

BRE Global Client Report

Review of Environment Agency Fire Prevention Plan

Prepared for: Environment Agency
Date: 26 August 2016
Report Number: P104794-1000 Issue: 1

BRE Global Ltd
Watford, Herts
WD25 9XX

Prepared for: Environment Agency

Customer Services 0333 321 8811

From outside the UK:
T + 44 (0) 1923 664000
F + 44 (0) 1923 664010
E enquiries@bre.co.uk
www.bre.co.uk



Prepared by

Name Steve Manchester

Position Director, Fire Safety

Date 26 August 2016

Signature 

Authorised by

Name Martin Shipp

Position Technical Director

Date 26 August 2016

Signature 

This report is made on behalf of BRE Global and may only be distributed in its entirety, without amendment, and with attribution to BRE Global Ltd to the extent permitted by the terms and conditions of the contract. Assessments relate only to the items tested/assessed. BRE Global has no responsibility for the design, materials, workmanship or performance of the product or items tested/assessed. This report does not constitute an approval, certification or endorsement of the product tested/assessed.

BRE Global's liability in respect of this report and reliance thereupon shall be as per the terms and conditions of contract with the client and BRE Global shall have no liability to third parties to the extent permitted in law.



Version History

Version	Date	Status	Changes Overview
1	26/08/2016	Final	



Table of Contents

1	Introduction	5
2	Review of Fire Prevention Plan	6
2.1	Specific comments	6
2.2	General comments	10
3	Self-heating analysis for pile size management	11
3.1	Wood chips	12
3.1.1	Environment Agency samples	12
3.1.2	Wood chips from Jack Moody waste recycling site	13
3.2	Rubber tyres	14
3.3	SRF	14
3.4	Summary of analysis	15
4	References	18
Appendix A	Thermal Ignition Theory	20
	Nomenclature	32
Appendix B	Notes to explain self-combustion	34



1 Introduction

This report details the results of the review undertaken for the Environment Agency on their Fire Prevention Plan document '160527 FPP v3 final draft', intended for use by waste site operators following acceptance of the BRE Proposal No. P104794-1000 dated 26th May 2016.

The scope of the work was to undertake a detailed review of the sections relating to detection, suppression, pile sizes, separation distances, storage times and self-combustion. This has taken into account relevant research, fire trials and thermal ignition theory calculations conducted by BRE, where the information is in the public domain or with the written acceptance of commercial clients for commercially confidential information.

In relation to the table which sets out the maximum pile sizes for storage of waste in the open, this report provides comments in terms of safe dimensions and volumes for the various types of waste from the risk of self-heating leading to spontaneous combustion. This has, where possible, been based on isothermal test data and used Thermal Ignition Theory calculations to ascertain safe storage volumes, temperatures and timescales.

In addition, a Powerpoint presentation has been produced giving an overview of the fire safety work BRE has undertaken in this industry sector.



2 Review of Fire Prevention Plan

The methodology used has been to review each section of the document and to provide comments and these are set out in the Table 1 below. Supporting calculations on setting out the safe storage criteria on the self-heating risk of piles of waste are provided in Section 3 of this report.

2.1 Specific comments

Table 1 FPP v3 comments

These comments are based on v3 of the draft fire prevention plan guidance. It is recognised that the structure and style of the plan may vary as it progresses through the publication process.

Section	Comments
Introduction: 2 nd para	<p>Add a sentence to say that under certain circumstances additional time for extinguishment may be acceptable, e.g. for remote sites away from populated areas.</p> <p>Additional bullet</p> <ul style="list-style-type: none"> · minimise the spread of fire within the site and to neighbouring sites.
Introduction: 4 th bullet	Add on end 'under certain circumstances, such as for remote sites away from populated areas'.
Waste types this guidance applies to	Add 'Waste Derived Fuel' (dried sewage sludge)? This material self-heats but I don't think there are currently any Waste Water Treatment sites in England and Wales operating drying plants I believe they are all mothballed. Such plants do still operate in Scotland though.
Waste types this guidance applies to	Add 'batteries' as a separate bullet point rather than within the waste electrical items to more clearly highlight this type of waste as I know of a number of significant fires and an explosion on battery recycling sites. Unless this comes under the 'hazardous wastes' in the section below.
Waste types this guidance applies to	Do Anaerobic Digestion sites come under this document? They store and process large quantities of food and farm waste products – see below.
Waste this guidance does not apply to	I think this section should refer to the Dangerous Substance and Explosive Atmosphere Regulations (DSEAR) as many of the materials in this section such as batteries, low flash point flammable liquids, aerosols, flammable gas cylinders and dust extraction systems can all produce explosive atmospheres and hence need to be assessed to comply with DSEAR.



	I have done a number of DSEAR assessments on waste recycling sites and some have flammable dust extraction systems incorporating explosion protection devices. So I would include flammable dusts in the list.
Scope for Sectors: 1 st para	Delete 'or propose to depart from the aim to extinguish a fire within 4 hours'
Scope for Sectors: Table	Table has no heading and needs to be introduced in the text.
Scope for Sectors: Table 2 nd Row	I went to one site which used waste straw to feed into the digester so not all waste used is wet. However, these plants are covered under DSEAR so perhaps they don't need to be included.
Scope for Sectors: Table 8th Row	Agriculture, justification column – Biomass boilers burning wood pellets also need a DSEAR assessment as the loading of storage silos creates flammable dust clouds.
Scope for Sectors: Table last row	Cement lime and minerals –insert 'waste used as fuels for kilns' to first column just to make it clear it's the waste not the Cement lime and minerals.
Contents of your fire prevention plan	Perhaps require the site operator to send a copy to their local Fire and Rescue Service?
Managing the common causes of fire: Hot works	Add 'a fire watch for a suitable period should be implemented once hot works have ceased and in particular at the end of a working day'.
Managing the common causes of fire: sources of ignition	6m seems excessive for hot pipes and light bulb, and even for some of the other ignition sources.
Managing the common causes of fire: Self combustion	I would change the first word of the 1 st para from 'Some' to 'Many'. 4 th paragraph is potentially confusing as it switches the maximum time from 6 months to 3 months. 4 th bullet point: delete as it is impossible to control moisture content for outside storage and materials can undergo self-heating within a very wide range of moisture levels so controlling moisture levels is not a practical way of managing the risk of self-heating. 8 th bullet point remove reference for obtaining moisture levels. 9 th bullet point remove reference to moisture levels.
Managing waste piles Piles sizes for waste stored in the open.	Based on the analysis undertaken in Section 3 it appears that significant piles can be stored with relatively high critical ignition temperatures compared to ambient outside temperatures in the UK. In addition, ignition times also appear quite long. However, the presence of warm/hot materials can have a big impact and lead to self-heating in piles where the majority of the material is at ambient temperatures. To account for this complexity and to enable any fires to be managed effectively pile heights should be restricted to no more than 4m and storage time periods no more than 3 months, unless



	they have undertaken isothermal self-heating testing of the material that demonstrates otherwise. See also Appendix B.
Table 1	Add a column showing the separation distances required as per the previous FPP v2.
Table 1 pile sizes do not apply to	No comments on this section. Advice seems reasonable.
Pile sizes for waste stored in a building	<p>By implication it seems to suggest the site personnel will have to tackle the fire which they will not be trained to do and won't have the appropriate means (equipment or available water supply) to tackle such fires. So perhaps add a sentence to confirm that you are not expecting site staff to tackle the fire.</p> <p>General principles for fire prevention and mitigation of fires in waste stored in buildings would include:</p> <ul style="list-style-type: none"> · Keep waste pile sizes and separation distances no greater than for outdoor areas. · If the building is heated this could affect the potential for self-heating of the waste and should be taken into account when assessing self-heating risks. · Ensure escape routes, fire exits, alarm points and fire extinguishers are kept free from waste. · Ensure electrical equipment and heaters are kept free from waste, including dust and packaging materials. · Waste storage areas should be fire compartmented away from office areas. · Waste storage areas should have some means of clearing smoke from the building, such as openable skylights or roller shutter doors, to aid fire-fighting. <p>Further guidance is given in the DCLG document 'Fire Safety risk assessment - factories and warehouses'^[1].</p>
Separation distances	From radiation calculations we have undertaken, for example from our work for the Home Office on tyres dumps ^[2] , wood chips piles ^[3] and bales of stored RDF ^[4] , 6m seems a reasonable separation distance. However, it should be noted that under certain conditions certain materials could still ignite even with a 6m separation distance, e.g. a strong prevailing wind may result in a flame leaning over to directly impinge on material resulting in direct ignition, or some sensitive material receptors may ignite from a relatively low irradiance level even at 6m. So 6m will not necessarily stop fire spread in all situations and specific radiation calculations should be conducted for the specific materials stored as part of the fire safety management plan.
Fire walls and bays	BS EN 13501-1:2007+A1:2009. This is not the correct standard – this is for classifying materials which have been tested to the various Reaction to Fire tests and is intended for wall linings to stop excessive and rapid spread of flame. If the intention is for bay walls to resist fire (radiative heat and flaming) then better to specify a fire resistance period of say 120 minutes. I imagine



