ANALYSIS OF A 10 MW FIRE IN AN UNDERGROUND RAILWAY STATION USING FULL SCALE TESTS AND CFD

J. Rodler¹, A. Bassler², E. Schnell²
¹Gruner GmbH Consulting Engineers, ²Austria, Gruner AG

ABSTRACT

The railway line operated by Zentralbahn Luzern (zb) was expanded to two tracks and re-routed underground on the section from Lucerne Station to Kriens Mattenhof Station. The new route section consists of a tunnel about 550 m long constructed by underground means, an underground railway station nearly 300 m long with three access points, a cut-and-cover tunnel about 470 m long and a ramp 140 m long, the total length thus being 1460 m.

The underground railway station is equipped with a smoke extraction system. The latter consists of a smoke extraction duct with openings along the platform, two axial fans in a ventilation building and an exhaust air flue. During project approval the Swiss Federal Office of Transport (FOT) stipulated that the performance of the smoke extraction system be verified by testing prior to commissioning and that the achievement of safety objectives be documented.

For this reason, a test concept was developed that not only comprises aerodynamic tests and hot smoke tests on a 1:1 scale with fire loads of 1 MW max. but also involves a mathematical proof based on three-dimensional flow simulations (3D computational fluid dynamics or 3D CFD).

As a result, it was possible to produce objective evidence that the safety objectives were achieved in a fire scenario with a heat release of 10 MW. In addition, the use of computational simulations for obtaining objective evidence meant it was possible to investigate certain influences more closely within the scope of a sensitivity analysis.

Keywords: underground railway station, smoke extraction system, hot smoke tests, computational simulation of hot smoke tests, smoke extraction

1. INTRODUCTION

Within the scope of the "Zentralbahn Upgrade" construction project, the railway line operated by the regional railway company Zentralbahn (zb) in Central Switzerland on the section from Lucerne Station to Kriens Mattenhof Station was upgraded to two tracks and re-routed underground. The new route section consists of a tunnel about 550 m long constructed by underground means (Hubelmat), an underground railway station nearly 300 m long with three access points, the Allmend cut-and-cover tunnel about 470 m long and the Mattenhof ramp 140 m long.

The underground railway station "Luzern Allmend/Messe" is equipped with a smoke extraction system for the safety of users. The latter consists of a smoke extraction duct along the platform, two axial fans in a ventilation unit and an exhaust air flue. During planning approval the Swiss Federal Office of Transport (FOT) stipulated that the performance of the smoke extraction system be verified by testing prior to commissioning and that the achievement of safety objectives defined in the safety concept [3] be documented.

Since at the scheduled time of testing the overhead line and other sensitive fittings had already been attached to the ceiling of the tunnel, the plan to simulate a 5 MW fire incident with hot smoke test apparatus had to be discarded.
Instead, in addition to aerodynamic tests and hot smoke tests with fire loads of 1 MW max., three-dimensional flow simulations (3D computational fluid dynamics or 3D CFD) were conducted. Apart from a check on aerodynamic design and the fire scenarios realised in the test, the aim was particularly to produce mathematical evidence that the safety objectives were achieved in a fire scenario with a heat release of 10 MW.

The use of computational simulations for obtaining objective evidence meant it was possible to investigate certain influences on the behaviour of the fire smoke extraction system more closely within the scope of a sensitivity analyses.

2. DESCRIPTION OF THE SMOKE EXTRACTION SYSTEM

At the "Luzern Allmend/Messe" station there is a ceiling duct made of fire-resisting material mounted above the platform, via which smoke can be mechanically removed from the station. The smoke extraction duct has a length of approximately 220 m and it follows the course of the platform. Due to the arrangement of several ceiling columns and 3 staircases the cross-section of the smoke extraction duct varies between 3 m² and 10 m². In addition, there are subsections with a united smoke extraction duct and subsections with two separate smoke extraction ducts. The ducts are routed past the stairs on the left and right (Figure 2).

![Figure 1](image)

**Figure 1:** Cross-section of "Luzern Allmend/Messe" station with extraction duct

Smoke extraction takes place via extraction openings distributed at equal intervals along the length of the platform. Their size can be varied with the aid of slides and they are always adjusted so that the flow of air (approx. 6.5 m³/s) is the same at each opening. There are 11 x 2 extraction openings altogether, which means they are positioned at intervals of about 20 m. The openings are located on the side of the duct facing the track and do not have any flaps, i.e. they are always open.

The total volumetric flow is extracted by two parallel fans (partial redundancy) in the ventilation building. The system is designed for a rated volumetric flow of 140 m³/s but it has some reserve capacity so a maximum working point of 175 m³/s can be reached.

