# SPONTANEOUS COMBUSTION IN BAGASSE STOCKPILES

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## Introduction

The Sugar Industry is confronted with the problem of safe bagasse storage over extended periods. For long term storage, bagasse is accumulated in large exterior stockpiles of 200-3 000 tonne capacity for periods ranging from six months to three years. The quantity in storage is determined by the specific steam production requirements of an individual mill. Current storage capacity is relatively small. If an alternative paper or chemical feedstock usage for bagasse developed, the quantity in storage at one site could exceed 100 000 tonnes.

In all mills the bagasse bin operates as a buffer fuel storage and is a critical part of the boiler fuel supply system. Spontaneous combustion of bagasse in this situation represents a significant threat to the integrity of capital plant in addition to the loss of a valuable energy source. The paper is concerned primarily with external bagasse storage.

## Bagasse properties

The inherent properties of bagasse from numerous countries have been studied extensively by many researchers (Lamb and Bilger, 1976). It has been shown that the tissues of all woods and sugar cane contain the same major components. The proportions of the components vary according to species or variety. Slight variations may be found at different parts of the one plant and under different climatic conditions. Table I lists the principal bagasse constituents for Australian conditions.

**TABLE I**—Typical analysis of Australian bagasse

| Constituent | % |
|---|---|
| Bagasse Constituents (wet basis) | |
| Moisture | 44 - 53 |
| Brix | 1 - 2 |
| Ash | 1 - 5 |
| Fibre Constituents (dabf)* | |
| Cellulose | 45 - 55 |
| Hemicellulose | 20 - 30 |
| Lignin | 15 - 26 |
| Proximate Analysis of Fibre (daf)** | |
| Hydrogen | 6.0 |
| Oxygen | 44.7 |
| Carbon | 49.0 |
| Sulphur | 0.03 |
| Nitrogen | 0.27 |

* Dry, ash and Brix free.
** Dry, ash free.

**KEYWORDS: Spontaneous Combustion, Degradation, Microbiological Heating, Storage, Stockpile Heating**

The extraction treatment which bagasse receives prior to bulk storage has a significant influence on subsequent spontaneous combustion behaviour. Upstream of the final mill bagasse is saturated with high temperature water (80-90 °C). Final bagasse leaves the milling train by open conveyor at a temperature of 55-65 °C. When bagasse is loaded into storage piles, the temperature has decreased slightly to 48-60 °C and the pH lies in the range 5.5-6.7.

**Microbiological considerations**

The microbiological activity of fresh bagasse at mill exit is negligible. Spore counts for a range of thermophilic types is low (Ashbolt, 1986). After two days the number and activity of these microbial species has increased to a level where significant heat production can occur. High bagasse temperature (greater than 45 °C) and low bound nitrogen concentration favour the growth of species of *Thermoactinomyces* and *Bacillus*, which remain active up to 65°C. Beyond this temperature the activity of all bagasse thermophiles decreases significantly.

A succession of thermophilic species convert organic matter to a range of volatile and non-volatile byproducts. Sucrose and reducing sugars are readily consumed followed by hemicellulose, cellulose and lignin. The predominant by-product compounds identified include ethanol, acetic acid, furfural, acetoin, diacetyl and carbon dioxide. A multitude of other organic compounds may be produced but the types and concentrations have yet to be quantified. Microbiological activity in the stored bagasse is primarily dependent on the availability of free water. Activity is maximised at bagasse moisture contents greater than 60 per cent (wet basis). Below 40 per cent moisture content the activity is significantly retarded and ceases below 25 per cent moisture.

**Bagasse stockpile characteristics**

*Construction*

The geometry of bagasse stockpiles has centred on two types. Large rectangular stockpiles vary widely in plan area and range in height from 3 to 9 m. The largest stockpile measures 75 m × 25 m × 6 m high. Elongated stockpiles of triangular cross-section have been preferred for ease of assembly and weatherproof covering to prevent water ingress. Bagasse storage occurs outdoors on ground which is generally well-drained. The exterior surface of an uncovered bagasse stockpile forms a relatively impermeable skin, up to 30 mm thick, of matted bagasse fibres and microorganisms. The skin can serve as an effective water shield in average rainfall conditions. The total effectiveness of weather protection for an uncovered stockpile depends on the provision of good runoff drainage at the base of the stockpile and the maintenance of a convex geometry over the whole of the stockpile surface. Packing density of bagasse stockpiles depends on the loading technique. Loosely packed storage ranges between 100-150 kg/m$^3$ (50 per cent moisture basis). Where mechanical compaction occurs during the loading process, the density increases to 180-250 kg/m$^3$.