	<p>the material used for such bays will be concrete and so they should be able to meet 120 minutes.</p> <p>2nd bullet point - take out requirement for moisture monitoring.</p>
Quarantine area	<p>The benefit of having a quarantine area, used in conjunction with a separation distance, not only allows material that is burning to be spread out and extinguished, but also enables unburnt material to be placed there at the early stages of a fire to reduce the overall fuel load of the pile burning resulting in a smaller fire and reduced burn time. However, removing either burning or unburnt material must only be undertaken if safe to do so under supervision of the fire service.</p>
Detecting fires	<p>Last paragraph, remove 'where applicable' as it could be read that not all detection systems need to be third party approved.</p>
Suppressing fires	<p>2nd and third paragraphs contradict each other. 2nd para says 'the system should enable a fire to be extinguished within 4 hours', and 3rd says 'A Suppression system may not extinguish a fire'. It is highly unlikely a water spray or sprinkler system will extinguish a fire unless it has initiated on the surface of the pile – deep seated fires won't be extinguished. Even containing such fire could be challenging as the fuel loading is so high, the suppression system would need to be activated quickly and deliver a large quantity of water very quickly. They will also need to be activated quickly, which may be challenging if the sprinkler heads are in the roof of the building which is very large and so dissipates the heat and smoke across a wide area. Activation of the system linked to detection may be an option.</p> <p>Any system used should ideally have some supporting test or assessment evidence that it will work for the waste types and building being protected. The system used must be designed for this type of scenario.</p> <p>Last paragraph - take out 'where applicable'.</p>
Fire Fighting Techniques	<p>Remove 4 hour time period – see above.</p> <p>No specific comments - seems reasonable. I would ask the Fire Service to review this section.</p>
Water supplies	<p>No specific comments.</p>
Managing fire water	<p>The only comment I have is that any bunds used to contain water around a waste pile must be demonstrated to be effective when subjected to radiative heat from the fire, i.e. the bund material does not melt from the high surface temperatures it is subjected to, which will depend principally on the nature of the material and its distance from the waste pile.</p>
During and after an incident	<p>No comments.</p>



2.2 General comments

4 hour extinguishing requirement: I would emphasize that the 4 hour time scale is aspirational and under certain circumstances additional time periods may be acceptable, such as for remote sites away from populated areas.

Layout of piles: the Figure 1 in the current FPP has been removed – I understand it will be included in the templates to accompany the new version.

Self combustion moisture content: I would remove references to monitoring and controlling moisture contents on piles as I can't see how this can be practically undertaken and it has minimal impact on the self-heating process compared to other factors.

Two or more piles: This seems to be excluded. The advice given in the current FPP version seems reasonable i.e. "treat 2 or more piles as 1 pile if:

- they are within an area not exceeding 235m² and the longest dimension doesn't exceed 20m
- the space between them doesn't meet the minimum separation distances in table 1"



3 Self-heating analysis for pile size management

This section uses isothermal self-heating basket test data, based on the test methodology in BS EN 15188^[5] and Thermal Ignition Theory (see Appendix A), to estimate appropriate piles sizes to ensure self-heating cannot occur. Times to ignition are also estimated to assist in determining appropriate storage times for different waste. The methodology has been used for many years in the bulk powder handling industry to specify safety storage volumes, temperatures and time to ignition. It has also been applied to the bulk transportation of material such as dried sewage sludge to ascertain if a 27m³ volume of the material is likely to self combust^[6].

The following wastes are assessed in this section:

- Wood chips
- Rubber crumb
- Secondary Recovered Fuel (SRF)

Details of the equations used are given in Appendix A.

To ascertain if a material will self-heat to combustion the equation below must be solved to determine the value of the Frank-Kamenetskii parameter d and then this is measured against the critical value of d_c obtained from Table A1 in Appendix A for the geometry of the pile being assessed.

$$d = \exp(P) \times \frac{r^2}{T_R^2} \times \exp\left(-\frac{E}{RT_R}\right)$$

To determine the Frank-Kamenetskii parameter d for the material under test, a plot of $\ln(d_c T_R^2 / r^2)$ against $1/T_R$ was drawn for each sample and a linear regression analysis of this data performed. The values of P , the Y intercept of the straight line graph, and $-E/R$, the gradient of the slope of the graph, are inserted into the equation above and values obtained for different sizes of pile (r) and temperature (T_R).

Estimates of times to ignition at ambient temperatures above the critical ignition temperature can be determined by using equation 21 in Appendix A. An illustration of the relationship is given in Figure 1 below using data from a sample of wood chips (Sample 1 - see section 3.1 below) provided by the Environment Agency. It should be noted that the times are only estimates to be used as an indicator and are not absolutes.

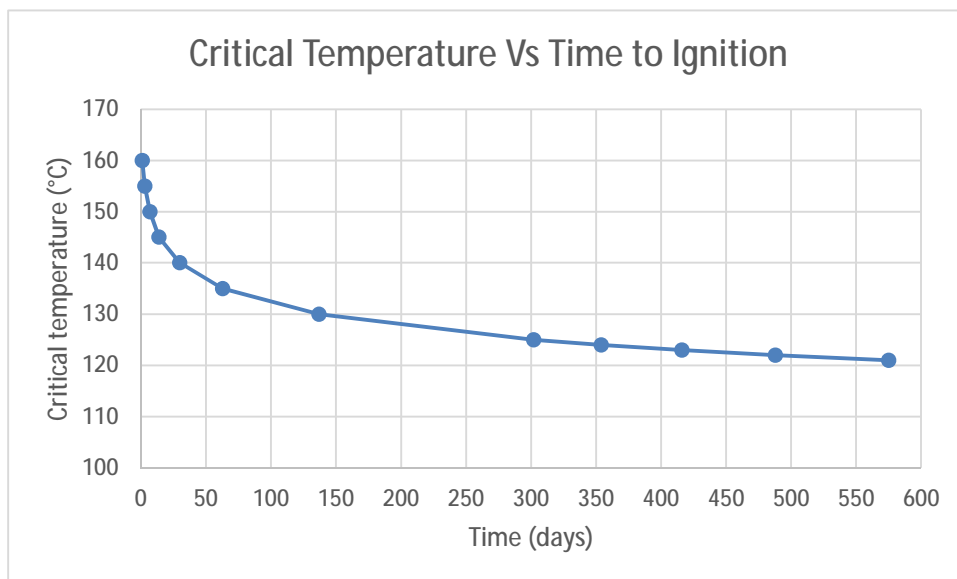


Figure 1 Relationship between critical temperature and time to ignition.

Key points to note are:

- For the same material a larger pile will have a lower critical ignition temperature, and hence actions to cool the waste to ensure this temperature is not reached must be undertaken at an early stage of the storage period. For materials having a relatively low critical temperature (<50°C) intensive cooling and temperature monitoring activities will be necessary.
- The use of Thermal Ignition Theory to predict self-heating leading to ignition using the equation above assumes the material is at a constant and uniform ambient temperature, such as might be found on industrial processing sites or the hold of a ship. Whereas bulk storage of waste outdoors is likely not to be at a constant temperature.
- If a 'hot spot' or warm/hot material is introduced into the pile this can have a dramatic effect on the time to ignition, reducing it to days or even hours depending on the temperature. However, in the first instance if the temperature of this 'hot spot' or warm/hot material is known then Thermal Ignition Theory can be used to determine if ignition is likely to occur.