In addition, the duct is provided with a smoke apron along the station. The distance between the smoke apron and the top of the platform is 2.5 m.
3. PROTECTION OBJECTIVES

The aerodynamic tests, hot smoke tests and ensuing 3D flow simulations are designed to produce objective evidence that the safety objectives defined in the safety concept [3] are achieved:

- **Safety objective 1 - Accesses to the station:**
  The three accesses to the station remain low-smoke zones for at least 15 minutes.

- **Safety objective 2 - Height of the low-smoke layer within the station:**
  For the first 10 minutes the average height of the smoky layer in the platform area does not drop below 2.5 m. In this area of the station the height of the low-smoke layer does not drop below 2.0 m during the first 10 minutes, neither temporarily nor locally.

Compliance with the safety objectives is assessed by analysing the two parameters of temperature and extinction coefficient. The quantitative criteria indicated in Table 1 are examined in order to produce objective evidence.

**Table 1:** Criteria for producing objective evidence that protection objectives are achieved (quantitative analysis)

<table>
<thead>
<tr>
<th>No.</th>
<th>Criteria</th>
<th>Limit</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Height of the low-smoke layer</td>
<td>2 m</td>
<td>Applies to a period of 10 min</td>
</tr>
<tr>
<td>4.</td>
<td>Extinction coefficient K of the low-smoke layer</td>
<td>≤ 0.15m-1</td>
<td>The recognisability of escape route pictograms is only severely restricted as of approx. K = 0.4m-1 (&gt;&gt; 0.15m-1) (cf. Fehler! Verweisquelle konnte nicht gefunden werden.).</td>
</tr>
</tbody>
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4. HOT SMOKE TESTS

4.1. Test Setup

In order to minimise the temperatures at the ceiling of the station and at the conductor rail low rates of heat release (< 1 MW) were realised at the site of the fire. With several small gas burners positioned directly above the tracks it was possible to generate relatively large amounts of flue gas at relatively low temperatures (cf. Figure 2). The volumetric flow of flue gas from all the burners together corresponded approximately to that of a 5 MW fire. To protect the conductor rail a fire protection blanket was also suspended above the burners, directly under the conductor rail.

The flow situation in the station was recorded by simultaneous measurement of air flow velocity on the platform, in the staircases and in the two tunnel tubes. In addition, meteorological measurements were taken in the area of the tunnel approach in Mattenhof.

Temperature measurements were taken at the staircases in the two tunnel sections, at the Allmend portal and in the station, especially in the area of the fire directly below the conductor rail. The volumetric flow extracted by the two smoke extraction fans was measured and recorded in the control room.
4.2. Result of the hot smoke tests

On 25 and 26 September 2012 the I.F.I. (Institut für Industrieaerodynamik GmbH) conducted a total of 6 hot smoke tests with various boundary conditions in collaboration with HBI AG.

The flow situation in the station prior to activation of the smoke extraction system depends not only on temperature differences between inside and outside but also on the wind forces acting on the tunnel portals and staircases. The temperature differences were not very substantial and the maximum was 4°C. During the first 4 tests, wind activity was also only moderate. Wind velocity fluctuated between 0 and 1.5 m/s. As of the 4th test the wind activity increased and in the 6th test it reached peaks of up to 9 m/s (1min means). As a result, flow velocities of up to 2.5 m/s were induced in the station.

At the beginning of the first 4 tests a basic flow of < 1 m/s was measured in the station. The air flowed out of the station via the staircases. When the ventilation system was activated the direction of flow was reversed. The same happened at the portal where the basic flow had previously excited. The total air flow entering the station is extracted by the two axial fans through the smoke extraction duct. When the ventilation system is activated, the flow velocity in the staircases temporarily rises excessively due to the smaller masses of air that have to be displaced.

At the beginning of fire development, the smoke within the track area rises to the ceiling and spreads out below the ceiling on either side of the fire site. Spread in one direction is slightly more intense due to the prevailing basic flow and the smoke ultimately reaches the end of the station.

Activation of the smoke extraction system draws the smoke back into the area of the fire source, from where it can be completely extracted. Temporarily, and only in the area of the fire source, there are also minimal smoke immissions into the low-smoke layer. After about 8 minutes a quasi steady state develops, in which the smoke layer remains stable and extends from the ceiling to the bottom of the smoke apron at most.
5. SIMULATION ANALYSES

5.1. Simulation Program

To obtain mathematical objective evidence (achievement of safety objectives) the flow simulation program STAR-CCM+ was used. The three-dimensional geometry of the station was modelled on the basis of CAD drawings. A train standing in the station was also modelled (cf. Figure 3).

