WISH

Waste Industry Safety and Health Forum

INFORMATION DOCUMENT

WASTE FIRE BURN TRIALS

Summary non-technical report

This document provides a non-technical summary of waste fire burn tests conducted in 2015, 2016 and 2017 – the 'phase 1, 2 and 3 tests'. Formal and detail academic reports on the tests will be produced in the future, but not until academic peer review has been carried-out. This non-technical summary report aims to fill this gap in the interim. It is aimed at providing underpinning and background information for readers of the WISH waste fires guidance and to waste operators in general. This document is a revision of the original non-technical summary produced and released in conjunction with the revised WISH fires guidance issued in April 2017. It is an update to take account of the phase 3 fire tests conducted in late 2017.

Contents

1. Introduction

Prior to the publication of the original 2014 WISH ‘reducing fire risk at waste management sites’ guidance (WISH 28 fires guidance) a thorough literature search was made by the HSL (Health and Safety Laboratories), and the authors of the guidance. The aim was to identify any existing waste fires guidance, research and similar information on the combustion properties of wastes from across the world. Very little relevant information was found. This weakness was noted in the consultation process for the 2014 WISH waste fire guidance.

In the absence of comprehensive detail information on the combustion properties of wastes, and with an urgent need at the time in 2014 to provide the waste industry with guidance on waste fire risk management, what information sources which could be found were used for the 2014 WISH guidance. Sources included buildings fire research, caravan fire research, information from standard insurance industry codes and other similar sources. WISH was not alone in this approach. Various other waste management fire guidance and similar documents from other bodies also being based on the same or similar, and generally non-waste, information sources. The flaws of this approach were noted in the 2014 WISH fire guidance, which stated: *“As knowledge on the burn properties of specific wastes improves, experience of real fires accumulates and as better information becomes available, revisions of this guidance will be made to keep it up to date.”*

Specifically, on waste storage the consultation letter accompanying the 2014 WISH fires guidance (included in the guidance as an appendix) stated: *“There is little available fire testing or science specific to wastes to provide a firm under-pinning for the available information on stack sizes and separation distances – most of the current information is based on operational and fire-fighting experience. There is data on raw materials. Much of this indicates that the separation distances in table 1 in appendix 1 are conservative and separation distances in excess of those currently available for wastes may be required at sites with no fire prevention measures. For example, data on virgin, raw paper and plastics suggests separation distances between 10 - 11 metres and 18 - 27 metres respectively – that is well in excess of those distances quoted in table 1 of appendix 1. Whether this data for raw materials can be applied direct to wastes is not known - real testing on wastes is required.”*

To address this gap in knowledge, in late 2015 and throughout 2016 and 2017 a series of waste burn test were conducted. In late 2015 smaller scale laboratory type testing was conducted at the FPA (Fire Protection Association) research premises. These 'phase 1' tests provided baseline data on parameters such as burn rates and thermal outputs. However, some of the results obtained from this laboratory type testing did not reflect the experience of the Fire and Rescue Services (FRS) when actually tacking waste fires. In brief, for some parameters the laboratory type testing was missing some factor or factors relevant to actual large-scale waste fires.

In 2016 larger-scale waste burn trials were conducted at sites in Yorkshire and Essex (the phase 2 tests). These tests involved much larger volumes of waste and aimed to replicate as closely as practical 'real life' waste fires. The results of these tests matched much more closely the experience of the FRS when fighting real waste fires, and revealed some of the different mechanisms at play during waste fires. Both phase 1 and phase 2 tests were conducted on a variety of wastes such as loose and baled wastes, plastics, paper and board, rubber, wood wastes, waste derived fuels such as RDF and SRF and others.

These phase 1 and 2 tests provided a much better understanding of how wastes burn, and firmer fire science on which to base guidance on issues such as waste storage stack separation distances. The tests also provided useful additional information, such as on the interlacing of stored waste bales as a potential method of reducing chimney effects. The results of the phase 1 and 2 tests were used in part as the basis for the revision of the 2014 WISH guidance. Revised WISH guidance including the outputs from the phase 1 and 2 tests was issued in April 2017. To accompany this revised 2017 WISH guidance a non-technical summary of the phase 1 and 2 tests was also released.

However, the phase 1 and 2 tests did not provide all of the information required. It was always anticipated that a phase 3 series of tests would be required, in particular to test the effectiveness of different fire-fighting techniques and media on waste fires. These phase 3 tests were conducted at the National Fire Training College in Gloucestershire in late 2017.

This report is an update of the original summary non-technical report produced and released in tandem with the revised WISH guidance in April 2017. It repeats the information originally provided on both the phase 1 and phase 2 tests as before, but then adds to this with further information based on the phase 3 tests conducted in late 2017.

2. Phase 1, 2 and 3 tests and methods used

As noted above, the waste burn trials were conducted in three phases:

- **Phase 1:** Smaller scale laboratory type waste burns, conducted at the FPA (Fire Protection Association) research facility in Gloucestershire
- **Phase 2:** Larger scale waste burns tests, conducted at Pollington in Yorkshire and Barling in Essex
- **Phase 3:** Specific tests aimed primarily at testing the effectiveness of different fire-fighting techniques and media, conducted at the National Fire Training College

Phase 1: Smaller scale laboratory type tests

Nine types of waste were tested:

1. Baled cardboard
2. Baled LDPE plastic
3. Baled HDPE plastic
4. Baled RDF (refuse derived fuel)
5. Baled SRF (solid recovered fuel)
6. Loose tyre crumb
7. Loose screened wood chip
8. Loose pre-crush wood
9. Loose wood fines

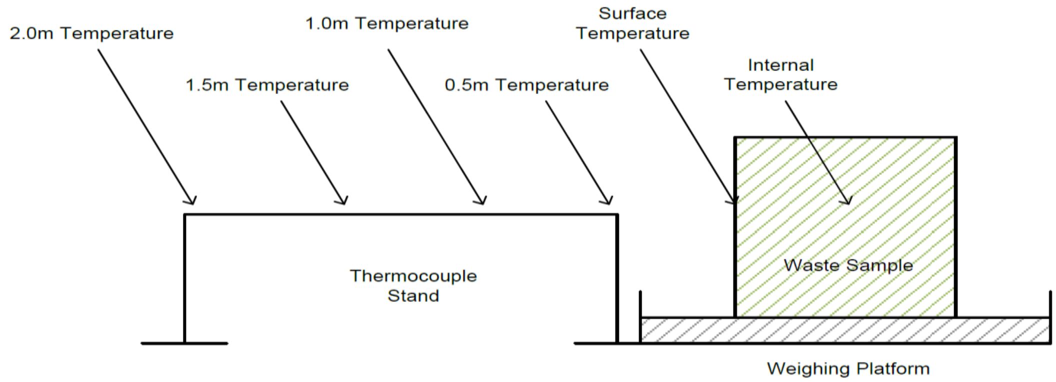
Sample size varied from 42 kg to 1,350 kg. This being largely conditioned by the configuration of the wastes tested: Bales of waste were impractical to split, and would have defeated the object of the tests on baled wastes, representing the top-end of these weights. Loose wastes represent the lower end. Loose wastes were contained in a mesh 'cage' for the purposes of testing. Bales were burnt whole.

All samples were burnt on the same test rig. This rig included load cells to allow weight loss during burning to be measured, thermocouples to measure temperatures within the waste sample and at the surface, and heat sensors at various distances from the samples.

A diagram of the test rig is shown below. Ignition of the samples was via the use of domestic fire-lighters, supplemented in some cases by the use of petrol as an accelerant (some wastes proved difficult to ignite). Samples were not allowed to 'burn-out' but rather were extinguished once steady state burning had been achieved.

Heat flux sensors were used to measure heat outputs, and fumes emitted during tests were captured via a 'smoke hood' allowing measurement of carbon monoxide concentration. A summary of the findings from the smaller scale tests is given in section 4.

Diagram 1: Test rig used in smaller scale tests



Phase 2: Larger scale tests

The larger scale phase 2 tests were aimed at replicating actual conditions experienced during waste fires. Thirteen waste types were tested:

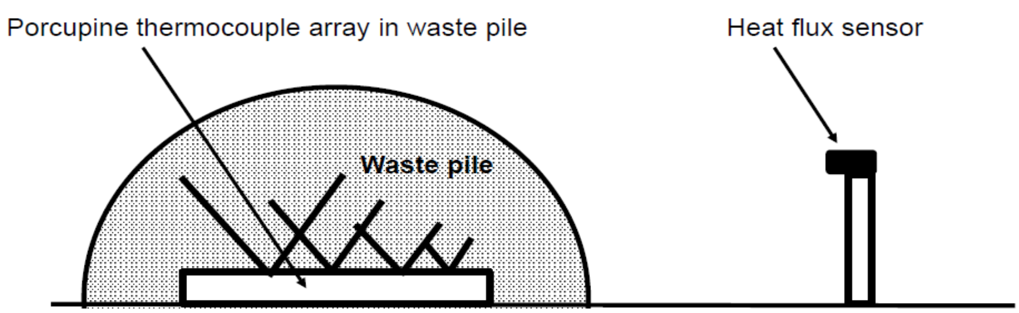
1. Loose untreated (raw) wood waste
2. Loose un-screened pre-crushed wood
3. Loose screened pre-crush wood
4. Loose wood fines
5. Loose RDF (refuse derived fuel)
6. Baled RDF (refuse derived fuel)
7. Loose SRF (solid recovered fuel)
8. Baled SRF (solid recovered fuel)
9. Baled high-density plastic
10. Baled low-density plastic

11. Baled paper and card
12. Loose frag fluff (plastics, foams etc from dismantling of end-of-life vehicles)
13. Shredded rubber (tyre)

The phase 2 tests were conducted externally (in the open-air). This was the only practical option, but did result in restrictions associated with preventing environmental nuisance.