*Temperature and degradation*

Extensive temperature measurements have been obtained from numerous bagasse stockpiles since March, 1983, when the first confirmed occurrence of spontaneous combustion occurred. Three outbreaks of spontaneous combustion have been recorded since 1983. Two were localised outbreaks in elongated piles and the third involved the complete destruction of a rectangular pile. Stockpile data indicate no consistent trends related to bagasse degradation and spontaneous combustion for the external parameters affecting bagasse stockpiles. The parameters of interest include:

- Packing density;
- Stockpile size and shape;
- Coverage;
- Ambient conditions;
- Cane variety;
- Initial bagasse moisture.

Measured temperature profiles and bagasse decomposition patterns are consistent for the majority of bagasse stockpiles examined. Where sustained stockpile heating has occurred, maximum pile temperatures are at depths of between 1.5 and 2.0 m, perpendicular to the exterior surface of the pile. The size and shape of the pile are not significant. Temperatures decrease at depths greater than 2.5 m. There is a corresponding variation in the colour of the bagasse with depth indicative of the chemical reactions in progress at elevated temperature. Four distinct layers can be identified. A surface layer of 150-300 mm shows no obvious degradation. A second layer extends to a depth of 500-600 mm and consists of bagasse of a medium brown colour. This material shows no physical change but exhibits an extremely strong acetic acid odour. A transition layer exists to a depth of 800-1000 mm. In the fourth layer beyond 1000 mm, the bagasse has a dark brown colour, shows indications of physical degradation and exhibits a strong odour of acetic acid and furfural. The size of the fourth layer shows some variation between piles and can be 1.0-3.0 m deep. In a number of storages, bagasse similar to that found in layers 1 and 2 has been observed below layer 4. In piles where the maximum temperature exceeds approximately 70 °C, blackening and charring of bagasse fibres is clearly evident in the fourth layer below 1000 mm. The concentration of blackened fibres varies significantly between stockpiles. A number of stockpiles have continuously cooled, after an initial heating period, with no evidence of bagasse degradation.

The consistency in the physical and thermal characteristics of bagasse stockpiles suggests that oxygen diffusion may be an important limiting factor in spontaneous combustion. Maximum stockpile temperatures after an extended period (approximately 5 months) have been found to vary between stockpiles. Table II summarises temperature data obtained under various stockpile conditions. The bagasse moisture content in all stockpiles remained relatively unaltered from the nominal 50 per cent which existed at the time of pile construction. In the darkened sections of piles at depths greater than 2 m bagasse moisture content may increase to 55-60 per cent depending on moisture migration, coverage and drainage. Partial drying occurs to varying degrees in the surface layer of piles to a depth of 0.5 m. Bagasse moisture content in this layer can vary between 25 and 45 per cent.

**TABLE II**—Average temperatures (°C) recorded in bagasse stockpiles

| Location | Time (mths) | Size (m) | Cover | Measurement Depth (m) | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | 0.5 | 1.0 | 1.5 | 2.0 | 2.5 |
| Goondi | 6[b] | 60 x 18 x 3.5 | Yes | 65.9 | 75.0 | 75.9 | – | – |
| Bingera | 8[b] | 90 x 12 x 3 | No | 55.4 | 60.2 | 69.1 | 74.3 | 78.7 |
| Mossman | 7 | 30 x 25 x 8 | Yes | – | – | 76.0 | – | – |
| North Eton | 4 | 120 x 9 x 3 | No | – | – | – | 64 | – |
| | | 48 x 12 x 4 | No | – | 72 | – | – | – |
| Pleystowe | 1 | 50 x 9 x 4 | No | 60.1 | 63.0 | 63.4 | 62.5 | 61.0 |
| Tully | 4 | 59 x 22 x 3.5 | Yes | 48 | 56 | 58 | 64 | 56 |
| Farleigh | 8 | 75 x 25 x 6 | Yes | 57.4 | 70.8 | 77.6 | 81.6 | – |
| Pioneer | 11 | 100 x 10 x 4 | No | 60.4 | 72.3 | 76.9 | 77.8 | – |
| Mourilyan[a] | 6 | 46 x 18 x 4 | Yes | – | 93.0 | – | 84 | 78 |

[a] Measurements taken 6 days after initial outbreak of flaming combustion.

