Full scale fire-test of an electric hybrid bus

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Abstract

In November 2014 a full scale fire test was conducted on an electric-diesel hybrid bus at the rescue-service training facility Guttasjön outside of Borås. The fire was started in the engine compartment and allowed to spread and grow until the entire bus was consumed in the fire. Temperature measurements were conducted in the engine compartment, passenger compartment, air-channels within the passenger compartment and on the battery. In addition were gas analysis, useful for evaluation of evacuation, performed within the passenger compartment and extra detectors installed in the engine compartment. The test was video-recorded from several angles. The purpose of the test and measurements were several; study the fire behaviour of an electric-hybrid bus, i.e. would the battery fall down into the passenger compartment and thus pose a new risk, or would the battery explode and pose a new risk, investigate the benefits of early detection of fires in the engine compartment and to provide a set of measuring data that can be used by researchers and others that are evaluating and modelling different fire safety means and rescue for buses.

Key words: Fire, bus, hybrid, electric vehicle, battery, full-scale fire test

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Preface

The work presented here has been conducted as a joint effort between SP Fire Research, Volvo Bus Corporation and The Rescue service in Borås. Several people have contributed immensely to the tests, special thanks are directed to:

- Sven Olovson and Frede Overby of Volvo Bus Corporation who initiated the work and provided the bus. The test had not taken place without Sven and Frede. Sven and Frede also involved several people from Volvo Bus Corporation to set-up the experiment including Kent Karlsson who dismantled the drive shaft from the bus.
- Krister Palmqvist from SÄRF the Rescue service in Borås who allowed their testing facility for the test and made sure that rescue personnel was at sight and also had a dialogue with the municipality of Borås in order to get permission to conduct the test.
- Christoffer Nylander from Consilium who provided fire detectors and installed these in the engine compartment.
- Tarmo Karjalainen and Lars Gustavsson from SP Fire Research who set up all measurement points and logging instruments and Alen Rakovic who assisted with the videos and observations during the test.
Sammanfattning


Temperaturen mättes i motorrummet, i passagerarutrymmet samt på batteriet. Extra detektorer installerades i motorrummet för att utvärdera om det är möjligt att erhålla tidigare detektion av bränder som starta i motorrummet. Vidare mättes syrgas, CO₂ och CO på tre ställen i passagerarutrymmet.

Testet visade att batteriet stannade på sin plats under hela branden och föll inte ner, vidare exploderade det inte utan brann långsamt, det mest dramatiska som hände under testen var en kraftig däckexplosion.

Detta test genomfördes på en buss från Volvo Bussar och det går inte att säga att alla el-drivna bussar och el-hybrider kommer att uppföra sig lika väl. En säker konstruktion runt batteriet och god design av batteriet är viktiga faktorer.
1 Introduction

The vehicle sector is currently in a rapid stage of development with introduction of new fuels and drives in order to meet environmental requirements in terms of CO₂, NOx and particles emissions. As new fuels and drives are introduced there is always a concern of how these will behave in case of a fire and how the rescue service should attack a fire in such a vehicle, and if such a vehicle pose a new unidentified risk? This concern is valid for all type of new fuels and drives including electric drives.

For electric drives research has for some time focused on extrication of people in case of a crash, extinguishing issues and emission of gases in the case of a fire [1, 2, 3, 4]. The majority of the work has been conducted on cars and not on buses or trucks. Very little research and investigations has been performed on how a battery will behave in a large fire. Questions that are of interest is if there is a risk that the battery falls down if it is placed on the roof similar to what has happened with gas tanks in some cases; will the fire development be different from a conventional bus; are there any risks for explosions or rapid fire development. In order to investigate this a complete hybrid bus (electric and diesel) denoted B5LH, was set on fire in a full scale fire test November 12th 2014. The test was conducted as a joint effort between Volvo Bus Corporation, The Rescue Service in Borås and SP Fire Research. The test was conducted at Guttasjön, the training site owned by The Rescue Service in Borås (SÄRF). The bus was provided by Volvo Bus Corporation and measurements during the test were conducted by SP Fire Research.

2 Scenario

In order to mimic a realistic scenario it was agreed to start the fire in the engine compartment as the majority of fires start there. Also it was decided to leave the engine idling and the doors open in order to mimic an evacuation situation.

The rear door was left closed to mimic a bus without any rear door. Also it was interesting to be able to study the smoke spread from the engine compartment into the passenger compartment at the early stages of the fire. This would be compromised if the rear door was left open.

The fire was allowed to spread and involve the entire bus, no extinguishing attempts were made. The entire fire development was video recorded from several angles.

2.1 Status of bus before fire start

The bus was equipped with a diesel tank which was about half full with diesel and a battery which was at 40-42% State of Charge (SOC) before the fire start according to readings from the Controller Area Network (CAN).

