Abstract

Prolonged storage of large quantities of bagasse for off-season power generation presents challenges different from those associated with small-scale storage or large-scale, wet storage for pulp and paper production. The challenges include loss of fuel value, spontaneous combustion, bagasse handling and a variety of health and environmental impacts. Experiences with these challenges in Australia and Brazil are reviewed and suggestions made for alternative storage methods. Theoretical requirements for good storage are outlined. The possible special requirement of pasteurised bagasse from diffusers is highlighted.

Keywords: bagasse, storage, power generation, bagassosis, combustion, diffuser bagasse

Introduction

The increased demand for renewable energy has created opportunities for selling energy derived from bagasse. The simplest route to such energy is combustion accompanied by steam and electricity generation. For commercial success, it is important that the expensive capital equipment is used throughout the year despite the seasonal production of bagasse. This dictates that bagasse be stored for use during off-crop, or that an alternative fuel be used during off-crop. In most cases it is not viable to use an alternative fuel, therefore storage of large quantities of bagasse is a requirement. Very large quantities (>100 000 t) may be involved in cases where an optimised (high pressure) power generation unit draws surplus bagasse from a number of surrounding factories.

The storage of large quantities of bagasse presents challenges that are not faced by the existing small-scale, short-term storage systems that are operated by factories for use during start-ups and short stoppages. It might be assumed that experience with large-scale storage systems has been developed in countries like Mauritius and India, where off-crop power generation takes place. In these countries, however, most of the mill-based generation systems form an integral part of the national power supply, so they are sized to burn all the bagasse as it is produced and to then use coal during off-crop. There is thus no need to store bagasse.

Knowledge based on large-scale storage at pulp and paper factories is of limited value because the bagasse is stored in a water-saturated state. The storage system delivers bagasse that is too wet for combustion.
The trend towards power generation from bagasse has been accompanied by progress in developing other large-scale uses for the material, e.g. ethanol production (www.betarenewables.com) and bagasse-to-fuel via small-scale Fischer-Tropsch technology (www.oxfordcatalysts.com). Most of these other uses require minimum water in the bagasse and maximum preservation of the fuel components. They add to the need for effective non-saturated storage techniques.

This paper highlights the new challenges and gives perspectives on storage systems and their potential for large-scale application.

**Perspectives on various options**

**Wet (saturated) bulk storage**
This is appropriate where the bagasse is to be used in a wet state, e.g. for pulping. The bagasse is hydraulically transported and deposited in a pile that is kept saturated so as to minimise oxygen within the pile. This method has major application at present, but it has obvious disadvantages for bagasse that is to be used for combustion. In South Africa, it is applied at Felixton and Gledhow for depithed bagasse that is used in paper and cardboard. There is some loss of material during storage and handling (Morgan et al., 1974). A disadvantage of this system is that the bagasse is laid down and retrieved as a dilute (3-5%) slurry, meaning that considerable energy has to be spent in moving water.

**Bulk storage without added water**
The bagasse is piled without adjusting the moisture content. This method has been used for relatively small-scale projects, but is currently of interest for the increasing number of projects that require large-scale storage for co-generation. There are, however, challenges associated with large-scale application of the method, and these justify a separate section within this paper.

**Baled storage**
Bales are formed, either with or without binding material. The bale size and degree of compaction vary according to requirements. By selecting an appropriate bale size and by stacking bales with air spaces between them, it has been possible to control the heat build-up in the bales and to enable the heat and air circulation to dry the bagasse from 50% to about 20% moisture. This is the basis of the so-called ‘Bagatex-20’ (Anon, 1986) method of bagasse storage. Compared to pile storage, it involves the additional expense of baling equipment and bale breaking equipment but it may reduce transport costs and allow long periods of stable storage. The moisture reduction leads to less loss of dry matter during prolonged storage and to higher net fuel value for combustion.

Baling was commonly used when bagasse was stored for manufacture of boards because it was thought to give better quality boards than bagasse from wet bulk storage. However, there are examples of bales having to be discarded because deterioration during storage caused the bagasse to form boards of unacceptable quality. This, together with high labour requirement for handling of bales, caused some conversion from baling to wet-bulk storage (Bernhardt, 1968).
Baling is generally used when trash is collected from the fields. It may also be appropriate where large quantities of bagasse need to be moved between mills. This is practised in India, where large continuous bales are ‘extruded’ into vehicles as a means of loading.

**Briquetting**

Briquetting involves higher compression than baling. It produces a fuel with low moisture and high calorific value that can be used as a substitute for coal, or as a convenient cooking fuel. The bagasse must first be ground to uniform small particle size. It may then be charred (to increase carbon content and reduce moisture), mixed with a binder (molasses or flour) and compressed into a cylindrical form. Alternatively, it is not charred but is compressed and heated so that the lignin melts and acts as a binder, thereby saving the need for added binder (charring destroys the binding properties of lignin).

