 presents five different estimates of the amount of CO_2 emitted from the mine shaft.

Source	Comment	Method for estimating CO_2 outburst volume	CO_2 outburst Nm^3	CO_2 left in mine Nm^3	CO_2 ejected Nm^3	CO_2 ejected tonnes
In: Junghans 1953b	Salt burst measured to 65,000 t	Original extremely crude assessment (inaccurate)	700,000	436,000	264,000	518
In: Duchrow 1997	Salt burst stated to be 100,000 t	No explanation offered	1,000,000	436,000	564,000	1,107
From: Wolf 1965	Measured ratio of 15 Nm^3/t salt	Assuming salt burst of 65,000 t	975,000	436,000	539,000	1,058
From: Wolf 1965	Measured ratio of 15 Nm^3/t salt	Assuming salt burst of 100,000 t	1,500,000	436,000	1,064,000	2,089
From: Wolf 1965	Measured average intensity of 2,000 Nm^3/s	Assuming a duration of 20 minutes	2,400,000	436,000	1,964,000	3,855

Table 8 *Five different estimates of the amount of CO_2 emitted from the mine shaft. The possible range is 1,100 - 3,900 tonnes.*

3.7 Dispersion modelling

Dispersion modelling was carried out using PHAST version 6.54 to compare the consistency of predicted concentrations levels with observed harm, in particular asphyxiation harm. Ideally this could help to determine which of the three outburst sizes would be the most likely.

During the outburst, the liberated CO_2 will purge some sections of the mine and entrap, compress and mix with tunnel air in inner sections of the mine in a complex manner which cannot be quantified. Gas ejected from the mine shaft will first be displaced air, then increasingly concentrated CO_2, possibly followed by less concentrated CO_2 as the inner sections of the mine depressurizes. Simplifications are required in order to apply the PHAST model. The source term is modelled as a continuous release of pure CO_2 similar to the outburst intensity, assuming an effective outburst duration of 20 minutes. Because the actual release was not pure CO_2 this simplification is conservative and will tend to overestimate cloud contours.

While the main route to the surface was clearly through #2 Shaft, some gas was also vented through #3 Shaft through an unspecified hole. The destructive release through #2 shaft was obviously highly turbulent. The minor damage to #3 shaft indicates that gas velocities there were more modest. Therefore, two source terms are modelled in PHAST: a large un-impinged high-momentum release through #2 Shaft and a smaller low-momentum release through #3 Shaft. Due to absence of data, it is arbitrarily assumed that the split was 90% and 10%. This simplification serves to examine the overall behaviour of a large near-vertical turbulent jet and a much smaller near-vertical low-velocity gas release. The high- momentum release is modelled as an infinite reservoir of CO_2, at 18 °C, a circular orifice with an area of 8.31 m^2 and adjusting the reservoir pressure to fit the outburst intensity. There is no information on the release from #3 Shaft and in the absence of an orifice area estimate the low-momentum release is arbitrarily defined as having an exit velocity of 10 m/s. Both source terms are set at 8 m height, the assumed elevation of the roof of the Shaft Houses, slightly deviated from vertical (10°) towards the east. Meteorological conditions are defined as wind speed 1 m/s, overcast conditions at night is specified as Pasquill stability class D, ambient temperature 18°C and a surface roughness parameter representative of a suburb/forest. PHAST does not allow specification of topography.

PHAST outputs for the three scenarios are qualitatively similar. Invariably, the high-momentum releases from #2 Shaft are predicted to disperse safely, incapable of cause harm at ground level. The low-momentum releases from #3 Shaft would quickly slump to the ground. Only the largest release scenario will produce concentrations above 15% at ground level. The range is limited and is less than the distance between the two shafts. The shaft gas velocity was estimated by using the reservoir pressure to compute the shaft gas density, and assuming full bore flow. Results are summarized in Table 9. Since model outputs were qualitatively similar, only plots for scenario 3 are presented in Figure 8 and Figure 9 - for better visualization the axes are scaled.