The drive shaft was disconnected before fire start in order to remove the risk for the bus to suddenly start driving during the fire. A fire can cause spurious signals that might make the vehicle jump forward, a scenario that has been observed during fires and needed to be avoided as this could destroy the measurements. In addition were gas dampers removed from hatches as the purpose of the test was not to investigate the danger posed form these in the form of projectiles.

The engine hatch was removed and replaced by 5 mm fire resistant glass in a steel frame in order to enable taking photos and videos of the early fire spread in the engine compartment.
The engine was left running before the test to make sure the engine temperature was at a reasonable driving temperature. The readings from the CAN-bus showed that the engine temperature was 74°C before fire start.

The front and middle doors were left open while the rear door was closed. The engine was left running also after the fire was initiated.

2.2 Fire initiation

The fire was initiated in a fuse box by applying a current of 40 Amps to a steel wire that was installed in the fuse box. In addition was a LPG-pipe installed into the engine compartment in order to supply the fire with extra fuel, roughly 50 kW, in the case of
doubt that the fire would spread into the passenger compartment. Fires are stochastic phenomena and it is not certain that a fire would spread in all cases. The pipe was located on the back side of the fuse box.

![Figure 3](image-url)

**Figure 3** Wire installed in fuse box to mimic overheating due to electrical fault.

### 3 Experimental Set-up

In order to study the fire development in the bus and also to compare with other tests previously conducted on conventional and gas buses a number of temperature and gas measurements were conducted. These consisted of temperature measurements on the top of the backrest of the seats and three “thermocouple trees” placed in the front, middle and rear end of the bus. In addition thermocouples were placed in the air tunnels placed on both sides of the bus in order to investigate if these tunnels contributes to a more rapid fire spread in the bus as one would have without these. The thermocouples were 0.5 mm type K thermocouples. Thermocouple placement and gas sampling in the passenger compartment is indicated in the schematic of the bus in Figure 4.

Thermocouples were also placed in the engine compartment in those places were temperature readings usually are conducted in order to activate the extinguishing system. No extinguishing system was present in this case however as we wanted the fire to continue. The thermocouples in the engine compartment were sheathed 1 mm type K thermocouples. Finally 0.5 mm type K thermocouples were placed on the battery.
3.1 Thermocouples - Engine compartment

Five sheeted thermocouples were located in the engine compartment and marked with white arrows in Figure 5. The intention was to indicate the spread of the fire from the fire initiation area (marked in Figure 5 with a red x) to the lower left side of the engine and to the hydraulic oil container on the upper left side.
3.2 Passenger compartment

Both gas and temperature measurements were conducted in the passenger compartment. The measuring points were placed on a “tree” in the front middle and rear end of the bus, in the middle of the alley nearby the doors (i.e. 1.75, 6.75 from the rear and 1.10 m from the front respectively). Each tree consisted of 5 thermocouples (TC) and 1 gas sampling point. The five TCs were placed 1.5 m, 1.7 m, 1.8 m and 1.9 m above the floor, the final TC was placed 5 cm below the ceiling. The gas sampling which was connected to O₂, CO₂ and CO analysers were placed at 1.5 m above the floor. The rear end and front end tree is seen in Figure 6 and Figure 7 respectively. A close-up of the rear end gas sampling and TCs is seen in Figure 8.
Figure 6  Thermocouple tree in rear end of bus.

Figure 7  Thermocouple tree in front end of bus.
Figure 8 Close-up of gas sampling and TCs.

Thermocouples were placed in the air tunnels placed on both sides of the bus in order to investigate the tunnels possible contribution to the fire spread. The TCs were placed in the channels on both sides in the vicinity of the doors in the rear, middle and front end. The two TCs near the rear door were placed 1.6 and 2.05 m from the rear end respectively. The middle door TCs were placed 6.0 and 6.6 m from the rear end respectively, while the front end TCs were both placed 9.6 m from the rear end. An example of a TC mounting (front end) is seen in Figure 9, the hatches over the air tunnel were put in place again once the TCs were installed.

Figure 9 Thermocouple in front end air channel left hand side.
Finally thermocouples were placed on the back rest of a number of seats. One TC was placed on the chair in the first row on the left hand side and the right hand side respectively, on the wheel chair place on the left hand side and on the right hand side chair in row three (chair closest to the alley), on the right hand side and left hand side chairs closest to the alley in the first row after the middle door, on the chair closes to the alley in the row just in front of the rear door and finally on the seat nearest to the middle in the rear end of the bus and the seat closes to the rear end door. Examples of TC placing on back rest is shown in Figure 10 and Figure 11.

