FIRE TESTS IN A LARGE HALL, USING MANUALLY APPLIED HIGH- AND LOW-PRESSURE WATER SPRAYS

Stefan Särdqvist
Stefan Svensson

Swedish Rescue Service Agency, Revingehy, 247 81 Södra Sandby, Sweden

ABSTRACT

Large-scale fire fighting was investigated, including a comparison between high-pressure and low-pressure manual fire fighting systems and measurements of heat stress on fire fighters. Six tests were performed in a room measuring 14.0 × 7.7 m². The fuel in each test consisted of wooden pallets arranged in 6 stacks with 13 pallets in each stack. Weight loss, gas temperature, heat radiation and room pressure were measured. The nozzle pressures were 7 bar and 25 bar and the flow rates were 1.92, 3.83 and 5.75 kg/s. The tests showed that the ability to reach the burning fuel with water limits the capacity of the fire-fighting attack. The high-pressure system proved more efficient than the low-pressure system. It gave a faster response and required a lower flow to attain the same extinction effect as the low-pressure system.

Keywords: large-scale extinguishing tests, fire suppression, fire fighting, water, high-pressure, BA team.

1. INTRODUCTION

Fire fighting using manually applied water sprays is generally considered to be the basic concept of the fire service. In some situations, the question is raised, as to use the available water in the most efficient way. This includes problems such as minimising water application rate to minimise secondary damage, speeding up the fire fighters work when stretching hoses or when attaching the pump to a fire hydrant. It also includes the actual fire fighting. Apart from organisational matters, for example the required number of fire fighters, regulations prescribe that a safe supply of water should be available to the fire fighters. There is, however, no definition of what is a safe supply. There is also a wide variation in existing recommendations, as has previously been shown [1].

In fire fighting, the surface cooling effect of water sprays is commonly used, and when needed, cooling of hot smoke is employed to make it possible for the fire fighters to approach the fire. The Fire Point Theory, suggested by Rasbach [2] and developed by Beyler [3], predicts the critical water flow rate for extinction. This theory has been validated for the extinction of fires using manually applied sprays [4]. However, the critical flow rate does not give the best use of resources, as it requires a more or less infinite time. Increasing the flow rate above the critical value, causes the total mass of water required to control the fire to decrease, as is shown in Figure 1 [4]. There is an optimum flow giving the smallest total water mass. Above this flow, the total mass of water increases again.

Many fire suppression tests have been reported in the literature. Unfortunately, most of them do not fulfil scientific demands on reproducibility and documentation, due to poorly defined fire scenarios or lack of measurements. The limited number of scientific fire suppression tests reported do not, in general, consider manual fire suppression but rather suppression using sprinkler systems. Also, manual fire suppression tests in which both the rate of mass loss of fuel and gas
temperatures are recorded, are usually concerned with set-ups on a small scale or a medium scale, where the fire is relatively small in comparison with the water flow from the nozzle [5], [6], [7], [8] and [9].

![Graph showing control time and total amount of water as a function of water flow rate.](image)

Figure 1. The control time (solid) and the total amount of water (dotted) as a function of the water flow rate. (Figure from ref. [4].)

As reported by Dotson et al. [10], the workload during fire fighting is very high, especially when using breathing apparatus. This has also been pointed out by Kilbom [11] who, based on investigations among Swedish fire fighters, suggested that firemen over the age of 50 should not perform fire fighting using breathing apparatus, due to an increased risk of physical exhaustion, orthostatic responses and cardiac complications.

A number of tests on physiological aspects of fire fighting have been reported. In these tests, the workload was high in combination with heat stress. The tests indicated that increases in heart rate and body temperature were related to both physical and environmental stress [12], [13], [14]. However, no tests have been found in which heat stress on fire fighters equipped with breathing apparatus, BA teams, has been measured under real fire-fighting conditions and where the workload was low.

This paper describes a series of tests performed in a large-scale structure, using manually applied high- and low-pressure water sprays. The experimental set-up and test procedures were chosen to provide a fire-fighting attack close to the critical capacity of the fire fighters and their equipment. The set-up and details regarding the results are described in greater depth in another report [15]. The purpose of the tests was

- to investigate the capacity of the fire service to fight fires in large spaces,
- to obtain data with the purpose of quantifying this capacity,
- to compare a high-pressure with a low-pressure fire fighting system (pump, hose and nozzle) and
- to measure the heat stress on BA-equipped fire fighters during fire attack.

2. EXPERIMENTAL SET-UP

The tests were performed in a room measuring 14.0 × 7.7 m², 6.3 m in height, constructed with 0.4 m thick walls of concrete. The door used for fire fighter access, measured 1.48 × 2.98 m² (width × height). Inside the room, perpendicular to one side and beside the left side of the door opening was a 2.00 m wide, 1.95 m high radiation shield of lightweight concrete. The distance between the shield and the wall was 0.5 m. See Figure 2 for details.

