



SRA FINAL REPORT

Develop a blueprint for the introduction of new processing technologies for Australian factories: final report 2015/043

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ABSTRACT

Several overseas factories are using technologies that reduce their process steam consumptions to very low levels, *e.g.* lower than 32% on cane, which are much lower than achieved by the most steam efficient Australian factories (~40% on cane). The steam efficient technologies that are not currently being used in Australian factories include:-

- Falling film tube evaporators and Kestner evaporators;
- In-line juice heaters on vapour from the final evaporator;
- Barriquand juice heaters;
- Use of vapour from the 3rd evaporator for pan boiling;
- Direct contact pan feed conditioning systems; and
- Vapour recovery systems such as in condensate cigars.

The project has shown that Australian factories should consider the application of these technologies when planning factory upgrades or replacement of existing equipment as these technologies can provide benefits of increased crushing rate, improved sugar recovery and be suitable for reducing the process steam consumption, if and when required. This project provides a blueprint with the details of the new technologies and their recommended application into Australian factories.

A major finding from the project was that substantial sucrose losses are occurring through hydrolysis in the current evaporator stations in Australia's steam efficient sugar factories. These losses can be reduced substantially through application of the new technologies.

Follow on projects are required to determine processing solutions to reduce the impact of sucrose hydrolysis during evaporation and to determine the required design and operational changes for pan stages to allow the existing batch pans in Australian factories to operate effectively on low pressure vapour.

EXECUTIVE SUMMARY

Australian sugar factories are now amongst the least energy efficient in the world with process steam consumption levels being ~40% steam on cane for our most steam efficient factories. Several overseas cane factories are now operating with process steam consumptions below 35% on cane and some as low as 28% on cane. In many cases the technologies being used in these steam efficient factories can be introduced into Australian factories to provide capacity and operational benefits. The technologies that are not currently being used in Australian factories include:-

- Falling film tube evaporators and Kestner evaporators;
- In-line juice heaters on vapour from the final evaporator;
- Barriquand juice heaters;
- Use of vapour from the 3rd evaporator for pan boiling;
- Direct contact pan feed conditioning systems; and
- Vapour recovery systems such as in condensate cigars.

The project investigated these technologies to determine those that are most suited for adoption into Australian factories now, for our current operational objectives, and are well suited to providing major reductions in process steam consumption in the future. Without the developed blueprint for implementation of these technologies Australian factories could make poor and very expensive investments without considering alternative technologies that may be better suited to operations in the future for more steam efficient and diversified operations.

The configuration of the juice evaporation station and the manner in which juice heating and pan boiling operations utilise bleed vapour from the evaporators determines the process steam consumption of the factory. In Australian sugar factories the evaporator stations almost universally comprise Robert (rising film tube) evaporators with calandrias comprising tubes of 2 m length and 44.45 mm outside diameter. Relative to other designs of evaporators such as Kestners, falling film tube evaporators (FFTEs) or Robert vessels with longer tubes of smaller diameter these commonly used Robert evaporators have larger juice volumes and hence longer residence times for juice.

The methodology for undertaking the project was:-

- Inspect the operations of several steam efficient factories in South Africa, Mauritius, Reunion and India and, based on their performance data, assess the suitability of the technologies for application into Australian factories;
- Determine the magnitude of sucrose losses that are currently occurring during juice evaporation in several Australian sugar factories;
- Model the operations of four Australian sugar factories to assess the suitability of using the alternative evaporator designs and the novel process steam efficient technologies to suit nominated objectives for each of the factories;
- Investigate the effect on pan stage productivity when using low pressure vapour such as vapour from the 3rd effect for boiling the pans; and
- Investigate the effects on whole of factory operations (including electricity export, surplus bagasse generation and water balance) resulting from the adoption of the new technologies into Australian sugar factories.

The outputs from the project for Australian sugar factories are:-

- Knowledge of the magnitude of sucrose losses currently experienced in evaporator stations in Australian factories;
- Detailed knowledge of the novel technologies being used in the highly steam efficient overseas factories;

- Potential application of these technologies into Australian factories for benefits of increasing crushing rate, increasing sugar recovery (mainly through reduced sucrose losses in the evaporators) and reduced process steam consumption;
- Implications for the productivity (pan cycle times and exhaustion) for the current batch pans in Australian factories from using vapour from the 3rd evaporation stage;
- Impact on whole of factory operations from implementing the steam efficient technologies; and
- Recommendations (the blueprint) for Australian factories in applying the steam efficient technologies.

The project provides large economic, social and environmental benefits which are available to all Australian factories and their technologists.

The economic benefits based on a factory crushing 1.5 Mt per year include:-

- The capital investment is expected to exceed \$25 million to transform from a process steam consumption of 50% on cane to 35% on cane. Substantial capital can be wasted unless well informed decisions using the blueprint are taken; and
- For current steam efficient configurations of Australian evaporator stations sucrose losses could be 0.85%, equivalent to nearly \$900,000 per year in lost revenue. These losses would increase if further reductions in steam consumption are sought based on the continued use of conventional technologies. These losses can be reduced substantially through application of the new technologies.

The social benefits include:-

- Increased knowledge of industry technologists to better define upgrades of evaporator stations, pan stages and utility systems in Australian factories for increased capacity, operational efficiencies and transforming to more steam efficient operations.

The environmental benefits include:-

- Increased outputs from bagasse and enhancement of the renewable energy credentials of the industry.

Follow on projects are required to determine processing solutions to reduce the impact of sucrose hydrolysis during evaporation and to determine the required design and operational changes for pan stages to allow the existing batch pans in Australian factories to operate effectively on low pressure vapour.

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1. BACKGROUND

1.1. The issue for Australian factories

Australian sugar factories are now amongst the least energy efficient in the world with process steam consumption levels being for most factories ~50% on cane. The most steam efficient Australian factories operate at ~40% steam on cane. Several overseas cane factories are now operating with process steam consumptions below 35% on cane and some as low as 28% on cane. In many cases the technologies being used in these energy efficient factories can be introduced into Australian factories to provide capacity and operational benefits.

The project investigated these technologies to determine those that are most suited to adoption into Australian factories now, for our current operational objectives, and are well suited to providing major reductions in process steam consumption in the future. The project developed a blueprint for Australian factories to utilise when making capital decisions for new plant and for upgrades in the process sections of the factories.

Without the blueprint Australian mills could make poor and very expensive investments without considering alternative technologies that may be better suited to operations in the future for more steam efficient and diversified operations.

1.2. The situation in overseas cane factories and available process technologies

1.2.1. General comments

Several technologies that are being used in overseas sugar factories in order to provide major reductions in process steam consumption are not currently used in Australian sugar factories. These technologies include:-

- Falling film tube evaporators and Kestner evaporators;
- In-line juice heaters;
- Barriquand juice heaters;
- Use of vapour from the 3rd evaporator for pan boiling;
- Direct contact pan feed conditioning systems; and
- Vapour recovery systems such as in condensate cigars.

In most cases these technologies also boost plant capacity and processing efficiency such as sucrose recovery. While the economic circumstances in Australia do not currently justify major investments to achieve high levels of steam efficiency, Australian factories could benefit now from these technologies to provide capacity and operational efficiencies. These technologies would then be familiar and established when the industry seeks to achieve greater process steam efficiencies.

The configuration of the juice evaporation station and the manner in which juice heating and pan boiling operations utilise bleed vapour from the evaporators determines the process steam consumption of the factory. In Australian sugar factories the evaporator stations almost universally comprise Robert (rising film tube) evaporators with calandrias comprising tubes of 2 m length and 44.45 mm outside diameter. Relative to other designs of evaporators such as Kestners, falling film tube evaporators (FFTEs) or Robert vessels with longer tubes of smaller diameter, these commonly used Robert evaporators have larger juice volumes and hence longer residence times for juice.

1.2.2. Process steam consumption in overseas and Australian cane factories

Several overseas cane factories are now operating with process steam consumption levels around 35% and some between 28 and 30% on cane (Broadfoot, 2014a; Lehnberger & Mallikarjun, 2014; Awasthi, 2014). The most steam efficient factories are in India, Mauritius, Reunion, Argentina and Central America (Petit & Mace, 2014). It is expected that Brazil will make major investments in the next decade to boost cogeneration output (and reduce steam consumption) in order to broaden the revenue base (Czarnikow Sugar, 2014).

Currently, the majority of Australian mills consume process steam at ~50% on cane (or greater) while the lowest consumption (achieved by four Australian mills) is ~40% on cane (Rose *et al.*, 2009; Hodgson *et al.*, 2004; Lavarack *et al.*, 2004).

An essential requirement to reduce the process steam consumption to lower than 35% on cane is to operate the pan stage on low pressure vapour such as vapour from the 3rd effect. Changing the vapour supply to the pan stage from vapour 1 to vapour 3 reduces the process steam consumption by ~6% on cane. However, to use low pressure vapours has adverse effects on pan stage productivity which must be addressed.

1.2.3. Juice evaporation technologies

The standard evaporator technology in Australian factories is almost universally the rising film Robert evaporator.

Rising film plate evaporators have been installed into a few Australian factories as booster vessels (de Viana *et al.*, 1993) but the generally disappointing experience would exclude this technology from widespread adoption. Tableland Mill has installed a falling film plate evaporator at the No 1 effect position with good success (Sichter *et al.*, 2004). However this technology has not been widely adopted in the world cane industry and recent information indicates that only 15 of a total of 40 installations are currently being used (Morgenroth, 2014). The inability to physically access the heating surface area to remove accumulated scale should this be necessary is a major limitation of this technology, so widespread adoption in Australian factories is unlikely.

During the past decade several installations of falling film tube evaporators (FFTEs) including full evaporator sets have been installed in the cane industry (Lehnberger and Mallikarjun, 2014; Awasthi, 2014; Brahim *et al.*, 2015). There are no FFTEs currently in Australian sugar factories. The main advantages of FFTEs are high heating surface areas per footprint area, ability to operate with low temperature differences (particularly at the tail end of the set compared with the Robert evaporator) and short residence time for juice, resulting in reduced sucrose degradation (a greater problem at the front end of the set). The main disadvantages of FFTEs at least from an Australian perspective are potential for maldistribution of juice, potential severe scaling (more likely in the final vessel) and propensity to cause entrainment of juice into vapour. Until recently little has been published on the industrial experience with using FFTEs in the cane industry.

Improvements in the design of FFTEs have progressed this technology and it appears now suitable for implementation into Australian Mills.

The heat transfer coefficients for FFTEs at the Nos 1 and 2 positions in evaporator stations (Morgenroth, 2014) appear to be similar to typical Robert evaporators although suppliers often quote much higher values. Little data were available in the literature on heat transfer performance for FFTEs late in the evaporator set. The study aimed to obtain reliable data on the heat transfer performance of FFTEs.

Several studies on sucrose degradation during cane juice evaporation have determined that the long residence times in Robert evaporators may cause large sucrose losses and this is substantially greater where large heating surface areas are provided at the Nos 1 and 2 effects, such as in configurations to provide high levels of steam efficiency. Application of the Vukov (1965) expressions to calculate the sucrose degradation in a steam efficient configuration of Robert evaporators shows sucrose degradation of 0.4% (Broadfoot, 2014b). The process variables having the greatest influence on sucrose losses early in the set are residence time and juice temperature. Several researchers believe that the Vukov expression underestimates the rate of sucrose degradation. Edye & Clarke (1995) determined that the sucrose losses could be as high as 1.39% in a conventional configuration of the set. South African researchers have been prolific in reporting losses in Robert evaporators (Schaffler *et al.*, 1985; Purchase *et al.*, 1987; Hoi & Shum, 1996) with sucrose losses reported up to 0.75%.

It is for the benefit of short residence times that the South African industry (and Indian industry to a lesser extent) has adopted Kestner evaporators (climbing film evaporator with tubes 6 to 7 m long) at the Nos 1 and 2 positions. Kestner evaporators generally require a large external entrainment separator so the footprint can be large. The heat transfer efficiency of Kestner evaporators (Rein & Love, 1995; Schorn, 2014) appears to be comparable to that achieved by Australian Mills with Robert evaporators. Kestner vessels are not generally used at other than the Nos 1 and 2 effect positions. This study also investigated the suitability of Kestner evaporators for Australian factories.

1.2.4. In-line juice heaters and other process technologies for increased steam efficiency

In-line juice heaters are frequently used in Indian factories as the initial stage of juice heating using vapour passing from the final effect to the condenser. This process recovers a large proportion of the heat in the final vapour. Besides reducing the process steam consumption for the factory the cooling water demand and heat load on the cooling water systems are reduced. No information on the designs is available in the literature. Details of efficient designs and information on realistic heat transfer performance were obtained.

