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# Tracer gas experiments in subways using an integrated measuring and analysis system for sulfur hexafluoride

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**Abstract.** Several sulfur hexafluoride ($SF_6$) tracer gas experiments were conducted in a subway system to measure the possible pathways of toxic gas for subway tunnels and stations empirically. A new mobile integrated measuring and analysis system was used to achieve high sample rates and a long measurement time. Due to the mobility of the sensors, tracer gas experiments were also carried out inside running subway coaches. All experiments showed a common pattern: the pathways of tracer gas dispersion overlapped with some escape routes, which were contaminated within a few minutes. So in case of catastrophic circumstances like terrorist attacks or subway fires, some escape routes will become deathly traps, but the results also showed free escape routes. With the new sensor technique it will be possible to conduct safety assessments for escape routes in underground transportation facilities.

## 1 Introduction and motivation

The results of tracer gas experiments help to understand the possible spread of toxic airborne substances for example in subway stations, which are vulnerable in the face of terrorism. In contrast to the period of 1982–1991, where deliberate acts of malice caused 1327 deaths among air travelers and none among subway commuters, the pattern reversed between 2002 and 2011 (Barnett, 2015). As preventing terrorists from entering subway stations is very difficult, preparedness and response are very important. This includes the pathways of airborne toxic substances in subway stations needing to be known and not overlap with emergency escape routes. Sulfur hexafluoride ($SF_6$) has become an accepted standard in underground ventilation studies (Kennedy et al., 1987). In the past, the contamination of air with $SF_6$ was often determined by manual air probes with a 60 mL syringe sand subsequent analysis with a gas chromatograph. This method, however, has some disadvantages: the number of syringes is limited to the laboratory capacity, which results in a short measurement time and a low sample rate. Notably, the time period between taking and analyzing the samples can pollute the probes. The involvement of a large number of people is also a possible source of error. The development of a mobile battery powered integrated measuring and analysis system for $SF_6$ recording with a sample rate of 2 s solves these problems.

## 2 Tracer gas experiments

In February 2014, several tracer gas experiments were conducted in the subway system of a major European city. The objectives of these experiments were the following.

- Determine pathways of gas dispersion inside subway stations.
- Determine the influence of train traffic.
- Determine the effect on large parts of a subway system if a tracer gas is released inside a running subway coach.

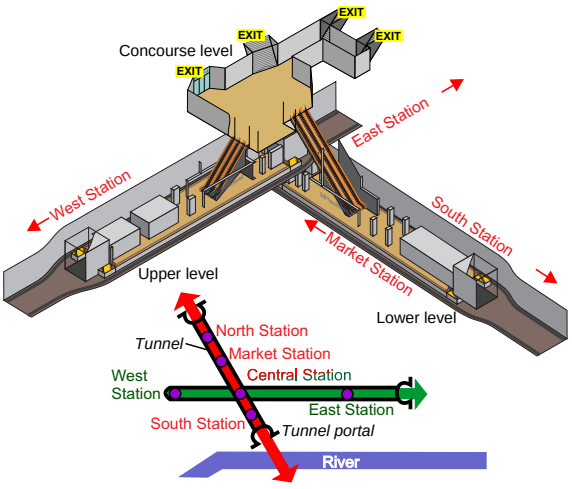


**Figure 1.** Three-dimensional view of Central Station and overview of underground stations of the subway system.

## 2.1 The experimental site: the subway system

The experiments were carried out inside the underground station of the subway of a major European city. The underground network consists basically of two lines, running north to south and east to west with a total length of about 4 km. At Central Station, both lines cross. This station has a concourse level connecting all platforms and also a shopping mall (see Fig. 1). Due to orography, the tunnel of the east–west line climbs from East Station to West Station by 15 m, while the north–south line climbs approximately 30 m towards North Station.