The fire was similar in all six tests, and is shown in its early stages in Figure 3. The fuel consisted of standard wood pallets arranged in 6 stacks with 13 pallet in each stack. The mean distance between the stacks was 0.4 m. Two different types of pallets were used, measuring 1.2 × 0.8 m² and 1.2 × 1.0 m². The exposed fuel surface was calculated as the surface area exposed to the fire, i.e. all surfaces of the pallets except the surfaces covered by stacking. The moisture content of the fuel was approximately 13%. The pallet arrangement was placed on a load platform in order to measure the weight loss.
The load platform was a steel structure, 4.05 x 3.53 m² and 0.25 m high, resting on three load cells, L1 – L3 (see Figure 2 and Table 1). As an ignition source, a 0.035 m² porous fibreboard soaked in diesel fuel was placed at the bottom of each stack of pallets. All six stacks were ignited manually within a period of 30 s. Times given in this paper are the time from which the first pallet was ignited.

![Diagram of experimental setup and table](image)

**Figure 2.** Experimental set-up used for the tests

**Table 1.** Measuring range and accuracy of measurements as stated by the manufacturer. Item numbers are in accordance with Figure 2.

<table>
<thead>
<tr>
<th>Item #</th>
<th>Measurement (number of devices)</th>
<th>Device denomination</th>
<th>Measuring range</th>
<th>Accuracy of instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1-S2</td>
<td>Radiation (2)</td>
<td>Gunner's radiometer</td>
<td>0 - 100 kW/m²</td>
<td>± 5%</td>
</tr>
<tr>
<td>L1</td>
<td>Mass (1)</td>
<td>Load cell, TML CLP-2000KA</td>
<td>0 - 2000 kg</td>
<td>± 0.5%</td>
</tr>
<tr>
<td>L2-L3</td>
<td>Mass (2)</td>
<td>Load cell, TML CLP-1000KA</td>
<td>0 - 1000 kg</td>
<td>± 0.5%</td>
</tr>
<tr>
<td>T1-T10</td>
<td>Temperature (90)</td>
<td>Thermocouple type K, 0.25 mm</td>
<td>0 - 1300°C</td>
<td>± 0.4%</td>
</tr>
<tr>
<td></td>
<td>Temperature on load cell (1)</td>
<td>Thermocouple type K, 0.25 mm</td>
<td>0 - 1300°C</td>
<td>± 0.4%</td>
</tr>
<tr>
<td>P1</td>
<td>Pressure gauge (1)</td>
<td>Pressure gauge, SI Digima LP</td>
<td>0 - 20 mbar</td>
<td>± 0.5%</td>
</tr>
<tr>
<td>F1</td>
<td>Flow rate (1)</td>
<td>GPI turbine flow meter</td>
<td>1.67 – 16.7 kg/s</td>
<td>± 1%</td>
</tr>
<tr>
<td></td>
<td>Skin &amp; clothing temperature (8)</td>
<td>Thermistor gauge AT31/40</td>
<td>-40 - +120°C</td>
<td>± 0.4°C</td>
</tr>
<tr>
<td></td>
<td>Body temperature</td>
<td>Thermometer, Terumo C402ø</td>
<td></td>
<td>± 0.1°C</td>
</tr>
</tbody>
</table>
The temperature was measured at 60 points in the fire room. Thermocouples were arranged in 10 stacks containing 6 thermocouples equidistant from ceiling to floor, starting 0.30 m from the ceiling and ending 1.00 m above floor (T1 – T10 in Figure 2 and Table 1). The thermocouples in stacks T1, T2, T6 and T7 were located 0.25 m from the walls. The radiation was measured at 2 locations in the room, S1 and S2, using Gunner's radiometers [16]. S1 was placed at the same distance from the fire as the point of fire attack by the fire fighters and S2 was located close to the point where the fire first affected the fire fighters. Both radiometers were located 1.35 m above the floor, pointing 10° upwards towards the longitudinal centre of the fire. The pressure difference between the fire room and the surroundings was also measured 1.10 m above the floor, using a pressure gauge connected to a copper tube (P1). The measurements of the conditions in the fire room were made at a sampling rate of 0.1 Hz.

Measurements on the two fire fighters engaged in fire fighting were also performed of body temperature, weight and fluid balance before and after the attack, and pulse rate during the attack. The skin temperature was measured on one of the fire fighters during the attack. These measurements were registered with a rate of 1 Hz. The fire fighters were dressed in a Rescue Suit 90°, Swedish turnout gear, and they were using Interspiro Spiromatic breathing apparatus.

