Sugar Research Australia

FINAL REPORT 2020/204

INVESTIGATING THE CORROSIVITY OF EVAPORATOR CONDENSATES AND THE CONTRIBUTING FACTORS

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QUT

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ABSTRACT

Recent studies of steam efficient evaporator stations in Australian factories have shown that sucrose degradation and the subsequent formation of acids in the juice produces final evaporator condensates of low pH (sometimes less than 5). Using corrosion coupons this study investigated the corrosivity of final condensates at four factories for four materials commonly used in the construction of evaporators and the ancillary pipework. As well, on-line measurements of pH and instantaneous corrosion rates were made.

The results have shown that the two steam efficient factories in the study had very high corrosion rates for the carbon steel coupons (pipework and tube plate materials) while the factory with no vapour bleed (low steam efficiency configuration) had much lower corrosion rates for these materials. One factory with relatively low pH of condensate, but with low pH not as a consequence of sucrose degradation, showed intermediate corrosion rates. For all four factories, 304 stainless steel coupons showed extremely low corrosion rates.

The results demonstrate the need for steam efficient factories to determine appropriate solutions to extend the service lives of the evaporator vessels. Such solutions may include operational changes, design changes to evaporators and/or the use of alternative materials such as 304 stainless steel for vessel construction.

EXECUTIVE SUMMARY

Australian sugar factories almost universally use the Robert design of evaporator for concentration of juice to syrup. These vessels comprise carbon steel bodies and tube plates with expanded 304 stainless steel tubes. Several factories are experiencing high corrosion rates of carbon steel condensate pipes and tube plates.

Recent studies by QUT have established that factories that extensively use vapour bleed for juice heating and pan boiling (steam efficient factories) experience a large reduction in the pH of condensate in the tail end of the evaporator set. The condensate from the final effect has the lowest pH (sometimes pH is less than 5). The acidic conditions are attributed to high levels of sucrose and monosaccharide degradation in the juice and the subsequent volatalisation of the acids into the vapour and condensate. Low steam efficiency factories (using little vapour bleed for heating duties) have final condensates of pH above 7.

The study has measured the corrosion rates of coupons of the commonly used materials (ASME-B36 (pipework); 304 stainless steel (tubes); PT460 (tube plate) and welded tube plate (designated WTP)) at four factories (two steam efficient factories and two factories of low steam efficiency). The weight loss of the coupons was measured after 30-day, 60-day and 90-day exposures to the final evaporator condensates. As expected, for most cases, a protective layer formed on the coupon surface, which reduced the average corrosion rate for the longer times of exposure. On-line measurements of the instantaneous corrosion rate and pH of the final condensates at each factory were also undertaken.

The results based on the coupons with 90-day exposure demonstrated that:

- The corrosion rates of 304 stainless steel in the condensate at all four sites were negligible and reasonably similar. The 304 stainless steel corrosion rates were between 1/50th and 1/1000th of the corrosion rates of the carbon steel coupons;
- The carbon steel coupons at the least steam efficient mill (condensate pH ~9) corroded at about 1/20th of the corrosion rates at the two steam efficient factories (condensate pH 5 to 6) and about 1/6th the rate of the coupons at the other non-steam efficient factory (condensate pH ~6.8); and
- For the two steam efficient factories, the welded tube plate coupons corroded at a slightly higher rate (10 to 30% higher rate) than the plain sections of tube plate material. The ASME-B36 pipework coupons also corroded at a faster rate than the tube plate material.

The project has demonstrated that, for Australian factories to operate with high process steam efficiency, changes are needed to the evaporation plant and ancillary equipment to substantially reduce the impacts of high corrosion rates and extend the service lives of the installed equipment. Modified designs of evaporators, uses of alternative materials of construction (e.g., 304 stainless steel) and/or chemical dosing to mitigate the acid formation are possible corrective measures.

It is noted that the use of smaller diameter, longer heating tubes incorporated into the SRI design of Robert evaporator reduces the residence time for juice, the extent of sucrose degradation and the subsequent acid formation. The use of falling film tube evaporators instead of Robert evaporators would also provide shorter residence times for juice and reduced sucrose degradation and acid formation. Also, a current SRA project (2017/007) is being undertaken by QUT to identify suitable chemical dosing mitigation strategies to limit sucrose degradation and subsequent acid formation.

Final condensate pipework should be replaced with 304 stainless steel when the carbon steel pipes need replacing.

It is recommended that a cost benefit analysis is undertaken into the construction of Robert evaporators with 304 stainless steel to compare with the conventional construction of carbon steel bodies and tube plates. The study must also consider the potential galvanic corrosion between dissimilar metals.

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1. BACKGROUND

1.1 Issue concerning potentially high corrosion rates in evaporator stations

In recent years some Australian factories have experienced high corrosion rates in condensates at the tail end of the evaporator set, requiring premature replacement of pipework and valves. Of greater concern is whether the evaporator tube plates are also being corroded at accelerated rates. Some mills have reported severe corrosion in tube plates in the region of the condensate outlets. The asset value (replacement cost) of evaporators in Australian mills is estimated at $500 m and premature failure of tube plates would be a crippling cost to the industry.

Two recent projects (Broadfoot et al., 2018; Rackemann, 2021) have determined that when factories operate steam efficient evaporator sets, condensate pH reduces significantly late in the set. One cause is the degradation of monosaccharides to acids which is attributed to the higher juice temperature and longer residence times in evaporator sets which are configured for steam efficient operation. Broadfoot et al., (2018) highlighted the magnitude of sucrose degradation occurring in juice for steam efficient evaporator configurations and the associated formation of acids and the low pH of condensates. The condensate from the final evaporator has the lowest pH (sometimes <5). Rackemann (2021) is investigating the chemical pathway between sucrose degradation, monosaccharide destruction and acid formation with the aim to identify a cost-effective mitigation strategy.

1.2 Summary of previous investigations at evaporator stations

The sucrose degradation studies and measurements of pH of condensates in the aforementioned projects were undertaken at Isis, Pioneer, Invicta and Condong Mills. Table 1 provides the status of the process steam efficiency at these mills and the typical pH of the final evaporator condensates that had been measured during previous investigations at these mills (numerous spot measurements).

Table 1 Summary of pH data for final evaporator condensates in four Australian mills

Mill	Description of evaporator configuration	Typical pH of final condensate from previous studies (at 25 ℃)
Isis	Non steam efficient	8.4 to 9.5
Pioneer	Steam efficient	5.3 to 6.8
Invicta	Non steam efficient	4.6 to 4.8
Condong	Steam efficient	4.6 to 4.8

The studies determined that the steam efficient factories experienced larger pH reductions in condensate across the evaporator set, with the condensate from the final evaporator having the lowest pH. This reduction in pH is attributed to the degradation of monosaccharides in the juice with an associated formation of acids such as acetic acid which subsequently volatilise from the juice. Even though Invicta Mill is a non-steam efficient factory the final condensate has been frequently measured to have very low pH. Invicta Mill has a diffuser and it is suspected that the composition of the crushing juice and perhaps the formation of acetic acid due to the thermal breakdown of hemicellulose (pH, longer residence time at higher temperature) are the most likely factors contributing to this lower pH condensate (Schaffler et al., 1988; Beckett and Graham, 1989; Cox et al., 1993).

This study measured the corrosion rates in final evaporator condensates as these have the lowest pH of the condensates from the different effects. As well, the measurements were undertaken in the final evaporator condensates at the same four mills which had participated in the earlier studies as these mills were known to provide a range of compositions and pH values for the final condensates.

1.3 Techniques for measuring corrosion rates

As described in the NACE International Technical Report (Anon, 1999) the most common techniques for measuring corrosion rates in the field are mass-loss coupons, electrical resistance probes, linear polarisation probes and ultrasonics. This NACE Report also recommends that more than one technique should be used as each has weaknesses and advantages.

For this investigation, two procedures, as described in the NACE Report, were used to measure the corrosion rates viz.,

- Rate of loss of mass of specially prepared coupons. In this technique specially prepared coupons of the materials of interest are prepared and installed into the process solution (usually at the typical process conditions) for nominated test periods. The coupons are removed at the end of the test period and any adhering corrosion products are mechanically and/or chemically removed. After cleaning and drying the removed coupons the average corrosion rate (mm per year (mmpy)) can be determined from the loss in mass for the period (Anon, 1999). Disadvantages of this technique are: it does not provide a real time measurement; mass loss may also be due to the effects of erosion as well as corrosion; only an average metal loss over the period is provided; and short exposure times normally yield unrealistically high average rates of metal loss until the clean metal surfaces become 'passivated' with corrosion products. Advantages of the mass-loss coupon techniques are that coupons of different metals and different fabrication methods can be tested simultaneously in the same process conditions; the coupons are relatively cheap (although the cleaning and weighing steps are expensive) and that visual inspection of the coupons allows assessment of pitting, crevice corrosion and other non-uniform corrosion; and

- Linear polarisation resistance (LPR) technique. The LPR technique determines the corrosion rate of an electrode. The NACE International Technical Report (Anon, 1999) describes the propensity of the metal ions of the electrode (cathode) to pass into solution (corrode) is determined by the ratio of the small change in the applied potential (10 to 20 mV) around the open-circuit potential of the electrode and the corresponding change in the current density. The ratio of the change in potential to the change in the current density relates to the corrosion rate. The electrode is normally polarised cathodically and anodically by reversing the impressed current and held at the polarised potential until a stable current density is measured.

