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Full-scale tests of alternative methods for fire fighting in underground structures.

Anders Palm1,2, Mia Kumm1, & Haukur Ingason3
1Mälardalen University, Västerås, Sweden
2Greater Stockholm Fire Brigade
3SP Technical Research Institute of Sweden, Borås, Sweden

ABSTRACT

The paper describes the full-scale fire and rescue tests performed in Tistbrottet in Sala, Sweden, in autumn 2013. A total of six different approaches to fight a full scale fire in a tunnel were tested. The six approaches involved different fire-fighting equipment but were performed from an equal point regarding fundamental conditions such as length of response-route, fire-fighting set-up, smoke and fire size. The aim was to compare different equipment and methods to reach and eventually put out the fire. Fire fighters using breathing apparatus (BA) were monitored regarding air consumption, movement speed and local actions and decisions. The results are presented and analyzed in respect to fire-fighting efficiency, front BA operations including moving speed and performed actions, as well as the time to successfully put out the fire. Measurements of heat release rates (HRR) and temperatures are given in order to quantify the efficiency of the operation.

KEYWORD: full-scale fire experiments, tunnel, fire-fighting, heat release rate (HRR), oxygen, walking speed.

INTRODUCTION

The fire and rescue services possibility to reach fires in tunnels and other underground constructions have in some content been discussed and tested practically both in earlier Swedish research projects [1-4] and in real fires [5-7]. In many of the earlier research projects the main focus has been on the fire and rescue services limitations and not on the possibilities to solve the fire fire-fighting task. Considerable problems to perform effective fire-fighting and rescue operations are inherent in real situations and are experienced during training of fire-fighting crews. Underground structures represent a complex environment with other risks than the everyday enclosure fires. Some of the issues concern long response-routes, lack of overview and difficulties for the fire-fighting personnel to orientate in the environment. Based on the experience from real fires and earlier fire and rescue full-scale tests, there is a need to define the risks and difficulties, to adapt the tactics and methods to the risks and to provide guidance to perform adequate risk evaluation prior BA-fire and rescue operations in these specific premises. As the response route can be very long, especially in rail and distribution tunnels, air consumption in many cases is the limiting factor in these underground fires.

Earlier work by Swedish researches has been focusing on tactics and possible scenarios that the fire services can manage [2, 8-13]. This research has resulted in handbook chapter on fire-fighting in tunnels [14]. This research project aims at mapping different methods for fire-fighting in underground structures using different types of equipment. In order to do a complete analysis a realistic fire scenario was needed. The full scale test presented here consists of a series of total six different approaches to fight a full scale fire. The approaches were conducted with professional firefighters and the conditions were simulated to be as close to reality as possible. During each test approach, basic variables such as moving speed, air consumption, communication and co-operation among the teams were monitored and documented. Every approach was compared to parameters concerning fire and
smoke development such as, fire size, backlayering, smoke production and temperature. This is a unique experimental setup which analyses the effect of a standardized 18 MW on the BA-teams as they advance in the tunnel using different equipment. This paper presents the main results from these experiments which were carried out in Tistbrottet in Sala north of Stockholm, Sweden in October 2013.

TEST SITE

The hard rock dolomite mine where the fire tests were performed is owned by Björka Mineral AB and is located on the outskirts of Sala, Sweden. The fire tests were conducted at level 55 (55 m from the top of the mine) which is a non-active part of the mine that is connected to an open pit. The non-active part is connected to an active part that goes down to level 90, see figure 1. The fire tests were performed in a part of the tunnel system which was relatively straight. This part is shown in figure 1 and is designated as the mine drift. The length of this part was 100 m with an average width of about 8 m and a height of 6 m. The ground consists of hard packed gravel. The fire was at the center of the mine drift, i.e. 50 m into the mine drift. For safety reasons the mine drift was rock bolted at all fire-exposed areas both down- and upstream the fire. A 50 mm thick stone wool insulation was placed on a metal grid fastened to the rock bolts and was placed in the tunnel roof over the test site. A non-insulated grid covered the full roof area of the tunnel past the measurement container to the middle of the first cross-tunnel. The main objective was to protect the rock and prevent cracked stones to fall on the BA-fire fighters.