Various designs of molasses feed conditioning systems were investigated with emphasis on determining a simple, easily retrofitted unit that can utilise low pressure vapour. It is known that several designs of feed conditioners are being used in Indian factories.

Barriquand juice heaters are being utilised in several overseas factories as they allow operation with multiple heating streams, *e.g.* vapour 4 and vapour 3, provide access for physical cleaning of the total heating surface area if required and allow operation to a close approach of the juice temperature to the temperature of the vapour sources.

1.2.5. Pan stage operations

Australian pan stages predominantly use large batch unstirred pans which make it difficult to reduce the process steam consumption to below ~40% on cane, as these pans require process steam or vapour 1 for efficient operation. Continuous pans can operate effectively on vapour 2 or 3 and so substantial savings in process steam can be obtained through their use. In general, unstirred batch pans cannot operate on low pressure vapour without incurring major operational problems such as poor massecuite exhaustions and long cycle times.

As continuous pans are expensive capital items and will not be installed readily to replace batch pans, it is desirable that the capability of the existing batch unstirred pans is defined for operation on lower pressure vapours and procedures such as the supply of superheated (conditioned)

molasses feed, use of mechanical agitators, and use of jigger systems are considered in order to increase their capability. No suitable references were found to quantify these effects with pans on low pressure vapour. This project used SysCAD modelling to better define the limitations of the currently installed batch pans in terms of production capacity and exhaustion for operation with vapour of various saturation temperatures and as low as 90 °C. Because of the lack of suitable data for evaporation rates when the pans are supplied with low pressure vapour, these studies provide an indication only of the magnitude of the limitations to performance. A much more detailed investigation is required in a subsequent project.

1.2.6. Vapour recovery systems

Morgenroth & Pfau (2010) described the application of condensate flash systems (commonly referred to as condensate cigars) in the beet industry to enhance the steam economy of factories. Australian factories have generally made little use of the flash vapours, *e.g.* from heaters and pans and only a few factories employ flashing of condensates at the evaporators (Rose *et al.*, 2009). There is scope for more extensive and more efficient flash vapour recovery to be employed. Various designs of flash vapour recovery systems were investigated to determine the arrangement(s) most suited to Australian factories.

1.2.7. Development of the Blueprint technologies

Australian factories will need to adopt some or all of these overseas process technologies, or adaptations to suit our current equipment, if major reductions in process steam consumption are to be achieved. Such changes will be necessary if Australian factories are to diversify their revenue from predominantly crystal raw sugar.

Importantly these new technologies provide capacity and operational benefits which are likely to be financially attractive to Australian Mills at current low returns for renewable energy. If adopted now, these new technologies would suit plant configurations in the future if, and when, attractive financial returns exist for investing for much lower process steam consumption levels.

This project has developed for Australian factories a blueprint which defines the favoured technological changes to obtain capacity and operational benefits while ensuring compatibility for future operation with much lower process steam consumptions than the current best practice of 40% on cane. The costs and benefits of each technology have been examined under various conditions as to their suitability for Australian milling conditions. The preferred designs (and design variations where appropriate) have been documented.

The study has developed practical solutions for future steam efficient operation in Australian factories based on the recent experiences of overseas energy efficient factories and applied those technologies to the more immediate objectives for Australian mills of factory throughput and sugar recovery. The investigations have included inspections of plant in overseas factories, obtaining reliable operating data, obtaining design details and discussing designs with overseas suppliers. Extensive modelling using SysCAD and other SRI models has been undertaken in the study to define suitable practical options for Australian factories. The extent of sucrose destruction in evaporator sets at several Australian factories was measured and the results applied in the determination of the preferred evaporation technology.

2. PROJECT OBJECTIVES

The aim of the project was to develop for Australian factories a blueprint which defines the favoured technological changes to obtain capacity and operational benefits while ensuring compatibility for future operation with much lower process steam consumptions than the current best practice of 40% on cane.

At the outset of the project the specific aims of the project were nominated to answer the following questions:-

- Does the magnitude of sucrose destruction in the first two Robert evaporators in a steam efficient evaporator station warrant that short residence time evaporators, *e.g.* falling film tube or Kestner evaporators, be used as an alternative to Robert evaporators?
- Are the scaling rates and effectiveness of chemical cleaning in falling film tube evaporators now sufficiently manageable at the final effect to warrant their adoption? If so, to what extent do these evaporators provide scope for increased juice processing capacity and substantial reductions in steam consumption?
- What are the implications of using condensate cigars for collection and flashing of condensates in Australian evaporator stations?
- By how much will a direct contact feed conditioning system impact on pan cycle times, exhaustions, ability to use low pressure vapours on pans?
- Under what circumstances will in-line juice heating be financially attractive?
- Through the implementation of new technologies (or adaptations to suit Australian factories), what will be the impact on steam consumption for the factory, the cogeneration potential and generation of surplus bagasse?
- To what extent will the water balance of the factory be affected through the implementation of the new technologies?

3. OUTPUTS, OUTCOMES AND IMPLICATIONS

3.1. Outputs

The main outputs from the project were stated at the outset to be:-

- Knowledge of sucrose losses in Robert evaporators in Australian factories.
- Knowledge of the practical application of FFTEs and Kestner evaporators into evaporator sets.
- Assessment of FFTEs and Kestner evaporators in terms of reduced sucrose degradation, heat transfer efficiency and suitability for configurations which provide major reductions in steam consumption relative to Robert evaporators.
- Impact of low vapour pressure on the cycle times and exhaustions of batch pans and the production rates of continuous pans through SysCAD modelling.
- Description of techniques adopted by overseas factories to achieve process steam consumption levels between 28 and 35% on cane.
- SysCAD 'whole of factory' models which incorporate technologies to reduce the process steam consumption to lower levels than currently achieved in Australian factories, *e.g.* target to 28 - 35% on cane.

- A blueprint for Australian sugar factories to guide future investment decisions in the process stations to boost the capacity and operational performance using technologies that are suited to future major reductions in process steam consumption.
- Capacity building in QUT staff (Darryn Rackemann, David Moller and Anthony Mann) in succession planning for the pending retirement of Ross Broadfoot.

The above list of project outputs has been satisfied although some minor changes have been necessary.

The project outputs include numerous technologies that are not currently adopted in Australian factories. The project outputs are suitable for implementation by all Australian factories. Some of the technologies may be sourced by Australian factories by purchasing equipment directly from suppliers. For example, this equipment includes falling film tube evaporators, Kestner evaporators, Barriquand juice heaters, condensate cigars, molasses pre-conditioning systems. Currently no Australian manufacturer supplies this equipment and it would be sourced from overseas. In the future Australian manufacturers will likely take up licences for the equipment designs and technologies or develop their own designs of equipment, based on increasing demand.

The adoption pathway to implement the new technologies into Australian factories is likely to follow one of two routes *viz.*,

- For sugar factories to approach the equipment suppliers directly; or
- For sugar factories to request QUT staff to provide technical support to define the features of the preferred design and to define the preferred arrangements for implementing the new technologies. This technical assistance would likely include wide ranging consultations to define the numerous changes to the factory's configuration to achieve new processing targets such as increases in crushing rate, increased recovery or reductions in process steam consumption.

Australian factories have shown strong interest in the outputs of the project. At the time of preparing this final report:-

- Several factories have altered their set point values for clarified juice pH to reduce the magnitude of sucrose losses in evaporators and are consciously watching the juice operating levels in the early vessels of the evaporator set to reduce the juice residence time.
- One factory is proceeding with the installation of a falling film tube evaporator to replace a Robert evaporator at the front end of the set. It is likely that this decision was made without reference to the outputs of this project as SRA milestone reports are not provided to factories.
- Several factories are interested in understanding what changes should be incorporated into the designs of new batch pans to allow successful operation on low pressure vapour such as vapour 3. A major follow-on research investigation is required to define the required changes which will likely incorporate:-
 - Changes to the pan design (calandria dimensions, downtake diameter, shape of the base);
 - Specification of an effective mechanical stirrer (with high volumetric pumping rate per unit of power input);
 - Changes to the feed streams through pre-concentration and pre-conditioning;
 - Changes to the flowscheme for sugar boiling to better suit operation with low pressure vapour; and

- Changes to the profile of set points for run up of batch pans when using low pressure vapour.

An application has been made to SRA for funding this project in the call for new research projects commencing in July 2018.

In the interim (prior to this work being undertaken) QUT has been requested to design batch pans for an Australian factory using the best available knowledge to suit operation on intermediate pressure vapour (lower than currently used in Australia but pressure not as low as used in the steam efficient overseas factories). The designs need to be suitable for retrofitting mechanical agitation in the future.

- Two of the host factories for which their process stations were modelled for potential incorporation of the blueprint technologies are planning to implement some of those recommended changes.

3.2. Outcomes and Implications

The main outcomes for the factories are financial benefits through capital savings and increased efficiencies by incorporating the blueprint of new processing technologies when making investment decisions for boosting capacity and operational performance, and reducing steam consumption.

The blueprint provides Australian factory staff with the details of the new technologies (and their recommended application) which can be considered against the conventional technologies in cost/benefit analyses, and taking into account compatibility with potential future plans for the factory. The investigation team at QUT will be able to assist factories in the design, application, sourcing and implementation of the equipment and technologies.

The project provides large economic, social and environmental benefits which are available to all Australian factories.

The economic benefits based on a factory crushing 1.5 Mt per year include:-

- The capital investment is expected to exceed \$25 million to transform from a process steam consumption of 50% on cane to 35% on cane. Substantial capital can be wasted unless well informed decisions using the blueprint are taken. The expenditure on the process stations could be part of a major cogeneration project which would have potential income from export power of greater than \$15 m per annum.
- For current steam efficient configurations of Australian evaporator stations sucrose losses could be 0.85%, equivalent to nearly \$900,000 per year in lost revenue. These losses would increase if further reductions in steam consumption are sought based on the continued use of conventional technologies.

The social benefits include:-

- Increased knowledge of industry technologists to better define upgrades of evaporator stations, pan stages and utility systems in Australian factories for increased capacity, operational efficiencies and transforming to more steam efficient operations.

The environmental benefits include:-

- Increased outputs from bagasse and enhancement of the renewable energy credentials of the industry.

4. INDUSTRY COMMUNICATION AND ENGAGEMENT

4.1. Outputs for adoption by sugar factories

The project has delivered the following key information for Australian sugar factories. This information is described in terms of the blueprint recommendations in Table 1.

Table 1 Blueprint recommendations

Technology /processing aspect	Key information from the project	Recommendations
Sucrose losses during juice evaporation	<p>Sucrose losses are substantial in Robert evaporator stations in steam efficient factories (steam% cane ~40%) – losses ~0.85% sucrose in clarified juice.</p> <p>The losses are attributed to the long residence times for juice in Robert evaporators and the high boiling temperatures. The majority of the loss (85%) occurs in the No 1 and No 2 effects of the evaporator set.</p> <p>Losses in the evaporator stations using exhaust steam at 200 kPa abs and minimal vapour bleeding are very low (0.05% sucrose in clarified juice).</p> <p>Low juice pH increases the sucrose degradation rate. It also appears that the degradation rate is faster when the heating surfaces are scaled.</p>	<p>Increase ESJ pH so the pH of the syrup at the operating temperature is 6.3 to 6.5. However a check is needed that scaling in the evaporators does not increase substantially.</p> <p>If an evaporator station is to undergo a major revamp, <i>e.g.</i> install additional area at the early effects then a shorter residence time design compared with the traditional Robert evaporator is recommended. Options here include to install:-</p> <ul style="list-style-type: none"> • Robert evaporator with calandria of smaller diameter and longer tubes (output of QUT2012/054: Thaval and Broadfoot, 2017) • Kestner evaporator • Falling film tube evaporator <p>The magnitude of the sucrose losses in the evaporation station is an important financial consideration. Where a factory is planning a major upgrade to the evaporator station and vapour bleed arrangements the estimated sucrose losses for current operation and for the changed configurations should be calculated and included in the overall financial assessment.</p>
Kestner evaporators	<p>Kestner evaporators provide a short residence time for juice (~1/3rd that of a conventional Robert evaporator).</p> <p>Heat transfer performance appears inferior (by ~15%) to Robert evaporators.</p> <p>The favoured Kestner evaporators have a juice recirculation line from above the top tube plate to the base of the evaporator.</p>	<p>Kestner evaporators are only recommended for No 1 or No 2 effects of the evaporator set.</p> <p>Where a new evaporator is required at the front end of a set in a steam efficient configuration either a Robert evaporator with smaller diameter and longer tubes</p>