Sce-nario	Outburst volume (Nm³)	Source term (kg/s)	Est. back pressure (kPa)	Orifice area (m²)	Est. exit velocity (m/s)	Est. exit temp (°C)	Est. shaft velocity (m/s)	Est. distance (m) to CO_2 concentration			
								5%	10%	15%	20%
High-momentum release from roof of #2 Shaft House, 90% of outburst intensity											
1a	975,000	1,435	121	8.31[a]	139	6	31	-[d]	-[d]	-[d]	-[d]
2a	1,500,000	2,208	146	8.31[a]	195	-6	40	-[d]	-[d]	-[d]	-[d]
3a	2,400,000	3,533	198	8.31[a]	260[b]	-24	47	-[d]	-[d]	-[d]	-[d]
Low-momentum release from roof of #3 Shaft House, 10% of outburst intensity											
1b	975,000	159	-[c]	-[c]	10[a]	18[a]	4	210	95	-[d]	-[d]
2b	1,500,000	245	-[c]	-[c]	10[a]	18[a]	6	275	160	10	-[d]
3b	2,400,000	393	-[c]	-[c]	10[a]	18[a]	10	365	240	160	-[d]

Table 9 *Release scenarios and dispersion model outputs.*

[a] *value set to define scenario*

[b] *sonic release (choked flow)*

[c] *value not relevant for scenario*

[d] *concentration contour does not reach ground level*

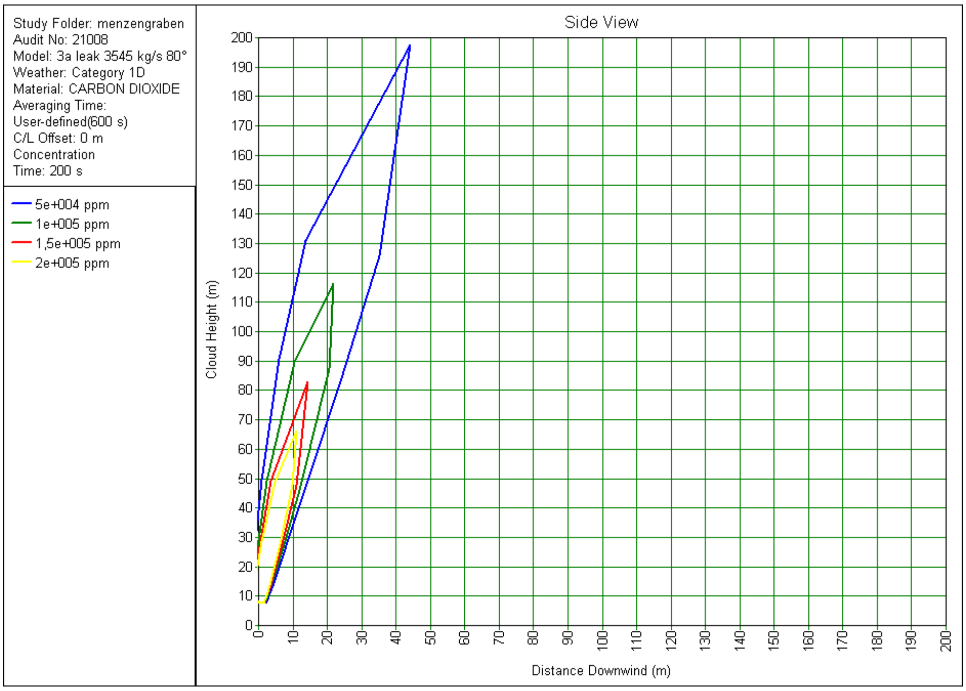

Figure 8 Scenario 3a - large high-momentum release.. Plot shows 5, 10, 15 and 20 vol% CO_2 plume concentration contours. Jet is predicted to dilute safely.