For loose pile waste burns a thermocouple array (the ‘porcupine’) was embedded in the waste piles allowing temperature measurement at varying depths through the pile. This was obviously not possible with baled waste burns. Temperature measurement at the surface using external sensors was conducted for all burns.

Diagram 2: Test arrangement used in larger scale tests on loose waste pile stacks



Ignition for surface (outside-in) burns was via use of a ‘blow-torch’, or in some cases for bales domestic fire-lighters. Ignition for deep (inside-out) burns was via domestic fire-lighters introduced to the centre of piles. Unlike the smaller scale phase 1 tests, wastes were allowed to ‘burn-out’, with the exception of loose plastics, which emitted large volumes of black smoke and was extinguished before burn-out occurred.

Weight of waste burnt varied, for the same reasons as above for the smaller scale tests. Maximum weight in any one burn was circa 10 tonnes. Multiple burns on some waste types were used to check test methods and repeatability. The most burnt wastes being pre-crushed wood waste and RDF. A summary of the findings from larger scale tests is given below.

Phase 3: Fire-fighting tests

The primary aim of these tests was to determine the effectiveness of different fire-fighting techniques and media on waste fires. Much of the value of these tests accrues to the Fire and Rescue Services (FRS), and is not of primary, direct interest to waste operators.

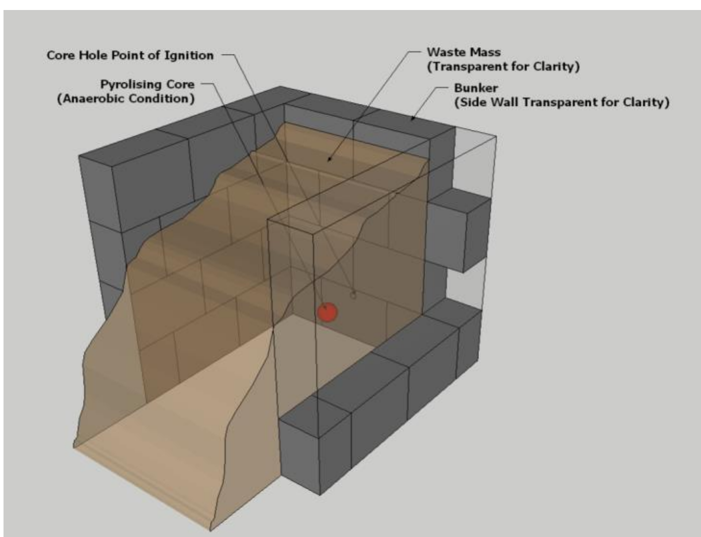
The phase 3 tests took place at the National Fire Training College in Gloucestershire. Different fire-fighting techniques, such as where hose streams are aimed at, were tested, and different fire-fighting media, in particular:

1. Water (by far the most common media used against waste fires)
2. Foams ('CAFs') as an alternative to the use of water on its own
3. Water + wetting agent, aimed at reducing surface tension and enhancing water penetration into wastes which are on fire

While the phase 3 tests were primarily aimed at fire-fighting, the opportunity was also taken to clarify and confirm some of the results of the phase 1 and 2 tests, in particular:

1. Effectiveness of interlocking block walls and bunkers against fire spread
2. Practical test of the modelled free-air separation distances from phase 2

Diagram 3: General arrangement of bunker tests



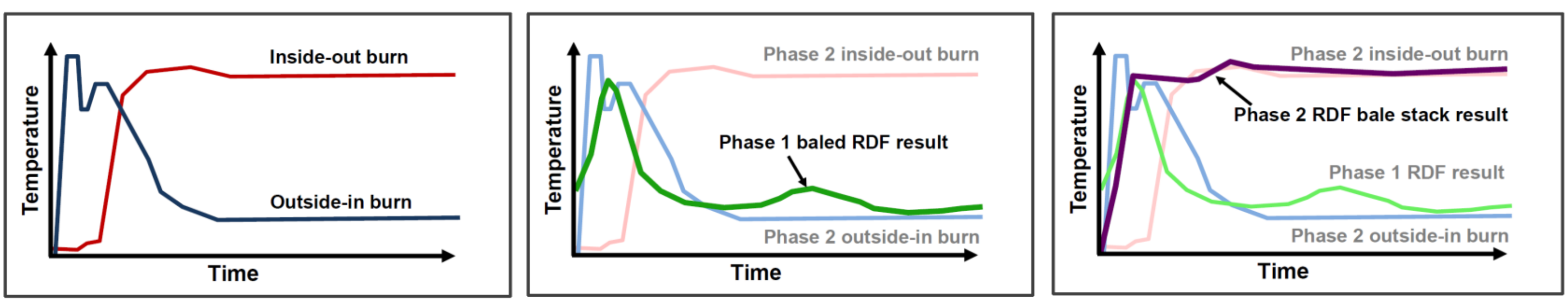
3. Summary of findings phases 1 and 2

Note: All of the graphs in this section are indicative only. They are aggregates or examples from data from the various waste burn tests conducted. Lines on the graphs are relative to each other, but no units have been given on axis scales (see text). Please note in particular than vertical axis scales have been set to allow best presentation of the data. The graphs are illustrative and provided for ease of understanding rather than as absolute data.

3.1 Overview

The primary aim of the phase 1 and 2 waste burn trials was to provide underpinning science on which to base waste stack separation distances for the 2017 revision of the WISH fire guidance. The original 2014 guidance distances having been based typically, and in common with much other similar guidance, on non-waste data. However, other outcomes were expected to be of benefit to current knowledge on how wastes burn. This summary simply presents the results of the tests without interpretation or indication of their application. The use of these results will be in their application over time.

The smaller scale phase 1 tests provided much useful data. However, they often did not reflect Fire and Rescue Services (FRS) experience of real-life waste fires. It became obvious during the tests that the phase 1 trials were sometimes missing one or more factors at play in real-life waste fires. The phase 2 larger scale tests aimed to rectify this by replicating as closely as practical the conditions of real-life waste fires.



Some of the graphs used in this section are 'sequential' with following graphs showing lines from previous graphs as tints. This is for illustrative purposes and to allow an easier view of the information in the text of this section

3.2 Burn mechanisms and other factors

Industry and Fire and Rescue Services (FRS) experience is that waste fires often do not behave in the same manner as fires in other materials. With loose waste stacks/piles, sometimes a smouldering, slow fire with fairly low heat outputs occurs, while in other cases fires in loose waste stacks are energetic with higher heat outputs. For baled waste stacks rapid spread of fire is often noted across the stack, and fires are typically energetic and have high heat outputs. One desired outcome of the waste burn trials was to try and explain these differences, and why they occur.

Baled wastes phase 1 smaller scale tests

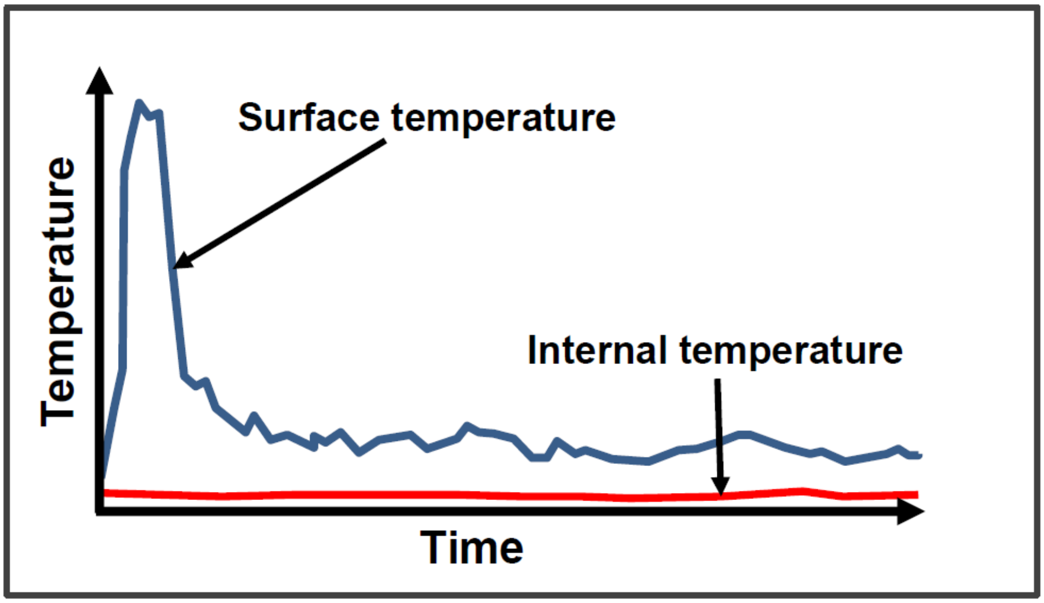
For baled wastes during the smaller scale phase 1 laboratory type tests the typical pattern observed for fire development was: Initiation of the fire followed by a rise in surface temperature once the fire ‘caught’. However, after a fairly short period of time surface temperature then fell to a steady-state burn at lower temperatures than expected, and lower than often experienced by the FRS when tackling real-life waste bale stack fires.