[b] Localized spontaneous combustion at this time.

Bagasse degradation, even to the extent of charring, generally does not result in a significant (less than 5 per cent) reduction in the calorific value of dry bagasse fibre. Stored bagasse is readily usable as a fuel under these conditions and exhibits no combustion problems if the moisture content is less than 55 per cent. The thermal history of several bagasse stockpiles is shown in Figure 1. After an initial rapid heating rate which occurs over two days, stockpile temperatures in the principal reaction zone (1-2 m depth) stabilise at approximately 64 °C. Subsequent cooling or slow heating at constant rate then proceeds for an extended period. In other stockpiles the maximum temperature remained close to the initial stable value (64 °C) throughout the life of the stockpile (180 days).

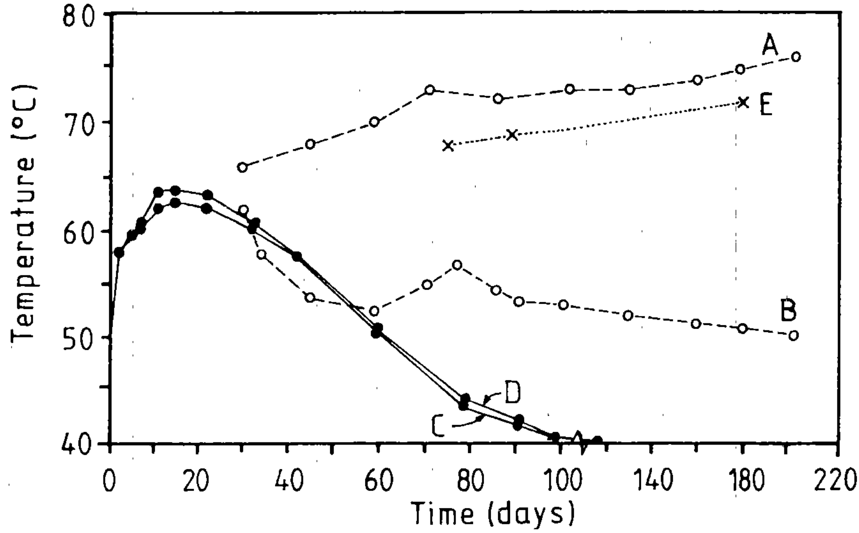


Fig. 1—Thermal history of bagasse stockpiles.

| | | |
|---|---|---|
| A,B | Mossman | 1.5 m depth covered |
| C,D | Pleystone | 1.5 m depth covered |
| E | North Eton | 1.0 m depth uncovered |

Bagasse reclaimed from the stockpile located at Pleystowe Mill after 194 days showed no physical degradation or discolouration and exhibited only a faint odour of acetic acid. The average moisture content of this bagasse was 48 per cent. Bagasse reclaimed from stockpiles which had remained at elevated temperature exhibited the characterisitic brown colour and pungency. The pH level of these bagasses was reduced to 2.0-3.0.

*Mourilyan bagasse stockpile*

The Mourilyan stockpile (46 × 18 × 4 m) was assembled in a fully enclosed shed with a narrow roofline opening allowing only limited ventilation. Approximately 700 tonnes of bagasse had been stored. No temperatures were recorded until after the initial occurrence of flaming combustion. At this stage a depression had been burned in the bagasse stockpile 3.75 m diameter and 2.5 m deep. Figure 2 shows a plan view of the stockpile. Temperatures were measured at a depth of 1 m. Sample measurements taken at 2 m depth indicated temperatures approximately 5 °C below those at 1 m. Bagasse samples analysed from points A (1 m) and B (0.5 m) showed moisture contents of 42 per cent and 31 per cent respectively.