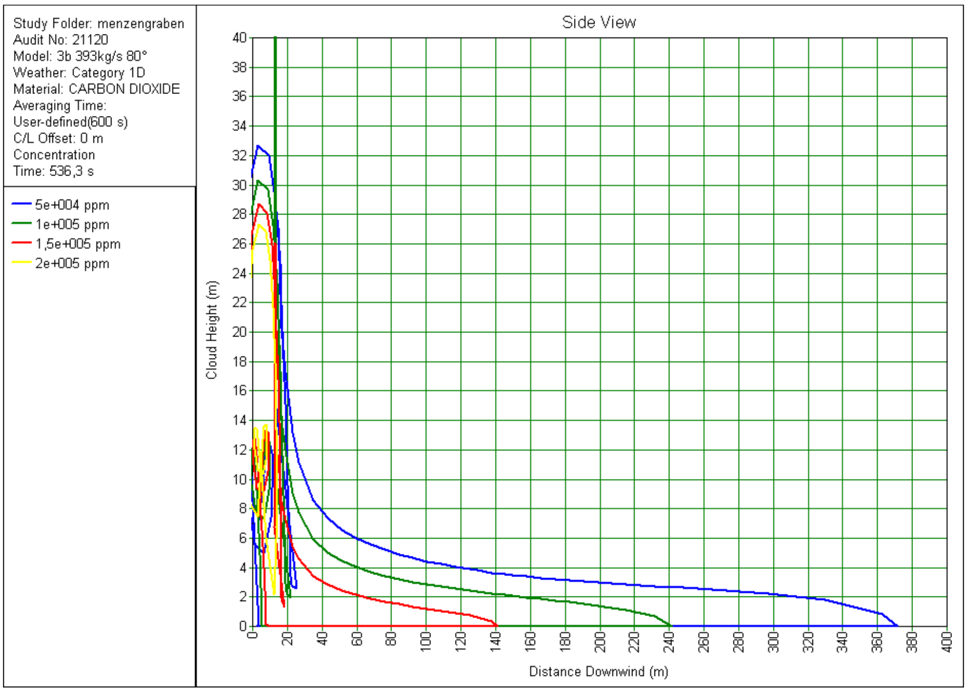

Figure 9 Scenario 3b - small low-momentum release. Plot shows 5, 10, 15 and 20 vol% CO_2 plume concentration contours. Predicted ground level concentrations are 15 vol% @ 160 m, 10 vol% @ 240 m.

The principal interest concerns the dispersion result for the main CO_2 release. For a high-momentum release, an essential parameter in PHAST is the nozzle exit velocity, which is determined from the release rate and the orifice area. Sensitivity analysis shows that gravity effects only become apparent at nozzle exit velocities below about 50 m/s and that significant touch down of the CO_2 plume takes place at exit velocities below about 30 m/s. Plots for scenario 1a and 3a are shown in Figure 10 and Figure 11, results for scenario 2a are qualitatively similar and not shown due to space restrictions. The estimated nozzle exit velocities for the three outburst sizes (Table 9) are well above these values. The dispersion modelling results are therefore robust to considerable variation in both outburst size and orifice area, two important but uncertain inputs.

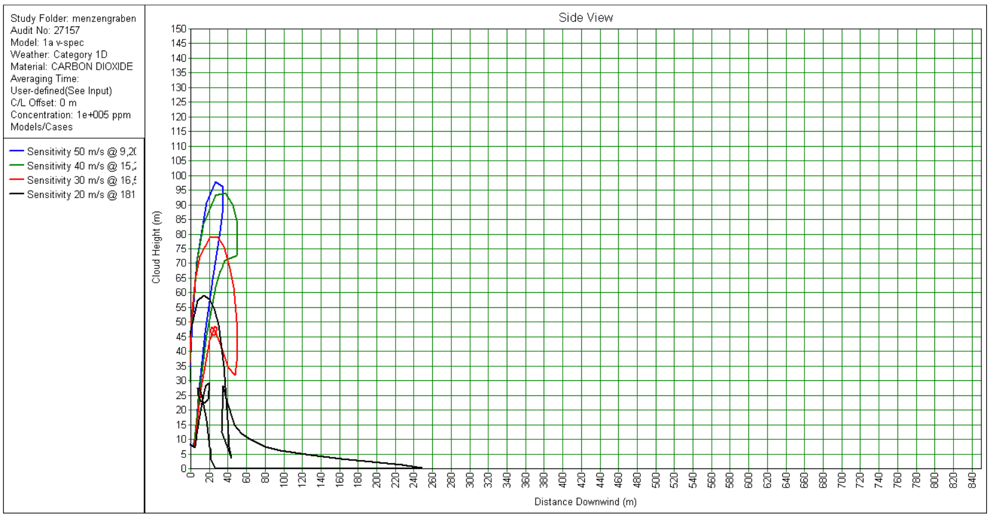

Figure 10 *Scenario 1a, sensitivity analysis. Exit nozzle velocity set to 50, 40, 30 and 20 m/s. Plot shows 10 vol% CO_2 plume contours.*