## 2.2 The gas sensor

In contrast to former experiments, which only reflect rough pictures of the gas dispersion (Pflitsch et al., 2010), the new mobile integrated measuring and analysis system can provide much more detailed data (Potje-Kamloth, 2014). As the sensor platform is a battery powered hand-held device, more experiment settings are possible. The device can be connected to temperature sensors and ultra-sonic anemometers, and is thus able to record all parameters to feed a numerical simulation (CFD) with margin conditions. The tracer gas data can be used to validate dispersion forecasts of numerical simulations with empirical data. The heart of the device for measuring the smallest $SF_6$ concentrations consists of the integrated gas sensor. This is a robust nondispersive infrared sensor (NDIR) assembly optimized for reliable detection of concentrations $\leq 50$ ppb $SF_6$. The performance of the gas sensor had to be improved by a factor of 4 compared to the state of the art. The method of measurement of infrared absorption is based on the Lambert–Beer law, so there are several basic approaches to improve the signal/noise performance. According to the theory for this purpose, the radiation intensity $I_{(0)}$ must be increased substantially. The optical key components for this are a powerful and modular blackbody radiator, an interference filter tuned to the absorption of $SF_6$ in the range of 10.6 µm (see Fig. 2), a sensor cuvette with low optical attenuation and a low-noise and highly sensitive detector. Novel amplifying and signal evaluation topologies with performance electronic components as well as the emulation of a lock-in amplifier with software also provide an important contribution. Particularly noteworthy here is the specially developed map-correction algorithm (matrix calibration). The result is that the measurement setup during exposure to ambient air is ideally if possible decoupled from either static temperature or pressure fluctuations. Therefore a very low nonlinearity is achieved (the excessive amount maximum in the measuring range is 0.2 ppm, or 0.4 % of the upper full scale) even in the sub-ppm range for a temperature range of −10 to 40 °C (see Fig. 3).

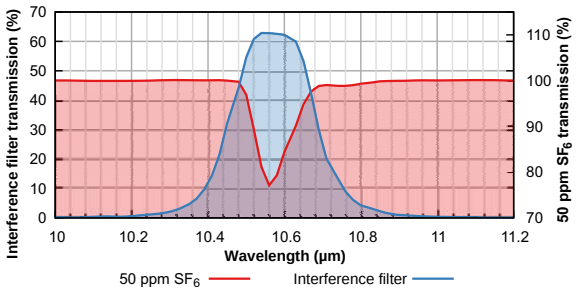


**Figure 2.** Transmission of the interference filter and absorption bands of $SF_6$.

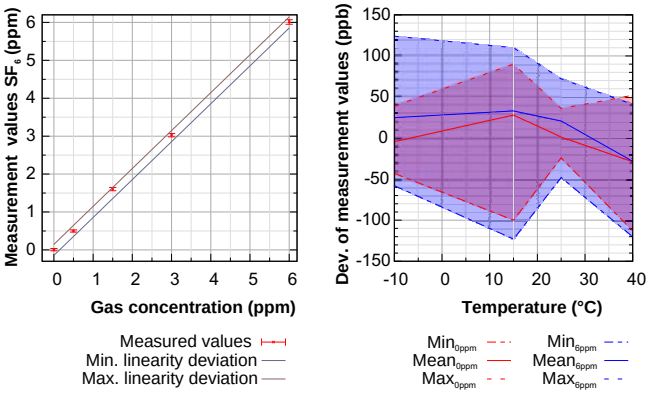


**Figure 3.** Designated representation of nonlinearity in the sub-ppm range over a temperature range of −10–40 °C.

## 2.3 The influence of train traffic

During the night of 22 February, two tracer gas experiments were conducted to track the gas propagation for a station and its adjacent tunnels and stations. Therefore, Central Station was chosen, as it consists of two platform levels and a mezzanine. The experiment was carried out twice. The first gas