![Diagram of the mine setup](image)

**Figure 1.** Plan view of the non-active part dolomite of the mine in Sala, Sweden. The entrance was in a pit at level 55. The entrance to the mine is indicated on the right hand side of the sketch and the exhaust on the left hand side.

FIRE SOURCE

The fire source consisted of two 20 ft steel containers welded together. The external measures of both are 12.19 m long, 2.44 m wide and 2.59 m high. On both the long sides of the steel container 6 windows with the measures of 1 x 0.84 m (w x h) was opened up. The c/c distance between the windows was 1.5 m. An additional window was placed at the rear end of the container measuring 2 x 0.84 m. The lower ends of the windows were elevated 1.5 m from the ground. Two doors were mounted at the front of the steel container. The windows were used in order to control the fire size by creating a ventilation-controlled fire, and at the same time make it impossible to attack the fire by direct hit of the extinguishing media. This would for example simulate a situation in a train or a metro wagon. This was thought to be a good way to test this type of difficult fire-fighting approach inside a narrow tunnel. The free space between the walls and the steel container was about 1.5 m. At the upstream end of the steel container the door was opened during loading of the wood pallets. During ignition, except from the first test, the doors were closed. The ignition source which consisted of a steel pan measuring 0.2 x 0.8 m was placed on the lowest wood pallets and close to the doors through
a hole fixed at the side of the container. It was filled with 2.5 l of heptane before ignition. Directly after ignition the two fire fighters that ignited started to walk back to the entrance. The ignition itself postulate the time equal to zero in operational part of the fire attack and all other times given in the paper. The smoke machines were started by the fire fighters on their way out from the scene of the fire and the operational part of the fire-fighting could start. Unfortunately, during the first test, the doors were not closed properly so they opened up partly, which had dramatic effects on the fire growth and the maximum HRR. This was not repeated in the following five tests, where instead the ignition was performed through a small cut open hole with the area of approximately 5 dm².

The container was loaded with wooden pallets with a total mass of approximately 2000 kg. The pallets were piled up to 1.5 m, filling up the entire width of the container. Due to safety reasons, as the fire fighters were instructed not to pass behind the container, the pallets were piled in the upstream end of the container, leaving the last third part of the container empty. The windows were just above the piled wood pallets. The moisture content of the wood pallets was measured and in average it was about 20 %. Pre-calculations estimated the maximum HRR to be 18 MW, assuming that the only access of air was through the windows of the container.

**INSTRUMENTATION AND EQUIPMENT FOR THE TEST**

The center of the fire source was 200 m from the entrance to the mine and 76 meters from the exhaust opening. The mine drift used as test site was approximately 100 meters long. The difference in height between the entrance of the mine and the exhaust was slightly less than 1 m.

The test site has neither mechanical ventilation nor any reliable natural ventilation and was therefore equipped with a mobile ventilator (Tempest model MGV L125). The ventilator is diesel powered and has a flow rate of 217,000 m³/h. Depending on the relatively small exhaust area and the exhaust rugged structure and the mines s-shape with corners and bends the maximum airflow at cold temperature (10°C) reached approximately 2 m/s. The main airflow became more or less as a bulk flow bypassing the short mine drifts from the fan towards the entrance. The velocity increased slightly when heat was produced from the wooden pallets. The location of the mobile fan is shown in figure 1, about 60 m from the entrance to the tunnel. Also three white smoke producers with a total capacity of 7000 m³/min were placed at the entrance, in the middle and at the end of the tunnel. This made it possible to fill the tunnel with white smoke over a distance of 150 m, i.e. from the mobile fan and towards the fire. This is the distance the fire fighter had to perform a BA-operation in order to get to the scene of the fire. The visibility in the white smoke was less than 0.5 – 1 m. It was impossible to find the way to the fire without an IR image camera. There was only one exhaust at the test site – all other mine drifts were dead ends – allowing for all the smoke to be ventilated out through the single entrance and thus allowing for HRR measurements at the end of the mine drift.