3.1 Wood chips

3.1.1 Environment Agency samples

Two samples of wood chips, supplied to BRE Global by the Environment Agency, were investigated for self-heating using BS EN 15188:2007.

Sample 1

The first sample supplied had a wide range of particle sizes from large sticks of 200mm to fine dust and appeared to be unprocessed. The material tested was not prepared or sieved but samples used generally had particle sizes of <50mm.

Critical temperatures measured for the different basket sizes:

50mm basket: 207°C



75mm basket: 201°C

100mm basket: 195°C

125mm basket: 191°C

A pile with dimensions of 20m x 20m x 4m would need to be heated to 133°C to self combust and would take 86 days. For a pile with dimensions 20m x 10m x 4m the critical ignition temperature has no change.

Increasing the pile height to 10m reduces the critical ignition temperature to 123°C.

Keeping the height at 4m but increasing the length and width of the pile to 50m has minimal effect and only reduces the critical temperature to 132°C.

A 10m x 50m x 50m pile has a critical temperature of 121°C and this in ideal controlled conditions would take 575 days. See Appendix B why this would not occur in practice.

Sample 2

The second wood chip sample supplied to BRE Global by the Environment Agency had a particle size of <30mm in size. The material tested was not prepared or sieved.

Critical temperatures measured for the different basket sizes:

50mm basket: 205°C

75mm basket: 189°C

100mm basket: 182°C

125mm basket: 176°C

A pile with dimensions of 20m x 20m x 4m would need to be heated to 83°C to self combust and would take 96 days. For a pile with dimensions 20m x 10m x 4m the critical ignition temperature is 84°C.

Increasing the pile height to 10m reduces the critical ignition temperature to 70°C.

Keeping the height at 4m but increasing the length and width of the pile to 50m has no effect with the critical temperature remaining at 83°C.

A 10m x 50m x 50m pile has a critical temperature of 67°C and this in ideal controlled conditions would take 594 days. See Appendix B why this would not occur in practice.

3.1.2 Wood chips from Jack Moody waste recycling site

Two samples of wood chips, supplied to BRE Global by the Jack Moody Recycling Ltd, were investigated for self-heating^[7] using BS EN 15188:2007. These are referred to below as samples 3 and 4.

Sample 3

Sample 3 had particle sizes ranging between 0 – 20mm in size. Critical temperatures measured for the different basket sizes:

50mm basket: 210°C

75mm basket: 192°C

100mm basket: 183°C



125mm basket: 170°C

A pile with dimensions of 20m x 20m x 4m would need to be heated to 58°C to self combust and would take 97 days. For a pile with dimensions 20m x 10m x 4m the critical ignition temperature increases slightly to 59°C.

Increasing the pile height to 10m reduces the critical ignition temperature to 43°C.

Keeping the height at 4m but increasing the length and width of the pile to 50m has minimal effect and only reduces the critical temperature to 57°C.

A 10m x 50m x 50m pile has a critical temperature of 40°C and this in ideal controlled conditions would take 582 days. See Appendix B why this would not occur in practice.

Sample 4

Sample 4 had particle sizes ranging between 10 – 75mm. Critical temperatures measured for the different basket sizes:

50mm basket: 212°C

75mm basket: 201°C

100mm basket: 194°C

125mm basket: 188°C

For the larger particle sizes tested it can be seen from Table 2 below that a pile of dimensions 4m x 20m x 20m would need to be at a temperature of 109°C before it would self-ignite and this would take approximately 74 days. Increasing the pile height to 10m reduces the ignition temperature to 94°C but in ideal controlled conditions would take approximately 489 days to get to this ignition. See Appendix B why this would not occur in practice.

3.2 Rubber tyres

Self-heating tests were undertaken in 2004 by BRE Global on waste tyres as part of the Defra / Environment Agency Flood and Coastal Erosion Risk Management R&D Programme project Sustainable Re-use of Tyres in Port, Coastal and River Engineering. Guidance for planning, implementation and maintenance. Rubber tyres were chopped up to relatively small pieces and self-heating tests undertaken. The tyres used in the tests had the iron reinforcing material present and so is not exactly the same material as rubber crumb that has been processed to remove the metal reinforcing.

Critical temperatures measured for the different basket sizes:

50mm basket: 325°C

75mm basket: 310°C

100mm basket: 300°C

125mm basket: 290°C

For this material the ambient temperatures required for self-heating to lead to combustion are much greater than for wood chips at 179°C for a 4m high pile and 159°C for a 10m high pile.

3.3 SRF

Two secondary recovered fuel (SRF) samples were tested by Chilworth Technology^[7], samples tested were 'normal density' and 'high packing density'. The critical temperatures measured were:



Normal density

50mm basket: 173°C

75mm basket: 155°C

100mm basket: 145°C

High packing density

50mm basket: 148°C

75mm basket: 142°C

100mm basket: 132°C

3.4 Summary of analysis

The table below summarises the analysis undertaken for each of the different waste types above.

For wood chips generally there are a number of factors to consider that will affect the propensity for self-heating leading to combustion, these are:

- Particle size distribution – finer material will generally be more susceptible to self-heat.
- Type of wood – some will have more natural oils present than others.
- Presence of applied oils or treatments on the wood from its original use.
- Whether the wood has been processed – potential for the material to be stored when warm.

Of the four samples of wood chips tested it can be seen there is a wide variety of critical temperatures for the same pile sizes with the different samples. A 10m x 50m x 50m pile can have a critical temperature varying between 40 – 21°C. This underlines the variability of such waste material in terms of propensity to self-heat.

The variation of the critical temperatures obtained for the SRF material indicates how the packing density affects the self-heating process. The high packing density material was hand pressed into the baskets rather than using the 'tip-fill' method which is usually undertaken for these tests whereby the material is poured into the baskets and then levelled off.

So the above analysis would appear to allow significant pile sizes to be possible before self combustion is likely to occur. However, the calculations assume the material in the pile is at the same ambient temperature as the surroundings and in reality this may not be the case. If warm or hot material is stored, and this includes hot spots of material from processing activities or decomposing material, then this can affect the time to ignition. So even though the pile temperature generally may be cool, at say 20°C, which would be below the critical ignition temperature for most materials, a hot spot at 200°C would initiate self-heating leading to combustion and the time to ignition would be dramatically reduced. These variables will reduce the time to ignition set out in Table 2.

Table 2 Summary results

Fuel type	Pile size	Critical temperature (°C)	Time to ignition (days) in controlled conditions
Wood chips Sample 1	4m x 10m x 20m	133	86



	4m x 20m x 20m	133	86
	10m x 20m x 20m	123	416
	4m x 50m x 50m	132	100
	10m x 50m x 50m	121	575
Wood chips Sample 2	4m x 10m x 20m	84	86
	4m x 20m x 20m	83	96
	10m x 20m x 20m	70	417
	4m x 50m x 50m	83	96
	10m x 50m x 50m	67	594
Wood chips Sample 3	4m x 10m x 20m	59	88
	4m x 20m x 20m	58	97
	10m x 20m x 20m	43	426
	4m x 50m x 50m	57	106
	10m x 50m x 50m	40	582
Wood chips Sample 4	4m x 10m x 20m	109	74
	4m x 20m x 20m	108	83
	10m x 20m x 20m	96	369
	4m x 50m x 50m	108	83
	10m x 50m x 50m	94	478
Rubber tyres	4m x 20m x 20m	179	76
	4m x 50m x 50m	179	76
	10m x 50m x 50m	159	489
SRF normal density	4m x 20m x 20m	30	93



	4m x 50m x 50m	29	102
	10m x 50m x 50m	13	572
SRF high packing density	4m x 20m x 20m	59	101
	4m x 50m x 50m	59	101
	10m x 50m x 50m	47	568