Figure 3: Geometric mathematical model with train

5.2. Result of the Simulations

Several simulations of the fire scenarios were performed using various boundary conditions. The check on the hot smoke tests was mainly used for calibration of the mathematical model and for validation.

The check on the 2nd hot smoke test was used for validation proper of the CFD simulation model and it consisted of several computation runs, of which some are accounted for by the modelling of energy release in the fire volume and for reproduction of temperature measurements in the area of the conductor rail above the fire location and some were used for a sensitivity analysis of the thermal boundary conditions. This involved the temperatures at the pressure boundaries (portals and exits) and temperature initialisation in the area of the fire. In addition, portal pressure difference was checked which generated a longitudinal flow through the structure corresponding to test conditions.

There was also an evaluation of the computation runs with regard to all the necessary state and flow parameters in the computational domain, such as visibility, smoke concentration (extinction), temperature, volumetric flows, flow velocities, turbulence parameters, etc. and an assessment of convergence characteristics.

The check on the second hot smoke test indicated that the simulation produces plausible results with regard to temperature distribution and smoke spread (cf. [9]). This can be very clearly seen in Figure 4. The latter shows photographic documentation of the smoke density situation in the station during test 2, alongside the same situation with a superimposed CFD simulation result. The level of smoke-free vision correlates well in both cases.
Several simulations were also performed with a constant heat release of 1 MW, which served to identify the influence of different longitudinal velocities in the structure. For this purpose the static pressure at one tunnel portal was successively increased from 0 Pa, as a result of which the longitudinal flow velocity induced in the station increases. At a longitudinal flow in the structure of about 2.5 m/s with the smoke extraction system activated the smoke layer of a 1 MW fire becomes unstable on the side facing away from the fire. This correlates well with the observations made in the 5th hot smoke test.

The mathematical proof of compliance with the safety objectives was obtained by means of flow simulation for a fire incident with a fire load of 10 MW. A total of 7 computation runs were performed with an energy release rate of 10 MW. Three were conducted without a rail vehicle in the station and four were conducted with. Within the scope of a sensitivity analysis, additional investigations were performed which produced findings concerning the following points:

- The stability of the smoke layer in relation to fire load and basic flow
- The influence of extraction flow on the quality of smoke extraction
- The influence of the rail vehicle in the station

A high basic flow in the station due to meteorological pressure differences has a detrimental effect on the smoke density situation because the spread of the stable smoke layer is disrupted. At high longitudinal flows (> 3 m/s) the smoke extraction system reaches the limits of its performance.

The investigations also showed that an increase in extraction flow to 175 m$^3$/s has a positive influence on the smoke density situation in the station because then meteorological influences can be kept under control more easily and the continuous inflow via the staircases is improved.

The rail vehicle in the station also has a positive influence on the smoke density situation because, on the one hand, a considerable volume of smoke can accumulate inside the vehicle, and on the other hand, the restricted inflow to the fire source leads to higher temperatures in the smoke layer, which therefore remains at the tunnel ceiling for a longer period.
Figure 5: Example of compliance with the safety objective "temperature in the low-smoke layer" - longitudinal section of the station

6. SUMMARY

The newly built underground railway station of Zentralbahn, "Luzern Allmend/Messe", was equipped with a mechanical smoke extraction system. To produce evidence of the fact that it achieves the protection objectives specified by the safety documentation, the performance of the smoke extraction system was investigated by conducting hot smoke tests and three-dimensional flow simulations (3D CFD) prior to commissioning.

Several hot smoke tests in the station with fire loads of up to 1 MW were used to validate a 3D simulation model. For this purpose, simultaneous measurements of air flow velocity on the platform, in the staircases and in the two tunnel tubes were taken at the same time. In addition, air temperature was measured at numerous positions. Meteorological measurements in the portal area produced the initial boundary conditions.

Based on the validated simulation model, the mathematical proof of compliance with the protection objectives was obtained by means of flow simulation for a fire incident with a fire load of 10 MW. Several computation runs were performed with and without a rail vehicle in the station. Within the scope of a sensitivity analysis, additional findings were obtained with regard to the following points:

- The stability of the smoke layer in relation to fire load and basic flow
- The influence of extraction flow on the quality of smoke extraction
- The influence of the rail vehicle in the station

Evaluation of the state parameters obtained from the simulations, i.e. visibility, smoke concentration (extinction) and temperature in the computational domain, permitted a simple assessment of the criteria for producing evidence of safety objective achievement.
7. REFERENCES