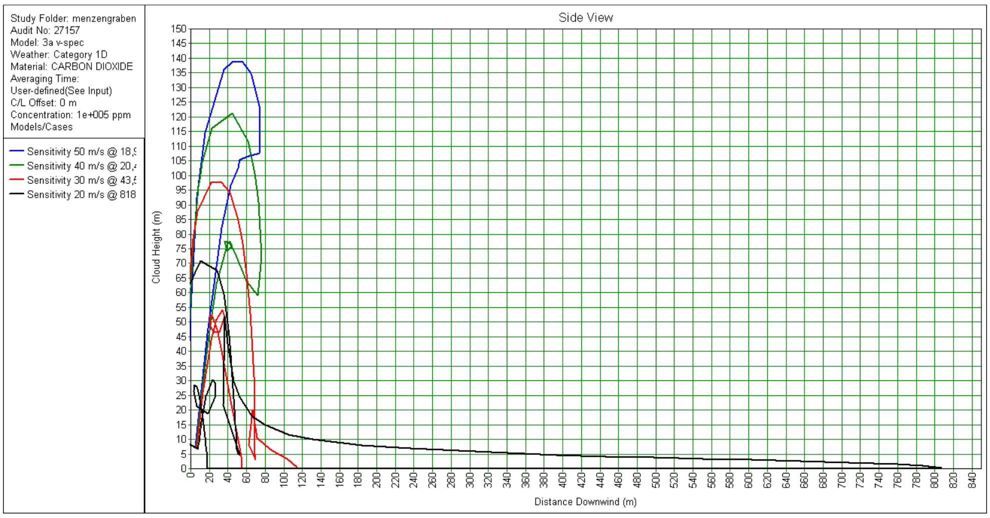

Figure 11 *Scenario 3a, sensitivity analysis. Exit nozzle velocity set to 50, 40, 30 and 20 m/s. Plot shows 10 vol% CO_2 plume contours.*

PHAST takes loss of momentum due to obstacle impingement into account by specifying a reduced “nozzle” velocity, which reflects the presumed release velocity after impingement has taken place. PHAST applies a velocity modification factor, which defaults to 0.25 for impinged releases, i.e. the jet is assumed to lose 75 percent of its nozzle exit velocity. There is no evidence suggesting that significant impingement took place, but even if impingement were assumed, PHAST model output indicates that the large release would disperse safely.

4 Discussion

Temporary Emergency Exposure Limits (TEEL) and Immediately Dangerous to Life or Health (IDLH) end-points are regularly used in risk analysis studies. For CO_2, the values seem to define protection from harm rather than harm itself, employing unstated safety factors. Using risk terminology, protection from harm translates into a low probability of harm; a probability, which if unaccounted for, may distort estimated risks systematically. Because accident reports usually specify harm, not absence of harm, other end-points are required for analysis of reported effects. This would be particularly true for the1953 outburst which affected a miner's community, presumably healthy adults, for whom large safety factors would seem unwarranted.

The largest evaporite CO_2 outbursts on record have taken place in the Werra potash mining district. Key data are often lacking. Specific instrumentation, e.g. a CO_2 gas analyzer in the exit ventilation stream in combination with a flow meter, is required to estimate outburst volumes routinely and reliably. For old CO_2 outbursts, only crude assessments of outburst volumes are available, if at all, and the computation procedure is rarely stated. The priority was prognosis work; to reliably predict the outburst potential of the underground and act accordingly to protect people and limit damage. The focus was clearly outburst risk management, less so outburst volume estimation.