Briquetting is an expensive process suited to small-scale niche markets, but generally not economical for large-scale storage. Some bagasse briquettes resembling small logs were made by UCL Company Ltd. Most bagasse briquetting takes place in South East Asia.

**Pelleting**

This is essentially similar to briquetting but produces smaller and denser particles. The energy consumption by the pelleting process is substantial, being approximately as follows (www.cpmeurope.nl):

<table>
<thead>
<tr>
<th>Process:</th>
<th>Drying</th>
<th>Grinding</th>
<th>Pelleting</th>
<th>Cooling</th>
<th>Other</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>kWh/t:</td>
<td>5</td>
<td>15</td>
<td>50</td>
<td>2.5</td>
<td>2.5</td>
<td>75</td>
</tr>
</tbody>
</table>

Pellet diameters range between 6 and 18 mm, with the smaller pellets being ideal for household furnaces and the larger ones for industrial furnaces. Pelleting offers advantages of dust control, reduction of shipping costs, ease of feeding and improved control of combustion. It also enables convenient presentation of materials for animal feeds.

During the 1980s, pelleted bagasse, combined with molasses and minerals, was produced at Maidstone for export to Europe as an animal feed. Sand in the bagasse caused costly wear of the pelleting dies. Some pelleting is done in Brazil for export to Europe as a biomass fuel, but the quantity is small and dependent on a market incentivised to reduce CO$_2$ emissions.

**Torrefication with briquetting (bio-coal production)**

This involves drying and heating the bagasse under controlled conditions such that some volatiles are driven off but most of the energy value remains in the dried residual material, which can be briquetted and stored (Bergman *et al.*, 2005). This torrefication process might have future potential for satellite processing of biomass prior to transport to a central facility. It is essentially an energy-efficient form of charcoal production.

**Bio-oil production**

Thermal treatment of bagasse to produce volatile oils is another means of ‘compressing’ bagasse for storage and transport purposes. The development of a mini, modular SASOL-type process by Oxford Catalysts (www.oxfordcatalysts.com) has led to a recent announcement of a joint venture in Brazil aimed at producing liquid fuels from bagasse. It is anticipated that if this process is successful it will be more profitable than electricity sales from bagasse, but it is unlikely to be commercialised in the immediate future.
Challenges associated with large-scale, non-saturated storage

Compared to most boiler fuels, bagasse has the disadvantage of a high (about 50%) moisture content. This diminishes its fuel value and makes the fuel prone to deterioration during storage. Another disadvantage is that the bagasse is produced at the factory (not the farm) so there is no opportunity for off-site scattered storage. Fuels such as switchgrass are relatively dry (<20% moisture) when harvested, and can be stored on farms without significant loss. The major challenges in storing large quantities of bagasse include:

- loss of fuel value due to microbial activities during prolonged storage,
- chances of spontaneous combustion,
- environmental impacts and
- health issues associated with bagassosis.

Some bulk storage guidelines are available from research in the timber industry (reviewed by Searcy and Hess, 2010), but this research highlights differences that exist between different circumstances and sources of wood. Care is needed in applying the timber-based information to bagasse. An increasing source of biomass fuel is young trees that are grown in rows and harvested by chipping the entire tree, including leaves and bark. The harvested material is similar to bagasse in texture and moisture content. Storage of this material presents similar challenges to those of bagasse and has prompted research on storage techniques (Springer, ca.1979). A distinct disadvantage of whole-tree harvesting is that the bark and leaves provide nutrients for the agents of decay. Although bagasse is relatively free of these nutrients, the timber experience suggests that diffuser bagasse to which filter mud has been returned may behave differently because the mud is rich in nutrients.

Loss of fuel value due to deterioration

Measurement of losses from bulk piles is difficult and seldom attempted. Using open-weaved bags containing bagasse buried in wet bulk piles, Morgan et al. (1974) measured the following losses of dry mass:

<table>
<thead>
<tr>
<th>Storage period (wks)</th>
<th>Loss of dry mass (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.7</td>
</tr>
<tr>
<td>8</td>
<td>4.3</td>
</tr>
<tr>
<td>20</td>
<td>5.3</td>
</tr>
</tbody>
</table>

In this case, losses were minimised by the anaerobic and acid conditions in the saturated storage system. Much higher losses can be expected from moist (unsaturated) conditions if the microorganisms have greater access to air.

One of the early reports of bulk storage without moisture adjustment (Bernhardt, 1968) suggested that there was less than 5% loss but gave no details of how this was measured. The author assumed that the high pile (18 m) prevented air ingress, thereby preserving the bagasse. Bernhardt’s estimated (not measured) loss for baled material was 15%; however, Lois-Correa et al. (2010) made careful measurements and found that the loss in a closely packed stack of bales was 20-25% after only 40 days. Drying the bagasse to 25% moisture before baling reduced the loss to about 3% in 40 days, rising to only 6.5% after 120 days.
Dos Santos et al. (2011) observed that, in Brazil, bagasse is stored in piles of about 100 000 t by simply dozing the bagasse into place without much planning. Dos Santos et al. used thermo-gravimetric methods to track changes in the major components of bagasse during storage in one such pile (no added water). They concluded that after 150 days of storage, the loss in calorific value could be up to 32%, due mainly to the loss of the hemicellulose component.