The tests were documented using an external video camera pointing towards the entrance to the fire room. The fire fighters continuously reported their actions by radio, and the radio traffic was recorded using the microphone on the external video camera. After each test, the fire fighters gave statements regarding their work, and on how the situation felt during the test. The interior of the fire room was documented using a small video camera (K1), with a water-cooled housing. This camera was located 0.5 m above floor, just inside the entrance to the fire room, pointing towards the centre of the fire. During tests 4 and 5,
a hand-held infrared camera was used to document the actions of the fire fighters at position K2. Infrared photography proved to give an excellent view of the actions of the fire fighters through the smoke-filled room, as shown in Figure 4.

![Figure 4](image-url) Photograph taken through smoke during the attack in test 4, using an infra-camera (from position K2 in Figure 2).

Weather conditions, wind and temperature were recorded at the time of each test. The wind speed was measured on the roof of the building, 10 m above the ground, and also just outside the entrance of the fire room, which was protected by surrounding buildings. The temperature was measured in the shade. The wind speed was less than 4 m/s on the roof and less than 1 m/s at the opening during all tests. The weather was sunny and the ambient temperature 17 – 23°C during the tests.

### 3. TEST PROCEDURE

Two different nozzles were used at three different water flow rates. A Protek style #366 low-pressure nozzle and an Akron Force style 751 high-pressure nozzle were used at flow rates of 1.92 and 3.83 kg/s and the Protek nozzle was also used at 5.75 kg/s. The high-pressure pump used during the tests delivered water at approximately 40 bar, giving nozzle pressures of approximately 25 bar. The low-pressure pump delivered water at approximately 11 bar, giving nozzle pressures of approximately 7 bar, see Table 1. The flow rate was registered once per second.

The arithmetic mean water droplet size using the low-pressure nozzle was approximately 0.30 mm at 3.83 kg/s and 7 bar nozzle pressure [17]. The Sauter mean diameter of the droplets from the high-pressure nozzle was 0.487 mm, and the arithmetic mean 0.2122 mm at 6.9 bar and 2.73 kg/s [18].

Six tests were performed. Two parameters were varied, the type of nozzle and the flow rate, while employing a similar extinguishing procedure during all six tests (see Table 3 for details).

Fire fighting commenced when the temperature had reached its peak and stabilised. At this time, the temperature was approximately 700°C at the left-hand end of the room (at T1 and T6) 5 m above the floor. The temperature at the sides (position T2 and T7) was about 600°C and in the rest of the room (T3 – T5 and T8 – T10), the temperature was 450-500°C, at the same height. The pre-burn time was between 6.0 and 7.5 minutes for all tests. Fire fighting was performed at a location 3.0 m from the fuel, see Figure 2. At this location, there was no protection for the fire fighters against radiation from the fire or from water vapour.

Fire fighting was performed manually, and the fire fighters were instructed to act in the same way during the different tests. The same two fire fighters, both of them well-trained professionals, took part in all tests. They had the same assignment in all tests. The attack route was through the doorway, advancing into the room parallel to the radiation shield, then turning left and advancing straight towards the fire along the centreline of the room. On a level with the first radiometer (S2), a short sweep was made with the water spray, 45° upwards, in order to cool the hot gases. Three metres from the fire, on a level with the
second radiometer (S1), the fire fighter with the nozzle halted and started to work on the fire. He used sweeping movements of the water spray alternately towards the fuel in order to cool the fuel surface and reduce the pyrolysis rate, and towards the flames and smoke in order to decrease the temperature to ameliorate the environment in the room and to make it possible to continue the attack.

The test supervisor terminated the fire fighting in tests 2, 3 and 6 when the temperature stabilised at a low level. Tests 4 and 5 were cut short by the fire fighters due to heat penetration. Test 1 was interrupted after the initial attack. This test was much shorter than the others were and is therefore excluded from the results.

<table>
<thead>
<tr>
<th>Test</th>
<th>Net load [kg]</th>
<th>Number of pallets*</th>
<th>Exposed fuel surface [m²]</th>
<th>Pre-burn time [s]</th>
<th>Mass loss rate [kg/s]</th>
<th>Average burning rate [g/m²s]</th>
<th>Estim. rate of heat release [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1269</td>
<td>52+26</td>
<td>185</td>
<td>533</td>
<td>-0.99</td>
<td>5.4</td>
<td>16.8</td>
</tr>
<tr>
<td>2</td>
<td>1234</td>
<td>26+52</td>
<td>198</td>
<td>398</td>
<td>-1.20</td>
<td>6.1</td>
<td>20.4</td>
</tr>
<tr>
<td>3</td>
<td>1435</td>
<td>63+15</td>
<td>179</td>
<td>422</td>
<td>-0.93</td>
<td>5.2</td>
<td>15.8</td>
</tr>
<tr>
<td>4</td>
<td>1159</td>
<td>78+0</td>
<td>172</td>
<td>472</td>
<td>-0.76</td>
<td>4.4</td>
<td>12.9</td>
</tr>
<tr>
<td>5</td>
<td>1411</td>
<td>77+1</td>
<td>172</td>
<td>438</td>
<td>-0.86</td>
<td>5.0</td>
<td>14.6</td>
</tr>
<tr>
<td>6</td>
<td>1294</td>
<td>78+0</td>
<td>172</td>
<td>426</td>
<td>-0.86</td>
<td>5.0</td>
<td>14.6</td>
</tr>
</tbody>
</table>