Outburst volumes can in principle be computed from the amount of expelled salt and an assumed ratio of gas per tonne of salt. Reported ratios exhibit a large variation however. Also, only the amount of salt hauled to the surface is known reliably, which is a problem particularly for large outbursts where the cavity may be unsafe to access or the innermost salt deemed too laborious to extract. There is also the complication, that low or inner cavities can be buried under piles of expelled salt and remain undetected. In the more recent literature, the consensus seems to be that the 7 July 1953 salt burst was 100,000 tonnes (Duchrow 1997) and that typical ratios are 10-15 Nm^3/t (Duchrow et al. 1988). The problem is that the 100,000 tonnes salt burst is based on speculation and that the amount measured by Junghans (1953b) is only 65,000 tonnes. Because Junghans' lower value was challenged relatively soon after publication (Duchow 1959) and because the 140 m long cavity was indeed very difficult to access (Junghans 1955), the 100,000 tonnes estimate is probably the best available[7]. The best estimate for the ratio is provided by Wolf (1965). Using the salt-ratio method, the best outburst estimate is 1.5 mio. Nm^3 of CO_2.

Wolf (1965) reports an extremely violent outburst in the Menzengraben mine in 1963, which had many similarities with the 1953 outburst. Despite the outburst destroying many of Wolf's instruments, he nevertheless provided an estimate of the outburst volume of 300,000 Nm^3 (Table 7). This round figure may hint that it is indeed a very crude estimate. Using the intensity method, the 1953 outburst estimates to 2.4 mio. Nm^3. Interviewees state that such large outbursts are rare, but not unheard of. An outburst in 1984, presumably when suitable instrumentation was available, is reported to 2.3 mio. m^3 (Table 3). The upper estimate is therefore possible, it is within the experience base, but the likelihood is impossible to assess.

The average velocity of the gas in #2 Shaft computes to 31-47 m/s (Table 9). This is comparable to hurricane force wind speeds, category one (33-42 m/s) or two (43-49 m/s) according to the Saffir–Simpson Scale. Such winds are known to cause destruction, uprooting trees, damaging buildings and hurling debris around. The #2 Shaft contained compartment dividers made of wood which were completely destroyed. It seems plausible that gas travelling at hurricane force wind speeds expelled the construction materials with great force from the shaft opening. It must have been projectiles of timber that shattered the iron reinforced concrete roof, bent the steel deck plate upwards and deformed steel beams, not the gas itself.

A high-velocity gas jet is a very significant generator of noise. Broadband noise is generated due to turbulence and shearing stresses as the high-velocity gas interacts with the ambient air. The velocity of a gas jet attains a maximum value, the speed of propagation of sound in the gas, when the ratio of the orifice back pressure and the ambient pressure become sufficiently high; the flow is said to be sonic (or choked). The 1953 outburst sounded "*like four to five large locomotives blowing steam at the same time accompanied by a deep rumbling undertone*" (Junghans 1953b:458). Large steam locomotives are certainly operated at pressures high enough for steam blowing to result in sonic flow suggesting that the 1953 outburst gave rise to a sonic release. Some uncertainty arises however, because the forceful expulsion of construction timber will also generate considerable noise. .

Standard dispersion modelling with conservative inputs predicts that the high-momentum release from the roof of #2 Shaft House dilutes safely and never reaches ground. The low-momentum release from the roof of #3 Shaft House, about 220 m behind #2 Shaft, is predicted to produce ground-hugging clouds with dangerously high concentrations, though with limited reach. Interpretation

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[7] When the 1953 outburst area was mined again in 1988/89 from the opposite side, i.e. from the east, a new branch of the 1953 cavity was discovered, confirming the speculation of Duchrow (1959) that the cavity was indeed extending further inwards. Consensus seem to be that the 1953 cavity length exceeded 200 m, that the salt amount was closer to 100,000 t than to 65,000 t, and the likely outburst volume was 1.5 mio m^3. (Personal communication, Dr. P Marggraf, e-mail 29.3.2011)

of predicted concentration contours is not straightforward. Carbon dioxide easily stratifies because of its high density and it may flow by gravity following the local topography. The Shaft Yard is sloping slightly, and the slope is steeper where the canteen was located. Still, the predicted concentration contours cannot possibly explain the harm observed. Dispersion modelling output thus suggests that the gas cloud that filled the "entire valley from Stadtlengsfeld to Dietlas" with carbon dioxide can only originate from the smallest release and the largest release disperses safely, a counter-intuitive result.