Measurements in the timber industry (summarised by Searcy and Hess, 2010) confirmed that drying to below 25% moisture almost eliminated subsequent deterioration, but that above 25% moisture, losses were proportional to initial moisture content. At 51% moisture, fine wood chips deteriorated at a rate of 2.2% per month, averaged over six months. The rate of loss (with timber) is generally much higher in the first few weeks than later. If similar dynamics apply to bagasse, this suggests that the bagasse storage system should be run on a last-in-first-out (LIFO) basis, at least for the early off-crop.

Although definitive information is lacking, the threat of serious loss during storage is evident. In the context of overall efficiency in the conversion of biomass to electricity, the storage stage is critical because it can probably affect energy recovery by as much as 25%.

**Spontaneous combustion**

Large piles of biomass are prone to self-heating that can lead to spontaneous combustion. Compared to timber, bagasse has the advantage that the plant cells have been killed and therefore do not contribute to the heating effect. However, spontaneous combustion, or accidental ignition, is a real problem. Bagasse fires in India have caused the loss of entire (10 000 t) storage piles (Lokapure et al., 2012).

The Australian industry has had partial success in developing a computer model that is reasonably accurate in predicting heat, moisture and oxygen movements in piles of loose or baled bagasse (Hobson and Mann, 2005, www.assct.com.au/). This has some value in anticipating fires, but its major future use is in decisions relating to the influence of storage formats on bagasse drying during storage. The model highlights the wide range of temperature and moisture conditions that exist in a pile of stored bagasse, even after 200 days. For example, a small (3 x 3 m) pile of closely stacked bales is likely to have a core temperature of 65°C, with only the outer 25 cm being close to ambient temperature.

In Australia, there is a tendency to store in multiple piles so as to mitigate the effect of fire. Fire fighting equipment is an important component of bagasse storage systems.

**Bagassosis**

This is a respiratory disease resulting from exposure to fungal spores from mouldy bagasse. It is thought to be the result of hypersensitivity to the spores rather than infection, but this is not proven. The disease is sometimes misdiagnosed as tuberculosis. In one case, a factory using bagasse to make boards had no cases of bagassosis for 12 years but suddenly had a severe outbreak affecting more than 50% of the workers. The outbreak coincided with a change in source of bagasse from heat-dried bagasse to bagasse that was stored without drying. The outbreak occurred despite the use of masks (McMaster, 1974).

**Environmental issues**

**Water pollution** is caused by run-off from bagasse piles. It is therefore necessary to have an impervious base with channels leading to a collection pond, from which the polluted water
can be passed to effluent treatment if necessary. The pond provides a convenient source of water for fire-fighting.

**Bagasse dust** is a major problem in windy areas and at bagasse transfer points. The problem has been so severe in Australia that consideration has been given to depithing the bagasse before storage. Models suggest that depithed bagasse will create 70% less dust than whole bagasse (Rainey et al., 2012). Surrounding storage areas with a barrier of trees and/or high wooden fencing helps to reduce the problem. Loading and transfer points may need to be enclosed. It is significant that the large storage piles at Felixton and Gledhow in South Africa consist of depithed bagasse. This, together with wet storage, has probably precluded the development of dust problems.

**Noise and light** have caused problems at storage sites close to residential areas. Reversing beepers have had to be disabled, thereby compromising safety.

**Odour** is sometimes a problem, particularly when piles are being broken.

From the foregoing, it is evident that there are significant environmental challenges associated with large-scale storage. Although the Australian sugar industry has co-operated with the Environment Protection Agency in drawing up guidelines, there has been strong community activism against a proposed large bagasse storage project.

**Recent Australian and Brazilian experiences with piled storage**

Developments in Australia have been summarised in a workshop on bagasse storage (www.assct.com.au/) and by Trayner (2008). This information is further summarised below.

**Bagasse quantities and equipment at Pioneer cogeneration plant**

At Pioneer cogeneration plant, about 110 000 t of bagasse is stored for use during off-crop. This amount is transferred in from three surrounding mills with the stock being built up over about 24 weeks and reclaimed in ten weeks.

The decision to transfer bagasse to a central plant rather than to generate at each of the four mills was based on:

- The critical role of fuel handling for cost effective operations.
- The requirement for close management of the bagasse storage to ensure:
  - Minimum fuel degradation.
  - Cost effective and safe handling without interruption by wet weather.
  - Minimum environmental impact.
- Ensuring economy of scale and energy efficiency by using the bagasse in a modern 65 bar, 37 MW condensing power plant.

Bagasse is transported to the central plant using six walking floor trucks with load volumes of 106 m$^3$ (23 t). No baling is involved.