  The commercial instrument Corrator was purchased for this measurement. This is a two-electrode system whereby the corrosion rate is the average of the rate calculated for both electrodes. The electrodes use the metal of interest in the process. The advantages of the LPR technique are: the measurements are rapid (every few minutes); the measurement is particularly useful in water systems which experience rapidly changing corrosive conditions and so allow remedial action to be taken.

1.4 Mathematical models of corrosion rate

Prediction of corrosion rate over time using empirical/semi-empirical corrosion-rate models makes it possible to assess the reliability of the corrosion monitoring devices. These models are developed by combining knowledge of the chemistry of corrosion, mathematical modelling techniques and laboratory experiments. Several corrosion rate models have been introduced for the representation of corrosion rate in terms of time. Linear corrosion rate models assume that the rate of corrosion constantly increases in time. These simple models were among the first corrosion rate models introduced in the literature, an example of which can be found in the work of Din et al. (2009). In the real world, however, corrosion rate does not follow a linear trend. Non-linear corrosion rate models better represent the non-linear characteristics of corrosion. A widely used non-linear corrosion model, introduced by Kucera and Mattsson (1987), is a power-law formula:

$$CR(t) = at^b, \qquad (1)$$

where t is the exposure time, a and b are the regression constants. The power-law corrosion rate model assumes that the corrosion rate changes in time because of the formation of the protective layer on the metal surface. Because of its generalisability and its simple mathematical formulation, the power-law model has been extensively used for modelling corrosion rate in various applications. There exist other non-linear corrosion rate models such as the two-phase model and bi-modal model. These models are corrosion environment-specific and may not apply to final evaporator condensates in sugar mills. An example of the bi-modal model, by Melchers (2013), was developed for the representation of corrosion rate in marine environments. This report utilises the power-law corrosion rate model for the prediction of corrosion rate to maintain generality.

2. PROJECT OBJECTIVES

The objectives of the project are to:

- measure the average corrosion rates of four materials using coupons in the final condensates at four factories.

- measure the pH and instantaneous corrosion rates of tube plate and pipework materials using an online sensing package in the final condensates at four factories and correlate the results to the factories' processing circumstances.

- develop a corrosion growth model, based on experimental data and available mathematical relationships, useful for predicting remaining useful life of evaporators.

- provide a report to the industry including recommendations on risk mitigation by utilising other materials for replacement/refurbishment of evaporators. This work complements the SRA2017/007 research project which aims to identify chemical solutions.

3. OUTPUTS, OUTCOMES AND IMPLICATIONS

3.1 Outputs

The outputs from the project include:

- The average corrosion rates of coupons constructed of 304 stainless steel, mild steel pipework material and tube plate grade material in final evaporator condensates at four factories. Corrosion rates for welded tube plate material were also assessed;
- The instantaneous corrosion rates of mild steel electrodes in the final evaporator condensates and correlation to the on-line measurement of pH of the condensates;
- The mean and extent of variation of the pH of the final condensates during the test periods at the four mills;
- Development of power law models to describe the corrosion rates of each of the coupon types at each of the four mills. In a few instances the data did not allow a power law model to be fitted; and
- Comparison of the serviceability of 304 stainless steel to be used as an alternative material for pipelines and tube plates.

3.2 Outcomes and Implications

In order for the industry to implement high levels of steam efficiency, solutions must be found to limit corrosion rates of tube plates and condensate pipelines that are initiated primarily through the sucrose and monosaccharide degradation reactions that are most severe at the high temperature front end of the evaporator set. These solutions could be to use different designs of evaporators which incorporate shorter residence times (in order to limit the extent of sucrose degradation, monosaccharide destruction and acid formation), to use different materials of construction for the evaporators e.g., use 304 stainless steel for tube plates and condensate pipelines and/or to mitigate the corrosivity of final condensates by using chemical additives into the juice streams within the evaporator set.

A cost/benefit analysis should be undertaken on the capital cost and maintenance cost for the lives of evaporator vessels constructed with 304 stainless steel tube plates and mild steel bodies and vessels fully constructed with 304 stainless steel to compare with conventional evaporator vessels constructed in mild steel. As part of this analysis the likely effects of galvanic corrosion where dissimilar metals are joined e.g., stainless steel tube plates welded to mild steel bodies, would need to be investigated. The investigation can also look into the feasibility and cost of applying corrosion control techniques (e.g., coatings) on these joints since they are limited and much more accessible compared to the contact area between tube plate and tubes where the existing vessels show galvanic reaction (mild steel tube plate in contact with stainless steel tubes).

4. INDUSTRY COMMUNICATION AND ENGAGEMENT

4.1 Industry engagement during course of project

The main findings from the investigation are that, in the steam efficient factories, the corrosion rates of mild steel pipelines and tube plate material in final evaporator condensates are very high and are a cause of great concern for millers. On the other hand, 304 stainless steel experienced very low corrosion rates. For steam efficient factories, procedures to substantially reduce the corrosion rates of condensate pipelines and tube plates must be determined. One option may be to manufacture pipelines and tube plates in 304 stainless steel. In fact, a cost/benefit analysis should be undertaken also for an evaporator constructed totally of 304 stainless steel. The costs may not be excessively high as the cost of installing an evaporator into the factory site is often more than twice the cost of constructing the vessel.

To date there has been no communication with any of the SRA Adoption Officers.

The information available for adoption by the Australian sugar industry is listed in the Outputs.

The authors intend to prepare a paper for the 2022 ASSCT Conference to present the results. The authors presented a brief overview of the project objectives and preliminary results at the Research Seminars in March

2021. As well QUT will present a seminar on the results at the Research Seminars to be held in the five main cane growing regions in March/April 2022.

4.2 Industry communication messages

The communication message from the project is summarised in the first paragraph of section 4.1. It is repeated here for completeness.

The main findings from the investigation are that, in the steam efficient factories, the corrosion rates of mild steel pipelines and tube plate material in final evaporator condensates are very high and are a cause of great concern for millers. On the other hand, 304 stainless steel experienced very low corrosion rates. For steam efficient factories procedures to substantially reduce the corrosion rates of condensate pipelines and tube plates must be determined. One option may be to manufacture pipelines and tube plates in 304 stainless steel. In fact, a cost/benefit analysis should be undertaken also for an evaporator constructed totally of 304 stainless steel. The costs may not be excessively high as the cost of installing an evaporator into the factory site is often more than twice the cost of constructing the vessel.

5. METHODOLOGY

5.1 Corrosion monitoring rig design

Figure 1 shows the design of the corrosion monitoring rig. Each of the three top lines includes four tee fittings where the coupons can be readily inserted and removed. The rig was designed to hold coupons at a total of 12 locations (being three locations for each of the four different coupon types) and a Corrator and pH transducer. The three lines allow coupons to be removed for mass-loss measurement at 30, 60 and 90 day intervals. As shown in Figure 2, each tee incorporates a holder for installing the coupons of a particular material. The rig is designed in this way to allow the coupons in any one line (of Line 1, 2 and 3) to be removed when sampling at a time interval without interrupting the exposure of the coupons to the condensate flow in the other two lines. The two tees on Line 4 are for installation of the pH probe and Corrator. At each factory the rig was installed so each line is in the same horizontal plane.

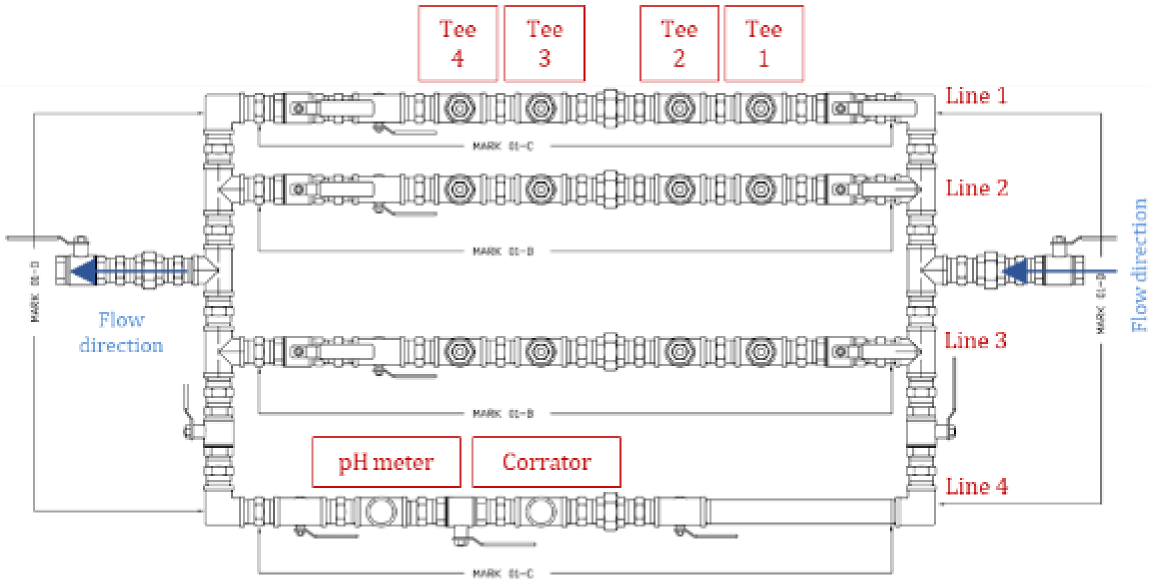

Figure 1 The corrosion monitoring rig design (top view)