4 References

1. Fire Safety Risk Assessment. Factories and warehouses. Department for Communities and Local Government.2006.
2. Home Office/Scottish Office. Fire Safety for Tyre Sites. HMSO 1995.
3. BRE Global Client Report. Fire Spread Analysis. BRE Global Report No. 136540. Jack Moody Recycling Ltd. October 2014.
4. BRE Global Client Report. Radiant Heat Calculations – Fire Booms. BRE Global Report No. P105031-1000. Terraconsult Ltd. June 2016.
5. British Standards Institution, Determination of the spontaneous ignition behaviour of dust accumulations, BS EN 15188:2007.
6. Approved Requirements and test methods for the classification and packaging of dangerous goods for carriage. 1996. Health & Safety Commission. HMSO.
7. BRE Global Client Report. Isothermal self-heating assessment. BRE Global Report No. 300036. Jack Moody Recycling Ltd. January 2015.
8. Fire Risk & Thermal Stability Testing on Secondary recovered Fuel. Chilworth Global. Report number: S106885R1V1/11. 26th September 2011.
9. Frank-Kamenetskii, D. A., Diffusion and Heat Transfer in Chemical Kinetics, 2nd. Ed., Translated by J. P. Appleton, Plenum Press New York (1969).
10. Bowes, P. C., Self-Heating: Evaluating and Controlling the Hazards, HMSO, London (1984).
11. Thomas, P. H., Trans. Farad. Soc., **54**, 60 (1968).
12. Barzykin, V. V., Gontlovskaya, V. T., Merzhanov, A. G. and Khudyaeu, S. I **3**, 188 (1964).
13. Boddington, T., Gray, P., and Harvey, D. I., Phil. Trans. Roy. Soc. Lond., **270**, 467 (1971).
14. Parks, J. R., J. Chem. Phys., **34**, 46 (1961).
15. Tyler, B. J. and Wesley, T. A., Combust. Inst. (Internat) 11th Symp., 1115 (1967).
16. Carter, M. R., Druce, O. J., and Wake, G. C., Proc. R. Soc. Lond. **A367**, 411 (1979).
17. Alder, J., and Enig, J. W., Combust. Flame, **8**, 97 (1964).
18. Takeno, T., and Sato, K., Combust. Flame, **38**, 75 (1980).
19. Thomas, P. H., Combust. Flame, **21**, 99 (1973).
20. Gray, B. F., and Scott, S. K., Combust. Flame, **61**, 227 (1985).
21. Ohlemiller, T. J., and Rogers, E. F., Combust. Sci. and Technol., **24**, 139 (1980).
22. Rogers, E. F., and Ohlemiller, T. J., J. Macromol. Sci-chem., **A15**, 169 (1981).
23. Beever, P. F., SFPE Handbook of Fire Engineering, Society of Fire Prevention Engineers/National Fire Prevention Association, Quincy MA (1988).



24. Boddington T., Feng C-G., and Gray, P., Proc. R. Soc. Lond., **A385**, 289 (1983).
25. Boddington T., Feng C-G., and Gray, P., Proc. R. Soc. Lond., **A391**, 269 (1984).
26. Beaver, P. F., Spontaneous Combustion - Isothermal Test Methods, Building Research Establishment Information Paper IP23/82 (1982).



Appendix A Thermal Ignition Theory

Background

The term spontaneous combustion (or self-heating) is used to describe the culmination of a runaway temperature rise in a body of combustible material, arising as a result of heat generated by some process taking place within the body. The theoretical treatment which follows was developed to describe the ignition of explosives, propellants and unstable materials, and of liquid and gas systems. In such systems the reactants are essentially premixed.

Here we describe the application of the theory to accumulations of materials which can react exothermically with oxygen in the air, for this is the case when spontaneous fires start most unexpectedly. The approach described has been found useful in the study of self-ignition in bulk storage of material at relatively low temperatures and in smaller accumulations at higher temperatures.

The Critical Parameter d_c

Whether a pile of material is liable to self-ignition or not, depends on the balance between the rate of heat generation within the pile and the rate at which heat is lost to the surroundings. Frank-Kamenetskii^[9] highlighted the importance of a dimensionless group of terms d , known as the Frank-Kamenetskii parameter, which is determined by the relevant physical and chemical properties of the material together with the size of the pile and a reference temperature. All these factors are important; more heat will be generated at elevated temperatures and by highly exothermic reactions, less heat is lost by large piles with poor thermal conductivity. Materials which are safe in one set of conditions may not necessarily be so in another.

For a given system, it is possible in general terms to determine a critical value for d_c . This may be taken from literature, calculated from known methods or derived from first principles by solving the equations for the heat balance. If the evaluated value for d is greater than d_c then the system will self-ignite; the heat generated at all times exceeds that which is lost. The temperature rise is slow at first, and then rapid until ignition occurs.

If the calculated value of d is less than the critical value, only moderate self-heating can occur. The theory predicts that the maximum temperature rise which can safely be sustained in a body is low, of the order of a few tens of degrees centigrade in practice, above this temperature self-heating to ignition will occur. The distinction between ignition and non-ignition is in principle sharp and arises as a consequence of the assumption in theory that the heat-generating reaction is highly sensitive to temperature. In general this is true and the distinction between sub-critical (non-ignition) and super-critical (ignition) states is also sharp in practice.

It is important to understand the assumptions of the theory in order to assess to what extent these are borne out in practice and under what circumstances corrections must be made.

The basic assumptions made by Frank-Kamenetskii are as follows:

- (i) Heat is generated by a single reaction whose rate is not a function of time. The rate of reaction is assumed to be a function of Absolute temperature, T , according to the Arrhenius equation;



$$\text{rate} \propto \exp(-E/RT) \quad (1)$$

where E is the activation energy and R the universal gas constant.

- (ii) The activation energy is sufficiently high for the condition;

$$\varepsilon = RT_R/E \gg 1 \quad (2)$$

to hold. T_R is a reference temperature, typically taken to be ambient.

- (iii) Heat transfer through the body is by conduction.
 (iv) Heat transfer at the surface to the surroundings, by convection and radiation, is high, such that the surface temperature of the body is at ambient.
 (v) The material is isotropic and homogeneous with physical properties that do not depend upon temperature.

These assumptions hold sufficiently well in many cases for predictions to be made on the basis of them. They rarely are so unrealistic so as to preclude useful estimates being made using the theory.

The foregoing assumptions allow the heat balances in the body which is simultaneously generating and losing heat to be written, subject to suitable boundary conditions, as;

$$\tilde{N}^2 q + d \exp q = 0 \quad (3)$$

where θ is an approximate form of the Arrhenius Equation (1). θ is a dimensionless temperature given by;

$$q = \frac{E}{RT_R^2} (T - T_R) \quad (4)$$

where T_R is a reference temperature. Suitable forms for the differential operator \tilde{N} depend on the geometry of the body. The appropriate space variable is made dimensionless using a characteristic dimension, r , of the body.

Equation (3) has no time dependence and its solutions are steady state temperature profiles. If d is made sufficiently large, no solutions can be found for Equation (3). At this transition, the value of d is identified as the critical value for ignition in practice, d_c . Solutions of the equation also yield a value θ_0 , the maximum central temperature which may be attained at the critical value of d . At $d > d_c$, the central temperature becomes (theoretically) infinite.

Critical Values of the Frank-Kamenetskii Parameter

Table A1^[10] gives values of the critical Frank-Kamenetskii parameter for a range of shapes, calculated on the basis of the assumptions for bodies exposed to a steady uniform ambient temperature. The reference temperature in all cases is ambient, and the characteristic dimension used in deriving d_c is given.



Equation (3) is only amenable to exact solution for the simplest geometries and many of the values given in Table A1 are approximate. Where the values given are exact, this is indicated.

Table A1. Values of d_c for Various Geometries

Geometry	Dimensions	d_c	θ_o
Infinite plane Layer	Thickness $2r$	0.878^*	1.12
Rectangular Box	side $2r, 2l, 2m$ $r < l, m$	$0.873 (1+r^2/l^2+r^2/m^2)$	
Cube	sides $2r$	2.52^*	1.89
Infinitely long Cylinder	radius r	2.00^*	1.39
Short cylinder	Radius r height $2l$	$2.00 + 0.841 (r^2/l^2)$	
Equicylinder	radius r height $2r$	2.76^*	1.78
Sphere	radius r	3.32^*	1.61

* Exact value

The expressions and values given in Table A1 all yield d_c to within a few per cent. As will be illustrated later, errors of this magnitude do not give rise to unacceptably large errors when applied to practical problems.