Technology /processing aspect	Key information from the project	Recommendations
	<p>Adequate juice flow to the base of the evaporator is essential to maintain wetting of the total heating surface area. Favoured design has de-entrainment in the head space of the vessel rather than use an individual vapour-juice separator.</p>	<p>or a falling film tube evaporator is recommended to be installed. Features for the preferred design for the Kestner evaporator are provided.</p>
<p>Falling film tube evaporators (FFTEs)</p>	<p>FFTEs provide a short residence time for juice (~1/3rd that of a conventional Robert evaporator). FFTEs must be fitted with a juice circulation pump that supplies juice at a nominated rate to the juice distributor in the top of the evaporator in order to provide guaranteed wetting of the total heating surface area. The juice distributor is the critical component for a FFTE. FFTEs can be designed to operate with smaller temperature differences (vapour in calandria – vapour in the head space) by providing more heating surface area. Compared with the HTC for Robert evaporators in Australian factories the HTCs of FFTEs are comparable at No 1 effect, slightly superior at No 3 effect and possibly inferior at the final effect. Scaling rates appear comparable to Robert evaporators at effects No 1 to No 3. Little data on scaling rates are available for FFTEs in the final effect but it may be more severe than for Robert evaporators. Chemical cleaning procedures are comparable to those used for Robert evaporators. It is common practice in overseas factories to install a spare FFTE to be brought into service when one evaporator is being cleaned. Where multiple FFTEs are used in the one effect position series flow of juice is recommended rather than parallel flow.</p>	<p>The juice wetting rate should be ~1800 L/m/h. The installations of FFTE at No 1, No 2 or No 3 effects seem to be performing well in overseas factories and are suitable for Australian factories. No spare evaporator is required for the practice where the whole evaporator set is taken off line for cleaning as the FFTE is expected to remain in service between cleans for at least 2 weeks at these positions. For an installation of an FFTE at No 4 or No 5 of a quintuple set it is recommended that either a standby FFTE is installed or an existing Robert evaporator is retained as a standby unit. The concern (until proven otherwise) with a FFTE at No 4 or No5 is that a rapid scaling rate may require that the FFTE is cleaned every 5 days or so. Where smaller temperature differences are required in the vapour across a FFTE a larger surface area can be installed. This is a major advantage compared with a Robert evaporator. The power consumption of the juice circulation pumps is quite high and needs to be considered in a financial assessment when selecting FFTEs versus other evaporator designs. Features for the preferred design of FFTE are provided.</p>
<p>Technologies to suit steam</p>	<p>Several technologies that are suited to factories aiming to operate with low</p>	<p>Factories seeking reductions in process steam consumption should consider the listed juice heating options as</p>

Technology /processing aspect	Key information from the project	Recommendations
efficient operation	<p>process steam consumption were investigated. Comments follow:-</p> <p><i>In line juice heaters:</i></p> <p>Benefits include low heat load on the cooling water circuit. Well designed heater with adequate vapour supply rate and temperature provides heating of juice by 10 to 12 °C. In line juice heaters can also be on the vapour pipe from continuous pans.</p> <p><i>Barriquand juice heaters:</i></p> <p>Temperature difference between vapour and heated juice only ~4 ° C compared with 8 ° C for a shell and tube exchanger; suited for multiple heating streams; lower pressure drop than shell and tube heater.</p> <p><i>Heating juice with condensate:</i></p> <p>Ideal first stage of juice heating.</p> <p><i>Direct contact heaters:</i></p> <p>Many operational advantages but not suited to very high steam efficiency applications except as a top up heater.</p> <p><i>Use of condensate cigar for managing flash vapours to evaporators:</i></p> <p>Use of flash vapour in evaporator calandrias reduces process steam consumption but is likely to reduce the juice processing rate.</p> <p>Boosts vapour rate in the latter vessels so of benefit to boiling intensity, mixing of juice and brix control of syrup.</p> <p>Methodology has been developed for sizing the components of a condensate cigar.</p> <p><i>Use of a high vapour pressure in the head space of the final effect</i></p> <p>Provides vapour late in the set that is hot enough for more extensive juice heating. However more evaporator area is required and/or the steam pressure to the calandria of the No 1 effect is increased with adverse consequences for sucrose degradation.</p>	<p>alternatives to shell and tube juice heaters because of the various advantages.</p> <p>If a higher head space pressure is to be used in the final effect aspects such as sucrose losses need to be considered as average juice temperatures will increase.</p>

Technology /processing aspect	Key information from the project	Recommendations
<p>Application of the novel processing technologies into Australian sugar factories</p>	<p>The four Australian factories nominated their target objectives for the investigations. These objectives included increasing crushing rate, increasing sugar recovery by reducing sucrose losses in the evaporators, reducing process steam consumption and increasing the pressure of bleed vapour to the pan stage.</p> <p>For all four factories the use of FFTEs at the front end of the set was a preferred solution, mainly because of the ability to reduce the sucrose losses but also to be able to operate with relatively small temperature differences.</p> <p>An alternative to the FFTE is to use a Robert evaporator comprising longer tubes of smaller diameter, e.g. 3 m length and 38.1 mm outside diameter, rather than the conventional tubes, as evaporators with these tubes have substantially less juice hold up volume. Nevertheless the residence time is still longer than in a FFTE as the juice hold up volume is still larger.</p>	<p>The technologies which were recommended to satisfy the new objectives include further implementation of technologies currently used in Australian factories, e.g. juice heating using vapour from late in the set, using vapour from the evaporators for pan boiling, flashing of vapour from evaporator condensate in order to increase vapour flows late in the set, conditioning of the molasses feed to continuous and batch pans.</p> <p>New technologies which were recommended include falling film tube evaporators, use of Barriquand juice heaters and the flashing of vapour from pan and heater condensates to evaporator calandrias.</p> <p>The use of a FFTE at the final effect position is a technically feasible option for two of the factories. In both cases the advantage of the FFTE over a Robert evaporator at the final evaporation stage is the ability to operate at much lower ΔT than a Robert evaporator. For one factory the attraction was a substantial increase in juice processing rate. For the other factory the benefit was the reduction in sucrose loss in the Robert evaporators at the front of the set, by being able to reduce the pressure of the exhaust steam, and still maintain juice processing rate.</p> <p>For several factories the bottleneck to rate was because one effect stage had insufficient heating surface area. One attractive option is to replace the calandria in the current Robert evaporator vessel with a calandria of longer smaller diameter tubes, thus providing a substantial increase in the heating surface area.</p>

Technology /processing aspect	Key information from the project	Recommendations
		<p>None of the investigations recommended heating primary juice with condensate but this is an option that could be considered for further reductions in process steam consumption.</p> <p>The use of a vapour line juice heater on final effect vapour was not recommended for any of the four factories for their nominated objectives. This is primarily because for each factory the current configuration uses a relatively high vacuum on the final effect and so the final vapour temperature is too cool to provide a viable increase in the primary juice temperature. The use of a vapour line juice heater may be attractive where substantial changes are made to the evaporator station and allow a higher final vapour temperature is to be used.</p>
Use of low pressure vapour for pan boiling operations	<p>The use of vapour 3 instead of vapour 1 for pan boiling reduces the process steam consumption by 6% on cane (based on the pan stage vapour consumption being the typical 15% on cane). For factories seeking process steam consumptions less than 35% on cane then low pressure vapour (e.g. vapour 3) must be used for most if not all pan boiling operations. Overseas factories are using batch pans with stirrers and operating to a low boiling level, horizontal continuous pans, vertical continuous pans with mechanical stirrers in each module, conditioning of the molasses feed streams to provide a small flash of vapour as the feed enters the pan and in most cases the CBA boiling scheme (instead of the three massecuite boiling scheme used in Australian factories).</p> <p>A dynamic SysCAD model was developed to simulate the run up and heavy up</p>	<p>The modelling results have reinforced the practical observations that reduced evaporation rates when using low pressure vapour slow the crystallisation rates, increase boil-on times, slow the heavy up process, increase the total cycle times and reduce the exhaustion. The model demonstrated that with low pressure vapour supply the boil on rates and heavy up rates may become so slow that these operations are terminated prior to reaching target conditions such as pan full or a target dropping brix, in order to maintain the productivity of other pans on the stage.</p> <p>An application has been made to SRA to fund a major study to identify the most appropriate changes to pan stage equipment, operating procedures and control to minimise the capital investment required while maintaining</p>

Technology /processing aspect	Key information from the project	Recommendations
	<p>operations of a batch natural circulation pan. Simulations were undertaken for typical A, B and C massecuite strikes for vapour supply pressures of 200, 140, 100 and 70 kPa abs.</p>	<p>production performance with respect to rate, sugar recovery and sugar quality.</p>
<p>Implications of steam efficient process technologies on whole of factory operations (water balance, cogeneration output and surplus bagasse)</p>	<p>Modelling was conducted for three scenarios at two Australian factories to examine the flows in the high pressure (HP) steam circuit, cogeneration output, surplus bagasse production and changes to the water balance of the factory as a result of implementing various process steam efficient technologies. For the most part the general effects are well known to industry technologists.</p> <p>The water flows in sugar factories are markedly different for situations of low process steam efficiency and use of low pressure inefficient boilers coupled with steam turbine drives - the traditional sugar factory and a factory with high process steam efficiency and high pressure efficient boilers, condensing TAs and widespread use of electric drives.</p> <p>The former arrangement can readily lead to situations of insufficient available condensate and the need to intake raw water or implement drastic steps to cut water use (e.g. cut maceration rates).</p> <p>For factories with high process steam efficiency and high pressure boiler a large surplus of condensate exists and its disposal must be managed in an environmentally sustainable manner. For factories operating with a condensing TA to process any steam which is surplus to the process requirements the increase in power export is estimated at 0.133 MW per unit reduction in process SOC per 100 t/h cane. Thus for a factory crushing at 500 t/h changing the pan stage operations from vapour 1 to vapour 3 would generate additional export power of 3.9 MW.</p>	<p>The modelling has highlighted that when process steam efficient technologies are employed close consideration needs to be given to the impacts on the water balance of the factory as operational changes and capital investment may be required to mitigate any adverse effects in the water balance.</p>

4.2. Industry engagement during course of project

The progress on the project has been communicated to Australian factory staff at the Regional Research Seminars that are conducted each year in March/April. Table 2 shows the year of the seminars and the main aspect of the work that was covered in each seminar. Seminars based on outputs from the project will also be presented at the 2018 Regional Research Seminars. These seminars will include an overview of the outputs of the whole project and discussion on the studies into the use of low pressure vapour on the pan stage.

Table 2 Project industry engagement

Year of seminar	Main topics
2016	<p>Overview of the blueprint project (information from overseas factory visits in South Africa, Mauritius, Reunion, India; Kestner evaporators, their designs, performance and costs relative to Robert evaporators; discussion on steam efficient technologies being used in overseas factories).</p> <p>Sucrose losses in Australian evaporator stations (results of trials in the 2015 seasons at two factories; presence of low pH condensates; financial implications).</p>
2017	<p>Suitability of falling film tube evaporators for Australian factories (designs; designs of distributors; heat transfer performance; scaling rates; efficiency of cleaning; capital cost relative to Robert evaporators; control and operation)</p> <p>Sucrose losses in Australian evaporator stations (results of trials in the 2015 and 2016 seasons at five factories; effect of juice pH and scale; presence of low pH condensates; compositional changes in juice and condensates through the evaporators; financial implications).</p> <p>Technologies to reduce process steam consumption (various types of juice heaters, using flash vapour from condensate, pre-conditioning of molasses supplies to pans; high pressure vapour in the final effect; simulation of using the new technologies into four Australian factories).</p> <p>Impact of low pressure vapour on pan stage productivity (description of the problem; options for boosting productivity; description of the dynamic SysCAD model).</p>

Other than the presence of the SRA Communications staff at the Regional Research Seminars there has been no communication with the SRA Adoption staff regarding the project.

The following conference papers have been presented:-

- Rackemann, DW, Broadfoot, R, 2016, Evaluation of sucrose loss in evaporators of different processing configurations, In *Proceedings International Society of Sugar Cane Technologists*, 29, pp 262-271.
- Rackemann, DW, Broadfoot, R, 2017, Effect of operating conditions on sucrose losses in evaporators in Australian factories, In *Proceedings Australian Society of Sugar Cane Technologists*, 39, pp 435-444.
- Broadfoot, R, Rackemann, DW, 2017, Direct contact juice heating – when to use and when not to use. In *Proceedings Australian Society of Sugar Cane Technologists*, 39, pp 427-434.