An overview of the test site in the drift mine is shown in more details in figure 2. The distances and the locations of measuring devices are also given. At the measuring station downstream the fire the HRR was determined. This included measurements of the mass flow rate, oxygen concentrations and gas temperatures at certain heights at the measuring station (pile). Five thermocouples (Tc) of type K 0.5 mm, were mounted on the vertical pile indicated in figure 2. The heights are given as distances from the ceiling. Velocity was measured at two heights. They are indicated as Bd and are found at the highest point and the half the tunnel height. One oxygen probe was used and that was located at the highest point. The gas temperatures were used to calculate the average oxygen concentration over the cross-section. The ceiling temperatures inside the insulation and the gas temperature 0.1 m below the ceiling were measured at the center of the fire. The upstream ceiling gas temperature were measured 28 m from the end of the container (0.1m below) as well as the velocity and gas temperature 3 m above the surface of the tunnel. This measuring point was important for monitoring the situation close to the burning steel container. If this gas temperature would exceed 300°C for 10 minutes it was decided to stop or hold the fire-fighting operation until the temperature lowered under the limit. If the temperature would exceed 500°C for more than 5 minutes the fire-fighting operation would be stopped and the tests would only continue after the tunnel had been inspected.
**Figure 2 The instrumentation layout. All measures are in meters.**

**MEASUREMENT AND CALCULATION PROCEDURE**

The HRR in the fire experiments was determined with aid of the oxygen calorimetry concept [15]. The measuring station was 10 m from the back side of the steel container. The measurements used to determine the HRR were thermocouples, pressure probes for determining the velocity and a gas instrument to measure the oxygen content in the hot fire gases. The loggers and computers were placed inside a measurement container indicated in figure 1.

The calculation of the HRR applied here is based on method presented by Ingason [16] using many thermocouples distributed over the actual cross-section and only a single point for measuring gas concentrations. The HRR is calculated according to the following equation derived from [17]:

\[
\dot{Q} = 13100 m_a \left( \frac{M_{O_2}}{M_a} \right) (X_{O_2,0} - X_{O_2,\text{avg}}) \quad [\text{kJ/s}] 
\]  

(1)

The molecular weight of oxygen \( M_{O_2} \) is 32 g/mol. The molecular weight of air \( M_a \) is 28.95 g/mol. The mole fraction of oxygen in the ambient air \( X_{O_2,0} \) is 0.2095. In equation (1) it is assumed that 13100 kJ/kg (E-factor) is released per kg of oxygen consumed and that air mass flow rate of combustion gases equals the ambient air mass flow rate, \( m_a = \rho_0 u_0 A \). Here \( \rho_0 \) is the ambient density of air (kg/m\(^3\)), \( u_0 \) is the average ambient velocity measured on the warm side. The warm velocity is converted to ambient velocity through the ideal gas law:

\[
u_0 = u_{\text{avg}} \left( \frac{T_0}{T_{\text{avg}}} \right) \quad [\text{m/s}] 
\]

(2)

It has been shown by Ingason [16], that it is possible to relate multiple gas temperatures measurements in a single tunnel cross-section to the average oxygen concentrations in a longitudinal tunnel flow, see equations (3). The average concentration of oxygen was calculated using the following equations:
\[ X_{O_2,\text{avg}} = X_{O_2,0} - \frac{\left( X_{O_2,0} - X_{O_2,0} \right) \sum_{i=1}^{N_T} \left( T_i - T_0 \right)}{N_T} \] [mol/mol] (3)

where \( T_i \) is the individual thermocouples, each on different heights and \( N_T \) is the number of temperature measuring points. The number of points in our case is 5. The measured average oxygen concentration is then put into equation (1) to calculate the HRR.