* Pallets with widths of 1.2 · 0.8 m² and 1.2 · 1.0 m² was used.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.0</td>
<td>6.0 ± 0.5</td>
<td>3.83</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>83</td>
<td>1.52</td>
<td>8</td>
<td>10.4</td>
<td>0.40</td>
</tr>
<tr>
<td>2</td>
<td>39</td>
<td>25 ± 5</td>
<td>3.83</td>
<td>210</td>
<td>253</td>
<td>0.00608</td>
<td>1.28</td>
<td>694</td>
<td>1.46</td>
<td>62</td>
<td>11.2</td>
<td>0.38</td>
</tr>
<tr>
<td>3</td>
<td>7.0</td>
<td>6.0 ± 0.5</td>
<td>3.83</td>
<td>240</td>
<td>286</td>
<td>0.00693</td>
<td>1.66</td>
<td>692</td>
<td>1.26</td>
<td>42</td>
<td>16.5</td>
<td>0.33</td>
</tr>
<tr>
<td>4</td>
<td>5.2</td>
<td>4.5 ± 0.5</td>
<td>1.92</td>
<td>360 **</td>
<td>303 **</td>
<td>0.00479</td>
<td>1.76 **</td>
<td>298</td>
<td>0.843</td>
<td>26</td>
<td>11.5</td>
<td>0.44</td>
</tr>
<tr>
<td>5</td>
<td>35</td>
<td>23 ± 5</td>
<td>1.92</td>
<td>360 **</td>
<td>255 **</td>
<td>0.00404</td>
<td>1.48 **</td>
<td>284</td>
<td>0.708</td>
<td>28</td>
<td>10.2</td>
<td>0.37</td>
</tr>
<tr>
<td>6</td>
<td>8.0</td>
<td>7.0 ± 0.5</td>
<td>5.75</td>
<td>130</td>
<td>152</td>
<td>0.00680</td>
<td>0.88</td>
<td>755</td>
<td>1.50</td>
<td>35</td>
<td>21.6</td>
<td>0.26</td>
</tr>
</tbody>
</table>

* Test halted after initial attack.
** Did not reach the control criterion within six minutes.
4. RESULTS

Figure 5 shows the rate of loss of fuel mass up to the initiation of fire fighting for the six tests. The growth phases of the fires in the individual tests do not show significant differences, which is noteworthy, considering the scale of the tests. When the fire fighting started, the average rate of mass loss was 0.93 kg/s. Standard wooden pallets proved to be a good fire source in a large-scale experiment such as this. As pallets collapse during fire, however, some kind of support is necessary for high stacks. Porous fibreboard soaked in diesel fuel proved to be a very safe and highly reproducible ignition source.

![Graph showing mass change over time](image)

Figure 5. Rate of mass loss up to the time when extinguishing was initiated, represented by the symbols ∗.

The rate of heat release can be estimated using measurements of the rate of mass loss and the equation:

\[ \dot{q} = \dot{m} \cdot \Delta h_f \]

where \( \dot{q} \) is the rate of heat release [MW], \( \dot{m} \) [kg/s] is the rate of mass loss and \( \Delta h_f \) [MJ/kg] is the total heat of combustion, which was based on the value for wood, 17.0 MJ/kg [19]. This method of calculation, which does not consider the limitation in energy release due to the restricted access of air, gives heat release rates according to Table 2. On average, the heat release rate was 15.9 MW when fire fighting was initiated. The chemical heat release can be lower, in small-scale tests, 12.4 MJ/kg [19].

The average burning rate of the fuel, i.e. the rate of mass loss divided by the exposed fuel area, is also given in Table 2. At the commencement of extinction, the burning rate was approximately 5.2 g/m²s. The average burning rate is low, probably due to non-complete involvement of the pallets, especially the pallets at the bottom of the stacks. For comparison, it can be mentioned that the rate of mass loss during the extinction of particleboard was determined to be 5.5 g/m²s, using a flammability apparatus [20].