The following papers have been prepared for presentation at the 2018 Conference of the Australian Society Sugar Cane Technologists:

- Broadfoot, R, Rackemann, DW. Implications of using condensate cigars on factory operations.
- Broadfoot, R, McFeaters, J. Predicting batch pan operation when using low pressure vapour.

4.3. Industry communication messages

The main message from the project is that overseas factories are using several technologies that allow the factories to reduce their process steam consumptions to very low levels, *e.g.* lower than 32% on cane. Australian factories are advised to consider the application of these technologies when planning factory upgrades or replacement of existing equipment as these technologies will likely provide benefits of increased crushing rate, improved sugar recovery and be suitable for reducing the process steam consumption if and when required.

This project provides a blueprint of these technologies which allows Australian mills to make informed decisions and financial justifications on the suitability of these technologies for their factories.

4.4. Examples of adoption by industry

As previously listed the industry has already adopted changes associated with the work undertaken in this project. These examples include:-

- Through awareness of the magnitude of sucrose losses in Robert evaporators in steam efficient configurations, factories have adjusted the pH of their clarified juice and are monitoring closely the juice levels in the front end evaporators;
- An Australian factory is installing a falling film tube evaporator to replace a Robert evaporator at the front end of the set. As stated above, it is likely that this decision was made without reference to the outputs of this project as SRA milestone reports are not provided to factories. However, the presentations at the Regional Research Seminars would have benefited the sugar company in obtaining a better understanding of the application of falling film tube evaporators;
- An Australian milling company has requested QUT to design replacement batch pans using the best available knowledge to suit operation on intermediate pressure vapour (lower than currently used in Australia but not as low pressure as used in the steam efficient overseas factories). The designs of the pans need to be suitable for retrofitting mechanical agitation in the future if lower pressure vapour is used; and
- Two of the host factories for which their process stations were modelled for potential incorporation of the blueprint technologies are planning to implement some of those recommended changes.

5. METHODOLOGY

5.1. Overview of methodology

The methodology for undertaking the project was:-

- Determine the magnitude of sucrose losses that are occurring during juice evaporation in Australian sugar factories. Australian sugar factories almost universally use Robert

evaporators and the majority of these use tubes of 44.45 mm outside diameter and 2 m length. The residence time for juice in these Robert evaporators is longer than for Kestner or falling film tube evaporators.

- Investigate the suitability of using Kestner evaporators in the evaporator stations at Australian sugar factories.
- Investigate the suitability of using falling film tube evaporators (FFTEs) in the evaporator stations at Australian sugar factories.
- Investigate the potential application of novel process steam efficiency technologies for application into Australian sugar factories.
- Undertake modelling studies for four Australian sugar factories to assess the suitability of using the alternative evaporator designs and the novel process steam efficiency technologies to suit nominated objectives for each of the factories. The nominated objectives included increasing crushing rate, reducing sucrose losses during juice evaporation and reducing process steam consumption.
- Investigate the effect on pan stage productivity (production rate and exhaustion) when using low pressure vapour for boiling the pans.
- Investigate the effects on whole of factory operations (including electricity export, surplus bagasse generation and water balance) resulting from the adoption of the new technologies into Australian sugar factories.

Details of each of these methodologies are provided below.

5.2. Determine the magnitude of sucrose losses in evaporator stations

Juice and condensate samples were collected at various locations in the Robert evaporator sets at five Australian sugar factories and were characterised to investigate the magnitude of sucrose degradation and the consequences of those degradation reactions, such as reduced pH of condensate. The factories were chosen because their different evaporator configurations allowed investigation of the impact on sucrose degradation caused indirectly by steam economy measures, such as extensive vapour bleeding (required for maximising cogeneration). Sampling was undertaken across two seasons, for different clarifier juice pH set points and whilst the evaporator sets were both clean and dirty. This test program examined the impacts of clarified juice pH and the presence of scale on the magnitude of the sucrose losses.

The test program was undertaken at Pioneer, Condong and Broadwater Mills as factories that operate with low steam on cane (high steam efficiency) and at Invicta and Isis Mills as factories with low steam efficiency, for comparison. Testing involved obtaining composited samples of juices and condensates from along the evaporator set and analysing pH, solids concentration, organic acids, colour and sugars. Sucrose loss was determined by changes in glucose% sucrose, glucose% brix and glucose% chloride ratios. The glucose% sucrose method was found to be most reliable and reproducible in measuring sucrose losses.

Operating data (flows, juice and vapour temperatures) were collected and the test conditions (residence time, pH, temperature, and sucrose concentration) were used with the expression of Vukov (1965) (a function of juice pH, juice brix, temperature and residence time) to empirically predict sucrose losses and compare these with measured values.

The financial costs of sucrose losses in juice evaporation were determined.

5.3. Investigate the suitability of using Kestner evaporators

Kestner evaporators are long tube (~7 m long) climbing film evaporators and are widely used in several countries, mainly at the No 1 and No 2 effect position. Semi-Kestner evaporators have shorter tubes (~4.5 m) and operate on the same principle.

The investigations into the suitability of using Kestner evaporators instead of Robert evaporators in the evaporation sets at Australian factories included the following phases:-

- Literature review.
- Inspections of Kestner and semi-Kestner evaporators in factories in South Africa, Mauritius, Reunion and India to:-
 - Observe the installations;
 - Discuss design and operational features;
 - Obtain performance data including data when the set is clean or scaled; and
 - Discuss cleaning procedures.
- Simulations of the process steam usage for several factories using Kestner evaporators to allow a comparison of heat transfer coefficients (HTCs) with typical HTC values for Robert evaporators in Australian factories.
- Comparison of the magnitude of sucrose losses in Kestner evaporators compared with Robert evaporators.
- Determination of the preferred design of Kestner evaporator for Australian sugar factories.
- Estimation of the cost of fabricating Kestner evaporators and comparison with the estimated costs for fabricating Robert evaporators of the same heating surface area.

5.4. Investigate the suitability of using falling film tube evaporators

The methodology for investigating the suitability of falling film tube evaporators was similar to that used to investigate the suitability of the Kestner evaporators. The information from overseas factories was obtained at the same time as information obtained for the Kestner evaporators.

Three additional steps were included in the methodology:-

- Discussions were held with several supplier companies including those in India and BMA and IPRO in Germany.
- A questionnaire was sent to five sugar companies in India that have FFTEs. The requested information included data to allow simulation of the steam flows in the process stations and so allow calculation of the HTC values for the FFTEs. One factory has FFTEs installed at every stage of evaporation.
- Investigation of the preferred arrangements for operating FFTEs where multiple FFTEs are installed at the one effect, *i.e.* for juice flow in series or parallel arrangement.

5.5. Investigate the potential application of novel process steam efficiency measures into Australian sugar factories

The highly steam efficient factories in Reunion, Mauritius and India were inspected to obtain information first hand on their adopted processing technologies and operating procedures. Technical papers related to steam efficient measures in cane factories were also reviewed. This information was then investigated in the context of the current equipment and technologies used in Australian factories. Several of the technologies used in these steam efficient overseas factories

form part of the blueprint for Australian factories to transition to process steam on cane values of 30% and lower, when financially justified.

5.6. Implementation of novel technologies into Australian sugar factories for rate, recovery and steam efficiency benefits

While Australian factories are not currently investing to make substantial reductions in process steam consumption, some of the technologies being used in these energy efficient overseas factories may be suitable for use in Australian factories to provide capacity and operational benefits. These objectives are of immediate interest for most Australian factories. Importantly, implementation of these technologies would then suit Australian factories in the future to achieve major reductions in process steam consumption, when required.

The results of the above investigations were examined for potential application in four Australian factories to suit the specific objectives related to these factories. These studies were undertaken for the process stations at South Johnstone, Tully, Pioneer and Broadwater Mills. The chosen factories provide a range of existing configurations which collectively should provide a reasonably representative base for the conditions existing in Australian factories.

The methodology adopted for the investigations was as follows:-

- In collaboration with the mill staff obtain the details of the current equipment, operation and performance for the evaporator station, juice heaters and pan stage.
- Undertake modelling of the evaporator station and the process steam usage to define the current performance parameters.
- Determine the objectives for the upgraded factory. These objectives included changes to:-
 - Crushing rate;
 - Process steam consumption;
 - Reduction in sucrose losses in the evaporator station; and
 - Replacement or refurbishment of existing equipment.
- Model several scenarios for the upgraded process sections using traditional and new technologies. Compare the use of traditional and new technologies.
- Determine the preferred configurations for the upgraded process stations and provide recommendations for implementing the new technologies.

5.7. Investigate the impact of using low pressure vapour on pan stage productivity

Australian pan stages predominantly use large batch unstirred pans which make it difficult to reduce the process steam consumption of the factory to below ~40% on cane, as these pans typically require process steam (at 200 kPa abs) or vapour 1 (at a minimum of 180 kPa abs) for efficient operation. In general, unstirred batch pans of the conventional design in Australian factories cannot operate on low pressure vapour without incurring major operational problems such as poor exhaustions and long cycle times (or reduced capacity).

Poor exhaustion of high grade massecuites results in increased massecuite production loadings because of the increased recirculation of sucrose in the A and B molasses. Poor exhaustion of C massecuite results in increased sucrose loss to final molasses and reduced shipment sugar production.

The overseas sugar factories that operate with process steam/cane (SOC) of below 35% invariably use vapour 3 for batch pan operation and in almost all cases these pans are stirred and often utilise conditioned (slightly superheated) molasses feed. In some cases the batch pans are started on

vapour 4 and finish off the strike with vapour 3. Vapour 3 is typically at 91 kPa g (saturation temperature 97 °C) and vapour 4 at 56 kPa g (saturation temperature 84 °C).

Evaporator modelling shows that changing the vapour use on a pan stage from vapour 1 to vapour 3 reduces the SOC by ~6%, *e.g.* from 40% to 34%. The ability to operate the pan stage efficiently on vapour 3 is therefore an essential requirement to reduce the SOC of the factory to very low levels.

A dynamic model using the SysCAD software was developed to simulate batch pan operation and used to investigate the changes in pan cycle times and exhaustion of massecuites at pan drop as a function of vapour supply pressure. The modelling is considered to be a preliminary study as little data are available on the changes in evaporation rates (and hence crystallisation rates) that result when a low pressure vapour is used. The model was used to investigate typical duties for the A, B and C massecuite strikes.

The methodology adopted for the investigations was as follows:-

- Undertake literature review to determine the effects of using vapour of different supply pressures on evaporation rates and massecuite circulation rates in batch pans.
- Establish a correlation to define the expected evaporation rate in batch pans as a function of vapour supply pressure.
- Develop a dynamic model of batch pan operation using the SysCAD software. The model includes conditions to define when the crystallisation rate in the run up stage and heavy up stage may become so slow as to require the operation to be terminated.
- Use the dynamic model to simulate the operation of a typical design of batch pan when undertaking the A, B and C massecuite strikes. The simulations included operation with vapour supplies of 200, 140, 100 and 70 kPa abs.
- Use the model to determine the effects of using syrup/molasses feed of higher brix and/or at a higher temperature on the productivity of the batch pans.

This work is the first step in a planned major study to determine the preferred changes that Australian factories can make to their current suite of unstirred batch pans to allow effective operation with lower pressure vapour.

5.8. Whole of factory impacts of applying process steam efficient technologies to Australian Mills

Modelling was conducted for three scenarios at two Australian factories (Broadwater and Tully Mills) to examine the flows in the high pressure (HP) steam circuit, cogeneration power output, surplus bagasse production and changes to the water balance of the factory as a result of implementing various process steam efficient technologies.

The methodology conducted for the investigations was as follows:-

- Conduct a literature review to determine the preferred procedure to estimate the evaporation of vapour in cooling water systems (cooling towers and spray ponds). These evaporation losses to atmosphere have a strong influence on the water balance for the factory.
- Develop a SysCAD model for the boiler station to determine a correlation for the evaporation losses in wet scrubber systems as a function of the final flue gas temperature.
- Upgrade the SRI-QUT evaporator/process steam model to include a water balance of the whole factory.

- Model three scenarios for Tully and Broadwater Mills based on the work undertaken in sections 5.5 and 5.6 using the SRI-QUT high pressure steam circuit model and the SRI-QUT evaporator/process steam model. These investigations determined the impact on the high pressure steam generation, the cogenerated power output, the bagasse surplus and the water balance as a result of implementing different process steam efficiency measures.