The measurements in Figure 2 were obtained six days after the initial outbreak of flaming combustion. Similar outbreaks occurred 10 days and 12 days after these temperatures were recorded. Following the third outbreak the stockpile was dismantled. The rejected bagasse, to a depth of 2 m, developed flaming combustion within a short period after exposure to ambient conditions.

## Experimental investigations

Laboratory and small scale bagasse self-heating experiments commenced in 1983 following the spontaneous combustion outbreak in the Mourilyan stockpile.

Investigations have been continuing in three areas:

(a) Spontaneous combustion behaviour of dry bagasse;
(b) Microbiological aspects of heating;
(c) Moisture effects in stockpile heating.

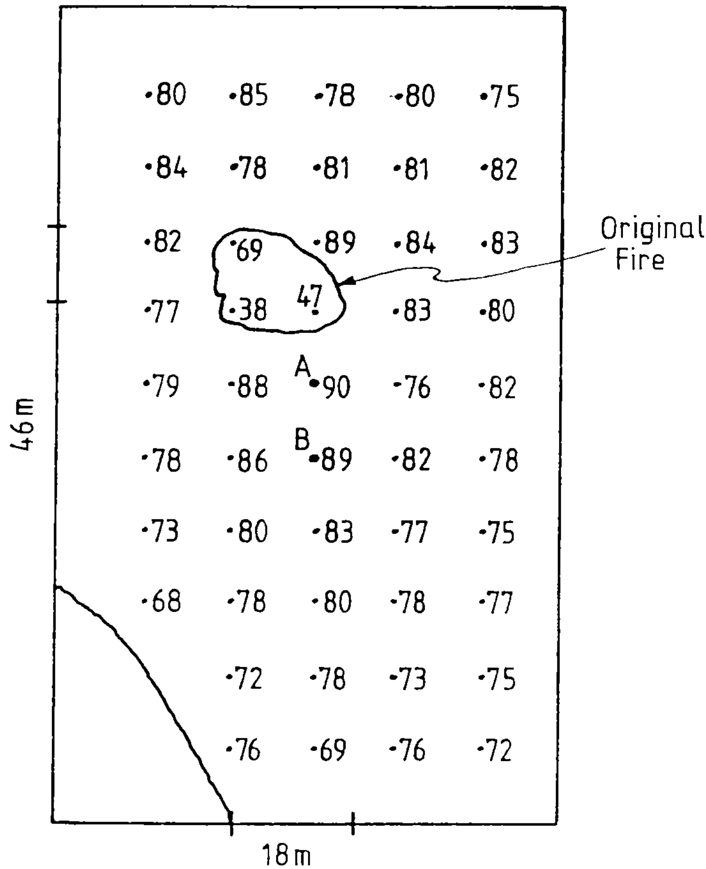


Fig. 2—Plan view of Mourilyan bagasse stockpile showing temperatures measured at 1.0 depth.

*Dry bagasse behaviour*

Investigations at the laboratory scale (Gray *et al.*, 1984) examined the ambient temperatures at which spontaneous combustion could be initiated in dry bagasse. For small bagasse samples of varying size (20-150 mm dia.) ambient temperatures resulting in combustion were found to lie in the range 175-245 °C for packing density variations between 100 kg/m$^3$ (loose packed) and 180 kg/m$^3$ (compressed). The heating behaviour and temperature above ambient were shown to vary with sample shape and packing density.

Scaling criteria for small laboratory tests have been shown to correlate satisfactorily experimental results (Egeiban *et al.*, 1982). Application of the scaling criteria (Gray *et al.*, 1984) has shown that variations in ambient temperature, packing density, stockpile shape and stockpile size were adequately accommodated. This included experimental data for a much larger bagasse mass (equicylinder, 1.0 m half-dimension) with a critical ambient temperature of 112 °C. An effective activation energy of 125 $\pm$ 6 kJmol$^{-1}$ was determined for dry bagasse.