Ultimately if the required value cannot be found, then d_c must be calculated by studying solutions to Equation (3). This equation may be solved numerically using standard procedures; the value of d being increased until solutions fail to converge. This can give d_c to any required degree of accuracy. Numerical



approaches can dispense with many of the assumptions outlined above, to yield values highly specific to the problem.

Corrections to d_c

General Remarks

The assumptions of the simple theory will generally not be met in practice and where the departures are significant or where particularly accurate values are required, corrections will have to be made to the value of d_c . The corrections given below are those judged to be of greatest use for practical problems. The corrections are all approximations in themselves to a greater or lesser extent and in each case the range of values over which they hold and the expected accuracy are indicated.

The expressions given here are very often not the only ones which could be applied and in the literature others may be found which are better but perhaps less convenient to apply or which provide more valid results in certain limits. For typical values of the relevant parameters, errors of up to 10% in the determination of d_c will give errors of about 1°C in the prediction of the critical temperature or 5% in critical size.

Finite Heat Transfer Coefficient

Assumption (iv) set the surface temperature of the body to ambient which implies a high heat transfer coefficient, H , at the surface. If H is not sufficiently large, the surface temperature will be above ambient.

It is important to correct d_c for this failure as a low heat transfer coefficient will make ignition more likely, as heat losses are consequently reduced. Predictions made using uncorrected values of d_c will therefore fail to err on the safe side. The way in which the rate of heat transfer from the surface affects the value of d_c is embodied in a dimensionless group of numbers known as the Biot number, a , given by;

$$a = \frac{Hr}{l} \quad (5)$$

where l is the thermal conductivity and r is the characteristic dimension from Table A1. The Biot number represents the ratio of external to internal heat transfers. If the thermal conductivity is low, the surface heat transfer coefficient high or the pile large then $a \gg 1$ and no correction is necessary. The error in d_c is about 2% when $a = 100$ and still less than 10% when $a = 25$.

If the thermal conductivity is high compared with the heat transfer coefficient at the surface then $a \ll 1$. The body is effectively at uniform internal temperature with a step to ambient temperature occurring at the surface. This is the Semenov condition and as this limit is approached d_c is given, for all geometries, as;

$$d_c = \frac{a}{e} \frac{Sr}{V} \quad (6)$$



where S is the surface area and V the volume of the body. This expression is appropriate to low values of a . It overestimates d_c by less than 3% when $a = 0.1$ and 10% when $a = 0.3$ [9].

Intermediate values of a use an expression by Barzykin et al^[12] which is appropriate for all geometries;

$$d_c(a) = d_c(a @ \text{¥}) \frac{a}{2} (\sqrt{a^2 + 4} - a) \exp\left(\frac{\sqrt{a^2 + 4} - a - 2}{a}\right) \quad (7)$$

where $d_c(a @ \text{¥})$ is the value taken from Table A1.

This expression gives results which are within 2% of the exact results of Thomas^[11] for $a > 2$.

Low Activation Energy

In setting up Equation (3) it has been assumed that the quantity $\epsilon\theta$ is small. Since maximum values of θ are of the order of unity (see Table 1) this is equivalent to the assumption that ϵ is small.

Typical values of E/R are of the order of 10^4 so that in most cases this assumption is correct. If correction for large values of ϵ is necessary, the following expression by Boddington, Gray and Harvey^[13] may be used;

$$d_c(\epsilon) = d_c(\epsilon = 0)(1 + 1.07\epsilon) \quad (8)$$

This equation was derived from numerical results by Parks^[14] and is valid for $\epsilon < 0.05$.

Reactions which are not sufficiently sensitive to temperature, i.e. low E/R , cannot exhibit self-ignition. There is a sharp cut off at definite values of ϵ , above which ignition will not be observed. These values vary slightly with geometry and Biot number but are in the region of $\epsilon = 0.25$. Such large values of ϵ are very far from those normally encountered in practice.

Reactant Consumption

Assumption (i) assumes that the rate of the heat-generating reaction is a function of temperature only. In practice the reactants are inevitably depleted over a period of time and the reaction slows down as a consequence. The assumption is good if the reaction is sufficiently exothermic for negligible reactant consumption to have occurred at the point of ignition. The parameter which governs the effects of reactant consumption is the dimensionless adiabatic temperature rise, B , given as;



$$B = \frac{E}{RT_R^2} \frac{Q}{C} \quad (9)$$

Highly exothermic reactions have high values of B, whilst a low heat of reaction gives a low value for B.

The correction to be applied also depends on the order of reaction, n, where rate of reaction depends on the reactant concentration, c, such;

$$\text{rate of reaction} \propto c^n \quad (10)$$

B and n for the reaction must be determined before correction can be made. For materials undergoing a simple reaction, it may be possible to obtain n and Q from the literature and to calculate B. In most cases, especially where natural materials are involved, the reaction responsible for self-heating is not a simple one. The heat of reaction is, in general, not the same as the heat of combustion of the material. Techniques for establishing Q will be covered later. These are not straightforward however and the evaluation of B is not easy in many cases. Assuming the values for B and n are available, the correction for a large B takes the form;

$$\frac{d_c(B)}{d_c(\infty)} = \frac{1}{a + b(n/B)^{2/3}} \quad (11)$$

Tyler and Wesley^[15] have obtained values for a and b for a range of values of ε (see Table A2). If these values are used, Equation (11) reproduces numerically obtained values for d_c to within 2% for B > 25, n = 1 and for B > 100, n = 2. For B = 25, n = 2 the error is about 10%.



Table A2. Values of a and b as a Function of ϵ (Equation 11)

ϵ	a	b
0.000	1.000	2.28
0.025	0.973	2.35
0.050	0.944	2.41
0.075	0.916	2.49
0.100	0.895	2.56

Tyler and Wesley^[15] do not examine the problem of $B < 25$ but these values have been studied under Semenov conditions. For large B Equation (11) may be used. For smaller B , Carter, Druce and Wake^[16] suggest for a first order reaction ($n=1$);

This expression does have the advantage of including a dependence of d_c on ϵ .

$$\frac{d_c(B, \epsilon)}{d_c(\infty, 0)} = \frac{(3 - 4\epsilon)(1 - 4\epsilon)}{e(1 - 2\epsilon)(1 - 4\epsilon - 4/B)} \quad (12)$$

Under Semenov conditions, this expression predicts the numerical results of Adler and Enig^[17] for $\epsilon = 0$ to better than 7% for $100 > B > 25$. The error increases to 14% when $B = 10$.

If the same correction is applied to values of d_c under Frank-Kamenetskii conditions and compared with the numerical work of Tyler and Wesley^[15], the error is probably no worse than under Semenov conditions and the above equation may be used. For more exact work at low values of B , a proportional correction to d_c based on the numerical work of Adler and Enig^[17] for Semenov conditions is probably quite accurate for Frank-Kamenetskii conditions.

The maximum central temperature attained by a system without ignition increases as B is decreased. For $B > 100$ Tyler and Wesley found the following to hold for $\epsilon = 0$;



$$\frac{q_o(B)}{q_o(\infty)} = 0.88 + 5.58(n/B)^{2/3} \quad (13)$$

The coefficients vary as ϵ is increased. As B decreases θ_o increases and the maximum temperature reached at ignition decreases. Ultimately, for B sufficiently small, the sub-critical temperature rise approaches the super-critical temperature rise and ignition cannot be recognised. Under such circumstances d_c cannot be defined. In theory ignition is not possible if $B < 4$ for $n = 1$. In real systems, however, it appears that ignition may be observed at lower values of B .

Oxygen Diffusion

If a reaction proceeding in a porous body requires oxygen, then this must diffuse into the body from the surrounding atmosphere. The effects of oxygen diffusion are found to be governed by a parameter f given by;

$$f = \frac{n I T_R}{c_o Q_o D} \quad (14)$$

c_o is the concentration of oxygen in the voids by volume and Q_o is the heat of reaction by volume of oxygen. n is the order of reaction with respect to oxygen concentration. Frank-Kamenetskii theory assumes $f \ll 1$.