6. RESULTS AND DISCUSSION

6.1. Overview of the results and discussion

The results from each phase of the work program have been provided in a separate comprehensive document. In many cases these documents (or the bulk of the information on the phase of work) were provided to SRA as Milestone Reports when a phase of the work program was largely completed. The template used for those reports is the standard QUT format which differs from that nominated by SRA for the Final Report.

Some of these individual documents are marked Confidential meaning that their access should be restricted to staff at Australian Sugar Mills. The main reasons for nominating Confidential are:-

- Staff at some overseas factories would prefer that the results of our assessments of their evaporator station performance were not published in an open forum.
- The reports include design recommendations for equipment which could be interpreted as providing a commercial bias to the design from a particular supplier. QUT staff was very fortunate to be given extensive operational data and design information. QUT staff would prefer to see this information restricted for the commercial benefit of Australian Mills.

The supplied separate reports have the titles:-

- FINAL REPORT 2015/043 - Develop a blueprint for the introduction of new processing technologies for Australian factories.
Appendix 1. Sucrose loss studies in evaporator stations in five Australian sugar factories
Not restricted
- FINAL REPORT 2015/043 - Develop a blueprint for the introduction of new processing technologies for Australian factories.
Appendix 2. Assessment of the suitability of Kestner evaporators for Australian sugar factories
Confidential
- FINAL REPORT 2015/043 - Develop a blueprint for the introduction of new processing technologies for Australian factories.
Appendix 3. Assessment of the suitability of falling film tube evaporators for Australian sugar factories
Confidential
- FINAL REPORT 2015/043 - Develop a blueprint for the introduction of new processing technologies for Australian factories.
Appendix 4. Potential application of novel process steam efficiency measures into Australian sugar factories
Confidential
- FINAL REPORT 2015/043 - Develop a blueprint for the introduction of new processing technologies for Australian factories.

Appendix 5. Implementation of novel technologies into Australian sugar factories for rate, recovery and steam efficiency benefits

Confidential

- FINAL REPORT 2015/043 - Develop a blueprint for the introduction of new processing technologies for Australian factories.

Appendix 6. Impact of low pressure vapour on pan stage productivity

Not restricted

- FINAL REPORT 2015/043 - Develop a blueprint for the introduction of new processing technologies for Australian factories.

Appendix 7. Whole of factory impacts of applying steam efficient process technologies to Australian factories

Confidential

6.2. Determine the magnitude of sucrose losses in evaporator stations

A comprehensive report on the results of the investigations into quantifying the magnitude of the sucrose losses that are occurring in the evaporator sets of Australian sugar factories is provided as the separate document in Appendix 1.

Introduction

Australian sugar factories almost universally use Robert evaporators for each stage of evaporation and the majority of these use tubes of 44.45 mm outside diameter and 2 m length. These Robert evaporators have large juice hold up volumes (typically 9 to 11 L per m² of heating surface area).

Sucrose losses in evaporators result from the hydrolysis of sucrose under mildly alkaline and acidic conditions, with the magnitude of the losses depending on temperature, juice pH and composition, sucrose concentration, and residence time. Other factors such as the presence of scale and the juice constituents may also influence the rate of sucrose degradation.

An assessment of the magnitude of sucrose destruction that is currently occurring in the Robert evaporators in Australian factories was undertaken. Juice and condensate samples were collected at various locations in the Robert evaporator sets at five Australian sugar factories and were characterised to investigate the magnitude of sucrose degradation and the consequences of those degradation reactions, such as reduced pH of condensate. The factories were chosen because their different evaporator configurations allowed investigation of the impact on sucrose degradation caused indirectly by steam economy measures, such as extensive vapour bleeding (required for maximising cogeneration). Sampling was undertaken across two seasons, for different clarifier juice pH set points and whilst the evaporator sets were both clean and dirty. This test program examined the impacts of clarified juice pH and the presence of scale on the magnitude of the sucrose losses.

Description of the test program

The test program was undertaken at Pioneer, Condong and Broadwater Mills as factories that operate with low steam on cane (high steam efficiency) and at Invicta and Isis Mills as factories with low steam efficiency, for comparison. Testing involved obtaining composited samples of juices and condensates from along the evaporator set and analysing pH, solids concentration, organic acids, colour and sugars. Sucrose loss was determined by changes in glucose% sucrose, glucose% brix and glucose% chloride ratios. The glucose% sucrose method was found to be most reliable and reproducible in measuring sucrose losses.

Operating data (flows, juice and vapour temperatures) were collected and the test conditions (residence time, pH, temperature, and sucrose concentration) were used with the expression of Vukov (1965) (a function of juice pH, juice brix, temperature and residence time) to empirically predict sucrose losses and compare these with measured values.

Results of the sucrose loss studies

Sucrose losses across the evaporator sets in steam efficient Australian sugar factories were found to be substantial. For the intensive testing at Pioneer and Condong Mills (sextuple effect - steam efficient factories), the predicted sucrose degradation using the Vukov expression varied from 0.91 to 1.19% and the measured sucrose loss based on glucose/sucrose was 0.52 to 1.08%. The magnitudes of the sucrose losses predicted by the Vukov correlation were ~20-40% larger than the measured losses. Over 50% of the total measured and predicted sucrose loss occurred across the No 1 effect and 70-90% across the first two effects. These large sucrose losses are attributed to the use of large Robert evaporators at the front end of the set (providing long juice residence times) and the high boiling temperatures in the No 1 effect due to the process steam supplied to the calandria of No 1 effect being at ~125 °C saturation temperature.

Slightly lower predicted sucrose degradation of ~0.5% and measured sucrose losses of ~0.3% were determined for the quintuple steam efficient factory (Broadwater Mill). The predicted sucrose losses across the evaporator sets at Isis and Invicta Mill (<0.2%) were much lower than at the steam efficient Australian sugar factories.

Other evidence of sucrose degradation occurring at the evaporator station was given by: (i) large pH drop from ESJ to syrup; (ii) small increase in colour (measured at pH 4) and increase in Indicator Value across the set; (iii) large decline in condensate pH across the set; and (iv) presence of acetic acid in the condensates.

Juice pH, temperature and residence time were found to impact substantially on sucrose degradation rates. A number of operational strategies and equipment options that can be implemented by factories were then examined and modelled to propose recommendations on ways that such large losses during juice evaporation can be reduced. A sensitivity analysis of parameters used in the Vukov expression showed that reducing residence time and juice temperatures in the first effects have the greatest impact on minimising the predicted sucrose loss across the evaporator station. It appears that the pH of the ESJ should be increased from typical values of ~7.2 at 20 °C so that the syrup pH at the final effect boiling temperature is 6.3 to 6.5. Based on data obtained during the trials it appears that an ESJ pH of ~8.1 at 20 °C would be required to achieve this target. This operational change should result in a substantially lower sucrose loss (~20% reduction). However, the increased lime usage may result in increased scaling in the evaporators so further trials are warranted to determine the recommended ESJ pH.

Application of the Vukov expression to the juice conditions in the incubator tank indicate that partial liming at the mixed juice tank should be undertaken to limit the extent of sucrose losses that occurs when juice pH is <5, which is most likely to occur when processing stale cane.

From the limited number of tests with the clean and dirty sets and the inherent variability in the measured values it appears from this work that the presence of scale increases the sucrose degradation rate. Trends observed at Broadwater Mill, where substantial superheat of the low pressure steam supply to the first effect was occurring, suggest that the large superheat leads to higher measured sucrose losses in the first effect.

Financial implications of sucrose degradation

Australian Mills need to seriously consider the potential sucrose losses that may be occurring in the evaporator stations under these current arrangements and determine how to best achieve production and efficiency targets while containing these losses to acceptable levels. The study has determined that a sucrose loss of 1% across the evaporators would likely cause a 1.6% reduction in sugar production compared with a factory operating with a 0.1% sucrose loss at the evaporators. The reduction in annual revenue for an Australian factory processing 1.5 Mt cane per season would be ~\$1M. Thus, when planning changes to improve factory energy efficiency and reduce the steam consumption, predictions of sucrose loss for the upgrade options need to be considered in the financial analysis. These options may include falling film tube and/or Kestner evaporators at the first effect (and perhaps second effect), as these technologies have much shorter residence times for juice, and losses should be substantially reduced. Consideration should also be given to the use of Robert evaporators with tubes of smaller diameter and greater length than the Robert evaporators conventionally used by the industry. Other than sugar losses, the decision on appropriate evaporator technology would be based on capital costs, footprint availability and operating issues (e.g. ease of cleaning and robustness of control to handle process variations, de-entrainment efficiency of juice droplets from vapour).

The investigation has highlighted the potential for large sucrose losses in the evaporator station under adverse conditions, the associated reduction in revenue from sugar sales, and considered design and operational changes that may be employed to best achieve production and efficiency targets, while containing sucrose losses in the evaporators to acceptable levels.

Other consequences of sucrose degradation and need for follow on studies

The investigations also highlighted the prevalence of low pH vapours and condensates in steam efficient factories which cause substantial corrosion of mild steel pipes, valves and tube plates or are transferred to the condenser and increase the organic loading on the cooling water system (with increased chemical dosing demand). The acidic components are volatilised from juice but the origin of their formation is not known. The concentration of organic acids in vapour condensates was too high to be based solely on sugar degradation pathways. Characterisations of the components in vapour and vent streams of evaporator installations that utilize high temperature steam and conventional lower temperature steam are required to elucidate the mechanisms and initiation of acid formation reactions. These investigations are now being undertaken in a follow on project with SRA viz., "SRA 2017/007 Investigations to mitigate the effects of juice degradation in factory evaporators on sugar recovery and quality, corrosion and effluent organic loading".

Increased knowledge of degradation and acid formation reactions is required in order to develop methods of reducing, mitigating or eliminating these reactions and to minimise the detrimental impacts that are currently experienced (and are more pronounced in high steam efficient factories).

6.3. Investigate the suitability of using Kestner evaporators

A report on the results of the investigations into assessing the suitability of Kestner evaporators for Australian sugar factories is provided as the separate document in Appendix 2.

Introduction

In the period 2 November to 12 November 2015 Darryn Rackemann and Ross Broadfoot visited Komati, Pongola and Felixton factories in South Africa; Le Gol and Bois Rouge factories in Reunion; and Alteo and Omnicane factories in Mauritius with the purpose of obtaining a better understanding

of the design, installation procedures and operating performance of Kestner and falling film tube evaporators. Subsequent visits were undertaken to Senapati and KPR factories in India in February 2016 for the same purpose. The report in Appendix 2 describes the observations on the Kestner and semi-Kestner evaporators.

Description of Kestner evaporators in the cane industry

Kestner evaporators (with ~7 m long tubes) are considered to be viable at only No 1 and No 2 effect positions. The favoured design for Kestner evaporators into Australian mills is a design with vapour/juice de-entrainment integrated into the head space of the vessel rather than a Kestner evaporator with independent separator. A recommended design concept for an integrated Kestner evaporator has been proposed. Semi-Kestner evaporators with tubes ~4.5 m long may be feasible at No 3 effect if the vapour condensation coefficient (VCC) is consistently at or above 20 kg/h/m².

Main outcomes of the investigations

Simulations of the heat transfer performances of the evaporator stations were undertaken for the factories visited and the data compared with the heat transfer results for seven Australian factories. On average, for No 1 effect, the heat transfer coefficients for Kestner evaporators appear to be 15% lower than is typical for No 1 effect Robert evaporators in Australian mills. For No 2 effect, the heat transfer coefficients appear to be 10% lower. The apparently superior HTC performance of the Robert evaporators in Australian factories is even more substantial when it is considered that Australian factories typically operate for two weeks (or longer) between chemical cleans whereas the majority of the Kestner vessels were cleaned weekly.

The investigations did not determine a clear understanding of the scaling propensity of Kestner evaporators but it appears that scaling is faster than is experienced with Robert evaporators in Australian factories. This observation may be a consequence of the composition and concentration of scaling compounds in the juice supply in factories in South Africa, Reunion, Mauritius and India compared with those in Australian factories.