Figure 10  Example of TC placed on seat in front of middle door.

Figure 11  Close-up of TC placed on backrest.
3.3 Battery

Five thermocouples were placed on the top of the battery, in addition were 2 thermocouples placed on each side of the battery and one thermocouple on the rear side of the battery. Most of the TCs can be seen in Figure 12.

![Figure 12 Thermocouples placed on battery.](image)

3.4 Detectors

Commercial fire detectors, including both heat and smoke sensors, were installed in the engine compartment to evaluate the response of these in a realistic fire scenario. A linear heat detector with activation temperature of 180°C, commonly used in buses, was mounted throughout the engine compartment including the critical point above the fire origin. In addition, six ordinary point smoke and heat detectors, whereof two of aspirating type, were installed as seen in Figure 13. Red arrows in the figure indicate the aspirating type detectors, these detectors sampled air from two separated locations to the position of the detector. However, the detector unit was the same type for all six specimens, which means a smoke sensor with activation at an obscuration level of 0.1-0.15 dB/m and a heat sensor with activation at 54°C.
3.5 Video recordings

The test was video recorded from several angles. In addition were photos taken including some infrared photos. Time 0 was set to the time when the measurements started, i.e. 3 minutes before the fire was initiated.

The test was video-recorded and time set from the following angles:

- Behind the bus: one video-camera that provided in total 4 video films from time 2 minutes and 15 seconds until time 2 hours 46 minutes and 13 seconds
- In front of the bus from time 0 minutes until 2 hours 35 minutes and 54 s. After that the video was closed up to the battery area and continued to record for about 40 minutes.
- Behind the bus a bit to the left from time 1 minute 45 seconds until time 1 hour 5 minutes and 37 seconds when the camera was moved to the left hand side perpendicular to the left front wheel and was left recording until time 1 hour and 19 minutes.
- From the right hand side up from a small hill from time 8 minutes and 48 seconds until time 37 minutes and 37 seconds.
- From the front a bit to the right hand side from time 2 minutes and 15 seconds until time 46 minutes and 57 seconds

In addition was video recordings taken from other angles also from other people but these recordings did not contain a synchronized time signal and were also moved around a bit. Also the photos lacked a synchronized time signal.
4 Observations during the test

Observations from the tests were noted both during the test and afterwards by watching the videos. Observations have been divided into different parts of the fire development in Table 1 and Table 2. The time accuracy for the observations is ± 5 s. Figure 14 and Figure 15 provides a video snapshot at times 33:05 and 34:35 respectively, i.e. the time when the fire is intense in the battery area.

<table>
<thead>
<tr>
<th>Time</th>
<th>Observation/event</th>
</tr>
</thead>
<tbody>
<tr>
<td>0:00</td>
<td>Start of time</td>
</tr>
<tr>
<td>0:00-3:00</td>
<td>Videos started at different times</td>
</tr>
<tr>
<td>2:15</td>
<td>Hand-waving to synchronize videos</td>
</tr>
<tr>
<td>3 minutes</td>
<td>Start of fire by applying current through the wire</td>
</tr>
<tr>
<td>3:22</td>
<td>First flames from fuse box</td>
</tr>
<tr>
<td>5:30</td>
<td>Flame spread from fuse box</td>
</tr>
<tr>
<td>6:40</td>
<td>Smoke visible in passenger compartment</td>
</tr>
<tr>
<td>7 minutes</td>
<td>Burning droplets</td>
</tr>
<tr>
<td>9:30</td>
<td>Air hose bursts</td>
</tr>
<tr>
<td>10:00</td>
<td>People are asked to back away from the bus as the fire is growing</td>
</tr>
<tr>
<td>11:40</td>
<td>Burning parts falling down</td>
</tr>
<tr>
<td>14:30</td>
<td>Some fire on ground</td>
</tr>
<tr>
<td>15:10</td>
<td>Engine stops</td>
</tr>
<tr>
<td>16:40</td>
<td>Fire breaks through roof in rear end</td>
</tr>
<tr>
<td>17 minutes</td>
<td>Fire decreases</td>
</tr>
<tr>
<td>18:40</td>
<td>LPG added to fire</td>
</tr>
</tbody>
</table>