THE FULL SCALE FIRE-FIGHTING TESTS

The six different tests were performed and set-up to meet the working legislation that Swedish fire fighters have to meet in order to perform BA-operations in smoke filled environments. The first test is a standard procedure with equipment that can be found on many fire stations in Sweden as well as abroad. The first test was used as a “model” or a reference test to which the other tests were to be compared to. Before each test was conducted a thorough briefing was performed. This was to ensure that each one of the fire fighters were familiar to the test and the task that was expected of each member in the BA-team. For safety reasons the fire fighters were shown the test area without smoke prior the tests. The initiation of the full-scale fire and the production of artificial smoke were adjusted to reach the peak when the teams were expected to reach the scene of the fire. The personnel that were performing the tests consisted of professional fire fighters, both men and women from three different fire brigades. The fire brigades in turn represent organizations from larger urban zones (>1 Million inhabitants), large cities (>100,000 inhabitants) and provincial towns (<25,000 inhabitants). Each test was closely documented by a camera team of fire fighters with IR image cameras as well as fixed IR image cameras. The BA-teams were also equipped with IR image cameras of four different models. The criteria for when each fire was considered extinguished were when no flames could be seen or no re-ignition occurred. The six tests were as follows:

1. Traditional hose lay-out with traditional fire hose baskets and the hoses pressurized.
2. Traditional hose lay-out with “quick hose harnesses” and the hoses pressurized.
3. Traditional hose lay-out with traditional fire hose baskets and empty hoses.
4. Advancement in tunnel and extinguishing sequence with CAFS (Compressed air foam system) 38 mm hose lay-out.
5. Advancement in tunnel and extinguishing sequence with cutting extinguisher.
6. Advancement in tunnel with aid of a trolley for transportation of traditional equipment and extinguishing sequence. Extra bottles of transport air in trolley.

Method and procedures

The organization used during the tests consisted of three BA-teams with 2 fire fighters in each team. The organization and the modus operandi is basically the same throughout the test series. The front BA-team i.e. the pair that was in the front and always performed the extinguishing sequences was named the Red team. The second BA-team that also functioned as a safety team to the Red team was named the Green team and was located at Assembly Point 2 (AP2). The third team was named the Black team (AP1) and functioned as a safety team to the Green team. In figure 1 the positions of each team are indicated. A BA coordination officer was placed in a smoke free environment just outside the entrance of the tunnel on the assembly point zero (AP0). For additional safety an extra emergency BA-team with one extra BA coordination officer was on standby at AP0. Additional personnel were the incident commander (IC) and the firefighter that was managing the water pumps. The communication and the documentation of the tests were monitored by two operators in a command vehicle just outside the tunnel entrance. A crew of technicians monitored the measuring equipment installed in the tunnel. The basic procedures for the test 1 to 5 were as follows:

a) The operational part of the test started when the safety team who ignited the wood pallets in the container is back to the tunnel entrance (AP0).
b) The green and black teams begin to enter the tunnel together and in a joint effort set up the internal assembly point AP2, see figure 1.

c) The black team returns to AP0 to function as a safety team for the green team.

d) The green team prepares their hoses and equipment and get ready for the task of being a safety team to the red team.

e) When the black and green teams are at AP2 the red team begin their route to AP2 (to connect their hoses) and then onward to the scene of the fire.

Test 6 was conducted somewhat different because of the joint transportation of equipment. The equipment was arranged on a trolley and the three teams moved together to AP2 and then the red team further to the scene of the fire to extinguish the fire.

The overall fire-fighting hose line from the pumper at AP0 via the assembly points inside the tunnel, AP1 and AP2, and then further to its full extent was made up of the following hose components:

- 2 supply lines of 63 mm (25 m) hoses
- Manifold 1
- 3 supply lines of 63 mm (25 m) hoses
- Manifold 2
- 3 attack lines of 42 mm (25 m) hoses
- Which sums up to 200 m of attack hose line.

The criteria for the extinguishment of the fires were objectively estimated by noting when there were no more flames and no re-ignition. In the full-scale fire and rescue tests the 150 meters transportation was combined with extinguishing a potentially 18 MW fire. In table 1, a summary of the walking speeds and consumption of air is given for each test. This will be compared with the measured HRRs given in next section. The minimum pressure in the BA air cylinders were set to be 100 bar. After reaching this level each fire fighter had to start the retreat. This gives a theoretical limit for the group of six fire fighters of: 300 (bar) x 13.4 (l) x 6 => 24 120 (l), given the simplification that each individual has the same air consumption.