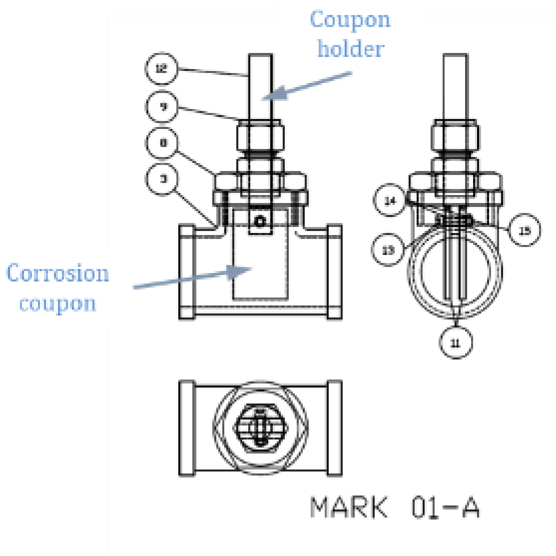

Figure 2 Corrosion coupon holder design

The rig was constructed at each of Isis, Pioneer, Invicta (on the A side evaporator set) and Condong Mills and installed for the duration of the 2020 season to pass final condensate from a branch off the discharge of the final effect condensate pump to the monte reservoir (or the suction side of the pump). A small flow of condensate (~5 t/h) was proposed to pass through the rig continuously whenever final condensates were being produced. When there was no condensate produced (e.g., during a factory shutdown) the rig was to be isolated but left full of condensate.

5.2 Corrosion coupons selection and preparation

In order to select the most appropriate materials for the corrosion coupons, staff at Isis Mill, QUT, Wilmar Sugar and Bundaberg Walkers Engineering were consulted. The materials that are used most commonly in the manufacture of evaporators and their pipework were selected. These include:

- AS1548-PT460, common material for tube plates
- ASME B36.10, common pipework material
- 304 Stainless steel, common evaporator tube material and used in the pipework at some mills.

Table 2 lists the chemical composition of the materials chosen for corrosion testing.

The proposal for this project indicated the intention to assess a coupon manufactured in API 5L X60, a more corrosion resistant material that would be suitable for tube plates. However, the difficulty in sourcing this material and high price determined that it would not likely be a practical option for tube plates in future installations of evaporator calandrias. For this reason, an alternative fourth coupon was required. As suggested by Bundaberg Walkers, welded PT460 tube plate (WTP) material was tested as the fourth coupon type as there is some concern that the heat affected zones on the welded tube plates are more susceptible to corrosion. The welded tube plate was included to allow comparison with plain tube plate.

Table 2 Chemical composition of the materials used for making corrosion coupons

Material	C	Mn	Si	P	S	Nb	Al	Ti	Cu	Ni	Cr	Mo	V
AS1548-PT460	0.2	1.7	0.6	0.04	0.03	0.01	0.1	0.04	-	-	-	-	-
ASME B36.10	0.3	1.2	-	0.05	0.045	-	-	-	0.4	0.4	0.4	0.15	0.08
304 Stainless steel	0.08	2	1	0.045	0.03	-	-	-	-	10.5	0.18	-	-

In order to achieve a high level of accuracy and consistency, all coupons were manufactured by the Design and Manufacturing Centre (DMC) of QUT. This involved cutting the coupons into the dimensions shown in Figure 3 using the wire cut method. The coupon dimensions in Figure 3 are for the three non-welded coupons. For the welded tube plate, the coupon was 6 mm thick. To minimize corrosion effects the coupon holders were made from stainless steel 304 rod. The surfaces of each coupon were ground and polished to an appropriate finish, to prevent excessive corrosion caused by material defects. Figure 4 presents an example of the surface finish on the prepared coupons.

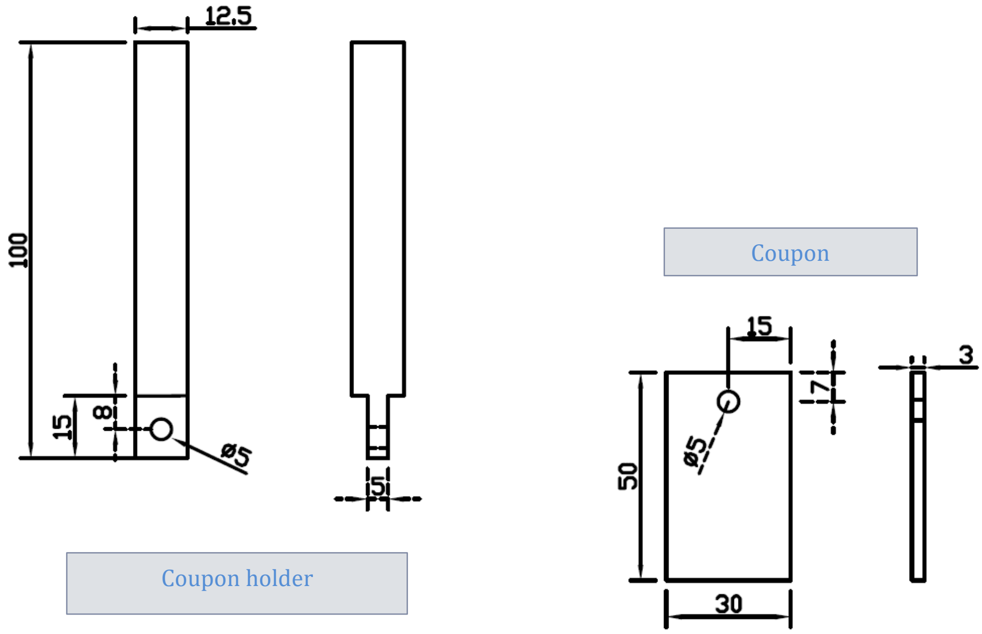

Figure 3 Dimensions of holder and coupons used in the experiment (in mm)

In total ten coupons of each material and five coupons with the welded tube plate were manufactured for each mill. This provided five coupons of each material for testing at each mill for periods of 30 days (two series), 60 days (two series) and 90 days (one series). Each coupon of the three materials with no weld had a duplicate at each location to allow checking for repeatability of the simulated corrosion damage.

Figure 4 Example of coupon surface finish to avoid excessive corrosion caused by surface defects.

To test the performance of tube plate material in the vicinity of welded joints against the corrosivity of condensate, 6 mm thick coupons were made from the tube plate material and cut transversely before welding the two sections together. Thicker samples were cut for the trial of welded materials in order to avoid deformation of the coupons during the welding process. Figure 5 shows an example of a welded coupon after assembling on a holder. Only one welded coupon could be attached to the holder because of its increased thickness.

Figure 5 Welded tube plate (WTP) coupon assembled on the holder

By obtaining repeat measurements for 30- and 60-day periods the assessments provided an indication of the variability in measurements and also generated more data for development of the mathematical relationship. The entire dataset from the 30-day, 60-day and 90-day observations were used to determine the model of corrosion for each material at each factory site.

5.3 Installation of coupons

In order to prevent the coupons from corroding between the time of preparation and the start of testing, the coupons were covered with oil. Prior to assembly to the holders, the coupons were degreased and hot air dried and their mass was recorded. This preparation step was undertaken at the test site just prior to loading the coupons and holder into the rig. Figure 6 shows the entire set of coupons for one mill prior to assembly.

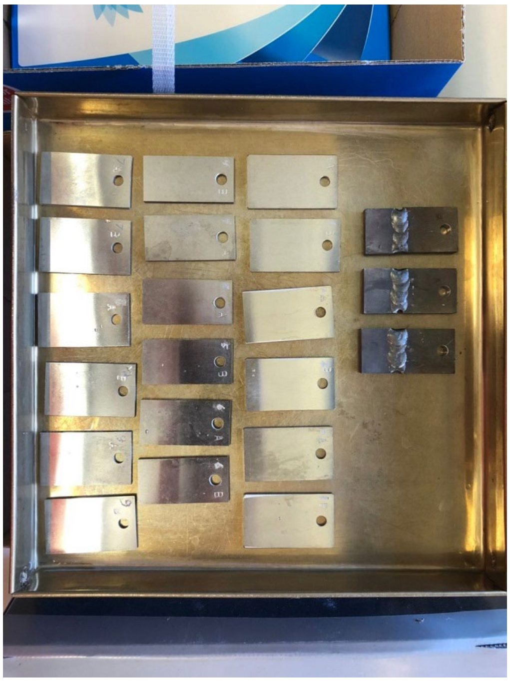

Figure 6 Degreased and dried coupons ready for installation on holder.