Table 2 Observations from onset of LPG

<table>
<thead>
<tr>
<th>Time</th>
<th>Observation/event</th>
</tr>
</thead>
<tbody>
<tr>
<td>18:40</td>
<td>LPG on</td>
</tr>
<tr>
<td>18:45</td>
<td>LPG flames visible</td>
</tr>
<tr>
<td>21:20</td>
<td>Spread to roof</td>
</tr>
<tr>
<td>21:35</td>
<td>LPG off</td>
</tr>
<tr>
<td>25:20</td>
<td>Flame spread a bit forward on roof</td>
</tr>
<tr>
<td>25:30</td>
<td>Hatch above engine compartment falls down</td>
</tr>
<tr>
<td>25:45</td>
<td>Flame seen along floor inside</td>
</tr>
<tr>
<td>26 minutes</td>
<td>Smoke from middle door</td>
</tr>
<tr>
<td>26:55</td>
<td>Winding sound</td>
</tr>
<tr>
<td>26:55</td>
<td>A lot of smoke from front part</td>
</tr>
<tr>
<td>27:10</td>
<td>Fire spread along top of roof to front</td>
</tr>
<tr>
<td>27:20</td>
<td>A lot of flames and sound around battery</td>
</tr>
<tr>
<td>27:35</td>
<td>Rear door cracks</td>
</tr>
<tr>
<td>27:55</td>
<td>Side-window in rear end cracks</td>
</tr>
<tr>
<td>28:10</td>
<td>Next window</td>
</tr>
<tr>
<td>28:30</td>
<td>Window sucked inwards</td>
</tr>
<tr>
<td>29:20</td>
<td>Intense fire, a lot of flames in front end</td>
</tr>
<tr>
<td>30:10</td>
<td>Front window cracks</td>
</tr>
<tr>
<td>33-36 minutes</td>
<td>Large flame out of front window, fire in front end intense</td>
</tr>
<tr>
<td>40:30</td>
<td>Tyre explodes</td>
</tr>
<tr>
<td>41:40</td>
<td>Large tyre explosion which causes the entire bus to jump and be lowered</td>
</tr>
</tbody>
</table>
Various small explosions from different locations around the bus

Mainly tyres that are burning

A bit more fire gases from battery

Tyres and battery the only thing burning

Flames start to get visible from battery again

Measurements ended

Last video turned off, battery still burns slowly

<table>
<thead>
<tr>
<th>Time</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>43:30-51:20</td>
<td>Various small explosions from different locations around the bus</td>
</tr>
<tr>
<td>57</td>
<td>Mainly tyres that are burning</td>
</tr>
<tr>
<td>1 hour</td>
<td>A bit more fire gases from battery</td>
</tr>
<tr>
<td>1:04:00</td>
<td>Tyres and battery the only thing burning</td>
</tr>
<tr>
<td>1:20:00</td>
<td>Flames start to get visible from battery again</td>
</tr>
<tr>
<td>2:17:29</td>
<td>Measurements ended</td>
</tr>
<tr>
<td>3 hours and 15 minutes</td>
<td>Last video turned off, battery still burns slowly</td>
</tr>
</tbody>
</table>

5 Results

A complete set of the measurement results are provided in Appendix A. Some of the most interesting results are discussed below.
5.1 Temperature readings in engine compartment

The temperature readings from the engine compartment during the first 20 minutes of the test are presented in Figure 16. As seen very little happens with the temperature until a bit more than 9 minutes when all 5 temperature readings start to rise, at time 10 minutes people were asked to back away from the engine. None of temperature readings reaches 100°C except the temperature close to the diesel hose which reaches 100 shortly before time 14 minutes. The temperature at the hydraulic oil container rises rapidly at time 15 minutes which is about the time when the engine stops. The hydraulic oil container temperature rises again when the LPG is added to the fire at time 18 minutes and 40 seconds.

![Temperature readings in engine compartment during the early stages of the fire. The ignition time of 3 minutes (current on) and the onset of the LPG are marked with arrows.](image)

5.2 Temperature readings from TC trees

The temperature readings from the TC tree in the rear end is presented in Figure 17 with a focus on the time when the temperature started to increase, i.e. between time 22 minutes and 30 minutes. As seen very little happens with the temperature until almost time 25 minutes when the temperature closest to the ceiling starts to rise and then at time 26 minutes all of temperatures at the TC tree starts to rise.

The temperature readings from the TC tree in the middle of the bus during time 22-30 minutes are presented in Figure 18, in this case the temperature rise starts on the temperature closest to the ceiling a little bit later i.e. at time 25 and a half minute. A bit after 26 minutes the other temperature readings start to rise but a bit slower than in the rear end. The slower slope is even more pronounced in Figure 19 where the temperature readings from the front end are presented, in this case all the temperatures starts to rise slowly at around 26 minutes.
Figure 17  Temperature readings from the TC tree in rear end of bus during time 22 - 30 minutes.

Figure 18  Temperature readings from thermocouple tree in the middle of the bus with a focus on the early stages of the fire
Figure 19  Temperature readings from thermocouple tree in the front of the bus with a focus on the early stages of the fire.

