Motorcoach Fire Safety

Final Report
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In July 2012 the Moving Ahead for Progress in the 21st Century (MAP-21) Act was enacted, which instructed NHTSA to research the most prevalent causes of motorcoach fires and methods to prevent them, both inside and on the exterior of the vehicles. Southwest Research Institute was contracted to develop test procedures and performance criteria to assess fire detection and suppression for engine compartment fires and fire detection in wheel wells. SwRI was also tasked to develop a bench scale test to evaluate the performance of exterior fire-hardening materials. The goal of this program was to develop and validate procedures and metrics to evaluate current and future detection, suppression, and exterior fire-hardening technologies that prevent or delay fire penetration into the passenger compartment of a motorcoach, in order to increase passenger evacuation time.

Objective tests, methods, and metrics were developed for analyzing wheel well detection/warning systems, engine compartment detection and suppression/extinguishment systems, and flammability/fire-hardening of exterior materials between the wheel well and the passenger compartment. A literature review and characterization of the thermal environment of motorcoach fires and survey of engine compartments, firewalls, and wheel wells of motorcoaches currently in North American service began. These characterizations assisted in the development of test methods and identification of the metrics for analysis. Test fixtures were designed and fabricated to simulate a representative engine compartment and wheel well. Fire scenarios were developed, the current detection, suppression, and fire-hardening technologies were reviewed, and a sample set selected to validate the test procedures developed during this program. Based on the results, test methods and metrics were developed to evaluate wheel well warning systems, engine compartment detection and suppression systems, and fire-hardening systems.

16. Key Words
motorcoach, fire, flammability, fire suppression, fire detection, fire hardening, MAP-21

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EXECUTIVE SUMMARY

The National Highway Traffic Safety Administration awarded a contract to Southwest Research Institute (SwRI) to conduct research and testing in accordance with Solicitation No. DTNH22-12-R-00574. The goal of this program was to develop and validate procedures and metrics to evaluate current and future detection, suppression, and exterior fire-hardening technologies that prevent or delay fire penetration into the passenger compartment of a motorcoach, in order to increase passenger evacuation time. In 2007, NHTSA published a comprehensive plan to assess motorcoach safety in several areas to improve occupant protection, including evaluation of fire protection technologies. The same year, the National Transportation Safety Board (NTSB) made recommendations to NHTSA related to motorcoach fire safety, stemming from their investigation of the 2005 Wilmer, Texas, motorcoach fire that resulted in 23 fatalities. In 2008, NHTSA initiated research at the National Institute of Standards and Technology (NIST) to understand the development of motorcoach fires, assess tenability within the occupant compartment, identify bench-scale flammability tests, and determine feasibility of requirements for fire-hardening of exterior components. In 2009, DOT published the department-wide Motorcoach Safety Action Plan which directed multiple agencies to pursue an integrated approach to enhance motorcoach safety, including fire safety.

This research is a follow-on to the NIST research program, and is responsive to the requirement at Section 32704(a) of the Moving Ahead for Progress in the 21st Century Act (MAP-21),¹ that NHTSA² conduct research to assess the most prevalent causes of motorcoach fire, and the best methods to prevent such fires, and mitigate the damage from them. As specified in the solicitation, objective tests, methods, and metrics were developed for analyzing wheel well detection/warning systems (Topic 1), engine compartment detection and suppression/extinguishment systems (Topic 2), and flammability/fire-hardening of exterior materials and the bulkhead (firewall) between the engine compartment and the passenger compartment (Topic 3).

The program was initiated with a literature review and characterization of the thermal environment of motorcoach fires and survey of engine compartments, firewalls, and wheel wells of motorcoaches currently in North American service. These characterizations assisted in the development of test methods and identification of the metrics for analysis.

Test fixtures were designed and fabricated to simulate a representative engine compartment and wheel well. Fire scenarios were developed for each fixture, the current detection, suppression, and fire-hardening technologies were reviewed and a sample set selected to validate the test procedures developed during this program. Based on the results of testing and feedback from stakeholders, test methods and metrics were developed for evaluating wheel well warning systems, engine compartment detection and suppression systems, and fire-hardening systems. Detailed program conclusions and

¹ Public Law 112-141 (July 6, 2012)
² MAP-21 directs the Secretary of Transportation to conduct this research. This authority has been delegated to the NHTSA Administrator.
recommendations for areas of interest for further research and testing are also discussed. A brief summary of the project conclusions are as follows.

**Engine Compartment**
The following conclusions can be made about the engine compartment test procedure and fixture used to evaluate detection and suppression systems.
- The SwRI team designed, fabricated, and commissioned a simulated motorcoach engine compartment fixture. It is representative of the motorcoaches currently sold in the United States. It is larger than those used typically in Europe, but has comparable air flow.
- The fixture contains a substantial amount of obstructions to simulate the major components (including the engine) and various hoses, pipes, and electrical wires.
- Criteria are proposed for successfully completing this series of 12 engine compartment fire tests.

**Wheel Well**
The following conclusions can be made about the wheel well test procedure and fixture used to evaluate hot wheel early warning devices.
- The SwRI wheel well test fixture uses a dragging brake to add heat into the wheel assembly. It is capable of raising both rotating and stationary parts of the wheel assembly to very high temperatures.
- There are several commercially available tire pressure monitoring systems (TPMS) that are capable of detecting a hot wheel and alerting the driver before the tire catches fire. Most motorcoach OEMs that sell in the United States are now installing TPMS as optional or standard equipment.
- There are several locations where a simple thermocouple sensor on a stationary component can detect a hot wheel far in advance of a tire fire. But this solution does not provide high or low tire pressure warnings.
- It is important to train drivers to rapidly stop the motorcoach after receiving a hot wheel warning.

**Fire Hardening**
The following conclusions can be made about the fire hardening test procedures used to evaluate fire hardening materials.
- A relationship seems to exist between time to flame penetration into the passenger compartment in full-scale tests conducted by the National Institute of Standards and Technology (NIST) and data gathered in a bench-scale (Cone Calorimeter) and intermediate-scale (Parallel Panel) test apparatus.
- A screening heat release rate value of 200 kW or 200 kW/m² can be used to indicate a potential propagating or non-propagating fire hardening material in the Parallel Panel or Cone Calorimeter test apparatus, respectively.
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1.0 INTRODUCTION
Southwest Research Institute (SwRI) was awarded the contract under the National Highway Traffic Safety Administration solicitation number DTNH22-12-R-00574, dated June 29, 2012, for Motorcoach Fire Safety Research. This program was conducted by the Fire Technology Department (FTD) in the Chemistry and Chemical Engineering Division, and the Engine and Vehicle Research and Development Department in the Engine, Emissions, and Vehicle Research Division.

In addition, SwRI assembled a team of subject matter experts to assist in the development and review of the test procedures created during this program. These experts have a breadth of knowledge in all aspects of fire hazard assessment and safety of road transportation vehicles.

The following sections discuss the program objectives and goals, findings from the literature review and interaction with industry stakeholders throughout the program, development and fabrication of the test fixtures, development of test procedures, and results from vendor testing. Program conclusions and recommendations for areas of further research and testing are discussed.

2.0 PROGRAM OVERVIEW
The goal of this program was to develop and validate procedures and metrics to evaluate current and future detection, suppression, and exterior fire-hardening technologies that prevent or delay fire penetration into the passenger compartment of a motorcoach, in order to increase passenger evacuation time. As requested in the solicitation, objective tests, methods, and metrics were developed for analyzing wheel well detection/warning systems (Topic 1), engine compartment detection and suppression/extinguishment systems (Topic 2), and flammability/fire-hardening of exterior materials between the wheel well and engine compartment and the passenger compartment (Topic 3).

This report summarizes tasks performed in the design and fabrication of the test fixtures, development of test procedures, representative detection/warning/suppression/fire-hardening supplier testing, and conclusions and recommendations for further areas of interest.

3.0 BACKGROUND
The following sub-sections provide additional background to the current project.

3.1 Background
NHTSA has been conducting flammability and fire protection assessment of motorcoaches and motorcoach materials since 2008, in accordance with agency and departmental plans and NTSB recommendations. In addition, the Motorcoach Enhanced Safety Act of 2012, which is part of the Moving Ahead for Progress in the 21st Century Act (MAP-21), calls for research and testing to improve fire safety through evaluation of flammability criteria for exterior components of motorcoaches, smoke suppression, prevention of and resistance to wheel well fires to mitigate propagation into the passenger compartment, and evaluation of automatic suppression systems.

In response to this statutory requirement, NHTSA has funded research to develop test apparatuses and test procedures to evaluate candidate fire detection and

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3 Public Law 112-141 (July 6, 2012)
4 Section 32704(a).
suppression systems for motorcoach engine compartments, and hot wheel warning systems to prevent tire fires in the wheel well.

Additionally, the Department of Transportation Motorcoach Safety Action Plan of 2009 includes research on motorcoach occupant protection related to fire safety. Accordingly, NHTSA is evaluating the feasibility of more-stringent flammability requirements for interior and exterior materials, and the need for regulations requiring installation of fire detection and protection systems.

3.2 Literature Review

Motorcoach fires without injury are fairly common. However, in 2005 a motorcoach that was transporting assisted living facility residents in the Hurricane Rita evacuation effort caught fire, killing 23 of the elderly occupants of the vehicle. This event was documented in a highway accident report by the National Transportation Safety Board (NTSB) [1].

Estimates range from 160 reported motorcoach fires to 2,200 total bus fires per year in the United States. The majority of these fires start outside the occupant compartment, in the wheel well or engine compartment, as shown in Figure 1. The components that have been identified to be the most common ignition points are the brakes, turbochargers, tires, electrical sources, and wheel/hub bearings [2].

![Figure 1. Percentage of Motorcoach Fire Records by Fire Origin Location, (2004-2006) [2].](image)

In 2009 NHTSA funded the National Institute of Standards Technology (NIST), Building and Fire Research Laboratory (BFRL) to conduct research to:

1. Understand the development of motorcoach fires and its subsequent spread into the passenger compartment,
2. Evaluate and identify bench-scale material flammability test methods,
3. Test the effectiveness of fire hardening of motorcoach exterior components around the wheel well, and
4. Assess tenability within the passenger compartment in the event of a wheel-well fire.

Conclusions from the NIST assessment were [3]:

1. Materials designed to meet FMVSS 302, Flammability of Interior Materials, do not meet the more stringent Federal Aviation Administration (FAA) and Federal Rail Administration (FRA) requirements (i.e., vertical burn rate, heat release, smoke density, etc.).
2. Fire-hardening to isolate a tire fire from surrounding combustible materials delayed fire spread.
3. The time from fire penetration to untenable conditions in the vehicle interior was from 5 to 9 min.

There has been prior research focused on the development of test procedures to evaluate engine compartment detection and suppression systems. Kidde has published research on development of a standard test for transit vehicle (motorcoach) extinguishing (suppression) systems [4] and in comparing various fire detection systems for engine compartment fires [5]. At the 2006 SAE Congress there was a session devoted to fire suppression research needs, which was summarized by Hamins [6].

SP Technical Research Institute of Sweden has published several reports [7-10] on this research topic and has also developed a standard test methodology [11] for evaluating suppression systems installed in a motorcoach engine compartment.

### 3.3 Research Objectives

The major objectives of this research project were the following:

1. Develop a test fixture and test procedures for evaluating fire detection and fire suppression systems for motorcoach engine compartments.
2. Develop a test fixture and test procedures for evaluating tire fire warning systems for motorcoach wheel well areas.

The secondary objective of the current research project was to further investigate the topic of fire hardening of a motorcoach and propose a standard test method that would be useful to compare potential fire hardening materials for this purpose.

### 4.0 Engine Compartment and Wheel Well Characterization

The purpose of this task was to characterize several typical engine compartments and wheel wells from current model year motorcoaches. The intent was to allow for a realistic development of an engine compartment and wheel well test mockup consistent with actual designs currently being sold in the United States. In February of 2013, representatives of the SwRI Project Team conducted on-site surveys at three OEM maintenance facilities to document the engine compartments and wheel wells of 2013 model year motorcoaches by gathering photographs and measurements, and documenting locations of system components and combustibles.

The developed mockups will not necessarily be applicable to all designs, shapes, and sizes of engine compartments and/or wheel wells. However, it should allow comparison with other test beds and an evaluation of the applicability of these other test beds to the motorcoach compartments currently being sold in the US.

#### 4.1 Wheel Well Characterization

During the motorcoach survey, the wheel well area was inspected for each motorcoach OEM. Photographs and measurements of these areas were documented, and analyzed in greater detail between motorcoaches to further determine the impact on the wheel well test fixture. In general, the wheel well areas were very similar between motorcoaches, as compared to the engine compartments. In this regard, the task of developing a representative test fixture for wheel well warning system evaluation

...
is more straightforward than for engine compartments. Figure 2 – Figure 4 provides photographs of the three OEM wheel well areas.

Figure 2. Photograph of Motorcoach A Wheel Well.

Figure 3. Photograph of Motorcoach B Wheel Well (without fender side panel).
4.2 Engine Compartment Characterization

As a result of the survey of motorcoaches work, a few major observations can be made. The largest components of a typical motorcoach engine compartment were noted and Table 1 provides a summary of where several of the major components in the engine compartment are located. Figure 5 – Figure 7 shows a photograph of each motorcoach engine compartment surveyed (view from rear of coach).

It can be observed that the motorcoaches surveyed as part of this project all had engine compartments sizes greater than the range specified in the SP Technical Research Institute of Sweden method - SP 4912. The motorcoaches surveyed had gross volume estimates of 6-9 m$^3$ and the gross volume range found in SP 4912 is 2–6 m$^3$. The SP survey included European transit buses in addition to European motorcoaches.
Table 1. Summary of Location of Major Engine Compartment Components

<table>
<thead>
<tr>
<th>Component Description</th>
<th>Motorcoach A</th>
<th>Motorcoach B</th>
<th>Motorcoach C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine assembly</td>
<td>Middle</td>
<td>Middle</td>
<td>Middle</td>
</tr>
<tr>
<td>Two coolers and fan</td>
<td>Left</td>
<td>Left</td>
<td>Left</td>
</tr>
<tr>
<td>Air filter (vertical/horizontal)</td>
<td>Top - middle</td>
<td>Top - right</td>
<td>Middle – Left</td>
</tr>
<tr>
<td>Lavatory equipment</td>
<td>Right</td>
<td>Right</td>
<td>Right</td>
</tr>
<tr>
<td>Emissions control (vertical/horizontal)</td>
<td>Lower Left</td>
<td>Middle Left</td>
<td>Top Left</td>
</tr>
<tr>
<td>A/C Compressor</td>
<td>Lower right</td>
<td>Lower right</td>
<td>Lower right</td>
</tr>
<tr>
<td>Turbo</td>
<td>Left side of engine</td>
<td>Left side of engine</td>
<td>Left side of engine</td>
</tr>
<tr>
<td>Surge tank – engine coolant</td>
<td>Above engine cooler</td>
<td>Above engine cooler</td>
<td>Above engine cooler</td>
</tr>
<tr>
<td>Alternators</td>
<td>Left side</td>
<td>Left side</td>
<td>Right side</td>
</tr>
</tbody>
</table>

Figure 5. Photograph of Motorcoach A with Gross Volume of 7.4 m³.
Based on the survey task, three-dimensional models of each motorcoach were developed so that they could be overlaid and compared and contrasted. Figure 8 – Figure 10 show each of these motorcoach representations and provide size comparisons to the SP mockup (white outlines). Based on these models, a single representative model was created, which is shown in Figure 11.
Figure 8. 3-D Model of Motorcoach A Engine Compartment.

Figure 9. 3-D Model of Motorcoach B Engine Compartment.
5.0 ENGINE COMPARTMENT FINAL DESIGN, FIRE SCENARIO DEVELOPMENT AND TESTING

5.1 Engine Compartment Final Test Fixture Design

The average model depicted in Figure 11 was then adapted into a final test fixture design. Two views of this test fixture are shown in Figure 12 and Figure 13.
Appendix B provides detailed drawings of the engine compartment test fixture. The racks of cylindrical and rectangular obstructions colored white/silver in these figures represent clutter in the engine compartment and also are used to support and obstruct ignition sources and to provide secondary combustibles that will be utilized for a given fire scenario.

5.2 Engine Compartment Ventilation

The specifications for the fan, which provides the airflow through the test fixture, were derived from several discussions with motorcoach OEMs, during which they shared detailed information about the airflow through their compartment based both on proprietary experimental measurements and CFD calculations.

It was also determined through these meetings that most of the driving time correlates to a condition when the fan is not operating and there is minimal airflow throughout the engine compartment. In addition, the second most common condition is when the fan is at some intermediate speed, which corresponds to a volumetric flow of approximately 4.2 m$^3$/s (8,833 CFM) at no static back pressure. Based on this information, it is recommended in the draft test procedures and relevant fire scenarios that two ventilation conditions be represented (fan off and fan at a typical intermediate operating speed).

Figure 12. Engine Compartment Mockup Test Fixture Design (View from Rear Driver’s Side Corner).
In addition to the airflow capacity in the engine compartment, it was also determined that there were two typical airflow designs employed in the engine compartment. In one design, the compartment exhausted most of the airflow through the floor of the compartment, which is about 40–50% open, because of the obstructions such as the emissions control equipment, the engine block, and the lavatory holding tank. In the other design, the floor of the compartment is less open and the fan exhaust airflow is directed to the passenger side louvers, louvers in the rear door, and the floor.

In the final fixture design, it is recommended to represent a worst case condition for detection and suppression systems by combining these two air flow designs and selecting the most open compartment, which will challenge the detection and suppression systems more rigorously. Therefore, the final test fixture design considers a mostly open floor and open passive ventilation vents on the passenger side and rear door.

Figure 14 provides a characterization of the air speed (m/s) from the fan measured between the fan shroud and the louver that simulates the interior edge of the radiator. Figure 15 provides a characterization of the air speed from the fan measured between the louver and the hot side (left as viewed from rear) clutter racks.
Figure 14. Engine Compartment Ventilation (Between Fan and Louver).

Figure 15. Engine Compartment Ventilation (Between Louver and Hot Side Clutter).
The average air speed and volumetric flow across the fan area between the fan and louver is 7.4 m/s and 3.6 m$^3$/s, respectively. The average air speed and volumetric flow across the fan area between the louver and hot side engine clutter is 5.9 m/s and 2.9 m$^3$/s, respectively. Air speed was also measured at each fire source location and this data will be presented in Section 5.5 of this report.

5.3 Engine Compartment Test Fixture Fabrication

Figure 16 – Figure 20 show selected photographs during the final assembly of the engine compartment fixture.

Figure 16. Engine Compartment Mockup Test Fixture (View of Rear Driver Side – Prior to Installation of Fan).
Figure 17. Engine Compartment Mockup Test Fixture (View of Forward Passenger Side).

Figure 18. Engine Compartment Mockup Test Fixture (View of Rear Passenger Side).
Figure 19. Engine Compartment Mockup Test Fixture (View of Forward Side).

Figure 20. Engine Compartment Mockup Test Fixture (View of Rear Side).
5.4 Engine Compartment Test Fixture Instrumentation

Several measurements were taken during baseline and vendor testing in this fixture. A single data acquisition unit (DAQ) was used to record 23 channels of data.

There were 4 voltage output devices used to measure pressure and amperage. In addition, 19 thermocouples were used to measure temperature at various locations. Table 2 summarizes the channel layout on the DAQ.

Table 2. Summary of Engine Compartment Test Fixture Instrumentation.

<table>
<thead>
<tr>
<th>Device No.</th>
<th>Device Identification</th>
<th>Device Units</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Diesel Pressure</td>
<td>psig</td>
<td>Used to measure and control pressure during diesel spray fires</td>
</tr>
<tr>
<td>2</td>
<td>Power Steering Fluid Pressure</td>
<td>psig</td>
<td>Used to measure and control pressure during PSF spray fires</td>
</tr>
<tr>
<td>3</td>
<td>Motor Oil Pressure</td>
<td>psig</td>
<td>Used to measure and control pressure during hot surface re-ignition fires</td>
</tr>
<tr>
<td>4</td>
<td>Amp Reader</td>
<td>Amps</td>
<td>Used to measure current in overheated wire in battery compartment fire</td>
</tr>
<tr>
<td>5</td>
<td>Heater 1</td>
<td>°C</td>
<td>Surface thermocouple on hot surface (opposite No. 6)</td>
</tr>
<tr>
<td>6</td>
<td>Heater 2</td>
<td>°C</td>
<td>Surface thermocouple on hot surface (opposite No. 5)</td>
</tr>
<tr>
<td>7</td>
<td>Diesel Spray</td>
<td>°C</td>
<td>Located 0.5 m in front of diesel spray nozzle</td>
</tr>
<tr>
<td>8</td>
<td>Plastic Mid</td>
<td>°C</td>
<td>Located halfway up shelf holding plastic fire source materials</td>
</tr>
<tr>
<td>9</td>
<td>Plastic Bottom</td>
<td>°C</td>
<td>Located above ignition pan for plastic fire scenario</td>
</tr>
<tr>
<td>10</td>
<td>Battery Comp. 32&quot;</td>
<td>°C</td>
<td>Located 32 in. above center of overheated wire</td>
</tr>
<tr>
<td>11</td>
<td>Battery Comp. 24&quot;</td>
<td>°C</td>
<td>Located 24 in. above center of overheated wire</td>
</tr>
<tr>
<td>12</td>
<td>Battery Comp. 16&quot;</td>
<td>°C</td>
<td>Located 16 in. above center of overheated wire</td>
</tr>
<tr>
<td>13</td>
<td>Battery Comp. 8&quot;</td>
<td>°C</td>
<td>Located 8 in. above center of overheated wire</td>
</tr>
<tr>
<td>14</td>
<td>Power Steering Spray</td>
<td>°C</td>
<td>Located 0.5 m in front of PSF spray nozzle</td>
</tr>
<tr>
<td>15</td>
<td>Back Right Top</td>
<td>°C</td>
<td>Viewed from the rear of the coach – local gas temperature</td>
</tr>
<tr>
<td>16</td>
<td>Back Right Bottom</td>
<td>°C</td>
<td>Viewed from the rear of the coach – local gas temperature</td>
</tr>
</tbody>
</table>
Table 2. Summary of Engine Compartment Test Fixture Instrumentation (continued).

<table>
<thead>
<tr>
<th>Device No.</th>
<th>Device Identification</th>
<th>Device Units</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>Back Left Top</td>
<td>°C</td>
<td>Viewed from the rear of the coach – local gas temperature</td>
</tr>
<tr>
<td>18</td>
<td>Back Left Bottom</td>
<td>°C</td>
<td>Viewed from the rear of the coach – local gas temperature</td>
</tr>
<tr>
<td>19</td>
<td>Front Left Top</td>
<td>°C</td>
<td>Viewed from the front of the coach – local gas temperature</td>
</tr>
<tr>
<td>20</td>
<td>Front Left Middle</td>
<td>°C</td>
<td>Viewed from the front of the coach – local gas temperature</td>
</tr>
<tr>
<td>21</td>
<td>Front Left Bottom</td>
<td>°C</td>
<td>Viewed from the front of the coach – local gas temperature</td>
</tr>
<tr>
<td>22</td>
<td>Front Right Top</td>
<td>°C</td>
<td>Viewed from the front of the coach – local gas temperature</td>
</tr>
<tr>
<td>23</td>
<td>Front Right Bottom</td>
<td>°C</td>
<td>Viewed from the front of the coach – local gas temperature</td>
</tr>
</tbody>
</table>

5.5 Engine Compartment Fire Scenarios

The scope of the project requires the development of test procedures to evaluate both detection and suppression systems in the engine compartment. As such, it is planned to include fire scenarios which incorporate both the detection and suppression system in a given test. In addition to this integrated testing, there will be the option to conduct one or more tests with the detection system assumed to either have failed or not be present (as in a manual activation system). In this way, the final test protocol will be applicable to both detection and suppression system evaluation.

In order to identify the most common fire scenarios for the engine compartment, detailed discussions with the NHTSA Office of Defects Investigation (ODI) were held in addition to discussions with motorcoach manufacturers, suppliers, and operators. As a result, the following fire scenarios (12 total tests) are included in the testing protocol for evaluating engine compartment detection and suppression systems:

1. Hot Surface Re-Ignition Test (One Test)
   a. Real Bus Hazard: hot surface in engine compartment such as turbo and exhaust manifold.
   b. Ignition Material: continuous feed of lube oil through Hago Model 1.50/80°H nozzle to drip oil at nominally 7 ml/min.
   c. Ignition Source: steel plate representing hot surface of turbo/exhaust manifold. Heated from behind by quartz IR panel heater.
   d. Location: upper left (hot) side of engine.
   e. General Procedure: raise nominal temperature of hot plate to 750 °C, open oil valve, observe dripping fire, after 15 s, turn off power to heaters for hot surface, after additional 15 s, discharge suppression system and record time to re-ignition, if any.
   f. Ventilation: conduct test without the fan running.
2. Diesel Spray Fires (Four tests)
   a. Real Bus Hazard: diesel spray fire as a result of a leak in the Diesel Particulate Filter (DPF) system. The diesel flow rate nominally equates to a 1.25 mm leak diameter with nominal operating conditions per motorcoach OEM for diesel line on DPF.
   b. Ignition Material: continuous feed of diesel fuel through Monarch F-80 nozzle, 10.0 gal/hr flow rate, and 80° spray angle. The diesel spray nozzle is mounted in a small flame stabilizer (metal can nominally 3 in diameter and 3 in long).
   c. Ignition Source: tell-tale cup nominally 3 in diameter and 2 in high, filled with 130 ml heptane (approximate 1-in. depth), positioned below the spray nozzle.
   d. Locations: lower left (hot) side of engine and upper left (hot) side of engine.
   e. General Procedure: ignite the tell-tale cup, after 30 s, discharge the diesel, after an additional 30 s discharge the suppression system and record observations.
   f. Ventilation: perform tests with and without fan running.
      i. Nominal air speeds with fan running:
         1. Lower Diesel Spray: 1.75 m/s
         2. Lower Tell-Tale Cup: 0.60 m/s
         3. Upper Diesel Spray: 0.40 m/s
         4. Upper Tell-Tale Cup: 0.40 m/s

3. Power Steering Fluid (PSF) Fires (Two tests)
   a. Real Bus Hazard: PSF spray fire as a result of a leak in the power steering system. The PSF flow rate will nominally equate to a 0.375 mm leak diameter with nominal operating conditions per motorcoach OEM for PSF line.
   b. Ignition Material: continuous feed of PSF through Monarch F-80 nozzle, 15.5 gal/hr flow rate, and 80° spray angle. The PSF nozzle is mounted in a small flame stabilizer (metal can nominally 3 in diameter and 3 in long).
   c. Ignition Source: tell-tale cup nominally 3 in diameter and 2 in high, filled with 130 ml heptane (approximate 1-in. depth), positioned below the spray nozzle.
   d. Location: middle right (cold) side of engine.
   e. General Procedure: ignite the tell-tale cup, after 30 s, discharge the PSF, after an additional 30 s discharge the suppression system and record observations.
   f. Ventilation: perform tests with and without fan running.
      i. Nominal air speeds with fan running:
         1. PSF Spray: 4.33 m/s
         2. PSF Tell-Tale Cup: 0.82 m/s

4. Distributed Pool Fires (Two tests)
   a. Real Bus Hazard: multiple fire locations after incipient fire have spread through compartment. This fire scenario also evaluates the ability of the system under test to adequately cover the full volume of the test fixture.
   b. Ignition Materials:
i. 8 tell-tale cups, nominally 3 in diameter and 2 in high, each filled with 130 ml of heptane (approximate 1-in. depth)
ii. 2 rectangular pans, each measuring $8 \times 18 \times 1$ in. high, filled with 1750 ml of heptane (approximately 0.5–0.75 in. depth).

c. Location: throughout the entire test fixture, eight tell-tale cups in nominal eight corners of primary compartment space (not including battery compartment), one rectangular pan in left (hot) side clutter and one rectangular pan in right (cold) side clutter.

d. General Procedure: The cups and rectangular pans are ignited within 30 s (pan is the last to be ignited) and 30 s after ignition of pan, the suppression system is manually discharged and observations are recorded.

e. Ventilation: perform tests with and without fan running.

i. Nominal air speeds with fan running:

   1. View from Front of Coach
      a. Tell-Tale Cup 4: 0.19 m/s
      b. Tell-Tale Cup 5: 0.92 m/s
      c. Tell-Tale Cup 6: 0.62 m/s
      d. Tell-Tale Cup 8: 5.46 m/s
      e. Pan 1: 6.58 m/s

   2. View from Rear of Coach
      a. Tell-Tale Cup 1: 0.40 m/s
      b. Tell-Tale Cup 2: 0.17 m/s
      c. Tell-Tale Cup 3: 0.40 m/s
      d. Tell-Tale Cup 7: 0.34 m/s
      e. Pan 2: 0.35 m/s

5. Plastics Fire (Two Tests)
   a. Real Bus Hazard: Class A material (plastics) fire close to the toilet holding tank and air filter housing components.
   b. Ignition Materials:
      i. 8 vertical strips of plastic, 4 Acrylonitrile butadiene styrene (ABS) and 4 Polypropylene plastic (PP), each measuring 2 in $\times$ 28.75 in. long (nominally 1/8 in. thick)
      ii. 4 horizontal strips of plastic, 1 of each type of plastic on lower two shelves of clutter rack adjacent to vertical strips and ignition pan.
      iii. The material flammability of these materials has been characterized and can be referenced in Appendix C.
   c. Ignition Source: 1 rectangular pan (same as pool fire test) with 120 ml of heptane used to ignite the plastic.
   d. Location: lower right (cold) side of engine.
   e. General Procedure: Ignite the pan fire, after 105 s of pre-burn, discharge the suppression system and record observations.
   f. Ventilation: conduct test with and without the fan running.

i. Nominal air speeds with fan running:

   1. Ignition Pan: 0.43 m/s
   2. Shelf 1 (Lowest): 0.33 m/s
   3. Shelf 2: 0.27 m/s
   4. Shelf 3: 0.25 m/s
   5. Shelf 4 (Highest): 0.34 m/s
6. Battery Compartment Fire (One Test)
   a. Real Bus Hazard: overheated cable in battery compartment, which leads to a growing Class A fire.
   b. Ignition Materials:
      i. 1-in diameter pipe insulation – two horizontal sections 30 in long and one vertical section 25 in long. Prior to installation, each section is sprayed lightly with approximately 25 ml of diesel fuel. These sections are mounted just above the egg-crate foam and over the overheated cable.
      ii. Egg-crate foam plastic insulation – one 16 × 18-in panel applied to back wall of battery compartment directly over the overheated cable.
      iii. Plastic toolboxes – these are used to approximate battery boxes. Four of these boxes are placed in the compartment and 10 ml of grease is applied to the top surface of the back two boxes.
      iv. The material flammability of these materials has been characterized and can be referenced in Appendix C.
   c. Ignition Source: 23.5-in long thermoplastic cable overheated to ignition by discharging a 200-amp load from two motorcoach batteries in series (24 volts). The cable also has approximately 5 ml of lubricating grease applied evenly over the surface of the cable insulation.
   d. Location: battery compartment.
   e. General Procedure: discharge battery current into test cable and allow cable to ignite, 30 s after cable ignition, discharge suppression system and record observations.
   f. Ventilation: conduct test without the fan running.

As discussed in Section 5.2 of this report, it is recommended that the fan speed be set to an intermediate representative speed (volumetric flow rate), typical to that of the majority of motorcoach driving time. This equates to an average air velocity of approximately 6 m/s at the outlet of the fan after the louvered radiator enclosure and nominally 3 m$^3$/s of volumetric airflow.

Figure 21 – Figure 30 provide drawings of each fire scenario location within the test fixture.
Figure 21. Hot Surface Re-Ignition Fire Scenario (View of Forward Side).

Figure 22. Diesel Spray Fire Scenario (View of Rear Side: Lower Position).
Figure 23. Diesel Spray Fire Scenario (View of Rear Side: Upper Position).

Figure 24. PSF Spray Fire Scenario (View of Forward Side).
Figure 25. Distributed Pool Fire Scenario
(View of Forward Side).
Figure 26. Distributed Pool Fire Scenario (View of Rear Side).

Figure 27. Plastics Fire Scenario (Wide Angle View).

Figure 28. Plastics Fire Scenario (Close-up View).
Figure 29. Battery Compartment Fire Scenario (Wide Angle View).

- 3 EACH, PIPE INSULATION 1-3/8" ID X 1/2" WALL X 28" PRE-SPRAYED WITH DIESEL FUEL
- 18" X 16" EGG-CRATE FOAM PLASTIC INSULATION
- OVER HEATED TO IGNITION CONTROL CABLE
- 4 EACH PLASTIC TOOL BOXES SIMULATING BATTERIES

Figure 30. Battery Compartment Fire Scenario (Close-up View).
5.5.1 Engine Compartment Ignition Source Testing (in open)

During the development of the ignition sources for the final fire scenarios described above, several tests were conducted in the open to help select final components and arrangement. Figure 31 – Figure 34 show selected photographs from this initial baseline fire scenario testing.

During this testing, several decisions were made about the fire scenarios, such as the following.

- Operating temperature of hot surface,
- Configuration between electrical heaters and hot surface (steel plate),
- Types of spray nozzles required for testing,
- Optimal way to ignite sources (spray fires, Class A fuels, etc.)
- Flammability of several ignition sources, such as the plastics and other materials required for the battery compartment test, and
- Effect of ventilation on ignition sources.
Figure 31. Hot Surface Ignition Testing.
Figure 32. Spray Fire Ignition Testing
(Power Steering Fluid-Top Nozzle and Diesel Fuel-Bottom Nozzle).
Figure 33. Plastic Fire Ignition Testing (ABS (Black) and PP (White).
5.5.2 Engine Compartment Fire Scenario Baseline Testing

After the test fixture was fabricated, the fire scenarios were tested within the fixture and in the absence of a fire detection or suppression system so baseline data could be gathered to help determine appropriate pre-burn times, as well as to understand the overall temperature evolution in the fixture without a fire suppression system. Appendix D provides a summary of these baseline data gathered for each fire scenario described above. Figure 35 provides selected photographs from this baseline testing.