Addition of water to the laboratory scale bagasse samples prolonged the heating period during which drying occurred. Each sample exhibited a quasistationary centre temperature associated with the evaporation of water. After drying was completed and ambient temperature was achieved uniformly throughout the sample, the same rate and extent of self-heating followed regardless of the amount of water that was initially present. Interestingly, this relatively constant centre temperature (67 °C) was also observed in the much larger test sample and is routinely measured in full scale bagasse stockpiles.

Scale up of the laboratory heating data to the dimensions of full size stockpiles indicated that at an ambient temperature of 40 °C, a pile depth of 66 m would be required for spontaneous combustion of dry bagasse. At 20 °C, a very large depth (276 m) would be necessary. Application of thermal explosion theory for the experimental dry bagasse activation energy (Gray, 1984) showed that for a bagasse stockpile of 4 m depth, at an ambient temperature of 30 °C, spontaneous combustion would occur for a bagasse temperature greater than 93.4 °C. This critical temperature was estimated to change by less than 2 °C for the variations in ambient temperature, pile size and geometry, and packing density which occur in full size piles. Clearly this high temperature (greater than 90 °C) dry bagasse reaction alone is not sufficient to cause spontaneous combustion in full size piles. There are other contributions to heat generation below this temperature.

*Influence of initial bagasse temperature*

A consideration which appears exclusive to bagasse is assembly of the stockpile at temperatures above ambient. Analysis by Gray and Scott (1985) showed that for dry bagasse initial temperatures greater than 90 °C would be necessary to initiate spontaneous combustion. There would appear to be no possibility that ignition by the high temperature reaction can occur in bagasse stockpiles due to initial bagasse temperatures above ambient. The effect which the initial temperature may have on spontaneous combustion associated with the one or more low temperature reactions which appear to exist has yet to be determined.

*Microbiological heating*

Initial temperature increases in stockpiles of hay, woodchip, etc. have usually been attributed to microbial action (Armstrong, 1973). Conflict remains as to the division between microbiological and chemical heating and the significance of the latter at low temperatures. Experimentation with compost, soils etc. has determined the numbers of active microbial species which are present in these media. Calculations indicate that if the corresponding numbers of active microbial species were to be established in bagasse stockpiles, heating rates of the order of 20 °C per day may be achieved (Ashbolt, 1984). However consideration of the limited published data for cell counts in hay, woodchip and bagasse suggest that, in the initial stages, microbiological heating rates of less than 2 °C per day would be sustained (Gray, 1984).

Figure 3 shows the results of heating trials conducted with three chemically treated bagasse stockpiles (Ashbolt, 1986). The piles were constructed from fresh bagasse in which treatment agents were mixed. Bagasse was allowed to cool to 40 °C before pile construction. The piles were cones 2.5 m high with a base diameter of 3.5 m and were totally covered. The control pile had water added to raise the bagasse moisture content to the same level as that of the test piles (52 per cent wet basis). Treatment agents in the other two piles were sulphuric acid (0.3 w/w) and a commercial biocide AC3360 (methylene bis-thiocyanate, 400 ppm). Bagasse samples for analysis and temperatures (portable insertion thermocouple) were taken at regular intervals.

The temperature history of the stockpiles [Figure 3(a)] also includes results taken from a larger uncovered pile (16 × 5 × 1.75 m) in which bagasse was cooled to approximately 30 °C prior to pile construction.

All stockpiles exhibited high heating rates (15 °C per day) within the first two days before temperatures stabilised at the quasi-steady state value of 65 °C noted previously. There would appear to be little distinction between the untreated and treated bagasse in this respect. In the $H_2SO_4$ treated pile, the very low pH level [Figure 3(c)] and low microbiological $CO_2$ production [Figure 3(b)] strongly indicate the absence of any significant microbiological activity during this period. This was supported by an estimation of bacteria numbers including inactive spores, of $5 \times 10^7$ CFU (colony forming units) per gram. Estimated numbers in the untreated control pile were in excess of $6 \times 10^9$ CFU per gram. After a period of three weeks all stockpiles were estimated to contain about $10_8$ CFU per gram.