The bagasse is stored in discrete piles of about 10 000 t each so as to minimise the impact of fire.
Existing equipment at the mills was considered inappropriate for the large quantities involved. Appropriate equipment selected after consultation with mining, grain and cotton industries consisted of:

- a storage pad and surrounding roads designed to ensure that operations can continue during wet weather. This requires a compacted sloping hard-core with run-off collection and facilities for transfer of the run-off to the factory effluent plant. If run-off is not facilitated, there is a danger of water being ‘wicked’ into the bagasse and initiating conditions for spontaneous combustion,
- a special all-weather pad for use in extreme wet conditions,
- two dozers with extended blades for building and compressing piles,
- one front-end loader with a ‘pusher-bar’ that was designed in-house and resembles an inverted inclined ‘scratcher’ powered by the loader power-take-off. The pusher bar pushes bagasse up into piles while the loader remains on the ground,
- two 30 t excavators with extended buckets (5 m$^3$) used for reclaiming the bagasse and loading into trucks. These, being tall, have also been used for dragging tarpaulins into place over the piles,
- two high-sided 15 t trucks for transporting reclaimed bagasse to the mill,
- sixty tarpaulins (55 x 24 m) for covering the piles,
- two stitching machines for tarpaulin repairs,
- thermocouples for monitoring pile temperatures, and
- a fire fighting system, including run-off storage dam for water supply.

**Experiences with equipment at Pioneer**

Experience with this equipment highlighted:

- piles built by dozer are about 25% more compact than those built by pusher-bar, and the bagasse in the more compact piles has longer storage life but
- pusher bars could handle bagasse at three to four times the rate of dozers, and at significantly lower cost. A dozer can handle about 30 t/h.
- excavators could reclaim bagasse at a rate of 200 t/h whereas front end loaders performed at about half this rate,
- wind has a major effect on bagasse handling operations, especially when dozers are building piles,
- during reclamation, tarpaulins need to be peeled back little by little so as to maintain dust control and rain protection,
- dust control has proved a major challenge, such that truck loading from the mills now tends to take place within a closed building,
- good lighting and good traffic control with planned sequencing of pile reclamation have proven critical, and
- environmental issues of noise, dust, odour, light and traffic management have required attention.

**Covering of piles**

For the Pioneer project the covering is considered necessary to:

- reduce water ingress,
- provide a barrier against oxygen,
- protect against external sources of ignition and
- minimise dust and odour problems and to minimise the amount of polluted leachate requiring effluent treatment.
In drier climates there is no need to cover the bagasse with tarpaulins. Calculations based on the water-holding capacity of bagasse suggest that rain penetration would be as shown in Table 1.

<table>
<thead>
<tr>
<th>General condition</th>
<th>Surface density (kg dry/m³)</th>
<th>Initial surface moisture (%)</th>
<th>Penetration by 100 mm rain (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air laid pile (no compaction)</td>
<td>74</td>
<td>50</td>
<td>37</td>
</tr>
<tr>
<td>Compacted pile</td>
<td>100</td>
<td>50</td>
<td>27</td>
</tr>
<tr>
<td>Air laid, part dry</td>
<td>74</td>
<td>25</td>
<td>32</td>
</tr>
<tr>
<td>Compacted, part dry</td>
<td>100</td>
<td>25</td>
<td>23</td>
</tr>
</tbody>
</table>

This shallow penetration, alternating with surface drying, explains the minimal penetration by rain, often referred to as the ‘self-thatching’ effect. Prolonged light rain without intermittent drying would be problematic.

**Other Australian projects**

**Bundaberg Sugar** operates six mills with a variety of cogeneration activities at each. Some inter-mill transfer of bagasse takes place and up to 35 000 t of bagasse has been stored at one site. The technology is essentially similar to that described for Pioneer but, being in a drier area, not all piles are covered. The uncovered piles are relatively small (100 x 25 m) and profiled to minimise rain ingress.

**Mackay Sugar** has small stockpiles at each of four mills. Each mill exports some power to the grid, and excess bagasse is transported to Racecourse mill for off-crop refining. In 2004, Racecourse had a 59 000 t stockpile.

Multiple small piles are built with wheeled front-end loaders and covered. The piles stand on a hard pad with drainage to a holding dam. Tall wooden fences combined with tree screening help to reduce dust. A road irrigation system has proved necessary to minimise road dust. Odour has proved problematic, especially when breaking down old piles. There have been two instances of spontaneous combustion, each seemingly related to excess water in the pile, resulting in heat generation about 1.5 m from the surface.

Based on past experience, Mackay Sugar’s future plans to store 100 000 t of bagasse will incorporate:

- better dust containment facilities at loading points, including fully enclosed buildings with dust extraction facilities,
- vacuum cleaning facilities within the bagasse systems,
- improved sealing of truck doors,
- conveyer systems that are completely enclosed and fitted with dust extraction systems at transfer points,
- full sealing of roads,
- storage times limited to 16 weeks, and
- storage areas that are far from residences and are screened.
Experience in Brazil
Judging from Google Earth images, the Boa Vista mill has a circular pile with a diameter of about 150 m. A conveyer drops bagasse at a fixed point near the edge of the pile and a dozer (or loader) works on top of the flat pile, either distributing the incoming bagasse or retrieving bagasse for return to the mill via a second conveyer.