Figure 34. Overheated Cable Ignition Testing
Several baseline tests were conducted with the hot surface ignition scenario to characterize the heating and cool-down periods, as well as to determine the best operating temperature for the hot surface. Figure 36 provides the heating and cooling temperatures.

Figure 36 illustrates approximate linear cooling on the hot surface from ~760 – 500 °C. Over this temperature range, the slope of the line is essentially the same with and without continued oil drip during cool down. A slower cool down rate can be observed with and without continued oil drip between 500 – 300 °C.

During the initial baseline tests in the open, the minimum temperature for oil ignition on the hot plate was observed to be approximately 520 °C. It can be noted from Figure 36 that the natural cool down period of the hot plate between 750-520 °C is approximately 7 min, which is more than adequate to evaluate the cooling capability of a suppression system under test. In other words, the hot plate will remain above the oil ignition temperature for a long time. The only way to prevent re-ignition is to cool the hot surface to below the ignition temperature.
5.6 Engine Compartment Vendor Testing

Several sessions of vendor testing were performed with three companies that sell commercial detection and/or suppression systems. The following subsections provide a brief summary of the testing that was conducted and the results.

5.6.1 Vendor A Test Results

Vendor A conducted two test sessions. The first test session was conducted April 28-30, 2014, and the second session was conducted on July 29, 2014. In total, 14 tests were conducted in the engine compartment test fixture.

Detection/Suppression System Description

The vendor installed their detection and suppression system in the test fixture after an initial survey of the geometry, obstructions and summary of the test fires.

The integrated system consisted of linear thermal detection (LTD) and optical detection as well as a dry chemical based suppression system (5 nozzles, 25 or 30-lb capacity). In addition, a cooling agent was used for the hot surface fire. Table 3 provides a summary of the tests conducted and the detection/suppression devices used for each test.

![Figure 36. Hot Surface Re-Ignition Test Characterization.](image)
<table>
<thead>
<tr>
<th>Test No.</th>
<th>Fire Scenario</th>
<th>Detector Description</th>
<th>Suppression Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PSF Spray without Fan</td>
<td>No Detector</td>
<td>25-lb dry chemical, 5 nozzles</td>
</tr>
<tr>
<td>2</td>
<td>PSF Spray without Fan</td>
<td>Linear Heat Detector Wire</td>
<td>25-lb dry chemical, 5 nozzles</td>
</tr>
<tr>
<td>3</td>
<td>Hot Surface Re-Ignition</td>
<td>Linear Heat Detector Wire</td>
<td>Cooling agent only (no dry chemical)</td>
</tr>
<tr>
<td>4</td>
<td>Diesel Spray with fan (lower position)</td>
<td>Linear Heat Detector Wire and Optical Detector</td>
<td>25-lb dry chemical, 5 nozzles</td>
</tr>
<tr>
<td>5</td>
<td>Battery Compartment Fire with fan</td>
<td>Linear Heat Detector Wire</td>
<td>25-lb dry chemical, 5 nozzles</td>
</tr>
<tr>
<td>6</td>
<td>Plastics Fire with Fan</td>
<td>Linear Heat Detector Wire</td>
<td>25-lb dry chemical, 5 nozzles</td>
</tr>
<tr>
<td>7</td>
<td>Pool Fires with Fan</td>
<td>No Detection</td>
<td>25-lb dry chemical, 5 nozzles</td>
</tr>
<tr>
<td>8</td>
<td>Hot Surface Re-Ignition</td>
<td>No Detection</td>
<td>25-lb dry chemical, 5 nozzles</td>
</tr>
<tr>
<td>9</td>
<td>Hot Surface Re-Ignition</td>
<td>No Detection</td>
<td>Cooling agent only (no dry chemical)</td>
</tr>
<tr>
<td>10</td>
<td>Diesel Spray with Fan (upper position)</td>
<td>Optical Detector</td>
<td>25-lb dry chemical, 5 nozzles</td>
</tr>
<tr>
<td>11</td>
<td>PSF Spray with Fan</td>
<td>Optical Detector</td>
<td>25-lb dry chemical, 5 nozzles</td>
</tr>
<tr>
<td>12</td>
<td>Pool Fires with Fan</td>
<td>Optical Detector</td>
<td>25-lb dry chemical, 5 nozzles</td>
</tr>
<tr>
<td>13</td>
<td>Pool Fires with Fan</td>
<td>Optical Detector</td>
<td>25-lb dry chemical, 5 nozzles</td>
</tr>
<tr>
<td>14</td>
<td>Plastics and Battery Compartment Fire (combined due to time constraints)</td>
<td>No Detector</td>
<td>30-lb dry chemical, 5 nozzles</td>
</tr>
</tbody>
</table>

The cooling agent is typically used by this vendor to address potential hot surfaces in an engine compartment, and is normally integrated into the detection and dry chemical system, which is installed throughout the rest of the engine compartment. For this testing, it was decided on a test-by-test basis if all systems would be used together or separated. In addition, all suppression was initiated manually, with a mechanical valve.

Test Results
Temperature data in the engine compartment for each test can be referenced in Appendix E. Table 4 provides a summary of the test results for Vendor A. Detection times are relative to ignition of the fire source or in the case of the pool fires, ignition of the last rectangular pan. Extinguishment times are relative to the start of agent discharge.

Table 4. Summary of Vendor A Test Results.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Fire Scenario</th>
<th>Detection Time (s)</th>
<th>Extinguishment Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PSF Spray without Fan</td>
<td>N/A</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>PSF Spray without Fan</td>
<td>14</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Hot Surface Re-Ignition</td>
<td>Activated during heating period at 600 °C, prior to start of test, at 750 °C</td>
<td>2, No Re-ignition</td>
</tr>
<tr>
<td>4</td>
<td>Diesel Spray with fan (lower position)</td>
<td>No activation</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>Battery Compartment Fire with fan</td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>Plastics Fire with Fan</td>
<td>No activation</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>Pool Fires with Fan</td>
<td>N/A</td>
<td>No full extinguishment</td>
</tr>
<tr>
<td>8</td>
<td>Hot Surface Re-Ignition</td>
<td>N/A</td>
<td>1, Re-ignition in 32 s</td>
</tr>
<tr>
<td>9</td>
<td>Hot Surface Re-Ignition</td>
<td>N/A</td>
<td>1, No Re-ignition</td>
</tr>
<tr>
<td>10</td>
<td>Diesel Spray with Fan (upper position)</td>
<td>No activation</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>PSF Spray with Fan</td>
<td>No activation</td>
<td>2</td>
</tr>
<tr>
<td>12</td>
<td>Pool Fires with Fan</td>
<td>No activation</td>
<td>No full extinguishment</td>
</tr>
<tr>
<td>13</td>
<td>Pool Fires with Fan</td>
<td>10 (adjusted settings on optical detector)</td>
<td>3 (adjusted nozzle placement slightly)</td>
</tr>
<tr>
<td>14</td>
<td>Plastics and Battery Compartment Fire (combined due to time constraints)*</td>
<td>N/A</td>
<td>2</td>
</tr>
</tbody>
</table>

N/A: not applicable since a detection system was not installed on this test.
*: pre-burn times were aligned such that system could be discharged at appropriate time.

Several interesting observations can be made as a result of this testing.

- If the detection system activated, it did so within the proposed pre-burn times. However, in some cases, the detection system did not activate and
this occurred for tests with the fan running, which provides some convective cooling to the linear heat detector and may also affect the fire size and shape for the optical detectors.

- The average discharge time of the dry chemical system is 15–20 s. Typically, if extinguishment is to be observed, it occurs within 3 s. This is the time period that the system has the most momentum to penetrate obstructed fires and if the fire cannot be extinguished quickly, it tends to not be extinguished at all.
- The most challenging fire appears to be the distributed pool fire scenario with the fan running.
- Dry chemical does not seem to be an ideal agent for the hot surface re-ignition scenario and the cooling agent performed much better. In addition, the average discharge time for the cooling agent (discharged at a lower pressure) was 60 s.

5.6.2 Vendor B Test Results

Vendor B conducted a test session July 15-18, 2014. In total, 15 tests were conducted in the engine compartment fixture.

Detection/Suppression System Description

The vendor installed their detection and suppression system in the test fixture after an initial survey of the geometry, obstructions and summary of the test fires.

The integrated system consisted of linear and optical heat detectors as well as a dry chemical based suppression system (2 or 4-nozzle system, 10-kg capacity). The 2-nozzle system is discharged at a higher pressure than the 4-nozzle system. All suppression was initiated manually, with a mechanical valve, after the proposed pre-burn time.

In terms of detection, Vendor B provided four different types of detector circuits that could be monitored during each test. Two different types of LTD wire was used; one set that activates at nominally 180 °C and another that activates at nominally 232 °C. Another LTD was used that averages the heat it senses and is identified as LTD-Avg. In addition to the linear thermal detectors, an optical detector circuit was used, similar to Vendor A.

Table 5 provides a summary of the tests conducted and the detection/suppression devices used for each test.
Table 5. Summary of Vendor B Detection and Suppression System.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Fire Scenario</th>
<th>Detector Description</th>
<th>Suppression Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Diesel Spray without Fan (lower position)</td>
<td>LTD-180, LTD-232, Optical, LTD-Avg</td>
<td>10-kg dry chemical, 2 nozzles</td>
</tr>
<tr>
<td>2</td>
<td>Diesel Spray with Fan (lower position)</td>
<td>LTD-180, LTD-232, Optical, LTD-Avg</td>
<td>10-kg dry chemical, 2 nozzles</td>
</tr>
<tr>
<td>3</td>
<td>PSF Spray with Fan</td>
<td>LTD-180, LTD-232, Optical, LTD-Avg</td>
<td>10-kg dry chemical, 2 nozzles</td>
</tr>
<tr>
<td>4</td>
<td>PSF Spray without Fan</td>
<td>LTD-180, LTD-232, Optical, LTD-Avg</td>
<td>10-kg dry chemical, 2 nozzles</td>
</tr>
<tr>
<td>5</td>
<td>Pool Fires without Fan</td>
<td>LTD-180, LTD-232, Optical, LTD-Avg</td>
<td>10-kg dry chemical, 2 nozzles</td>
</tr>
<tr>
<td>6</td>
<td>Pool Fires with Fan</td>
<td>LTD-180, LTD-232, Optical, LTD-Avg</td>
<td>10-kg dry chemical, 2 nozzles</td>
</tr>
<tr>
<td>7</td>
<td>Plastics Fire without Fan</td>
<td>LTD-180, LTD-232, Optical, LTD-Avg</td>
<td>10-kg dry chemical, 2 nozzles</td>
</tr>
<tr>
<td>8</td>
<td>Pool Fires with Fan</td>
<td>No Detector Installed</td>
<td>10-kg dry chemical, 4 nozzles</td>
</tr>
<tr>
<td>9</td>
<td>PSF Spray with Fan</td>
<td>No Detector Installed</td>
<td>10-kg dry chemical, 4 nozzles</td>
</tr>
<tr>
<td>10</td>
<td>PSF Spray without Fan</td>
<td>No Detector Installed</td>
<td>10-kg dry chemical, 4 nozzles</td>
</tr>
<tr>
<td>11</td>
<td>Diesel Spray with Fan (lower position)</td>
<td>No Detector Installed</td>
<td>10-kg dry chemical, 4 nozzles</td>
</tr>
<tr>
<td>12</td>
<td>Pool Fires without Fan</td>
<td>No Detector Installed</td>
<td>10-kg dry chemical, 4 nozzles</td>
</tr>
<tr>
<td>13</td>
<td>Plastics Fire without Fan</td>
<td>No Detector Installed</td>
<td>10-kg dry chemical, 4 nozzles</td>
</tr>
<tr>
<td>14</td>
<td>Battery Compartment Fire without Fan</td>
<td>No Detector Installed</td>
<td>10-kg dry chemical, 4 nozzles</td>
</tr>
<tr>
<td>15</td>
<td>Battery Compartment Fire without Fan</td>
<td>No Detector Installed</td>
<td>10-kg dry chemical, 2 nozzles</td>
</tr>
</tbody>
</table>

Test Results

Table 6 provides a summary of the test results for Vendor B. Temperature data in the engine compartment for each test can be referenced in Appendix F. Detection times are relative to ignition of the fire source or in the case of the pool fires, ignition of the last rectangular pan. Extinguishment times are relative to the start of agent discharge.
Table 6. Summary of Vendor B Test Results.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>LTD-180 (s)</th>
<th>LTD-232 (s)</th>
<th>Optical (s)</th>
<th>LTD-Avg (s)</th>
<th>Extinguishment Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No Activation</td>
<td>No Activation</td>
<td>No Activation</td>
<td>No Activation</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>No Activation</td>
<td>No Activation</td>
<td>No Activation</td>
<td>No Activation</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>32</td>
<td>No Activation</td>
<td>No Activation</td>
<td>No Activation</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>N/A</td>
<td>No Activation</td>
<td>1</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>N/A</td>
<td>28</td>
<td>No Activation</td>
<td>16</td>
<td>8</td>
</tr>
<tr>
<td>6</td>
<td>19</td>
<td>22</td>
<td>No Activation</td>
<td>18</td>
<td>5</td>
</tr>
<tr>
<td>7</td>
<td>N/A</td>
<td>N/A</td>
<td>No Activation</td>
<td>26</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>No full extinguishment</td>
</tr>
<tr>
<td>9</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>3</td>
</tr>
<tr>
<td>12</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>2</td>
</tr>
<tr>
<td>13</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>1</td>
</tr>
<tr>
<td>14</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>4</td>
</tr>
<tr>
<td>15</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>2</td>
</tr>
</tbody>
</table>

N/A: not applicable since new detectors were not installed on this test.

Several interesting observations can be made as a result of this testing.

- If the detection system activated, it typically did so within the proposed pre-burn times. However, in some cases, the detection system did not activate and this occurred primarily for tests with the fan running, which provides some convective cooling to the linear heat detectors and may also affect the fire size and shape for the optical detectors.

- The average discharge time of the 2-nozzle (high pressure) dry chemical system is 2 seconds. The average discharge time of the 4-nozzle (low pressure) dry chemical system is 11 seconds. An interesting difference is
seen with the extinguishment times between the 2-nozzle and 4-nozzle systems.

- For the 4-nozzle system (similar in design to Vendor A), typically, if extinguishment is to be observed, it occurs within 3 seconds. This is the time period that the system has the most momentum to penetrate obstructed fires and if the fire cannot be extinguished quickly, it tends to not be extinguished at all.

- However, for the 2-nozzle system, since the discharge is so fast, it takes a few additional seconds to observe extinguishment in some of the fire scenarios.

- The most challenging fire appears to be the distributed pool fire scenario with the fan running.

5.6.3 Vendor C Test Results
Vendor C conducted two test sessions. The first test session was conducted July 22-23, 2014, and the second session was conducted on August 19-20, 2014. In total, 26 tests were conducted in the engine compartment test fixture.

Suppression System Description
Vendor C did not test with a detection system. The suppression system design was a hybrid between compressed air foam (CAF) and water mist. The suppression agent was CAF, but two different types of nozzles were utilized; one more typically found on commercial pre-engineered CAF systems and one more typically found in commercial pre-engineered water mist systems.
Table 7 provides a summary of the tests conducted and the suppression devices used for each test.

### Table 7. Summary of Vendor C Tests and Suppression System.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Fire Scenario</th>
<th>Suppression System Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PSF Spray without Fan</td>
<td>10-nozzle System (5 CAF and 5 Water Mist)</td>
</tr>
<tr>
<td>2</td>
<td>PSF Spray without Fan</td>
<td>10-nozzle System (5 CAF and 5 Water Mist)</td>
</tr>
<tr>
<td>3</td>
<td>Diesel Spray without Fan (low position)</td>
<td>10-nozzle System (5 CAF and 5 Water Mist)</td>
</tr>
<tr>
<td>4</td>
<td>Diesel Spray with Fan (low position)</td>
<td>Same nozzle array, plugged half the nozzles to evaluate change in rate of application</td>
</tr>
<tr>
<td>5</td>
<td>Diesel Spray with Fan (low position)</td>
<td>Same nozzle array, plugged half the nozzles to evaluate change in rate of application</td>
</tr>
<tr>
<td>6</td>
<td>Diesel Spray with Fan (low position)</td>
<td>Same nozzle array, plugged half the nozzles to evaluate change in rate of application</td>
</tr>
<tr>
<td>7</td>
<td>Plastics Fire without Fan</td>
<td>Same nozzle array, plugged half the nozzles to evaluate change in rate of application</td>
</tr>
<tr>
<td>8</td>
<td>Battery Compartment Fire without Fan</td>
<td>Same nozzle array, plugged half the nozzles to evaluate change in rate of application</td>
</tr>
<tr>
<td>9</td>
<td>Diesel Spray without Fan (high position)</td>
<td>12-nozzle System (7 CAF, 3 Water Mist, 2 Smaller Water Mist)</td>
</tr>
<tr>
<td>10</td>
<td>Diesel Spray with Fan (high position)</td>
<td>12-nozzle System (7 CAF, 3 Water Mist, 2 Smaller Water Mist)</td>
</tr>
<tr>
<td>11</td>
<td>Diesel Spray with Fan (high position)</td>
<td>12-nozzle System (7 CAF, 3 Water Mist, 2 Smaller Water Mist) – Adjusted positions</td>
</tr>
<tr>
<td>12</td>
<td>Diesel Spray with Fan (high position)</td>
<td>12-nozzle System (7 CAF, 3 Water Mist, 2 Smaller Water Mist) – Adjusted positions</td>
</tr>
<tr>
<td>13</td>
<td>Diesel Spray without Fan (low position)</td>
<td>12-nozzle System (7 CAF, 3 Water Mist, 2 Smaller Water Mist) – Adjusted positions</td>
</tr>
<tr>
<td>14</td>
<td>PSF Spray without Fan</td>
<td>Same as Test 13</td>
</tr>
<tr>
<td>15</td>
<td>PSF Spray with Fan</td>
<td>Same as Test 13 and 14</td>
</tr>
<tr>
<td>16</td>
<td>Pool Fires with Fan</td>
<td>Same as Tests 13-15</td>
</tr>
<tr>
<td>17</td>
<td>Pool Fires with Fan</td>
<td>Adjusted nozzle positions</td>
</tr>
<tr>
<td>18</td>
<td>Pool Fires with Fan</td>
<td>Changed CAF nozzles to a different model number, same configuration as Test 17</td>
</tr>
<tr>
<td>19</td>
<td>Pool Fires with Fan</td>
<td>Same nozzles as Test 18, adjusted position</td>
</tr>
<tr>
<td>20</td>
<td>Pool Fires with Fan</td>
<td>Changed CAF nozzles to a different model number, same configuration as Test 19</td>
</tr>
<tr>
<td>21</td>
<td>Pool Fires with Fan</td>
<td>Changed CAF nozzles to a different model number, same configuration as Test 19-20</td>
</tr>
<tr>
<td>22</td>
<td>Diesel Spray with Fan (low position)</td>
<td>Same as Test 21</td>
</tr>
</tbody>
</table>
Table 7. Summary of Vendor C Tests and Suppression System (continued).

<table>
<thead>
<tr>
<th>Test No</th>
<th>Fire Scenario</th>
<th>Suppression System Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>23</td>
<td>Diesel Spray with Fan (low position)</td>
<td>Changed CAF nozzles to different model number, same configuration as Test 22</td>
</tr>
<tr>
<td>24</td>
<td>Diesel Spray without Fan (low position)</td>
<td>Same as Test 23</td>
</tr>
<tr>
<td>25</td>
<td>Plastics Fire without Fan</td>
<td>Same as Tests 23-24</td>
</tr>
<tr>
<td>26</td>
<td>Plastics Fire with Fan</td>
<td>Same as Tests 23-25</td>
</tr>
</tbody>
</table>

Test Results

Table 8 provides a summary of the fire tests and the extinguishment time observed. Temperature data in the engine compartment for each test can be referenced in Appendix G.

Table 8. Summary of Vendor C Test Results.

<table>
<thead>
<tr>
<th>Test No</th>
<th>Fire Scenario</th>
<th>Extinguishment Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PSF Spray without Fan</td>
<td>No extinguishment</td>
</tr>
<tr>
<td>2</td>
<td>PSF Spray without Fan</td>
<td>No extinguishment</td>
</tr>
<tr>
<td>3</td>
<td>Diesel Spray without Fan (low position)</td>
<td>No extinguishment</td>
</tr>
<tr>
<td>4</td>
<td>Diesel Spray with Fan (low position)</td>
<td>No extinguishment</td>
</tr>
<tr>
<td>5</td>
<td>Diesel Spray with Fan (low position)</td>
<td>No extinguishment</td>
</tr>
<tr>
<td>6</td>
<td>Diesel Spray with Fan (low position)</td>
<td>No extinguishment</td>
</tr>
<tr>
<td>7</td>
<td>Plastics Fire without Fan</td>
<td>No extinguishment</td>
</tr>
<tr>
<td>8</td>
<td>Battery Compartment Fire without Fan</td>
<td>3</td>
</tr>
<tr>
<td>9</td>
<td>Diesel Spray without Fan (high position)</td>
<td>2</td>
</tr>
<tr>
<td>10</td>
<td>Diesel Spray with Fan (high position)</td>
<td>No extinguishment</td>
</tr>
<tr>
<td>11</td>
<td>Diesel Spray with Fan (high position)</td>
<td>2</td>
</tr>
<tr>
<td>12</td>
<td>Diesel Spray with Fan (high position)</td>
<td>2</td>
</tr>
<tr>
<td>13</td>
<td>Diesel Spray without Fan (low position)</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 8. Summary of Vendor C Test Results (continued).
<table>
<thead>
<tr>
<th>Test No.</th>
<th>Fire Scenario</th>
<th>Extinguishment Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>PSF Spray without Fan</td>
<td>2</td>
</tr>
<tr>
<td>15</td>
<td>PSF Spray with Fan</td>
<td>3</td>
</tr>
<tr>
<td>16</td>
<td>Pool Fires with Fan</td>
<td>No extinguishment</td>
</tr>
<tr>
<td>17</td>
<td>Pool Fires with Fan</td>
<td>No extinguishment</td>
</tr>
<tr>
<td>18</td>
<td>Pool Fires with Fan</td>
<td>No extinguishment</td>
</tr>
<tr>
<td>19</td>
<td>Pool Fires with Fan</td>
<td>No extinguishment</td>
</tr>
<tr>
<td>20</td>
<td>Pool Fires with Fan</td>
<td>No extinguishment</td>
</tr>
<tr>
<td>21</td>
<td>Pool Fires with Fan</td>
<td>No extinguishment</td>
</tr>
<tr>
<td>22</td>
<td>Diesel Spray with Fan (low position)</td>
<td>No extinguishment</td>
</tr>
<tr>
<td>23</td>
<td>Diesel Spray with Fan (low position)</td>
<td>3</td>
</tr>
<tr>
<td>24</td>
<td>Diesel Spray without Fan (low position)</td>
<td>3</td>
</tr>
<tr>
<td>25</td>
<td>Plastics Fire without Fan</td>
<td>49</td>
</tr>
<tr>
<td>26</td>
<td>Plastics Fire with Fan</td>
<td>No extinguishment</td>
</tr>
</tbody>
</table>

Several interesting observations can be made as a result of this testing.

- In general, the CAF/mist system was challenged by the fire scenarios and in particular the heavily obstructed fires. This is likely due to this type of technology typically being used for local applications, rather than a total flooding application, which is more representative of an engine compartment.

- The average discharge time of the CAF/mist system was 1–1.5 min. Similar to the Vendor A and B test results, if the fire is not extinguished within the first few seconds of application, typically the fire will not be extinguished at all.

- The most challenging fire appears to be the distributed pool fire scenario with the fan running.

5.7 Engine Compartment Fire Detection System Discussion

This section provides a summary of how fire detection in engine compartments is typically addressed in the field currently and discusses how detection is to be integrated into the proposed test procedure, but also requires further research.

Types of detectors
A number of detectors can and are being used in engine compartments. They include:

- **Linear Thermal Detectors (LTDs)** – these are a pair of wires covered in insulation with a specific melting point. When the plastic insulation melts, the two wires short and this provides an alarm signal.
- **Spot detectors** – these devices measure the temperature at a point. They are usually set to signal at a specific temperature – similar to a bi-metallic strip.
- **Thermocouple detectors** – these are also "point" detectors. The temperature is measured continuously, and the trigger temperature can be programmed into the software.
- **Rate of rise detectors** – These are sensitive to the rate of change of temperature rather than its actual value. The detector could be the same as a thermocouple detector. The software can be programmed to trigger at a specific rate or rise.
- **Optical detectors** – these detect temperature or a flame by monitoring the radiation intensity in one or two bands of the spectrum of light. Multi-channel detectors may have a lower false alarm rate. These detectors are sensitive to a size and shape of a fire.

A good summary of various detection technologies can be referenced in Appendix A [5].

**Quantity and Location of detectors**

It normally takes several detectors to cover an entire engine compartment. Most electronic boxes can accept several independent inputs. Many detectors can also be “daisy-chained” together in series.

Detectors are usually installed after conducting a hazard analysis of the engine compartment. Most engines have a “cold side” for the air intake and fuel injectors, and a “hot side” where the exhaust manifold, exhaust gas recirculator (EGR) valve, turbocharger, and emissions control canisters are located. The alternators and starter motor can be on either side of the engine and are usually down low. The engine block effectively separates the cold and hot side – so detectors are needed on both sides. To protect high current electrical cables, such as from the alternators or to the starter motor, LTDs are sometimes attached directly to the cables with cable ties.

In principle, one could cover the entire engine compartment with LTDs or other detectors. But both the OEMs and operators want to minimize the objects that must be removed and replaced in order to perform maintenance on other engine compartment components. Thus there are practical limitations on where detectors can be placed.

Since heat rises, there is a rationale for installing detectors near the top of the engine compartment. If there is no airflow, a detector directly over the fire will usually detect it. The heat will flow upward by convection. But if there is airflow, the fire plume will be displaced to the side, and the fire may not be detected. All inspected motorcoaches had the engine radiator located on the driver’s side of the engine compartment with the airflow toward the passenger’s side. The air exits through louvers on the rear engine compartment door or small louvers on the passenger side, or via the bottom of the engine compartment. None of the engine compartments inspected had floor pans, but the downward airflow area is limited by the presence of the engine block, the emissions control equipment, and the lavatory holding tank. The downward airflow area is limited to about 40–50% of the available footprint. Thus the airflow will tend to displace the fire plume toward the passenger side.
Vendors A and B primarily used LTDs for detection. Vendor C did not test any detectors. Both vendor A and B had optical sensors available and Vendor B also tested a TLSE.

The LTD material comes with different temperature ratings – most of the motorcoach installations use LTDs designed to provide a signal at 180 °C (356 °F). Vendor B also tested a LTD set to activate at 232 ºC. Based on the results of this testing, it seems that the LTDs work well if they are close to the fire and get heated. But for distant fires, or situations with the radiator fan on, they may not detect the fire.

It was originally planned to use the automatic detection system to trigger the release of the fire suppression agent. However, the detection system was not always successful, so manual suppression system activation was elected with a specific pre-burn time. This allowed the test procedure to evaluate both the detection and suppression components.

The hot surface re-ignition test simulates an overheated turbocharger. It is represented by a flat steel plate heated from behind by two quartz heaters. It was found that the LTD routed high in the engine compartment activated relatively quickly and radiation may have been the primary mode of heat transfer in this case.

Summary

The details of the test procedures evolved as more tests were performed. As expected, it was observed that fires were detected when they were close to the detector. A failure to activate was typically related to proximity to the fire source or ventilation effects, rather than specific detector technology.

Further research is recommended to determine quantitatively how each type of detector responds to a fire at a given distance and view angle. This will provide the data on how many detectors are needed and where to optimally locate them. It may not be necessary to use the large engine compartment test fixture to evaluate single detector types.

The final test procedures allowed for a simplified evaluation of the detection systems installed in an engine compartment. This is reflected in the recommended test criteria in Section 5.8. However, it is also recommended that future research be conducted with respect to detection in engine compartments to further refine the optimal test methods.

5.8 Engine Compartment Test Procedure and Test Criteria

The following test criteria have been developed for evaluating detection and suppression systems in motorcoach engine compartments.

- The detection and suppression system is installed per manufacturer direction and/or specifications.
- The installation remained unchanged for the twelve fire tests. In other words for a given single system configuration, all the tests are conducted with the same detector and suppression system (nozzle) locations. If the system design/configuration is changed, all tests will be conducted again for that new design/configuration.
- For all of tests described in Section 5.5 of this report, with the exception of the hot surface re-ignition test, the design fire must be extinguished.
- For all of tests described in Section 5.5 of this report, with the exception of the hot surface re-ignition test, the detection system must have activated prior to the end of the pre-burn time of the design fire.
• For the hot surface re-ignition test, the installed system must prevent re-ignition for a minimum of 150 seconds. This time limit is derived from a recent Volpe Center report, which discusses egress times from a full motorcoach after an accident [13].

• It is typical that detection and suppression systems that meet this test criterion also meet testing requirements for their individual system components. This is a common requirement of active fire protection systems. Successful fire testing is an important aspect of a good system, but the fire testing on its own does not address the robustness of the system design, with respect to individual component reliability. An example of this type of component testing method is FM 5320, Approval Standard for Dry Chemical Extinguishing Systems, December 2013.

• Additional details about the recommended test procedure and criteria can be referenced in Appendix H.

6.0 WHEEL WELL FINAL DESIGN, FIRE SCENARIO DEVELOPMENT AND TESTING

6.1 Wheel Well Fire Scenario Development and Final Design

The project team has determined, based on the literature and discussions with stakeholders (manufacturers, carriers, etc.), that the major heat sources for tire fires are (in order of importance):

1. Dragging brakes;
2. Failed bearings (these are becoming less frequent with the new “maintenance free” bearings which do not require addition of lubricant oil). However, there still are a significant number of coaches on the road with the older style bearings that fail more readily without good maintenance
3. Underinflated tires (especially the inner tire of a set of dual drive axle tires). The National Transportation Safety Board (NTSB)/Greyhound track tests were not able to cause a fire this way (they stopped the test at thread separation) [12]. However, NTSB has implicated underinflated tires in another motorcoach fire investigation, and most experts still believe that under inflation can cause fires; The most vulnerable tires to overheat are on the tag axle (un-driven axle), followed by the drive axle, and then the steering tires. An early warning sensor system would have a higher likelihood of success than an active detection and suppression system in the wheel well area. This is due to the fact that the wheel well is an extremely challenging fire area, due to its relatively open geometry, harsh environment, and the aggressive nature of a tire fire. If an impending fire event can be detected prior to heating the tire to its ignition temperature, then it should be possible to avoid the event before it starts. A wheel well fire early warning system test procedure has been developed, which evaluates sensors and algorithms that can detect a hot wheel in advance of a tire fire.

This test procedure is based on a single tag axle that is supported at one end with a bearing structure and driven by an electric motor connected to the wheel lug nut assembly. The wheel is heated by partially engaging the brakes on the tag axle, causing heat to be transferred through the rotor and wheel assembly and into the tire. There is also direct radiative heat transfer from the hot brake components to the inside of the wheel. The goal is to show that some quantity can be measured and used to predict an abnormal wheel heating condition, and to warn the driver before a tire fire would develop.
Based on the work conducted by NIST, tires are estimated to ignite at approximately 400 °C [3]. Currently available Tire Pressure Monitoring System (TPMS) sensors measure the temperature and pressure of the air inside the tire. These existing sensors can be set to issue a high temperature alarm at a specific temperature (adjustable by user). This alarm temperature can be considerably higher than what is encountered during hard braking and thus should not result in excessive false alarms.

It is important to show that the heat stored in the metal components is not enough to exceed the ignition temperature and allow a fire to start even after the wheel (motorcoach) has stopped. Therefore, two extended tests were conducted until a tire fire/blowout was observed. This demonstrated that the test fixture is sufficient to add enough heat into the system for a dangerous event, and also allow the study of the temperature distributions up to that point. Finally, this information can be used analytically to quantify the margins between false alarms and an actual tire fire. Figure 37 provides several views of the final wheel well test fixture design. Appendix I provides detailed drawings of the wheel well test fixture.

![Motorcoach Wheel Well Test Fixture Final Design](image)

**Figure 37. Motorcoach Wheel Well Test Fixture Final Design.**

### 6.2 Wheel Well Test Fixture Fabrication

Figure 38 and Figure 39 show selected photographs of the fabricated wheel well early warning device test assembly.
6.3 Wheel Well Test Fixture Instrumentation

Several measurements were taken during baseline and vendor testing in this fixture. Two DAQs were used; one for stationary measurements and one for rotating measurements.
On the stationary DAQ, 5 voltage output devices were used to measure pressure, speed, frequency and amperage. In addition, 14 thermocouples were used to measure temperature at various locations. Table 9 summarizes the channel layout on the stationary DAQ. Figure 40 depicts selected stationary thermocouples that were important to the development of the fixture test procedure. Additional information is provided about the brake pad temperature measurements in Section 6.5 of this report.

On the rotating DAQ, 6 thermocouples were used to measure temperature at various locations. Figure 41 shows a photograph of the rotating DAQ transmitter. Thermocouples were hard-wired between this module and the measurement location. This module then transmitted the temperature data to a receiver, which was connected to a laptop where the data was stored. Table 10 summarizes the channel layout on the rotating DAQ. Figure 42 and Figure 43 depict the six rotating thermocouple locations.
Table 9. Summary of Stationary Wheel Well Test Fixture Instrumentation.