Fire penetration into the baled waste samples was not high, likely partially the result of poor air-flow within the bale and relatively high density. In addition, typically a ‘char’ layer formed on the surface of the bale restricting fire penetration, and so access for the fire to new fuel. This is illustrated by the differences observed between surface and internal temperatures in baled wastes during the phase 1 burns (see example of baled SRF in graph 1 below). Examination of bale samples post-burn also showed ‘charring’ at the surface, but little or no fire penetration into the bale.

As an observation from the baled waste tests, many bales were difficult to ignite requiring substantive heat inputs before a fire occurred. This would tend to mitigate against casual arson as a major cause of fires in baled wastes – a determined attack is likely required.

From left: Baled RDF pre-burn, baled LDPE plastic pre-burn, during burn and post-burn (note bale post-burn showing relative lack of fire penetration leaving the bale largely unburnt)

Graph 1: Phase 1 illustrative baled SRF burn internal and surface temperatures



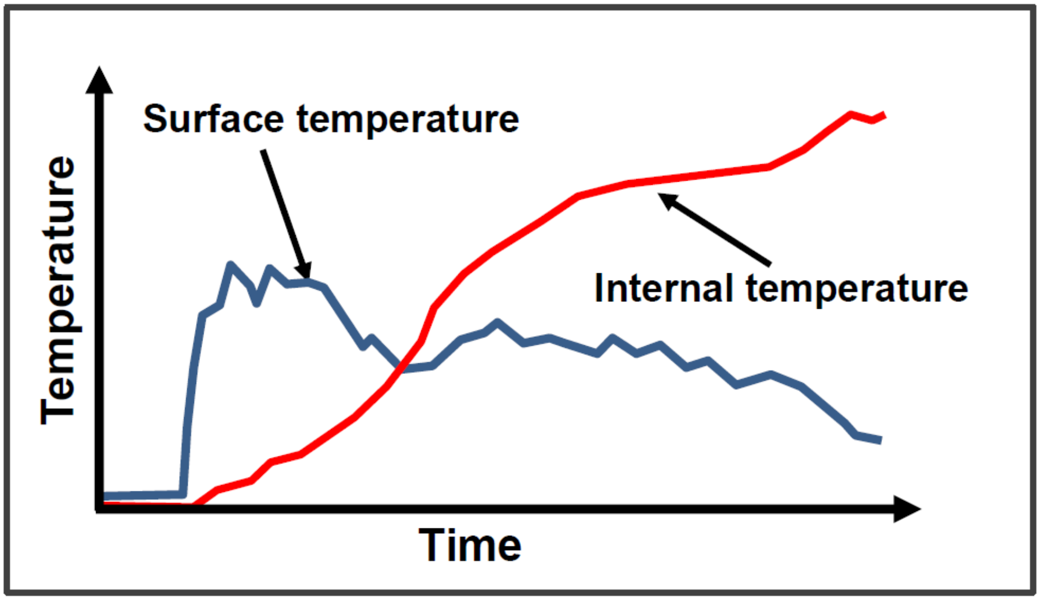
Loose wastes phase 1 smaller scale tests

Conversely, for most loose wastes a different pattern was observed: As for baled wastes, surface temperature rose rapidly once the fire 'caught', but surface temperatures remained higher, and internal temperature also rose (see graph 2 loose pre-crush wood).

The lower densities and more open structure in the smaller loose waste samples in phase 1 laboratory type tests seems to have allowed more air-flow into the waste, better fire penetration and a 'cleaner' burn. As for baled waste phase 1 burns, this is often not the experience of the FRS when tackling actual loose waste storage stacks where 'smouldering' type burns have been noted. Unlike baled wastes, examination of most smaller loose waste samples post-burn during the phase 1 tests revealed much more complete combustion, with little unburnt waste.

From left: Loose pre-crush wood waste pre-burn (note retained in mesh 'cage'), in initial phases of burn, during steady state burn and post-burn (note much more complete combustion than for baled wastes)

Graph 2: Phase 1 illustrative loose pre-crush wood internal and surface temperatures



Issues with phase 1 smaller scale tests

As noted in section 3, the weight of samples used in phase 1 varied significantly (42 kg to 1,350 kg). Using the examples of pre-crush wood and baled SRF as above, approximate densities of samples were: Baled SRF 0.5 tonnes/m^3, and for pre-crush wood 0.14 tonnes/m^3. In addition, the more open structure of larger sized loose wastes, with typically more 'rigid' particles, allowed more air-spaces in the sample promoting a more complete burn.

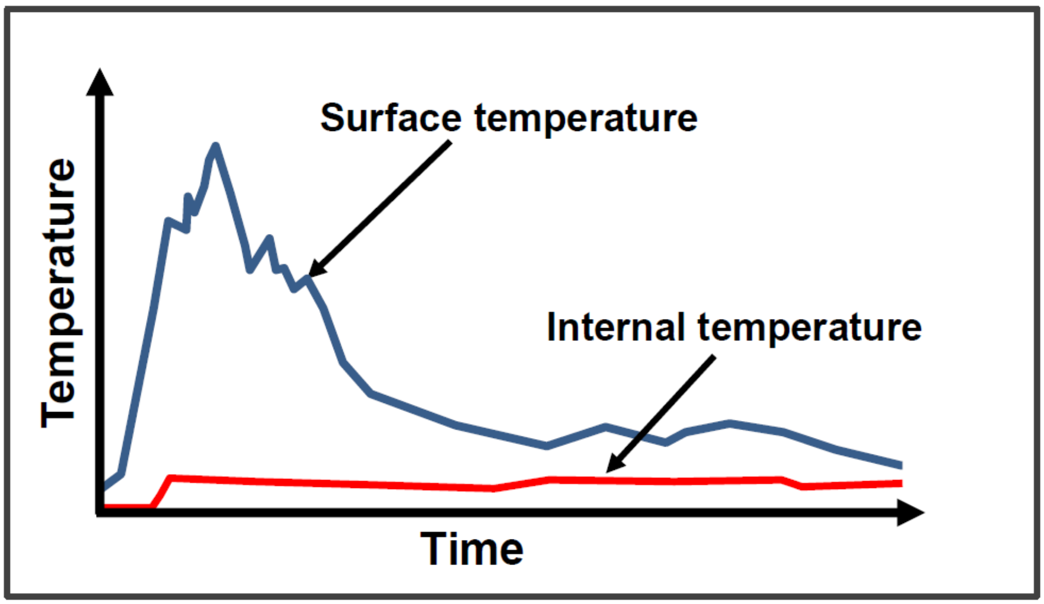
For baled wastes densities are realistic – they are as presented in baled wastes. For loose wastes the smaller sample size results in densities which do not completely replicate real-life storage conditions: Loose wastes stored in real life will compact to a degree under their own weight because of the qualities stored. In addition, any air spaces may be degraded. These factors were missing in the phase 1 tests (although see below on raw wood and other very large particle size wastes, which may not compact as much).

Issues such as sample size and an inability to replicate real-life during laboratory tests are not that unusual. For example, and while outside of the waste burn trials conducted in 2015 and 2016, laboratory tests to determine any self-heating properties for various waste types suffer from the same effect: The densities and sample size which can practically be achieved during small scale laboratory testing do not replicate real-life, and the results of such small scale laboratory tests need to be viewed with caution.

Phase 2 loose waste larger scale tests and checking scalability

To check the scalability of phase 1 tests on loose wastes, one of the first tests conducted in phase 2 was a large-scale loose pre-crush wood stack burn. This large scale test provided different results to the small scale laboratory type test on the same waste type (see graph 3 below). The pattern shown being more like that for baled wastes than for the small scale loose waste tests conducted in phase 1, although less distinct than for baled waste.

Graph 3: Phase 2 illustrative large scale burn loose pre-crush wood



Also as for baled wastes a 'char' layer formed at the surface of the pile on most of the larger loose waste storage piles, restricting fire penetration, and resulting in a more prolonged 'smouldering' type burn once the initial phase of burn had declined. This pattern replicates more closely typical FRS experience when tackling some loose waste pile fires.

This is not to say that the results obtained from phase 1 smaller scale burn tests are not useful. However, because of scalability issues some of the results need to be treated with caution as they may not replicate real-life.