5.3  Temperature readings in air channels

The temperature readings from the air channels along the sides of the bus during the first 30 minutes are presented in Figure 20. A seen the temperature first rises on the left hand side at time 23 minutes, i.e. about one and a half minute after the LPG was turned off. The LPG flame was however a bit more to the left and can thus have started the burning there first. Also before the LPG was added one could observe more burning on the left hand side of the bus. The temperature rises on the right hand side about 2 minutes later. The temperatures in the middle of the bus start to rise a bit later and then the temperatures in the front even later at time 26 minutes with a rapid increase around 28 minutes.

In Figure 21 the temperatures in the rear end of the air channel are compared to the readings from the TC tree. One sees clearly that the temperature increases first in the left hand side channel and then, a bit later, the temperature increases in the right hand side air tunnel and on the TC tree about the same time. A comparison between the TC tree and the air channel is made for the middle and front end in Figure 22 and Figure 23 respectively. In the middle the temperature rises somewhat earlier in the air channel while it is the opposite in the front end.
Figure 20  Thermocouple readings in the air channels throughout the bus with a focus on the early stages of the fire.

Figure 21  Thermocouple readings in the rear end of the bus, one clearly sees the first temperature rise on the left hand side and then the reading closest to the ceiling in the thermocouple tree and the right hand side air channel rises about the same time.
5.4 Temperature readings on battery

The temperature readings on the battery throughout the measurements are presented in Figure 24 where the prolonged battery fire can be observed. Many of the signals show large variations/disturbances. This is something that can happen when the thermocouples are damaged in the fire and could in this test also be observed for the readings in the air channel. In this test the thermocouple wires from the battery were hanging down from the roof of the bus and thus experienced some mechanical strain during the test which can cause the disturbance of the signal later in the test.

In Figure 25 one clearly see that the temperature readings on the battery all increase rapidly at time before 33 minutes. The battery has a large thermal mass and the thermocouples are placed on different places around the battery which means it is difficult to get such a rapid increase in thermocouple readings as seen before time 33 minutes without something happening inside the battery. In addition, if this rapid increase was caused by flames the temperatures would vary a lot instead of as now follow each
other closely. Figure 26 shows a close-up on the same time period with an enlarged temperature scale. As seen the Top rear left hand side, Top Middle and Top rear right hand side all show temperature readings of about 110 and above when the rapid increase occurs. Temperatures of 110-130 degrees are often reported as onset temperatures of thermal runaways [5] and there is therefore reason to believe that this is the time when one or more cells of the battery runs into thermal runaway.

In Figure 27 the temperature readings on the battery are compared with the readings in the front end. As seen the temperature rise on the battery occurs later than the rise in the passenger compartment.

Figure 24  Temperature readings from battery, note the prolonged fire.

Figure 25  Temperature readings from thermocouples placed on the battery. Note the rapid increase in temperature on all thermocouples shortly before 33 minutes.
In Figure 26 a close-up on the temperature scale during the rapid increase is shown.

In Figure 27, a comparison of TC readings on the battery and readings from the TC tree in front is presented.

In Figure 28, a screenshot from the video in front of the bus at time 32 minutes and 30 seconds is shown. This is followed by Figure 29, showing the same view at 32 minutes and 48 seconds, i.e., the time when the rapid temperature increase on the battery occurs. Finally, Figure 30 shows the same view 13 seconds later, with flames coming out from the battery hatch visible.
Figure 28  Bus at time 32 minutes and 30 seconds.

Figure 29  Bus at time 32 minutes and 48 seconds.

Figure 30  Bus at time 33 minutes and 1 second.
Temperature readings from the TCs placed on the seats are presented in Figure 31. As seen the temperature starts to rise in the back rows (row 8 and the rear) first and then the rise occurs at the same time for rows 4 and 6 while row 1 and 3 occurs at a later stage. The earlier temperature rise of row 8 on the left hand side is in line with the earlier temperature rise in the air tunnel on the left hand side.

![Temperature readings on the seats. As seen the temperature starts to rise in the back row first and then the rise occurs at the same time for rows 4 and 6 while row 1 and 3 occurs at a later stage.](image)

Gas analysis

The gas analysis results with a focus on the period of time 22-35 minutes where a rapid change in concentration is occurring is shown in Figure 32- Figure 34. The figures clearly show that the change in gas composition occurs a bit earlier in the rear end while the change occurs at about the same time in the front and middle.
Figure 32  Oxygen concentration with a focus on the time when a rapid change occurs.

Figure 33  Carbon dioxide with a focus on the time when a rapid change occurs.
Some changes in gas composition could also be observed in the rear end around time 10 minutes, i.e. the time when people were asked to back away from the bus as the fire in the engine compartment was increasing, as presented in Figure 35.