Table 1 A summary of the front movement times, time to extinguishment criteria, time to extinguish the fire and amount of extinguishing agent and amount of consumed air for each test water (w), foam concentrate (f)

<table>
<thead>
<tr>
<th>Test nr</th>
<th>approach</th>
<th>Time to reach AP1 [min]</th>
<th>Time to reach AP2 [min]</th>
<th>Time to reach fire source [min]</th>
<th>Time to reach extinguishing criteria [min]</th>
<th>Time to extinguish [min]</th>
<th>Ext. agent</th>
<th>Consumed air (tot) [l]</th>
<th>Consumed air (tot) [l]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - Conv.</td>
<td>1 min 30 s</td>
<td>7 min 40 s</td>
<td>14 min 45 s*</td>
<td>15 min **</td>
<td>15 s **</td>
<td>471 (w)</td>
<td>930</td>
<td>6324</td>
<td></td>
</tr>
<tr>
<td>2 - Conv./JT pac</td>
<td>1 min 3 s</td>
<td>5 min 8 s</td>
<td>18 min 9 s</td>
<td>20 min 23 s</td>
<td>2 min 14 s</td>
<td>1498 (w)</td>
<td>878</td>
<td>11765</td>
<td></td>
</tr>
<tr>
<td>3 - Conv./empty</td>
<td>1 min 17 s</td>
<td>5 min 11 s</td>
<td>11 min 30 s</td>
<td>15 min 25 s</td>
<td>3 min 55 s</td>
<td>494 (w)</td>
<td>946</td>
<td>12676</td>
<td></td>
</tr>
<tr>
<td>4 - CAFS</td>
<td>1 min 7 s</td>
<td>5 min 49 s</td>
<td>21 min 22 s</td>
<td>23 min 4 s</td>
<td>1 min 42 s</td>
<td>400 (w), 1.8 (f)</td>
<td>1163</td>
<td>15584</td>
<td></td>
</tr>
<tr>
<td>5 - Cutting ext.</td>
<td>1 min</td>
<td>5 min 57 s</td>
<td>16 min 10 s</td>
<td>-</td>
<td>-</td>
<td>250 (w)</td>
<td>958</td>
<td>12837</td>
<td></td>
</tr>
<tr>
<td>6 - Conv/trolley</td>
<td>1 min 29 s</td>
<td>12 min 49 s</td>
<td>29 min 12 s</td>
<td>31 min 9 s***</td>
<td>1 min 30 s***</td>
<td>Transep. air: 665</td>
<td>1260</td>
<td>Transp. air: 4522</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>BA: 595</td>
<td>12495</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total: 1260</td>
<td>12495</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* BA-teams stand-by at AP2 due to high temperatures. Decision was made not to repeat test 1, as movement tests with same set up were performed earlier in May 2013. ** Due to high HRR the test ran out of fire load. *** 27 s delay due to problem with water pressure from fire truck.
DISCUSSION AND RESULTS

Fire tests
First, the HRR measurements from the six tests are presented in figure 3. The figure on the left side shows a comparison of all HRRs. The figure on the right hand side shows only three tests (2, 3 and 6) in order to clarify the effects of different tactics. In test 1, the front doors never closed properly after ignition and they maintained open during the test. This clearly influenced the fire growth rate, the peak HRR and the duration of the fire. The increase is about factor 1.5 in peak HRR and a factor 6 in fire growth rate. As the door is open the wind pushed the flames through the wood pallet piles and the fire spread through the piles and increased dramatically resulting in much faster fire growth rate. The increase in peak HRR is related to intensifying the combustion process and surface combustion of the wood due to the wind. When the door is closed, the only access of air is through the windows and the combustion process becomes totally different. In this case fire becomes more like a compartment fire, and the process becomes dependent on the air exchange through the windows. The bypassing wind flow partly affects this process but not dramatically as in the flow-through case. Due to a restrained test schedule it was decided to follow the planned test schedule and not to repeat test 1. Beside the practical complication the research team has access to movement tests that were performed earlier in May 2013 and they will be used to put test 1 into the perspective of the other tests.