According to an informal report of the International Cane Energy Network (1994), the Sao Martino mill stores up to 200,000 t of bagasse at 50% moisture in triangular piles that are packed down with bulldozers and front-end loaders.

The option of baling

History
In the 1920s, the Celotex corporation experimented with baling and suffered numerous fires due to spontaneous combustion. The fire problem was solved by making small bales (250 kg at 50% moisture) and carefully stacking these to ensure that heat could escape through gaps between the bales. This method was used for 40 years but was abandoned due to its high labour requirement.

Attempts to reduce labour costs by making bigger bales (600-800 kg at 50% moisture) and mechanically stacking them reduced the costs but gave poor quality product, because the centres of the bales overheated (70°C) and accumulated acid that attacked the hemi-cellulose.

In 1968, Bernhardt reported that Valentine Pulp and Paper Co had tried storing bagasse in large bulk piles (without wetting or compaction) and had found it significantly less expensive and more effective than their previous system of bales, which often deteriorated. Since that time, bulk piles have generally replaced baled storage.

The Bagatex-20 process
This process was patented in the 1980s and hailed as the best solution for bagasse storage (Anon, 1986). The process was developed by the Brazilian sugar factory Usina Santa Lydia, with the objective of storing bagasse for use as boiler fuel. Its success was claimed to depend on the addition of a ‘bio-chemical catalyst’ which causes controlled fermentation of residual sugars resulting in heating of the baled bagasse, and consequential drying from 50 to 20% moisture without overheating. It was claimed that large size bales could be used because the additive slows the rate of fermentation thereby preventing overheating. Vented stacking of the treated bales is still critical for achieving the necessary heat dissipation and drying. The drying prevents subsequent deterioration of the bagasse and raises the net calorific value (NCV).

The Bagatex-20 report (Anon, 1986) has some seemingly contradictory claims, in that the additive supposedly accelerates fermentation to cause timely drying, but it also inhibits the fermentation to prevent overheating. It was claimed that bales without additive took between 62 and 111 days to dry to 20%, whereas with additive the drying was complete within 20 days. Without additive, the bales developed hot spots with charring of the bagasse.

Australian researchers (Dawson et al., 1990) conducted trials with baled bagasse in which they compared storage with and without a simulated Bagatex additive. They found that they could achieve drying to 20% within 30 days without additive and that the various additive
components had little effect apart from slight acceleration of heating when yeast was included.

Despite numerous references to the Bagatex-20 publications of the 1980s, no reference has been found to commercial application of the process on the large scale required for weeks of off-crop power generation. This is probably due to the costs implicit in the following process summary:

- Prepare special catalytic bio-chemical fluid (seemingly consisting of yeast, vinasse and sucrose, urea and ethanol).
- Spray the fluid onto bagasse at the entrance to the baler.
- Bale into bales measuring 0.8 x 1.05 x 1.2 m or 1.6 m and weighing 600 or 900 kg respectively, bound with four strands of wire.
- Palletise (three bales in height) with wooden spacers between the bales to allow good ventilation.
- Transport by fork lift to a special conditioning warehouse that facilitates escape of moisture, heat and acids released from the bales (The required floor-space is approximately 10 m$^2$/daily ton of bagasse input (wet basis)).
- Transport to storage site and cover with tarpaulins.

The changes that take place in the first 34 days of the Bagatex process are shown in Table 2.

<table>
<thead>
<tr>
<th>Day</th>
<th>Moisture (%)</th>
<th>Temperature (°C)</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>50</td>
<td>28</td>
<td>7.1</td>
</tr>
<tr>
<td>2</td>
<td>42</td>
<td>-</td>
<td>4.4</td>
</tr>
<tr>
<td>4</td>
<td>35</td>
<td>46</td>
<td>3.9</td>
</tr>
<tr>
<td>7</td>
<td>33</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>28</td>
<td>61</td>
<td>2.9</td>
</tr>
<tr>
<td>12</td>
<td>27</td>
<td>62</td>
<td>2.8</td>
</tr>
<tr>
<td>14</td>
<td>25</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>20</td>
<td>20</td>
<td>57</td>
<td>2.8</td>
</tr>
<tr>
<td>23</td>
<td>19</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>26</td>
<td>17</td>
<td>55</td>
<td>3.6</td>
</tr>
<tr>
<td>30</td>
<td>15</td>
<td>51</td>
<td>5.5</td>
</tr>
<tr>
<td>34</td>
<td>14</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The reason for giving details of the Bagatex-20 process, despite its limited use, is covered later.