For evacuation purposes one usually say that critical limits has been reached if the temperature at 1.8 m above floor is above 80°C, the oxygen concentration at 1.5 m above floor is belowe 15%, the CO₂ concentration is more than 5% or the CO concentration is more than 0.2%. Time to when the different thresholds are reached are presented in Table 3. As seen it is the temperature value that is reached first even if all four values are reached about the same time for the different locations.

### Table 3  Time to evacuation threshold values in the passenger compartment.

<table>
<thead>
<tr>
<th>Position</th>
<th>Height</th>
<th>Threshold</th>
<th>Time until threshold reached</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rear end</td>
<td>1.8 m</td>
<td>T &gt; 80°C</td>
<td>25.9 minutes</td>
</tr>
<tr>
<td></td>
<td>1.5 m</td>
<td>O₂ &lt; 15%</td>
<td>27.2 minutes</td>
</tr>
<tr>
<td></td>
<td>1.5 m</td>
<td>CO₂ &gt; 5 %</td>
<td>27.3 minutes</td>
</tr>
<tr>
<td></td>
<td>1.5 m</td>
<td>CO &gt; 0.2%</td>
<td>26.8 minutes</td>
</tr>
<tr>
<td>Middle</td>
<td>1.8 m</td>
<td>T &gt; 80°C</td>
<td>26.7 minutes</td>
</tr>
<tr>
<td></td>
<td>1.5 m</td>
<td>O₂ &lt; 15%</td>
<td>27.5 minutes</td>
</tr>
<tr>
<td></td>
<td>1.5 m</td>
<td>CO₂ &gt; 5 %</td>
<td>27.7 minutes</td>
</tr>
<tr>
<td></td>
<td>1.5 m</td>
<td>CO &gt; 0.2%</td>
<td>27 minutes</td>
</tr>
<tr>
<td>Front</td>
<td>1.8 m</td>
<td>T &gt; 80°C</td>
<td>27 minutes</td>
</tr>
<tr>
<td></td>
<td>1.5 m</td>
<td>O₂ &lt; 15%</td>
<td>27.5 minutes</td>
</tr>
<tr>
<td></td>
<td>1.5 m</td>
<td>CO₂ &gt; 5 %</td>
<td>27.7 minutes</td>
</tr>
</tbody>
</table>
5.7  **Activation of detectors in the engine compartment**

Activation times of the detectors in the engine compartment are listed in Table 4. For comparison the temperature readings in the engine compartment for the first 30 minutes are presented in Figure 36. As seen in the graph, it takes over 20 minutes before temperatures close to alarm levels are reached at these positions (TC’s positions are shown in Figure 5). At this time the fire has already spread to the roof, see Table 1 and Table 2.

**Table 4  Detector alarms in the engine compartment. Position reference to Figure 13 within brackets.**

<table>
<thead>
<tr>
<th>Detector alarm</th>
<th>Activation time</th>
<th>Time from start of fire</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aspirating smoke sensor at fuse box and engine block (A+B)</td>
<td>3:27</td>
<td>0:27</td>
</tr>
<tr>
<td>Point smoke sensor at fuse box (A)</td>
<td>3:35</td>
<td>0:35</td>
</tr>
<tr>
<td>Linear heat detector (A)</td>
<td>4:56</td>
<td>1:56</td>
</tr>
<tr>
<td>Point heat sensor at fuse box (A)</td>
<td>5:06</td>
<td>2:06</td>
</tr>
<tr>
<td>Aspirating heat sensor at fuse box and engine block (A+B)</td>
<td>5:50</td>
<td>2:50</td>
</tr>
<tr>
<td>Point smoke sensor at engine block (B)</td>
<td>6:26</td>
<td>3:26</td>
</tr>
<tr>
<td>Aspirating smoke sensor at upper left part of engine compartment (C+D)</td>
<td>6:45</td>
<td>3:45</td>
</tr>
<tr>
<td>Point smoke sensor in front of radiator fan (C)</td>
<td>7:00</td>
<td>4:00</td>
</tr>
<tr>
<td>Point smoke sensor behind hydraulic oil container (D)</td>
<td>7:20</td>
<td>4:20</td>
</tr>
</tbody>
</table>

After 8:00 the cabling to the detectors burned resulting in short circuit.
6 Comparison with other bus fires

Full scale burns of buses are rare. One test was conducted on a bus indoors in the fire hall at SP in 2007 [6]. Another test was performed outdoors at Guttasjön in 2012 [7].

6.1 Indoor test

The 2007 test was conducted indoors and had thus to be extinguished before the whole bus was involved in the fire in order not to compromise the building. That fire was initiated in the rear luggage room of the bus in order to mimic an engine fire in the rear end. The fire was started with a LPG burner of 100 kW. Thermocouples were placed on the seats as in the test reported here. In addition were two thermocouple trees placed in the bus, one between the back and middle door and one between the front and middle door. Gas analysis was performed nearby the rear thermocouple tree at a height of 175 cm. The back door was closed.