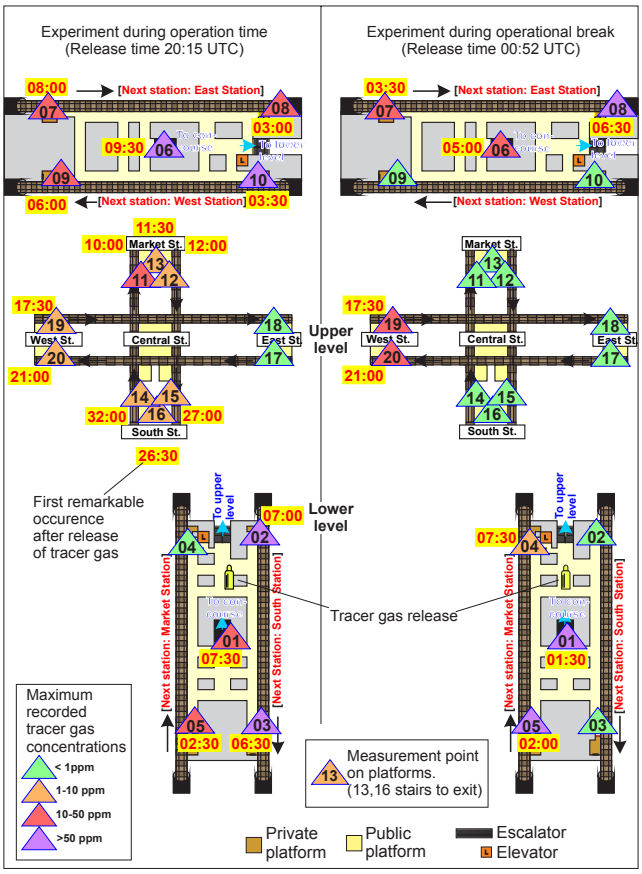


**Figure 4.** Comparison of tracer gas experiments during traffic times (left) and operational break (right).

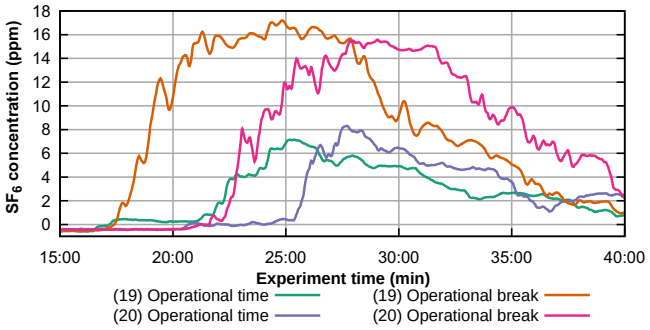


**Figure 5.** $SF_6$ concentrations at North Station. The numbers in parentheses contribute to the measurement points (see Fig. 4).

release was done during the operational time of the subway at 20:15 GMT. For 10 min, an amount of 2.15 kg $SF_6$ was released. In order to compare traffic times with the operational break, the experiment was repeated on the same night. At 00:52 GMT 2.06 kg of $SF_6$ were released for about 8 min. The upper level (platforms 3/4) was contaminated within 3 min during the train traffic experiment and within 5 min without traffic. This confirms an experiment undertaken 1 day earlier (Spiegel et al., 2014a), which focused only on the station. The maximum value of recorded tracer gas concentration was higher and larger parts of the platform levels were affected. The propagation paths were chaotic due to several train movements (see Fig. 4). A similar picture emerged when focusing on the adjacent stations, but here the maximum recorded concentration was found at West Station during the operational break. During the operational time, sensor (19) detected the first values at 17:30 min after the gas release. Sensor (20) followed at 21:00 min. However, the first measured concentrations were on a very low level. As a subway train reached West Station from Central Station at around the same time, it can be assumed that this first detected concentration is influenced by train movements. A steeper rise of the values occurred approximately 5 min later. In contrast, during operational break this steep rise coincided with the first remarkable increase in concentration (see Fig. 5). Market Station and South Station were affected by traffic during the experiment. As the track rises from South Station to North Station, a natural background air flow from south to north is established due to the buoyancy effect. Of course, running trains disturbed the background airflow, but the gas reached the station in the direction of the natural flow 10 min after the gas release. At South Station, on the other hand, it took three times longer for gas to be transported against the direction of natural flow by the piston effect of the trains.

## 3 Tracer gas release inside a subway train

The hand-held integrated analysis and measuring system offered the possibility to measure tracer gas inside operating trains. An $SF_6$ bottle was boarded in the back coach of a two-wagon subway train. At 2 min before the train reached Central Station, in the back coach tracer gas was released continuously with a relatively low flow rate. The release was stopped 7 min later when the doors closed at North Station. By then, an amount of 1.49 kg $SF_6$ was released from the gas bottle. The contaminated coach reached very high values of 800 ppm for a period of 2 min. This experiment was repeated in the opposite direction about 90 min later, releasing 1.91 kg $SF_6$.