Takeno and Sato^[18] show that as f is increased d_c increases, and therefore the system ignites less easily. Thus low concentrations of oxygen, low heats of reaction and low diffusivity increase d_c .

The evaluation of f in practice may present problems. Suitable values for Q_o may be found in literature, otherwise a method for measuring Q_o directly must be sought. The diffusion coefficient, D , depends on the porosity of the powder and the temperature. Bowes^[10] suggests the following form;

$$D = D_o (T/273)^{1.75} p^{1.5} \quad (15)$$

where D_o is the diffusion coefficient for oxygen in free air at 0°C and p is the porosity (fraction of voids) in the material. For typical values the parameters in Equation (14), f is frequently much less than unity and the correction to d_c will not be necessary.

Hot Material

Thomas^[19] has developed an approximate method for dealing with hot materials in cooler surroundings. It is included as it is especially useful in many industrial situations where hot material from processing may be stored in bags or bins. It is possible that instead of cooling to ambient the material may self-heat to ignition.

This analysis involves the use of a parameter θ ; where;



$$q_i = \frac{E}{RT_i^2} (T_i - T_a) \quad (16)$$

where T_i is the initial temperature of the hot material. This parameter is then related to values of d_c , which is defined with T_i as the reference temperature.

Values for d_c including the dependence on a are given by Bowes^[10], with a correction for an error in the original paper by Thomas^[19]. The method suggested by Thomas is flexible and the derivation of $d_c(\theta_i)$ for other geometries is not too difficult in principle.

The analysis of Thomas assumes that $\epsilon = 0$. Numerical results for the same type of problem and covering a range of values of ϵ are given by Gray and Scott^[20]. Their formulation of the problem is rather different from that of Thomas however, with d and θ being defined with ambient temperatures as reference.

As a result the curves of $\theta_i(d)$ become very steep in the region of small d giving inaccurate predictions of θ_i in the region where critical initial temperature is well above ambient. In many cases this will be the region of practical interest. Otherwise the results of Gray and Scott are useful, particularly for large ϵ .

Summary

The corrections given in the present section can be applied successively to a value of d_c to obtain a suitable value for a given set of circumstances. On occasions this procedure will increase the errors somewhat. In most cases this will not matter greatly for practical purposes. It will be rare for all the corrections to be necessary in a particular case.

Practical Evaluation of the Frank-Kamenetskii Parameter

Direct Measurement of the Material Properties

To determine whether self-heating in a body is destined to culminate in ignition, the value of the parameter d must be determined and compared to the value predicted above. The definition of the Frank-Kamenetskii parameter is;

$$d = \frac{E}{R} \frac{r Q}{l} \frac{r^2}{T_R^2} A \exp \frac{-E}{RT_R} \quad (17)$$

where T_R is a suitable reference temperature and r a characteristic dimension, defined as before.

In principle the parameters in the Equation (17) may be measured or taken from the literature and d evaluated directly. Care is required in the choice of technique used to evaluate E , A and Q (together with n if a correction for B is applied). Such values are usually established using differential thermal analysis (DTA) or differential scanning calorimetry (DSC) possibly combined with thermo-gravimetric analysis (TGA).



These techniques work best on materials which exhibit a single reaction which behaves according to a simple rate law. Complications arise when the material is a naturally occurring compound with various possible decomposition routes. All that can be hoped for in practice is to obtain "effective" parameters which describe the reaction. It is important that an accurate and precise value for the effective activation energy, E , is obtained.

Because of the exponential dependence of d on E , it is crucial to the success of the method that this parameter is determined with a high degree of reliability.

The direct evaluation of d may not therefore be straightforward. However, if only small amounts of material are available, the methods mentioned above may be the most suitable and appropriate references should be consulted. Ohlemiller and Rogers^[21] have calculated critical conditions numerically using reaction parameters determined as outlined above. The agreement with experiment is good. The analytical techniques used on the DSC and DTA curves to deduce E , A and Q were however quite sophisticated. These are described in detail by Rogers and Ohlemiller^[22].

Indirect Evaluation

It is possible to obtain values for groups of parameters in Equation (17) by searching for critical behaviour under controlled ambient conditions. The theory predicts that material will either undergo moderate self-heating for $d < d_c$ or will ignite for $d > d_c$.

The critical condition is in principle very sharply defined and it proves to be in practice, except for materials with very low B values.

In searching for critical behaviour in a material, the parameters under the control of the experimenter are the size (r) and the ambient temperature (T_R). Thus the critical size may be determined for a given temperature or, more simply in practice the critical temperature may be determined for a known size. To see how this helps, Equation (17) is rewritten as;

$$\ln \frac{d T_R^2}{r^2} = P - \frac{E}{RT_R} \quad (18)$$

where,

$$P = \ln \left\{ \frac{E}{R} r \frac{QA}{l} \right\} \quad (19)$$

If T_R and r are known for the critical case then the appropriate value of d_c may be substituted in Equation (18).

A plot of $\ln(d_c T_R^2 / r^2)$ against $1/T_R$ should yield a straight line of slope $-E/R$ and intercept P . Once these two parameters are known d can be calculated for any T_R and r from equation 18.

Any system for which d_c is known can be used in the experimental arrangement. In practice two types of set up have been found useful.

The first involves exposing a sample of material held in a wire mesh basket to a uniform temperature in an oven. The baskets might be cubes or short cylinders and appropriate values of d_c would be taken from Table A1. The central and surface temperatures are monitored by thermocouples.



An alternative method involves the determination of the critical temperature of a hot plate for a layer of known thickness of material upon it. The value of d_c appropriate for this case is given by Beever^[23]. The reference temperature in the definition of d_c and θ_A is the hot plate temperature T_p . In practice layer thicknesses of 5 mm to 25 mm are used.

In order to calculate d_c , which will be different for each layer thickness, a has to be estimated. The diameter of the layer must be at least six times its thickness in order for it to be assumed that it is of infinite extent. Tests of this type have been used for many years for the assessment of the ignition behaviour of dusts which are processed in hot environments, i.e. driers.

Times to Ignition

For many practical purposes it is not sufficient to know that a system is super-critical. It is usually important to have some idea of the time which will elapse before ignition occurs.

Very large piles of material, not much above critical, can in ideal and controlled conditions have very long times to ignition. If storage times are appreciably less than the times to ignition, no hazard arises in practice. However, Annex B sets out an assessment of the variable factors in the waste industry that are likely to significantly reduce the time to ignition from those based on Boddington, Feng and Grey.

Boddington, Feng and Gray^[24,25] have derived an expression for time to ignition, t_i , for; systems not too far above critical

$$t_i = M t_{ad} \left[\frac{d}{d_c} - 1 \right]^{-1/2} \quad (20)$$

where t_{ad} is the adiabatic time to ignition given by:

$$t_{ad} = \frac{RT_R^2}{E} \frac{C}{QA} \exp \frac{E}{RT_R} \quad (21)$$

The adiabatic time is the ignition time in the absence of any heat losses and is the shortest possible time in which a system could ignite. M is a constant which depends on the geometry and a . Some values for M are given in Table A3 and Boddington et al^[22] indicate how M could be calculated for other conditions.

The variation in M is however not large and for most work an estimate based on the average value would be perfectly adequate. M also depends upon reactant consumption but Boddington et al^[19] have shown that this variation is not large either.



Table A3. Values for M in Equation (20)

a ≠ 0			a = 0
∞ layer	∞ cylinder	sphere	All geometries
1.534	1.429	1.316	1.634

It can be seen from Equation (20) that the times tend to infinity under conditions which are close to critical and reduce sharply as d is increased. The expression given predicts times to ignition well for $d/d_c < 2$ and better than 20% for $d/d_c < 3$.

In the evaluation of t_{ad} , the product QA may be estimated from P , Equation (19), if values can be obtained for l and r . T_R is the critical value of the reference temperature.

By comparing Equation (21), with the definition of d , Equation (17), it can be seen that;

$$d_c = \frac{t_F}{t_{ad}} \quad (22)$$

where $t_F = rCr^2/l$ is known as the Fourier time and is a characteristic cooling time for the system. Bowes^[10] suggests the correlation $t_i \mu r^2$ for estimating times to ignition from experimental results. If Equation (22) is substituted into (19) it can be seen that this is true for a given value of d/d_c . However in experimental work, the closeness of d to the real value d_c is never accurately known, and since times to ignition vary most steeply when d is close to d_c , Equation (20) is preferable for all but order-of-magnitude estimates.