The attractive features of Kestner evaporators (tubes 7.2 m long and 44.45 mm outside diameter) for Australian factories compared with Robert evaporators (with standard tubes of 2 m length tubes and 44.45 mm outside diameter) are:-

- Lower capital cost for the same heating surface area. The Kestner design with integrated vapour de-entrainment system is estimated to be cheaper than a Robert evaporator by 20% for 2000 m² vessels and by 27% for 5000 m² vessels. The total mass on foundations for an integrated Kestner evaporator is ~80% of that for a Robert evaporator of the same heating surface area.
- Kestner evaporators with integrated separator have a substantially smaller footprint than Robert evaporators. The diameter of the integrated design of Kestner evaporator is ~62% of the diameter of a Robert evaporator of the same heating surface area, and
- Shorter residence time and hence reduced extent of sucrose degradation. The juice hold up volume in a Kestner evaporator is ~33% of the juice hold up volume in a Robert evaporator of the same heating surface area. This difference is consistent for all heating surface areas. The smaller juice hold up volume in the Kestner evaporator results in a much shorter residence time for juice at the boiling conditions. In fact the reduction in residence time is likely to be even greater than indicated by the reduction in juice hold up volume as the juice

flow in Kestner evaporators is defined more by the inflow rate of juice rather than the outflow rate of juice, which is considered appropriate for Robert evaporators.

When determining the suitability of a Kestner evaporator for No 1 or No 2 effect positions the assessment needs to consider the above listed advantages and the likely disadvantage of lower HTC performance compared with a Robert evaporator. Unfortunately scaling rate was not definitively determined but it appears that scaling rate is likely to be faster than for a Robert evaporator.

For evaporators at the No 1 and No 2 effect positions the effect of the slightly reduced HTC needs to be considered in terms of:-

- Effect on juice processing rate for the set. The reduction in juice processing rate for the set is likely to be relatively small as the temperature differences on the vapour side at the early effects are small in comparison with the tail of the set; and
- Effect on the temperature of the vapour bleed to the heaters and pans. The importance of reductions in vapour temperature depends on the specific configuration for juice heaters, evaporators and pans at the factory.

The impact of a slightly larger temperature difference on the vapour side of a Kestner evaporator could be negated by providing additional heating surface area, as long as the vapour loading is sufficiently high to generate climbing film boiling for the full height of the tube. For No 1 effect and No 2 effect positions vapour loading values greater than 20 kg/h/m² are usually employed so this requirement will almost always be satisfied.

Staff in overseas factories that had experience with both Kestner and falling film tube evaporators consistently favoured the falling film tube design as it provided greater robustness in control and operation.

Overall assessment

As part of the project, modelling of the configurations at four Australian factories was undertaken to assess the implications of installing Kestner evaporators or falling film tube evaporators at No 1 effect, No 2 effect or at both positions (refer Appendix 4). The recommendation was that Australian factories may be better installing falling film tube evaporators instead of Kestner evaporators in those circumstances where short residence times are sought because falling film tube evaporators offer additional advantages over Kestner evaporators, including being able to be used at all effect positions. Robert evaporators are recommended at all effect positions including at No 1 and No 2 effect when the processing conditions are not conducive to substantial sucrose degradation.

6.4. Investigate the suitability of using falling film tube evaporators

A report on the results of the investigations into assessing the suitability of falling film tube evaporators for Australian sugar factories is provided as the separate document in Appendix 3.

Introduction

Falling film tube evaporators (FFTEs) have been widely adopted by the beet sugar industry for several decades and many beet factories have installed complete falling film evaporator stations, including stations comprising six and seven effects. Currently it is estimated that there are more than 350 FFTEs in the cane sugar industry and good reports are being provided. It appears that, for the newer installations, the earlier difficulties with encrustation and caramelisation on the juice side, and entrainment of juice in vapour streams have been overcome. The problems with FFTEs in the

cane industry have been mainly attributed to the increased scaling propensity of cane juice compared with beet juice.

As part of this investigation into the suitability of FFTEs for Australian factories, FFTEs were inspected in South Africa, Reunion, Mauritius and India. As well, completed questionnaires were provided by five Indian factories concerning their experiences with FFTEs. Heat transfer performance data were obtained for these factories and modelling has been undertaken to provide estimates of HTC for the FFTEs at each of the factories. As part of the project, discussions were held with several manufacturers of FFTEs. The investigations concentrated on heat transfer efficiency, scaling, suitability for chemical cleaning, de-entrainment of juice from the vapour stream and robustness in control. An estimation of the installation costs for FFTEs compared with Robert evaporators has also been made.

Description of FFTEs in the cane industry

The designs of FFTEs in cane factories most commonly use heating tubes of 35 or 45 mm outside diameter, 10 to 12 m long, 1.2 or 1.5 mm thick and made from SS 304 or SS 439.

One of the key requirements for effective operation and performance of FFTEs is to provide uniform and adequate wetting of the inside of each tube with a film of juice. Different designs of juice distributor are used by the various manufacturers and most (almost all) use multiple stages of distribution to provide uniform wetting of the tube surface. Most designs of distributor aim to place the juice uniformly onto the ligaments of the top tube plates to allow flow as a film onto the inner surfaces of the tubes rather than into the tube openings.

The required rate at which juice is pumped to the top of the distributor to satisfy the wetting number generally exceeds the inflow of juice (slightly for evaporators at the front of the set and to a large extent for FFTEs at the tail end of the set). Thus some of the juice that has passed down the heating tubes is mixed with the inflow juice to be returned to the juice distributor. Emergency water is supplied to the juice entry pipe at the top of the FFTE to ensure wetting of the tube surfaces is maintained at times of low juice circulation flow. The emergency water supply to early vessels in the set should be hot water (temperature $>90\text{ }^{\circ}\text{C}$) so that severe water hammer and thermal shock does not occur when the water is supplied.

Main outcomes of the investigations

The main conclusions from the investigations are summarised below:-

- FFTEs are able to operate with lower ΔT s than Robert evaporators owing to the guaranteed wetting of the tube surface. For the same reason FFTEs are able to operate with large turndown in terms of juice processing rate (*e.g.* to 20% of design rate).
- The heat transfer coefficients for FFTEs appear to be similar to those for Robert evaporators at No 1 and No 2 effects. For No 3 effect the HTC values for the FFTEs were slightly lower than for Robert evaporators but the vapour loadings were also lower than typical of operation of Robert evaporators.

The operating conditions for FFTEs at the tail end of the set were mostly for very low vapour rates and, for the factories included in the assessment, only a few FFTEs were operating at these positions. Comparisons of HTC values for No 4 and 5 effects to typical Robert values in Australian factories are not reliable.

- The experience, mostly obtained on juice sulphitation factories, is that chemical cleaning is required every 20 days for No 1 effect, 10 to 15 days for No 3 effect, and 5 to 7 days for the

final effect. A high pressure water clean is generally not required during the season for the early effects but is likely to be required for the final and penultimate effects after every second or third chemical clean.

The chemical cleaning procedures for FFTEs are similar to those commonly used for chemical cleaning of Robert evaporators. After a chemical clean any loose scale must be removed.

- The residence time for juice is about 1/3rd that of a conventional Robert evaporator of comparable heating surface area. As a result substantially less sucrose degradation would occur for FFTEs at the 1st and 2nd effects when boiling at high temperature.
- Most (virtually all) installations of FFTEs use a fixed speed drive on the juice recirculation pump and use a magnetic flow meter in the juice line for monitoring and alarms (*e.g.* to trigger the emergency water supply).
- The cost of constructing a FFTE comprising tubes of 44.45 mm outside diameter 10 m length is estimated to be between 16% and 27% cheaper than a Robert evaporator with the conventionally used tube (*viz.*, 44.45 mm outside diameter and 2 m length) of the same heating surface area. These savings correspond to evaporators with heating surface areas of 2000 m² and 5000 m² respectively. Larger cost savings were determined for the vessels of larger heating surface area.
- Most overseas installations of FFTEs include spare evaporator vessels so that when FFTEs are taken off line for cleaning the factory continues crushing, although maybe at reduced rate. Some manufacturers recommend that it is preferable to install two smaller FFTEs rather than one large FFTE at an evaporator stage. Series flow of juice through the two evaporators is recommended.

All factories with FFTEs that were contacted were satisfied with the performance and operation of the FFTEs. Those with no FFTE at the tail end were concerned about scaling in FFTEs in the tail end, while those factories with FFTEs at the tail end thought the scaling and chemical cleaning was manageable.

Overall assessment

The overall assessment is that FFTEs present an attractive alternative to Robert evaporators for Australian factories, particularly for evaporator stages #1 to #3. The strong attraction for FFTEs in No 1 and No 2 evaporator positions is to reduce the sucrose loss through degradation when these evaporators are operating at high boiling temperatures, such as in configurations where high exhaust steam pressures are used for steam efficiency reasons.

FFTEs also provide benefits compared with Robert evaporators for installation at the tail end of the set but it appears that high scaling rates are likely to be experienced. Standby vessels (perhaps existing Robert vessels) would likely be required at the final effect, and penultimate effect positions.

Recent investigations into the costs and juice volume intensities of Robert evaporators comprising tubes of smaller diameter (*e.g.* 38.1 mm outside diameter) and greater length (*e.g.* ~3 m length) than conventional Robert designs have determined that substantial cost savings and reduced residence times can be achieved. These designs of Robert evaporators should also be considered for No 1 to No 3 effect positions when selecting the design for an upgrade to an evaporator station. The assessment has shown that FFTEs still provide shorter residence times for juice than the Robert evaporators with smaller diameter and longer tubes.

One of the challenges in selecting the appropriate evaporator design is that the service life for the evaporator (typically 30 years) is likely to exceed the current plans for the factory with respect to

steam efficiencies. All potential configurations for the factory's process stations need to be considered when investing in major upgrades to the evaporator station.

The robustness of the design and operation of Robert evaporators will likely mean that Robert evaporators (perhaps with smaller diameter and longer tubes) will continue to be favoured by Australian factories for new installations except where the factory is targeting low steam consumption operation (or may target low steam consumption in the foreseeable future). FFTEs are favoured in these circumstances.

FFTEs may also be favoured at the tail end of the set in highly steam efficient configurations as vapour rates at the end of the set are very low. Robert evaporators when operated at low vapour rates experience poor mixing, poor heat transfer and are prone to heavy scaling and encrustation. The guaranteed wetting of the heating surface in FFTEs is an advantage compared with the rising film boiling action in Robert vessels under these circumstances.

6.5. Investigate the potential application of novel process steam efficiency measures into Australian sugar factories

A report on the results of assessing the suitability of novel steam efficiency technologies for Australian sugar factories is provided as the separate document in Appendix 4.

Introduction

The process steam configurations for eleven overseas sugar factories that achieve high levels of process steam economy were reviewed and have been described. These factories are located in Reunion, Mauritius and India.

Each of the steam economy measures that are being used in these overseas factories has been considered in terms of their advantages and disadvantages and potential application into Australian factories. The technologies which are discussed in the report in Appendix 4 include:-

- Flashing of vapour from condensate for use in subsequent stages of evaporation;
- Conditioning of molasses prior to feeding pans;
- Use of direct contact juice heaters;
- Use of juice heaters installed in the vapour line between the final effect and condenser;
- Use of condensate for heating juice;
- Use of vapour 3 (and vapour 4) for boiling pans;
- Use of Barriquand (welded plate) juice heaters;
- Recovery of heat from vapours flashed from juice in the clarifier flash tank;
- Use of a high final vapour temperature;
- Use of a low process steam temperature supplied to the first effect; and
- Use of falling film tube evaporators in steam efficient factories.

Overall assessment

There is no technical or major financial impediment to the adoption of each of these technologies into Australian factories apart from the use of vapour 3 (and vapour 4) for boiling pans. The typical Australian pan stage comprises large, unstirred batch pans and these will not be suitable for boiling with vapour 3. An assessment of the implications of using low pressure vapour in batch unstirred pans has been undertaken and is reported in Appendix 6. The future operation of Australian pan stages on low pressure vapour such as vapour 3 (or vapour 4) is a major challenge and further research is recommended to develop the most cost effective solutions.

Other matters that have been considered include the likely changes in scale formation rates and scale composition in evaporators, management of ethanol loadings in condensate, and the production of low pH condensate associated with adoption of some of these steam efficient technologies.

Several of the technologies adopted in the highly steam efficient cane factories in Reunion, Mauritius and India will very likely be adopted by Australian factories especially when these factories progress to lower process steam consumption rates than at present.

The information provided in Appendix 4 will assist in the planning, implementation and operation of these technologies.

6.6. Implementation of novel technologies into Australian sugar factories for rate, recovery and steam efficiency benefits

Modelling was undertaken for four Australian factories (South Johnstone, Tully, Pioneer and Broadwater) to determine appropriate upgrades of the process stations at the factories to suit the individual factories' nominated processing objectives. A report on the results of the modelling is provided as the separate document in Appendix 5.