<table>
<thead>
<tr>
<th>Device No.</th>
<th>Device Identification</th>
<th>Device Units</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Brake Pressure</td>
<td>psig</td>
<td>Use to measure pressure applied to brake caliper piston</td>
</tr>
<tr>
<td>2</td>
<td>Oil Pressure</td>
<td>psig</td>
<td>Used to measure pressure in gearbox</td>
</tr>
<tr>
<td>3</td>
<td>Tachometer</td>
<td>RPM</td>
<td>Used to measure rotational speed of test tire</td>
</tr>
<tr>
<td>4</td>
<td>VFD Frequency</td>
<td>Hz</td>
<td>Used to measure the rotational speed of the electric motor</td>
</tr>
<tr>
<td>5</td>
<td>VFD Current</td>
<td>Amps</td>
<td>Used to measure the current draw of the electric motor</td>
</tr>
<tr>
<td>6</td>
<td>Rear Rim *</td>
<td>°C</td>
<td>Aimed at inner part of rear side of test rim</td>
</tr>
<tr>
<td>7</td>
<td>Front Rim *</td>
<td>°C</td>
<td>Aimed at inner part of front side of test rim</td>
</tr>
<tr>
<td>8</td>
<td>Rear Rim Near Tire Bead *</td>
<td>°C</td>
<td>Aimed at rear side of test rim, close to the tire bead intersection</td>
</tr>
<tr>
<td>9</td>
<td>Rotor *</td>
<td>°C</td>
<td>Aimed at brake rotor</td>
</tr>
<tr>
<td>10</td>
<td>Top of Caliper Housing</td>
<td>°C</td>
<td>This is the component that the brake caliper bolts to – top</td>
</tr>
<tr>
<td>11</td>
<td>Top of Torque Plate</td>
<td>°C</td>
<td>This is the component that the brake caliper bolts to – middle</td>
</tr>
<tr>
<td>12</td>
<td>Bottom of Torque Plate</td>
<td>°C</td>
<td>This is the component that the brake caliper bolts to – bottom</td>
</tr>
<tr>
<td>13</td>
<td>Weld Pad Spindle</td>
<td>°C</td>
<td>Used to measure heat transferred out of test apparatus</td>
</tr>
<tr>
<td>14</td>
<td>ABS Sensor Location</td>
<td>°C</td>
<td>A thermocouple probe was inserted into the ABS sensor port</td>
</tr>
<tr>
<td>15</td>
<td>Brake Pad</td>
<td>°C</td>
<td>A thermocouple was inserted into the brake pad material</td>
</tr>
<tr>
<td>16</td>
<td>Wheel Well: Above Non-Test Tire (Drive Axle)</td>
<td>°C</td>
<td>Air temperature 1-in. above non-test tire</td>
</tr>
<tr>
<td>17</td>
<td>Wheel Well: Middle Between Tires</td>
<td>°C</td>
<td>Air temperature 1-in. above tire elevation, between tires</td>
</tr>
<tr>
<td>18</td>
<td>Wheel Well: Above Test Tire (Tag Axle)</td>
<td>°C</td>
<td>Air temperature 1-in. above test tire</td>
</tr>
<tr>
<td>19</td>
<td>Wheel Well: Above Test Tire (1-in below Housing)</td>
<td>°C</td>
<td>Air temperature 1-in. below wheel well housing over test tire</td>
</tr>
</tbody>
</table>

* These devices are optical thermometers – they were used to determine if some of the rotating measurements could be taken with stationary devices. Most of these data are not provided in this report, since it was determined that the measurements are greatly affected by the hot rotor and since the heat exposure is being cycled, the emissivity of the rotor fluctuates greatly, which makes it difficult to tune the optical thermometer to the correct range. Based on this testing, it is recommended to use a DAQ and instrumentation similar to what is described in Table 10 if rotating data is desired.
Table 10. Summary of Rotating Wheel Well Test Fixture Instrumentation.

<table>
<thead>
<tr>
<th>Device No.</th>
<th>Device Identification</th>
<th>Device Units</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Front Rim – Tire Bead</td>
<td>°C</td>
<td>Located close to the tire bead on the front of the rim</td>
</tr>
<tr>
<td>2</td>
<td>Front Rim – Middle</td>
<td>°C</td>
<td>Located closer to the middle of the rim on the front</td>
</tr>
<tr>
<td>3</td>
<td>Hub</td>
<td>°C</td>
<td>Located on coupling to universal joint that drives tire – measures heat that is lost through the front of fixture</td>
</tr>
<tr>
<td>4</td>
<td>Back Rim – Middle</td>
<td>°C</td>
<td>Located closer to the middle of the rim on the back (opposite No. 5)</td>
</tr>
<tr>
<td>5</td>
<td>Back Rim – Middle</td>
<td>°C</td>
<td>Located closer to the middle of the rim on the back (opposite No. 4)</td>
</tr>
<tr>
<td>6</td>
<td>Back Rim – Tire Bead</td>
<td>°C</td>
<td>Located close to the tire bead on the back of the rim</td>
</tr>
</tbody>
</table>
Figure 41. Rotating DAQ Transmitter.

Figure 42. Rotating Temperature Measurement Locations (Front of Rim).
6.4 Wheel Well Test Fixture Baseline Testing

After the fabrication and installation of the final test fixture was complete, a series of baseline tests were conducted to checkout instrumentation and to map the current drawn from the motor to the applied torque to the system.

The applied torque was measured with a torque meter as a function of the current draw from the motor and applied brake pressure for a variety of wheel speeds. This allowed for the development of a calibration curve that correlates amperage and brake pressure to applied torque. Figure 44 and Figure 45 shows the relationship between torque, motor current draw and applied brake pressure.

Subsequent to these baseline tests, the torque meter was removed from the system and replaced with a shear coupling that occupied the same physical space. The shear coupling limits the torque that can be applied to the wheel and thus adds a measure of safety to the system.
A baseline test was performed without a vendor sensor to determine how the wheel assembly heats up when a nominal 2000 N-m of torque was applied. During this baseline test, a phenomenon called ‘brake fade,’ or ‘brake glazing’ was observed. This
phenomenon occurs when the brakes are brought to a significantly elevated temperature without any burnishing, or breaking-in, of the brake pads.

Figure 46 shows the brake pad installation location and a photographic comparison of brake pads that have and have not been glazed. As a result of this observation during the first test, the brake pads were burnished in advance, the heating rate was modified and the final test procedure includes a cycling heat exposure, rather than a constant exposure.

An additional baseline test was taken to tire failure and subsequent fire. In this test, instead of attempting to apply maximum torque for maximum duration, maximum torque was applied for shorter durations and the entire assembly was brought to an elevated temperature more slowly and brake fade was avoided. This allowed the development of a much higher temperature of the overall wheel assembly than observed in the first test.

At the end of this test, while the wheel was coasting to a stop, a catastrophic blowout of the test tire was observed, which led to a small fire as a result of the tire being blown onto the hot components of the brake assembly, as well as the grease from the failed bearing. This fire was immediately suppressed and not allowed to develop. This event provides input to the development of a reasonable upper limit to observe sensor activation. Figure 47 provides a photograph of the stationary thermocouple locations on the torque plate and also various photographs of the wheel well test fixture components after this event. Figure 48 and Figure 49 provides selected data from this test.
Figure 47. Wheel Well Test Photographs: Top Left: Torque Plate Thermocouple Locations, Top Right: Just After Blowout, Bottom Left: Wheel Removed, Note Sheared Rotor Hub Assembly, Bottom Right: Rotor Hub Removed, Note Failed Bearing.

Figure 48. Heat Input Data from Tire Blowout/Fire Test.
6.5 Brake Glazing and Recommended Burnishing Procedure

After brake glazing was observed in initial baseline and vendor testing, the topic was investigated to determine a way to burnish the brake pads that would allow their extended use during this testing. The objective is to provide the best chance to supply maximum torque through the system. If possible, it would be a simpler test procedure to apply maximum torque until sensor activation or fire. However, this might not be a realistic objective.

Several options were considered for burnishing (or breaking-in) of the brake pads. Most brake pad manufacturers have recommendations for an abbreviated burnishing procedure. In addition, it was determined that there is a DOT precedent for burnishing pads in FMVSS 121D, Laboratory Test Procedure for Air Brake Systems – Dynamometer, TP-121D-01. This is an approval test procedure for evaluating air brake systems on a dynamometer.

There is a burnishing procedure in Section 12 of this document. An excerpt of this procedure is as follows:

*Place the brake assembly on an inertia dynamometer and adjust the brake as recommended by the brake manufacturer. Make 200 stops from 40 mph at a deceleration of 10 ft/s/s, with an initial brake temperature on each stop of not less than 315 °F and not more than 385 °F. Make 200 additional stops from 40 mph at a deceleration of 10 ft/s/s, with an initial brake temperature on each stop of not less than 450°F and not more than 550°F.*

The proposed test fixture in this project is not a commercial dynamometer, however, it is possible to follow this basic procedure and provide this standardized
burnishing. This procedure requires the use of a brake pad thermocouple. This is briefly described in Section 6.3 of this report, but additional detail is provided here. A single Type K thermocouple is installed in the nominal center of the brake pad material of the brake pad on the piston side of the disk brake assembly. Figure 50 provides a photograph array of the brake pad thermocouple location and installation.

![Figure 50. Brake Pad Thermocouple Location and Construction.](image)

This full burnishing procedure was followed prior to the first test for Vendor B. An abbreviated burnishing test was carried out prior to the second test for Vendor B. The abbreviated procedure was the same as the full procedure, except the number of cycles at each temperature range was changed from 200 to 20. Figure 51 – Figure 54 shows the heat input and stationary temperatures measured during these two burnishing tests.
Figure 51. Full Burnishing – Heat Input.

Figure 52. Full Burnishing – Stationary Temperatures.
In the first test for Vendor B, it was attempted to apply maximum torque for an extended period and observe whether brake glazing still occurred. Although, these
brake pads were fully burnished, brake glazing was still observed after approximately 10 min, as can be observed in Figure 61.

For the second test for Vendor B, an abbreviated burnishing procedure was utilized and a cycling approach to the heat input as show in Figure 48. Since it did not appear that brake glazing could be completely avoided, it would be beneficial to show that an abbreviated burnishing procedure could still be useful in an aggressive cycling approach. In addition, burnishing the brake pads in some standardized way prior to each sensor evaluation test should add repeatability and reproducibility to the test procedure.

As can be seen in Figure 55 and Figure 56, the heat was able to be continuously added to the system through several cycles until a maximum stationary temperature (top of torque plate) was achieved that indicates a tire fire was imminent, at which point, the test was aborted.

![Figure 55. Vendor B: Test 2 – Abbreviated Burnishing – Heat Input.](image)
Based on this testing and the discussion above, it will be recommended to perform the abbreviated burnishing procedure prior to each sensor evaluation test and the heat input procedure will be cyclical, rather than constant.

6.6 Aluminum versus Steel Wheels

Both aluminum and steel wheels were tested. For vendor A only steel wheels were used. For the other vendors both steel and aluminum wheels were tested.

To show the difference in the temperature response of aluminum vs. steel wheels both short duration and long duration tests were conducted. Short duration tests had heat input for about 20 minutes and dissipated about 40 MJ of energy. Figure 57 shows that the aluminum wheel heated somewhat faster than the steel wheel, but the difference is small. Due to the smaller amount of energy dissipated (compared to a longer test), the peak temperatures were less than 270 °C, which is well below the nominal tire ignition temperature.
Figure 57. Comparison of Steel and Aluminum Wheel Temperatures in Short Test.

Figure 58 shows the long duration tests where the heat input was applied for up to 46 minutes and the total heat input was 70 MJ. The stationary temperatures for steel and aluminum were about the same with only about a minute of time difference. These temperatures reached 400 °C, however, the tire was not in contact with the stationary parts, so no ignition would have occurred. The rotating temperatures only got to about 260 °C, which is well below the ignition temperature. For these tests the rotating temperatures were determined by an optical IR sensor. These signals are noisier because the sensor saw the hot disk brake rotor through the holes in the wheel. This is especially noticeable when the wheel RPM is slowing down and stopping.
Based on these results and the majority use of aluminum wheels on motorcoaches, it is recommended in the final procedure to conduct tests with aluminum wheels.

6.7 Wheel Well Vendor Testing

This section provides a detailed summary of one representative test for each vendor, followed by an overall summary of all the tests conducted. The three wheel well vendors are completely different companies from the three engine compartment detection and suppression system vendors.

For each of the tests 4 major quantities were reported:

1. Tire speed (MPH) (computed for wheel RPM – usually 60 MPH);
2. Torque (N-m) (computed from motor calibration curves)
3. Power (kW) (rate of heat dissipation – computed from torque and wheel RPM); and

6.7.1 Vendor A Test Results

Test Device Description

The Tire Pressure Monitoring System (TPMS) sensor was mounted on the valve stem. The sensor has short spacers (“feet”) on the bottom so that it doesn’t directly contact the metal rim. This partially isolates the sensor from the temperature of the metal parts, and allows the sensor to measure the tire air temperature – which is what is needed for the TPMS compensated tire pressure measurement. There may be some
conduction of heat to the sensor from the valve stem. There was a radio frequency (RF) connection to the electronic control unit (ECU). Several RF receiving antennas were attached to the safety cage about 15 feet from the tire being tested. The software was programmed to issue a hot wheel warning at 80 °C. The software was also programmed to issue a warning if there is a rapid pressure loss of more than 0.483 bar/min.

Test Results

The test was performed on May 20, 2014. The ambient temperature was 27 °C. All the tests for this vendor were done with steel wheels. Data recording and tire rotation was begun. See Figure 59. The tire rotation rate was equivalent to 60 MPH on the road. The air disk brake pressure was increased until the motor current was approximately 150 Amps. This occurred at approximately 20 psig. This corresponds to a torque of about 2700 N-m. The heat dissipation rate by the brake was approximately 135 kW. The total heat input during the test was approximately 35 MJ.

![Figure 59. Vendor A Heat Input Data.](image)

After about 5 minutes of heat input, the torque dropped to near zero because of brake pad glazing. Therefore the subsequent heat input power was near zero. A subsequent test showed that the torque could not be maintained under glazing conditions even at a brake pressure of 100 psig.

See Figure 60 for the summary of performance results. Plotted is the maximum stationary temperature measured (at the top of the torque plate) and the maximum rotating temperature (measured on the back of the wheel rim closest to the hot rotor). Also plotted in green are the temperature measurements from the Vendor A sensor.
Note that they lag the temperature measurements mounted on stationary and rotating metallic parts closer to the brake pad heat source. This implies that the sensor was measuring the temperature of the air in the tire and not the metal rim. It can be seen that the sensor output ramps up in a staircase fashion. This is because the sensor only reports to the ECU once a minute until an alarm code is received. Then it increases to a 1 Hz scan rate.

![Vendor A Temperature Data](image)

**Figure 60. Vendor A Temperature Data.**

The alarm was activated at approximately 7 min into the test. At this time the temperature of the stationary sensor was 290 °C, and the temperature of the rotating sensor was 160 °C. These temperatures are well below that of the tire ignition temperature of 400 °C. The temperature rise of the vendor sensor was rapid, and if the alarm set temperature was 100 °C (20 C above the nominal set point) the alarm time would only increase by about one minute.

This test shows that the Vendor A system can adequately warn the driver in advance of a tire fire. But it is important that the driver act quickly to stop the motorcoach and let the wheel cool. Appendix J can be referenced for additional summary plots for Vendor A.

### 6.7.2 Vendor B Test Results

**Test Device Description**

The TPMS tested is still under development and not yet available commercially. The sensor is embedded in a round rubber casing about the size of a hockey puck. It is designed to be adhesively mounted on the inside tread surface of the tire. An RF link sends the data to a Central Control Unit (CCU) which contains the receiving antenna.
and the receiver. An additional antenna/receiver unit can be installed for axles that are far to the rear. The electronic output signal is transmitted to a dedicated driver's display. The driver's display can be toggled between a display of tire pressure and a display of tire temperature. A preset high temperature alarm was set for 115 °C. If activated, the display provides an audible and flashing light alarm.

Test Results

The test was conducted on June 18, 2014. To prevent brake pad glazing the brake pads were burnished. The test duration was about 50 min with heat applied in two segments – the first about 20 min long, and the second about 3 min long. Figure 61 shows that the tire speed was 60 mph, the max torque was about 1500 N-m, and the heat input was about 75 kW.

![Figure 61. Vendor B Heat Input Data.](image)

Figure 61 shows the maximum stationary and rotating temperatures as well as the vendor sensor temperature as a function of time. The vendor sensor display readings were videotaped and subsequently transcribed into Excel to provide this plot.

For this test, an alarm was not received before the test was terminated. The stationary temperature was 330 °C, and the maximum rotating temperature was 245 °C. At the time of the peak temperatures experienced in this test (approximately 17 minutes) the vendor temperature sensor was reading only 30 °C. The highest temperature the sensor recorded near the end of the test was approximately 68 °C.

If the alarm sensor was set to a lower temperature, e.g., 60 °C, then an alarm would have been received. But this temperature may be so low that the false alarm rate would be unacceptably high. It is likely that the tread of the tire is just too far away from the heat source (the hot rim), and has a lot of air-cooling from the tire rotation. This result in no way detracts from the primary function of this sensor, which is compensated
tire pressure monitoring. Appendix K can be referenced for additional summary plots for Vendor B.

Figure 62. Vendor B Temperature Data.

6.7.3 Vendor C Test Results

Test Device Description

This TPMS is mounted on the part of the wheel closest to the wheel hub and bearing. It is held in place by a long stainless steel strap (like a long radiator hose clamp) and tightening device. The sensor has short spacers ("feet") on the bottom so that it doesn’t directly contact the metal rim. This partially isolates the sensor from the temperature of the metal parts, and allows the sensor to sense the tire air temperature – which is what is needed for the TPMS compensated tire pressure measurement. There was an RF connection to the Electronic Control Unit (ECU). The RF receiving antennas were located approximately 15 feet from the tire being tested. The software was programmed to issue a hot wheel warning at 85 °C.

Test Results

Three tests were performed on June 24 – June 26, 2014. Test 1 is reported in this section. Figure 63 shows the test inputs. You can see that there were four periods of heating. The first was about 5 minutes in duration – followed by three small heat input bursts of about 1 min each. The tire rotation was equivalent to 60 MPH. The torque was about 1600 N-m and the input power was about 75 kW. The total energy released in the test was about 39 MJ.
Figure 63. Vendor C Heat Input Data.

The temperature results are shown in Figure 64. Two different vendor sensors were tested. Sensor 1 is the commercial sensor which has higher “feet” under it, and thus is less coupled to the metal wheel. Sensor 2 is a device under development which has shorter feet and thus responds more quickly to wheel heating. The temperature alarm set point was 85 °C. You can see that sensor 1 triggered at approximately 18 minutes, and sensor 2 at approximately 11 minutes. At the time of the sensor 1 alarm, the max stationary and rotating temperatures were 250 °C and 180 °C, respectively. At the time of the sensor 2 alarm the stationary and rotating temperatures were 240 °C and 150 °C, respectively.
Figure 64. Vendor C Temperature Data.

Note that the temperatures continued to rise after each heat cycle. Sensor 2, with the shorter feet, triggered about 7 min earlier than Sensor 1, and thus would provide more warning time to the driver. Note that the stationary temperatures are well below the nominal tire ignition temperature – so either sensor should be adequate to provide warning. Appendix L can be referenced for additional summary plots for Vendor C.

6.7.4 Summary

Table 11 shows a summary of the heat input characteristics for all tests. The test procedure slowly evolved to an initial heat input of approximately 3 to 6 minutes, followed by a series of nominal one minute cycles of heat input. Some of the tests were “short” about 20 min, and others long about 40 min, depending on the response of the sensor under test. The max torque was about 1600 N-m, and the max power dissipated was from 75 to 80 kW, with the exception of the first calibration and Vendor A test with extreme brake glazing. The total energy dissipated was about 40 MJ for the shorter tests and 70 MJ for the longer tests.

<table>
<thead>
<tr>
<th>Test number</th>
<th>Type of wheel</th>
<th>Duration to end of heat input (min)</th>
<th>Number of heating pulses</th>
<th>Duration of pulses (min)</th>
<th>Max Torque (N-m)</th>
<th>Max Power (kW)</th>
<th>Total Energy Dissipated (MJ)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Steel</td>
<td>5</td>
<td>1</td>
<td>5</td>
<td>3100</td>
<td>150</td>
<td>150</td>
<td>43</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>The brake pads glazed on this test and the applied torque dropped to near zero after less than 6 minutes of exposure</td>
</tr>
<tr>
<td>2 Aluminum</td>
<td>45</td>
<td>24</td>
<td>3,2,then 22 cycles of 1 min each</td>
<td>1600</td>
<td>87</td>
<td>95</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Brake pads started glazing at 45 minutes and the test was ended at 50 minutes.</td>
</tr>
<tr>
<td>1 Steel</td>
<td>5</td>
<td>1</td>
<td>4</td>
<td>2800</td>
<td>154</td>
<td>39</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Brake pads glazed, no burnishing</td>
</tr>
<tr>
<td>2 Steel</td>
<td>45</td>
<td>16</td>
<td>1 or 2 min.</td>
<td>1700</td>
<td>70</td>
<td>68</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>No burnishing, tire burst at end when bead separated from rim</td>
</tr>
<tr>
<td>1 Aluminum</td>
<td>19</td>
<td>3</td>
<td>1,3,1</td>
<td>1600</td>
<td>75</td>
<td>42</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Full burnishing</td>
</tr>
<tr>
<td>2 Aluminum</td>
<td>40</td>
<td>9</td>
<td>6,then 8 cycles of 1 min each</td>
<td>1600</td>
<td>80</td>
<td>68</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Abbreviated burnishing</td>
</tr>
<tr>
<td>3 Steel</td>
<td>46</td>
<td>16</td>
<td>4,then 15 cycles of 1-min each</td>
<td>1700</td>
<td>80</td>
<td>73</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Abbreviated burnishing</td>
</tr>
<tr>
<td>1 Aluminum</td>
<td>21</td>
<td>5</td>
<td>5,1,1,1,1</td>
<td>1600</td>
<td>75</td>
<td>39</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Abbreviated burnishing</td>
</tr>
<tr>
<td>2 Steel</td>
<td>20</td>
<td>9</td>
<td>3,1,1,1,1,1</td>
<td>1600</td>
<td>80</td>
<td>36</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>,1, 1,1,2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Abbreviated burnishing</td>
</tr>
<tr>
<td>3 Aluminum</td>
<td>18</td>
<td>14</td>
<td>3,then 13 cycles of 1-min each</td>
<td>1500</td>
<td>75</td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Abbreviated burnishing</td>
</tr>
</tbody>
</table>

Table 12 shows a summary of the selected vendor test results. Two of the three systems provided alarms in advance of dangerous temperatures near the rubber tire. In most cases the rate of temperature rise is rapid, which means that a higher set temperature will not substantially increase the time to alarm. This result can be used to reduce the rate of false alarms.

Table 12. Summary of Selected Wheel Well Vendor Test Results.
<table>
<thead>
<tr>
<th></th>
<th>Vendor A</th>
<th>Vendor B</th>
<th>Vendor C (Sensor 1)</th>
<th>Vendor C (Sensor 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot Wheel Alarm Activated?</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Sensor Set Point (°C)</td>
<td>80</td>
<td>115</td>
<td>85</td>
<td>85</td>
</tr>
<tr>
<td>Maximum Rotating Temperature at Alarm (°C)</td>
<td>160</td>
<td>245</td>
<td>180</td>
<td>150</td>
</tr>
<tr>
<td>Maximum Stationary Temperature at Alarm (°C)</td>
<td>280</td>
<td>330</td>
<td>250</td>
<td>240</td>
</tr>
<tr>
<td>Vendor Sensor Temperature at Alarm (°C)</td>
<td>80</td>
<td>30</td>
<td>94</td>
<td>85</td>
</tr>
<tr>
<td>Nominal Time at Alarm (min)</td>
<td>7</td>
<td>No Alarm</td>
<td>18</td>
<td>11</td>
</tr>
<tr>
<td>Nominal Time at Alarm + 10 °C (min)</td>
<td>8</td>
<td>No Alarm</td>
<td>20</td>
<td>12</td>
</tr>
<tr>
<td>Nominal Time at Alarm + 20 °C (min)</td>
<td>8</td>
<td>No Alarm</td>
<td>No Alarm</td>
<td>13</td>
</tr>
</tbody>
</table>

### 6.8 Wheel Well Test Procedure and Test Criteria

The following test procedure and test criteria were developed for evaluating hot wheel early warning systems in motorcoach wheel wells.

- The early warning system is installed per manufacturer specifications.
- The test utilizes an aluminum wheel (Size: 22.5 × 8.25) and either a new or used tire (Size: 315/8OR22.5). The tire is pressurized with air to 30 psig (for safety reasons).
- The test is conducted at a tire rotation speed equivalent to 60 mph.
- The brake pads are burnished per the abbreviated procedure discussed in Section 6.5 of this report.
- The brakes are applied in order to input heat into the system until the brake pad temperature reaches 750 °C. Subsequent cycles from 650 – 750 °C are administered until sensor activation or until the maximum stationary temperature reaches 400 °C.
- If the sensor does not activate prior the maximum stationary temperature reaching 400 °C, the test is aborted and the sensor considered to have failed this evaluation.
• If the sensor activates, one additional heating cycle is performed, the wheel stopped, and the final observations made of additional heating and final sensor temperature.

• During the final cool down period, the fixture is monitored and during this time, if the maximum stationary temperature exceeds 400 °C, the sensor is considered to have failed this evaluation. If the stationary temperature remains below 400 °C during the cool down period, the sensor is considered to have passed this evaluation.

• Additional details about the test procedure and criteria are referenced in Appendix M.

7.0 FIRE HARDENING EVALUATION METHOD DEVELOPMENT

The objective of this topic is to develop test methods and performance criteria to assess effectiveness of fire-hardening materials in preventing or delaying fire propagation from the engine compartment or a wheel well into the passenger compartment.

7.1 Fire Hardening Background

A significant amount of research has been conducted on this topic by NIST [3], including large/full-scale tests on a motorcoach assembly and measurement of the time it takes for fire to penetrate into the passenger compartment from a wheel well fire (tire fire). In this research, several hardening materials were tested to see how the time was affected.

In their project, NIST looked at replacement of combustible motorcoach siding material above the wheel well and below the windows of the passenger compartment (fender and additional exterior siding panel). The replacement materials or modifications included steel, intumescent fire protection schemes (where a carbon foam is created to provide thermal insulation), and a fire plume deflector. While steel and the intumescent coating were effective at preventing or delaying fire spread into the passenger compartment, the fire plume deflector that would ideally direct the flame out and away from the bus was not.

One missing piece from the NIST work was a way to relate the times to fire penetration in full-scale to a laboratory-scale test method, so that new products and materials could be evaluated for this application.

The focus of this task is to recommend a standard fire test method that can be used to evaluate fire hardening materials and can also be related to the original NIST work.

7.2 Fire-Hardening Fire Test Methods

Several test methods were considered to evaluate suitability of materials for motorcoach fire hardening. The elements of the test methods that were considered in selecting a suitable test method included: cost of setup and/or to conduct test, scalability of test method, and the ability of the test method to be related to conditions seen in full scale tests.

One intermediate-scale test method was chosen and one bench-scale test method were chosen for this purpose. The same nominal materials that were tested by NIST were tested in these two apparatuses/procedures and the results are compared to obtain a relationship between small, intermediate and full-scale test data.
Additional details about these methods are provided below and the full test matrix and results from the data analysis are provided in subsequent sections of this report.

7.2.1 General Approach
For organic solids, liquids, and gases, a nearly constant net amount of heat is released per unit mass of oxygen consumed for complete combustion. An average value for this constant of 13.1 MJ/kg of O2 can be used for practical applications and is accurate with very few exceptions to within ±5%. Therefore, measurements of the oxygen consumed in a combustion system can be used to determine the net heat released. This technique, generally referred to as the “oxygen consumption technique”, is now the most widely used and accurate method for measuring heat release rate (HRR) in experimental fires.

The HRR of the NIST experiments was measured with the oxygen consumption technique and so this is the same method used in the two standard test procedures discussed below. It was expected that this particular quantity would able to be scaled between the NIST data and the standard test method data.

7.2.2 Cone Calorimeter Test Method
The Cone Calorimeter is a bench-scale test apparatus, which measures the rate of heat release of materials and products under a wide range of conditions using the oxygen consumption technique. A schematic of the instrument is shown in Figure 65. Other useful information obtained from Cone Calorimeter tests includes time to ignition, mass loss rate, smoke production rate, and effective heat of combustion.

In the Cone Calorimeter, a square sample measuring 100 × 100 mm (4 × 4-in.) is exposed to the radiant flux of an electric heater. The heater is in the shape of a truncated cone and is capable of providing heat fluxes to the specimen in the range of 0–100 kW/m². An electric spark igniter is used for piloted ignition of the pyrolysis gases produced by the radiant heater.

Figure 65. Schematic of the Cone Calorimeter Apparatus.
Test specimens are to be representative of the product’s end use and can have a maximum thickness of 50 mm (2 in.). Specimens with a thickness of less than 6 mm are to be tested using a substrate that is representative of end-use conditions. Prior to testing, the test specimen is wrapped in aluminum foil, backed with a layer of low-density refractory fiber blanket, and placed in a standard specimen holder. An optional edge frame can be used to retain the sample within the specimen holder during testing. A load cell is used to measure the mass loss of the specimen throughout the duration of the test.

At the start of a test, the specimen (in the appropriate holder) is placed on the load cell, which is located below the heater. The top edge of the specimen is typically positioned 25 mm below the base plate of the heater. The electric spark igniter is located 13 mm above the center of the specimen. Four seconds after the pyrolysis gases released by the specimen ignite; the electric spark igniter is removed.

The products of combustion and entrained air are collected in a hood and extracted through an exhaust duct by a fan. A gas sample is drawn from the exhaust duct and analyzed for oxygen concentration. The gas temperature and differential pressure across an orifice plate are used for calculating the mass flow rate of the exhaust gases. Smoke production is determined based on the measured light obscuration in the duct using a laser photometer located close to the gas sampling point.


The following terms and abbreviations are used in the Cone Calorimeter test results:

- \( t_{ig} \) time to ignition/sustained flaming (flame over specimen surface for at least 4 s)
- Test Duration total test duration (time from the start of test until any flaming or other signs of combustion cease, the average mass loss over a 1-min period has dropped below 150 g/m², or until 60 min have elapsed)
- C-Factor calibration constant for oxygen consumption analysis (m\(^{1/2}\) - kg\(^{1/2}\) - K\(^{1/2}\))
- \( HRR_{\text{peak}} \) maximum value of the heat release rate per unit area (kW/m²)
- THR total amount of heat released per square meter (MJ/m²)
- \( HRR_{60s} \) average heat release rate over the first 60 s (1 min) after ignition
- \( HRR_{180s} \) average heat release rate over the first 180 s (3 min) after ignition
- \( HRR_{300s} \) average heat release rate over the first 300 s (5 min) after ignition
- \( HRR_{30s, \text{max}} \) the maximum 30-s sliding average of the heat release rate per unit area (kW/m²)
- Initial Mass the initial mass of the test specimen, prior to testing (g)
- Mass at Ignition the mass of the test specimen at the time of sustained ignition (g)
• Final Mass  the mass of the test specimen at the end of the test (g)
• Mass Loss  total specimen mass loss over the test (g/m²)
• MLR  average specimen mass loss rate per unit area (g/m²·s) computed over the test duration
• 10-90 MLR  average specimen mass loss rate per unit area (g/m²·s) computed over the period starting when 10% of the specimen mass loss occurred and ending when 90% of the specimen mass loss occurred
• EHC  effective heat of combustion (the ratio of heat release rate to mass loss rate–MJ/kg) averaged over the test duration or the entire test if ignition does not occur
• \( S_{A,1} \)  smoke production per unit area of exposed specimen (m²/m²) prior to ignition
• \( S_{A,2} \)  smoke production per unit area of exposed specimen (m²/m²) from ignition until flameout or the end of the test; equal to zero if ignition does not occur
• \( S_A \)  total smoke production per unit area of exposed specimen during the test duration (\( S_{A,1} + S_{A,2} \))
• SEA  specific smoke extinction area (the ratio of smoke production to specimen mass loss–m²/kg) averaged over the test duration.

7.2.3 Parallel Panel Test Method

The Parallel Panel test method is standardized in Section 4.0 of ANSI/FM 4910, *American National Standard for Cleanroom Materials Flammability Test Protocol (October 2013)*. This specific standard is applicable to materials in cleanrooms, but the same basic parallel panel approach is also used in FM 4880, which is applicable to exterior wall systems. The derivation of the method is discussed in detail by FM Research [14]. The method was developed to relate intermediate-scale test results to full-scale fire test performance, in terms of material flammability (ignition and flame spread).

The 8-ft Parallel Panel Fire Test exposes two 2 × 8-ft (w × h) samples placed 1 ft apart to the effects of a 1 × 2-ft propane gas sand burner with an output of 60 kW for a 10-min duration followed by a 2 min observation period. The panel assembly is located on a load cell capable of measuring mass loss throughout the test. The test is performed under a calorimeter in order to measure heat release and smoke release rates during the test. Additionally, heat flux is measured at a height of 4 ft on the surface of one panel at the vertical centerline. In these specific tests, the backside temperature of the test assembly was also measured, although this is not required. Visual measurements of the flame height are recorded using digital video and still photographs.

The heat release rate is measured using the oxygen consumption technique. The gas temperature and differential pressure across a bi-directional probe are measured for calculating the mass flow rate of the exhaust gases. The smoke release rate is determined by the measured light obscuration in the exhaust duct using a vertically-oriented, white-light extinction photometer located close to the gas sampling point. Figure 66 shows a schematic of the parallel panel test apparatus.
7.3 Fire Hardening Test Plan

Several materials were tested in both the Cone Calorimeter and the Parallel Panel test apparatus. NIST performed four tests that utilized glass-reinforced plastic (GRP) exterior paneling. They conducted an additional test with the GRP coated with Pitt Char XP and an additional test with a sheet steel panel, instead of a combustible material, like the GRP panel. For this project, the same nominal materials used in the NIST work were tested, along with a few additional materials.

The following materials were used for fire hardening testing:

- GRP Sandwich Panel – donated by motorcoach OEM
  - Nominal thickness: 8.85 mm
  - Color: gray outer with white foam core
- Galvanized Sheet Metal Panel – donated by motorcoach OEM
  - Nominal thickness: 1.28 mm
  - Color: Silver with Green primer paint
- Gypsum Wallboard – obtained locally
  - Nominal thickness: 16 mm
  - Color: pink paper face
- Red Oak Plywood – obtained locally
  - Nominal thickness: 18.72 mm
o Color: natural wood (brown/tan)

- Pitt Char XP – obtained locally from a PPG, Industries, Inc. distributor
  - Each of the four materials above was tested with and without a Pitt Char XP coating.
  - PPG application instructions for troweling on the coating were followed and a nominal 150-200 mil (4-5 mm) coating thickness was applied to each material.