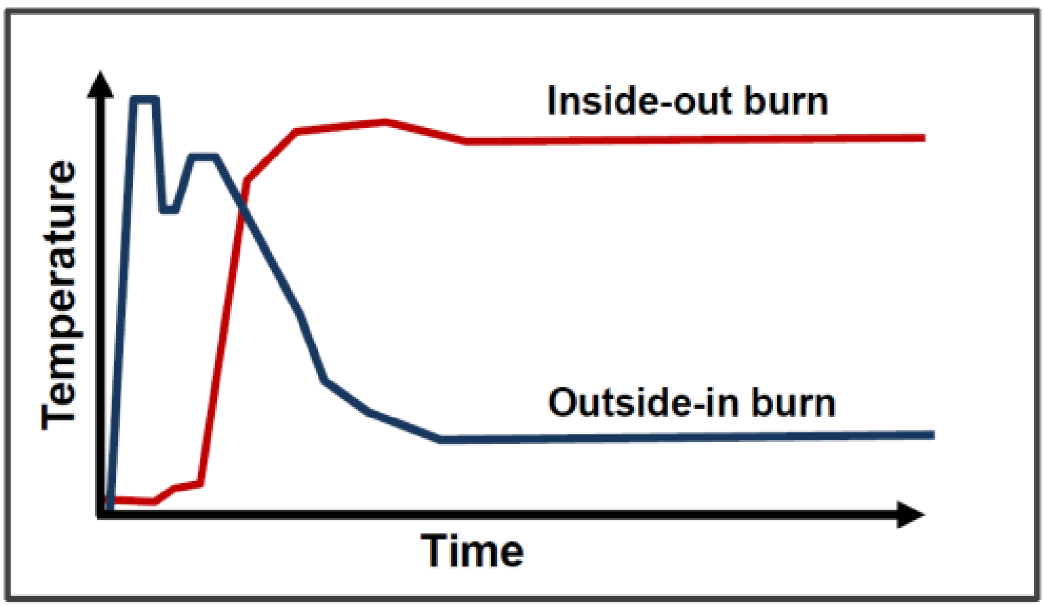
'Inside-out' and 'outside-in' mechanisms with loose waste stacks

All of the burns conducted during phase 1 smaller scale tests and the above loose pile larger scale burns were ignited at the surface of the pile or bale. This replicates some of the known causes of waste fires, such as discarded smoking materials, arson, direct heat, hot-works, open flames etc. However, not all waste fires start at the surface.

A significant number of waste fires start within the waste stack, such as from self-heating or hot/hazardous items buried in the waste. In particular, for loose waste stacks/piles such causes are significant (see below for baled wastes).

To replicate such 'inside-out' burns during phase 2 tests on loose waste stacks domestic fire-lighters were used, placed down a tube leading to the centre of a loose waste stack, and the tube then sealed to prevent air ingress. This resulted in quite different results than those identified during 'outside-in' burns where ignition is at the surface of a loose waste stack (see typical outside-in and inside-out burn results in graph 4 below).

Graph 4: Illustrative loose waste stack outside-in and inside-out burn temperatures



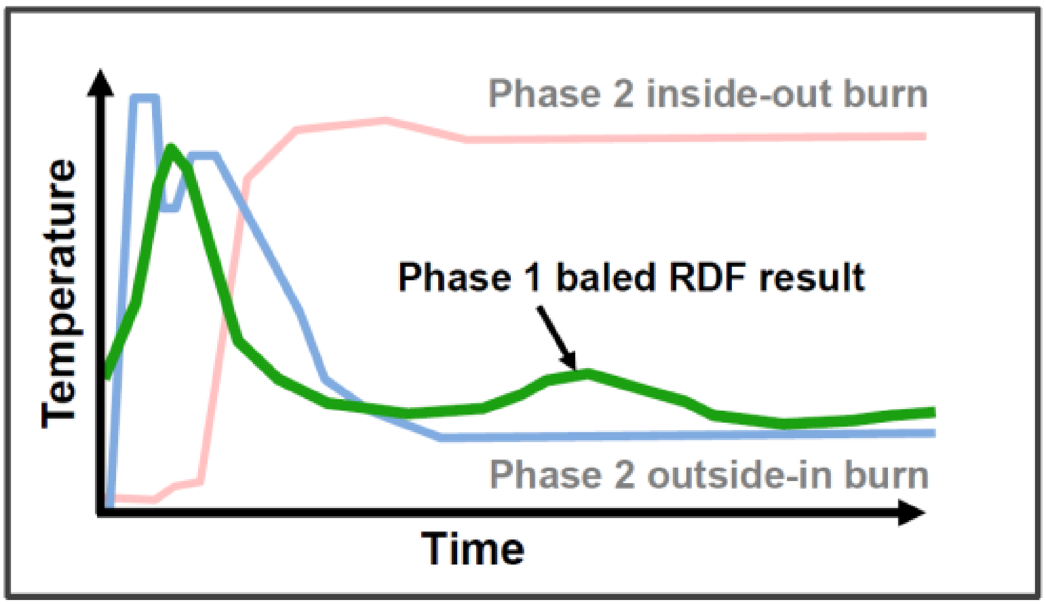
During inside-out burn tests fires took longer to develop. Probes within the loose waste stacks (the 'porcupine') show the build-up of a 'super-heated' bed within the waste stack. This slowly burns outwards, and then breaches the surface as a fully-developed and energetic fire. This inside-out mechanism results in sustained higher temperatures, rather than the dying-back of temperatures observed during loose waste stack outside-in fires.

These two mechanisms for loose waste storage stacks (inside-out and outside-in) agree with FRS experience of fighting actual loose waste stack fires. In some cases, a smouldering type fire is experienced (outside-in mechanism), whereas in other cases a vigorous and energetic fire is experienced (inside-out mechanism).

Phase 2 larger scale baled waste stack tests and ‘chimney’ effects

As stated above, the results obtained from phase 1 smaller scale tests for baled wastes do not reflect FRS experience when fighting real baled waste stack fires. In general, the results of phase 1 testing on baled wastes show a burn pattern similar to an outside-in fire with loose wastes (see graph 5 below). This type of ‘smouldering’ fire is not what is typically experienced in real-life with baled waste storage stacks, where the typical experience is of intense and energetic fires with sustained high heat outputs.

Graph 5: Illustrative outside-in and inside-out burn temperatures compared with an example smaller scale baled waste test result



Inside-out burns are relevant to bales of waste, but there are problems with this inside-out mechanism. Self-heating for some waste type bales, such as SRF and RDF, is an issue, but is likely to be less so for other waste types such as bales of plastics. Inside-out fires caused by hot/hazardous items in wastes is also less of an issue for baled wastes. Baled wastes are typically made of processed wastes, such as having been sorted by mechanical and/or manual means. Hot/hazardous items are more likely to have been removed during such processing (this may not be the case all of the time for some waste types such as ‘crude’ RDF which has not had extensive processing applied).

In addition, an inside-out burn in a bale would not account for the rapid and energetic spread of a fire across a baled waste storage stack, as is often observed in real-life.

Part of the phase 2 tests on multiple bales in a storage stack was to identify any mechanism not identified by the phase 1 tests on single bales which may be at work to produce the intense fires and rapid spread of fire often experienced by the FRS when tackling waste bale storage stack fires.

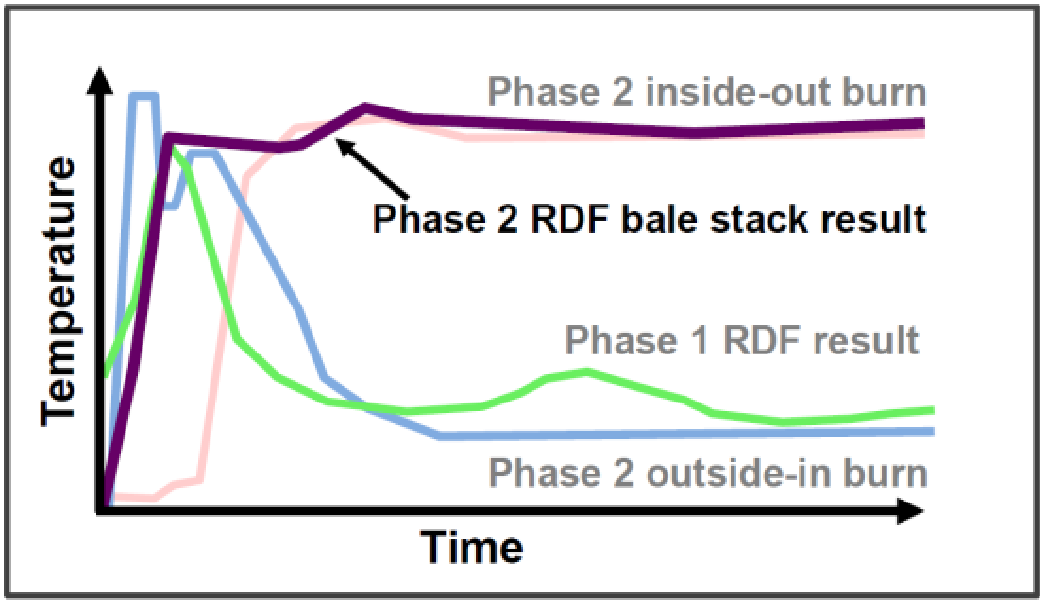
The phase 2 larger scale bale burn tests used ‘simulated’ baled waste storage stacks containing multiple bales. It was not practical to build stacks containing 100s of bales. For most phase 2 baled waste tests six bales were used, arranged as two columns. These were placed against a concrete bunker wall to replicate a wider stack, and for safety reasons related to stack collapse risks.

Ignition of the phase 2 larger scale bale waste fire tests was at the surface of the waste, as for phase 1 tests. Initially the fire progressed as for phase 1: Temperature rose and a ‘char’ layer started forming reducing the fire’s ability to access new fuel, until the fire reached the vertical gaps between the bales. At this point energetic air-flows (chimney type effects) were produced in these vertical gaps resulting in accelerated fire growth and an energetic burn which was sustained. Fire at these gaps was energetic enough to ‘strip’ any char layer from bales allowing the fire to access new fuel more readily. As a measure of how energetic the burns were fire ‘vortices’ were observed at the tops of vertical gaps between bales and between bales and supporting bunker walls (see photographs below).