For each of the non-welded materials, the two coupons were assembled on each holder using stainless steel bolts and nuts. Nylon washers were used to avoid contact between any two metals. Figure 7 presents an example of a coupon/holder assembly.

Figure 7 Coupon and holder assembly.

Each coupon holder was then fitted on the rig using a compression fitting that enabled the height and alignment of the coupons onto the tee to be adjusted, while maintaining the seal. A multi-meter was used to check that there was no electrical continuity between each coupon and the other components of the assembly. This check was also performed at the time of taking the coupons out of the rig. This was important to ensure isolation of the coupons from galvanic interactions with the coupon rack materials which could impact the corrosion rates of the coupons.

Figure 8 shows the installation of the rig at Isis Mill.

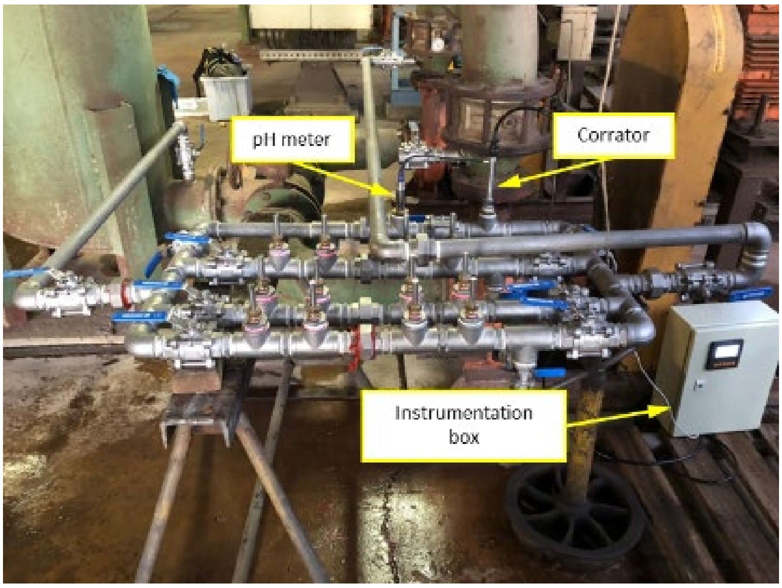

Figure 8 Installation of the corrosion assessment rig at Isis Mill.

5.4 Test schedule at the four mills

Table 3 provides details of the schedule when coupons were installed and removed at each of the mills and when the Corrator and pH transducer were installed, and their signals logged. As there was only the one Corrator and pH transducer, these instruments had to be moved among the four mills, giving test periods at the different sites of between 10 and 22 days.

As can be seen in Table 3 there was a delay in starting the test program until early August, due to the time taken to design, construct and install the rigs at each mill and the Corrator shipped from the USA and the pH transducer from Hong Kong. Also, other interruptions during the season at mills meant some variations in the 30-day, 60 day and 90-day test programs were unavoidable. The major impacts were that only one 30-day test and one 60 day test were conducted at Pioneer Mill and only one 30 day test at Condong Mill. At Pioneer Mill two tests of 90 days were conducted.

Table 3 Schedules of the test program at the four mills

Mill	Corrator and pH transducer schedule			Coupon testing schedule	
	Date start test	Date finish test	Period, days	Date of install/removal	Period, days
Isis	21/08/2020	3/09/2020	14	06/08/2020	
				04/09/2020	30
				1/10/2020	28, 58
				1/11/2020	59, 88
Invicta	14/10/2020	27/10/2020	14	11/08/2020	
				10/09/2020	31
				12/10/2020	33,63
				13/11/2020	65,95
Pioneer	27/10/20207	19/11/2020	22	10/09/2020	
				12/10/2020	33
				03/12/2020	55,86 (2 sets)
Condong	24/11/2020	04/12/2020	10	03/09/2020	
				06/10/2020	30
				05/11/2020	62
				04/12/2020	59, 92

5.5 Cleaning of coupons

The corroded coupons were removed from the manifold at their due time (and new coupons installed if applicable). Coupons were rinsed to clear them of any loose corrosion products and after being dried in an oven, they were kept in a desiccator to prevent further corrosion. Figure 9 shows the 30-day coupons removed from the corrosion rig at Isis Mill.

Figure 9 30-day corroded coupons at Isis Mill.

Figure 10 shows a greater presence of corrosion products on the 30-day coupons that were removed from the Invicta Mill installation. Figure 11 shows a substantially thick layer of rust separated from the coupon. The area around the bolt hole under the washer in each coupon experienced no corrosion, confirming that the insulating washer was effective in preventing contact between the coupon holder, connecting bolt and nut.

Figure 10 30-day corroded coupons at Invicta Mill.

Figure 11 60-day corroded tube plate coupon at Invicta.

After completion of the trials at all the four mills, the coupons were cleaned of corrosion products according to the ASTM G4 standard (ASTM, 2003). This standard suggests using HCL solution with inhibitor to avoid further damage to the material during the washing process. The standard also requires cleaning each coupon in 10-15 minute cycles, repeatedly, until a minimal difference in the mass is obtained between two consecutive wash and drying cycles. This physically means that with a good level of certainty the coupons can be considered to have no corrosion products remaining on their surfaces.

5.6 Corrosion rate calculations

The mass loss of each coupon during its exposure time is obtained following the completion of ASTM G4 standard for cleaning corrosion coupons (ASTM, 2003). The mass loss of the coupon due to corrosion damage is the original mass minus the final mass after the cleaning procedure is completed. The corrosion rate is then calculated using Eq. 1:

$$Corrosion\ rate\ \left({}^{mm}/_{year}\right) = 87.6\ {}^{W}/_{DAT} \qquad (1)$$

where W is mass loss in mg, D is the density of metal in g/cm^3, A is the initial area of exposure in cm^2 and T is exposure time in hours.

5.7 Corrosion growth model

As discussed in Section 1.4, the Power-Law function has been fitted to the dataset of the average corrosion rate for the three exposure times (30, 60 and 90 days) to determine the best regression fit to the data that shows the growth of damage. The regression process was performed in MATLAB 2021a, and the goodness of fitting is reported by R^2 values together with the obtained regression coefficients.

6. RESULTS AND DISCUSSION

6.1 General comments

As discussed, the aim of this project is to achieve a better understanding of the corrosion that is occurring in the final condensates in four sugar factory evaporator sets having a range of processing conditions. This section presents the results and major findings of the experimentation performed at the four factories, including observations from visual inspection of the coupons and measured pH and corrosion rates of the four different materials. The following sub-sections present the results in detail.

6.2 Visual observations of corrosion damage on the coupons

An important observation that was made by comparing the corroded coupons in the four factories is that at Isis mill all the coupons were deteriorated by a more localised type of corrosion while the corrosion at the other mills was generally spread across the entire surface. Figure 12 shows the coupons at Isis Mill after 30-day exposure to final condensate. It can be seen on the tube plate and pipe work coupons that the damage represents a type of acid etching or pitting with clear evidence of the condensate flow streamlines on the coupon shown in Figure 13. This type of damage is consistent in the other coupons with longer times of exposure to the Isis Mill final condensate flow. Following discussions with staff at Isis Mill it is possible that the streamline pattern is the result of flashing of vapour across the surface of coupons. Flashing could result where the valve near the pump discharge (i.e. at the entry to the rig) was throttled rather than the valve on the downstream side of the rig.

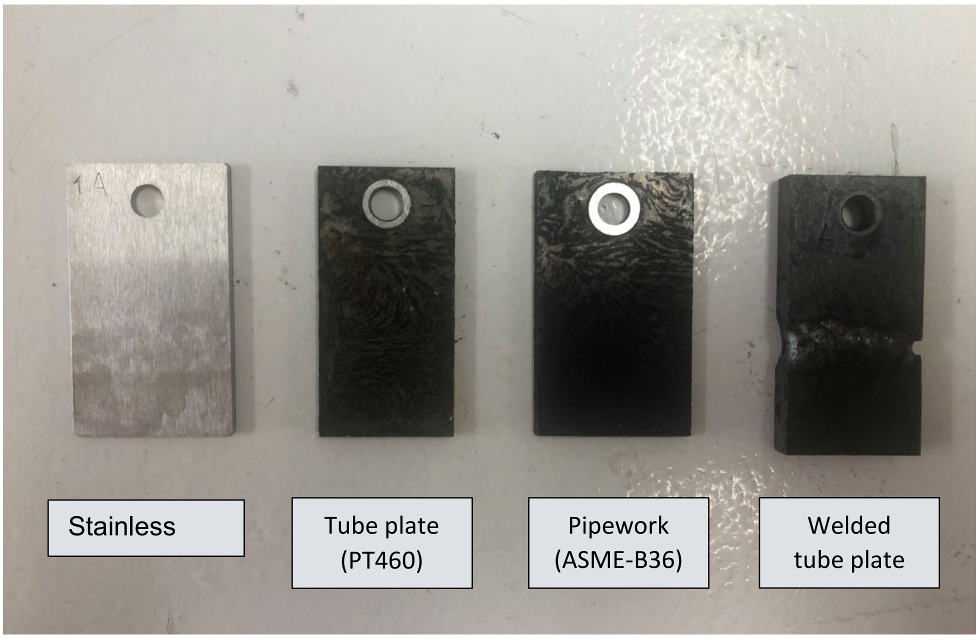

Figure 12 30-day corroded coupons from Isis Mill after being rinsed.