### 7.4 Fire Hardening Test Results

#### 7.4.1 Cone Calorimeter Testing

Cone calorimeter heat release rate testing was performed at an incident heat flux of 50 kW/m$^2$. Additional ignition testing was conducted to determine the critical heat flux for ignition (CHF) and the material’s thermal response parameter (TRP).

The TRP is a measure of the thermal inertia of a material (product of thermal conductivity, density, and specific heat). It is calculated by plotting the inverse square root of the ignition time versus the external heat flux and fitting a line through the data points. The inverse of the slope of this line is defined as the TRP. The fire propagation index (FPI) is a measure of full-scale flame spread propensity and is calculated based on ignition data (TRP) and HRR data (peak HRR). In general, fire performance is inversely proportional to the FPI. In other words, products with bad fire performance (high flame spread) typically have high FPI values. The FPI is calculated based on the following equation:

\[
FPI = \frac{1000(0.042 \cdot Q_{\text{peak}})^{1/3}}{\text{TRP}}, \text{ where}
\]

- \( Q_{\text{peak}} \) = peak heat release rate in cone at 50 kW/m$^2$ (kW/m$^2$);
- \( \text{TRP} \) = thermal response parameter (kW·s$^{1/2}$/m$^2$);

Figure 67 – Figure 70 provide the TRP plots for each material tested in the cone calorimeter.
**Figure 67. TRP Plot for GRP.**

**Figure 68. TRP Plot for Coated Galvanized Sheet Metal.**
Table 13 provides a summary of the cone calorimeter test results.
Table 13. Summary of Cone Calorimeter Fire Hardening Test Results.

<table>
<thead>
<tr>
<th>Test Material</th>
<th>CHF (kW/m²)</th>
<th>TRP (kW-s¹/₂/m²)</th>
<th>HRR&lt;sub&gt;peak&lt;/sub&gt; (kW/m²)</th>
<th>FPI (m⁵/₃/kW²/₃-s¹/₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncoated</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GRP Panel</td>
<td>13</td>
<td>446</td>
<td>342</td>
<td>5.45</td>
</tr>
<tr>
<td>Galvanized Sheet Metal</td>
<td>ND</td>
<td>ND</td>
<td>9</td>
<td>ND</td>
</tr>
<tr>
<td>Gypsum Wallboard</td>
<td>33</td>
<td>286</td>
<td>101</td>
<td>5.66</td>
</tr>
<tr>
<td>Red Oak Plywood</td>
<td>16</td>
<td>256</td>
<td>300</td>
<td>9.09</td>
</tr>
</tbody>
</table>

ND: not determined, this material is noncombustible, so these parameters cannot be calculated for the uncoated specimens.
Table 13. Summary of Cone Calorimeter Fire Hardening Test Results (continued).

<table>
<thead>
<tr>
<th>Test Material</th>
<th>CHF (kW/m²)</th>
<th>TRP (kW-s^{1/2}/m²)</th>
<th>HRR_{peak} (kW/m²)</th>
<th>FPI (m^{5/3}/kW^{2/3}·s^{1/2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coated with Pitt Char XP</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GRP Panel</td>
<td>19</td>
<td>270</td>
<td>156</td>
<td>6.93</td>
</tr>
<tr>
<td>Galvanized Sheet Metal</td>
<td>19</td>
<td>244</td>
<td>151</td>
<td>7.59</td>
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<tr>
<td>Gypsum Wallboard</td>
<td>22</td>
<td>238</td>
<td>153</td>
<td>7.81</td>
</tr>
<tr>
<td>Red Oak Plywood</td>
<td>21</td>
<td>270</td>
<td>148</td>
<td>6.81</td>
</tr>
</tbody>
</table>

It can be noted from Table 13 that the Pitt Char XP coating is able to reduce the peak heat release rate for all the materials that have some combustibility. The sheet metal and gypsum wallboard peak heat release rate actually increases with the Pitt Char XP coating application since these materials are inherently non-combustible (with exception to the paper face on the gypsum wallboard and very thin primer paint coat on the sheet metal).

It can be observed that for this data set, the FPI term does not seem to be a good indicator of better fire performance. This is primarily due to the fact that the Pitt Char XP coating is combustible and will ignite and spread flame. This skews the data slightly as the TRP typically goes down for the coated materials, but not as much as the heat release rate goes down, which inflates the FPI term.

A greater benefit of the Pitt Char XP coating in this data set can be seen for combustible materials, such as the GRP and red oak plywood. In the case of these materials, the peak heat release rate can be reduced by a factor of 2. Based on these observations, further analysis of the peak heat release rate is used to compare to full-scale fire spread data.

Full sets of cone calorimeter data can be referenced in Appendix N.
7.4.2 Parallel Panel Testing

Parallel Panel testing was conducted in general accordance with FM 4910. All samples were installed against a calcium silicate substrate and plywood backing. Heat flux was measured 4 ft from the bottom of one of the panels under test and an additional thermocouple was installed on the backside of the test assembly 4 ft from the bottom of the same panel.

Table 14 provides a summary of the parallel panel test results.

Table 14. Summary of Parallel Panel Fire Hardening Test Results.

<table>
<thead>
<tr>
<th>Test Material</th>
<th>HRR_{peak} (kW)</th>
<th>Time to HRR_{peak} (s)</th>
<th>Peak Heat Flux (kW/m²)</th>
<th>Peak Backside Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncoated</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GRP Panel</td>
<td>1196</td>
<td>146</td>
<td>111</td>
<td>100</td>
</tr>
<tr>
<td>Galvanized Sheet Metal</td>
<td>6</td>
<td>95</td>
<td>4</td>
<td>54</td>
</tr>
<tr>
<td>Gypsum Wallboard</td>
<td>5</td>
<td>96</td>
<td>5</td>
<td>44</td>
</tr>
<tr>
<td>Red Oak Plywood</td>
<td>365</td>
<td>113</td>
<td>60</td>
<td>72</td>
</tr>
<tr>
<td>Coated with Pitt Char XP</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GRP Panel</td>
<td>82</td>
<td>184</td>
<td>41</td>
<td>65</td>
</tr>
<tr>
<td>Galvanized Sheet Metal</td>
<td>72</td>
<td>187</td>
<td>28</td>
<td>62</td>
</tr>
<tr>
<td>Gypsum Wallboard</td>
<td>106</td>
<td>193</td>
<td>35</td>
<td>87</td>
</tr>
<tr>
<td>Red Oak Plywood</td>
<td>66</td>
<td>148</td>
<td>22</td>
<td>38</td>
</tr>
</tbody>
</table>

It can be noted from Table 14 that the Pitt Char XP coating has a similar effect on the materials in intermediate-scale. It increases the peak heat release rate for mostly noncombustible materials, but reduces it dramatically for combustible materials. Full sets of parallel panel data can be referenced in Appendix O. Figure 71 – Figure 73 show a few selected photographs from the fire hardening testing in the Parallel Panel test apparatus.
Figure 71. Parallel Panel Test – Left: Setup, Right: Peak HRR (Uncoated GRP Material Shown).

Figure 72. Parallel Panel Test – Left: Setup, Right: Peak HRR (Uncoated Sheet Metal Material Shown).
7.5 Fire Hardening Data Analysis

7.5.1 NIST Testing

Table 6 provides a summary of the tests that NIST conducted and the results.

Table 15. Summary of NIST Test Results.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Test Material</th>
<th>$HRR_{peak}$ (kW)</th>
<th>Time to $HRR_{peak}$ (s)</th>
<th>$HRR / Time to Peak$ (kW/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>GRP Panel (Tag Axle)</td>
<td>1175</td>
<td>280</td>
<td>4.2</td>
</tr>
<tr>
<td>2</td>
<td>GRP Panel (Drive Axle)</td>
<td>1480</td>
<td>363</td>
<td>4.1</td>
</tr>
<tr>
<td>3</td>
<td>Galvanized Sheet Metal</td>
<td>391</td>
<td>2464</td>
<td>0.2</td>
</tr>
<tr>
<td>4</td>
<td>GRP Panel Coated with Pitt Char XP</td>
<td>1043</td>
<td>1946</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Table 15. Summary of NIST Test Results (continued).

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Test Material</th>
<th>$HRR_{peak}$ (kW)</th>
<th>Time to $HRR_{peak}$ (s)</th>
<th>$HRR / Time to Peak$ (kW/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>GRP Panel with Steel Deflector above Fender</td>
<td>1136</td>
<td>588</td>
<td>1.9</td>
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<tr>
<td>6</td>
<td>GRP Panel (Tag Axle – Tenability Experiment)</td>
<td>950</td>
<td>679</td>
<td>1.4</td>
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</table>

Figure 74 plots the time to penetrate the passenger compartment versus heat release rate. It can be noted that there is not a clear demarcation in terms of heat release rate between good performers and bad performers, with respect to gaining time to penetration. However, Figure 75 plots the time to penetration versus the ratio of heat release rate to the time to penetration. In this plot it can be observed that there seems to be a demarcation between good and bad performers for an approximate ratio of $HRR/time=1$.

![Figure 74. NIST Data Plot – Time versus HRR.](image-url)
7.5.2 Predicting Full-Scale Test Results (Time to Penetration)

Table 16 shows a comparison of data between the NIST results and testing in the cone calorimeter and parallel panel test apparatuses. Figure 76 and Figure 77 show plots of the parallel panel and cone peak heat release rate versus NIST time to penetration.

Table 16. Comparison of NIST, Parallel Panel and Cone Test Results.

<table>
<thead>
<tr>
<th>Test Material</th>
<th>Parallel Panel $HRR_{peak}$ (kW)</th>
<th>Cone Calorimeter $HRR_{peak}$ (kW)</th>
<th>NIST Time to Penetration (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRP Panel (Tag Axle)</td>
<td>1196</td>
<td>342</td>
<td>280</td>
</tr>
<tr>
<td>GRP Panel (Drive Axle)</td>
<td>1196</td>
<td>342</td>
<td>363</td>
</tr>
</tbody>
</table>
Table 16. Comparison of NIST, Parallel Panel and Cone Test Results (continued).

<table>
<thead>
<tr>
<th>Test Material</th>
<th>Parallel Panel $HRR_{peak}$ (kW)</th>
<th>Cone Calorimeter $HRR_{peak}$ (kW)</th>
<th>NIST Time to Penetration (s)</th>
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<tbody>
<tr>
<td>Galvanized Sheet Metal</td>
<td>6</td>
<td>9</td>
<td>2464</td>
</tr>
<tr>
<td>GRP Panel Coated with Pitt Char XP</td>
<td>82</td>
<td>156</td>
<td>1946</td>
</tr>
<tr>
<td>GRP Panel with Steel Deflector above Fender</td>
<td>1196</td>
<td>342</td>
<td>588</td>
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<tr>
<td>GRP Panel (Tag Axle – Tenability Experiment)</td>
<td>1196</td>
<td>342</td>
<td>679</td>
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</tbody>
</table>

Figure 76. Parallel Panel Peak Heat Release Rate versus NIST Time to Penetration.
Figure 77. Cone Calorimeter Peak Heat Release Rate versus NIST Time to Penetration.

The blue diamonds in Figure 76 and Figure 77 represent direct comparison between NIST data and SwRI data either in the Parallel Panel test or in the Cone Calorimeter test. The red squares represent calculated data based on the linear regression of the blue data. These data are highlighted in yellow in each figure. These data could be used as a test for future additional full-scale test results in order to refine/validate the smaller-scale models.

There is a limited amount of full-scale data to rigorously evaluate this relationship between cone calorimeter and parallel panel test results with the results NIST obtained. However, it seems likely that a relationship does exist and could be refined if more full-scale data were made available.

As a screening tool, a limit between propagating and non-propagating performing materials may be on the order of 200 kW in the Parallel Panel test or 200 kW/m² in the Cone Calorimeter test.

### 7.6 Fire Hardening Recommended Test Criteria

It is likely that more research is necessary to recommend final test criteria. However, the following recommended screening criteria have been developed for evaluating fire hardening materials.

- Testing may be performed in general accordance with FM 4910 (Parallel Panel) or ASTM E1354 (Cone Calorimeter).
- If testing is performed in the Cone Calorimeter, the incident heat flux must be 50 kW/m².
In order to evaluate a material as ‘propagating’ and performing in a similar manner to typical exterior GRP materials in a tire fire, the peak heat release rate measured in the Parallel Panel test and Cone Calorimeter test will be greater than 200 kW and 200 kW/m², respectively.

In order to evaluate a material as ‘non-propagating’ and performing in a similar manner to typical exterior sheet metal materials in a tire fire, the peak heat release rate measured in the Parallel Panel test and Cone Calorimeter test will be less than or equal to 200 kW and 200 kW/m², respectively.

8.0 Final Observations

8.1 Engine Compartment

8.1.1 Observations

The following observations can be made about the engine compartment test procedure and fixture used to evaluate detection and suppression systems.

- The SwRI team designed, fabricated, and commissioned a simulated motorcoach engine compartment fixture. It is representative of the motorcoaches currently sold in the United States. It is larger than those used typically in Europe, but has comparable air flow.

- The fixture contains a substantial amount of obstructions to simulate the major components (including the engine) and various hoses, pipes, and electrical wires.

- The suppression systems of three vendors were tested. Two vendors tested both with detection systems and suppression systems. Linear Thermal Detectors were most frequently used, however, optical detectors were also used. The third vendor used a compressed air foam suppression system (no detection).

- It may be necessary to have a hybrid system with two different suppressants to extinguish all the fires as well as meet the re-ignition criteria.

- The distributed pool fire test with the fan running appears to be the most challenging test, based on vendor testing.

- Criteria are proposed for successfully completing this series of 12 engine compartment fire tests.

8.2 Wheel Well

8.2.1 Observations

The following observations can be made about the wheel well test procedure and fixture used to evaluate hot wheel early warning devices.

- The SwRI wheel well test fixture uses a dragging brake to deposit enormous amounts of heat into the wheel assembly. It is capable of raising both rotating and stationary parts of the wheel assembly to high temperatures.

- There are several commercially available TPMS’s that are capable of detecting a hot wheel and alerting the driver before the tire catches fire.
• Most motorcoach OEMs that sell in the United States are now installing TPMS’s as optional or standard equipment.

• The inside of the tire tread does not seem to be a good location to measure hot wheels for this simulated fire scenario.

• There are several locations where a simple thermocouple sensor on a stationary component can detect a hot wheel far in advance of a tire fire. But this solution does not provide high or low tire pressure warnings.

• It is important to train drivers to stop the motorcoach after receiving a hot wheel warning.

8.3 **Fire Hardening**

8.3.1 Observations
The following observations can be made about the fire hardening test procedures used to evaluate fire hardening materials.

- A relationship seems to exist between time to flame penetration into the passenger compartment in full-scale tests conducted by NIST [3] and data gathered in a bench-scale (Cone Calorimeter) and intermediate-scale (Parallel Panel) test apparatus.

- A screening heat release rate value of 200 kW or 200 kW/m² can be used to indicate a potential propagating or non-propagating fire hardening material in the Parallel Panel or Cone Calorimeter test apparatus, respectively.
APPENDIX A
REFERENCES
(CONSISTING OF 1 PAGE)
REFERENCES


APPENDIX B
ENGINE COMPARTMENT TEST FIXTURE DRAWINGS
(CONSISTING OF 74 PAGES)
SOME COMPONENTS NOT SHOWN FOR CLARITY

PRELIMINARY
NOT FOR PRODUCTION
SOME COMPONENTS NOT SHOWN FOR CLARITY

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SEE DETAIL A

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2) UNLESS OTHERWISE STATED:
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   b. FACES ALL SHARP CORNERS AND SHARP EDGES R .010 MAXIMUM
   c. MACHINED SURFACE FINISHES SHALL BE 125 MICROINCH OR BETTER
   d. TAP DRILL DEPTHS SHOWN ARE MAXIMUM
   e. FULL THREADS SHOWN ARE MINIMUM
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SECTION B-B

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3X 4"X.5"X.188 W CHANNEL IRON

4X 2"X .25"X1" ANGLE IRON

4X 1.5"X0.5" X .125" CHANNEL IRON

2"X1"X 125" CHANNEL IRON

3"X1.5"X.25" CHANNEL IRON

2X 1.5"X0.5" X .125" CHANNEL IRON

4 EA
GENERAL NOTES

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2) UNLESS OTHERWISE STATED:
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   e. FULL THREAD DEPTHS SHOWN ARE MINIMUM
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      d. TAP DRILL DEPTHS SHOWN ARE MAXIMUM
      e. FULL THREAD DEPTHS SHOWN ARE MINIMUM
      f. CHAMFER ALL TAPED HOLES TO (NOMINAL DIA 4 1/16) x 90°
   c. FINISH:

SOUTHWEST RESEARCH INSTITUTE
OFFICE OF AUTOMOTIVE ENGINEERING
6220 CULEBRA ROAD  SAN ANTONIO, TX 78238

WALL, FRONT RIGHT

APPROVED FOR PRODUCTION

DRAWING TITLE
17914-100-202
GENERAL NOTES

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2) UNLESS OTHERWISE STATED:
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   d. TAP DRILL DEPTHS SHOWN ARE MAXIMUM
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APPROVAL SIGNATURES

SOUTHWEST RESEARCH INSTITUTE
OFFICE of AUTOMOTIVE ENGINEERING
6200 CULEBRA ROAD - SAN ANTONIO, TEXAS 78238

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B 26401 17914-100-203 A
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SOUTHWEST RESEARCH INSTITUTE
OFFICE OF AUTOMOTIVE ENGINEERING
6220 CULEBRA ROAD  SAN ANTONIO, TEXAS 78238

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APPROVAL SIGNATURES

B. SHULTZ  DRFT  08-02-13
J. HURCZEK  PROJ  08-04-14
C. WRAY  DSN  INITIAL RELEASE

GENERAL NOTES

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APPROVED FOR PRODUCTION
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   c. MACHINED SURFACE FINISHES SHALL BE 125 MICROINCH OR BETTER
   d. TAP DRILL DEPTHS SHOWN ARE MAXIMUM
   e. FULL THREAD DEPTHS SHOWN ARE MINIMUM
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<td>1</td>
<td>BACK WALL</td>
<td>3/16 STEEL PLATE WELDMENT</td>
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</table>

SOUTHWEST RESEARCH INSTITUTE
OFFICE OF AUTOMOTIVE ENGINEERING
6297 CALLERA ROAD  SAN ANTONIO, TEXAS 78238

WALL, BACK LOWER SIDE

APPROVED FOR PRODUCTION
**General Notes**

1) Do not scale this drawing.
2) Unless otherwise stated:
   a. All dimensioning and tolerancing is in inches per ASME Y14.5-2009.
   b. Break all sharp corners and sharp edges to .010 maximum.
   c. Machined surface finishes shall be 125 microinches or better.
   d. Tap drill depths shown are maximum.
   e. Full thread depths shown are minimum.
   f. Chamfer all tapped holes to (nominal dia + 1/16) x 90°.

3) Finish: permanently mark with part number approved for production.

**Bill of Material/Parts List**

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Material/Specification/Notes</th>
<th>Item</th>
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<td>2</td>
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---

**SOUTHWEST RESEARCH INSTITUTE**

Office of Automotive Engineering
6220 Culebra Road
San Antonio, Texas 78238

**WALL, BACK TOP HALF**

B 26401 17914-100-206 A
1) DO NOT SCALE THIS DRAWING
2) UNLESS OTHERWISE STATED:
   a. ALL DIMENSIONING AND TOLERANCING IS IN INCHES PER ASME Y14.5-2009
   b. BREAK ALL SHARP CORNERS AND SHARP EDGES R .010 MAXIMUM
   c. MACHINED SURFACE FINISHES SHALL BE 125 MICROINCH OR BETTER
   d. TAP DRILL DEPTHS SHOWN ARE MAXIMUM
   e. FULL THREAD DEPTHS SHOWN ARE MINIMUM
   f. CHAMFER ALL TAPED HOLES TO (NOMINAL DIA + 1/16) x 90°
3) FINISH:

---

**GENERAL NOTES**

- DRAWING TITLE: LEFT WALL
- SIZE: 3/16" STEEL PLATE WELDMENT
- DRAWING NUMBER: 17914-100-207

**BILL OF MATERIAL/PARTS LIST**

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<td>LEFT WALL</td>
<td>3/16&quot; STEEL PLATE WELDMENT</td>
</tr>
</tbody>
</table>

---

**APPROVAL SIGNATURES**

- J. HURCZEK
  - DSGN
- C. WRAY
  - CHKD
- B. SCHULTZ
  - DRFT

**DEFAULT TOLERANCES**

- ONE PLACE (.01) ± .0 .01
- TWO PLACES (.001) ± .00 .001
- THREE PLACES (.0001) ± .000 .00001
- FOUR PLACES (.00001) ± .0000 .0000005

**FINISH:**

- PERMANENTLY MARK WITH PART NUMBER

---

**SCALE 0.500**

---

**APPROVED FOR PRODUCTION**
GENERAL NOTES:
1) DO NOT SCALE THIS DRAWING
2) UNLESS OTHERWISE STATED:
   a. ALL DIMENSIONING AND TOLERANCING IS IN INCHES PER ASME Y14.5-2009
   b. BREAK ALL SHARP CORNERS AND SHARP EDGES R .010 MAXIMUM
   c. MACHINED SURFACE FINISHES SHALL BE 125 MICROINCH OR BETTER
   d. TAP DRILL DEPTHS SHOWN ARE MAXIMUM
   e. FULL THREAD DEPTHS SHOWN ARE MAXIMUM
   f. CHAMFER ALL TAPPED HOLES TO (NOMINAL DIA x 1/16) x 90°
3) FINISH:
   - THREE PLACES (X.XXX) = # 0.005
   - TWO PLACES (X.XX) = # 0.01
   - ONE PLACE (X.X) = # 0.1

BILL OF MATERIAL/PARTS LIST

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<td>DAMPER PLATE-1</td>
<td>13/16&quot; STEEL PLATE WELDMENT</td>
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</table>

APPROVED FOR PRODUCTION

SOUTHWEST RESEARCH INSTITUTE
OFFICE OF AUTOMOTIVE ENGINEERING
6220 CULEBRA ROAD  SAN ANTONIO, TEXAS 78238

PLATE, VENT DAMPER
GENERAL NOTES

1) DO NOT SCALE THIS DRAWING
2) UNLESS OTHERWISE STATED:
   a. ALL DIMENSIONING AND TOLERANCING IS IN INCHES PER ASME Y14.5-2009
   b. BREAK ALL SHARP CORNERS AND SHARP EDGES R .010 MAXIMUM
   c. MACHINED SURFACE FINISHES SHALL BE 125 MICROINCH OR BETTER
   d. TAP DRILL DEPTHS SHOWN ARE MAXIMUM
   e. FULL THREAD DEPTHS SHOWN ARE MINIMUM
   f. CHAMFER ALL TAPED HOLES TO (NOMINAL DIA + 1/16) x 90°
3) FINISH

BILL OF MATERIAL/PARTS LIST

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<td>13/16&quot; STEEL PLATE WELDMENT WALL-1</td>
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SOUTHWEST RESEARCH INSTITUTE
OFFICE OF AUTOMOTIVE ENGINEERING
6200 CULEBRA ROAD     SAN ANTONIO, TEXAS 78238
GENERAL NOTES
1) DO NOT SCALE THIS DRAWING
2) UNLESS OTHERWISE STATED:
   a. ALL DIMENSIONS AND TOLERANCING IS 1 IN. INCHES PER ASME Y14.5-2009
   b. BREAK ALL SHARP CORNERS AND SHARP EDGES R .010 MAXIMUM
   c. MACHINED SURFACE FINISHES SHALL BE 125 MICROINCH OR BETTER
   d. TAP DRILL DEPTH SHOWN ARE MAXIMUM
   e. FULL THREAD DEPTH SHOWN ARE MINIMUM
   f. CHAMFER ALL TAPED HOLES TO (NOMINAL DIA + 1/16) x 90°
3) FINISH:

3/16" STEEL PLATE WELDMENT

BILL OF MATERIAL/PARTS LIST

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</table>

SOUTHWEST RESEARCH INSTITUTE
OFFICE OF AUTOMOTIVE ENGINEERING
6220 CULEBRA ROAD       SAN ANTONIO, TEXAS 78238

WALL, UPPER TOP HAT

APPROVED FOR PRODUCTION
GENERAL NOTES:

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2) UNLESS OTHERWISE STATED:
   a. ALL DIMENSIONING AND TOLERANCING IS IN INCHES PER ASME Y14.5-2009
   b. BREAK ALL SHARP CORNERS AND SHARP EDGES R .010 MAXIMUM
   c. MACHINED SURFACE FINISHES SHALL BE 125 MICROINCH OR BETTER
   d. TAP DRILL DEPTHS SHOWN ARE MAXIMUM
   e. FULL THREADED DEPTHS SHOWN ARE MAXIMUM
   f. CHAMFER ALL TAPED HOLES TO NOMINAL DIA + 1/16 x 90°
3) FINISH:
   a. PERMANENTLY MARK WITH PART NUMBER
   b. PERMANENTLY MARK WITH PART NUMBER

BILL OF MATERIAL/PARTS LIST

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<tr>
<th>ITEM</th>
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<td>13/16&quot;</td>
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</table>

SOUTHWEST RESEARCH INSTITUTE
OFFICE OF AUTOMOTIVE ENGINEERING
6229 CULEBRA ROAD, SAN ANTONIO, TEXAS 78238

WALL, REAR TOP HAT

APPROVED FOR PRODUCTION
GENERAL NOTES

1) DO NOT SCALE THIS DRAWING
2) UNLESS OTHERWISE STATED:
   a. ALL DIMENSIONING AND TOLERANCING IS IN INCHES PER ASME Y14.5-2009
   b. BREAK ALL SHARP CORNERS AND SHARP EDGES R .010 MAXIMUM
   c. MACHINED SURFACE FINISHES SHALL BE 125 MICROINCH OR BETTER
   d. TAP SHANK GEOMETRY SHOWN ARE MAXIMUM
   e. FULL THREAD DOTTING SHOWN ARE MINIMUM
   f. CHAMFER ALL TAPPED HOLES TO (NOMINAL DIA + 1/16) x 90°
   g. 3:1 FINISH

BILL OF MATERIAL/PARTS LIST

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3) FINISH:
   a. PERMANENTLY MARK WITH PART NUMBER

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APPROVED FOR PRODUCTION

APPROVAL SIGNATURES

SOUTHWEST RESEARCH INSTITUTE
OFFICE of AUTOMOTIVE ENGINEERING
6220 CULEBRA ROAD SAN ANTONIO, TEXAS 78238

WALL, TOP CENTER

B 26401 17914-100-213 A
GENERAL NOTES:
1) DO NOT SCALE THIS DRAWING
2) UNLESS OTHERWISE STATED:
   a. ALL DIMENSIONING AND TOLERANCING IS IN INCHES PER ASME Y14.5-2009
   b. SHEAR ALL SHARP CORNERS AND SHARP EDGES R = .010 MAXIMUM
   c. MACHINED SURFACE FINISHES SHALL BE 125 MICROINCH OR BETTER
   d. TAP DRILL DEPTHS SHOWN ARE MAXIMUM
   e. FULL THREAD DEPTHS SHOWN ARE MINIMUM
   f. CHAMFER ALL TAPED HOLES TO (NOMINAL DIA + 1/16) x 90°
3) FINISH:
   PERMANENTLY MARK WITH PART NUMBER

BILL OF MATERIAL/PARTS LIST

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<td>3/16&quot; STEEL PLATE WELDMENT</td>
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SOUTHWEST RESEARCH INSTITUTE
OFFICE OF AUTOMOTIVE ENGINEERING
6220 CULEBRA ROAD     SAN ANTONIO, TEXAS 78238
GENERAL NOTES

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   e. FULL THREAD DEPTHS SHOWN ARE MINIMUM
   f. CHAMFER ALL TAPPED HOLES TO (NOMINAL DIA + 1/16) x 90°
3) FINISH

QTY: 2 EACH

BILL OF MATERIAL/PARTS LIST

ITEM
1 WALL 3/16" STEEL PLATE WELDMENT

P/N DESCRIPTION MATERIAL/SPECIFICATION/NOTES
13/16" STEEL PLATE WELDMENT WALL-1

APPROVAL SIGNATURES

SOUTHWEST RESEARCH INSTITUTE
OFFICE OF AUTOMOTIVE ENGINEERING
6220 CALLEabra ROAD SAN ANTONIO, TEXAS 78238

WALL, FRONT CENTER

APPROVED FOR PRODUCTION
GENERAL NOTES

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   d. TAP DRILL DEPTHS SHOWN ARE MAXIMUM
   e. FULL THREAD DEPTHS SHOWN ARE MINIMUM
   f. CHAMFER ALL TAPED HOLES TO (NOMINAL DIA X 1/16") X 90°
3) FINISH:

APPROVED FOR PRODUCTION

BILL OF MATERIAL/PARTS LIST

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SOUTHWEST RESEARCH INSTITUTE
OFFICE OF AUTOMOTIVE ENGINEERING
6220 CULEBRA ROAD SAN ANTONIO, TEXAS 78238
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   d. FULL THREAD DEPTHS SHOWN ARE MINIMUM
   e. CHAMFER ALL TAPPED HOLES TO (NOMINAL DIA x 1/16) x 90°
   f. FINISH

REVISIONS

08-05-14 INITIAL RELEASE

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<td>APPROVAL SIGNATURES</td>
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APPROVED FOR PRODUCTION

SOUTHWEST RESEARCH INSTITUTE
OFFICE OF AUTOMOTIVE ENGINEERING
6250 CULEBRA ROAD, SAN ANTONIO, TEXAS 78238

WALL, FRONT RIGHT
1) DO NOT SCALE THIS DRAWING
2) UNLESS OTHERWISE STATED:
   a. ALL DIMENSIONING AND TOLERANCING IS IN INCHES PER ASME Y14.5-2009
   b. BREAK ALL SHARP CORNERS AND SHARP EDGES R .010 MAXIMUM
   c. MACHINED SURFACE FINISHES SHALL BE 125 MICROINCH OR BETTER
   d. TAP DRILL DEPTHS SHOWN ARE MAXIMUM
   e. FULL THREAD DEPTHS SHOWN ARE MINIMUM
   f. CHAMFER ALL TAPPED HOLES TO NOMINAL DIA x 1/16 x 90°
3) FINISH:
   i) PERMANENTLY MARK WITH PART NUMBER
   ii) FINISH:

**NOTICE:**
- APPROVED FOR PRODUCTION

**BILL OF MATERIAL/PARTS LIST**

**WALL, BOTTOM SIDE, LEFT**

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GENERAL NOTES

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   b. BREAK ALL SHARP CORNERS AND SHARP EDGES R .010 MAXIMUM
   c. WASHED SURFACE FINISHES SHALL BE .125 MICROINCH OR BETTER
   d. TAP DRILL DEPTHS SHOWN ARE MAXIMUM
   e. FULL THREAD DEPTHS SHOWN ARE MAXIMUM
   f. CHAMFER ALL TAPPED HOLES TO NOMINAL (DIA + 1/16) x 90°
3) FINISH:
   a. PERMANENTLY MARK WITH PART NUMBER

APPROVED FOR PRODUCTION

SOUTHWEST RESEARCH INSTITUTE
OFFICE OF AUTOMOTIVE ENGINEERING
6220 CULEBRA ROAD  SAN ANTONIO, TEXAS 78238

WALL BOTTOM CENTER

BILL OF MATERIAL/PARTS LIST

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APPROVAL SIGNATURES

B-29

FOR PRODUCTION
GENERAL NOTES

1) DO NOT SCALE THIS DRAWING
2) UNLESS OTHERWISE STATED
   a. ALL DIMENSIONING AND TOLERANCING IS IN INCHES PER ASME Y14.5-2009
   b. BREAK ALL SHARP CORNERS AND SHARP EDGES R .010 MAXIMUM
   c. MACHINED SURFACE FINISHES SHALL BE 125 MICROINCH OR BETTER
   d. TAPPED HOLE DEPTHS SHOWN ARE MAXIMUM
   e. FULL THREAD DEPTHS SHOWN ARE MINIMUM
   f. CHAMFER ALL TAPPED HOLES TO (NOMINAL DIA + 1/16) x 90°
3) FINISH:

PERMANENTLY MARK WITH PART NUMBER

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   a. ALL DIMENSIONING AND TOLERANCING IS IN INCHES PER ASME Y14.5-2009
   b. BREAK ALL SHARP CORNERS AND SHARP EDGES 0.010 MAXIMUM
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   d. TAP DRILL DEPTHS SHOWN ARE MAXIMUM
   e. FULL THREAD DEPTH SHOWN ARE MINIMUM
   f. CHAMFER ALL TAPED HOLES TO (NOMINAL DIA + 1/16) x 90°
3) FINISH:
   PERMANENTLY MARK WITH PART NUMBER

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**GENERAL NOTES**

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   a. ALL DIMENSIONING AND TOLERANCING IS IN INCHES PER ASME Y14.5-2009
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   d. TAP DRILL DEPTHS SHOWN ARE MAXIMUM
   e. FULL THREAD DEPTH SHOWN ARE MINIMUM
   f. CHAMFER ALL TAPED HOLES TO (NOMINAL DIA + 1/16) x 90°

**3) FINISH:**
   PERMANENTLY MARK WITH PART NUMBER
GENERAL NOTES

1) DO NOT SCALE THIS DRAWING
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   f. CHAMFER ALL TAPED HOLES TO (NOMINAL DIA + 1/16) x 90°
3) FINISH: PERMANENTLY MARK WITH PART NUMBER

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APPROVAL SIGNATURES

SOUTHWEST RESEARCH INSTITUTE
OFFICE OF AUTOMOTIVE ENGINEERING
6255 DULZORA ROAD, SAN ANTONIO, TEXAS 78238

WALL, FRONT TOP HAT

APPROVED FOR PRODUCTION
GENERAL NOTES

1) DO NOT SCALE THIS DRAWING
2) UNLESS OTHERWISE STATED:
   a. ALL DIMENSIONING AND TOLERANCING IS IN INCHES PER ASME Y14.5-2009
   b. BREAK ALL SHARP CORNERS AND SHARP EDGES R .010 MAXIMUM
   c. MACHINED SURFACE FINISHES SHALL BE 125 MICROINCH OR BETTER
   d. TAP DRILL DEPTHS SHOWN ARE MAXIMUM
   e. FULL THREAD DEPTHS SHOWN ARE MINIMUM
   f. CHAMFER ALL TAPPED HOLES TO (NOMINAL DIA 4 1/16) x 90°
3) FINISH:

APPROVED FOR PRODUCTION
GENERAL NOTES

1) DO NOT SCALE THIS DRAWING
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   a. ALL DIMENSIONING AND TOLERANCING IS IN INCHES PER ASME Y14.5-2009
   b. SHEAR ALL SHARP CORNERS AND SHARP EDGES R .010 MAXIMUM
   c. MACHINED SURFACE FINISHES SHALL BE 125 MICROINCH OR BETTER
   d. TAP DRILL DEPTHS SHOWN ARE MAXIMUM
   e. FULL THREAD DEPTHS SHOWN ARE MINIMUM
   f. CHAMFER ALL TAPED HOLES TO (NOMINAL DIA + 1/16) x 90°
3) FINISH:

Sheet 1 of 1
UNIT WEIGHT = 60 LBS
SCALE 6:100

STORAGE SPACE
FILE SURFACE FINISHES <= 125 MICROINCH RA
ANGLES = # 0.5 DEGREE
THRU CUT

BILL OF MATERIAL/PARTS LIST

<table>
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<tr>
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<tr>
<td>13/16&quot; STEEL PLATE BOX WELDMENT</td>
<td>BOX -1</td>
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</tbody>
</table>

APPROVED FOR PRODUCTION

SOUTHWEST RESEARCH INSTITUTE
OFFICE OF AUTOMOTIVE ENGINEERING
6220 CULEBRA ROAD SAN ANTONIO, TEXAS 78238

STORAGE SPACE

B-26
26401 17914-200-101 A
SCALE 3:100
UNIT REVERSE A
SHEET 1 OF 1
GENERAL NOTES

1) DO NOT SCALE THIS DRAWING
2) UNLESS OTHERWISE STATED:
   a. ALL DIMENSIONING AND TOLERANCING IS IN INCHES PER ASME Y14.5-2009
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   d. TAP DRILL DEPTHS SHOWN ARE MAXIMUM
   e. FULL THROAT DEPTHS SHOWN ARE MINIMUM
   f. CHAMFER ALL TAPPED HOLES TO (NOMINAL DIA + 1/16) x 90°
   g. FINISH:

   1) DO NOT SCALE THIS DRAWING
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      f. CHAMFER ALL TAPPED HOLES TO (NOMINAL DIA + 1/16) x 90°
      g. FINISH:

B 26401 17914-200-200 A
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1) DO NOT SCALE THIS DRAWING
2) UNLESS OTHERWISE STATED:
   a. ALL DIMENSIONING AND TOLERANCING IS IN INCHES PER ASME Y14.5-2009
   b. BREAK ALL SHARP CORNERS AND SHARP EDGES R .010 MAXIMUM
   c. MACHINED SURFACE FINISHES SHALL BE 125 MICROINCH OR BETTER
   d. TAP DETAIL DEPTHS SHOWN ARE MAXIMUM
   e. FULL THREAD DEPTHS SHOWN ARE MINIMUM
   f. CHAMFER ALL TAPED HOLES TO NOMINAL DIA + 1/16 x 90°
3) FINISH:

SECTION A-A

GENERAL NOTES
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   f. CHAMFER ALL TAPED HOLES TO NOMINAL DIA + 1/16 x 90°
3) FINISH:
**GENERAL NOTES**

1) **DO NOT SCALE THIS DRAWING**

2) **UNLESS OTHERWISE STATED:**
   a. ALL DIMENSIONING AND TOLERANCING IS IN INCHES PER ASME Y14.5-2009
   b. BRACKETS ALL SHARP CORNERS AND SHARP EDGES AT 0.010 MAXIMUM
   c. MACHINED SURFACE FINISHES SHALL BE 125 MICROINCH OR BETTER
   d. TAP DRILL DEPTHS SHOWN ARE MAXIMUM
   e. FULL THREAD DEPTHS SHOWN ARE MINIMUM
   f. CHAMFER ALL TAPPED HOLES TO (NOMINAL DIA + 1/16) x 90°

3) **FINISH:**
   - APPROVED FOR PRODUCTION

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   e. FULL THREAD DEPTHS SHOWN ARE MINIMUM
   f. CHAMFER ALL TAPED HOLES TO (NOMINAL DIA + 1/16) X 90°
3) FINISH:

ENGINE BLOCK SIMULATOR

BILL OF MATERIAL/PARTS LIST

ITEM | DESCRIPTION | MATERIAL/SPECIFICATION/NOTES
--- | --- | ---
1-1 | METAL BOX | 3/16" STEEL BOX WELDMENT

APPROVED FOR PRODUCTION

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OFFICE OF AUTOMOTIVE ENGINEERING
6220 CULEBRA ROAD   SAN ANTONIO, TEXAS 78238
GENERAL NOTES

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3) FINISH:

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<tr>
<td>1-1</td>
<td>C/LYMPER 3/16&quot; STEEL PIPE W/ CAPPED ENDS</td>
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**APPROVAL SIGNATURES**

- B SCHULTZ
- J HUCZEK
- C WRAY
- B 26401

**TURBO HEATER**

**COMPLETION DATE:** 08-05-13

**UNIT WEIGHT:** 0.500

**SCALE:** 1/16" = 1 FOOT
GENERAL NOTES

1) DO NOT SCALE THIS DRAWING
2) UNLESS OTHERWISE STATED:
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   d. TAP DRILL DEPTHS SHOWN ARE MAXIMUM
   e. FULL THREAD DEPTHS SHOWN ARE MINIMUM
   f. CHAMFER ALL TAPPED HOLES TO (NOMINAL DIA x 1/16) x 90°
3) FINISH:

SECTION A-A

SCALE 0.120

APPROVED FOR PRODUCTION

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SOUTHWEST RESEARCH INSTITUTE
OFFICE OF AUTOMOTIVE ENGINEERING
6220 CULEBRA ROAD SAN ANTONIO, TEXAS 78238

ALTERNATOR SIMULATOR

REVISIONS

DATE DESCRIPTION ZONES HT REV
08-05-14 INITIAL RELEASE A

B 26401 17914-300-304
GENERAL NOTES

1) DO NOT SCALE THIS DRAWING
2) UNLESS OTHERWISE STATED:
   a. ALL DIMENSIONING AND TOLERANCING IS IN INCHES PER ASME Y14.5-2009
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   d. TAP DRILL DEPTHS SHOWN ARE MAXIMUM
   e. FULL THREAD DEPTHS SHOWN ARE MAXIMUM
   f. CHAMFER ALL TAPED HOLES TO (NOMINAL DIA + 1/8) x 90°
3) FINISH:

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APPROVAL SIGNATURES

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<th>DEFAULT TOLERANCES</th>
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<tbody>
<tr>
<td>ONE PLACE 0.001 ± 0.0005</td>
<td>B. Schultz</td>
</tr>
<tr>
<td>TWO PLACES 0.003 ± 0.003</td>
<td>C. Wray</td>
</tr>
<tr>
<td>THREE PLACES 0.005 ± 0.005</td>
<td>C. Wray</td>
</tr>
<tr>
<td>FOUR PLACES 0.010 ± 0.005</td>
<td>C. Wray</td>
</tr>
<tr>
<td>ANGLES ± 0.5 DEGREE</td>
<td>C. Wray</td>
</tr>
<tr>
<td>SURFACE FINISHES 40-125 MICROINCH</td>
<td>B. Schultz</td>
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MANIFOLD HEATER ASSEMBLY

SOUTHWEST RESEARCH INSTITUTE
OFFICE OF AUTOMOTIVE ENGINEERING
6220 CULBERA ROAD  SAN ANTONIO, TEXAS  78238

APPROVED FOR PRODUCTION
GENERAL NOTES

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   a. ALL DIMENSIONING AND TOLERANCING IS IN INCHES PER ASME Y14.5-2009
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   c. MACHINED SURFACE FINISHES SHALL BE 125 MICROINCH OR BETTER
   d. TAP DRILL DEPTHS SHOWN ARE MAXIMUM
   e. FULL THREAD DEPTHS SHOWN ARE MINIMUM
   f. CHAMFER ALL TAPPED HOLES TO (NOMINAL DIA + 1/16) x 90°
3) FINISH:
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   e. FULL THREAD DEPTHS SHOWN ARE MINIMUM
   f. CHAMFER ALL TAPPED HOLES TO (NOMINAL DIA + 1/16) x 90°

3) FINISH:
   a. SURFACE FINISHES <= 125 MICROINCH RA
   b. ANGLES = # 0.5 DEGREE
   c. THREE PLACES (X.XXX) = # 0.005
   d. FOUR PLACES (X.XXXX) = # 0.0005

BILL OF MATERIAL/PARTS LIST

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<tr>
<td>1-1</td>
<td>3/16&quot; WALL PIPE W/CAPPED ENDS WELDMENT CYLINDER-1</td>
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APPROVAL SIGNATURES

SOUTHWEST RESEARCH INSTITUTE
OFFICE OF AUTOMOTIVE ENGINEERING
6220 CULEBRA ROAD     SAN ANTONIO, TEXAS 78238

RADIATOR SURGE TANK

DRAWING TITLE

SIZE CAGE DRAWING NUMBER

REV | DATE | DESCRIPTION | P/N |
--- |------|-------------|-----|
A | 12-04-14 | INITIAL RELEASE | |
A | 08-05-14 | APPROVED FOR PRODUCTION | |
GENERAL NOTES

1) DO NOT SCALE THIS DRAWING
2) UNLESS OTHERWISE STATED:
   a. ALL DIMENSIONING AND TOLERANCING IS IN INCHES PER ASME Y14.5-2009
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   d. TAPER DRILL DEPTHS SHOWN ARE MAXIMUM
   e. FULL THREAD DEPTHS SHOWN ARE MINIMUM
   f. CHAMFER ALL TAPPED HOLES TO (NOMINAL DIA + 1/16") x 90°
3) FINISH:

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APPROVED FOR PRODUCTION
**GENERAL NOTES**

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   d. **TAP DRILL DEPTHS SHOWN ARE MAXIMUM**
   e. **FULL THREAD DEPTHS SHOWN ARE MINIMUM**
   f. **CHAMFER ALL TAPPED HOLES TO (NOMINAL DIA + #1/16) X 90°**

3) **FINISH**

**APPROVAL SIGNATURES**

- **DEFAULT TOLERANCES**
  - ONE PLACE (X.X) = # 0.1
  - TWO PLACES (X.XX) = # 0.005
  - THREE PLACES (X.XXX) = # 0.0005
  - FOUR PLACES (X.XXXXX) = # 0.00005

- **ANGLES = ± 0.5° DEGREE**

- **SURFACE FINISHES = ≤ 125 MICROINCH RA**

- **COMPLETION DATE: 10-31-13**

- **MODEL: SCR DPF SIMULATOR**

---

**BILL OF MATERIAL/PARTS LIST**

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**REVISIONS**

- **DATE**
  - **INITIAL RELEASE: 08-05-14**

---

**APPROVED FOR PRODUCTION**
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3) FINISH

SOUTH WEST RESEARCH INSTITUTE
OFFICE OF AUTOMOTIVE ENGINEERING
6220 CULEBRA ROAD     SAN ANTONIO, TEXAS 78238

CONSUMABLE MODULE FRAME 2

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**CONSUMABLE MODULE 3**

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<tr>
<td>3</td>
<td>CONDUIT</td>
<td>5/8&quot; DIAMETER PVC CONDUIT, (OMITTED FROM TEST)</td>
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<tr>
<td>3</td>
<td>CONDUIT W/ WIRE</td>
<td>5/8&quot; PVC CONDUIT W/ WIRE, JAMECO #644463 (OMITTED FROM TEST)</td>
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<tr>
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<td>FRAME</td>
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**SPECIFICATIONS**

- **Surface Finish**: As-Machined
- **Tapped Holes**: As Drawn
- **Angles**: ± 0.5 degrees
- **Completion Date**: 01-10-14
- **Material**: Surface finish as-machined, tapped holes as drawn, angles ± 0.5 degrees

**BILL OF MATERIAL/PARTS LIST**

- **1** FRAME
- **4** HOSE
- **3** CONDUIT
- **3** CONDUIT W/ WIRE
- **1** SEE DRAWING 17914-1000-301

**APPROVED FOR PRODUCTION**

**SOUTHWEST RESEARCH INSTITUTE**
OFFICE OF AUTOMOTIVE ENGINEERING
6200 CULEBRA ROAD, SAN ANTONIO, TEXAS 78238
GENERAL NOTES

1) DO NOT SCALE THIS DRAWING
2) UNLESS OTHERWISE STATED:
   a. ALL DIMENSIONING AND TOLERANCING IS IN INCHES PER ASME Y14.5-2009
   b. AREA ALL SHARP CORNERS AND SHARP EDGES R .010 MAXIMUM
   c. MACHINED SURFACE FINISHES SHALL BE 125 MICROINCH OR BETTER
   d. TAP DRILL DEPTHS SHOWN ARE MAXIMUM
   e. FULL THREAD DEPTHS SHOWN ARE MINIMUM
   f. CHAMFER ALL TAPPED HOLES TO (NOMINAL DIA + 1/16) x 90°
3) FINISH:

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SOUTHWEST RESEARCH INSTITUTE
OFFICE OF AUTOMOTIVE ENGINEERING
6220 CULEBRA ROAD  SAN ANTONIO, TEXAS 78238
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3. FINISH:
   4X Ø0.406 THRU

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**SCALE 63:1000**

**APPROVED FOR PRODUCTION**

---

**SOUTHWEST RESEARCH INSTITUTE**

**OFFICE OF AUTOMOTIVE ENGINEERING**

6298 CULEBRA ROAD  \  SAN ANTONIO, TEXAS 78238
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<td>TRACK / FRAME</td>
<td>13/4&quot; X .120 W STEEL ROUND TUBING WELDENT</td>
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APPROVAL SIGNATURES

CONSUMABLE MODULE FRAME 5

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APPROVED FOR PRODUCTION

B-61

REV | SHEET NUMBERS | SHEET COUNT
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1   | 1-00-00-501    | A-01        
GENERAL NOTES

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   f. CHAMFER ALL TAPED HOLES TO (NOMINAL DIA + 1/16) x 90°

3) FINISH

SCALE 1:20

DRAWING TITLE
CONSUMABLE MODULE FRAME

FILE
SURFACE FINISHES <= 125 MICROINCH RA

COMPLETION DATE: 12-23-13

APPROWED FOR PRODUCTION

BILL OF MATERIAL/PARTS LIST

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<tr>
<td>3/4&quot; X .120 W STEEL ROUND TUBING WELDMENT</td>
</tr>
</tbody>
</table>

QTY: 4 EACH

SOUTHWEST RESEARCH INSTITUTE
OFFICE OF AUTOMOTIVE ENGINEERING
6220 CULEBRA ROAD     SAN ANTONIO, TEXAS 78238
GENERAL NOTES

1) DO NOT SCALE THIS DRAWING
2) UNLESS OTHERWISE STATED:
   a. ALL DIMENSIONING AND TOLERANCING IS IN INCHES PER ASME Y14.5-2009
   b. BREAK ALL SHARP CORNERS AND SHARP EDGES R .010 MAXIMUM
   c. MACHINED SURFACE FINISHES SHALL BE 125 MICROINCH OR BETTER
   d. TAP DRILL DEPTHS SHOWN ARE MAXIMUM
   e. FULL THREAD DEPTHS SHOWN ARE MINIMUM
   f. CHAMFER ALL TAPPED HOLES TO (NOMINAL DIA + 1/16) X 90°
3) FINISH:

QTY: 8 EACH
GENERAL NOTES

1) DO NOT SCALE THIS DRAWING
2) UNLESS OTHERWISE STATED:
   a) ALL DIMENSIONING AND TOLERANCING IS IN INCHES PER ASME Y14.5-2009
   b) RND ALL SHARP CORNERS AND SHARP EDGES R .010 MAXIMUM
   c) MACHINED SURFACE FINISHES SHALL BE 125 MICROINCH OR BETTER
   d) TAP OR DRILL DEPTHS SHOWN ARE MAXIMUM
   e) FULL THREAD DEPTHS SHOWN ARE MAXIMUM
   f) CHAMFER ALL TAPED HOLES TO (NOMINAL DIA + 1/16) x 90°
3) FINISH:
   SCALE 1:20

BILL OF MATERIAL/PARTS LIST

ITEM | DESCRIPTION | MATERIAL/SPECIFICATION | NOTES
--- | --- | --- | ---
1 | 3/4" X .120 W ROUND STEEL TUBING WELDMENT | FRAME / RACK | FRAME / RACK

APPROVAL SIGNATURES

SOUTHWEST RESEARCH INSTITUTE
OFFICE OF AUTOMOTIVE ENGINEERING
6250 CULEBRA ROAD SAN ANTONIO, TEXAS 78238

CONSUMABLE MODULE FRAME 7

REV | DATE | ZONE | CHKD | DRFT | DSGN | PROJ | HUCZEK | SCHULTZ | WRAY
--- | --- | --- | --- | --- | --- | --- | --- | --- | ---
A | 08-05-14 | A | A | A | A | A | A | B | A

CONSUMABLE MODULE FRAME 7

B 26401 17914-1000-701 A

APPROVED FOR PRODUCTION
MONARCH F-80, 15.5 GPH SPRAY NOZZLE
POWER STEERING FLUID SPRAY
SPRAY DIRECTION: REARWARD

PILOT LIGHT CUP

BILL OF MATERIAL/PARTS LIST

<table>
<thead>
<tr>
<th>ITEM</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>MONARCH F-80, 15.5 GPH SPRAY NOZZLE</td>
</tr>
</tbody>
</table>

POWER STEERING FLUID SPRAY

FIRE SCENARIO

SOUTHWEST RESEARCH INSTITUTE
OFFICE OF AUTOMOTIVE ENGINEERING
6220 CULEBRA ROAD
SAN ANTONIO, TEXAS 78238

APPROVED FOR PRODUCTION

B-67

REV | DATE | DESCRIPTION |
--- | --- | --- |
1 | 07-31-14 | INITIAL RELEASE
2 | 07-29-14 | COMPLETION DATE

APPROVAL SIGNATURES

B SCHULZ
J HUCZEK
B SCHULZ
J HUCZEK

DEFAULT TOLERANCES

ONE PLACE (X.X) = # 0.1
TWO PLACES (X.XX) = # 0.01
THREE PLACES (X.XXX) = # 0.005
FOUR PLACES (X.XXXX) = # 0.0005

ANGLES: ± 0.5 DEGREE
SURFACE FINISHES: 40 MICROINCH RMS
MONARCH SPRAY NOZZLE 10.0 GPH
SPRAYING DIESEL FUEL

PILOT FUEL CAN

BILL OF MATERIAL/PARTS LIST

<table>
<thead>
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<th>P/N</th>
<th>DESCRIPTION</th>
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<td>1-1</td>
<td></td>
<td>MONARCH SPRAY NOZZLE 10.0 GPH SPRAYING DIESEL FUEL</td>
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DIESEL SPRAY FIRE SCENARIO

SOUTH WEST RESEARCH INSTITUTE
OFFICE OF AUTOMOTIVE ENGINEERING
6220 CULEBRA ROAD
SAN ANTONIO, TEXAS 78238

APPROVAL SIGNATURES

DEPARTMENTS

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DIESEL SPRAY FIRE SCENARIO

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DIESEL SPRAY FIRE SCENARIO

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DIESEL SPRAY FIRE SCENARIO

SOUTH WEST RESEARCH INSTITUTE
OFFICE OF AUTOMOTIVE ENGINEERING
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DIESEL SPRAY FIRE SCENARIO

SOUTH WEST RESEARCH INSTITUTE
OFFICE OF AUTOMOTIVE ENGINEERING
6220 CULEBRA ROAD
SAN ANTONIO, TEXAS 78238

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DIESEL SPRAY FIRE SCENARIO

SOUTH WEST RESEARCH INSTITUTE
OFFICE OF AUTOMOTIVE ENGINEERING
6220 CULEBRA ROAD
SAN ANTONIO, TEXAS 78238

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DIESEL SPRAY FIRE SCENARIO

SOUTH WEST RESEARCH INSTITUTE
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6220 CULEBRA ROAD
SAN ANTONIO, TEXAS 78238

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<tr>
<td>1-1</td>
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<td>MONARCH SPRAY NOZZLE 10.0 GPH SPRAYING DIESEL FUEL</td>
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MONARCH SPRAY NOZZLE 10.0 GPH
ALTERNATE POSITION
HOT PLATE

BILL OF MATERIAL/PARTS LIST

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<th>ITEM</th>
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<th>MATERIAL/SPECIFICATION/NOTES</th>
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<td>1-1</td>
<td>HOT PLATE</td>
<td>APPROVED FOR PRODUCTION</td>
</tr>
</tbody>
</table>

DEFAULT TOLERANCES

- ONE PLACE (X.01) ± 0.01
- TWO PLACES (X.001) ± 0.001
- THREE PLACES (X.0001) ± 0.0001
- FOUR PLACES (X.00001) ± 0.00001

ANGLES = ± 0.5 DEGREE

SURFACE FINISHES = ± 125 MICROINCH RA
3 EACH PIPE INSULATION
1-3/8" ID X 1/2" WALL X 28"
PRE-SPRAYED WITH DIESEL FUEL

18" X 16"
EGG-CRATE FOAM
Plastic Insulation

OVER HEATED TO IGNITION CONTROL CABLE

4 EACH Plastic Tool Boxes
Simulating Batteries

BILL OF MATERIAL/PARTS LIST

<table>
<thead>
<tr>
<th>ITEM</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3 EACH, PIPE INSULATION</td>
</tr>
<tr>
<td>2</td>
<td>OVER HEATED TO IGNITION CONTROL CABLE</td>
</tr>
<tr>
<td>3</td>
<td>4 EACH PLASTIC TOOL BOXES SIMULATING BATTERIES</td>
</tr>
</tbody>
</table>

APPROVED FOR PRODUCTION

SOUTHWEST RESEARCH INSTITUTE
OFFICE OF AUTOMOTIVE ENGINEERING
6220 CULEBRA ROAD, SAN ANTONIO, TEXAS 78238

BATTERY COMPARTMENT FIRE SCENARIO

SOUTH WEST RESEARCH INSTITUTE
OFFICE OF AUTOMOTIVE ENGINEERING
6220 CULEBRA ROAD, SAN ANTONIO, TEXAS 78238

BILL OF MATERIAL/PARTS LIST

<table>
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<th>ITEM</th>
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<tbody>
<tr>
<td>1</td>
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</tr>
<tr>
<td>2</td>
<td>OVER HEATED TO IGNITION CONTROL CABLE</td>
</tr>
<tr>
<td>3</td>
<td>4 EACH PLASTIC TOOL BOXES SIMULATING BATTERIES</td>
</tr>
</tbody>
</table>

APPROVED FOR PRODUCTION
APPENDIX C
BENCH-SCALE MATERIAL FLAMMABILITY DATA FOR ENGINE
COMPARTMENT SOURCES
(CONSISTING OF 15 PAGES)
# Cone Calorimeter Test Report

**Client:** DOT/NHTSA  
**Material ID:** Polypropylene Plastic Sheet  
**SwRI Project No:** 01.17914  
**Heat Flux:** 50 kW/m²  
**Duct Flow:** 24 l/s  

**Orientation:** Horizontal  
**Sample Area:** 0.00884 m²  
**Distance:** 25 mm  
**Operator:** Abe Mata

## Test Results

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Test Date</th>
<th>t₀ (s)</th>
<th>Test Duration (s)</th>
<th>C-Factor (SI Units)</th>
<th>HRRₚₑᵃᵏ (kW/m²)</th>
<th>THR (MJ/m²)</th>
<th>HRR₆₀₀s (kW/m²)</th>
<th>HRR₁₈₀₀s (kW/m²)</th>
<th>HRR₃₀₀₀s (kW/m²)</th>
<th>HRR₃₀₀₀_max (kW/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14-238DOT-24</td>
<td>08/26/14</td>
<td>33</td>
<td>540</td>
<td>0.0419</td>
<td>114</td>
<td>124.9</td>
<td>251</td>
<td>536</td>
<td>407</td>
<td>1013</td>
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<tr>
<td>14-238DOT-25</td>
<td>08/26/14</td>
<td>32</td>
<td>481</td>
<td>0.0419</td>
<td>1271</td>
<td>130.7</td>
<td>247</td>
<td>602</td>
<td>430</td>
<td>1141</td>
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<tr>
<td>14-238DOT-26</td>
<td>08/26/14</td>
<td>32</td>
<td>537</td>
<td>0.0419</td>
<td>861</td>
<td>110.8</td>
<td>257</td>
<td>500</td>
<td>361</td>
<td>793</td>
</tr>
</tbody>
</table>

**Average**  
- Test ID: 14-238DOT-24  
- Test Date: 08/26/14  
- t₀: 32 s  
- Test Duration: 519 s  
- C-Factor: 0.0419  
- HRRₚₑᵃᵏ: 1092 kW/m²  
- THR: 122.2 MJ/m²  
- HRR₆₀₀s: 252 kW/m²  
- HRR₁₈₀₀s: 546 kW/m²  
- HRR₃₀₀₀s: 399 kW/m²  
- HRR₃₀₀₀_max: 982 kW/m²

## Initial and Final Masses

<table>
<thead>
<tr>
<th>Initial Mass (g)</th>
<th>Mass at Ignition (g)</th>
<th>Final Mass (g)</th>
<th>Mass Loss (g/m²)</th>
<th>MLR (g/m²-s)</th>
<th>10-90 MLR (g/m²-s)</th>
<th>EHC (MJ/m²)</th>
<th>Sₐ₁ (m²/m²)</th>
<th>Sₐ₂ (m²/m²)</th>
<th>Sₐ (m²/m²)</th>
<th>SEA (m²/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.2</td>
<td>30.1</td>
<td>2.8</td>
<td>3095</td>
<td>5.7</td>
<td>12.6</td>
<td>40.4</td>
<td>7</td>
<td>1773</td>
<td>1780</td>
<td>573</td>
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<tr>
<td>30.1</td>
<td>30.1</td>
<td>2.0</td>
<td>3177</td>
<td>6.5</td>
<td>15.9</td>
<td>41.1</td>
<td>0</td>
<td>1770</td>
<td>1771</td>
<td>557</td>
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<tr>
<td>30.1</td>
<td>30.8</td>
<td>4.0</td>
<td>2948</td>
<td>5.5</td>
<td>13.3</td>
<td>37.6</td>
<td>0</td>
<td>1575</td>
<td>1575</td>
<td>534</td>
</tr>
</tbody>
</table>

Initial: 30.1  
Final: 30.3  
Mass Loss: 3073 g  
MLR: 5.9 g/m²-s  
10-90 MLR: 13.9 g/m²-s  
EHC: 39.7 MJ/m²  
Sₐ₁: 3 m²/m²  
Sₐ₂: 1706 m²/m²  
Sₐ: 1709 m²/m²  
SEA: 555 m²/kg

## Heat Release Rate: Polypropylene Plastic Sheet

![Heat Release Rate Graph](image)
Client: DOT/NHTSA
SwRI Project No: 01.17914

Material ID: Polypropylene Plastic Sheet
Heat Flux: 50 kW/m²

**SMOKE PRODUCTION RATE: POLYPROPYLENE PLASTIC SHEET**

**SPECIMEN MASS: POLYPROPYLENE PLASTIC SHEET**

Notes & Observations:
CO PRODUCTION RATE: POLYPROPYLENE PLASTIC SHEET

Average CO Yield:
- 14-238DOT-24 - 0.045 kg/kg
- 14-238DOT-25 - 0.045 kg/kg
- 14-238DOT-26 - 0.041 kg/kg

CO₂ PRODUCTION RATE: POLYPROPYLENE PLASTIC SHEET

Average CO₂ Yield:
- 14-238DOT-24 - 2.703 kg/kg
- 14-238DOT-25 - 2.609 kg/kg
- 14-238DOT-26 - 2.557 kg/kg

Notes & Observations:
## Cone Calorimeter Test Report

**Client:** DOT/NHTSA  
**SwRI Project No:** 01.17914  
**Material ID:** ABS Plastic Sheet  
**Heat Flux:** 50 kW/m²  
**Duct Flow:** 24 l/s  
**Orientation:** Horizontal  
**Sample Area:** 0.00884 m²  
**Distance:** 25 mm  
**Operator:** Abe Mata

### Test Results

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Test Date</th>
<th>t₀ (s)</th>
<th>Test Duration (s)</th>
<th>C-Factor (SI Units)</th>
<th>HRR_peak (kW/m²)</th>
<th>THR (MJ/m²)</th>
<th>HRR_60s (kW/m²)</th>
<th>HRR_180s (kW/m²)</th>
<th>HRR_300s (kW/m²)</th>
<th>HRR₃₀₅ₐₓ (kW/m²)</th>
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<tbody>
<tr>
<td>14-141DOT-5</td>
<td>05/21/14</td>
<td>19</td>
<td>264</td>
<td>0.0449</td>
<td>1267</td>
<td>109.8</td>
<td>580</td>
<td>597</td>
<td>1091</td>
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<td>14-141DOT-6</td>
<td>05/21/14</td>
<td>21</td>
<td>286</td>
<td>0.0449</td>
<td>1350</td>
<td>112.7</td>
<td>621</td>
<td>614</td>
<td>1155</td>
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<td>14-141DOT-7</td>
<td>05/21/14</td>
<td>20</td>
<td>316</td>
<td>0.0449</td>
<td>1188</td>
<td>110.4</td>
<td>560</td>
<td>586</td>
<td>1060</td>
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</tr>
</tbody>
</table>

**Average:**  
|             | 20        | 289     | ---              | 1268               | 111.0           | 587         | 599            | N/A            | 1102           |

### Initial Masses

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<tr>
<th></th>
<th>Initial Mass at Ignition (g)</th>
<th>Final Mass Loss (g)</th>
<th>Mass Loss (g/m²)</th>
<th>MLR (g/m²-s)</th>
<th>10-90 MLR (g/m²-s)</th>
<th>EHC (MJ/kg)</th>
<th>Sₐ₁ (m²/m²)</th>
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<th>SEA (m²/kg)</th>
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</thead>
<tbody>
<tr>
<td>32.7</td>
<td>32.7</td>
<td>0.6</td>
<td>3628</td>
<td>13.6</td>
<td>29.0</td>
<td>30.3</td>
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<td>5587</td>
<td>5588</td>
<td>1540</td>
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<tr>
<td>33.0</td>
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<td>6</td>
<td>5598</td>
<td>5604</td>
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<td>30.3</td>
<td>0</td>
<td>5555</td>
<td>5555</td>
<td>1526</td>
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</tbody>
</table>

|          | 32.8                        | 32.9               | 0.7              | 3634          | 12.5             | 28.4        | 30.5        | 2           | 5580        | 5582        | 1536        |

### Heat Release Rate

**Heat Release Rate: ABS Plastic Sheet**

![Heat Release Rate Graph](image-url)
SOUTHWEST RESEARCH INSTITUTE
CONE CALORIMETER TEST REPORT

Client: DOT/NHTSA
SwRI Project No: 01.17914

Material ID: ABS Plastic Sheet
Heat Flux: 50 kW/m²

SMOKE PRODUCTION RATE: ABS PLASTIC SHEET

SPECIMEN MASS: ABS PLASTIC SHEET

Notes & Observations:
CO PRODUCTION RATE: ABS PLASTIC SHEET

Average CO Yield:
- 14-141DOT-5 - 0.088 kg/kg
- 14-141DOT-6 - 0.092 kg/kg
- 14-141DOT-7 - 0.087 kg/kg

CO₂ PRODUCTION RATE: ABS PLASTIC SHEET

Average CO₂ Yield:
- 14-141DOT-5 - 2.263 kg/kg
- 14-141DOT-6 - 2.335 kg/kg
- 14-141DOT-7 - 2.235 kg/kg

Notes & Observations:
**CONE CALORIMETER TEST REPORT**

**Client:** DOT/NHTSA  
**Material ID:** Egg-Crate Foam  
**SwRI Project No:** 01.17914  
**Heat Flux:** 50 kW/m²  
**Duct Flow:** 24 l/s  
**Orientation:** Horizontal  
**Sample Area:** 0.00884 m²  
**Frame:** Yes  
**Distance:** 25 mm  
**Operator:** Abe Mata

### Test Data

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Test Date</th>
<th>t_g (s)</th>
<th>Test Duration (s)</th>
<th>C-Factor (SI Units)</th>
<th>HRR_{peak} (kW/m²)</th>
<th>THR (MJ/m²)</th>
<th>HRR_{60s} (kW/m²)</th>
<th>HRR_{180s} (kW/m²)</th>
<th>HRR_{300s} (kW/m²)</th>
<th>HRR_{30s, max} (kW/m²)</th>
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<tbody>
<tr>
<td>14-141DOT-10</td>
<td>05/21/14</td>
<td>2</td>
<td>211</td>
<td>0.0449</td>
<td>406</td>
<td>23.5</td>
<td>272</td>
<td>130</td>
<td>352</td>
<td></td>
</tr>
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<td>14-141DOT-8</td>
<td>05/21/14</td>
<td>2</td>
<td>117</td>
<td>0.0449</td>
<td>416</td>
<td>19.8</td>
<td>286</td>
<td>109</td>
<td>352</td>
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<tr>
<td>14-141DOT-9</td>
<td>05/21/14</td>
<td>2</td>
<td>198</td>
<td>0.0449</td>
<td>397</td>
<td>22.7</td>
<td>260</td>
<td>125</td>
<td>345</td>
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</tr>
</tbody>
</table>

**Average**  
- t_g: 2  
- Test Duration: 175  
- C-Factor: 0.0449  
- HRR_{peak}: 407  
- THR: 22.0  
- HRR_{60s}: 273  
- HRR_{180s}: 121  
- HRR_{30s, max}: 350