Graph 6 below shows surface temperatures over time during phase 2 baled waste tests using RDF bales as an example. Compared to the phase 1 tests for the same waste, the larger scale phase 2 tests identified a much more energetic burn with higher temperatures sustained throughout the burn.

From left: Development of fire vortex behaviour during bale burn tests, visible fire vortex at top of gap between bales during bale tests, development of fire spread in gaps between bales, leading rapidly to a fully developed fire (see bale comments above)

Graph 6: Illustrative comparison with bale stack burn test temperatures



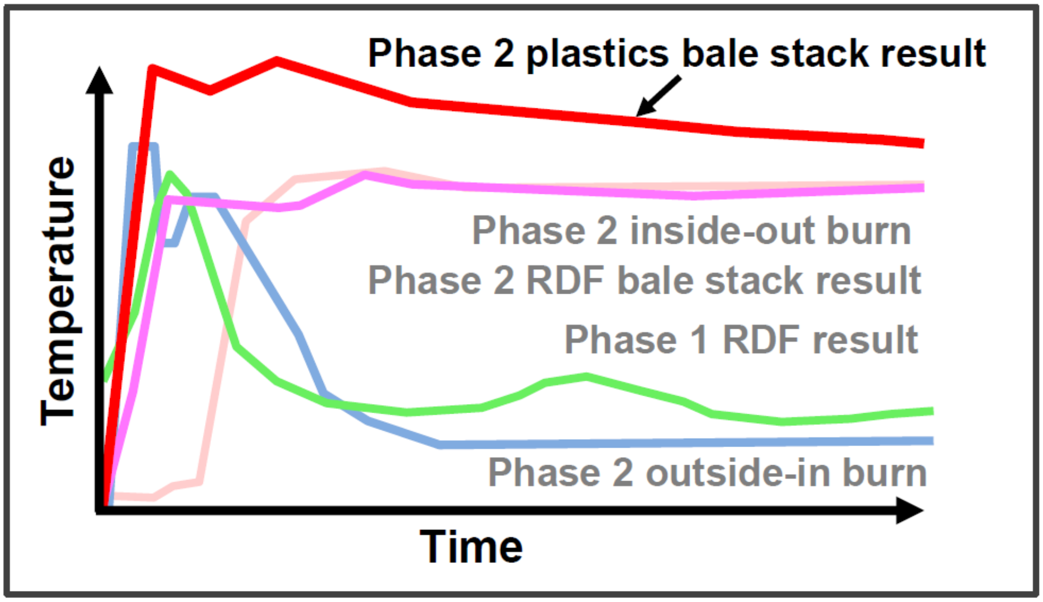
These chimney effects seem to be the likely cause of the energetic and sustained fires with rapid fire spread across baled waste stacks often experienced by the FRS when fighting baled waste stack fires.

Phase 2 baled waste tests burn temperature differences

Burn temperatures are discussed in more detail below. However, it is worth noting the results of the phase 2 baled waste tests on baled plastics. As for other baled stack tests the fire accelerated once it reached the vertical 'chimneys' between bales. In the case of baled plastics, temperatures rose to 1,200 degrees centigrade, or higher (the sensors used were calibrated to 1,200 degrees). These high temperatures were sustained, and resulted in a melted data-logger and blistered paint on a porta-cabin located 25 metres away from the fire.

From left: HDPE bale burn during phase 1 smaller scale tests, and same post-burn showing relatively intact bale. Compared to larger scale simulated plastics waste bale stack burns

Graph 7: Illustrative comparison between plastics and other typical other wastes during bale stack burn tests



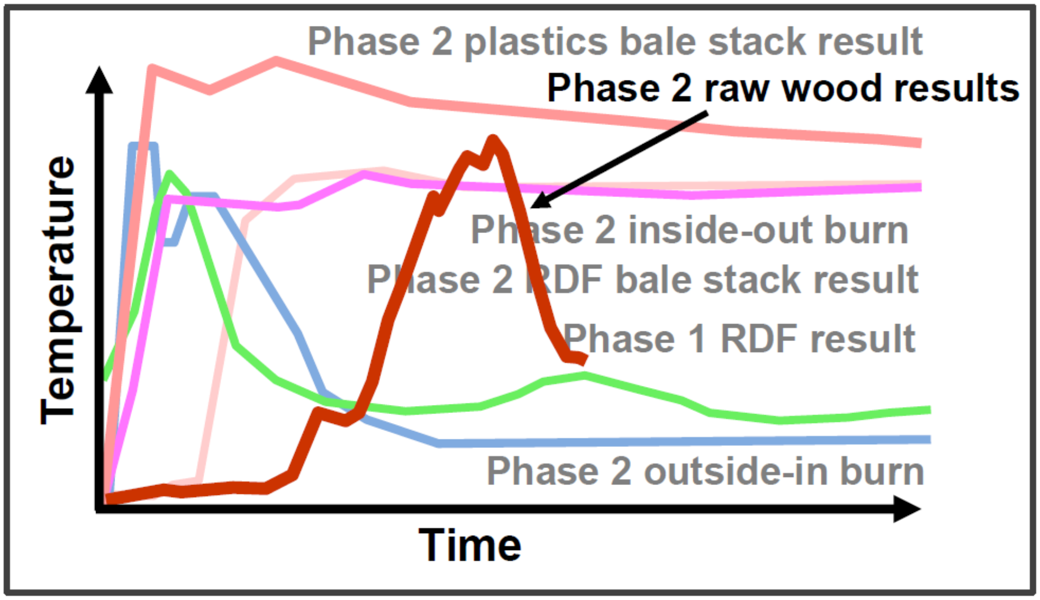
These results largely support FRS experience during fire-fighting of plastic waste bale stacks where temperatures were such that access to fight the fire was, at best, problematic.

Large particle size, 'rigid' waste types in loose piles

One exception to the above inside-out, out-side in and bale stack test results was raw wood waste. This waste type comprises larger particle size items, such as parts of pallets, discarded furniture and similar. In addition to be larger, these particles are also rigid and less prone to compaction when placed in a loose waste storage stack/pile.

Smaller particle size wood wastes (approximately 25 mm – 60 mm particle size), exhibit observed air-gaps when stacked of less than 10 mm. In the case of these smaller particle sized wood wastes fire penetration was limited to 50 mm – 150 mm before a smouldering burn set-in. This was not the case with larger particle sizes such as in raw wood waste where air gaps were larger, allowing fire penetration to the interior of the pile. Peak temperatures during burns of these larger particle size wastes were achieved and sustained as a steady state burn, the decay of which was linked to the available fuel being exhausted. In brief, the burn was similar to what would be expected from a 'bonfire'. This different burn progress is shown in graph 8 below, compared to other burns.

Graph 8: Illustrative comparison with raw wood (large particle size)



Raw wood is not the only larger particle size waste with rigid particles. Bulky hard plastics wastes (such as from discarded garden furniture, plastic pipes and larger children's toys) and whole tyres also have large particle sizes and are fairly rigid. These waste types were not tested and direct comparisons cannot be made. However, industry knowledge is that bulky plastic wastes have been involved in serious and energetic fires.

3.3 Burn temperatures

Various factors, such as the mechanisms outlined above, affect the burn temperature of wastes. For external stacks weather can also have a role to play, such as wind direction and strength. In practical terms there is no realistic method to 'chose' the type of waste fire which may occur, or what weather conditions may be if a fire occurs. The typical or 'realistic' worst case scenario needs to be used.

For many of the types of waste tested maximum burn temperatures occurred in a roughly 100-degree window, between 840^0C and 950^0C. There was then a roughly 200-degree gap to the maximum burn temperatures of plastic and rubber wastes (1,127^0C to 1,200^0C). Please note that at the top-end this maximum of 1,200^0C may have been more as the heat sensors used were only calibrated to 1,200^0C. Taking account of the variability in wastes and how they are presented and the test results, in practical terms this allows wastes to be placed into two 'bands' for the purposes of calculations for issues such as stack separation distances.

Table 1 below shows maximum burn temperatures for the various wastes tested. The shading applied indicates the two rough bands as described above.

Table 1: Summary burn temperatures for different waste types

Waste type	Surface temperature (typical maximum)
Pre-crush wood waste (un-screened)	**840^{0}C**
Raw wood waste	**850^{0}C**
Paper/ card baled	**850^{0}c**
Pre-crush wood waste (screened)	**860^{0}C**
Refuse derived fuel (RDF) loose	**900^{0}C**
Refuse derived fuel (RDF) baled	**900^{0}C**
Solid recovered fuel (SRF) loose	**950^{0}C**
Solid recovered fuel (SRF) baled	**950^{0}C**
Shredded rubber	**1,127^{0}C**
Plastic HD baled	**1,200^{0}C**
Plastic LD baled	**1,200^{0}C**

Note: Some wastes, such as RDF and pre-crush wood, data based on multiple burn tests, whereas for others based on a lower number of burns. Temperatures should be treated as summary – various factors can affect as noted above.

Subject to the information provided by the waste burn tests on various the burn mechanisms and factors outlined above, these results are perhaps not surprising. Some waste types are ‘single stream’ such as wood and paper wastes. These are likely to burn in a similar manner to raw materials of the same type, if presented in the same form and configuration and subject to the same burn mechanisms as their waste counterparts. Other wastes are mixtures, such as RDF and SRF. Also subject to form and configuration and burn mechanism considerations, the results above align with systems such as the commodity class system on which sprinkler and similar equipment specifications are based (at its upper end this commodity class system is largely based on the amount of specified plastics in a material).