Nomenclature

Symbol	Definition	Units
A	Pre-exponential factor in Arrhenius equation	s^{-1}
a	Constant, Table A2	-
B	Dimensionless adiabatic temperature rise	-
b	Constant, Table A2	-
C	Specific Heat	$Jkg^{-1}K^{-1}$
c	Concentration	-
c_o	Oxygen Concentration by Volume	-
D	Diffusion Coefficient	m^2s^{-1}
D_o	Diffusion Coefficient at 0°C	-
E	Activation Energy	$Jmol^{-1}$
H	Heat Transfer Coefficient	$Wm^{-2}K^{-1}$
l	Length, Table 1	m
m	Length, Table 1	m
n	Order of Reaction	-
P	Constant, Equation 18/19	-
p	Porosity	-
Q	Heat of Reaction	Jkg^{-1}
Q_o	Heat of Reaction by Volume of Oxygen	Jm^{-3}
R	Universal Gas Constant	$Jmol^{-1}K^{-1}$
r	Characteristic Length	m
S	Surface Area	m^2



T	Temperature	K
T _A	Ambient Temperature	K
T _i	Initial Temperature	K
T _R	Reference Temperature	K
t _{ad}	Adiabatic Time to Ignition,	s
t _f	Fourier Time, Equation	s
t _i	Time to Ignition	s
V	Volume	m ³
a	Biot Number,	-
∆	Laplacien Operator	-
d	Frank-Kamenetskii Parameter	-
d _c	Critical Value of d	-
ε	Small Parameter, Equation 2	-
q	Dimensionless Temperature, Equation 4	-
ε _o	Maximum Subcritical Value of ε	-
r	Bulk Density	kgm ⁻³
l	Thermal Conductivity	Wm ⁻¹ K ⁻¹



Appendix B Notes to explain self-combustion

Background

There are two types of Ignition; **external heating** e.g. piloted ignition or **internal heating** e.g. self-combustion. The two types of ignition have different characteristics in terms of the temperature, and the time to ignition.

By way of example, Babrauskas¹ concluded that if wood is externally heated then the minimum heat for ignition is approximately 250 °C. However wood can also ignite at much lower temperatures (77 °C), if these are sustained over a period of weeks or months. This ignition at lower temperature over a sustained period was caused by self-heating.

Many wastes undergo self-heating, but not all wastes will go on to self-combust. The three key criteria which determine whether or not a pile of waste will self-combust are:

- smallest dimension of the pile (in most cases this will be the height)
- particle size of the waste
- storage duration

The three key criteria exhibit interdependency and collectively contribute to the overall risk of self-combustion.

Smallest dimension of the pile (usually the height)

The smallest dimension of the pile (usually the height) will determine whether or not the pile can sustain thermal runaway and it also determines the temperature required to initiate thermal runaway. Thermal runaway is the point at which the rate of heat generation has overtaken the rate of heat loss and the temperature within the pile will continue to rise, and if left uncontrolled, will achieve combustion. Small piles of waste (those with a height of less than 1.5m) are highly unlikely to achieve thermal runaway at typical outside ambient temperatures, simply because the insulation capacity of the pile is insufficient. The sustained rate of heat generation is not greater rate than that corresponding rate of the heat loss. So whilst self-heating occur even in small piles, the pile dimensions are insufficient to sustain thermal runaway. As a consequence the pile will warm up and then cool down, rather than sustaining a continued rise in temperature.

Critical temperature is the temperature required to initiate thermal runaway. The relationship between pile height (assuming it's the smallest dimension) and critical temperature is expressed in thermal ignition theory, such that taller piles lead to a corresponding lower critical temperature.

Particle size of the waste

The particle size will also determine the temperature required to initiate thermal runaway. The smaller the particle size then the lower the corresponding critical temperature. If all particle sizes <150mm are excluded from a waste pile, and the dimensions are in accordance with those set in the FPP guidance, then the corresponding critical temperature will be relatively high. So high as to preclude self-combustion, unless a foreign object, heat source or localised hotspot is introduced into the waste mass.

¹ Barbauskas V, Ignition of Wood: A review of the state of the Art, journal o Fire Protection Engineering 12 p163-189



From the table in the main body of the report, it can be seen that the critical temperature will be much lower for a pile including wastes with a particle size <30mm than is the case for the same size of pile created from wastes including those with a particle size of 70mm.

Returning to interdependency, we could construct a simple risk matrix using these two key criteria of pile height and particle size.

	Pile height < 4m	Pile height = 4m	Pile height > 4m
Particle size >150mm	LOW	LOW	LOW/MEDIUM
Particle size 30 – 150mm	LOW/MED	MEDIUM	MEDIUM/HIGH
Particle size <30mm	LOW/MED	MEDIUM/HIGH	HIGH

High or medium/high risk scenarios are unlikely to be acceptable by the EA unless significant additional risk control measures are in place. Low/medium and medium risk scenarios would require adequate additional risk control measures.

The above assumes that the maximum storage durations with the FPP guidance are observed.

Storage duration

The storage duration will determine whether or not the pile can self-combust. The longer the storage duration then the greater the likelihood that combustion is achieved. For high, medium/high risk scenarios given in the matrix above, then time to ignition could literally be a matter of days. If a hotspot, heat source or additional heating (processing) occurred, in these medium/high risk wastes then the time to ignition could further be reduced to a matter of hours.

There is an interdependency with the two key criteria given above. So for particle size and pile height combinations which give rise to anything other than low risk, a corresponding reduction in storage duration from say three months to three weeks, would reduce the overall risk of self-combustion and be a valuable risk control measure. Clearly reduction in storage duration is a valuable risk reduction measure which could be used on it's own or in combination with other measures.

A modest heap of wood chip piled up, is known to exhibit self-heating tendencies. If the pile is not too large, the temperature inside will rise by maybe 10-50 °C, then, given typical ambient air temperatures in this country, will slowly drop back down. In a small pile of waste then the pile dimensions (critically pile height) will be insufficient for sustain thermal runaway. The self-heating that occurs will be matched by the



overall heat loss from the pile and therefore the pile temperature will drop back down. In small piles the critical temperature will be much greater than for larger piles of the same waste and whilst self-heating will occur, the temperature required to achieve thermal runaway is not going to be reached.

However, with a very big pile of the wood chip if heaped together, then the temperature inside will rise slowly at first, then start to accelerate very rapidly. The material will be the hottest in the inside. It will start to smoulder rapidly and the smoulder front will advance through the material. Finally, flaming may break out when the smoulder front reaches the outside surface. In other cases, the entire pile may be consumed by smouldering and flaming will not appear'. Other combustible wastes that self-heat will behave in the same way as wood chips.

Heat transfer mechanisms and thermal ignition theory

Heat transfer can occur by three mechanisms:

- conduction
- convection
- radiation

Self-heating occurs via conduction, and **thermal ignition theory** calculates the **critical dimension** above which the material will self-ignite as a function of the ambient temperature. The theory was initially developed by Semenov, Frank-Kamenetskii and subsequently Thomas (employed by Building Research Establishment).

The basis of the theory is that heat is generated by a **single reaction** whose rate at a given temperature is not a function of time. The rate of internal heating is assumed to be a function of temperature according to the **Arrhenius equation**²:

$$q' = Q\rho A e^{-E/RT}$$

From thermal ignition theory we can estimate:

- critical dimension of a pile
- critical temperature at which thermal runaway will commence

The Frank-Kamenetskii parameter (δ) is defined by:

$$\delta = \frac{\rho Q A}{\lambda} \cdot \frac{E L^2}{R T_0^2} \cdot e^{-E/RT_0}$$

There are two routes to determine the unknown components in the Frank-Kamenetskii (F-K) parameter (δ). One approach is to measure the reactions kinetics or to extract the relevant values for E, A and Q from literature. The second approach is to carry out small scale oven tests and plot of $\ln(\delta_c T_0^2/L^2)$ versus

² Blomqvist P and Persson B Spontaneous Ignition of biofuels – a literature survey of theoretical and experimental methods



$1/T_0$ where T_0 is the ambient temperature (Kelvin³) and L is the characteristic length (metres). In the experimental results described, four different basket sizes of known length L (between 50 – 125 mm) were used for each of the wastes.