### Initial and Final Mass

<table>
<thead>
<tr>
<th>Initial Mass (g)</th>
<th>Mass at Ignition (g)</th>
<th>Final Mass (g)</th>
<th>Mass Loss (g/m²)</th>
<th>MLR (g/m²-s)</th>
<th>MLR EHC (MJ/kg)</th>
<th>S_{A1} (m²/m²)</th>
<th>S_{A2} (m²/m²)</th>
<th>S_{A} (m²/m²)</th>
<th>SEA (m²/kg)</th>
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<tbody>
<tr>
<td>8.0</td>
<td>8.0</td>
<td>0.8</td>
<td>817</td>
<td>3.7</td>
<td>7.9</td>
<td>28.7</td>
<td>0</td>
<td>334</td>
<td>335</td>
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<tr>
<td>6.6</td>
<td>6.0</td>
<td>0.0</td>
<td>747</td>
<td>3.5</td>
<td>11.5</td>
<td>26.5</td>
<td>24</td>
<td>277</td>
<td>301</td>
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<tr>
<td>7.8</td>
<td>7.6</td>
<td>0.0</td>
<td>882</td>
<td>4.5</td>
<td>9.4</td>
<td>25.7</td>
<td>0</td>
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| 7.5             | 7.2                  | 0.3            | 815              | 3.9           | 9.6             | 27.0           | 8              | 326           | 334         | 398        |

---

**HEAT RELEASE RATE: EGG-CRATE FOAM**

![Heat Release Rate Graph](image-url)

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**Legend:**
- 14-141DOT-8
- 14-141DOT-9
- 14-141DOT-10
SMOKE PRODUCTION RATE: EGG-CRATE FOAM

SPECIMEN MASS: EGG-CRATE FOAM

Notes & Observations:
**CO PRODUCTION RATE: EGG-CRATE FOAM**

Average CO Yield:
- 14-141DOT-10 - 0.057 kg/kg
- 14-141DOT-8 - 0.012 kg/kg
- 14-141DOT-9 - 0.052 kg/kg

Notes & Observations:
Client: DOT/NHTSA  
Material ID: Pipe Foam Insulation  
SwRI Project No: 01.17914  
Heat Flux: 50 kW/m²  
Duct Flow: 24 l/s  
Orientation: Horizontal  
Sample Area: 0.00884 m²  
Frame: Yes  
Distance: 25 mm  
Spark Igniter: Yes  
Operator: Abe Mata

**CONE CALORIMETER TEST REPORT**

---

| Test ID | Test Date  | t₉ (s) | Test Duration (s) | C-Factor (SI Units) | C-Factor (MJ/m²) | THR (kW/m²) | HRR₉₀ (kW/m²) | HRR₁₈₀ (kW/m²) | HRR₃₀₀ (kW/m²) | HRR₃₀₅ (kW/m²) | Average MLR (g/m²) | Average (g/m²-s) | Average (m²/m²) | Average (kW/m²) | Average (kW/m²) | Average (kW/m²) | Average (kW/m²) | Average (kW/m²) |
|---------|------------|--------|-------------------|---------------------|------------------|-------------|--------------|---------------|----------------|----------------|-------------------|-----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 14-141DOT-11 | 05/21/14 | 3      | 85                | 0.0449              | 155              | 7.9          | 115           | 133           | | | | | | | | | |
| 14-142DOT-12 | 05/22/14 | 2      | 92                | 0.0415              | 135              | 6.9          | 98            | 118           | | | | | | | | | |
| 14-142DOT-13 | 05/22/14 | 2      | 80                | 0.0415              | 139              | 7.0          | 100           | 118           | | | | | | | | | |

**Average**

<table>
<thead>
<tr>
<th>Initial Mass (g)</th>
<th>Mass at Ignition (g)</th>
<th>Final Mass (g)</th>
<th>Mass Loss (g/m²)</th>
<th>MLR (g/m²-s)</th>
<th>10-90 MLR (MJ/m²)</th>
<th>EHC (m²/m²)</th>
<th>Sₐ₁ (m²/m²)</th>
<th>Sₐ₂ (m²/m²)</th>
<th>Sₐ (m²/m²)</th>
<th>SEA (m²/kg)</th>
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<td>6.8</td>
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<td>336</td>
<td>336</td>
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</tbody>
</table>

**HEAT RELEASE RATE: PIPE FOAM INSULATION**

- 14-141DOT-11
- 14-142DOT-12
- 14-142DOT-13

---

Initial Mass: 10-90 Mass Loss Ratio: 10-90 Heat Release Rate: 10-90
SMOKE PRODUCTION RATE: PIPE FOAM INSULATION

SPECIMEN MASS: PIPE FOAM INSULATION

Notes & Observations:
CO PRODUCTION RATE: Pipe Foam Insulation

Average CO Yield:
- 14-141DOT-11 - 0.061 kg/kg
- 14-142DOT-12 - 0.076 kg/kg
- 14-142DOT-13 - 0.087 kg/kg

CO₂ PRODUCTION RATE: Pipe Foam Insulation

Average CO₂ Yield:
- 14-141DOT-11 - 0.782 kg/kg
- 14-142DOT-12 - 0.96 kg/kg
- 14-142DOT-13 - 1.273 kg/kg

Notes & Observations:
CONE CALORIMETER TEST REPORT

Client: DOT/NHTSA  
Material ID: Battery Box Plastic
SwRI Project No: 01.17914  
Heat Flux: 50 kW/m²

Heat Flux: 24 l/s
Sample Area: 0.00884 m²

Orientation: Horizontal  
Sample Area: 0.00884 m²
Frame: Yes  
Distance: 25 mm
Spark Igniter: Yes  
Operator: Abe Mata

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Test Date</th>
<th>t_int (s)</th>
<th>Heat Duration (s)</th>
<th>C-Factor</th>
<th>THR (kW/m²)</th>
<th>THR (MJ/m²)</th>
<th>HRR_60s (kW/m²)</th>
<th>HRR_180s (kW/m²)</th>
<th>HRR_300s (kW/m²)</th>
<th>HRR_30s, max (kW/m²)</th>
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<tr>
<td>14-141DOT-2</td>
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<td>576</td>
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<td>885</td>
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<tr>
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<td>367</td>
<td>0.0449</td>
<td>1117</td>
<td>68.3</td>
<td>606</td>
<td>371</td>
<td>227</td>
<td>937</td>
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</table>

Average 26 418 --- 1067 68.6 591 368 227 911

<table>
<thead>
<tr>
<th>Initial Mass (g)</th>
<th>Mass at Ignition (g)</th>
<th>Mass Loss (g/m²)</th>
<th>MLR (g/m²-s)</th>
<th>10-90 MLR (MJ/m²)</th>
<th>EHC (m²/kg)</th>
<th>S_A,1 (m²/m²)</th>
<th>S_A,2 (m²/m²)</th>
<th>S_A (m²/kg)</th>
<th>SEA (m²/kg)</th>
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<td>42.2</td>
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<td>2005</td>
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<td>42.1</td>
<td>4</td>
<td>1850</td>
<td>1853</td>
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</table>

| 16.1 | 16.1 | 1.7 | 1628 | 4.0 | 13.4 | 42.1 | 2 | 1926 | 1929 | 1183 |

HEAT RELEASE RATE: BATTERY BOX PLASTIC
SMOKE PRODUCTION RATE: BATTERY BOX PLASTIC

SPECIMEN MASS: BATTERY BOX PLASTIC

Notes & Observations:
**CONE CALORIMETER TEST REPORT**

Client: DOT/NHTSA  Material ID: Battery Box Plastic
SwRI Project No: 01.17914  Heat Flux: 50 kW/m²

---

**CO PRODUCTION RATE: BATTERY BOX PLASTIC**

Average CO Yield:
- 14-141DOT-2 - 0.062 kg/kg
- 14-141DOT-3 - 0.059 kg/kg

---

**CO₂ PRODUCTION RATE: BATTERY BOX PLASTIC**

Average CO₂ Yield:
- 14-141DOT-2 - 2.75 kg/kg
- 14-141DOT-3 - 2.761 kg/kg

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Notes & Observations:
APPENDIX D
ENGINE COMPARTMENT FIRE SCENARIO BASELINE TEMPERATURE DATA
(CONSISTING OF 10 PAGES)
Baseline Test No. 5 - Distributed Pool Fires Without Fan

Department of Transportation
SwRI Project No. 01.17914
Test Date: July 9, 2014
Test ID: 14-190DOT001-5

Temperature (°C)

Time (min)
Baseline Test No. 6: Distributed Pool Fires With Fan

Temperature (°C)

Time (min)

Back right top
Back right bottom
Back left top
Back left bottom
Front left top
Front left middle
Front left bottom
Front right top
Front right bottom
Front right bottom
Baseline Test No. 7 – Battery Compartment Fire Without Fan

Temperature (°C) and Current (Amps)

Time (min)
APPENDIX E
ENGINE COMPARTMENT VENDOR A TEST DATA
(CONSISTING OF 14 PAGES)
Vendor A Test No. 2
PSF Spray Fire without Fan, LTD Detection
Vendor A Test No. 3
Hot Surface Re-Ignition Test, LTD Detection, Cooling Agent Only

Temperature (°C)

Time (min)
Vendor A Test No. 4
Diesel Spray Fire with Fan, LTD and Optical Detection

Temperature (°C)

Time (min)
Vendor A Test No. 6
Plastics Fire with Fan, LTD Detection

Temperature (°C)

Time (min)

- Plastic Middle
- Plastic Bottom
Vendor A Test No. 7
Distributed Pool Fires with Fan, No Detection

Temperature (°C)

Time (min)

- Diesel Spray
- Plastic Middle
- Plastic Bottom
- Battery Compartment 32 Inches
- Battery Compartment 24 Inches
- Battery Compartment 16 Inches
- Battery Compartment 8 Inches
- Power Steering Spray
Vendor A Test No. 9
Hot Surface Re-Ignition Test, No Detection, Cooling Agent Only

Temperature (°C)

Time (min)

Heater 1
Heater 2
Vendor A Test No. 11
PSF Spray Fire with Fan, Optical Detection

Temperature (°C)

Time (min)
Vendor A Test No. 12
Distributed Pool Fires with Fan, Optical Detection

Temperature (°C)

Time (min)
Vendor A Test No. 14: Plastics and Battery Compartment Fire
Combined without Fan, No Detection

Department of Transportation
SwRI Project No. 01.17914
Test Date: July 28, 2014
Test ID: 14-210DOT001-5

Temperature (°C)

Time (min)
APPENDIX F
ENGINE COMPARTMENT VENDOR B TEST DATA
(CONSISTING OF 15 PAGES)
Vendor B Test No. 1
Diesel Spray without Fan, LTD and Optical Detection, 2-Nozzle

- Diesel spray
- Back right top
- Back right bottom
- Back left top
- Front right top
- Diesel Pressure

Temperature (°C) vs. Time (min)
Pressure (psig) vs. Time (min)
Vendor B Test No. 2
Diesel Spray with Fan, LTD and Optical Detection, 2-Nozzle

Temperature (°C)

Pressure (psig)

Time (min)
Vendor B Test No. 3
PSF Spray Fire with Fan, LTD and Optical Detection, 2-Nozzle

- Power steering spray
- Back right top
- Back right bottom
- Back left top
- Back left bottom
- Front left top
- Front left middle
- Front left bottom
- Power Steering Pressure

Temperature (°C) vs. Time (min) vs. Pressure (psig)
Vendor B Test No. 4
PSF Spray Fire without Fan, LTD and Optical Detection, 2-Nozzle

Temperature (°C)

Pressure (psig)

Time (min)
Vendor B Test No. 6
Distributed Pool Fires with Fan, LTD and Optical Detection, 2-Nozzle

Temperature (°C)

Time (min)

- Red: Back right top
- Blue: Back right bottom
- Green: Back left top
- Orange: Back left bottom
- Purple: Front left top
- Pink: Front left middle
- Black: Front left bottom
- Cyan: Front right top
- Light blue: Front right bottom
Vendor B Test No. 8
Distributed Pool Fires with Fan, LTD and Optical Detection, 2-Nozzle

Temperature (°C)

0.0  0.5  1.0  1.5  2.0  2.5  3.0  3.5  4.0  4.5  5.0
Time (min)

- Back left top
- Back left bottom
- Front left top
- Front left middle
- Front left bottom
- Front right top
- Front right bottom

Department of Transportation
SwRI Project No. 01.17914
Test Date: July 16, 2014
Test ID: 14-197/DOT001-9
Vendor B Test No. 10
PSF Spray Fire without Fan, No Detection, 4-Nozzle

Graph showing temperature and pressure over time.
Vendor B Test No. 12
Distributed Pool Fires without Fan, No Detection, 4-Nozzle

Temperature (°C)

Time (min)

- Back left top
- Back left bottom
APPENDIX G
ENGINE COMPARTMENT VENDOR C TEST DATA
(CONSISTING OF 26 PAGES)
Department of Transportation
SwRI Project No. 01.17914
Test Date: July 22, 2014
Test ID: 14-208DOT001-1

Vendor C Test No. 1
PSF Spray Fire without Fan

Temperature (°C)

Time (min)

Power Steering Spray
Vendor C Test No. 2
PSF Spray Fire without Fan

Temperature (°C)

Time (min)
Vendor C Test No. 3
Diesel Spray (Low) without Fan

Temperature (°C)

Time (min)
Vendor C Test No. 4
Diesel Spray (Low) with Fan

Temperature (°C)

Time (min)
Vendor C Test No. 5
Diesel Spray (Low) with Fan

Temperature (°C)

Time (min)
Department of Transportation
SwRI Project No. 01.17914
Test Date: July 23, 2014
Test ID: 14-204DOT001-7

Vendor C Test No. 7
Diesel Spray with Fan

Temperature (°C)

Plastic Middle
Plastic Bottom

Time (min)

0 20 40 60 80 100 120 140 160 180

0.0 1.0 2.0 3.0 4.0 5.0 6.0
Vendor C Test No. 9
Diesel Spray (High) without Fan

Temperature (°C)

Time (min)
Vendor C Test No. 10
Diesel Spray (High) without Fan

Department of Transportation
SwRI Project No. 01.17914
Test Date: August 19, 2014
Test ID: 14-231DOT001-2

![Graph showing temperature over time for different locations with labels: Back Right Top, Back Left Top, Back Left Bottom.](image-url)
Vendor C Test No. 11
Diesel (High) Spray Fire without Fan

Temperature (°C)

Time (min)

- Back Right Top
- Back Left Top
- Back Left Bottom
Vendor C Test No. 12
Diesel Spray Fire (Low Position) with Fan

Temperature (°C)

Time (min)

- Back Right Top
- Back Right Bottom
- Back Left Top
- Back Left Bottom

Department of Transportation
SwRI Project No. 01.17914
Test Date: August 19, 2014
Test ID: 14-231DOT001-4
Vendor C Test No. 13
Diesel Spray Fire (Low Position) without Fan

- Back Right Top
- Back Right Bottom
- Back Left Top

Temperature (°C)

Time (min)
Vendor C Test No. 15
PSF Spray with Fan

Temperature (°C)

Time (min)

- Back Left Top
- Back Left Bottom
- Front Left Middle
- Power Steering Spray
Vendor C Test No. 17
Pool Fires with Fan
Vendor C Test No. 19
Pool Fires with Fan

Temperature (°C)

Time (min)

Back Right Top
Back Right Bottom
Back Left Top
Back Left Bottom
Front Left Top
Front Left Middle
Front Left Bottom
Front Right Top
Front Right Bottom
Vendor C Test No. 20
Pool Fires with Fan

Temperature (°C)

Time (min)

- Back Right Top
- Back Right Bottom
- Back Left Top
- Back Left Bottom
- Front Left Top
- Front Left Middle
- Front Left Bottom
- Front Right Top
- Front Right Bottom

Department of Transportation
SwRI Project No. 01.17914
Test Date: August 20, 2014
Test ID: 14-232DOT001-12
Vendor C Test No. 23
Diesel Spray (Low Position) with Fan

Temperature (°C)

Time (min)
APPENDIX H
ENGINE COMPARTMENT DETECTION/SUPPRESSION SYSTEM DRAFT TEST PROCEDURE
(CONSISTING OF 15 PAGES)
Engine Compartment Detection/Suppression System Draft Test Procedure

Purpose:
The purpose of this test procedure is to qualify detection and suppression systems for use in motorcoach engine compartments.

Basis of the Test:
This test procedure is based on a single tag axle that is supported at one end with a bearing structure and driven by an electric motor connected to the wheel lug nut assembly. The wheel is heated by partially engaging the disk brakes on the tag axle, causing heat to be transferred through the rotor and wheel assembly and into the tire.

Test Specimens:
Detection and suppression systems are to be provided by the manufacturer and installed per manufacturer’s instructions. Suppression nozzles are not permitted to be aimed directly at a known fire source location. The goal of the installation is to provide active fire protection to the entire engine compartment without knowledge of where the fire will originate. Additional details about nozzle placement for selected fire scenarios are provided below.

Test Fixture:
Figure 1 provides a representation of the test fixture and Figure 2 provides a photograph of the actual assembly. Full drawings can be referenced in Appendix B.
Figure 1. Engine Compartment Mockup Test Fixture Design.

Figure 2. Engine Compartment Test Fixture (Rear View).
Test Fixture Instrumentation:

Several measurements are required to be verified during each test. It is not required to record this data with a data acquisition system, but the measurements should be verified for each fire scenario. They are summarized as follows.

- Test Pressures
  - Oil pressure for hot surface re-ignition test. The oil is dripped at nominally 10 psig through the specified nozzle to achieve the required flow rate.
  - Diesel pressure and Power Steering Fluid (PSF) pressure for spray fire scenarios. Both spray fires require a nominal 100 psig discharge pressure to achieve the required flow rate.
  - Note that the flow rate specified in the fire scenario section is the requirement and alternative means of verifying the flow rate is acceptable. For example, the mass loss of supply fuel could be used as a way to verify the flow rate, or an inline flow meter could be used.
• Temperatures
  o A minimum of two thermocouples should be used on the hot surface to verify the nominal 750 ºC re-ignition temperature start time.
  o During the development of the procedure, additional thermocouples were utilized throughout the test fixture for additional data and to help confirm extinguishment. However, this is an optional requirement. The requirement is that the extinguishment time can be verified.

• Amp Reader
  o The current passed through the overheated wire ignition source in the battery compartment fire scenario should be verified to be at least 200 amps at initial discharge of the power source (e.g., bus batteries).

Fire Scenarios and Test Procedure:

The following fire scenarios (12 total tests) are required to be evaluated with the engine compartment detection and suppression system under test:

1. Hot Surface Re-Ignition Test (One Test)
   a. Real Bus Hazard: hot surface in engine compartment such as turbo and exhaust manifold.
   b. Ignition Material: continuous feed of lube oil through Hago Model 1.50/80ºH nozzle to drip oil at nominally 7 ml/min.
   c. Ignition Source: steel plate representing hot surface of turbo/exhaust manifold. Heated from behind by quartz IR panel heater.
   d. Location: upper left (hot) side of engine.
   e. Procedure: raise nominal temperature of hot plate to 750 ºC, open oil valve, observe dripping fire, after 15 s, turn off power to heaters for hot surface, after additional 15 s, discharge suppression system and record time to re-ignition, if any.
   f. Ventilation: conduct test without the fan running.

2. Diesel Spray Fires (Four tests)
   a. Real Bus Hazard: diesel spray fire as a result of a leak in the Diesel Particulate Filter (DPF) system. The diesel flow rate nominally equates to a 1.25-mm leak diameter with nominal operating conditions per motorcoach OEM for diesel line on DPF.
b. Ignition Material: continuous feed of diesel fuel through Monarch F-80 nozzle, 10.0 gal/hr flow rate, and 80º spray angle. The diesel spray nozzle is mounted in a small flame stabilizer (metal can nominally 3-in diameter and 3-in long).

c. Ignition Source: tell-tale cup (details below) positioned below the spray nozzle.

d. Locations: lower left (hot) side of engine and upper left (hot) side of engine.

e. Nozzle Placement: for the upper position diesel spray test, no suppression nozzles are permitted to be placed in the first bay of the clutter rack, while also being aimed toward the spray fire.

f. Procedure: ignite the tell-tale cup, after 30 s, discharge the diesel, after an additional 30 s discharge the suppression system and record observations.

g. Ventilation: perform tests with and without fan running.
  i. Nominal air speeds with fan running:
     1. Lower Diesel Spray: 1.75 m/s
     2. Lower Tell-Tale Cup: 0.60 m/s
     3. Upper Diesel Spray: 0.40 m/s
     4. Upper Tell-Tale Cup: 0.40 m/s

3. Power Steering Fluid (PSF) Fires (Two tests)

a. Real Bus Hazard: PSF spray fire as a result of a leak in the power steering system. The PSF flow rate will nominally equate to a 0.375-mm leak diameter with nominal operating conditions per motorcoach OEM for PSF line.

b. Ignition Material: continuous feed of PSF through Monarch F-80 nozzle, 15.5 gal/hr flow rate, and 80º spray angle. The PSF nozzle is mounted in a small flame stabilizer (metal can nominally 3-in diameter and 3-in long).

c. Ignition Source: tell-tale cup (details below) positioned below the spray nozzle.
d. Location: middle right (cold) side of engine.

e. Procedure: ignite the tell-tale cup, after 30 s, discharge the PSF, after an additional 30 s discharge the suppression system and record observations.

f. Ventilation: perform tests with and without fan running.
i. Nominal air speeds with fan running:
   1. PSF Spray: 4.33 m/s
   2. PSF Tell-Tale Cup: 0.82 m/s

4. Distributed Pool Fires (Two tests)
a. Real Bus Hazard: multiple fire locations after incipient fire has spread through compartment. This fire scenario also evaluates the ability of the system under test to adequately cover the full volume of the test fixture.

b. Ignition Materials:
i. 8 tell-tale cups, nominally 3-in diameter and 2-in high, each filled with 130 ml of heptane (approximate 1-in. depth)
   ii. 2 rectangular pans, each measuring 8 × 18 x 1-in. high, filled with 1750 ml of heptane (approximately 0.5-0.75-in. depth).

c. Location: throughout the entire test fixture, eight tell-tale cups in nominal eight corners of primary compartment space (not including battery compartment), one rectangular pan in left (hot) side clutter and one rectangular pan in right (cold) side clutter.

d. Procedure: The cups and rectangular pans are ignited within 30 s (pan is the last to be ignited) and 30 s after ignition of pan, the suppression system is manually discharged and observations are recorded.

e. Ventilation: perform tests with and without fan running.
i. Nominal air speeds with fan running:
   1. View from Front of Coach
      a. Tell-Tale Cup 4: 0.19 m/s
      b. Tell-Tale Cup 5: 0.92 m/s
c. Tell-Tale Cup 6: 0.62 m/s

d. Tell-Tale Cup 8: 5.46 m/s

e. Pan 1: 6.58 m/s

2. View from Rear of Coach

a. Tell-Tale Cup 1: 0.40 m/s

b. Tell-Tale Cup 2: 0.17 m/s

c. Tell-Tale Cup 3: 0.40 m/s

d. Tell-Tale Cup 7: 0.34 m/s

e. Pan 2: 0.35 m/s

5. Plastics Fire (Two Tests)

a. Real Bus Hazard: Class A material (plastics) fire close to the toilet holding tank and air filter housing components.

b. Ignition Materials:

i. 8 vertical strips of plastic, 4 ABS and 4 Polypropylene, each measuring 2-in × 28.75-in. long (nominally 1/8-in. thick)

ii. 4 horizontal strips of plastic, 1 of each type of plastic on lower two shelves of clutter rack adjacent to vertical strips and ignition pan.

iii. The material flammability of these materials has been characterized and can be referenced in Appendix C. The material flammability of test materials must be verified prior to each test session.

c. Ignition Source: 1 rectangular pan (same as pool fire test) with 120 ml of heptane used to ignite the plastic.

d. Location: lower right (cold) side of engine.

e. Procedure: Ignite the pan fire, after 105 s of pre-burn, discharge the suppression system and record observations.

f. Ventilation: conduct test with and without the fan running.

i. Nominal air speeds with fan running:

1. Ignition Pan: 0.43 m/s

2. Shelf 1 (Lowest): 0.33 m/s

3. Shelf 2: 0.27 m/s

4. Shelf 3: 0.25 m/s
5. Shelf 4 (Highest):  0.34 m/s

6. Battery Compartment Fire (One Test)
   a. Real Bus Hazard: overheated cable in battery compartment, which leads to a growing Class A fire.
   b. Ignition Materials:
      i. 1-in diameter pipe insulation – two horizontal sections 30 inches in length and one vertical section 25 inches in length. Prior to installation, each section is sprayed lightly with approximately 25 ml of diesel fuel. These sections are mounted just above the egg-crate foam and over the overheated cable.
      ii. Egg-crate foam plastic insulation – one 16 × 18-in panel applied to back wall of battery compartment directly over the overheated cable.
      iii. Plastic toolboxes – these are used to approximate battery boxes. Four of these boxes are placed in the compartment and 10 ml of grease is applied to the top surface of the back two boxes.
      iv. The material flammability of these materials has been characterized and can be referenced in Appendix C. The material flammability of test materials must be verified prior to each test session.
   c. Ignition Source: 23.5-in long thermoplastic cable overheated to ignition by discharging a nominal 200-amp load from two motorcoach batteries in series (24 volts). The cable also has approximately 5 ml of lubricating grease applied evenly over the surface of the cable insulation.
   d. Location: battery compartment.
   e. Nozzle Placement: suppression nozzles are not permitted to be installed in the space between the fuse box and the back wall of the battery compartment. If the nozzle installed for the purpose of extinguishing the battery compartment fire is outside the battery compartment, the access panel adjacent to the fuse box will remain open. If this nozzle is installed in the battery compartment, the access
panel adjacent to the fuse box will be closed during testing.

f. Procedure: discharge battery current into test cable and allow cable to ignite, 30 seconds after cable ignition, discharge suppression system and record observations.

g. Ventilation: conduct test without the fan running.

When a test is conducted with the fan running, the average air velocity measured at the outlet of the fan after the louvered radiator enclosure will be approximately 6 m/s and the volumetric airflow will be approximately 3 m³/s.

Figure 4 – Figure 13 provide drawings of each fire scenario location within the test fixture.

Figure 4. Hot Surface Re-Ignition Fire Scenario (View of Forward Side).
Figure 5. Diesel Spray Fire Scenario (View of Rear Side: Lower Position).

Figure 6. Diesel Spray Fire Scenario (View of Rear Side: Upper Position).
Figure 7. PSF Spray Fire Scenario (View of Forward Side).

Figure 8. Distributed Pool Fire Scenario (View of Forward Side).
Figure 9. Distributed Pool Fire Scenario (View of Rear Side).

Figure 10. Plastics Fire Scenario (Wide Angle View).
Figure 11. Plastics Fire Scenario (Close-up View).

Figure 12. Battery Compartment Fire Scenario (Wide Angle View).
Test Criteria:

The following test criteria apply for evaluating detection and suppression systems in motorcoach engine compartments.

- The detection and suppression system will be installed per manufacturer direction and/or specifications.

- The installation will not be changed for any of the twelve fire tests. In other words for a given single system configuration, all the tests will be conducted with the same detector and suppression system (nozzle) locations. If the system design/configuration is changed, all tests will be conducted again for that new design/configuration.

- For all of tests described above, with the exception of the hot surface re-ignition test, the design fire must be extinguished.
• For all of tests described above, with the exception of the hot surface re-ignition test, the detection system must have activated prior to the end of the pre-burn time of the design fire.

• For the hot surface re-ignition test, the installed system must prevent re-ignition for a minimum of 150 seconds.

• Detection and suppression systems that meet these test criteria also must test and approve the individual components of the system. An example of this type of component testing method can be referenced in FM 5320, Approval Standard for Dry Chemical Extinguishing Systems, December 2013.
APPENDIX I
WHEEL WELL TEST FIXTURE DRAWINGS
(CONSISTING OF 21 PAGES)
PRELIMINARY
NOT FOR PRODUCTION

GENERAL NOTES:
1) DO NOT SCALE THIS DRAWING
2) UNLESS OTHERWISE NOTED, ALL DIMENSIONS ARE IN INCHES AND TOLERANCES ARE IN HUNDREDTHS PER ANLEE T 4.5-2009
3) BREAK ALL SQUARES AND SHARP CORNERS AT .065 MAXIMUM
4) MACHINE SURFACE FINISH SHALL BE 850 MCR/150 OR BETTER
5) TAP DRILL DEPTHS SHOWN ARE MAXIMUM
6) FULL THREAD DURING SHOWN ARE MINIMUM
7) CENTER ALL TAPPED HOLES TD (COMBINED DIA + 1/8) ± .0007
8) FINISH

SCALE 3:64

SOUTHWEST RESEARCH INSTITUTE
OFFICE 1, AUTOMOTIVE ENG. DEPT.
9220 COLEBRA ROAD
SAN ANTONIO, TEXAS 78216

SPINDLE SUPPORT

26401
17914-200-201
**GENERAL NOTES**

1) DO NOT SCALE THIS DRAWING

2) UNLESS OTHERWISE STATED:
   a. ALL DIMENSIONING AND TOLERANCING IS IN INCHES PER ANSI Y14.5-2009
   b. BREAK ALL SHARP CORNERS AND SHARP EDGES
   c. MACHINED SURFACE FINISHES SHALL BE 125 MAX OR BETTER
   d. TAP DRILL DEPTHS SHOWN ARE MAXIMUM
   e. FULL THREAD DEPTHS SHOWN ARE MINIMUM
   f. CHAMFER ALL TAPPED HOLES TO (MINIMUM BIA + (/16) x 90°)

3) FINISH:

---

**SPECIFICATIONS**

- **PART NO.**: 5401
- **DRAWING NO.**: 17914-200-202
- **SCALE**: 1
- **DATE**: 3/1/2020
- **DRAWN BY**:...
- **INSPECTOR**:...

---

**DESCRIPTION**

- **ADAPTER**: STEEL TO 0.001 Equiv.
- **MATERIAL SPECIFICATION**:...
- **NOTES**:...