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Theory of controlled fermentation

*Acid and heat formation*

The microbiology and chemistry of changes taking place in stored bagasse are discussed in detail by Cusi (1980). Residual sugar in the bagasse provides substrate for rapid growth of yeasts and bacteria. Heat is generated and, in the absence of oxygen, the sugar is converted into organic acids, causing the pH to decline. The acid conditions inhibit microbial activity and thereby partly preserve the bagasse. The rise in temperature is usually sufficient to cause a change in microbial population from mesophilic to thermophilic organisms able to grow at
50°C. If moisture is able to escape then the heat causes drying of the bagasse, which is important for subsequent preservation.

**Acid and cellulose consumption**

After the readily available sugars have been consumed, the hemicellulose and cellulose in bagasse becomes the substrate for microbes. The rate of oxygen consumption slows and anaerobic conditions are slowly replaced by aerobic conditions in which the organic acids can be consumed, leading to a rise in pH and loss of preservative. The rate at which this occurs depends on the packing density. If there is sufficient moisture remaining then cellulose-digesting bacteria and fungi attack the bagasse, leading to loss of fuel value and development of fungal spores (bagassosis).

**Microbiology and chemistry**

It has been assumed that lactic acid formed by *Lactobacillus* bacteria is the main cause of acidity. On this assumption, the Ritter process for bagasse preservation involves the addition of *Lactobacillus* cultures, together with molasses. The exact composition of the Bagatex additive is not known for certain but is thought to involve yeast, vinasse, sugar, urea and ethanol. Presumably the ethanol is added because it is a good substrate for acetic acid production.

In retrospect, it seems unlikely that lactobacilli are the main players in acid formation. Analyses on stored bagasse from Felixton (Morgan *et al.*, 1974), where lactobacilli inoculum had been added as part of the Ritter process, showed only trace amounts of lactic acid but significant quantities of acetic, propionic and butyric acids. These three acids give the characteristic odour of overloaded anaerobic effluent ponds and are probably the cause of offensive odour from some bagasse piles. It is also these acids that cause severe inhibition (preservation) of anaerobic effluent treatment systems if they are allowed to accumulate.

The so-called controlled fermentation in the Bagatex process does involve elements of acceleration and inhibition in that sugar and urea are added to accelerate the formation of acids and heat but the acid accumulation (pH <3) then controls the fermentation by inhibiting bacteria, thereby preserving the bagasse and preventing spontaneous combustion. After the accelerated fermentation (7-10 days), the pH rises slowly due to oxidation of the acids as oxygen slowly enters the bagasse. This loss of acid inhibition takes place first in the surface layers, explaining why the dangerously high temperatures inevitably occur about 1.5 m below the surface (optimum combination of air access and heat insulation).

**Variability**

The wide variety of results associated with baling are not surprising when considering the range of factors that are influential, such as:

- quantity of residual sugar in bagasse,
- moisture content at baling,
- bale size and density and
- bale stacking/ventilation patterns.

These factors are highlighted by a 2010 study (Lois-Correa *et al.*.) in which adequate drying temperatures were achieved but, compared to the Bagatex process, relatively slow drying took place (bales were piled and covered immediately without provision for ventilation). The loss of dry matter due to deterioration was 20-25% within 40 days, but this loss was less than 3% in a treatment involving drying of bagasse prior to baling.
Suggested combination of Bagatex-20 with bulk piles

‘De-mystifying’ the technology of the Bagatex process could be important for enabling its application to bulk piles. The challenge is to ensure that sufficient sugar is feeding appropriate bacteria with limited access to oxygen but sufficient ventilation to enable drying. Monitoring of temperature and pH could provide valuable management information. If the piles could benefit from the extensive drying inherent in the Bagatex process then the substantial benefit of higher fuel value and long-term stability would apply.

Various reports (e.g. ASSCT workshop 2005 (www.assct.com.au/) and Cusi, 1980) indicate that air-laid piles do not store well unless some compaction is applied to minimise air ingress. A common means of compaction is the driving of dozers on the pile but this is inefficient and consumes fossil fuel (diesel). Perhaps compaction could be done as the bagasse leaves the mill by using a continuous baler (Figure 1).

The continuous baler:
- uses no binders,
- is powered by relatively inexpensive and renewable energy (electricity from bagasse),
- produces chunks of compressed bagasse (approximately 760 x 760 x 200 mm) that may be of appropriate configuration, when dumped randomly, to enable ventilation of moisture without allowing aerobic conditions in the bulk of the bale,
- enables control of dust, and
- would save diesel if dozers and loaders are subsequently used to build the bagasse piles, because the pre-compacted bagasse enables higher tonnages per load (with air-laid piles a ten-ton bulldozer with extended blade moves only about 600 kg (dry basis) of bagasse (Cusi, 1980)).
A disadvantage of the continuous baler is that some form of bale-breaker would be necessary to homogenise the bagasse for feeding to boilers.