The resulting plot is a straight line with $-E/R$ as the slope and P as the intercept. P and R are both constants, and through known formulae, E and QA can therefore be calculated.

The critical values of the FK parameter (δ_c) have been compiled⁴ for different geometries (dimensions). The interpretation is that if $\delta > \delta_c$ then self-combustion occurs. This interpretation is used for the material in question to calculate the **critical dimension** above which the material will self-ignite as a function of the sustained ambient temperature

However corrections to the critical parameter need to be applied to account for low activation energy and finite Biot number (finite heat transfer coefficient).

We understand from thermal ignition theory that the smallest dimension is the critical dimension. In the case of storage of waste in the open then this will be the pile height. We consider that a pile of waste of less than 1.5m in height would be unlikely to undergo self-combustion, unless the waste was already hot when stored. Even some Waste Derived Fuels (based on sewage sludges) can have relatively low critical temperatures in the mid forty degrees in piles only 3m high. These sludges are typically composed entirely of small particle sizes of < 10mm with some fine dust, which are much smaller than we currently observe for combustible wastes. In addition, they are also very susceptible to self-heating because of enhanced microbial degradation. Clearly if operators applied to store such material under a permit, then the Environment Agency would look to revise the FPP guidance to take into account an extreme material in relation to self-heating capability.

In summary, the maximum pile height of 4m in the FPP guidance is appropriate for the types of wastes, and particularly the current particle sizes encountered at permitted waste sites. Clearly as the particle size of the wastes decreases, then the corresponding risk of self-combustion increases. Where wastes of small particle sizes are being stored in piles up to a height of 4m, then the Environment Agency would look to the operator to implement significant additional risk control measures. This is likely to include reduced storage durations, actively cooling wastes and a comprehensive monitoring programme for review subsurface temperatures.

Repeating isothermal calorimetry testing for various fraction or particle sizes within the four different sizes of basket, enables both the **critical temperature and the critical dimension** to be calculated for the different particle sizes.

The critical temperature is the sustained ambient temperature of the waste which is required to initiate thermal runaway. For a pile of sufficient dimension, thermal runaway is the temperature at which the rate of heat generation (from self-heating) has overtaken the rate of heat loss. So the pile, on its own, is capable of generating a sufficient rise in temperature to achieve self-combustion.

In summary, thermal ignition theory, assumes that the rate of internal heating is a function of temperature according to the Arrhenius equation. The heat within the waste is generated by a single reaction whose rate at a given temperature is not a function of time. The critical temperature, or temperature required to initiate thermal runaway is related to the smallest critical dimension of the pile, which in the case of

³ Kelvin and °C have a linear relationship where 0 °C = 273K

⁴ Beever P F Self-heating and spontaneous combustion in the SFPE Handbook of Fire Protection Engineering



wastes is usually pile height. As the height of the pile increases the corresponding critical temperature decreases.

The **time to ignition**, is estimated from an expression derived by Boddington, Feng and Gray. It should be stressed that the time to ignition is only an estimate even when the volume and temperatures of the material are being carefully controlled, such as on an industrial food processing site. So if we apply this method for estimating the time to ignition to wastes stored in the open, because they are subjected to variable weather conditions, then the time to ignition can only ever be used as an indicator.

In addition, if something causes the temperature in the pile to rise eg hotspot, heating from processing, foreign object etc then the actual time to ignition would be significantly less than the estimate.

Further, naturally occurring substances eg wood, paper, cardboard and textiles undergo self-heating through a range of complex reactions. Microbial activity and biological degradation, for example, have the ability to generate heat and a consequential rise in temperature, much more rapidly than predicted by the time to ignition equation described above.

Similarly, physical processing of waste including mechanical loading and unloading can produce heat.

It is therefore important to recognise that the expression derived by Boddington, Feng and Gray need to be adjusted to take into account those factors and can be no more than indicative in ideal, and in the waste context hypothetical, conditions.

The rate of heat generation is exponential, so when a waste has commenced thermal runaway, the rise in temperature can accelerate very rapidly, and it is possible that the time to ignition may actually be hours rather than days or weeks.

Interpreting the indicative time to ignition

Comparing the critical temperature and time to ignition for a very large pile of size 10m x 50m x 50m of small wood chips. The critical temperature required for this particular sample of wood chip which may not be untypical to initiate thermal runaway is 40 °C and this temperature would need to be sustained for an estimated 582 days in order to cause ignition. However, this estimated time to ignition does not take into account the possible introduction of a hotspot, heat from processing or foreign object causing a localised rise in temperature. All these factors would significantly reduce the time to ignition. The number of variables mean that a simple calculation is not possible, but a modest increase in ambient temperature of the pile that could easily be caused by a hotspot, has a significant impact on the time to ignition.

For example, if the ambient temperature of the same pile is raised to a temperature of 57 °C, and this is sustained for an estimated 106 days, then self-combustion can occur. By raising the temperature within the waste mass by 17 °C, the estimated time to ignition reduces by a striking 476 days.

Once the critical temperature has been reached, then heating within the pile will continue unless there is intervention to stop it / slow it down. If both appropriate and frequent intervention is not carried out, then heating will continue until combustion occurs. In some cases (as shown in table 2 – summary of results) the critical temperature may be as low as 13°C for very large piles of certain waste types.

This can be schematically illustrated in the graph below. There are three key points to draw from this data for very large piles of wood chip (10m x 50m x 50m), which contain a proportion of wood with a particle size of < 20mm:

- the entire mass of the pile must at all times be kept below 40 °C to remain safe, to achieve this would require continuous core temperature monitoring, rotating and cooling
- It is a notional concept that the ambient temperature in a large pile will remain at a constant temperature of 40 °C for 582 days



- the reality is that many factors can contribute to raising the ambient temperature (including localised areas eg hotspots) in a large waste mass, and therefore the corresponding time to ignition is immediately and dramatically reduced

In practice the larger the pile the more effort is required with representative core temperature monitoring, coupled with frequent and repetitive turning and cooling. It is likely that the monitoring and cooling would need to be performed almost continuously in order to prevent the waste from achieving what is a low critical temperature and the commencement of thermal runaway. Realistically this would be practically impossible to achieve for piles of the dimension identified above, and as a consequence the risk of self-combustion would increase significantly.

Another important point to remember is that as the temperature of the waste rises, the corresponding time to ignition decreases (see Figure 1 in main report). So in a larger pile there is more ability of the material to be anisotropic, heterogeneous and contaminants or hotspots to provide differential rates of heating, all of which can combine to significantly increase the risk of self-combustion.

Therefore we can conclude that large piles in the order of 10m high are significantly more at risk of self-combustion than smaller piles kept at a maximum height of 4m. A very rapid turnover of stock on site would certainly reduce the requirement for monitoring and management of piles in order to prevent self-combustion. The only practical way of cooling waste stored in piles is to frequently turn the wastes, or to dig out material, spread it out onto the quarantine area, and allow the heat to dissipate before returning to a pile.

So returning to the maximum piles sizes permitted in table 1 of the Fire Prevention Plan Guidance v3, it is important to know what the critical temperature is for a pile of wastes. In the absence of isothermal calorimetry tests for the specified material then the results in table 2 can be used as a guide on which the pile sizes in the Fire Prevention Plan Guidance v3 are based. It is also important to be able to accurately monitor the temperature in the core of a pile, such that immediate and appropriate action can be taken to cool the pile of waste, if the temperature at the core of the pile is reaching the critical temperature. As the rate of heat generation progresses more and more rapidly, early intervention is critical in order to halt the rising temperature and keep the pile safe.

The critical temperatures required to initiate thermal runaway may appear to some readers, to be a surprisingly low. For materials such as wood and SRF, critical temperatures are between 30-109°C, and for the small fractions the critical temperatures are not significantly above summer ambient air temperatures.

In addition, physical processing can produce heat, taking some wastes above the critical temperature. It is therefore important that waste is completely cool before placing into piles, otherwise this can initiate increased rate of heat generation leading to self-combustion.