---

**REVIEWED**

- **SOUTHWEST RESEARCH INSTITUTE**: OFFICE OF AUTOMOTIVE ENGINEERING,
  7700 CERRO RADO, SAN ANTONIO, TX 78232

---

**SPINDLE ADAPTER**

- **DATE**: 3/1/2020
- **DRAWN BY**:...
- **INSPECTOR**:...
- **REVISED**: 1 OF 2

---

**APPROVED FOR PRODUCTION**
GENERAL NOTES

1) DO NOT SCALE THIS DRAWING
2) UNLESS OTHERWISE STATED:
   a. ALL DIMENSIONING AND TOLERANCING IS IN INCHES PER ASME Y14.5-2009
   b. BEND ALL SHARP CORNERS AND SHARP EDGES R 0.10 MAXIMUM
   c. MACHINED SURFACE FINISHES SHALL BE 125 MICROINCH OR BETTER
   d. TAP DRILL DEPTHS SHOWN ARE MAXIMUM
   e. FULL THREAD DEPTHS SHOWN ARE MINIMUM
   f. CHAMFER ALL TAPPED HOLES TO (NOMINAL DIA + 1/16) x 90°

3) FINISH:

APPROVED FOR PRODUCTION

SOUTHWEST RESEARCH INSTITUTE
OFFICE OF AUTOMOTIVE ENGINEERING
8220 CULEBRA ROAD, SAN ANTONIO, TEXAS 78250

LUG NUT GASKET
GENERAL NOTES:
1) DO NOT SCALE THIS DRAWING
2) UNLESS OTHERWISE STATED:
   a. ALL DIMENSIONS AND TOLERANCES IS IN INCHES PER ASME Y14.5-2009
   b. GRASS SHARP POINTS AND SHARP ROUNDS A .010 MAXIMUM
   c. MACHINING SURFACE FINISH SHALL BE .25 MICROINCHE OR BETTER
   d. TAP DRILL DEPTHS SHOWN ARE MAXIMUM
   e. TALL THREAD GAGE SHOWN ARE MINIMUM
   f. CHAMFER ALL TAPED HOLES TO <1/2 DIA + (1/8) x 10°
3) FINISH:

SOUTH WEST RESEARCH INSTITUTE
OFFICE 41 AEROSPACE (Bldg. 141)
6230 CULVER RD
SAN ANTONIO, TX 78228

SHEAR COUPLING - FEMALE

SHELL 5/16-18 UNC-2B TAP THRU
5/16 DRILL (.313) THRU
EQUALLY SPACED ON 5.110 BC

SCALE 0.500

APPROVED FOR PRODUCTION
GENERAL NOTES

1) DO NOT SCALE THIS DRAWING
2) UNLESS OTHERWISE STATED:
   a. ALL DIMENSIONING AND TOLERANCING IS IN INCHES PER ASME Y14.5-2009
   b. BREAK ALL SHARP CORNERS AND SHARP EDGES TO .010 MAXIMUM
   c. MACHINED SURFACE FINISHES SHALL BE 125 MICROINCH OR BETTER
   d. TAP DRILL DEPTHS SHOWN ARE MAXIMUM
   e. FULL THREAD DEPTHS SHOWN ARE MINIMUM
   f. CHAMFER ALL TAPPED HOLES TO (NOMINAL DIA + 1/16") X 30°
   g. FINISH
GENERAL NOTES

1) DO NOT SCALE THIS DRAWING

2) UNLESS OTHERWISE STATED:
   a. ALL DIMENSIONING AND TOLERANCING IS IN INCHES PER ASME Y14.5-2009
   b. BREAK ALL SHARP CORNERS AND SHARP EDGES R 0.010 MAXIMUM
   c. MACHINED SURFACE FINISHES SHALL BE 125 MICROINCH OR BETTER
   d. TAP DRILL DEPTHS SHOWN ARE MAXIMUM
   e. FULL THREAD DEPTHS SHOWN ARE MINIMUM
   f. CHAMFER ALL TAPPED HOLES TO NOMINAL DIA + 1/16" x 90°

3) FINISH:

- WHEEL WELL 150
  3/16 SHEET METAL & 1/2 SQ TUBING WELDMENT

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SOUTHWEST RESEARCH INSTITUTE
OFFICE 8, AUTOMOTIVE LS 36059
6330 CULEBRA ROAD, SAN ANTONIO, TEXAS 78238

WHEEL WELL 150
3/16 SHEET METAL & 1/2 SQ TUBING WELDMENT

APPROVED FOR PRODUCTION
APPENDIX J
WHEEL WELL VENDOR A TEST DATA
(CONSISTING OF 8 PAGES)
Test No. 1 - Wheel Well Vendor A
Steel Wheel, No Burnishing

Department of Transportation
SwRI Project No. 01.17914
Test Date: May 20, 2014
Test ID: 14-140DOT000-1

- Torque
- Power
- Tire Speed
- Energy

Speed (mph), Power (kW), Energy (MJ)

Time (min)
Test No. 1 - Wheel Well Vendor A
Stationary Temperatures

Wheel Temperatures (°C)

Time (min)

- Top of Caliper Housing
- Top of Torque Plate
- Bottom of Torque Plate
Test No. 1 - Wheel Well Vendor A
Rotating Temperatures

- Front Wheel TC1
- Front Wheel TC2
- Heat Loss into Drive Hub
- Back Wheel TC1
- Back Wheel TC2
- Front Tire Bead

Wheel Temperatures (°C)

Time (min)
Department of Transportation
SwRI Project No. 01.17914
Test Date: May 21, 2014
Test ID: 14-141DOT000-1

Test No. 2 - Wheel Well Vendor A
Rotating Temperatures

Wheel Temperatures (°C)

Time (min)
APPENDIX K
WHEEL WELL VENDOR B TEST DATA
(CONSISTING OF 9 PAGES)
Department of Transportation
SwRI Project No. 01.17914
Test Date: June 18, 2014
Test ID: 14-189DOT000-1

Test No. 1 - Wheel Well Vendor B
Aluminum Wheel, Full Burnishing

Graph showing Torque, Power, Tire Speed, and Energy over time (min).
Test No. 2 - Wheel Well Vendor B
Aluminum Wheel, Abbreviated Burnishing

- Front Rim
- Top of Caliper Housing
- Torque Plate - Top
- Torque Plate - Bottom
- Spindle Weld Pad
- Wheel Well Housing
- ABS Sensor Location
- Brake Pad
Test No. 3 - Wheel Well Vendor B
Steel Wheel, Abbreviated Burnishing

Department of Transportation
SwRI Project No. 01.17914
Test Date: June 20, 2014
Test ID: 14-171DOT000-5

Temperature (°C)

Time (min)

- Front Rim
- Top of Caliper Housing
- Torque Plate - Top
- Torque Plate - Bottom
- Spindle Weld Pad
- Wheel Well Housing
- ABS Sensor Location
- Brake Pad
APPENDIX L
WHEEL WELL VENDOR C TEST DATA
(CONSISTING OF 12 PAGES)
Wheel Well  Vendor C  
Test 1 Summary Chart

- Maximum Stationary Temperature
- Maximum Rotating Temperature
- Sensor 1 Temperature
- Sensor 2 Temperature
- Nominal Tire Ignition Temperature
- Sensor Alarm Threshold
- Sensor 1 Activation Point
- Sensor 2 Activation Point

Sensor 1 activated at 18:17 (94 °C) and Sensor 2 activated at 11:12 (85 °C)
Test No. 1 – Wheel Well Vendor C
Aluminum Wheel, Abbreviated Burnishing, Stationary Temperatures

Temperature (°C)

Time (min)

- Top of Caliper Housing
- Torque Plate - Top
- Torque Plate - Bottom
- Spindle Weld Pad
- Wheel Well Housing
- ABS Sensor Location
- Brake Pad
Test No. 1 – Wheel Well Vendor C
Aluminum Wheel, Abbreviated Burnishing, Rotating Temperatures
Wheel Well Vendor C
Test 2 Summary Chart

- Maximum Stationary Temperature
- Maximum Rotating Temperature
- Sensor 1 Temperature
- Sensor 2 Temperature
- Nominal Tire Ignition Temperature
- Sensor Alarm Threshold
- Sensor 1 Activation Point
- Sensor 2 Activation Point

Sensor 1 activated at 17:37 (95 °C) and Sensor 2 activated at 12:12 (85 °C)
Test No. 2 – Vendor C Testing
Steel Wheel, Abbreviated Burnishing

- Torque (N·m)
- Tire Speed
- Power (kW)
- Energy (MJ)

Time (min)
Test No. 3 – Vendor C Testing
Rotating Temperatures

Temperature (°C)

Time (min)

Front Rim - Tire Bead
Back Rim - Middle 1
Hub
Back Rim - Tire Bead
Back Rim - Middle 2
APPENDIX M
WHEEL WELL EARLY WARNING SYSTEM DRAFT TEST PROCEDURE
(CONSISTING OF 7 PAGES)
Wheel Well Warning System Draft Test Procedure

Purpose:

The purpose of this test procedure is to qualify systems/sensors and algorithms which can detect a hot wheel before a tire fire occurs. The goal is that, upon detection, the motorcoach driver will be warned and if action is taken quickly to stop the vehicle, the source of heating can be eliminated and an ensuing tire fire can be avoided.

Critical Temperature Conditions:

Tires will not typically ignite until they reach a temperature of approximately 400 ºC (References 1 and 2). This is well above the temperatures that tires, brakes, bearings, and wheel assemblies normally encounter under normal (and even emergency braking) conditions. In some circumstances, lube oil (or bearing grease) or brake pad resin may be the first item ignited. Their Hot Surface Ignition (HSI) temperatures are in the range of 382 ºC and above. (Reference 3).

Basis of the Test:

This test procedure is based on a single tag axle that is supported at one end with a bearing structure and driven by an electric motor connected to the wheel lug nut assembly. The wheel is heated by partially engaging the disk brakes on the tag axle, causing heat to be transferred through the rotor and wheel assembly and into the tire.

Test Specimens:

There are several sensors that could be used to detect a hot wheel well in advance of tire ignition:

a. Sensor mounted on stationary components of the axle/wheel assembly:
   i. Thermocouples attached to axle, spindle, or stationary part of brake assembly
   ii. Thermocouples attached at or near the ABS sensor.
   iii. ABS sensor. Sensor failure or loss of signal may indicate a hot wheel.
b. Sensor mounted on rotating part of wheel/tire:
   i. Tire Pressure Monitoring Systems (TPMS). Several of these commercial devices measure temperature as well as pressure. Some are mounted on the valve stem, some on the wheel hub, and some on the tire itself.
   ii. A dedicated thermocouple mounted on a metallic part of the rotating wheel components.

c. Specimens are to be provided by the manufacturer of the device and installed per manufacturer’s instructions.

Test Fixture:

Figure 1 provides a representation of the test fixture and Figure 2 provides a photograph of the actual assembly. Full drawings can be referenced in Appendix I.

![Motorcoach Wheel Well Test Fixture Final Design](image)

**Figure 1. Motorcoach Wheel Well Test Fixture Final Design.**
Figure 2. Wheel Well Mockup Test Fixture (Overall Plan View).

Figure 3. Wheel Well Mockup Test Fixture (Ground Level View).
The test will utilize an aluminum wheel (Size: 22.5 × 8.25) and new or used tire (Size: 315/80R22.5). The tire will be pressurized with air to 30 psig.

Test Fixture Instrumentation:

Several measurements are required to be recorded during each test. They are summarized as follows.

- **Tire Speed**
  - Burnishing is performed at 40 mph
  - Tests are conducted at 60 mph

- **Brake pressure**
  - The disk brake air or Nitrogen pressure must be monitored during testing to apply the correct torque through the system.
  - During the development of the procedure, this required brake pressure was typically between 20-25 psig.

- **Torque**
  - The torque is not required to be directly measured during every test, but it is required that it be calculated if not directly measured.
  - During the development of the procedure, this was accomplished by mapping the current draw from the electric motor with the torque and after initial calibration; the torque meter was removed and replaced with a safety shear coupling.

- **Temperatures (all Type K thermocouples)**
  - Brake Pad Temperature: a thermocouple is inserted in the nominal center of the brake pad material (see Figure 4 below) and this is used to control the burnishing and device tests.
  - Stationary Temperatures: it is required that thermocouples be attached to the top of the caliper housing, the top of the torque plate and the bottom of the torque plate. These are used to assess the maximum safe levels of heating before the test is terminated, assuming the device under test has not activated by this point.
Rotating Temperatures: it is recommended to measure the front and rear wheel/rim temperature in three locations each. Each side (front and rear) of the rim should be measured in two locations close to the tire bead and one location close the middle of the rim.

Figure 4. Brake Pad Thermocouple Location and Construction.

Brake Pad Burnishing:

This is an approval test procedure for evaluating air brake systems on a dynamometer, FMVSS 121D, Laboratory Test Procedure for Air Brake Systems – Dynamometer, TP-121D-01.

There is a burnishing procedure in Section 12 of this document. An excerpt of this procedure is as follows:
Place the brake assembly on an inertia dynamometer and adjust the brake as recommended by the brake manufacturer. Make 200 stops from 40 mph at a deceleration of 10 ft/s/s, with an initial brake temperature on each stop of not less than 315ºF and not more than 385ºF. Make 200 additional stops from 40 mph at a deceleration of 10 ft/s/s, with an initial brake temperature on each stop of not less than 450ºF and not more than 550ºF.

During the development of this procedure it was shown that an abbreviated burnishing cycle of 20 stops, instead of 200 was adequate for performance of the sensor evaluation test without observing brake glazing.

A new set of brake pads will be used for each test and they will be burnished following the procedure below.

- Set the tire speed to 40 mph.
- Conduct the first set of 20 stops between a brake pad temperature of 315-385ºF.
  - In order to meet the deceleration requirements on this test fixture, as opposed to a dynamometer, the torque is adjusted to approximately 1500 N-m and applied to the brake pads for approximately 9 seconds during each heating cycle.
- Allow the brake pad temperature to cool to below 100 ºF.
- Conduct the second set of 20 stops between a brake pad temperature of 450-550 ºF.
  - In order to meet the deceleration requirements on this test fixture, as opposed to a dynamometer, the torque is adjusted to approximately 1500 N-m and applied to the brake pads for approximately 9 seconds during each heating cycle.
- Allow the assembly to cool to less than 100 ºF before the start of the device evaluation test.

Test Procedure and Criteria:

- The early warning system will be installed per manufacturer specifications.
• Set the tire speed to 60 mph.

• Engage the brakes such that 1500-2000 N-m of torque is generated, which will apply heat into the system until the brake pad temperature reaches 750 °C. Relieve brake pressure upon a brake temperature of 750 °C.

• Subsequent heating cycles from 650 – 750 °C will be administered until sensor activation or until the maximum stationary temperature reaches 400 °C.

• If the sensor does not activate prior the maximum stationary temperature reaching 400 °C, the test will be aborted and the sensor considered to have failed this evaluation.

• If the sensor activates, one additional heating cycle will be performed, the wheel stopped, and the final observations made of additional heating and final sensor temperature.

• During the final cool down period, the fixture will be monitored and during this time, if the maximum stationary temperature exceeds 400 °C, the sensor will be considered to have failed this evaluation. If the stationary temperature remains below 400 °C during the cool down period, the sensor will be considered to have passed this evaluation.

References:
APPENDIX N
FIRE HARDENING CONE CALORIMETER TEST DATA
(CONSISTING OF 24 PAGES)
CONE CALORIMETER TEST REPORT

Client: DOT/NI-RTSA
SwRC Project No: D1.17914
Material ID: GRP - Uncoted
Heat Flux: 50 kW/m²
Duct Flow: 24 l/s
Orientation: Horizontal
Sample Area: 0.00884 m²
Distance: 25 mm
Operator: Abe Mata

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97.6 97.3 31.7 7451 5.8 7.9 21.5 4 6455 6459 866

HEAT RELEASE RATE: GRP - UNCOATED
CO₂ PRODUCTION RATE: GRP - UNCOATED

Average CO₂ Yield:
14-224DOT-6 - 1.763 kg/kg
14-225DOT-7 - 1.775 kg/kg
14-225DOT-8 - 1.859 kg/kg

Notes & Observations:
SOUTHWEST RESEARCH INSTITUTE
CONE CALORIMETER TEST REPORT

Client: DOT/NIH/HTSA  Material ID: GRP with Pitt Char Coating
SwRI Project No.: 01.17914  Heat Flux: 50 kW/m²
Orientation: Horizontal  Duct Flow: 24 l/s
Frame: Yes  Sample Area: 0.00884 m²
Spark Ignitor: Yes  Distance: 25 mm
Operator: Abe Mata

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HEAT RELEASE RATE: GRP WITH PITT CHAR XP COATING

N-5
SOUTHWEST RESEARCH INSTITUTE
CONE CALORIMETER TEST REPORT

Client: DOT/NHTSA  Material ID: GRP with Pitt Char Coating
SwRI Project No.: 01.17914  Heat Flux: 50 kW/m²

CO PRODUCTION RATE: GRP WITH PITT CHAR XP COATING

Average CO Yield:
14-225DOT-10: 0.07 kg/kg
14-225DOT-9: 0.081 kg/kg
14-225DOT-11: 0.044 kg/kg

CO₂ PRODUCTION RATE: GRP WITH PITT CHAR XP COATING

Average CO₂ Yield:
14-225DOT-10: 1.595 kg/kg
14-225DOT-9: 1.585 kg/kg
14-225DOT-11: 0.969 kg/kg

Notes & Observations:
CONE CALORIMETER TEST REPORT

Client: DOT/NHTSA
SwRI Project No: 01.17914
Material ID: Sheet Steel - Uncoated
Heat Flux: 50 kW/m²
Duct Flow: 24 l/s
Orientation: Horizontal
Sample Area: 0.008864 m²
Frame: Yes
Distance: 25 mm
Spark Igniter: Yes
Operator: Abe Mata

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Ni = No Ignition

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98.4 NI 96.0 45 0.1 0.1 6.8 62 N/A 62 323
CONE CALORIMETER TEST REPORT

Client: DOT/NHTSA  Material ID: Sheet Steel - Uncoated
SwRI Project No: 01.17914  Heat Flux: 50 kW/m²

(Smoke Production Rate: Sheet Steel - Uncoated)

(Specimen Mass: Sheet Steel - Uncoated)

Notes & Observations:
CO PRODUCTION RATE: SHEET STEEL - UNCOATED

Average CO Yield:
14-224DOT-1: 0.102 kg/kg
14-224DOT-2: 0.934 kg/kg

CO₂ PRODUCTION RATE: SHEET STEEL - UNCOATED

Average CO₂ Yield:
14-224DOT-1: -1.104 kg/kg
14-224DOT-2: -6.53 kg/kg

Notes & Observations:
# Cone Calorimeter Test Report

Client: DOT/NHTSA  
SwRI Project No: 01.17914  
Material ID: Sheet Steel - Coated  
Heat Flux: 50 kW/m²  
Duct Flow: 24 l/s  
Orientation: Horizontal  
Sample Area: 0.00864 m²  
Frame: Yes  
Distance: 25 mm  
Spark Igniter: Yes  
Operator: Abe Mata

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<td>111.7</td>
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</table>

**Heat Release Rate: Sheet Steel with Pitt Char XP Coating**

![Graph showing heat release rate over time](image)
CONE CALORIMETER TEST REPORT

Client: DOT/NHTSA  Material ID: Sheet Steel - Coated
SwRI Project No: 01.17914  Heat Flux: 50 kW/m²

CO PRODUCTION RATE: SHEET STEEL WITH PITT CHAR XP COATING

Average CO Yield:
- 14-224DOT-3: 0.08 kg/kg
- 14-224DOT-4: 0.08 kg/kg
- 14-224DOT-5: 0.089 kg/kg

CO₂ PRODUCTION RATE: SHEET STEEL WITH PITT CHAR XP COATING

Average CO₂ Yield:
- 14-224DOT-3: 1.456 kg/kg
- 14-224DOT-4: 1.315 kg/kg
- 14-224DOT-5: 1.391 kg/kg

Notes & Observations:
CONE CALORIMETER TEST REPORT

Client: DOT/NHTSA  Material ID: Gypsum Wallboard - Uncoated
SwRI Project No: 01.17914  Heat Flux: 50 kW/m²
Orientation: Horizontal  Duct Flow: 24 lbs
Frame: Yes  Sample Area: 0.00864 m²
Spark Igniter: Yes  Distance: 25 mm
Operator: Abe Mata

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<th>Test ID</th>
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<th>THR (MJ/m²)</th>
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114.8  114.1  112.7  240  3.7  4.4  5.7  6  2  8  9

HEAT RELEASE RATE: GYPSUM WALLBOARD - UNCOATED

N-14
CONE CALORIMETER TEST REPORT

Client: DOT/NHTSA  
Material ID: Gypsum Wallboard - Uncoated

SwRI Project No: 01.17914  
Heat Flux: 50 kW/m²

SMOKE PRODUCTION RATE: GYPSUM WALLBOARD - UNCOATED

SPECIMEN MASS: GYPSUM WALLBOARD - UNCOATED

Notes & Observations:

N-15
CONE CALORIMETER TEST REPORT

Client: DOT/NHTSA
SwRI Project No: 01.17914
Material ID: Gypsum Wallboard - Uncoated
Heat Flux: 50 kW/m²

**CO PRODUCTION RATE: GYPSUM WALLBOARD - UNCOATED**

Average CO Yield:
- 14-226DOT-12: 0.101 kg/kg
- 14-226DOT-13: 0.09 kg/kg
- 14-226DOT-14: 0.104 kg/kg

**CO₂ PRODUCTION RATE: GYPSUM WALLBOARD - UNCOATED**

Average CO₂ Yield:
- 14-228DOT-12: 1.089 kg/kg
- 14-228DOT-13: 0.717 kg/kg
- 14-228DOT-14: 0.780 kg/kg

Notes & Observations:
CONIC CALORIMETER TEST REPORT

Client: DOT/NHTSA  
SwRI Project No: 01.17514  
Material ID: Gypsum Wallboard - Coated

Heat Flux: 50 kW/m²  
Duct Flow: 24 l/s

Orientation: Horizontal  
Sample Area: 0.00884 m²

Frame: Yes  
Distance: 25 mm

Operator: Abe Mata

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152.6 152.1 128.6 2713 2.7 2.7 10.2 25 392 388 152

HEAT RELEASE RATE: GYPSUM WALLBOARD - COATED W/PITT CHAR

N-17
CONE CALORIMETER TEST REPORT

Client: DOT/NHTSA  Material ID: Gypsum Wallboard - Coated
SwRI Project No: 01.17914  Heat Flux: 50 kW/m²

Smoke Production Rate: Gypsum Wallboard - Coated

Specimen Mass: Gypsum Wallboard - Coated with Char

Notes & Observations:
CONE CALORIMETER TEST REPORT

Client: DOT/NHTSA
SwRI Project No: 01.17914
Material ID: Gypsum Wallboard - Coated
Heat Flux: 50 kW/m²

**CO PRODUCTION RATE: GYPSUM WALLBOARD - COATED**

Average CO Yield:
14-228DOT-15: 0.049 kg/kg
14-228DOT-16: 0.05 kg/kg
14-228DOT-17: 0.055 kg/kg

**CO₂ PRODUCTION RATE: GYPSUM WALLBOARD - COATED**

Average CO₂ Yield:
14-228DOT-15: 0.78 kg/kg
14-228DOT-16: 0.718 kg/kg
14-228DOT-17: 0.628 kg/kg

Notes & Observations:
CONCRETE CALORIMETER TEST REPORT

Client: DOT/HTSA
SwRI Project No: 01.17914
Material ID: Red Oak Plywood - Uncoated
Heat Flux: 50 kW/m²
Duct Flow: 24 l/s
Orientation: Horizontal
Sample Area: 0.00864 m²
Frame: Yes
Distance: 25 mm
Spark Igniter: Yes
Operator: Abe Meta

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Test Date</th>
<th>t_s (s)</th>
<th>Test Duration (s)</th>
<th>C-Factor (Sl Units)</th>
<th>HRR_cmax (kW/m²)</th>
<th>THR (kW/m²)</th>
<th>HRR_50s (kW/m²)</th>
<th>HRR_100s (kW/m²)</th>
<th>HRR_500s (kW/m²)</th>
<th>HRR_1000s (kW/m²)</th>
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<tbody>
<tr>
<td>14-22/DOA-18</td>
<td>08/15/14</td>
<td>23</td>
<td>854</td>
<td>0.0416</td>
<td>352</td>
<td>80.2</td>
<td>119</td>
<td>97</td>
<td>258</td>
<td></td>
</tr>
<tr>
<td>14-22/DOA-19</td>
<td>08/15/14</td>
<td>9</td>
<td>858</td>
<td>0.0416</td>
<td>241</td>
<td>84.4</td>
<td>141</td>
<td>102</td>
<td>204</td>
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<tr>
<td>14-22/DOA-20</td>
<td>08/15/14</td>
<td>20</td>
<td>920</td>
<td>0.0416</td>
<td>308</td>
<td>86.5</td>
<td>183</td>
<td>121</td>
<td>242</td>
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Average: 17 877 --- 300 83.7 110 114 94 234

<table>
<thead>
<tr>
<th>Initial Mass (g)</th>
<th>Mass at Ignition (g)</th>
<th>Mass Loss (g/m²)</th>
<th>MLR (g/m²·s)</th>
<th>10-60 MLR (g/m²·s)</th>
<th>BHC (kJ/kg)</th>
<th>S_A,1 (m²/m³)</th>
<th>S_A,2 (m²/m³)</th>
<th>S_A (m²/m³)</th>
<th>SEA (m²/kg)</th>
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<tbody>
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<td>73.4</td>
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<td>8.3</td>
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<td>3.3</td>
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<tr>
<td>82.1</td>
<td>82.0</td>
<td>17.9</td>
<td>7260</td>
<td>8.4</td>
<td>6.7</td>
<td>11.6</td>
<td>11.6</td>
<td>11.6</td>
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<tr>
<td>81.0</td>
<td>81.4</td>
<td>18.8</td>
<td>7360</td>
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<td>6.3</td>
<td>11.7</td>
<td>11.7</td>
<td>11.7</td>
<td>11.7</td>
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</table>

80.0 80.4 17.0 7219 8.2 8.4 11.8 1 310 312 43

HEAT RELEASE RATE: RED OAK PLYWOOD - UNCOATED

N-20
CONE CALORIMETER TEST REPORT

Client: DOT/NHTSA
SwRI Project No: 01.17914

Material ID: Red Oak Plywood - Uncoated
Heat Flux: 50 kW/m²

CO PRODUCTION RATE: RED OAK PLYWOOD - UNCOATED

Average CO Yield:
14-227DOT-18 - 0.021 kg/kg
14-227DOT-19 - 0.022 kg/kg
14-227DOT-20 - 0.023 kg/kg

CO₂ PRODUCTION RATE: RED OAK PLYWOOD - UNCOATED

Average CO₂ Yield:
14-227DOT-18 - 1.189 kg/kg
14-227DOT-19 - 1.148 kg/kg
14-227DOT-20 - 1.150 kg/kg

Notes & Observations:
CONE CALORIMETER TEST REPORT

Client: DOT/NHTSA
SwRI Project No: 01.17914
Orientation: Horizontal
Frame: Yes
Spark Igniter: Yes
Operator: Abe Mata

Material ID: Red Oak Plywood - Coated
Heat Flux: 50 kW/m²
Duct Flow: 24 lbs
Sample Area: 0.00884 m²
Distance: 25 mm

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Test Date</th>
<th>t₀ (s)</th>
<th>Test Duration (s)</th>
<th>C-Factor (SI Units)</th>
<th>HRR_peak (kW/m²)</th>
<th>THR (MJ/m²)</th>
<th>HRR10s (kW/m²)</th>
<th>HRR30s (kW/m²)</th>
<th>HRR60s (kW/m²)</th>
<th>HRR120s, max (kW/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14-22/07/DOT-21</td>
<td>08/15/14</td>
<td>29</td>
<td>2878</td>
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<td>08/15/14</td>
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<td>14-22/07/DOT-23</td>
<td>08/15/14</td>
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<td>2515</td>
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<td>121.9</td>
<td>100</td>
<td>75</td>
<td>65</td>
<td>134</td>
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</table>

Average: 33 2010 --- 148 115.9 99 74 62 127

<table>
<thead>
<tr>
<th>Initial Mass (g)</th>
<th>Mass at Ignition (g)</th>
<th>Final Mass (g)</th>
<th>Mass Loss (g)</th>
<th>MLR (g/m²-s)</th>
<th>10-60 MLR (g/m²-s)</th>
<th>EHC (MJ/kg)</th>
<th>S₁₀₂</th>
<th>S₅₀</th>
<th>S₁₀₀</th>
<th>SEA</th>
</tr>
</thead>
<tbody>
<tr>
<td>128.9</td>
<td>128.2</td>
<td>43.6</td>
<td>8532</td>
<td>3.3</td>
<td>3.7</td>
<td>12.3</td>
<td>24</td>
<td>459</td>
<td>484</td>
<td>48</td>
</tr>
<tr>
<td>112.9</td>
<td>126.6</td>
<td>50.1</td>
<td>7108</td>
<td>3.6</td>
<td>5.2</td>
<td>15.1</td>
<td>25</td>
<td>556</td>
<td>592</td>
<td>76</td>
</tr>
<tr>
<td>121.6</td>
<td>120.8</td>
<td>37.2</td>
<td>9541</td>
<td>3.8</td>
<td>5.1</td>
<td>12.8</td>
<td>47</td>
<td>518</td>
<td>586</td>
<td>54</td>
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</tbody>
</table>

Average: 121.1 258.8 43.8 8707 3.6 4.7 13.4 32 511 544 60

HEAT RELEASE RATE: RED OAK - COATED WITH PITT CHAR XP

N-23
CONE CALORIMETER TEST REPORT

Client: DOT/NHTSA
SwRI Project No: 01.17914

Material ID: Red Oak Plywood - Coated
Heat Flux: 50 kW/m²

SMOKE PRODUCTION RATE: RED OAK - COATED WITH PITT CHAR XP

SPECIMEN MASS: RED OAK - COATED WITH PITT CHAR XP

Notes & Observations:
CONE CALORIMETER TEST REPORT

Client: DOT/NHTSA  
Material ID: Red Oak Plywood - Coated

SwRI Project No: 01.17914  
Heat Flux: 50 kW/m²

**CO PRODUCTION RATE: RED OAK - COATED WITH PITT CHAR XP**

Average CO Yield:
14-227DOT-21 - 0.049 kg/kg
14-227DOT-22 - 0.05 kg/kg
14-227DOT-23 - 0.041 kg/kg

**CO₂ PRODUCTION RATE: RED OAK - COATED WITH PITT CHAR XP**

Average CO₂ Yield:
14-227DOT-21 - 1.071 kg/kg
14-227DOT-22 - 1.356 kg/kg
14-227DOT-23 - 1.046 kg/kg

Notes & Observations:
APPENDIX O
FIRE HARDENING PARALLEL PANEL TEST DATA
(CONSISTING OF 65 PAGES)
## SUMMARY OF TEST RESULTS

**Material:** GRP Uncoated - Run 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum HRR$_{total}$</td>
<td>1233 kW</td>
<td>2 min 21 sec</td>
</tr>
<tr>
<td>Average HRR$_{total}$</td>
<td>530 kW</td>
<td></td>
</tr>
<tr>
<td>Total Heat Released</td>
<td>318 MJ</td>
<td></td>
</tr>
<tr>
<td>Maximum HRR$_{excl. burner}$</td>
<td>1174 kW</td>
<td>2 min 21 sec</td>
</tr>
<tr>
<td>Average HRR$_{excl. burner}$</td>
<td>472 kW</td>
<td></td>
</tr>
<tr>
<td>Total Heat Released (Excluding Burner)</td>
<td>283 MJ</td>
<td></td>
</tr>
<tr>
<td>Maximum HRR$_{10\text{ min}}$</td>
<td>N/A*</td>
<td></td>
</tr>
<tr>
<td>HRR$_{12\text{ min}}$</td>
<td>N/A*</td>
<td></td>
</tr>
<tr>
<td>Maximum Flame Height</td>
<td>&gt; 2.4 m</td>
<td>7 min 0 sec</td>
</tr>
<tr>
<td>Heat Flux at 4 ft</td>
<td>92 kW/m²</td>
<td>2 min 40 sec</td>
</tr>
<tr>
<td>Maximum Smoke Generation Rate$_{0-10\text{ min}}$</td>
<td>3.58 g/s</td>
<td>3 min 31 sec</td>
</tr>
<tr>
<td>Smoke Generation Rate$_{12\text{ min}}$</td>
<td>N/A*</td>
<td></td>
</tr>
<tr>
<td>Total Smoke Generated</td>
<td>528 g</td>
<td></td>
</tr>
<tr>
<td>Maximum Smoke Release Rate</td>
<td>31.12 m³/s</td>
<td>2 min 40 sec</td>
</tr>
<tr>
<td>Average Smoke Release Rate</td>
<td>6.94 m³/s</td>
<td></td>
</tr>
<tr>
<td>Total Smoke Released</td>
<td>4162 m²</td>
<td></td>
</tr>
<tr>
<td>Maximum Optical Density</td>
<td>1.86 l/m</td>
<td>2 min 23 sec</td>
</tr>
<tr>
<td>Maximum Duct Flow Rate</td>
<td>6.93 m³/s</td>
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</tr>
<tr>
<td>Average Optical Density</td>
<td>0.321 l/m</td>
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</tr>
<tr>
<td>Average Volumetric Duct Flow Rate</td>
<td>6.60 m³/s</td>
<td></td>
</tr>
<tr>
<td>Total Mass Loss</td>
<td>11.11 kg</td>
<td></td>
</tr>
<tr>
<td>Smoke Yield</td>
<td>0.048</td>
<td></td>
</tr>
<tr>
<td>Maximum Sample Backside Temperature</td>
<td>99°C</td>
<td>13 min 38 sec</td>
</tr>
</tbody>
</table>
TEMPERATURES AT 2, 4, 6, AND 8 FT

BACKSIDE OF SAMPLE TEMPERATURES
## SUMMARY OF TEST RESULTS

**Material:** GRP Uncoated - Run 2

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum HRR$_{total}$</td>
<td>1277 kW</td>
<td>2 min 31 sec</td>
</tr>
<tr>
<td>Average HRR$_{total}$</td>
<td>456 kW</td>
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</tr>
<tr>
<td>Total Heat Released</td>
<td>274 MJ</td>
<td></td>
</tr>
<tr>
<td>Maximum HRR$_{excl.~burner}$</td>
<td>1218 kW</td>
<td>2 min 31 sec</td>
</tr>
<tr>
<td>Average HRR$_{excl.~burner}$</td>
<td>398 kW</td>
<td></td>
</tr>
<tr>
<td>Total Heat Released (Excluding Burner)</td>
<td>239 MJ</td>
<td></td>
</tr>
<tr>
<td>Maximum HRR$_{10~min}$</td>
<td>N/A*</td>
<td></td>
</tr>
<tr>
<td>HRR$_{12~min}$</td>
<td>N/A*</td>
<td></td>
</tr>
<tr>
<td>Maximum Flame Height</td>
<td>&gt; 2.4 m</td>
<td>7 min 0 sec</td>
</tr>
<tr>
<td>Heat Flux at 4 ft</td>
<td>130 kW/m²</td>
<td>2 min 46 sec</td>
</tr>
<tr>
<td>Maximum Smoke Generation Rate$_{0-10~min}$</td>
<td>3.82 g/s</td>
<td>2 min 38 sec</td>
</tr>
<tr>
<td>Smoke Generation Rate$_{12min}$</td>
<td>N/A*</td>
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</tr>
<tr>
<td>Total Smoke Generated</td>
<td>484 g</td>
<td></td>
</tr>
<tr>
<td>Maximum Smoke Release Rate$_{0-10~min}$</td>
<td>33.26 m³/s</td>
<td>2 min 46 sec</td>
</tr>
<tr>
<td>Average Smoke Release Rate$_{12min}$</td>
<td>5.86 m³/s</td>
<td></td>
</tr>
<tr>
<td>Total Smoke Released</td>
<td>3518 m³</td>
<td></td>
</tr>
<tr>
<td>Maximum Optical Density</td>
<td>1.96 l/m</td>
<td>2 min 38 sec</td>
</tr>
<tr>
<td>Maximum Duct Flow Rate</td>
<td>7.38 m³/s</td>
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</tr>
<tr>
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<td>Total Mass Loss</td>
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<tr>
<td>Maximum Sample Backside Temperature</td>
<td>100°C</td>
<td>12 min 7 sec</td>
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</table>

* N/A: Not Applicable
SMOKE RELEASE RATE AND TOTAL SMOKE RELEASED

VOLUMETRIC DUCT FLOW RATE AND OPTICAL DENSITY
### SUMMARY OF TEST RESULTS

**Material:** GRP - Coated - Run 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum $HRR_{\text{total}}$</td>
<td>152 kW</td>
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</tr>
<tr>
<td>Average $HRR_{\text{total}}$</td>
<td>89 kW</td>
<td></td>
</tr>
<tr>
<td>Total Heat Released</td>
<td>53 MJ</td>
<td></td>
</tr>
<tr>
<td>Maximum $HRR_{\text{excl. burner}}$</td>
<td>94 kW</td>
<td>3 min 21 sec</td>
</tr>
<tr>
<td>Average $HRR_{\text{excl. burner}}$</td>
<td>33 kW</td>
<td></td>
</tr>
<tr>
<td>Total Heat Released (Excluding Burner)</td>
<td>20 MJ</td>
<td></td>
</tr>
<tr>
<td>Maximum $HRR_{10 \text{ min}}$</td>
<td>N/A*</td>
<td></td>
</tr>
<tr>
<td>$HRR_{12 \text{ min}}$</td>
<td>N/A*</td>
<td></td>
</tr>
<tr>
<td>Maximum Flame Height</td>
<td>&gt; 2.4 m</td>
<td>7 min 0 sec</td>
</tr>
<tr>
<td>Heat Flux at 4 ft</td>
<td>45 kW/m²</td>
<td>2 min 48 sec</td>
</tr>
<tr>
<td>Maximum Smoke Generation Rate$_{0-10 \text{ min}}$</td>
<td>0.24 g/s</td>
<td>2 min 19 sec</td>
</tr>
<tr>
<td>Smoke Generation Rate$_{12 \text{ min}}$</td>
<td>N/A*</td>
<td></td>
</tr>
<tr>
<td>Total Smoke Generated</td>
<td>39 g</td>
<td></td>
</tr>
<tr>
<td>Maximum Smoke Release Rate</td>
<td>2.07 m²/s</td>
<td>2 min 48 sec</td>
</tr>
<tr>
<td>Average Smoke Release Rate</td>
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<td>Total Smoke Released</td>
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<tr>
<td>Maximum Optical Density</td>
<td>0.15 1/m</td>
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<td>Maximum Duct Flow Rate</td>
<td>6.04 m³/s</td>
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</tr>
<tr>
<td>Average Optical Density</td>
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<tr>
<td>Average Volumetric Duct Flow Rate</td>
<td>6.00 m³/s</td>
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</tr>
<tr>
<td>Total Mass Loss</td>
<td>2.01 kg</td>
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</tr>
<tr>
<td>Smoke Yield</td>
<td>0.019</td>
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</tr>
<tr>
<td>Maximum Sample Backside Temperature</td>
<td>68°C</td>
<td>11 min 59 sec</td>
</tr>
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</table>
SMOKE RELEASE RATE AND TOTAL SMOKE RELEASED