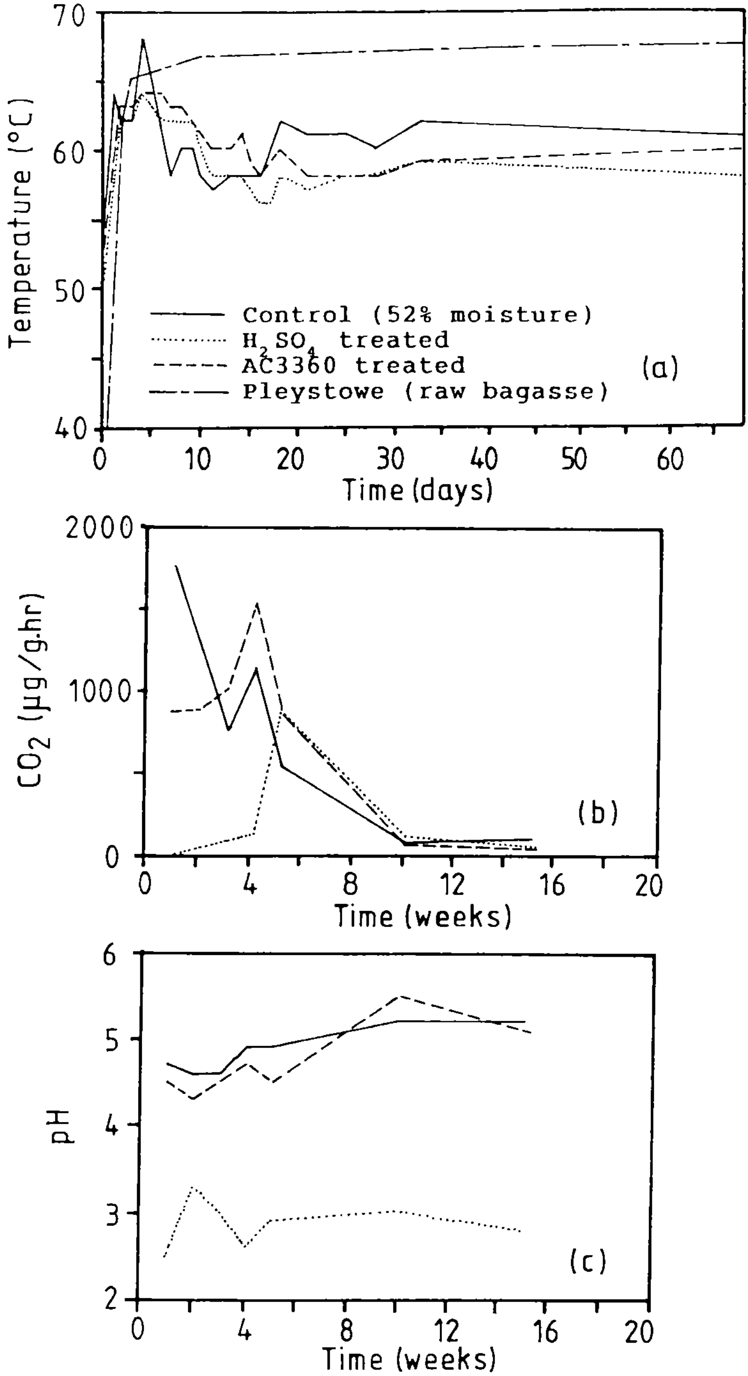


Fig. 3—Characteristics of chemically treated bagasse stockpiles.
(a) Temperature (°C)
(b) Carbon dioxide production (µg/g.h)
(c) pH

The marginally greater heating rate measured in the untreated bagasse pile may be the result of the microbiological heat production.

The conclusion to be drawn from Figure 3 is that microbiological heat generation can be of little significance in initial bagasse stockpile temperature increases. The presence of sulphuric acid and the low pH may have initiated additional hydrolysis reactions which would not normally be present in untreated bagasse. However there must exist one or more low temperature reactions which generate rapid initial chemical heating in bagasse stockpiles. A secondary consequence of microbiological activity is the production of chemical byproducts in the pile. These species remain after microbiological activity has ceased. They may act as important components in linking reactions (Gray, 1984) which raise pile temperatures from the quasi-steady state condition ($\simeq 65\,^\circ C$) to the onset of spontaneous combustion for dry bagasse ($\simeq 94\,^\circ C$).