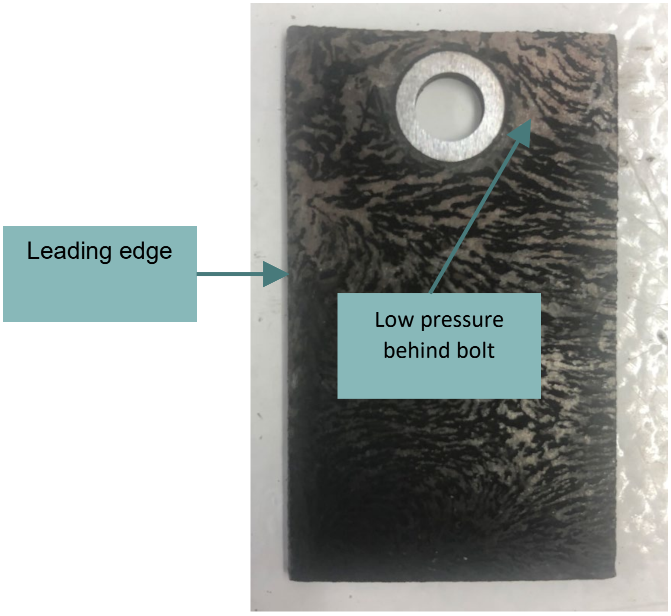

Figure 13 Distinct patterns of material loss on the pipework material after 30 days at Isis Mill.

At the other three factories (Invicta, Pioneer and Condong) the material loss was more consistently spread over the coupon surface indicating general corrosion to be the predominant form of damage. An example is shown in Figure 14 where significant material loss is caused over the entire coupon surface after 60 days of exposure to the final condensate.

Figure 14 Tube plate material coupons corroded at Invicta Mill by 60 days of exposure to final condensate.

6.3 Determination of corrosion rates by coupon mass loss

Figure 15 presents four examples of the recorded mass loss for various coupons at consecutive 10-minute wash cycles. This repetitive process ensured that every coupon has been cleared of the corrosion products as much as possible without causing further damage to the coupon material itself. While it is practically difficult to stop the material loss completely, achieving a slowing reduction in the rate of mass loss after the initial fast mass loss, followed by a near linear rate of mass loss for the latest three mass values was the aim of the cleaning process.

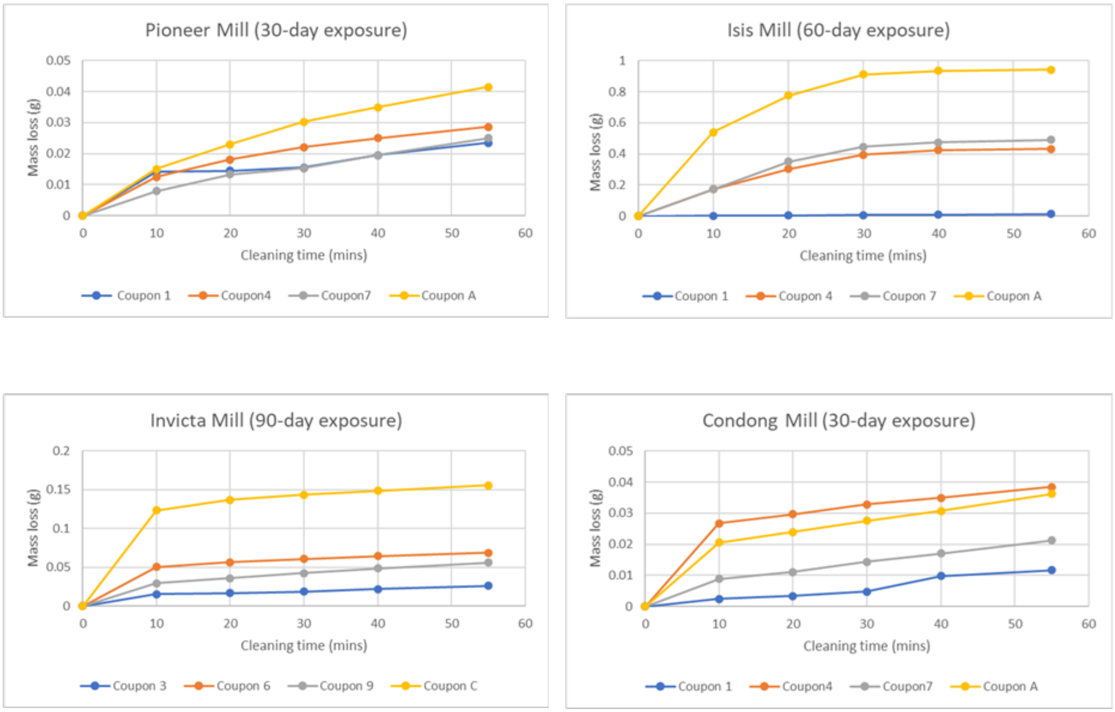

Figure 15 Examples of coupon mass losses obtained at consecutive 10-minute cleaning cycles.

6.4 Corrosion rates of the coupons

6.4.1 Coupon corrosion rates for Isis Mill

Figure 16 presents the corrosion rates calculated for the coupons of each material at 30, 60 and 90 day exposure to the Isis Mill final condensate. Although these exposure times may vary by a few days, for reporting purposes they are considered as 30, 60 and 90 days. Box plots are used to illustrate the level of variability in data. The bar in the middle of the box shows the median value of corrosion rate while the top and bottom of the box surrounding the median represent the range of the 50% of values closest to the median. The extensions above and below the box show the maximum and minimum values.

The highest corrosion rate for stainless steel coupons was found to be 0.0038 mm/year which is obtained from the 30-day coupons. The corrosion rate is then reduced to 0.0017 mm/year which is approximately half of the initial observation. As commonly known, stainless steel provides a strong resistance against corrosion damage to the equipment in many process industries. The predominant type of damage to stainless steel is through concentrated pits where the pit diameter and depth may be utilized for more in-depth analysis of corrosion growth rate. In this report, however, mass loss due to the growth of pits is used as an indication of damage growth.

As expected, the initial corrosion rates were found to be significantly higher for the other three materials, including a maximum of 0.18, 0.26 and 0.29 mm/year for the tube plate, pipework and welded tube plate (WTP) coupons, respectively. These rates are reduced in longer exposure times reaching average values of approximately 0.1 mm/year after 90 days of immersion into the condensate flow for all three materials. In most cases the exponential reduction in corrosion rate is observed confirming the suitability of the Power Law models for damage prediction. It can also be seen that there is larger variability in the rates at the beginning of exposure (i.e. in 30 day data) compared to those from 60 days of exposure. The minimum variation in the 90-day rates is due to having fewer samples.

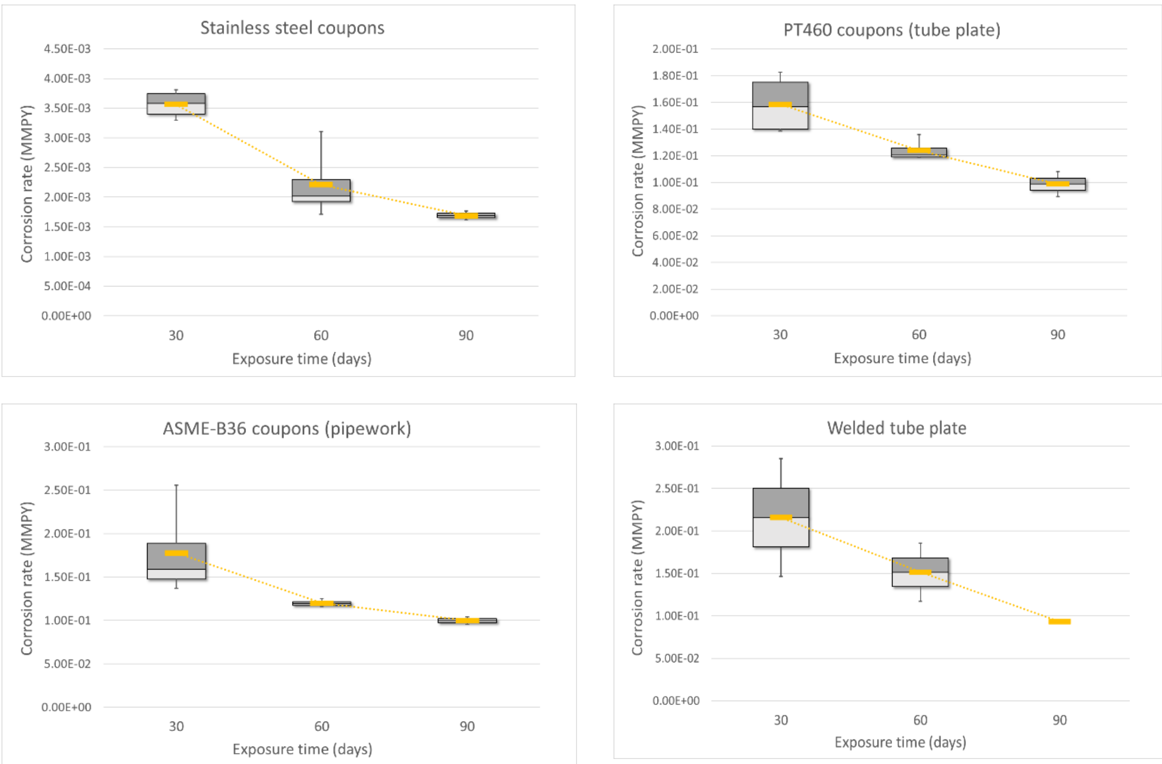

Figure 16 Calculated corrosion rates in mm/year for corroded coupons at Isis Mill.