For the controlled heating and drying stage (about 20 days) the bales would need to lie in a pile of limited height. Additional material would then be added to the pile at intervals. This implies the building of several piles simultaneously; however, the process could take place in a single pile covering a large area but with carefully managed distribution over the area. A view of the Boa Vista system in Brazil (Figure 2) suggests that this type of layering (without bales) takes place there. The circular pile has a diameter of approximately 150 m and the tracks of the dozer/loader can be seen radiating out from the fixed point where bagasse is deposited or retrieved.

The option of forced drying before storage

Springer (1979) gives results suggesting that it may be economical to dry whole tree chips before storage. These chips, containing leaves and bark, are prone to extensive deterioration if not dried. Bagasse drying, using flue gas, is applied at some sugar factories but the economics suggest that it is generally better to use the flue gas for heating air and water going to the boiler, rather than investing in bagasse driers. This logic may be different at factories that use substantial amounts of stored bagasse. If the bagasse is dried it:

- is stable in storage (i.e. fuel is saved),
- gives higher recoverable energy (less water to be evaporated),
- gives less flue gas to be cleaned (less fan power required) because there is less vapour (this is counteracted by the higher amount of flue gas produced during the drying process),
- enables higher furnace rating and boiler efficiency.
When burning partially dried bagasse the furnace temperature tends to be high enough to cause clinker. To prevent this, air heating needs to be reduced so as to reduce the grate temperature (Magasiner, 1987). This is an example of the interactions that arise in assessing bagasse storage together with best use of recovered heat. It is beyond the scope of this paper to assess the economics of different heat recovery systems for factories burning stored bagasse but, if the impact on bagasse storage is taken into account, it may yield results that are different from those for a standard sugar factory.

**The special case of diffuser bagasse**

When considering the theory of good bagasse storage, it is evident that diffuser bagasse requires special consideration because:

- The high extraction achieved in diffusers could mean that there is insufficient residual sugar in the bagasse for early generation of heat and acids.
- The pasteurisation of bagasse during diffusion eliminates all non-spore-forming bacteria, thereby giving spore-formers an early advantage. These include cellulose digesting species which might dominate and cause severe deterioration, especially if they are not inhibited by acids.
- In cases where filter mud is added to the diffuser, the nutrients in the mud would assist the cellulose digesting bacteria.
- Having been heated, the bagasse fibre is softened and therefore likely to behave differently when baled or compacted.
- Diffuser bagasse tends to have high levels of ash which would contribute to clinker formation if partially dried bagasse was retrieved from storage.

It is proposed that the first two items could be addressed by adding a small amount of cold, stale factory effluent mixed with molasses to the imbibition water at the final dewatering mill. Stale effluent contains many acid-forming bacteria (evidenced by its behaviour in overloaded anaerobic effluent dams).

**Alternative equipment options**

Equipment used for bagasse handling in Australian mills has been listed earlier. Other options are available, with the choice being dependent on local conditions. These options include the following:

*Mechanical loader/dozer stacking and reclaiming via a single discharge and reclaim point*

This is the system illustrated in Figure 2. Excess bagasse is dumped by an elevated conveyor at a fixed point. Front end loaders and/or bulldozers are used to back stack and compress the pile. The same vehicles then reclaim to feed hoppers. For larger storage piles, the disadvantage of this method is that the vehicles have to travel long distances. For indicative purposes, guidelines from an equipment supplier have been used to calculate vehicle requirements for reclaiming bagasse from different distances (Figure 3). The results indicate the vehicle requirements but highlight the need for care in eliminating bottle-necks. The figure shows a situation where multiple vehicles may waste time queuing at a bottle-neck caused by insufficient capacity at the reclaim hoppers.

It is possible to reduce vehicle travel, and number of vehicles, by having multiple discharge points, but the conveyer network is then more complex, with additional transfer points.
Figure 3. Calculated reclaim rates based on cycle time data and a fixed receiver capacity.

Linear mechanical stackers
Another alternative to a single discharge point is discharge via a linear discharge system. Figure 4 shows an elevated conveyor and travelling transfer device (tripper) which discharges to create a linear pile. This installation is at the Raizen Jatai sugar factory in Brazil (note the extended discharge chutes for reduction of dust).

Figure 4. Elevated conveyor with travelling discharge device (tripper) and associated vehicle. (Photo: N du Plessis)

A second option, a boom stacker, is illustrated in Figures 5 and 6. The bagasse in the illustrations is used for pulp and paper but the boom stacker could have a role in storage for co-generation. Boom stackers are common in other industries involving bulk handling.
Figure 5. Boom stacker in India.

Figure 6. Aerial view of Boom stacker piles.
Both types of linear stackers still require vehicles to distribute the bagasse and increase the width of the pile. Without these vehicles, the low bulk density of bagasse means that the required length of traverse would probably be too long to be economical.

**Radial boom stackers**

Depending on site layout, it may be appropriate to use radial boom stackers that slew in an arc, producing doughnut-shaped stacks on either side of a central conveyer. The length of the boom is a limiting factor, with costs going up exponentially as the length is increased.