The PHAST dispersion result does not appear to be in disagreement with other CO_2 dispersion modelling studies. As described above, studies using SLAB and CFD tools also predict that large horizontal high-momentum releases would dilute rapidly, surely even more so in case of a vertical release. It appears that the forceful and destructive 1953 outburst for unexplained reasons behaved as a low-momentum release. It may be speculated that #2 Shaft House was a source of some low-momentum emissions. The observed extensive damage there however, is consistent with a very forceful vertical expulsion. There may have been some impingement with the hoist frame but the evidence available indicates a relatively open truss-girder construction. The scattering of splintered construction timber within a radius of 150 m is also indicative that flow velocities were high and not particularly obstructed. The discrepancies are unresolved.

The topography of the area may have played a role, in particular the shielded location of the mine, on a hillside in a forest clearing, and the sloping terrain towards the valley bottom. The meteorological conditions were also adverse, with almost no wind, but no inversion layer. Such conditions are only to be expected however, and can obviously also be present at future accidental releases elsewhere. Specifically, it may be speculated if the artificial ridges and valleys of modern urban environments could produce comparable topographical conditions.

In other respects the circumstances were highly favourable, exposing a community of miners, presumably mostly healthy adults, who knew the dangers of carbon dioxide, had extensive practical experience with working in potentially hazardous carbon dioxide environments below ground and with an intact command structure. They quickly decided to flee and seek higher ground, in a coolheaded and organized manner, and the nearby hillsides offered plenty of escape options. The two asphyxiation fatalities were non-miners.

Mr PP was killed by asphyxiation at distance 275-300 m, a remarkably large distance. For sake of perspective, Baldock (1980) reviewed reported incidents with ammonia, including the catastrophic failure of large pressurized storage tanks, and concluded that nobody appears to have been killed at a distance greater than 200 m. If scored on confirmed ability to cause deadly harm, this brings carbon dioxide in the company of far more toxic industrial bulk chemicals.

5 Conclusion

Accidental releases of large quantities of CO_2 may provide an empirical perspective on predictive dispersion modelling. The extreme 1953 carbon dioxide outburst at Menzengraben fills a gap in the available accident history with an estimated release amount of 1,100-3,900 tonnes, almost two orders of magnitude larger than the largest industrial accidents currently on record. This is particularly relevant as releases of this magnitude may occur in the event of a transmission pipeline rupture associated with carbon dioxide capture and storage (CCS).

Evidence suggests that the Menzengraben outburst gave rise to a vertical high-momentum release with little impingement. There is a body of literature on the application of dispersion modelling techniques, which predicts that jet effects would rapidly dilute the carbon dioxide to harmless levels. Dispersion was modelled using PHAST, a widely used commercially available tool for hazard analysis. PHAST also predicts that the large energetic near-vertical expulsion of carbon dioxide from the Menzengraben mine shaft would disperse safely and never reach ground. This model output seems to be incorrect in the face of reports, that an entire valley several kilometres long was filled with dangerous concentrations of carbon dioxide. Model output is inconsistent with observed fatal asphyxiation harm. For model output to come into agreement with observed harm it would have to be assumed that the release behaved as a low-momentum jet.

6 Acknowledgements

I am particularly indebted to Dr P. Marggraf and Dipl. Ing. H. Ruck of Bad Salzungen for very helpful discussion; Dr Moczarski of the Staatsarchive Meiningen; Ms Werner of Freies Wort Archiv; Ms Dietzel of the City Hall in Stadtlengsfeld; and my colleagues at COWI: Mr J. Boier Pedersen who carried out PHAST calculations and Mr R. Selig for commenting on an early version of the manuscript.

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