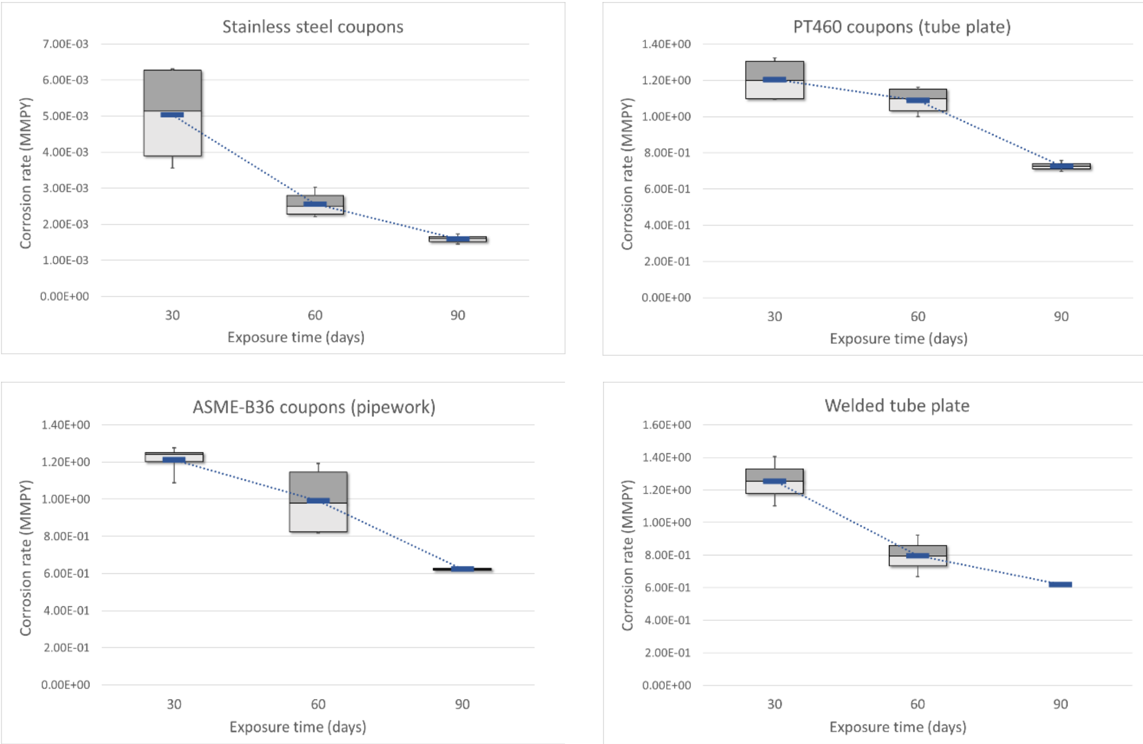

Figure 17 Calculated corrosion rates in mm/year for corroded coupons at Invicta Mill.

6.4.3 Coupon corrosion rates for Pioneer Mill

Figure 18 shows the trends and variations of corrosion rates obtained from the four materials immersed in the final condensate at Pioneer Mill. The average 90-day corrosion rate of the stainless steel samples is 0.002 mm/year. The average 90-day corrosion rates are 1.55, 1.92 and 1.7 mm/year for the tube plate, pipework and WTP materials, respectively.

Although corrosion rates are reduced by longer exposure to the condensate flow, the reduction from the shorter exposure times is less compared to that experienced at Invicta and Isis Mills. Less reduction in the corrosion rates from 30-day to 90-day data may indicate higher corrosivity of the condensate, meaning that a well-developed protective layer is formed in the initial period of exposure. The measured corrosion rates of the carbon steel materials at Pioneer Mill are 2-3 times higher than those at Invicta Mill.

It should be noted that the less variation in 60-day data is due to fewer coupons available in the test period. As a result of the limitations caused by the COVID-19 pandemic, the second set of the 60-day coupons were left in the rig until the end of experiment providing more information about 90-day corrosion rates.

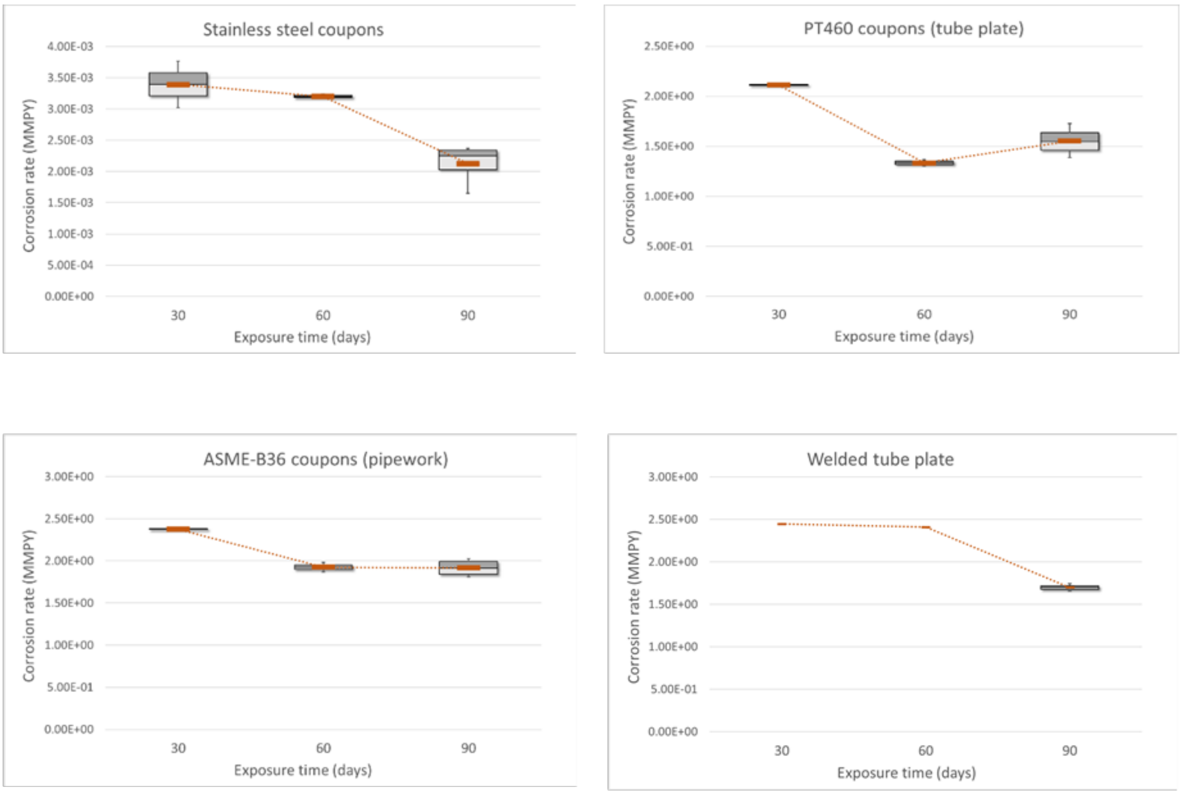

Figure 18 Calculated corrosion rates in mm/year for corroded coupons at Pioneer Mill.

6.4.4 Corrosion rates for Condong Mill

The corrosion rates of each of the four materials for different exposure times to the final condensate of Condong Mill are illustrated in Figure 19. For stainless steel, a significant reduction in the initial damage rate is observed, and the average corrosion rate at 90-day period is 0.0011 mm/year. This value is less than the 90-day rates from the other three sites. For the tube plate, pipework and welded tube plate coupons at Condong, the temporal trend of change in corrosion rate is not consistent and the reasons for this are unknown. There might be some operational parameters contributing to this inconsistency. For example, the final condensate flow at Condong Mill is very low (< 5 t/h) and intermittent flow through the rig may have occurred on occasions. Despite an insignificant change in the rate of tube plate coupon corrosion over 90 days of exposure to condensate flow, the average 90-day rate is 1.49 mm/year. The rate for corrosion of pipework coupons is increased over time, resulting in a 2.0 mm/year loss in 90 days. The 90-day corrosion rate of WTP at Condong was found to be 2.0 mm/year as well.

More investigations could be performed at Condong to achieve a better understanding of the corrosion growth rates.