The mean flow rate was calculated from the measurements of the flow rates. The number of sweeps of the nozzle was also counted and the mass of water per sweep was calculated. See Table 3 for details. It can be seen that the mean flow was considerably lower than the nominal flow. It can also be seen that the mass of water per sweep is slightly lower for the high-pressure nozzle (tests 2 and 5) than for the low-pressure nozzle (tests 3, 4 and 6).

The fire fighters were able to extinguish the fire in the front row of wood pallets, thereby reaching the control criterion, while the back row of pallets continued to burn more or less unaffected. This was illustrated by the load cell measurements in the tests. One row of wood pallets is thus a sufficient obstacle to conceal a fire and to prevent successful extinction.

Load cell 1 is located on the centreline of the platform. Therefore, it registers approximately half the total mass. Load cell 2 is located at the back of the platform, thus measuring primarily the part of the fuel that was not reached by the water. Load cell 3, finally, was located at the front, and registered an increase in weight due to the application of water.

There are also some singularities, which can
be seen in Figure 6 showing the mass on individual load cells and the total mass in test 2. At 750 s, one of the pallet stacks near load cell 1 collapsed, and some of the pallets slid off the load platform, causing a discontinuity in the load signal. At about 450 s a stack of pallets collapsed. This cannot be seen in the total mass curve, but load cell 3 indicated a weight loss while load cell 2 showed a similar increase in weight at that time.

Figure 7 shows individual temperature measurements from thermocouple stack T1. The diagram shows measurements from test 4, using a low-pressure nozzle at a water flow rate of 1.92 kg/s. The extinction period in this test was between 475 and 830 s from the start of the fire. Figure 8 shows the mean temperature of all thermocouples, together with the mean temperature for groups of thermocouples, the upper four and lower two thermocouples, in the front and back of the room, for the same test. In the test report [15], similar diagrams are available for all thermocouple stacks and for all tests.

In Figure 9, mean gas temperatures during the extinction phase are plotted for the completed tests. The mean gas temperature was calculated as an average of the measurements from the 60 thermocouples. The figure shows that the high-pressure system at flow rates of both 3.83 and 1.92 kg/s (tests 2 and 5) reduces the gas tem-
perature faster and to a lower level, than the low-pressure system. The high-pressure system reduces the temperature to its minimum within one minute. Thereafter, the temperature remains constant or increases slowly. The low-pressure system, on the other hand (tests 3, 4 and 6), gives a much slower decrease in gas temperature, reaching a minimum after about three minutes. The final temperatures were not as low as that achieved with the high-pressure system.

The control time can be defined as the time at which the derivative of the mass loss curve is zero, i.e. the time at which the fuel starts to gain weight due to water application. Using this definition, the flow of 1.92 kg/s was not sufficient to gain control of the fire within 360 s using either high or low pressure nozzles (tests 4 and 5), which can be seen in Figure 10. At 3.83 kg/s, the low-pressure system just reached extinction at 240 s (test 3). High-pressure sprays at 3.83 kg/s (test 2) and low-pressure sprays at 4.75 kg/s (test 6) clearly reached the control criterion within 130 s and 210 s, respectively. This is in accordance with the assessment of the fire fighters performing the tests, indicating that the definition of control time is reasonable although the rate of heat release may still be large when control is reached.

The physical workload during the tests was low, involving only movement from the doorway to the point of attack (see Figure 1). Figure 11 shows the pulse rate for the fire fighter operating the nozzle. In test 6, the fire fighter wore a cooling vest. The use of a cooling vest slows down the rise in pulse rate and gave a pulse rate approximately 10 beats per minute lower than in tests 2 - 5. The figure also indicates that the pulse rate increases further after 240 s.
Figure 12 shows the mean pulse rate for tests 2 - 5, the skin temperature and the temperature of the fabric between the inner and outer garment on the fire fighter operating the nozzle. The temperatures are the mean of measurements from both upper arms. The increase in mean pulse rate during tests 2 - 5 is approximately 45 beats per minute 30 seconds from the time when the fire fighters entered the room. The mean skin temperature is approximately 40°C after 240 seconds. This skin temperature is not high enough to cause pain. Pain occurs when the skin temperature exceed 44°C [21]. The mean fabric temperature is approximately 55°C after 240 seconds.

Figure 12. Mean pulse rate and mean temperature on skin and on fabric for the upper arms of the fire fighter operating the nozzle at tests 2-5

After leaving the room, the fire fighters also reported their protective clothing to be too hot to touch with bare hands for a few minutes.

A complete set of diagrams for each test is available in the test report [15]. This includes measurements of skin and fabric temperatures on the fire fighter operating the nozzle, the pulse rate of each fire fighter, water flow, change in mass of the fuel, radiation from the fire, room pressure, gas temperatures measured by individual thermocouples and mean gas temperatures. Tables of body mass for fire fighters are also available. Although written in Swedish, the diagrams are universally understandable.