*The effects of moisture*

The influence of moisture on spontaneous combustion in cellulosic and other materials has been researched extensively. The principal modes of influence have been identified (Walker, 1967). The significance of moisture in bagasse stockpiles can be summarised as follows:

- (i) Evaporation and loss of water is endothermic and removes reaction heat.
- (ii) Effective thermal conductivity can be enhanced due to mass transfer of water vapour from hot to colder zones; where water vapour diffusion ceases under equilibrium relative humidity conditions, thermal conductivity can significantly decrease.
- (iii) Hygroscopic effects are unlikely to be significant.
- (iv) Water availability permits liquid-phase oxidations and acid hydrolysis to occur.
- (v) Enhanced oxidation of cellulose can occur in the presence of water.

Research on the spontaneous combustion of hay (Rothbaum, 1963) has indicated the sensitivity of material self-heating below 100 °C to changes in the water content and relative humidity in the pile. Experiments with glucose (Rothbaum) and coal, charcoal, wool etc. (Walker, 1967), have shown that oxidation occurs more rapidly when water is present. Recent preliminary microcalorimetric investigations with bagasse at low temperature (60 °C) (Gray, 1987), show considerably enhanced heat generation in the presence of water.

Little is known of the low temperature reaction mechanisms in bagasse. The relative importance of wet cellulose oxidation and aqueous phase oxidation of microbiological and hydrolysis byproducts has not been established. The aqueous low temperature reactions may have critical conditions of their own. The controlling effects of oxygen and water vapour diffusion have also to be quantified.

**Consequences for bagasse storage**

Laboratory investigations and stockpile measurements of bagasse self-heating have established that:

- (i) Pile size and geometry are not significant.
- (ii) Maximum pile temperatures occur at a depth of 1.5 to 2.0 m, perpendicular to any external surface.
- (iii) Irrespective of initial bagasse conditions, maximum pile temperatures increase to approximately 65 °C within the first two days of storage.
- (iv) Subsequent slow heating or cooling will occur.
- (v) Dry bagasse will spontaneously combust above 94 °C.
- (vi) Little change will occur in the moisture content of the bulk of the bagasse stockpile during normal heating.

The factors which determine stockpile heating and which increase stockpile temperatures from the quasi-steady state level (65 °C) to the onset of dry bagasse spontaneous combustion (94 °C) have not been identified. Further microcalorimetry would establish the criticality conditions of the linking reactions. It is considered that specific identification of the reaction mechanisms and quantification of the controlling effects of physical diffusion processes may be necessary to provide practical directions for spontaneous combustion control. A consequence of these investigations would be the determination of appropriate pile monitoring procedures to identify the stages leading to spontaneous combustion.

Product quality constraints and logistics dictate that very limited action can be taken once pile overheating is suspected. Water cannot be used to reduce pile temperatures. The dismantling for cooling and rebuilding of a pile are time consuming, expensive and possibly dangerous. Where possible compressed air injection can be used for cooling but the dangers of accelerated heating remain.

Monitoring of bagasse stockpile behaviour is most conveniently undertaken by thermocouple temperature probing. In the absence of any confirmed critical temperatures in the pile heating sequence, periodic monitoring should occur at the zone of maximum temperature until this temperature exceeded 80 °C. From this time, more frequent monitoring should occur at several depths in the one location (0.5, 1.0, 1.5 m). When the position of the maximum temperature begins moving toward the pile surface, consideration should be given to undertaking detailed temperature measurements and bagasse sampling. However the time scale of the maximum temperature displacement toward the pile surface is unknown. Results of the Mourilyan stockpile investigations (Figure 2) show that thermal runaway leading to flaming combustion is imminent once the maximum pile temperature approaches 90 °C at a depth of 1.0 m.

Future progress in the prevention of spontaneous combustion in bagasse stockpiles would be enhanced if three factors could be quantified. These are:

(i) One or more critical temperatures in the pile heating sequence from 65 to 94 °C.

(ii) Pile temperature beyond which air injection or dismantling would result in accelerated heating.

(iii) Time scale associated with (i) and (ii).

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