In the 2007 test one could see a change in gas composition 5 minutes after ignition of the propane burner. In the current test a first change of gas composition was observed 150 cm above floor at 7 minutes after ignition in the rear end while no change could be observed until 23 minutes after ignition for the middle and front end. The ignition source was much smaller in the current case and the fire was about to self-extinguish until LPG had to be added after 15 minutes and 40 seconds.

In the 2007 test the temperature of the rear TC tree started to increase rapidly 14 minutes after ignition and reached a peak at about 16 minutes after ignition while the readings of the front TC started to increase a bit slower about the same time and reached a peak one minute later than the rear end, i.e. at time 17 minutes after ignition. In the current test with the three TC trees one do see even more clearly the more rapid temperature rise of the TC tree in the rear compared to the middle and front TC tree. In the current test the readings of the middle TC tree started to increase rapidly and peak about half a minute before the front TC tree. The rear TC tree showed a very rapid increase about 1 minute before the middle TC tree, i.e. 23 minutes after ignition. The TC closest to the ceiling started however to rise already 21.5 minutes after ignition.
The delay between the fire gases being noticed in the passenger compartment and the temperature increase was about 9 minutes (5 minutes for the gases, 14 minutes for the temperature) while the delay was longer in the current test (14.5 minutes). In the current test we did however have the situation that the fire had to be helped with LPG 15 minutes and 40 seconds after ignition and thus this delay is very difficult to compare between the tests.

In the 2007 tests the temperature readings on the seats on the left hand side (without the doors) showed a delay in temperature increase of half a minute between the rear seats and the seats in the front end while it was more difficult to determine a delay between the seat rows on the right hand side, probably due to the influence from the doors. In the current test the situation was similar, i.e. a delay between the seats on row 8 and 4 of a minute on the left hand side. It was however possible to notice a delay also on the right hand side of almost half a minute between the rear end and row 4 in the current test. In the front rows (rows 1 and 3), the temperature increase was even more delayed, i.e. over two minutes after the increase in the rear end. When comparing these times it is important to bear in mind though that in the 2007 test no large temperature increase was observed in the front row seats on the right hand side. So one should not conclude that the fire spread was slower in the current case.

Given the differences between the two tests one can observe that the fire spreads in a similar manner throughout the passenger compartment once the temperature starts to rise in the rear end.

6.2 Outdoor test in 2012

Two full scale bus fire tests were conducted at SP in 2012 on behalf of the Swedish Accident Investigation Authority [7]. The same fire scenario was repeated in two identical buses with the difference that in one of the buses, an automatic detection and extinguishing system was installed. The fires were started in the engine compartments, simulating a crash with minor leakage of oil and a short gas leak ignited by a spark. In those tests the fire spread from the engine compartment to the passenger compartment was faster than in the test described in this report due to the larger initial fire (gas leakage + hydraulic oil sprayed in the engine compartment). In the test all three doors were left open as compared to the closed rear door in this report. In addition the engine was not left running. Temperature and gas analysis were conducted on three thermocouple trees as in this report. As it was only one test that was left burning in the 2012 case comparisons are conducted with that test here.

In the 2012 test the temperature started to rise on the rear thermocouple tree 4 minutes after the fire was initiated. The pattern was similar as in this report with the temperature first rising close to the ceiling and the others following about 1.5 minutes later. The temperature increase was steep as in this report.

The temperature increase in the middle also showed similar pattern with a slower increase of the temperatures with the reading closest to the ceiling occurring first and the others about half a minute later. The difference between the rear and middle was however about half a minute for the reading closest to the ceiling in the 2012 case while it was about one minute here. In 2012 the temperature rise in the front was also a bit quicker than in the test reported here. Overall however the differences in fire spread within the compartment were minor between the two tests.
In the test reported here the oxygen concentration in the rear end dropped earlier than the middle and front concentration did. In the 2012 case it took longer time for the rear end concentration to reach its lowest value, this was probably due to the fact that the rear door was left open in the 2012 case. In the test reported here the gas concentrations started to change at around time 25 and a half minute, i.e. one a minute after the rear end ceiling thermocouple reading started to increase. In the 2012 case it was the other way around with the gas concentration starting to change 1 minute before the temperature close to the ceiling in the rear end. This difference is probably due to the closed and open rear door.

Also this comparison shows that given the differences in scenario the fire spreads in a similar way throughout the passenger compartment. These measurements provide thus good validation data for e.g. computer simulations.