VOLUMETRIC DUCT FLOW RATE AND OPTICAL DENSITY
TEMPERATURES AT 2, 4, 6, AND 8 FT

BACKSIDE OF SAMPLE TEMPERATURES
# SUMMARY OF TEST RESULTS

**Material:** GRP - Coated - Run 2

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<tr>
<th>Parameter</th>
<th>Value</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum $HRR_{total}$</td>
<td>128 kW</td>
<td>2 min 47 sec</td>
</tr>
<tr>
<td>Average $HRR_{total}$</td>
<td>97 kW</td>
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</tr>
<tr>
<td>Total Heat Released</td>
<td>58 MJ</td>
<td></td>
</tr>
<tr>
<td>Maximum $HRR_{excl. burner}$</td>
<td>69 kW</td>
<td>2 min 47 sec</td>
</tr>
<tr>
<td>Average $HRR_{excl. burner}$</td>
<td>20 kW</td>
<td></td>
</tr>
<tr>
<td>Total Heat Released (Excluding Burner)</td>
<td>12 MJ</td>
<td></td>
</tr>
<tr>
<td>Maximum $HRR_{10 \text{ min}}$</td>
<td>N/A*</td>
<td></td>
</tr>
<tr>
<td>$HRR_{12 \text{ min}}$</td>
<td>N/A*</td>
<td></td>
</tr>
<tr>
<td>Maximum Flame Height</td>
<td>&gt; 2.4 m</td>
<td>7 min 0 sec</td>
</tr>
<tr>
<td>Heat Flux at 4 ft</td>
<td>36 kW/m²</td>
<td>2 min 46 sec</td>
</tr>
<tr>
<td>Maximum Smoke Generation Rate$_{0-10 \text{ min}}$</td>
<td>0.18 g/s</td>
<td>2 min 32 sec</td>
</tr>
<tr>
<td>Smoke Generation Rate$_{12 \text{ min}}$</td>
<td>N/A*</td>
<td></td>
</tr>
<tr>
<td>Total Smoke Generated</td>
<td>34 g</td>
<td></td>
</tr>
<tr>
<td>Maximum Smoke Release Rate</td>
<td>1.55 m²/s</td>
<td>2 min 46 sec</td>
</tr>
<tr>
<td>Average Smoke Release Rate</td>
<td>0.60 m²/s</td>
<td></td>
</tr>
<tr>
<td>Total Smoke Released</td>
<td>360 m²</td>
<td></td>
</tr>
<tr>
<td>Maximum Optical Density</td>
<td>0.11 1/m</td>
<td>2 min 5 sec</td>
</tr>
<tr>
<td>Maximum Duct Flow Rate</td>
<td>5.95 m³/s</td>
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</tr>
<tr>
<td>Average Optical Density</td>
<td>0.032 1/m</td>
<td></td>
</tr>
<tr>
<td>Average Volumetric Duct Flow Rate</td>
<td>5.99 m³/s</td>
<td></td>
</tr>
<tr>
<td>Total Mass Loss</td>
<td>1.44 kg</td>
<td></td>
</tr>
<tr>
<td>Smoke Yield</td>
<td>0.024</td>
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</tr>
<tr>
<td>Maximum Sample Backside Temperature</td>
<td>62°C</td>
<td>15 min 0 sec</td>
</tr>
</tbody>
</table>
Sample Mass

Heat Flux at 4 FT
TEMPERATURES AT 2, 4, 6, AND 8 FT

BACKSIDE OF SAMPLE TEMPERATURES
## SUMMARY OF TEST RESULTS

**Material:** *Steel - Uncoated - Run 1*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum $HRR_{total}$</td>
<td>66 kW</td>
<td>1 min 35 sec</td>
</tr>
<tr>
<td>Average $HRR_{total}$</td>
<td>46 kW</td>
<td></td>
</tr>
<tr>
<td>Total Heat Released</td>
<td>28 MJ</td>
<td></td>
</tr>
<tr>
<td>Maximum $HRR_{excl. burner}$</td>
<td>35 kW</td>
<td>10 min 3 sec</td>
</tr>
<tr>
<td>Average $HRR_{excl. burner}$</td>
<td>0 kW</td>
<td></td>
</tr>
<tr>
<td>Total Heat Released (Excluding Burner)</td>
<td>0 MJ</td>
<td></td>
</tr>
<tr>
<td>Maximum $HRR_{10\ min}$</td>
<td>N/A*</td>
<td></td>
</tr>
<tr>
<td>$HRR_{12\ min}$</td>
<td>N/A*</td>
<td></td>
</tr>
<tr>
<td>Maximum Flame Height</td>
<td>&gt; 2.4 m</td>
<td>7 min 0 sec</td>
</tr>
<tr>
<td>Heat Flux at 4 ft</td>
<td>5 kW/m²</td>
<td>3 min 44 sec</td>
</tr>
<tr>
<td>Maximum Smoke Generation Rate$_{0-10\ min}$</td>
<td>0.02 g/s</td>
<td>5 min 55 sec</td>
</tr>
<tr>
<td>Smoke Generation Rate$_{12\ min}$</td>
<td>N/A*</td>
<td></td>
</tr>
<tr>
<td>Total Smoke Generated</td>
<td>6 g</td>
<td></td>
</tr>
<tr>
<td>Maximum Smoke Release Rate</td>
<td>0.15 m²/s</td>
<td>3 min 44 sec</td>
</tr>
<tr>
<td>Average Smoke Release Rate</td>
<td>0.08 m²/s</td>
<td></td>
</tr>
<tr>
<td>Total Smoke Released</td>
<td>51 m²</td>
<td></td>
</tr>
<tr>
<td>Maximum Optical Density</td>
<td>0.01 1/m</td>
<td>10 min 6 sec</td>
</tr>
<tr>
<td>Maximum Duct Flow Rate</td>
<td>6.37 m³/s</td>
<td></td>
</tr>
<tr>
<td>Average Optical Density</td>
<td>0.005 1/m</td>
<td></td>
</tr>
<tr>
<td>Average Volumetric Duct Flow Rate</td>
<td>6.45 m³/s</td>
<td></td>
</tr>
<tr>
<td>Total Mass Loss</td>
<td>2.17 kg</td>
<td></td>
</tr>
<tr>
<td>Smoke Yield</td>
<td>0.003</td>
<td></td>
</tr>
<tr>
<td>Maximum Sample Backside Temperature</td>
<td>49°C</td>
<td>12 min 3 sec</td>
</tr>
</tbody>
</table>
HEAT RELEASE RATE

- HRR Burner
- HRR Excluding Burner
- HRR Total

TOTAL HEAT RELEASED

- THR Excluding Burner
- THR Total
SMOKE RELEASE RATE AND TOTAL SMOKE RELEASED

VOLUMETRIC DUCT FLOW RATE AND OPTICAL DENSITY
## SUMMARY OF TEST RESULTS

**Material:** Steel - Uncoated - Run 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum $HRR_{\text{total}}$</td>
<td>64 kW at 1 min 36 sec</td>
<td></td>
</tr>
<tr>
<td>Average $HRR_{\text{total}}$</td>
<td>51 kW</td>
<td></td>
</tr>
<tr>
<td>Total Heat Released</td>
<td>31 MJ</td>
<td></td>
</tr>
<tr>
<td>Maximum $HRR_{\text{excl. burner}}$</td>
<td>55 kW at 12 min 13 sec</td>
<td></td>
</tr>
<tr>
<td>Average $HRR_{\text{excl. burner}}$</td>
<td>1 kW</td>
<td></td>
</tr>
<tr>
<td>Total Heat Released (Excluding Burner)</td>
<td>1 MJ</td>
<td></td>
</tr>
<tr>
<td>Maximum $HRR_{10\text{ min}}$</td>
<td>N/A*</td>
<td></td>
</tr>
<tr>
<td>$HRR_{12\text{ min}}$</td>
<td>N/A*</td>
<td></td>
</tr>
<tr>
<td>Maximum Flame Height</td>
<td>&gt; 2.4 m at 7 min 0 sec</td>
<td></td>
</tr>
<tr>
<td>Heat Flux at 4 ft</td>
<td>3 kW/m² at 0 min 49 sec</td>
<td></td>
</tr>
<tr>
<td>Maximum Smoke Generation Rate$_{0-10\text{ min}}$</td>
<td>0.02 g/s at 9 min 46 sec</td>
<td></td>
</tr>
<tr>
<td>Smoke Generation Rate$_{12\text{ min}}$</td>
<td>N/A*</td>
<td></td>
</tr>
<tr>
<td>Total Smoke Generated</td>
<td>6 g</td>
<td></td>
</tr>
<tr>
<td>Maximum Smoke Release Rate</td>
<td>0.21 m³/s at 0 min 49 sec</td>
<td></td>
</tr>
<tr>
<td>Average Smoke Release Rate</td>
<td>0.09 m³/s</td>
<td></td>
</tr>
<tr>
<td>Total Smoke Released</td>
<td>56 m³</td>
<td></td>
</tr>
<tr>
<td>Maximum Optical Density</td>
<td>0.01 l/m at 10 min 4 sec</td>
<td></td>
</tr>
<tr>
<td>Maximum Duct Flow Rate</td>
<td>6.33 m³/s</td>
<td></td>
</tr>
<tr>
<td>Average Optical Density</td>
<td>0.006 l/m</td>
<td></td>
</tr>
<tr>
<td>Average Volumetric Duct Flow Rate</td>
<td>6.43 m³/s</td>
<td></td>
</tr>
<tr>
<td>Total Mass Loss</td>
<td>0.54 kg</td>
<td></td>
</tr>
<tr>
<td>Smoke Yield</td>
<td>0.011</td>
<td></td>
</tr>
<tr>
<td>Maximum Sample Backside Temperature</td>
<td>59°C at 11 min 48 sec</td>
<td></td>
</tr>
</tbody>
</table>
SMOKE RELEASE RATE AND TOTAL SMOKE RELEASED

VOLUMETRIC DUCT FLOW RATE AND OPTICAL DENSITY
TEMPERATURES AT 2, 4, 6, AND 8 FT

BACKSIDE OF SAMPLE TEMPERATURES
## SUMMARY OF TEST RESULTS

**Material:**  *Steel - Coated with Pitt Char XP*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum HRR(_{\text{total}})</td>
<td>130 kW</td>
<td>3 min 7 sec</td>
</tr>
<tr>
<td>Average HRR(_{\text{total}})</td>
<td>80 kW</td>
<td></td>
</tr>
<tr>
<td>Total Heat Released</td>
<td>48 MJ</td>
<td></td>
</tr>
<tr>
<td>Maximum HRR(_{\text{excl. burner}})</td>
<td>72 kW</td>
<td>3 min 7 sec</td>
</tr>
<tr>
<td>Average HRR(_{\text{excl. burner}})</td>
<td>23 kW</td>
<td></td>
</tr>
<tr>
<td>Total Heat Released (Excluding Burner)</td>
<td>14 MJ</td>
<td></td>
</tr>
<tr>
<td>Maximum HRR(_{10 \text{ min}})</td>
<td>N/A*</td>
<td></td>
</tr>
<tr>
<td>HRR(_{12 \text{ min}})</td>
<td>N/A*</td>
<td></td>
</tr>
<tr>
<td>Maximum Flame Height</td>
<td>&gt; 2.4 m</td>
<td>7 min 0 sec</td>
</tr>
<tr>
<td>Heat Flux at 4 ft</td>
<td>28 kW/m²</td>
<td>3 min 7 sec</td>
</tr>
<tr>
<td>Maximum Smoke Generation Rate(_{0-10 \text{ min}})</td>
<td>0.16 g/s</td>
<td>2 min 53 sec</td>
</tr>
<tr>
<td>Smoke Generation Rate(_{12 \text{ min}})</td>
<td>N/A*</td>
<td></td>
</tr>
<tr>
<td>Total Smoke Generated</td>
<td>32 g</td>
<td></td>
</tr>
<tr>
<td>Maximum Smoke Release Rate</td>
<td>1.37 m²/s</td>
<td>3 min 7 sec</td>
</tr>
<tr>
<td>Average Smoke Release Rate</td>
<td>0.51 m²/s</td>
<td></td>
</tr>
<tr>
<td>Total Smoke Released</td>
<td>307 m²</td>
<td></td>
</tr>
<tr>
<td>Maximum Optical Density</td>
<td>0.10 1/m</td>
<td>2 min 53 sec</td>
</tr>
<tr>
<td>Maximum Duct Flow Rate</td>
<td>5.92 m³/s</td>
<td></td>
</tr>
<tr>
<td>Average Optical Density</td>
<td>0.030 1/m</td>
<td></td>
</tr>
<tr>
<td>Average Volumetric Duct Flow Rate</td>
<td>6.02 m³/s</td>
<td></td>
</tr>
<tr>
<td>Total Mass Loss</td>
<td>1.44 kg</td>
<td></td>
</tr>
<tr>
<td>Smoke Yield</td>
<td>0.022</td>
<td></td>
</tr>
<tr>
<td>Maximum Sample Backside Temperature</td>
<td>62°C</td>
<td>10 min 27 sec</td>
</tr>
</tbody>
</table>
SMOKE RELEASE RATE AND TOTAL SMOKE RELEASED

Smoke Release Rate

Total Smoke Released

VOLUMETRIC DUCT FLOW RATE AND OPTICAL DENSITY

Volumetric Flow

Optical Density

Time (min)

Optical Density (m²)

Volumetric Flow Rate (m³/s)

Time (min)
TEMPERATURES AT 2, 4, 6, AND 8 FT

BACKSIDE OF SAMPLE TEMPERATURES
### SUMMARY OF TEST RESULTS

**Material:** Red Oak Plywood - Uncoated - Run 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum $HRR_{\text{total}}$</td>
<td>392 kW</td>
<td>1 min 55 sec</td>
</tr>
<tr>
<td>Average $HRR_{\text{total}}$</td>
<td>159 kW</td>
<td></td>
</tr>
<tr>
<td>Total Heat Released</td>
<td>96 MJ</td>
<td></td>
</tr>
<tr>
<td>Maximum $HRR_{\text{excl. burner}}$</td>
<td>333 kW</td>
<td>1 min 55 sec</td>
</tr>
<tr>
<td>Average $HRR_{\text{excl. burner}}$</td>
<td>102 kW</td>
<td></td>
</tr>
<tr>
<td>Total Heat Released (Excluding Burner)</td>
<td>61 MJ</td>
<td></td>
</tr>
<tr>
<td>Maximum $HRR_{10 \text{ min}}$</td>
<td>N/A*</td>
<td></td>
</tr>
<tr>
<td>$HRR_{12 \text{ min}}$</td>
<td>N/A*</td>
<td></td>
</tr>
<tr>
<td>Maximum Flame Height</td>
<td>&gt; 2.4 m</td>
<td>7 min 0 sec</td>
</tr>
<tr>
<td>Heat Flux at 4 ft</td>
<td>58 kW/m²</td>
<td>1 min 48 sec</td>
</tr>
<tr>
<td>Maximum Smoke Generation Rate$_{0-10 \text{ min}}$</td>
<td>0.08 g/s</td>
<td>9 min 46 sec</td>
</tr>
<tr>
<td>Smoke Generation Rate$_{12 \text{ min}}$</td>
<td>N/A*</td>
<td></td>
</tr>
<tr>
<td>Total Smoke Generated</td>
<td>17 g</td>
<td></td>
</tr>
<tr>
<td>Maximum Smoke Release Rate</td>
<td>1.58 m²/s</td>
<td>1 min 48 sec</td>
</tr>
<tr>
<td>Average Smoke Release Rate</td>
<td>0.28 m²/s</td>
<td></td>
</tr>
<tr>
<td>Total Smoke Released</td>
<td>170 m²</td>
<td></td>
</tr>
<tr>
<td>Maximum Optical Density</td>
<td>0.10 l/m</td>
<td>10 min 25 sec</td>
</tr>
<tr>
<td>Maximum Duct Flow Rate</td>
<td>6.63 m³/s</td>
<td></td>
</tr>
<tr>
<td>Average Optical Density</td>
<td>0.017 l/m</td>
<td></td>
</tr>
<tr>
<td>Average Volumetric Duct Flow Rate</td>
<td>6.55 m³/s</td>
<td></td>
</tr>
<tr>
<td>Total Mass Loss</td>
<td>7.58 kg</td>
<td></td>
</tr>
<tr>
<td>Smoke Yield</td>
<td>0.002</td>
<td></td>
</tr>
<tr>
<td>Maximum Sample Backside Temperature</td>
<td>70°C</td>
<td>11 min 59 sec</td>
</tr>
</tbody>
</table>

* N/A: Not Applicable
### SUMMARY OF TEST RESULTS

**Material:** Red Oak Plywood - Uncoated - Run 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum ( HRR_{total} )</td>
<td>455 kW at 1 min 52 sec</td>
</tr>
<tr>
<td>Average ( HRR_{total} )</td>
<td>163 kW</td>
</tr>
<tr>
<td>Total Heat Released</td>
<td>98 MJ</td>
</tr>
<tr>
<td>Maximum ( HRR_{excl.\ burner} )</td>
<td>396 kW at 1 min 52 sec</td>
</tr>
<tr>
<td>Average ( HRR_{excl.\ burner} )</td>
<td>106 kW</td>
</tr>
<tr>
<td>Total Heat Released (Excluding Burner)</td>
<td>63 MJ</td>
</tr>
<tr>
<td>Maximum ( HRR_{10\ min} ) ( HRR_{12\ min} )</td>
<td>N/A*</td>
</tr>
<tr>
<td>Maximum Flame Height</td>
<td>&gt; 2.4 m at 7 min 0 sec</td>
</tr>
<tr>
<td>Heat Flux at 4 ft</td>
<td>62 kW/m² at 1 min 39 sec</td>
</tr>
<tr>
<td>Maximum Smoke Generation Rate ( \text{tot}_{0-10\ min} )</td>
<td>0.05 g/s at 9 min 37 sec</td>
</tr>
<tr>
<td>Smoke Generation Rate ( \text{tot}_{12\ min} )</td>
<td>N/A*</td>
</tr>
<tr>
<td>Total Smoke Generated</td>
<td>16 g</td>
</tr>
<tr>
<td>Maximum Smoke Release Rate</td>
<td>1.09 m²/s at 1 min 39 sec</td>
</tr>
<tr>
<td>Average Smoke Release Rate</td>
<td>0.28 m²/s</td>
</tr>
<tr>
<td>Total Smoke Released</td>
<td>165 m²</td>
</tr>
<tr>
<td>Maximum Optical Density</td>
<td>0.07 l/m at 10 min 46 sec</td>
</tr>
<tr>
<td>Maximum Duct Flow Rate</td>
<td>6.45 m³/s</td>
</tr>
<tr>
<td>Average Optical Density</td>
<td>0.017 l/m</td>
</tr>
<tr>
<td>Average Volumetric Duct Flow Rate</td>
<td>6.61 m³/s</td>
</tr>
<tr>
<td>Total Mass Loss</td>
<td>7.31 kg</td>
</tr>
<tr>
<td>Smoke Yield</td>
<td>0.002</td>
</tr>
<tr>
<td>Maximum Backside Temperature</td>
<td>73°C at 11 min 59 sec</td>
</tr>
</tbody>
</table>
Heating Release Rate

- HRR Burner
- HRR Excluding Burner
- HRR Total

Total Heat Released

- THR Excluding Burner
- THR Total

Heat Release Rate (kW)

Time (min)

Total Heat Released (MJ)
SMOKE RELEASE RATE AND TOTAL SMOKE RELEASED

VOLUMETRIC DUCT FLOW RATE AND OPTICAL DENSITY
**SUMMARY OF TEST RESULTS**

Material: *Red Oak Plywood - Coated with Pitt Char XP*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum HRR&lt;sub&gt;total&lt;/sub&gt;</td>
<td>124 kW</td>
<td>at 2 min 28 sec</td>
</tr>
<tr>
<td>Average HRR&lt;sub&gt;total&lt;/sub&gt;</td>
<td>74 kW</td>
<td></td>
</tr>
<tr>
<td>Total Heat Released</td>
<td>45 MJ</td>
<td></td>
</tr>
<tr>
<td>Maximum HRR&lt;sub&gt;excl. burner&lt;/sub&gt;</td>
<td>66 kW</td>
<td>at 2 min 28 sec</td>
</tr>
<tr>
<td>Average HRR&lt;sub&gt;excl. burner&lt;/sub&gt;</td>
<td>18 kW</td>
<td></td>
</tr>
<tr>
<td>Total Heat Released (Excluding Burner)</td>
<td>11 MJ</td>
<td></td>
</tr>
<tr>
<td>Maximum HRR&lt;sub&gt;10 min&lt;/sub&gt;</td>
<td>N/A*</td>
<td></td>
</tr>
<tr>
<td>HRR&lt;sub&gt;12 min&lt;/sub&gt;</td>
<td>N/A*</td>
<td></td>
</tr>
<tr>
<td>Maximum Flame Height</td>
<td>&gt; 2.4 m</td>
<td>at 7 min 0 sec</td>
</tr>
<tr>
<td>Heat Flux at 4 ft</td>
<td>22 kW/m²</td>
<td>at 2 min 30 sec</td>
</tr>
<tr>
<td>Maximum Smoke Generation Rate&lt;sub&gt;0-10 min&lt;/sub&gt;</td>
<td>0.18 g/s</td>
<td>at 2 min 14 sec</td>
</tr>
<tr>
<td>Smoke Generation Rate&lt;sub&gt;12min&lt;/sub&gt;</td>
<td>N/A*</td>
<td></td>
</tr>
<tr>
<td>Total Smoke Generated</td>
<td>32 g</td>
<td></td>
</tr>
<tr>
<td>Maximum Smoke Release Rate</td>
<td>1.56 m²/s</td>
<td>at 2 min 30 sec</td>
</tr>
<tr>
<td>Average Smoke Release Rate</td>
<td>0.51 m²/s</td>
<td></td>
</tr>
<tr>
<td>Total Smoke Released</td>
<td>308 m³</td>
<td></td>
</tr>
<tr>
<td>Maximum Optical Density</td>
<td>0.11 1/m</td>
<td>at 2 min 23 sec</td>
</tr>
<tr>
<td>Maximum Duct Flow Rate</td>
<td>6.02 m³/s</td>
<td></td>
</tr>
<tr>
<td>Average Optical Density</td>
<td>0.030 1/m</td>
<td></td>
</tr>
<tr>
<td>Average Volumetric Duct Flow Rate</td>
<td>6.00 m³/s</td>
<td></td>
</tr>
<tr>
<td>Total Mass Loss</td>
<td>2.01 kg</td>
<td></td>
</tr>
<tr>
<td>Smoke Yield</td>
<td>0.016</td>
<td></td>
</tr>
<tr>
<td>Maximum Sample Backside Temperature</td>
<td>38°C</td>
<td>at 11 min 55 sec</td>
</tr>
</tbody>
</table>
SMOKE RELEASE RATE AND TOTAL SMOKE RELEASED

- Smoke Release Rate
- Total Smoke Released

VOLUMETRIC DUCT FLOW RATE AND OPTICAL DENSITY

- Volumetric Flow
- Optical Density
TEMPERATURES AT 2, 4, 6, AND 8 FT

BACKSIDE OF SAMPLE TEMPERATURES
## SUMMARY OF TEST RESULTS

**Material:** *Gypsum Wallboard - Uncoated - Run 1*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum HRR$_{\text{total}}$</td>
<td>67 kW</td>
<td>1 min 38 sec</td>
</tr>
<tr>
<td>Average HRR$_{\text{total}}$</td>
<td>50 kW</td>
<td></td>
</tr>
<tr>
<td>Total Heat Released</td>
<td>30 MJ</td>
<td></td>
</tr>
<tr>
<td>Maximum HRR$_{\text{excl. burner}}$</td>
<td>55 kW</td>
<td>12 min 9 sec</td>
</tr>
<tr>
<td>Average HRR$_{\text{excl. burner}}$</td>
<td>1 kW</td>
<td></td>
</tr>
<tr>
<td>Total Heat Released (Excluding Burner)</td>
<td>1 MJ</td>
<td></td>
</tr>
<tr>
<td>Maximum HRR$_{10 \text{ min}}$</td>
<td>N/A*</td>
<td></td>
</tr>
<tr>
<td>HRR$_{12 \text{ min}}$</td>
<td>N/A*</td>
<td></td>
</tr>
<tr>
<td>Maximum Flame Height</td>
<td>&gt; 2.4 m</td>
<td>7 min 0 sec</td>
</tr>
<tr>
<td>Heat Flux at 4 ft</td>
<td>4 kW/m²</td>
<td>1 min 45 sec</td>
</tr>
<tr>
<td>Maximum Smoke Generation Rate$_{0-10 \text{ min}}$</td>
<td>0.01 g/s</td>
<td>3 min 20 sec</td>
</tr>
<tr>
<td>Smoke Generation Rate$_{12 \text{ min}}$</td>
<td>N/A*</td>
<td></td>
</tr>
<tr>
<td>Total Smoke Generated</td>
<td>1 g</td>
<td></td>
</tr>
<tr>
<td>Maximum Smoke Release Rate</td>
<td>0.12 m²/s</td>
<td>1 min 45 sec</td>
</tr>
<tr>
<td>Average Smoke Release Rate</td>
<td>0.09 m²/s</td>
<td></td>
</tr>
<tr>
<td>Total Smoke Released</td>
<td>56 m²</td>
<td></td>
</tr>
<tr>
<td>Maximum Optical Density</td>
<td>0.01 l/m</td>
<td>11 min 54 sec</td>
</tr>
<tr>
<td>Maximum Duct Flow Rate</td>
<td>6.48 m³/s</td>
<td></td>
</tr>
<tr>
<td>Average Optical Density</td>
<td>0.001 l/m</td>
<td></td>
</tr>
<tr>
<td>Average Volumetric Duct Flow Rate</td>
<td>6.43 m³/s</td>
<td></td>
</tr>
<tr>
<td>Total Mass Loss</td>
<td>1.08 kg</td>
<td></td>
</tr>
<tr>
<td>Smoke Yield</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>Maximum Sample Backside Temperature</td>
<td>40°C</td>
<td>11 min 49 sec</td>
</tr>
</tbody>
</table>

*N/A* indicates not applicable.
HEAT RELEASE RATE

- HRR Burner
- HRR Excluding Burner
- HRR Total

TOTAL HEAT RELEASED

- THR Excluding Burner
- THR Total
SAMPLE MASS

HEAT FLUX AT 4 FT
## SUMMARY OF TEST RESULTS

**Material:** Gypsum Wallboard - Uncoated - Run 2

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Value</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum HRR_{total}</td>
<td>69 kW</td>
<td>8 min 46 sec</td>
</tr>
<tr>
<td>Average HRR_{total}</td>
<td>50 kW</td>
<td></td>
</tr>
<tr>
<td>Total Heat Released</td>
<td>30 MJ</td>
<td></td>
</tr>
<tr>
<td>Maximum HRR_{excl. burner}</td>
<td>37 kW</td>
<td>10 min 4 sec</td>
</tr>
<tr>
<td>Average HRR_{excl. burner}</td>
<td>0 kW</td>
<td></td>
</tr>
<tr>
<td>Total Heat Released (Excluding Burner)</td>
<td>0 MJ</td>
<td></td>
</tr>
<tr>
<td>Maximum HRR_{10 min}</td>
<td>N/A*</td>
<td></td>
</tr>
<tr>
<td>HRR_{12 min}</td>
<td>N/A*</td>
<td></td>
</tr>
<tr>
<td>Maximum Flame Height</td>
<td>&gt; 2.4 m</td>
<td>7 min 0 sec</td>
</tr>
<tr>
<td>Heat Flux at 4 ft</td>
<td>6 kW/m²</td>
<td>3 min 48 sec</td>
</tr>
<tr>
<td>Maximum Smoke Generation Rate_{0-10 min}</td>
<td>0.02 g/s</td>
<td>3 min 24 sec</td>
</tr>
<tr>
<td>Smoke Generation Rate_{12 min}</td>
<td>N/A*</td>
<td></td>
</tr>
<tr>
<td>Total Smoke Generated</td>
<td>5 g</td>
<td></td>
</tr>
<tr>
<td>Maximum Smoke Release Rate</td>
<td>0.13 m²/s</td>
<td>3 min 48 sec</td>
</tr>
<tr>
<td>Average Smoke Release Rate</td>
<td>0.06 m²/s</td>
<td></td>
</tr>
<tr>
<td>Total Smoke Released</td>
<td>36 m²</td>
<td></td>
</tr>
<tr>
<td>Maximum Optical Density</td>
<td>0.01 l/m</td>
<td>3 min 10 sec</td>
</tr>
<tr>
<td>Maximum Duct Flow Rate</td>
<td>6.52 m³/s</td>
<td></td>
</tr>
<tr>
<td>Average Optical Density</td>
<td>0.004 l/m</td>
<td></td>
</tr>
<tr>
<td>Average Volumetric Duct Flow Rate</td>
<td>6.46 m³/s</td>
<td></td>
</tr>
<tr>
<td>Total Mass Loss</td>
<td>1.35 kg</td>
<td></td>
</tr>
<tr>
<td>Smoke Yield</td>
<td>0.004</td>
<td></td>
</tr>
<tr>
<td>Maximum Sample Backside Temperature</td>
<td>60°C</td>
<td></td>
</tr>
</tbody>
</table>
SMOKE RELEASE RATE AND TOTAL SMOKE RELEASED

VOLUMETRIC DUCT FLOW RATE AND OPTICAL DENSITY
Heat Flux (kW/m²)

SAMPLE MASS

Time (min)

Mass (kg)

Sample mass values over time.

HEAT FLUX AT 4 FT

Time (min)

Heat Flux (kW/m²)

Heat flux values over time.
## SUMMARY OF TEST RESULTS

**Material:** *Gypsum Wallboard - Coated with Pitt Char XP*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maximum HRR$_{\text{total}}$</strong></td>
<td>164 kW</td>
<td>3 min 13 sec</td>
</tr>
<tr>
<td><strong>Average HRR$_{\text{total}}$</strong></td>
<td>78 kW</td>
<td></td>
</tr>
<tr>
<td><strong>Total Heat Released</strong></td>
<td>47 MJ</td>
<td></td>
</tr>
<tr>
<td><strong>Maximum HRR$_{\text{excl. burner}}$</strong></td>
<td>106 kW</td>
<td>3 min 13 sec</td>
</tr>
<tr>
<td><strong>Average HRR$_{\text{excl. burner}}$</strong></td>
<td>21 kW</td>
<td></td>
</tr>
<tr>
<td><strong>Total Heat Released (Excluding Burner)</strong></td>
<td>13 MJ</td>
<td></td>
</tr>
<tr>
<td><strong>Maximum HRR$_{10 \text{ min}}$</strong></td>
<td>N/A*</td>
<td></td>
</tr>
<tr>
<td><strong>HRR$_{12 \text{ min}}$</strong></td>
<td>N/A*</td>
<td></td>
</tr>
<tr>
<td><strong>Maximum Flame Height</strong></td>
<td>&gt; 2.4 m</td>
<td>7 min 0 sec</td>
</tr>
<tr>
<td><strong>Heat Flux at 4 ft</strong></td>
<td>35 kW/m²</td>
<td>3 min 19 sec</td>
</tr>
<tr>
<td><strong>Maximum Smoke Generation Rate$_{0-10 \text{ min}}$</strong></td>
<td>0.28 g/s</td>
<td>2 min 45 sec</td>
</tr>
<tr>
<td><strong>Smoke Generation Rate$_{12 \text{ min}}$</strong></td>
<td>N/A*</td>
<td></td>
</tr>
<tr>
<td><strong>Total Smoke Generated</strong></td>
<td>36 g</td>
<td></td>
</tr>
<tr>
<td><strong>Maximum Smoke Release Rate</strong></td>
<td>2.41 m²/s</td>
<td>3 min 19 sec</td>
</tr>
<tr>
<td><strong>Average Smoke Release Rate</strong></td>
<td>0.53 m²/s</td>
<td></td>
</tr>
<tr>
<td><strong>Total Smoke Released</strong></td>
<td>316 m²</td>
<td></td>
</tr>
<tr>
<td><strong>Maximum Optical Density</strong></td>
<td>0.18 l/m</td>
<td>2 min 45 sec</td>
</tr>
<tr>
<td><strong>Maximum Duct Flow Rate</strong></td>
<td>5.96 m³/s</td>
<td></td>
</tr>
<tr>
<td><strong>Average Optical Density</strong></td>
<td>0.031 l/m</td>
<td></td>
</tr>
<tr>
<td><strong>Average Volumetric Duct Flow Rate</strong></td>
<td>5.90 m³/s</td>
<td></td>
</tr>
<tr>
<td><strong>Total Mass Loss</strong></td>
<td>1.44 kg</td>
<td></td>
</tr>
<tr>
<td><strong>Smoke Yield</strong></td>
<td>0.025</td>
<td></td>
</tr>
<tr>
<td><strong>Maximum Sample Backside Temperature</strong></td>
<td>87°C</td>
<td>10 min 25 sec</td>
</tr>
</tbody>
</table>

*O-62*
SMOKE RELEASE RATE AND TOTAL SMOKE RELEASED

VOLUMETRIC DUCT FLOW RATE AND OPTICAL DENSITY
SAMPLE MASS

HEAT FLUX AT 4 FT
TEMPERATURES AT 2, 4, 6, AND 8 FT

![Graph showing temperatures at different depths](image)

BACKSIDE OF SAMPLE TEMPERATURE

![Graph showing backside temperature](image)