5. DISCUSSION

During large-scale experiments such as these, especially those involving human performance, a large number of problems, questions and potential errors occur. Problems that arise are primarily associated with the geometry of the fire room, the characteristics of the fuel, fire-fighter performance and the performance characteristics of the measuring equipment. Large-scale experiments are also very time-consuming. The planning process prior to the experiments was, to a great degree concerned with solving these problems.

One of the purposes of the tests was to investigate capability of the fire service to fight fires in large spaces, which strongly influenced the choice of location and fire room. The influence of weather and wind are other factors that must be considered when performing large-scale experiments, to get reproducible results. The time of year and also the time of day for performing such tests can be of vital importance for the results. During the tests described in this paper, the weather was excellent.

The large amount of fuel required for these tests led to the choice of standard sized wooden pallets as fuel. The advantages of this type of fuel are, amongst others, that the pallets are standardised in size, cheap, accessible and manageable. Pallets are also frequently used in industry and their response to fire is predictable. The development of the fire is greatly influenced by the moisture content. The pallets were therefore stored on the same location for a relatively long period of time and the moisture content was uniform in all the fuel.

Due to the purpose of the experiments, which was to compare a high-pressure, manual fire-fighting system (pump, hose and nozzle) with
a low-pressure, manual fire-fighting system, a
human operator was chosen to apply water to the
dire. A professional fire fighter handled the nozzle
and worked the water spray at his own discretion.
This type of procedure can, of course, jeopardise
the reproducibility of the tests, complicate the
comparison between tests and also comparisons
with other tests. These problems were minimised
by restrictions on the fire fighter regarding his
choice of attack route/point of attack, and the
flow rate and cone angle of the water spray. The
fire fighters were also given instructions and were
monitored continuously during the tests. Con-
tinuous monitoring is also an important safety
feature when using human operators in large-
scale experiments, as the risk of injury is high.

Measurements in the field, as opposed to
measurements in a laboratory, place special dem-
ands on the set-up and choice of measuring
equipment. The set-up must be adapted to the fire
room and the equipment must have adequate re-
sistance to wind, weather and particles. The per-
formance characteristics of the measuring equip-
ment are summarised in Table 2. The accuracy of
measurements during large-scale experiments can
be questioned. Based on the information pre-

duced in Table 2 and comparisons of the results
from the six tests, the accuracy is within ac-
ceptable limits. Some data from measurements of
the skin temperature of the fire fighter were lost
due to moisture and poor contact between the
skin and the sensor in combination with the fire
fighter's movements.

The following estimates of heat release rate,
gas temperature and water demand, made using
available models, support the assessment of the
accuracy of the tests. Using the mean rate of mass
loss, the rate of heat release was estimated to be
15.9 MW. The rate of heat release from burning
wooden pallets can also be estimated using the
expression [22]:

\[ \dot{q} = A \cdot 0.97(1 + 2.14 \cdot h_c)(1 - 0.027M) \]

where \( A \) [m\(^2\)] is the floor area of the burning
wood pallets, \( h_c \) [m] is the height of the pallet
stack and \( M \) [%] is the moisture content. This
expression was generated empirically using data
from free-burning stacks of wooden pallets. Us-
ing representative values, the rate of heat released
in the tests carried out here can be estimated:

\[ \dot{q} = 6 \cdot (1.2 \cdot 0.8) \cdot 0.97(1 + 2.14 \cdot 1.85)(1 - 0.027 \cdot 14) \cdot 17 \text{MW} \]

This expression gives a result in accordance
with the values in Table 3 based on the rate of
mass loss of fuel.

Figure 13 shows the results from a compar-
able simulation using HazardI [23]. This model
can be used until the start of extinction, and until
this time, it predicts the descent of the smoke
layer interface and the temperature in the upper
and lower parts of the room. This can be com-
pared, for example, with the photographs in Fig-
ure 3, from camera position K1 in Figure 2. The
photographs show how smoke fills the room at 90
s, 120 s and 180 s after ignition. Provided that the
two-zone approach of HazardI is accepted, the
prediction of the descent of the smoke layer inter-
face is good. However, HazardI predicts, a
smoke-free layer of one metre. In our tests, the
smoke completely filled the room at about 390 s,
mainly due to re-circulation. In fact, the visibility
was so poor in some tests that it was difficult to
find the correct position for the fire fighters.
When the fire fighters approached the fire, they
reported the flames to be just barely visible in
spite of being close to the fire and the flames
being high, from floor to ceiling. Nevertheless,
the fire had grown so large at this stage, that the
two-zone concept of HazardI can be questioned.