The pre-calculation estimated the fire to become ventilation controlled and 18 MW was expected. This appears to fit very well to the results, see table 2, where peak HRRs are summarized. The maximum values tend to be closer to 20 MW. The integrated energy $E_{\text{tot}}$ is about 20 GJ. This can be seen in test 6, which is more or less a free burn test as almost no wood pallets were left. Assuming 2000 kg and heat of combustion for wood of 0.012 GJ/kg, the total energy should be 24 GJ. In test 2 and test 3, the lowest $E_{\text{tot}}$ values were obtained which was reflected in the number of pallets remained after the test. Also the peak HRRs are slightly lower, or about 18 MW. This shows that the fire was clearly affected by the firefighters. This fits well with values given in table 1 about action times and time to extinction. Tests 4 and 5, are also affected slightly, at least the $E_{\text{tot}}$ indicates that. The temperature measurements given in table 2 do not reveal any indications on the performance. However, the backlayering temperature $T_{\text{max},b}$, 28 m upstream the fire is alarming high. The protection of the tunnel indicates a very good function. The HRR curves have also been integrated in order to estimate the energy content, $E_{\text{tot}}$ in GJ.

In table 2, the maximum temperatures in the ceiling, $T_{\text{max,ceiling}}$ as well as the plate temperatures, $T_{\text{max,p}}$ beside the container, which indicates the effects of radiation, are given.

Figure 3    The measured HRR for the six tests performed. To the left all tests are shown, and to the right, only three tests are shown in order to better see the effects of different methods.
**Table 2 Summary of data from the six full scale tests.**

<table>
<thead>
<tr>
<th>Test nr</th>
<th>$Q_{\text{max}}$ (MW)</th>
<th>$T_{\text{max, ceiling}}$ (°C)</th>
<th>$T_{\text{max,p}}$ (°C)</th>
<th>$T_{\text{max,b}}$ (°C)</th>
<th>$E_{\text{tot}}$ (GJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>33.0</td>
<td>715</td>
<td>325</td>
<td>402</td>
<td>19.4</td>
</tr>
<tr>
<td>2</td>
<td>18.1</td>
<td>401</td>
<td>340</td>
<td>349</td>
<td>11.6</td>
</tr>
<tr>
<td>3</td>
<td>18.7</td>
<td>366</td>
<td>371</td>
<td>337</td>
<td>8.0</td>
</tr>
<tr>
<td>4</td>
<td>17.6</td>
<td>368</td>
<td>397</td>
<td>387</td>
<td>14.4</td>
</tr>
<tr>
<td>5</td>
<td>25.5*</td>
<td>425</td>
<td>311</td>
<td>312</td>
<td>14.9</td>
</tr>
<tr>
<td>6</td>
<td>21.0</td>
<td>412</td>
<td>336</td>
<td>334</td>
<td>20.9</td>
</tr>
</tbody>
</table>

* This value is a single value, most of the data is around 20 MW as peak.

**Fire-fighting tests**

All the tests show the importance of preparation for both the individual team member and the group. It is vital that everyone knows what is expected of him/her and the standard operation procedures that are to be executed. Any flaw or mistake could result in a “system break down” and that the task has to be reset and started all over again or are severely delayed. The limiting factor aside from knowing how to perform the fire-fighting task is the air consumption. This can be clearly seen in table 1. The air consumption is highly dependable on each team members physical prerequisites i.e. body mass, fitness, workload and strain etc. As the amount of air is a limiting factor, the individuals in the team with less amount of air for disposal often will set the duration for the complete BA-team. In the tests it’s clearly shown that a lot of energy is consumed just to move in the environment and to carry or pull the equipment. Test 3 shows that time and energy is saved when the teams can advance with empty hoses i.e. light equipment. This also has the benefit of advancing the team early into a fire or a rescue operation. Test 6 shows that the use of special equipment such as trolleys for transportation, additional air-supply etc. carefully should be tested and practiced before taken into action. What seems to be easy in a bright and smoke free environment during exercises and preparation could be a difficult and even impossible task in a smoke-filled and complex environment.