**Summary and Conclusions**

Bulk storage in piles without addition of water is recommended as the choice method for large quantities of bagasse boiler fuel, but care is needed in managing the piles. The two-phase nature of the storage chemistry needs to be recognised with the need to encourage acid formation in stage one and to protect the acids from oxidation in stage two. The need to meet biological requirements within the constraints of engineering realities, presents challenges for further research and innovation.

Where storage periods exceed about three months some form of compaction of the bagasse is necessary to restrict aeration during stage two. This can be achieved by driving vehicles over the bagasse piles, but an alternative of compaction by a continuous baler located at the factory deserves investigation.

International experiences with bulk piles should continue to be monitored, with cognisance taken of probable opportunities for cost reduction by avoiding extensive use of dozers and loaders. Development of alternative stacking and compacting techniques is called for, preferably allowing controlled ventilation for about 20 days after depositing the bagasse.

The opportunity to increase the fuel value of bagasse by drying during storage is worth pursuing. Judging from the Bagatex-20 process, this could be achieved by simultaneously building multiple piles of bagasse ‘chunks’ (produced by a continuous baler) such that each layer dries for 7-10 days before being covered by another layer. The space between chunks would assist with initial ventilation but most of the bagasse would be sufficiently compacted to restrict access to oxygen. The electrically driven stationary baler would reduce costs of pile compaction and stacking, and would reduce dust.

Significant environmental challenges exist and require early recognition and planning.

The likely difference in behaviour of diffuser bagasse (compared to mill-run bagasse) needs to be recognised – the possible benefit of adding sugar and bacteria to this bagasse before storage requires investigation.
REFERENCES


Searcy EM and Hess JR (2010). Uniform-format feedstock supply system: A commodity-scale design to produce an infrastructure-compatible biocrude from lignocellulosic biomass. Idaho National Laboratory Ext-10-20372, USA.

Springer EL (1979). Should whole-tree chips for fuel be dried before storage? Forest Products Laboratory Research Note FPL-0241, United States Department of Agriculture, USA.

APPENDIX
DATA RELEVANT TO BAGASSE STORAGE

Densities of piled bagasse
If fresh bagasse is deposited from an overhead conveyer without mechanical compaction (i.e. air-laid) it tends to form a conical pile with angle of repose of 47°. The average density (dry basis) of the whole pile depends on the height of the pile, approximately as follows (Cusi, 1980):

<table>
<thead>
<tr>
<th>Height (m)</th>
<th>Average density (dry basis) (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>88</td>
</tr>
<tr>
<td>15</td>
<td>94</td>
</tr>
<tr>
<td>20</td>
<td>100</td>
</tr>
<tr>
<td>25</td>
<td>105</td>
</tr>
</tbody>
</table>

These densities are about 45 kg/m³ less than those for equivalent water-laid piles, which have flat tops (Cusi, 1980). It is emphasised that the figures refer to whole piles, not columns of different heights within a pile. Morgan et al. (1974) cut and weighed columns of different heights from water-laid piles. Their ‘spot’ measurements gave appreciably higher average density figures than those quoted by Cusi for entire piles because the average for the pile is influenced by the shape of the pile.

Area requirements
Based on the air-laid densities and angle of repose given above by Cusi, the following storage area requirements can be calculated for different pile heights and lengths (assuming the piles are linear and have a triangular cross-section). The calculations include a 20 m space between piles.

<table>
<thead>
<tr>
<th>Ridge length (m)*</th>
<th>Area (ha) required for 10 000 t fresh bagasse (50% moist.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td>25</td>
<td>4.31</td>
</tr>
<tr>
<td>50</td>
<td>3.49</td>
</tr>
<tr>
<td>75</td>
<td>3.16</td>
</tr>
<tr>
<td>100</td>
<td>2.97</td>
</tr>
</tbody>
</table>

*The ridge is shorter than the base of the pile

Compaction perspective

<table>
<thead>
<tr>
<th>Compaction instrument</th>
<th>Compaction pressure (kg/cm²)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top 1 m of air-laid bagasse</td>
<td>0.02</td>
<td>Calculated from Morgan et al. (1974)</td>
</tr>
<tr>
<td>Top 1 m of water-laid bagasse</td>
<td>0.08</td>
<td>Cusi (1980)</td>
</tr>
<tr>
<td>Tracks of bulldozer</td>
<td>0.60</td>
<td><a href="http://www.ishaengineering.com">www.ishaengineering.com</a></td>
</tr>
<tr>
<td>Continuous baler</td>
<td>5.20</td>
<td></td>
</tr>
</tbody>
</table>

Densities of baled bagasse
Continuous balers produce bales with densities of 600 to 700 kg of fresh bagasse/m³ (www.ishaengineering.com and Dawson et al., 1990). Bales used in the Bagatex-20 process had densities of 600 to 670 kg/m³.