Nominated processing objectives

The target objectives for upgrading the process stations differed among the factories and collectively included:-

- Increase in crushing rate;
- Reduction in process steam consumption;
- Reduction in sucrose loss in the evaporators; and
- Increase in the pressure of the bleed vapour to the pan stage.

It should be noted that, while the processing objectives were nominated by factory staff, they do not necessarily represent the immediate objectives for the factories.

By undertaking the assessments for four factories the investigations have considered changes for widely different existing process configurations.

General comments on the recommended technologies

The technologies which have been recommended to satisfy the new objectives include further implementation of technologies currently used in Australian factories, *e.g.* juice heating using vapour from late in the set, using vapour from the evaporators for pan boiling, flashing of vapour from evaporator condensate in order to increase vapour flows late in the set, conditioning of the molasses feed to continuous and batch pans.

New technologies which have been recommended include falling film tube evaporators, use of Barriquand juice heaters and the flashing of vapour from pan and heater condensates to evaporator calandrias.

In all factories where an increase in heating surface area is required at No 1 effect the installation of an FFTE has been recommended because of the much shorter residence time and the reduced sucrose loss that would be encountered. The benefit of the FFTE at No 1 effect is greater for those situations where the exhaust steam temperature is high, *e.g.* 124 °C and higher. The residence time

for juice in a FFTE is about $1/3^d$ (and less) than that of a Robert evaporator with conventional tube dimensions.

An alternative to the FFTE is to use a Robert evaporator comprising longer tubes of smaller diameter, *e.g.* 3 m length and 38.1 mm outside diameter rather than the conventional tubes, as evaporators with these tubes have substantially less juice hold up volume (*e.g.* 6.5 L/m² compared with ~10 L/m²). Nevertheless the residence time is still longer in the Robert evaporator than in a FFTE as the juice hold up volume is still larger.

List of recommended process changes for the individual factories

Table 3 lists the recommended changes to the process stations for the four factories. The changes that are recommended among the factories differ not only because of the different objectives for the upgrades but because of the differences among the existing configurations. The future service lives of existing evaporators were also a consideration.

Table 3 Summary of target objectives and recommendations for the four Australian factories

Factory	Target objectives	Recommended changes
Tully	<p>Increase crushing rate by 8%.</p> <p>Increase syrup brix.</p> <p>No increase in exhaust steam temperature.</p>	<p>Install a new clarified juice heater.</p> <p>Install a 5000 m² FFTE at No 1 effect.</p> <p>Install pipework to supply vapour 1 to the pan stage (for 55% of the total pan stage steam consumption).</p> <p>Install a conditioning system for the A molasses feed to the continuous B pan.</p>

Factory	Target objectives	Recommended changes
Broadwater	<p>Increase crushing rate by ~50%.</p> <p>Reduce process steam consumption.</p> <p>Reduce sucrose loss in evaporators.</p>	<p>In order to satisfy the other objectives and achieve a reduction in SOC of 2.9% the following changes are recommended:-</p> <ul style="list-style-type: none"> • Install a 5000 m² FFTE evaporator at No 1 effect. The configuration of the evaporator set is kept as a quintuple set. • Remove the current No 3 effect vessel. • Replace the calandria in the current Robert No 2 effect vessel (now No 3 effect) with a calandria of longer smaller diameter tubes to increase the heating surface area. • Replace the current No 5 effect vessel with a FFTE of 2500 m² which will allow this vessel to operate with a much smaller ΔT_{eff}. • Install a pipe system to supply vapour 2 to the high grade pans. • Upgrade the capacity of the primary, secondary and clarified juice heaters for the increased rate. <p>In order to satisfy the other objectives and achieve a reduction in SOC of 5.4% the following additional changes to the above configuration are recommended:-</p> <ul style="list-style-type: none"> • Increase the use of low pressure vapour for juice heating. • Operate the total pan stage on vapour 2. • Install a condensate cigar to provide flash vapour to the calandrias of No 3, 4 and 5 effects.

Factory	Target objectives	Recommended changes
<p>South Johnstone</p>	<p>Increase crushing rate by ~16%. Reduce process steam consumption. Reduce sucrose loss in evaporators.</p>	<p>In order to satisfy the other objectives and achieve a small reduction in SOC (by 1.6%) the following changes are recommended:-</p> <ul style="list-style-type: none"> • Upgrade the clarified juice heater for operation on vapour 1. • Install a 5000 m² FFTE at effect#1 to operate in series with the existing No 1 effect. • Replace the calandria in the current Robert No 2 effect vessel with a calandria of longer smaller diameter tubes to increase the heating surface area. • Upgrade the primary juice heaters to handle the increased rate. • Upgrade the secondary juice heaters to handle the increased rate and use vapour 2 and vapour 1. A Barriquand heater may be appropriate. • Increase the capacity of the pan stage for the increased rate (probably by installing a continuous C pan). The pan stage will continue to be operated on exhaust steam. <p>In order to satisfy the other objectives and achieve a reduction in SOC of 5.6% the following additional changes are recommended:-</p> <ul style="list-style-type: none"> • Increase the exhaust steam saturation temperature to 124 °C (from 120 °C). • Provide a pipe system to operate the whole pan stage on vapour 1 (~75 kPa g). • Upgrade the performance of the existing pans to maintain productivity on the lower pressure vapour supply. • Upgrade the primary juice heaters to use vapour 4 and vapour 3 in non-contact heaters. A two stage Barriquand heater may be appropriate. • Install a throttle valve between No 1 and No 2 effects in order to control the vapour 1 pressure to suit the pan stage.

Factory	Target objectives	Recommended changes
Pioneer	No increase in rate. Reduce process steam consumption. Reduce sucrose loss in the evaporators (target to halve loss). Increase production capacity of the pan stage which is lagging at the current vapour pressure of 80 to 85 kPa g.	Install a Barriquand two stage heater for clarified juice heating using vapour 2 and vapour 1. Install a continuous pan to use 30 t/h of vapour 2 (pressure 20 kPa g). [Instead of the continuous pan on vapour 2 a similar result could be achieved by installing a 2500 m ² FFTE as a final effect to replace the two existing Robert evaporators. The pan stage would continue to operate on vapour 1]. Install stirrers, jigger system and molasses conditioning system on the pan stage to allow operation with vapour 1 at 70 kPa g pressure. Exhaust steam saturated temperature reduced from 124 to 121 °C and sucrose loss estimated to reduce by 0.27% from current operation. Consideration should be given to moving the throttle valves on the vapour lines to the manifolds after the pre-evaporators as this provides a further reduction in sucrose loss (up to 0.1% reduction).

General comments on the upgrade options

For all four factories it is envisaged that the pressure of the vapour supply to the pan stage will ultimately be reduced. The use of bleed vapour of lower pressure on the pan stage (*e.g.* sourced from later in the set) is effective in increasing the juice processing rate of the evaporators and also reducing the process steam consumption. However it is inevitable that any reduction in the pressure of the vapour supply to the pans will reduce the productivity (rate and exhaustion) and may adversely affect the sucrose recovery from final molasses. Measures will need to be implemented to alleviate the effects of low pressure vapour to the pan stage. These measures are discussed in Appendix 6.

The use of a FFTE at the final effect position is a technically feasible option for Broadwater and Pioneer Mills. In both cases the advantage of the FFTE over a Robert evaporator at the final evaporation stage is the ability to operate at much lower ΔT than a Robert evaporator. For Broadwater Mill the attraction was a substantial increase in juice processing rate. For Pioneer Mill the benefit was the reduction in sucrose loss in the Robert evaporators at the front of the set, by being able to reduce the pressure of the exhaust steam, and still maintain juice processing rate. An associated problem with this solution is that the vapour pressure to the pan stage is reduced, thus requiring investment in measures to maintain pan stage productivity.

None of the investigations recommended heating primary juice with condensate but this is an option that could be considered for further reductions in process steam consumption. This latter option often results in a reduction in the juice processing capacity of the set where condensate is used instead of vapour taken from an evaporator late in the set. Also the use of a vapour line juice heater was not recommended for any of the four factories for their nominated objectives. This is primarily because for each factory the current configuration uses a relatively high vacuum on the final effect and so the final vapour temperature is too cool to provide a viable increase in the primary juice

temperature. The use of a vapour line juice heater may be attractive where the upgrade provides for a higher final vapour temperature. An assessment for Tully Mill for operation at a low SOC included a vapour line juice heater on the final vapour.

The magnitude of the sucrose losses in the evaporation station is an important financial consideration. For each factory the estimated sucrose losses for current operation and for the changed configurations were calculated and are provided in Appendix 5.

6.7. Impact of low pressure vapour on pan stage productivity

A report on the results of the investigations of using low pressure vapour on the pan stage is provided as the separate document in Appendix 6.

Introduction

Australian pan stages predominantly use large batch unstirred pans which make it difficult to reduce the process steam consumption of the factory to below 38 to 40% on cane, as these pans typically require process steam (at 200 kPa abs) or vapour 1 (at a minimum of 180 kPa abs) for efficient operation. Evaporator modelling shows that changing the vapour use on a pan stage from vapour 1 to vapour 3 reduces the steam/cane by ~6%, *e.g.* from 40% to 34%. The ability to operate the pan stage efficiently on vapour 3 is therefore an essential requirement to reduce the SOC of the factory to very low levels.

This phase of the project investigated the expected changes in batch pan productivity, through changes in cycle times and exhaustions, when the typical Australian batch pans are operated with vapour supplied at a range of pressures. This work is the first step in a planned major study to determine the preferred changes that Australian factories can make to their current suite of unstirred batch pans to allow effective operation with lower pressure vapour.

Development of a dynamic model of a batch pan

A dynamic model in SysCAD was developed to allow the syrup/molasses feed on operations and heavy up operations of a batch pan to be modelled to determine the effects of using vapour supply at different pressures. The model is comprehensive in that it incorporates sugar specific physical properties models, detailed geometry, integrated models for crystallisation, heat transfer and evaporation rate, superheat and industrial type PID control. The physical model is solved exactly at every time step.

The dynamic model was developed for a batch pan of 100 m³ massecuite volume. The design of this selected pan is considered to be typical of a well designed straight sided, fixed calandria unstirred pan currently used in the Australian sugar industry. The dynamic model incorporates the control loops of head space pressure, steam flow control and syrup/molasses feed rate control to a defined crystal content profile and so replicates the actual controls on a factory pan. The model runs at 1/600 of the speed of a factory batch pan and so provides trends of data for an A massecuite at a supply pressure of 200 kPa abs in less than 30 seconds. The run speed is adjustable.

Control logic has been incorporated in the model to activate termination conditions for (1) the feed of syrup/molasses when the feed on rate or crystallisation rate is uneconomically slow; and (2) the heavy up step when the rate of brix increase in heavy up or crystallisation rate is uneconomically slow.

No data were found in the literature to define the evaporation rate (or heat transfer coefficient) for a natural circulation batch pan for a range of supply vapour pressures including low pressure vapour.

A correlation developed in a pilot vacuum pan over 30 years ago was modified based on the expected performance in factory pans for operation with vapour through a range of supply pressures.

Results of applying the dynamic model to Australian pan boiling duties

Modelling of typical A, B and C massecuite strikes was undertaken for vapour supply at 200, 140, 100 and 70 kPa abs. The results are a good approximation of industrial behaviour, for the known performance with steam supply at 200 kPa abs. As expected, when a lower pressure vapour is used, a greater proportion of the run up of the pan is evaporation limited.

The modelling results have reinforced the practical observations that, when using lower pressure vapour, reduced evaporation rates slow the crystallisation rates, increase boil on times, slow the heavy up process, increase the total cycle times and lead to reduced exhaustion of the product massecuite (depending on the specified termination conditions). With low pressure vapour supply the boil on rates and heavy up rates may become so slow that these operations are terminated prior to reaching pan full or a target dropping brix, in order to maintain the productivity of the whole pan stage.

The results showed that the use of low pressure vapour has a greater influence on the productivity of pans boiling massecuites of higher viscosity, *i.e.* C massecuite more than B massecuite and B massecuite more than A massecuite. This observation is in line with industrial experience and expectations.

For the nominated termination conditions the simulations showed that the pan is able to operate to 100% full and complete the strike to the dropping condition for the four selected vapour pressures for all three grades of massecuite. This result is considered to be incorrect for the runs with 100 and 70 kPa abs and is a consequence in part of the nominated termination conditions. Factories commonly experience reductions in pan stage productivity if the pressure of the vapour supply reduces by more than 10 to 20 kPa, say from 180 to 160 kPa abs. Most likely B and C massecuites could not be boiled satisfactorily in terms of run up rate and heavy up rate for vapour at lower pressure than 140 kPa abs. It is also likely that most A massecuite batch pans in the industry would find difficulty in achieving adequate heavy up performance when operating with vapour supply pressure below 140 kPa abs.