Tests 4 and 5 which were the only tests where a different extinguishing method and extinguishing media (4) was used also show the importance of the maneuverability of the equipment. In test 4 the CAFS-system demonstrated a good performance in extinguishing the fire and with a low amount of water and foam, but it came with a high effort for the team to pull the hose the given distance. Earlier tests performed in the same mine in May 2013 indicates that advancement with an empty hose even here could be less strenuous. The IR images, taken approximately 5 minutes after the extinguish criteria was reached, though indicated that most of the foam was consumed and the approximately 0.4 to 0.5 m thick layer of glowing remains could re-ignite. As the glowing layer later was soaked in water in order to make it possible to clean the container for the next test, a re-ignition never occurred. The long-term success to extinguish a fibrous fire will to some extent always correlate to the amount of used water. In test 5 the effort to pull the hose was less, but in addition the performance to put out the fire in the container was not as good as in the other tests using water (normal pressure) or foam. The configuration of the burning object seems to be a factor to take into consideration when fighting fires underground. The steel container added some difficulties for the BA-teams in the way that the openings were somewhat elevated (1.5m) to imitate a real train or metro carriage. Some fire fighters complained that it was hard to direct the spray of the water or foam in through the openings and on to the burning fuel surface. The main cause was the height of the opening and radiating heat from the container. The heat and backlayering distance, especially in test 1, made it impossible for the team to continue and the advancement of the team actually had to be halted half-way in the tunnel for safety reasons. The main reason for the high HRR was that the container doors suddenly swung open during the test.

From fire energy consumption point of view it is clear the test 2 and 3 were very successful; especially test 3, which consumed least energy in the fire. In test 3, the fire fighters were also fastest to reach to the scene of the fire, mainly because they had no water in the hoses. They started to fight the fire before it reached its peak HRR. In tests 2 and 3 it took them about 3-4 minutes to suppress the
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fire. Due to the fact that test 1 had much faster development it is difficult to compare that test to the others. When they arrived the HRR was going down very rapidly and the fuel was almost totally consumed, see table 1 and 2. The short extinguishing time may be explained by this fact.

CONCLUSIONS

To perform a safe BA-operation in a smoke filled environment underground and over longer distances than 75 meters, is complicated and requires a team effort. The tests show that the time to reach the fire source is between 15 to 30 minutes. A limiting factor is the available amount of air. As the air consumption is highly dependent on the physical strain one of the ways to enhance the endurance is to make movement in the tunnel and the transportation of equipment easier. Another way to accomplish this could be to use bigger air cylinders or to use rebreathes with oxygen. The latter system could however have other negative consequences and should be further tested and evaluated under similar conditions. Another way to enhance endurance and to also benefit from a quick response time is to use light equipment such as dry hoses or take use of a pre-fitted fire hose-system if that option is available. Water spray from a standard nozzle (300 l/min, 6 bar) has a good extinguishing effect on the burning wooden pallets. High pressure water spray (> 250 bar, 58 l/min.) had some problems to penetrate the water droplets on to the surface of the pallets. The use of a trolley for transportation of equipment might prolong the endurance for the BA teams, but must be carefully exercised and planned to function in a real-life situation. The use of a common (each team) additional air supply combined with separate air hoses on the trolley was somewhat cumbersome to handle. The hoses got tangled to each other and mixed in the dense smoke. When fighting fires or performing rescue operations in tunnels with bare rock or concrete lining with risk of spalling, safety measures must be taken to prevent the risk of falling material (rock, concrete etc.) as a result of weakened surfaces due to heat exposure. Even though there was as safety net bolted to the walls and ceiling of the drift the risk of falling rock is well documented in the films that was taken with the IR image cameras.

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