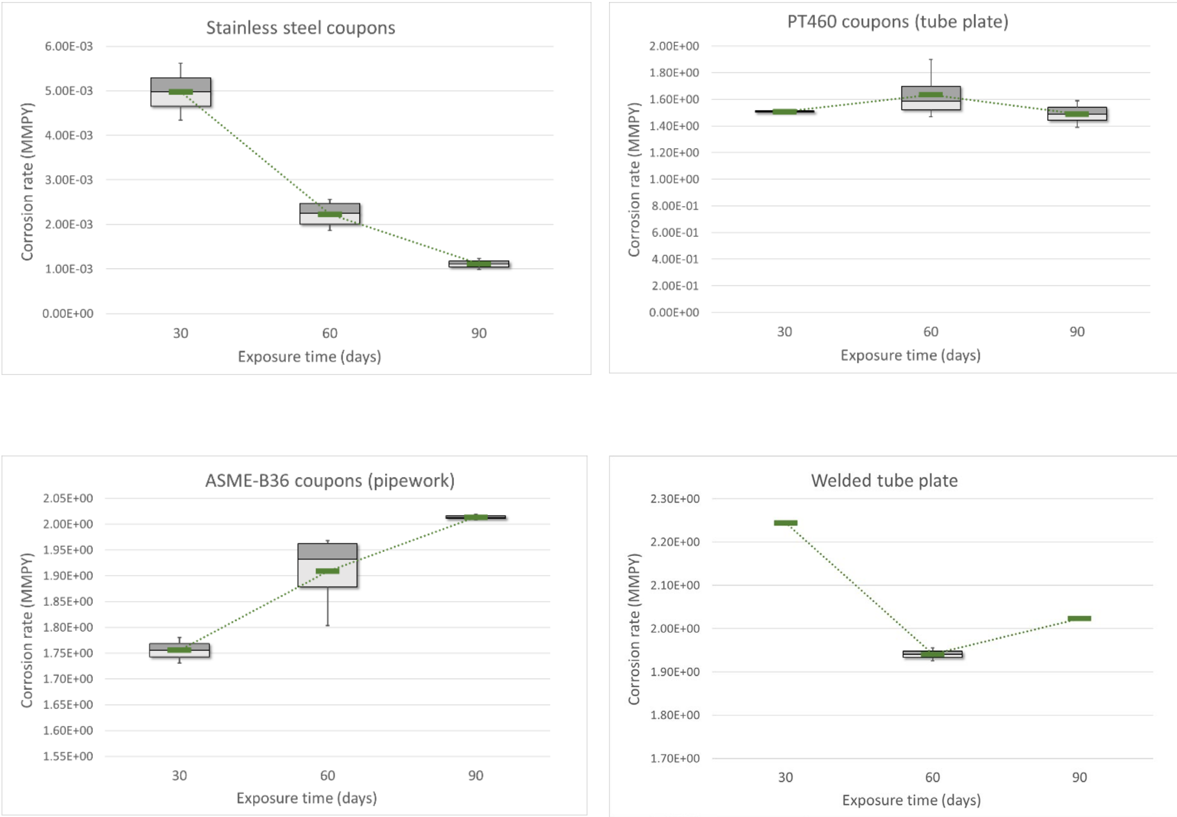

Figure 19 Calculated corrosion rates in mm/year for corroded coupons at Condong Mill

6.4.5 Comparison of coupon corrosion rates among factories

Figure 20 provides a comparison of the stainless-steel corrosion rates of the four factories at three exposure times. A decreasing rate can be seen at all sites. In 30 days the Condong coupons showed the highest rate of damage while in 90 days the Pioneer coupons had the highest rate. For all four factories, the growth rate of corrosion after 90 days was below 0.0025 mm/year, confirming a very high resistance to corrosion by this material.

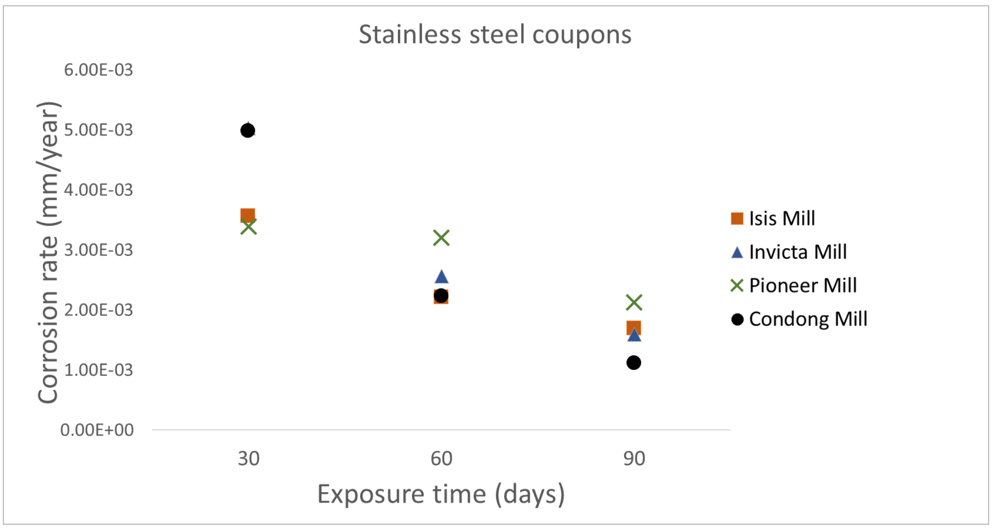

Figure 20 Comparison of observed corrosion rates from stainless steel coupons installed at four factories.

Figure 21 compares the corrosion rates of tube plate material at the four factories for the three exposure times. The reported rates represent the average of available values from replicate coupons. The most notable feature in this figure is that the corrosion rates of Isis coupons are substantially lower than for the other three mills. The fact that vapour bleeding is not performed at Isis Mill may be the major contributor to the very large difference in corrosion rates. The two factories with steam efficient operation viz., Pioneer and Condong Mills show the highest corrosion rates of the four factories. Based on 90-day exposure the long-term damage rates are found to be the highest at Pioneer Mill, 1.55 mm/year, followed by Condong Mill which is 1.49 mm/year. These rates are more than two times higher than that from Invicta Mill which is 0.72 mm/year.

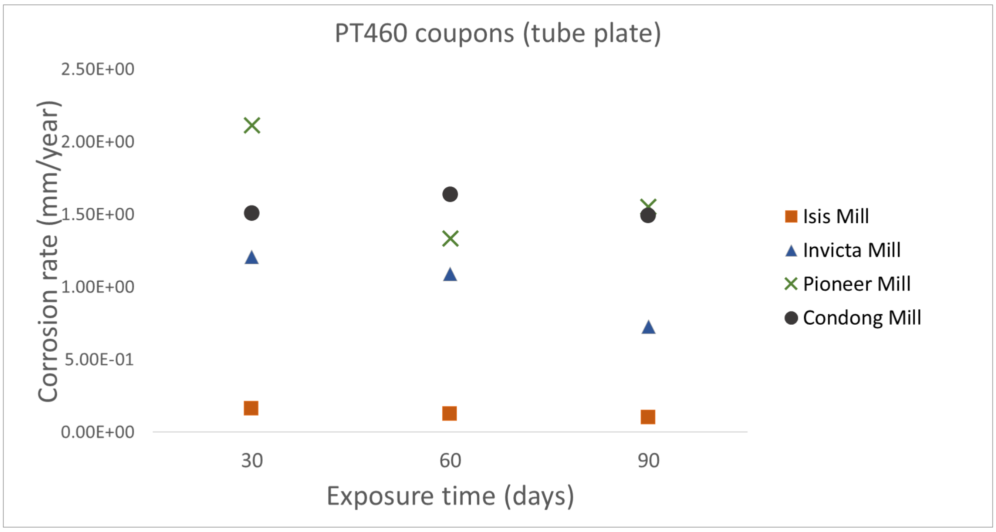

Figure 21 Comparison of observed corrosion rates from tube plate coupons (PT460) installed at the four factories.

A comparison of the corrosion rates of the pipework material coupons installed at the four factories is presented in Figure 22. Similar to the tube plate results, the corrosion rates for the Isis Mill coupons are much lower. Except for the coupons from Condong Mill, the rates are reduced by increasing the period of immersion. Invicta Mill had a 90-day corrosion rate of 0.62 mm/year. The pipework material experienced the worst deterioration at Condong Mill where the corrosion rate was 2.0 mm/year. The damage on this material was slightly less at Pioneer Mill with 1.9 mm/year of loss.