3.4 Mass loss/burn rate

During the smaller scale phase 1 tests the rate of mass loss during burns was measured via load cells underneath the test rig on which wastes were placed. This was not practical for the larger scale phase 2 tests. Mass loss during phase 1 burn tests was measured during the initial stages of burning, at steady state burn and peak burn. These mass loss results from phase 1 are summarised in table 2 below.

Table 2: Summary rate of mass loss data from phase 1 smaller scale tests

Waste type	Rate of mass loss (grammes/second)		
	Initial burning	Steady state burning	Peak burn rate
Baled cardboard	59.5	3.5	63.3
Baled LDPE plastic	87.3	NA*	184.3
Baled HDPE plastic	39.0	66.4	106.9
Baled RDF (refuse derived fuel)	32.8	12.8	33.6
Baled SRF (solid recovered fuel)	20.2	10.7	37.7
Loose tyre crumb	17.6	5.7	17.6
Loose screened wood chip	6.2	2.8	10.9
Loose pre-crush wood	32.1	3.5	32.6
Loose wood fines	5.3	0.5	8.3

** NA. LDPE extinguished early as a result of the ferocity of burn for safety reasons*

Ignoring the very low steady state mass loss for wood fines, lowest mass loss rate was 2.8 grammes/second (loose screened wood chip at steady state burn), and highest 184.3 grammes/second (baled LDPE at peak burn). In more practical terms, these lower and upper figures being 0.01 tonnes per hour, and 0.66 tonnes per hour respectively. All of these results were obtained from tests involving the surface ignition of wastes and do not account for some of the burn mechanisms outlined above.

As noted above, in many respects the smaller scale burn tests did not replicate fully Fire and Rescue Services (FRS) experience of real waste fires, or in some cases the results of the larger scale phase 2 burn tests. However, the mass losses noted at peak burn temperatures obtained during the smaller scale tests indicate that for many wastes burn-out times are likely to be extended. There are variables here, and the data cannot be directly applied to real life waste fires, but it does give an indication.

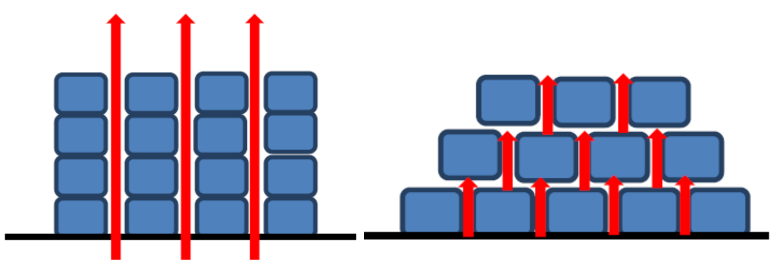
This may have implications if a ‘controlled burn’ strategy is pursued by the FRS, such as for reasons of reducing potential contaminated fire-water run-off. Even for smaller waste storage stacks, burn-out times are likely to be measured in days rather than hours.

3.5 Other findings: Interlacing bales and carbon monoxide

The above represents the main outcome of the waste burn trials. However, two other outcomes are worth noting:

Interlacing of bales to reduce chimney effects

As noted above chimney effects during the larger scale burns on baled wastes are a significant factor in fire spread and how energetic a waste stack burn will be. This prompted consideration of alternative bale stack configurations which may reduce these chimney effects. For one burn test bales were interlaced – placed as bricks in a wall rather than stacked vertically on top of each other. The aim being to break-up the vertical gaps.



Far left: Standard bale storage, and left: Interlaced bales. Red arrows indicate potential air flows

The results of this test revealed that once the fire was fully developed peak temperatures were not affected. As such interlacing bales would not, for example, be a reason for shorter separation distances between stacks aimed at reducing fire spread risk. What was affected was the rate of fire growth in its initial stages. Interlacing bales roughly doubled the time required for the fire to develop fully. This may allow a bale stack fire to be fought more effectively in its early stages, so preventing its development into a full fire. However, this was only one test and the results should be treated as indicative. Future waste burn tests aimed at proving this theory have been suggested.

Carbon monoxide (CO) emissions in phase 1 tests

The phase 1 smaller scale tests were conducted on a test rig, including an air extraction hood and system located over the rig. This allowed CO concentrations during burns to be measured using a flue-gas analyser. CO concentration is an indicator of inefficient combustion. The results obtained were generally as expected: Smouldering fires produced the highest CO concentrations, whereas ‘cleaner’ burns exhibited lower concentrations. However, as the phase 1 tests in many cases failed to replicate real-life waste fires there are few conclusions which can be applied to such real-life situations.

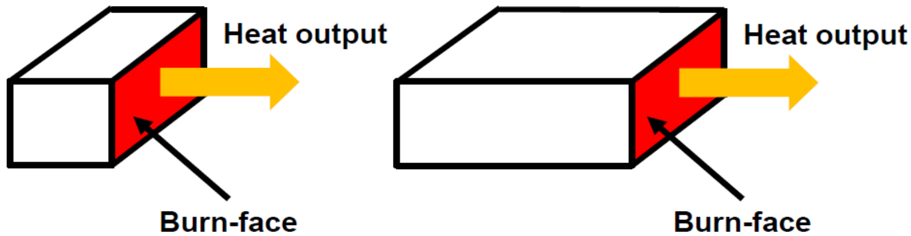
3.6 Application of phase 1 and 2 tests to WISH waste fires guidance

One of the primary aims of the phase 1 and 2 waste burn trials was to provide data from which waste storage stack separation distances information to reduce the risk of fire spread could be calculated. In this respect the trails were successful, and the separation distances information in the revised 2017 WISH waste fires guidance is based on the results of the tests. This was to address the acknowledged gaps/flaws in previous guidance which are often largely based on non-waste data.

The waste burn trials also aimed to provide data on which maximum stack sizes information could be based. In this respect the results were more mixed. Modelling using the data from the waste fire tests to determine stack separation distances did reveal that such distances seem to be relatively insensitive to overall stack size/volume. Two overall stack sizes were used in the modelling: A 450 m^3 stack and a 750 m^3 stack. The differences in modelled separation distances using these two stack sizes was less than 1 metre, and for all but one waste type less than 0.5 metres. This would indicate that overall stack volume is not a highly significant input to determining separation distance. This is not to say that stack size is irrelevant to fire management, only that overall volume does not seem to affect separation distance significantly.

However, modelling of the results did indicate that stack configuration, or more accurately stack length and ‘burn-face’ area, did have a significant effect on separation distance. When a stack of waste is on fire it will emit heat. If the separation distance between the stack and another combustible object is insufficient then this heat may cause the second object to ignite. However, the amount of heat emitted in any one direction will depend on the dimensions of the ‘burn-face’ of the stack facing the second object, and not primarily its overall volume.

The diagram below illustrates this. The two waste stacks shown are of different volumes, but the burn-faces are the same dimension, and the heat output (represented by the amber arrows) in any one direction will likewise be largely the same.



Separation distance is largely a function of the amount of heat emitted per unit of area of a burn-face, and the dimensions of the burn-face. As noted above, wastes can practically be split into two categories: General wastes such as wood, paper, RDF etc which exhibit maximum burn temperatures of some 850 - 950 degrees centigrade and plastics and rubber wastes with temperatures of up to some 1,200 degrees centigrade. The revised 2017 WISH fires guidance provides a maximum stack height of 4 metres, for practical fire-fighting reasons. This leaves stack length as the variable to determine separation distance.

As a result of the above, the data from the waste burn trials can be modelled to provide separation distances as graphs showing a ‘sliding scale’ between stack length and separation distance. An example graph of this for general wastes (850 – 950 degrees’ centigrade burn temperatures) is shown below.

To produce this modelling various assumptions needed to be made, such as angle of repose for loose waste stacks. A summary of these assumptions is given in appendix 1 of the 2017 revised WISH waste fires guidance.

Other results and outcomes of the phase 1 and 2 waste burn trials were also used in the revised 2017 WISH fires guidance, such as on interlacing bales in stacks as a potential method for reducing initial fire growth. As further fire research and testing is undertaken on wastes the outcomes will be included in future iterations of the WISH fires guidance.

General views of the phase 3 fire-fighting tests – see section 4 below for detail

4. Summary of findings phase 3

Note: All of the data and information given in this summary are averaged and summary based on multiple burns of wastes to ensure a reasonable level of consistency. As with all of the tests, the variability of wastes, weather conditions and similar mean that results should not be taken to the 'last decimal point'. However, they are indicative and from multiple tests.

Most of the detail results of the phase 3 tests were aimed at informing the Fire and Rescue Services (FRS) regards effective means of fighting waste fires. These results will be included in National Operational Guidance for fire brigades. However, the tests are also of interest to waste operators. The sections below give a summary of the tests, and points of interest to waste management site operators and other interested parties.

Note: Some or the information below is firmly aimed at the Fire and Rescue Services. It is **NOT** the intent of this section to encourage or inform waste operators on fire-fighting techniques for their own operatives. Fighting fires is a specialist area requiring training, specialised equipment and clothing, and experience – waste operatives should **ONLY** attempt to fight any fire if it is safe to do so.