Figure 13 also shows the gas temperatures
calculated using HazardI, which can be compared
with the gas temperature in the room, shown in
Figure 8. The model gives quite good agreement,
although the temperature increase in the tests is
slower during the first stage and faster in the later
stage of increase than predicted by HazardI. One
problem lies in selecting suitable thermocouples with which to calculate a representative mean gas temperature in the upper and lower gas layers for comparison with temperatures predicted by HazardI.

The extinction phase can be modelled using the Fire Demand Model (FDM) [24]. This is a one-zone model for the prediction of the water demand when fighting post-flashover fires, by calculating the temperature of the gas and of the walls. Although the model has been developed for external fire fighting, it gives the right trend for the scenario studied here. The water flows required for control are, however, over-predicted. Figure 14 shows the gas temperature predicted by the FDM with input data according to the conditions in our tests. Figure 15 shows the correlation between water droplet size and the water flow required for control.

The result of extinction attempts depends on the coverage of the water spray, which is governed by the nozzle movement, the position of the nozzle and the cone angle. Normally, the nozzle has to be moved and the position varied to cover the whole fuel area. Therefore, the larger the nozzle, the lower the mobility and the lower the efficiency. However, a larger nozzle generally delivers more water, and it can be located a greater distance from the fire, thus covering a larger area.

The cone angle of the water sprays was kept
constant during the tests, see Figure 16. If the spray is idealised by a cone and gravity is neglected, the flow density of the cone [kg/m²s] can be estimated by elementary geometry:

\[ v'_{\text{mean}} = \frac{v}{\pi (L \cdot \tan \alpha / 2)^2} \]

where \( v [\text{kg/s}] \) is flow rate from the nozzle, \( L [\text{m}] \) is the distance from the nozzle and \( \alpha \left[ ^\circ \right] \) is the cone angle. For ordinary nozzles (such as the nozzle used during the tests) the throw of the water \( L_{\text{max}} [\text{m}] \) can be estimated by [25]:

\[ L_{\text{max}} = \frac{18 \cdot v^{0.36} \cdot P^{0.28}}{\alpha^{0.37}} \]

where \( P [\text{bar}] \) is the nozzle pressure. The correlation was developed using visual observations from photographs of water sprays. Estimates of the applied water densities, using the two equations, are shown in Figure 17. During the tests, the fire fighters were positioned 3 m from the fire, giving a distance of 6 m to the far corner of the pallet arrangement.

If the distance between the nozzle and the fire is long, a nozzle with a high flow rate and a small cone angle must be used to obtain the desired throw. This has the further implication that the water density will be high where the water hits the fuel and that the nozzle must be moved vigorously to cover the large area that the amount of water enables. This is also accentuated by non-uniformity of the sprays. A long-distance stream is thus oversized where it hits the fire leading to ineffective use of the extinction capacity of the water.

This problem of distributing the water can be seen in fire tests where the nozzle is fixed in one place, either by mechanical means or by instructing the fire fighter to hold the nozzle stationary. The water flow rate may be sufficient to control the fire, but due to restrictions in nozzle movement, the water flow cannot penetrate the
fire or reach the edges of the fuel exposed to fire.

Fire in wooden fuels cannot normally be extinguished unless the fuel surface is cooled down. This cooling is achieved by spraying the surface with water and in some cases by stopping re-radiation from the flames back to the fuel. This explains why fires, for example, in storage facilities pose considerable problems, as outlined below:

- Knowing where the seat of the fire is. The fire must be located, both on the macro-level (the right street, building and room) and on the micro-level (finding the seat of the fire in a smoke-filled room).
- Approaching the fire. The most efficient way to fight fires is, in many cases, to get a fire fighter with a nozzle close to the fire. There may be physical barriers stopping the fire fighters, or hazards, such as high levels of heat radiation.
- Getting water onto the fuel surfaces. The water from the nozzle must hit the fuel surface to enable cooling. Physical objects can conceal fires although the flames are highly visible, or the fire can be concealed by smoke.

If the fire fighters maintain their positions and do not reposition or by other means redirect their attack, the attack may no longer be regarded as offensive. The aim of an offensive attack is to extinguish the fire. By not repositioning the nozzle (for whatever reason), steady state is established and the aim changes to simply maintaining the current position, strategically speaking. The aim is no longer offensive but rather defensive. So, in spite of the fire fighters working in an extremely vulnerable situation, the aim has implicitly changed to defensive, and the fire fighters will not be able to extinguish the fire. It will instead burn out due to lack of fuel.

![Figure 18. Heat radiation in all tests, measured by radiometer S1.](image)

The total water flow was sufficient to control the fire in some of the tests. The problem was in applying the water locally and in sufficient amounts to all parts of the fire. There is no point in soaking the front row of pallets, if no water reaches the back row. This was clearly illustrated by the fire fighters when they were allowed freedom of movement, after the final measurements. When they were able to move freely, they extinguished the remaining fire in test 6 within one minute using the low-pressure system at a flow rate of 5.75 kg/s.