There are two main reasons why the termination conditions (pan filled to 100% and massecuite at the nominated dry substance for completing the strike) were able to be reached for all three grades of massecuite, even with vapour supply as low as 70 kPa abs pressure:-

- The termination growth rates (40 $\mu\text{m}/\text{h}$ for A massecuite, 20 $\mu\text{m}/\text{h}$ for B massecuite, 5 $\mu\text{m}/\text{h}$ for C massecuite) were most likely set lower than factories could accept in a production environment.
- The sole use of an evaporation rate correlation to define pan behaviour with low pressure vapour is a gross simplification of the requirements to achieve adequate boiling. In a natural circulation pan the ebullition provides not only evaporation of water from the massecuite but affects
 - Extent of mixing of the massecuite within the pan and hence the uniformity of contents;
 - Velocity of massecuite into the base of the tubes which affects heat transfer and evaporation rate; and

- Superheat that may generate within the massecuite by virtue of slow movement of massecuite from the tube surface. Increased superheat reduces the temperature difference between the vapour in the calandria and the massecuite, and so contributes to reduced heat transfer.

There is a need to develop a parameter that defines limiting circulation movement in the pan as an additional descriptor of the effectiveness of a pan to undertake a boiling duty.

For runs with steam supply at 200 kPa abs (typical of current operation), the profiles of conductivity from the model were similar to those used by factories for current control of batch pans *viz.*, for A massecuites the conductivity profile is flat while syrup is fed, ramp down of conductivity while A molasses is fed and steep decline in conductivity during heavy up. The conductivity profiles for the B and C massecuites showed conductivity ramping down during run up to pan full and then a steep decline during heavy up.

The conductivity profiles alter when lower pressure vapour is used as the supersaturation profile is altered. The change is most pronounced for the A and B massecuite boilings.

Proposed follow on work

The work undertaken in this phase of the project was a preliminary investigation only. A proposed follow on study will involve further development of the dynamic model and importantly incorporate improved evaporation rate data and definitions for the effects of ebullition for operation with lower pressure vapour. Experimental investigations are planned on several batch and continuous pans to measure vapour rates, production rates (cycle times for batch pans) and exhaustion performance under simulated 'low pressure' conditions and observe other behaviours when using lower pressure vapours. These data will be incorporated into the model.

Another important aspect of the proposed study is to undertake CFD modelling of the circulation in batch and continuous pans using the latest version of commercially available software to simulate operation of specific factory pans with different vapour pressures. The models will be developed using the evaporation data from the factory trials. It is anticipated that the outputs of the CFD modelling will also be utilised in the improved dynamic model to better define the impact of using low pressure vapour. The CFD modelling will also investigate the effects of retrofitting stirrers and/or jigger tube systems.

The objectives of this follow on major study are to identify the most appropriate changes to pan stage equipment, operating procedures and control to minimise the capital investment required to allow operation of existing batch pans with low pressure vapour, while maintaining production performance with respect to rate, sugar recovery and sugar quality.

6.8. Whole of factory impacts of applying process steam efficient technologies to Australian Mills

A report on the results of the investigations into the impact of steam efficient processing technologies on whole of factory operations is provided as the separate document in Appendix 7.

Introduction

Modelling has been conducted to examine the flows in the high pressure (HP) steam circuit, cogeneration output, surplus bagasse production and changes to the water balance of the factory as a result of implementing various process steam efficient technologies. The assessments were based on the process configurations for Broadwater and Tully Mills. The assumptions used for the water

balance and for the boiler stations are generalisations based on typical factory arrangements and data for the different scenarios and are not specifically for Broadwater or Tully Mill.

Two conditions were modelled for the boiler station and powerhouse *viz.*, (1) Small Cogen - typical of the traditional factory arrangement with a low pressure boiler and minimal export of cogenerated power; and (2) Large Cogen - the case where a high pressure boiler is employed and cogenerated power is maximised.

Results of the modelling investigations

The results from modelling the scenarios for the different process station configurations at Tully and Broadwater Mills and combining these with the two main HP steam generation and powerhouse models have shown many and widely varying effects on the water balances of factories. For the most part these effects are well known to industry technologists in general terms. The investigations highlighted several important observations that occur when various process steam efficiency measures are implemented.

The following general observations are made:-

- The water flows in sugar factories are markedly different for situations of low process steam efficiency and Small Cogen arrangements (use of low pressure inefficient boilers coupled with steam turbine drives - the traditional sugar factory) and a factory with high process steam efficiency and Large Cogen arrangements (high pressure efficient boilers, condensing TAs and widespread use of electric drives).

The former has minimal surplus water and the potential for a shortage of water as an imbalance of high pressure steam production over low pressure steam demand requires large make-up with condensate to compensate for venting of process steam (when pan stage demand is low), high evaporation losses in process cooling towers and in wet scrubbers (if employed). These conditions can readily lead to situations of insufficient available condensate and the need to intake raw water or implement drastic steps to cut water use (*e.g.* cut maceration rates).

For factories with high process steam efficiency and Large Cogen the evaporation losses from cooling towers and wet scrubber systems are reduced, minimal venting of steam to atmosphere occurs and there is a greatly reduced demand for the available condensate. A large surplus of condensate exists and its disposal must be managed in an environmentally sustainable manner. Ideally clean surplus condensates would be cooled and used as irrigation water rather than processed in the liquid effluent treatment plants.

- For factories with low process steam efficiency and Small Cogen arrangements the need for raw water intake can be reduced by:-
 - Achieving a better balance between the HP steam demand and the low pressure steam demand through implementing more efficient arrangements in the HP circuit;
 - Using dry scrubbers instead of wet scrubbers if feasible while still meeting the air quality licence specification;
 - Minimising vent losses to atmosphere (*e.g.* by achieving a steady pan stage demand which would be assisted by using continuous pans); and
 - Reducing evaporation losses in the process cooling tower. No simple means exist to reduce the evaporation losses. Cooler water at the inflow to the cooling tower would reduce the losses (as a percentage of the inflow water rate) but this would most likely only be achieved by having a larger recirculation of cooling water in the circuit, *e.g.* to achieve an increased vacuum or to operate the condensers with a

larger approach temperature. Adoption of process steam efficiency measures that reduce the vapour flow to the effect condenser would assist.

- For factories with high process steam efficiency and Large Cogen arrangements the adoption of additional process steam efficiency measures:-
 - Provides opportunities for increased power export (estimated at 0.133 MW per unit reduction in process SOC per 100 t/h cane);
 - Increases the return of TA condensate and increases the make-up for condensate due to an increased evaporation rate in the cogeneration cooling tower; and
 - Increases or decreases the evaporation rate from the process cooling tower depending on the process efficiency procedure. Any process steam efficiency steps that increase the vapour flows to the effect condenser (*e.g.* use of condensate for heating juice instead of vapour, use of condensate flashing into subsequent evaporators) increase the evaporation at the process cooling tower. Any process steam efficiency steps that reduce the vapour flows to the effect condenser (*e.g.* use of vapour from later in the set for juice heating or pan boiling operations) reduce the evaporation at the cooling tower. The net effect of changes to the inflow of vapour to the condensers and evaporation at the cooling tower on the surplus (overflow) water in the cooling water circuit depends strongly on the temperature of the water inflow to the cooling tower as this affects the magnitude of the evaporation. For a factory crushing at 500 t/h the modelling indicates that the evaporation rate from the process cooling tower would vary by 37 t/h for the inlet temperature varying between 45 and 50 °C.
- The limited investigations in this study did not provide a consistent relationship between overflow quantity from the cooling water system versus process steam% cane as proposed by Lavarack (2001) and Wright (2016). The reason is attributed to the inclusion in this study of several variations in the HP steam system and variations in the temperature of the water inflow to the cooling tower.

Comment on the need to consider changes to the water balance of factories

The modelling has highlighted that when process steam efficient technologies are employed close consideration needs to be given to the impacts on the water balance of the factory as operational changes and capital investment may be required to mitigate any adverse effects in the water balance.

7. PUBLICATIONS

The following conference papers arising from the work undertaken in this project were published.

- Rackemann, DW, Broadfoot, R, 2016, Evaluation of sucrose loss in evaporators of different processing configurations, In *Proceedings International Society of Sugar Cane Technologists*, 29, pp 262-271. This paper was awarded the Best Paper in the Factory Commission at the 2016 ISSCT.
- Rackemann, DW, Broadfoot, R, 2017, Effect of operating conditions on sucrose losses in evaporators in Australian factories, In *Proceedings Australian Society of Sugar Cane Technologists*, 39, pp 435-444.

- Broadfoot, R, Rackemann, DW, 2017, Direct contact juice heating – when to use and when not to use. In *Proceedings Australian Society of Sugar Cane Technologists*, 39, pp 427-434. This paper was awarded the President’s Medal for Best Industrial paper at the 2017 ASSCT.

The following two papers for the 2018 Australian Society Sugar Cane Technologists Conference have also been accepted.

- Broadfoot, R, Rackemann, DW. Implications of using condensate cigars on factory operations.
- Broadfoot, R, McFeaters, J. Predicting batch pan operation when using low pressure vapour.

8. CONCLUSIONS

A comprehensive evaluation of the suitability for Australian factories of the processing technologies being used in overseas factories to reduce the process steam consumption to levels as low as 30% on cane (and lower) was undertaken.

One of the key findings was that the sucrose losses across the evaporator sets in steam efficient Australian sugar factories were found to be substantial (between 0.5 and 1% sucrose in clarified juice). These large sucrose losses are attributed to the use of large Robert evaporators at the front end of the set (providing long juice residence times) and the high boiling temperatures in the No 1 effect due to the process steam supplied to the calandria of No 1 effect being at ~125 °C saturation temperature. As a consequence evaporator designs with inherently smaller juice hold-up volumes (such as Kestner, falling film tube and Robert evaporators with longer tubes of smaller diameter) are preferred in these applications. The study determined that the falling film tube evaporator is recommended for use in Australian factories instead of the Kestner evaporator. Robert evaporators with longer tubes of smaller diameter should also be considered as a new vessel or as a retrofit to existing vessels to provide more heating area, although the juice hold-up volume is still greater than the falling film tube evaporator.

There are numerous technologies that are being used in overseas factories to reduce the process steam consumption (including options for heating juice, operating pans on low pressure vapour and recovering waste heat). The investigations have shown that is no technical or major financial impediment to the adoption of each of these technologies into Australian factories apart from the use of vapour 3 (and vapour 4) for boiling pans.

The typical Australian pan stage comprises large, unstirred batch pans and these will not be suitable for boiling with vapour 3 (pressure as low as 90 kPa abs). An assessment of the implications of using low pressure vapour in unstirred batch pans has been undertaken and showed that major reductions in pan stage productivity would occur for vapour pressures below 140 kPa abs. The future operation of Australian pan stages on low pressure vapour such as vapour 3 (or vapour 4) is a major challenge and further research is recommended to develop the most cost effective solutions.

Modelling was undertaken for four Australian factories to examine the implementation of the process steam efficient technologies for factory specific nominated objectives including to increase crushing rate, increase sucrose recovery and provide steam efficiency benefits. These four factories provided widely different existing process configurations and so provided a good representation of industry configurations. The modelling demonstrated that the novel technologies are suitable for implementation into Australian factories.

Modelling of the whole of factory operations for factories including assessments of the high pressure steam circuit, export power, bagasse surplus and water balance has highlighted that when process steam efficient technologies are employed close consideration needs to be given to the impacts on the water balance of the factory, as operational changes and capital investment may be required to mitigate any adverse effects in the water balance.

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The assistance provided by the Production Managers at Tully, Broadwater, South Johnstone and Pioneer Mills in supplying performance data and the target objectives for the modelling studies of Australian factories is much appreciated. The agreement of the managers of these companies to allow publication of the data for their factories is acknowledged.

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11. APPENDIX

11.1. Appendix 1 METADATA DISCLOSURE

Table 4 Metadata disclosure 1

Data	Data from sucrose loss trials in five Australian factories Modelling simulations for overseas factories Modelling simulations for four Australian factories Modelling of the high pressure circuit, power generation, bagasse surplus and water balance for two Australian factories Design and cost assessment of Kestner and falling film tube evaporators
Stored Location	QUT server for CTCB
Access	Restricted to CTCB staff
Contact	Ross Broadfoot/Darryn Rackemann/David Moller