4.1 Fire-fighting media and techniques

Two configurations of stored wastes were used in the phase 3 tests:

- Piled loose stacks of waste in interlocking block bunkers
- Baled waste tests in 'open-yard' conditions

These configurations were chosen to replicate as close as practical typical fire scenarios encountered by the Fire and Rescue Services (FRS) at real waste site fires.

Three types of fire-fighting media were tested on these two waste storage configurations:

- Water on its own
- Water plus wetting agent
- Wet class A CAFS (foam)

Piled loose waste tests in bunkers

Bunker bays were filled with circa 17 tonnes of RDF (refuse derived fuel), and ignited via lance inserted in a pipe to middle of the pile to simulate an ‘inside-out’ burn. Thermocouples to monitor internal temperatures were installed within the waste piles. Fire were allowed to breach the surface and develop, and then attacked with the three fire-fighting media. Not all inside-out fires developed fully during the tests, although test results and conclusions were not significantly affected by this.

Water: Use of water jets knocked the visible fire down, but had little effect on the internal temperature recorded by thermocouples only 1 metre below surface of the piles. That is temperature within the piles was largely unaffected. From observation, penetration of water into the piles was only circa 0.2 metres, accounting for the lack of significant effect on below-the-surface temperatures. The application of copious amounts of water did not result in lower internal temperature – the water simply ran-off without significant effect, other than posing a potential environmental risk.

Foam: The use of foam also resulted in visible flame being knocked-down, but quicker than was the case with water. Sub-surface temperatures at 1 metre below surface level were more affected than with water. Foam also seemed more effective at preventing burn-back than water (that is flames knocked-down by the foam tended not to reappear).

Water plus wetting agent: As with water on its own, jets knocked the visible fire down. However, penetration into the waste was much better at 1 – 1.5 metres, and sub-surface temperature was even more affected than with foam, down to 2 metres below surface level. As with water on its own the application of copious amounts of water plus wetting agent did not result in any further reduction in internal temperature – the water plus wetting agent simply ran-off the pile with little or no further effect.

Re-ignition: Following the fire-fighting tests water plus wetting agent was ‘injected’ into the piles via the pipe used to ignite the wastes. This was continued until water was seem running out of the joints between the interlocking blocks of the bunkers and the internal temperature of the piles was at ambient. However, after some 12 hours, the internal temperature of the piles had risen again. In summary, the waste had re-ignited despite there being no external signs of a fire. Excavating the wastes and dousing them being the only effective method of preventing this re-ignition.

The results of these tests are of more direct use to the FRS. However, in summary:

- Water plus wetting agent proved the most effective, followed by foam, and then water on its own. However, in all cases penetration into the wastes was insufficient to fully extinguish the internal fire
- Continuing to apply water/foam/water plus wetting agent after visible flames had been extinguished provided no additional benefit, and poses the risk of environmental harm from contaminated water run-off
- Re-ignition of piled wastes is a significant risk, with excavation and dousing being the only practical method of extinguishing internal fires

Practical applications of the information above will require further consideration. For example, it may be of value for waste site operators to hold an IBC (intermediate bulk container) of wetting agent on site for use by the FRS in the event of a fire. Further consideration of this type of application is required before definitive advice can be given. Waste operators should consult with their local FRS on this aspect before taking any action.

It should be noted that the tests were on RDF, which has a relatively small particle size and is non-rigid – that is air spaces within the stack are negligible. The behaviour of the three media used is likely to be different with larger particle size and/or rigid wastes such as pre-crush or raw wood wastes, as media penetration into stacks of such wastes is likely to be much higher. These piles behave like a ‘bonfire’, of which the FRS has extensive experience already.

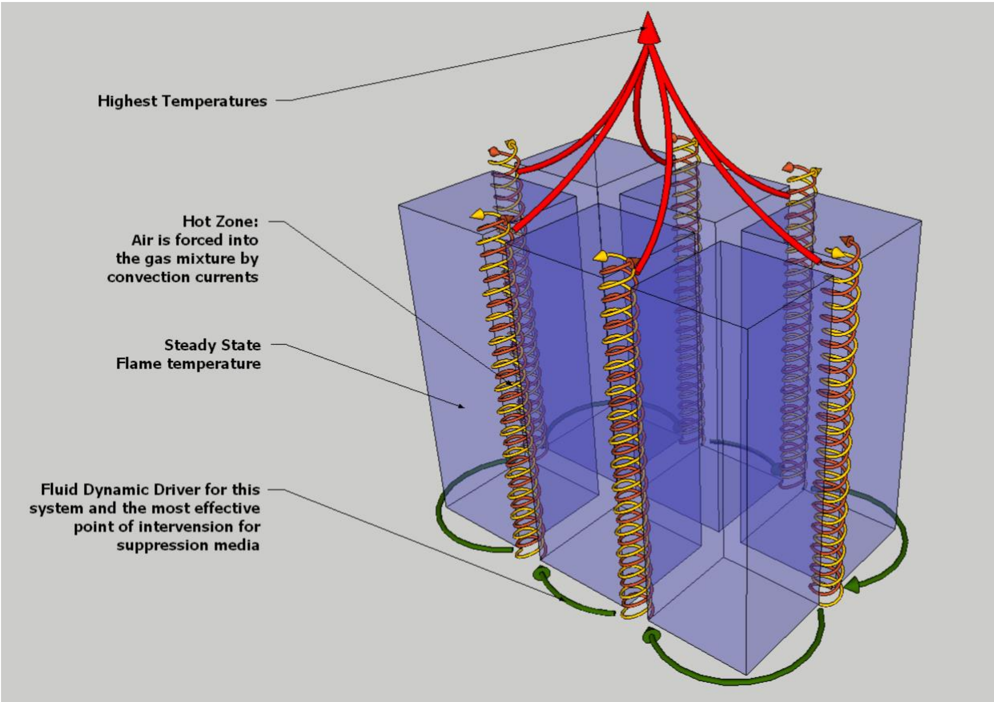
Note: While not tested, the use of inert materials such as soil or sand to ‘entomb’ a fire has been used effectively in the past on waste fires. However, this technique does not extinguish internal fires and gradual excavation and dousing would still remain the only practical option to extinguish a fire completely.

Baled waste tests

Mixed waste plastic bales were assembled into a ‘mini-stack’ three bales wide and long and three bales high (total of 27 bales). Waste plastics were used because of their higher burn temperatures (worst case scenario). Ignition was on the up-wind side of the bale stack producing an outside-in fire (inside-out fires are rare in bales because of their density). From ignition to full involvement of the stacks in the fires was less than 4 minutes.

As for the loose wastes in bunker tests, the three different fire-fighting media of water, foam and water plus wetting agent were then used to attempt to extinguish the fires. In addition, different fire-fighting techniques were used, such as directing jets from hoses into the gaps between bales and at the base of the fire. However, this type of information is likely of more use to the FRS than waste operators.

General arrangement of bales used in tests (only six bales shown)



Note: The diagram above incudes graphic representation of the chimney effects seen in baled waste fires, as discussed elsewhere in this report.

Water: Two 45 mm jets were applied to the fires (typical equipment used by the FRS when they first arrive at a site where a fire is occurring). Even after applying some 20,000 litres of water for 20 minutes the fire was not fully extinguished.

Foam: A class A wet solution CAF was used. This was significantly more effective than water, and resulted in the fires being extinguished on average in 7 minutes. Run-off was also markedly less than for water on its own. However, it was also observed that the ‘throw’ of foam from hoses was less than for water, making fire-fighting more difficult.

Water plus wetting agent: Two 45 mm jets were used, as for water on its own. Water plus wetting agent proved the most effective with fires being extinguished in on average 2 minutes, and with the least run-off.

Summary table of baled waste tests

Media	Detail	Volume water used	Time to extinguish
Water	2 x 45 mm jets at 7 bar	20,000 litres	20 minutes (not extinguished)
Foam	Class A wet solution CAF, 2 x 128 litre/minute jets	1,800 litres	7 minutes
Water plus wetting agent	2 x 45 mm jets at 7 bar, with wetting agent at 0.3% by volume	1,800 litres	2 minutes

As for the loose waste in bunkers tests, water plus wetting agent proved the most effective fire-fighting media, with foam second and water on its own last. Further consideration is required to make detail comment, and most of the information gained in these tests will be of most direct use to the FRS.

It is worth discussing the potential use of wetting agents in fixed fire systems such as sprinklers and deluge systems. To an extent, the design of systems with spray heads, such as sprinklers and deluges, relies on water droplet size. Wetting agents work by reducing water surface tension, and this may result in smaller droplet size so changing the behaviour of a sprinkler or deluge system. In brief, the use of wetting agents in sprinklers, deluges and similar is not currently recommended, and further research in this area is required.

However, the use of wetting agents in oscillating and fixed water monitors may be a valid option. Monitors emulate the action of hoses and are not as reliant on droplet size. But, there are variables here and the advice of a competent fire engineer would need to be sought, and effectiveness may well vary dependent on the design specifics of any system. In brief, this is unlikely to be as simple as adding an IBC of wetting agent with a proportionating valve in the water supply to a monitor system.

4.2 Effectiveness of bunkers in reducing fire spread

It is common for wastes to be stored in three-sided bunkers. The walls of these bunkers may be solid concrete, block construction, steel plate or other. For solid concrete and steel (fabricated, not A frames and similar – see the 2017 WISH guidance for this type of bunker construction) there are existing standards. It should be obvious that railway sleepers and non-interlocking blocks with gaps are unlikely to offer adequate fire spread protection.