The tests were performed in an enclosed environment with only one opening. Due to the high gas temperatures in the room, the evaporation of water in the gas phase contributed to the extinction. Evaporation lowered the gas temperature thus decreasing the rate of heat release due to decreasing re-radiation back to the fuel.

Figure 1 shows the principle relation between the control time and the flow rate of water applied to a fire. It can be seen that the tests employing 1.92 kg/s flow of water finished below the critical application rate. A higher flow rate allowed the tests to be controlled. It would, however, be possible to control the fire using a smal-
ler amount of water, if the flow rate were increased. On the other hand, the nozzle is not open continuously, which can be seen in Table 3. Due to the heat and steam generation, it was not possible for the fire fighter to apply a continuous spray.

Considering both fuel surface cooling effects and gas phase extinction effects, the high-pressure system proved to have a better extinguishing capacity per unit mass of water than the low-pressure system with this test set-up. Regarding fuel surface cooling effects, the high-pressure system at a flow rate of 3.83 kg/s was equally efficient as the low-pressure system at 4.75 kg/s, as shown in Figure 10. The gas cooling effect of the high-pressure system at its lowest flow rate was higher than the low-pressure system at all flow rates. When steady state was reached, the high-pressure system at 1.92 kg/s stabilised the gas temperature in the room at the same temperature as when the low-pressure system was employed at both 3.83 and 5.75 kg/s. This is illustrated in Figure 9. Under these test conditions, the high-pressure system only required approximately two-thirds of the water of the low-pressure system for the same extinction capacity.

A likely reason for the increase in the pulse rate of the fire fighters is that the body is trying to compensate for the increasing body temperature by increasing the blood flow. However, the increase in pulse rates during the test was faster than the increase in skin and textile temperature, which increased much more slowly (Figure 12). The pulse rate stabilises at a high level, and it also seems to increase slowly, as indicated in Figure 11. This may be due to the increase in pulse rate being triggered by (mental) stress, in combination with heat stress and body compensation for skin temperature by pulse rate.

The mental stress on the fire fighter was probably greatest in the first test, even though the first test was stopped early, giving a less representative result. The mental stress was probably also lowest in the final test (test 6) than during tests 2 - 5. Although the workload was low, the movements and work carried out by the fire fighters could have an effect on their pulse rate. However, the results from tests 1 and 6, compared with those from tests 2 - 5, indicate that mental stress has great effect on pulse rate.

Tests 4 and 5 were curtailed by the fire fighters due to heat stress and heat penetration through their protective clothing. This shows that the combination of high pulse rate and high skin temperature makes working conditions unbearable after only a few minutes, although the workload is low.

6. CONCLUSIONS

The tests presented in this paper show that good reproducibility and reliability can be achieved in fire suppression tests on a large scale, employing a human fire fighter.

The capability of the fire service to fight fires in large spaces is related to their ability to reach the burning area of the fuel. One row of wood pallets proved to be a sufficient obstacle to "protect" objects behind from the fire-fighting attack. The length of the throw of the water spray may limit the possibility of reaching the fire, regardless of whether the water pressure is high or low, thereby limiting the surface cooling effect.

A comparison between the results obtained when using the high-pressure and the low-pressure fire-fighting systems indicates that the high-pressure system has a better extinguishing effect regarding gas phase extinction. The high-pressure system at flow rates of 1.92 and 3.83 kg/s reduced the temperature more rapidly and to a lower level, than the low-pressure system at the same flow rates.

The flow rate of 1.92 kg/s was, however, not sufficient to attain the control criterion based on mass loss rate. At 3.83 kg/s, both systems attained the control criterion, but the low-pressure system attained it faster than the high-pressure system.

When both surface cooling effects and gas phase effects are considered, the high-pressure
system requires only approximately two-thirds of the water required by the low-pressure system to achieve the same extinction capacity in this scenario.

The increase in pulse rate of the fire fighters appeared to be triggered by mental stress and increased due to increasing skin temperature. Working conditions for fire fighters may be unbearable due to heat stress, although the workload is low.

A great deal of data was collected during these tests, which can be used for further work on quantifying the capacity of fire fighters and their equipment.

ACKNOWLEDGEMENT

The work presented in this paper was supported financially by the Swedish Rescue Services Agency and Brandforsk, the Swedish Fire Research Board.

REFERENCES


16, Gunners Nils-Erik, Methods of Measurement and Measuring Equipment for Fire Tests. Acta Polytechnica Scandinavica, Civil Engi-

17, Chen, M., Castek, MFG Corporation, personal communication Nov. 19 and Dec. 1 1999.