### 3.1 Contamination of stations

Moreover, the highest concentration inside the station was found in the staircases to the concourse levels and the exits astonishingly quickly. This is a further verification that staircases in subway stations are sucking air from the lower parts of the structure (see Fig. 6). During the repetition of this experiment, a slightly lower concentration was recorded, but the patterns of the spatial and temporal distribution were confirmed. An additional measurement sensor records the tracer gas concentration on the concourse level of Central Station,

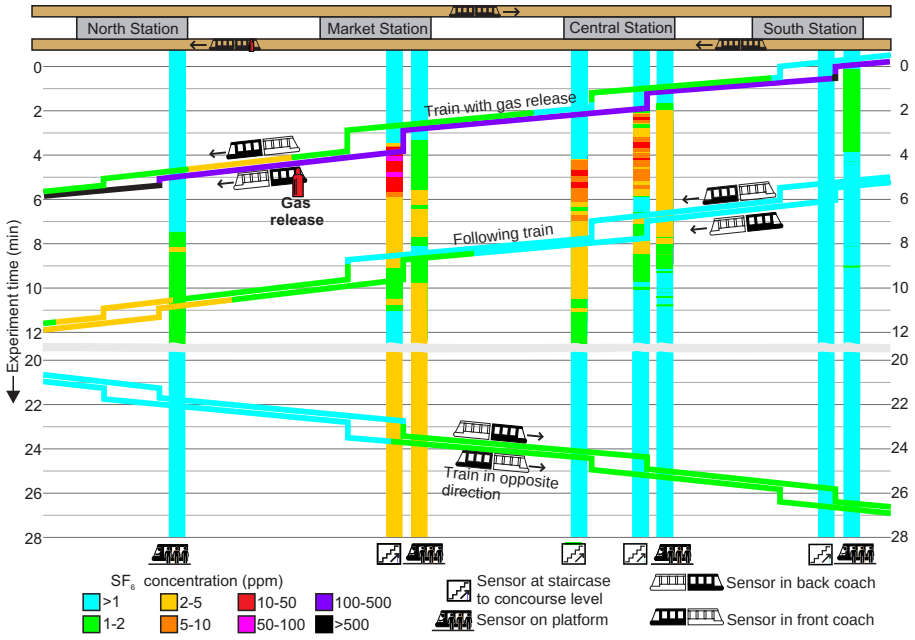


**Figure 6.** Tracer gas release inside a running train in the back coach. The lines represent the measured concentration while the train is running. The bars represent sensors on the platforms inside the station.

which represents the only escape route from the lower platform levels. As the contaminated train reaches Central Station, some remarkable concentrations were observed on the concourse level within 3 min (see Fig. 7).

## 3.2 Contamination of trains

The trains of the investigated subway system consist of two separate coaches. After the first stop, a small contamination was observed. At the third stop significantly higher values were logged. Using the mobile advantage of the new sensors, $SF_6$ was also measured inside the following train. At each station this train opens the doors and some contaminated air flows into the coaches. Consequently, the concentration accumulates up to 3 ppm after the passage of Market Station. The mobile sensor students were located in the trains and after riding from South Station to North Station they were replaced in the next train in the opposite direction, riding through the contaminated underground stations again. At Market Station, the concentration stabilized at 2–5 ppm. As trains called there some tracer gas was sucked inside the train and the concentration considerably increased (see Fig. 6). In order to measure the concentration over a longer time period, one mobile sensor remained in the contaminated train. After stopping at North Station, the train continues over ground. Concentrations remained at nearly 1000 ppm for three further stops. At 7 min after the end of gas release it decreased to 100 ppm, and after 11 further minutes, calling at the ninth overground station, values dropped to 10 ppm. At 50 min after the beginning of the gas release and 20 calls at overground