However, one of the most common forms of construction for bunkers is the use of interlocking concrete blocks. The effectiveness of this type of construction in preventing fire spread has been the topic of debate, although some suppliers have had their products tested.

Three waste types were used in these tests: RDF (refuse derived fuel), loose plastic wastes and wood waste. For some of the bunker walls the interlocking blocks were left 'dry assembled', for others proprietary intumescent sealant was applied between the blocks. The fires lit in these bunker tests varied in timescale, with some bunker walls being subjected to 48 hours plus of fire exposure. In summary of the results:

- In general, the interlocking block walls performed well. The outside walls of the bunkers exhibited little thermal transfer, remaining 'cool' (or at worst only warm) to the touch throughout the tests, and heat damage to the blocks was not substantive
- Smoke and heat was observed escaping from between the dry-assembled blocks. The risk of fire spread from such escape would depend what is on the other side of the bunker wall, it location and combustion properties
- The block walls sealed with intumescent sealant performed better than those dry-assembled, and the sealant was still intact after the fires. The use of intumescent sealant would seem a cheap and effective method of enhancing the effectiveness of interlocking block bunker walls regards restricting fire spread
- The 2017 WISH guidance includes that a 1 metre freeboard should be left between waste height and wall height. This is to account for flame height in a fire. During the tests, even with this 1 metre freeboard flames were observed to be drawn-up and lick-over the bunker walls. Similarly, to the case for small gaps in interlocking block walls, the impact on fire spread would depend on what is on the other side of the wall. However, it is impractical to build bunker walls of an infinite height, and greater freeboard would likely only draw the flames up higher. A 1 metre freeboard is not perfect, but does provide a significant reduction in fire spread risk

Note: The importance of considering what is on the other side of a bunker wall is critical. If what is on the other side of the wall is a free-air gap of sufficient distance or a non-combustible material then the protection any bunker wall needs to provide is lower than if a building, another stack of combustible wastes or similar is on the other side of the wall. This type of consideration should be part of site storage planning.

Summary table of interlocking block bunker tests

Material in bay	Duration	Max temperature	Comments
RDF (refuse derived fuel)	50 hours	400 – 500 ºC	Slight heating through block, but still able to hold bare hand on the outside edge of blocks. Some flame penetration through gaps in blocks down wind of the fire
Loose plastic wastes	2 hours	1,100 ºC	Slight heating through block, but still able to hold bare hand on the outside edge of blocks
Pre-crush wood	20 hours	950 ºC	Post fire spalling of the inner face of block but remained stable

4.3 Practical test of separation distance

As described in section 3 of this report, the results of the phase 2 tests were used to model free-air separation distances required to prevent fire spread from thermal radiation, and resulted in the separation distances noted in the 2017 WISH guidance. However, some readers of the WISH guidance have expressed a level of disbelief regards the often relatively wide separation distances included in the 2017 WISH guidance, compared to the separation distances included in some other documents on waste fires.

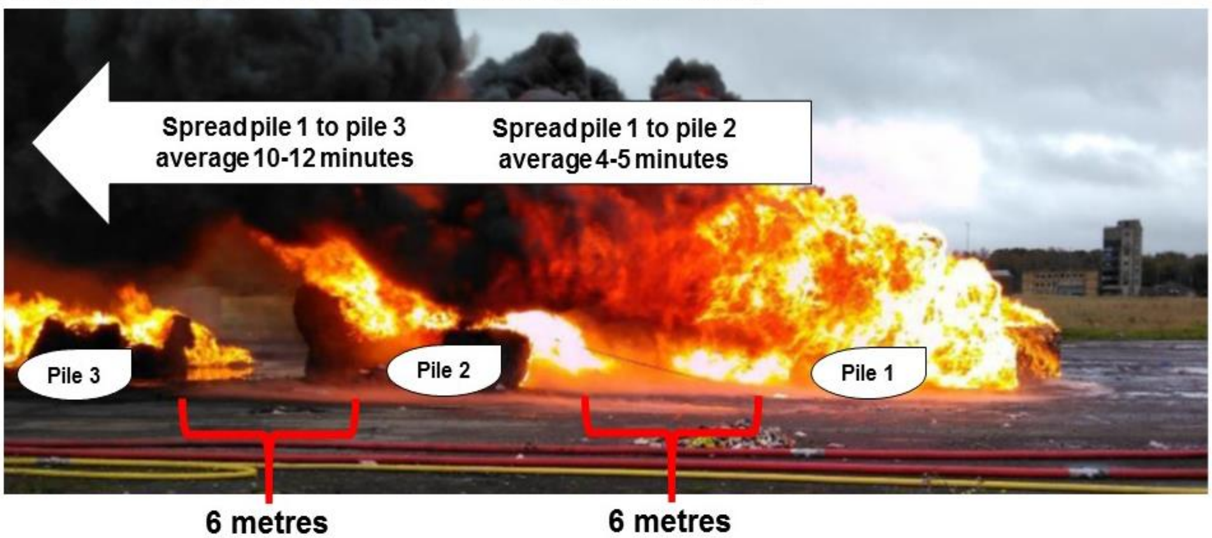
The opportunity was taken during the bale fire-fighting tests in the phase 3 tests to undertake an empirical test of separation distance. During these tests a main bale stack was constructed (as detailed above). Two further, smaller piles were also assembled, the first 6 metres from the first stack, and the second a further 6 metres away (see diagram below).

Fire spread between pile 1 and pile 2 occurred within 4-5 minutes, and all three piles were fully involved in the fire within 10-12 minutes. This test was repeated, with the same results.

Instinctively, the relatively wide separation distances in the 2017 WISH guidance may seem excessive, and the use of plastic wastes for the tests is a worst case scenario because of their higher burn temperature. However, as these empirical tests indicate the WISH guidance distances are realistic. Certainly relying on relatively narrow separation distances is unlikely to be effective in preventing fire spread.

Photograph with overlaid graphics of empirical test of separation distance

Photograph of actual tests. Note, bale stacks in partial collapse and extensive flames result in pre-burn distances not being clear in photograph. This test repeated four times to ensure consistency.



4.4 Other findings

During the phase 3 tests on bunkered wastes various fire detection companies took the opportunity to perform tests of their detection products, in particular of visual heat and smoke detection systems. In summary:

- All of the detector systems used detected fires once they had breached the surface and became open flame fires

- However, none of the detector systems tested were 100% effective in detecting sub-surface fires in the RDF used in the tests. This is likely the result of the lack of significant air-gaps in loose stacks of RDF (or other smaller particle size/non-rigid wastes). This lack of air gaps means that heat and/or smoke cannot effectively escape from the stack, and as a result there is nothing for the detector to detect. This effect is likely to also apply to other small particle size/non-rigid wastes where any air gaps are likely small and/or insignificant
- For stacks of larger particle size/rigid wastes such as raw and pre-crushed wood waste, or stacks of bagged waste, the air gaps present in such stacks may likely allow hot air and smoke to escape so allowing better detection at the surface
- Obviously placing thermocouples through a pile of waste will detect heat, but this type of technique is likely only practical if wastes are being stored for longer time periods as the thermocouples are effectively sacrificial

Note: The thermocouples placed in the waste stacks used in the bunker tests allowed sub-surface temperatures throughout the stacks to be monitored. The sub-surface heat from internal fires appears to ‘move around’ in the stack, and is often localised (heat is apparent in one part of a stack but not in another). The use of thermal probes to monitor for internal fires in waste stacks has been the topic of debate, in particular the practicality of pushing a thermal probe into some types and configurations of waste stack. The results of the phase 3 tests would indicate that the use of thermal probes, where practical, may be of use, but may depend on a level of ‘chance’ as to whether the probe hits a hot spot or misses.

As noted above, fires in loose waste stacks may re-ignite after the obvious surface fire has been extinguished, and that this re-ignition may take place many hours after apparent extinguishing of the fire. In addition, wastes and other materials which have been burnt may undergo chemical change which makes them more prone to re-ignition. Landfill is the most common disposal route for wastes from waste fires. Unless the waste is excavated and thoroughly doused before such disposal, landfill may not be a wise disposal route.

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Nothing in this information document constitutes legal or other professional advice and no warranty is given nor liability accepted (to the fullest extent permitted under law) for any loss or damage suffered or incurred as a consequence of reliance on this document.

As a non-technical summary report, the information in this document should be viewed as being subject to change, further clarification and/or addition. Future academic reports on the waste fire burn trials may result in this document being revised.

The Waste Industry Safety and Health (WISH) Forum exists to communicate and consult with key stakeholders, including local and national government bodies, regulators, equipment manufacturers, trade associations, professional associations and trade unions.

Acknowledgements

The waste burn trials conducted in 2015, 2016 and 2017 are, to the best of the authors of the WISH fire guidance's current knowledge, the most extensive ever conducted on wastes, globally. The time, effort and funding required to complete these tests was substantive. In total, the phase 1, 2 and 3 tests have cost in excess of £180,000, not including materials, services and equipment provided free of charge by various providers. In addition, many services, equipment and materials were provided at less than cost. WISH would like to thank and acknowledge all those involved, and in particular:

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- Staff at Stobarts Pollington Site in Yorkshire, and Stobarts for use of the site
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- All of the suppliers who provided services, materials and equipment, often at cost or lower or in some cases free of charge