## 7 Conclusions

The main purpose of the test was to investigate whether a burning electric/hybrid bus would pose a significantly different challenge to the rescue service than what they normally are exposed to. Of particular interest was to see if the battery would fall down into the engine compartment as one had observed in some cases for gas tanks on buses. Also explosion risk were of interest. No extinguishing attempts were made as the interest was to see how the battery behaved in a complete fire.

A large number of measurements were performed, i.e. temperature and gas analysis that can be used for evacuation studies and measurements in the engine compartment to study detection possibilities. In addition were measurements conducted in order to be able to compare with other full scale bus fire tests, these types of measurements are interesting for scientists who would like to validate computer models and find parameters for testing.

The test showed that the battery did not fall into the compartment. In addition, the temperature rise on the battery occurred about 7 minutes later than the temperature rise in the passenger compartment.

When the battery started to burn the fire was intense. An increase in fire was observed when the battery started to burn but it was difficult to judge how much fuel the battery added to the fire even if it is clear that it added. It might be possible that small explosion occurred from the battery, it was not possible to distinguish these in the fierce fire during time 33-36 minutes. However possible explosions during that time were all minor compared to the tyre explosions. Finally the battery burned slowly for a very long time in the end.

It was shown that heat detectors must be in direct proximity of the fire to give an alarm and detectors positioned in some places would not be activated before the fire had spread outside the engine compartment. Smoke detectors, on the other hand, gave relatively fast response also at positions far away from the fire origin. However, also consider that smoke detectors could be more prone to false alarms due to the harsh environment in engine compartments.

The engine was running for nearly 12 minutes after the first flames were visible. In a normal traffic situation, it may be very difficult for the driver to discover a fire in the rear of the bus. The test shows that the fire may develop substantially before the engine shuts down due to damage from the fire which emphasizes the need of fire detectors in the engine compartment alerting the driver of the fire.
The fire did almost suffocate 14-15 minutes after the fire start which is quite unusual for this type of fire. The fire resistant glass used to improve the transparency may have contributed to this and delayed the flame spread. While a standard engine compartment hatch of glass-fiber would have decomposed and allowed more oxygen to contribute to the fire, the fire resistant glass was continuously tight allowing less oxygen to enter the fire zone. This indicates the positive effect construction solutions which confines the flame spread may have.

The measurements conducted were compared to two other bus fire tests. The scenarios in these two tests were not identical to the test conducted here and they were conducted on other buses. The measurements show however agreement considering these differences and the measurements provides thus good validation data for computer simulations.

8 References

1. www.EVsafetytraining.org
7. Slutrapport RO 2013:01, Brand med två biogashussar i stadstrafik i Helsingborg, Skåne län, den 14 februari 2012, Dnr O-03/12, SHK Statens haverikommission (2013)
Appendix A

All measurement readings are presented in this appendix over the complete measurement period. Close ups are included and discussed in the main text of the report.

Figure 37  Temperature readings in the engine compartment.

Figure 38  Temperature readings from thermocouple tree in the rear end.
Figure 39  Temperature readings from thermocouple tree in the middle of the bus.

Figure 40  Temperature reading from the "temperature tree" in the front.
Temperature readings from the battery are presented in Figure 42- Figure 46. Figure 42 shows the readings from the sides of the battery and Figure 43 from the top with a close up on the early stages in Figure 44 and Figure 45 respectively. In Figure 46 the readings with large disturbances have been removed to give a better picture of the temperature development.
Figure 43  Temperature readings on the top of the battery.

Figure 44  Temperature reading on thermocouples placed on the sides of the battery with a focus on the early stages.
Figure 45  Temperature readings on the top of the battery with a focus on the early stages.

Figure 46  Temperature readings without the signals that had a large variation around time 34 minutes. For the thermocouple placed on the sides of the battery all thermocouples had that large variation however.

Figure 47 and Figure 48 shows the readings on the left hand side and right hand side respectively.
Figure 47  Temperature readings from seats on the left hand side.

Figure 48  Temperature readings from the seats on the right hand side.

The Oxygen, Carbon dioxide (CO₂) and Carbon monoxide (CO) concentration throughout the whole measured period is shown in Figure 49- Figure 51 respectively.
Figure 49  Oxygen concentration.

Figure 50  Carbon dioxide concentration.
Figure 51  Carbon Monoxide concentration.
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Our work is concentrated on innovation and the development of value-adding technology. Using Sweden’s most extensive and advanced resources for technical evaluation, measurement technology, research and development, we make an important contribution to the competitiveness and sustainable development of industry. Research is carried out in close conjunction with universities and institutes of technology, to the benefit of a customer base of about 10000 organisations, ranging from start-up companies developing new technologies or new ideas to international groups.