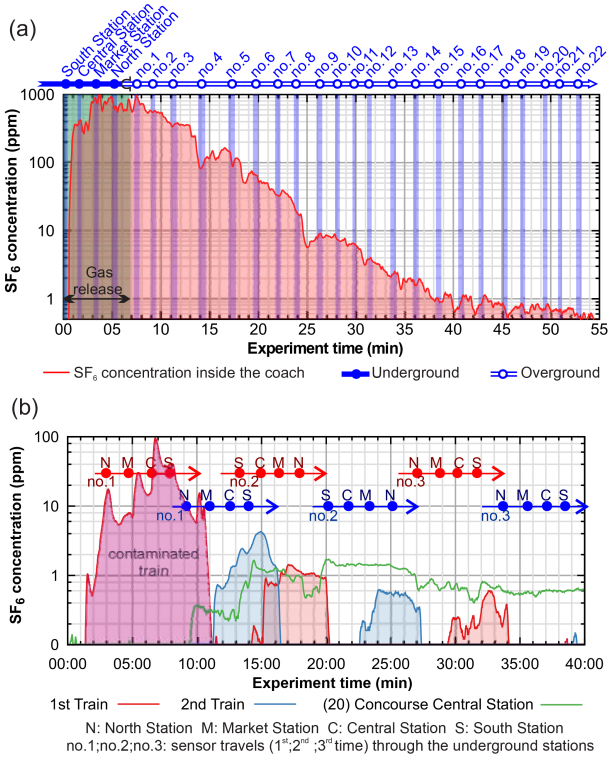


**Figure 7. (a)** Remaining concentration level inside a subway train after the initial gas release; **(b)** contamination of running subway trains while passing the contaminated underground track and of the concourse level at Central Station (see Fig. 1).

stations, there were still measurably elevated levels in gas concentration (see Fig. 7). The sensors traveled three times on two trains through the underground station in the repetition experiment. The sensor's positions were changed to trains in the opposite direction as they leave the experiment area. Whereas the concentrations were slightly lower in the repetition, the tracer gas remained in the system for a longer period. Therefore, even during the third transit 30 min after the gas release, a demonstrable increase in concentration levels was observed in a train. Furthermore, about 40 min after the release, some notable peaks were recorded (see Fig. 7).

## 4 Main results of the tracer gas experiment

Subway stations are mostly relatively overwarmed in the temperate climatic zone. With increasing depths of stations, and lengths of staircases, the buoyancy effect, which pushes air upwards, also increases. The experiments have shown that the tracer gas propagates to upper parts within a few minutes. Unfortunately, the propagation path overlaps with escape routes for passengers. The geometry of tunnels has an effect, as differences in elevation drive a natural background air flow. However, more detailed climatological data have to be considered to forecast the spreading of toxic gas in subway systems. The gas release inside a running subway coach can affect wide parts of stations and even harm passengers in following trains up to 30 min later.

## 5 Conclusions

Using the new integrated analysis and measuring system opens new opportunities, as more complex field tests can be conducted with less effort. During the measurement campaign five tracer gas experiments were conducted. Collecting this amount of data with previous methods like air samples using syringes, over 6000 samples were necessary to cover the same measuring time, with a sample rate of only 1 min. The new sensors could measure with a sample rate of 2 s, which is a big advantage. Experiment costs are reduced to a tenth with the method covered in this paper. The threshold limit of $SF_6$ is 1000 ppm for an average working day of 8 h, so it is possible to conduct such tracer gas experiments during operational times without harming the passengers. Gas chromatographs cannot be used in high numbers. Existing hand-held measuring systems are used for leak detection of high voltage switch gears, the measuring range is too big, or the high power consumption for the devices makes them utilizable for a long-term continuous mobile measurement. The new sensors can accurately detect $SF_6$ contamination from 0.05 to 50 ppm. A very low detection limit is warranted due to the high greenhouse potential of $SF_6$. Results of the field, as mentioned in this paper, can be coupled with numerical simulations (Spiegel et al., 2014b) or with pedestrian simulations (Qian et al., 2014; Brüne et al., 2014) to assess subway systems in many safety questions.

**Acknowledgements.** Conducting research into critical infrastructures like subway systems is very difficult and only possible with the permission of the operator. Our research caused a lot of effort on the part of the operators. We are grateful that subway operators provide us with their tunnels and stations. We also focused on safety questions and we are very pleased that we find operators who have the courage to work with us on these issues. This work was part of research project "Measuring system for the determination of the dispersal of hazardous materials in critical infrastructures and complex building for the prevention of civil disasters" (MAusKat) by the German Federal Ministry of Education and Research (funding code 13N11673-678).

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