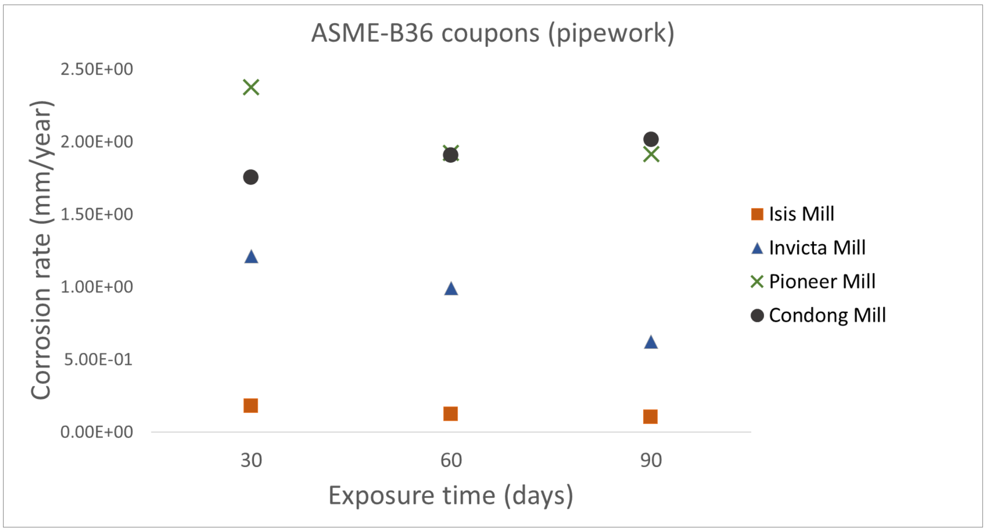

Figure 22 Comparison of observed corrosion rates from pipework coupons (ASME-B36) installed at the four factories.

The trends of 90-day WTP corrosion rates of the different sites are very similar to those of the pipework coupons. Isis coupons experienced the least amount of material loss. Condong final condensate had the strongest corrosive effect on the 90-day WTP coupons, reducing this material by 2.0 mm/year. The corrosion rates of the WTP coupons at Pioneer Mill were the next fastest losing 1.7 mm/year. The corrosion rate experienced by the WTP coupons at Invicta Mill was 0.62 mm/year.

Overall, for the three carbon steel materials, Condong and Pioneer Mills experienced the highest corrosivity in the final evaporator condensate which is most likely due to the lower pH of their final condensates, as a consequence of higher levels of sucrose degradation and acid formation in the juice at these two factories.

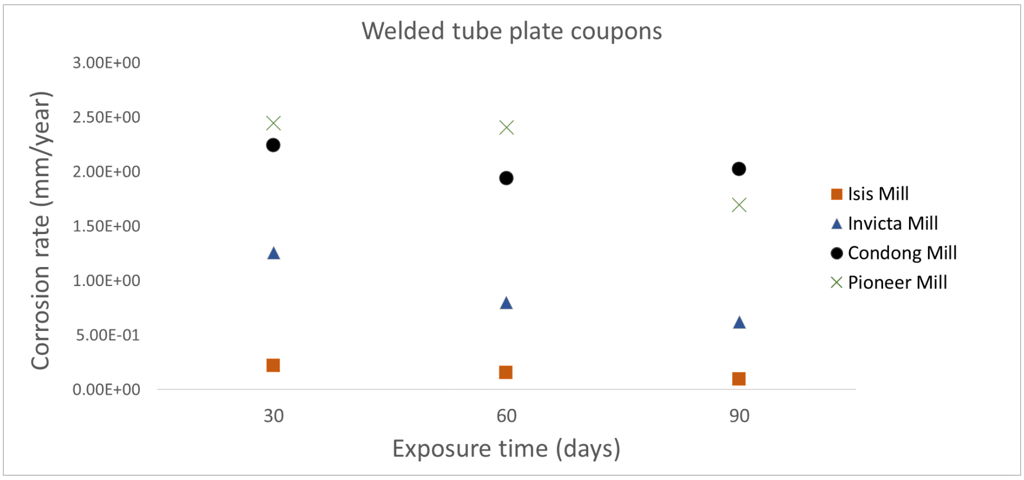

Figure 23 Comparison of observed corrosion rates from welded tube plate coupons (PT460) installed at the four factories.

The measured corrosion rates on the carbon steel coupons at Pioneer, Invicta and Condong Mills in particular appear to be substantially higher than is being experienced in practice. For example, factory experience indicates that tube plate corrosion is not as high as 2 mm/year. Possible reasons for the higher measured coupon corrosion rates have been considered. Erosion and vibration releasing the protective layer are considered as potential causes. The coupons installed at Isis, Invicta and Pioneer factories may have been subjected to a high flow rate of condensate (greater than 50 t/h through the 4 lines of 32 mm diameter), they may have also experienced erosive effects and vibration resulting in the loss of corrosion protective film over the surface of each coupon. However, at Condong Mill where the final condensate flow rate is significantly lower (less than 5 t/h) erosion and vibration are unlikely to be factors, yet the measured corrosion rates are still very high. Moreover, upon extraction from the rig, none of the coupons (regardless of the exposure times, type of material and factory) was observed to have lost a corrosion protective film, completely or even partially. This makes it unlikely that vibration was a factor causing an increase in corrosion rates.

Table 4 summarises the main findings for the coupon corrosion rates after 90-day exposure. The data are presented to show the corrosion rates at each site for 304 stainless steel and the carbon steel coupons collectively.

Table 4 Summary of corrosion rate measurements using coupons after 90-day exposure

Factory	Corrosion rate of coupons after 90-day exposure (mm/year)	
	304 stainless steel	**Carbon steel**
Isis	0.0017	ASME-B36, PT460 and WTP are reasonably similar at 0.1 mm/year
Invicta	0.0016	ASME-B36, PT460 and WTP are reasonably similar being 0.62, 0.72 and 0.62 mm/year respectively
Pioneer	0.0020	1.55, 1.92 and 1.7 mm/year for the tube plate, pipework and WTP materials respectively
Condong	0.0011	1.5, 2.0 and 2.0 mm/year for the tube plate, ASME-B36 and WTP materials respectively

The main observations for the corrosion of the coupons after 90-day exposure are:

- The corrosion rates of 304 stainless steel in the condensate at all four sites were negligible and reasonably similar. The 304 stainless steel coupon corrosion rates were 1/50th of the carbon steel corrosion rates at Isis Mill, 1/400th of the carbon steel corrosion rates at Invicta Mill and ~1/1000th of the corrosion rates of the carbon steel coupons at Pioneer and Condong Mills;
- The carbon steel coupons at Isis Mill corroded at about 1/20th of the corrosion rates at Pioneer and Condong Mills and about 1/6th the rate of the coupons at Invicta Mill;
- At the steam efficient factories (Pioneer and Condong) the ASME-B36 pipework coupons corroded at a faster rate (~30% faster) than the tube plate material. At Isis and Invicta Mills (non-steam efficient factories) the ASME-B36 pipework coupons corroded at a similar rate as the tube plate material; and
- For both Pioneer and Condong Mills the welded tube plate coupons corroded at a faster rate (10 to 30% faster) than the plain sections of tube plate material. On the other hand, at Isis and Invicta Mills the corrosion rates of the welded tube plate material and the plain tube plate coupons corroded at similar rates.

6.5 Corrosion growth models

Table 5 lists the mathematical Power Law relationships that were developed for the corrosion growth rates of each material for the four factories. The a and b parameters of equation 1 (with time t in days) in Table 5 are only reported when the Power Law is found to be applicable to the observed damage data. The highlighted cells show the cases for which the Power Law has been a very good fit. These values can be best used when updated with more data from actual measurements of damage on equipment. The updating process can be readily performed by probabilistic modelling when the new information becomes available. The regression parameters, when expressed as probability distributions, are very useful for developing reliability models of the asset, as well as implementing risk-based maintenance plans. Further research into this area of asset management in the sugar industry is highly recommended to optimize the use of capital for maximum availability.

Table 5 Estimated Power Law parameters for corrosion rates.

Material	Factory			
	Isis	Invicta	Pioneer	Condong
Stainless steel	$\boldsymbol{R^2 = 0.9999}$ $\boldsymbol{(a,b) = (0.03633, -0.6827)}$	$\boldsymbol{R^2 = 0.9987}$ $\boldsymbol{(a,b) = (0.1583, -1.013)}$	$R^2 = 0.6981$ $(a,b) = (0.01103, -0.3363)$	$\boldsymbol{R^2 = 0.9949}$ $\boldsymbol{(a,b) = (0.3578, -1.256)}$
PT460 tube plate	$\boldsymbol{R^2 = 0.9863}$ $\boldsymbol{(a,b) = (0.6478, -0.4116)}$	$R^2 = 0.7757$ $(a,b) = (4.443, -0.3747)$	$R^2 = 0.6830$ $(a,b) = (7.037, -0.3641)$	N/A
ASME-B36 pipework	$\boldsymbol{R^2 = 0.9977}$ $\boldsymbol{(a,b) = (1.103, -0.5376)}$	$\boldsymbol{R^2 = 0.8722}$ $\boldsymbol{(a,b) = (6.904, -0.5043)}$	$\boldsymbol{R^2 = 0.8978}$ $\boldsymbol{(a,b) = (4.885, -0.2158)}$	$\boldsymbol{R^2 = 0.9994}$ $\boldsymbol{(a,b) = (1.148, 0.1246)}$
Welded PT460	$\boldsymbol{R^2 = 0.9553}$ $\boldsymbol{(a,b) = (2.152, -0.6718)}$	$\boldsymbol{R^2 = 0.9999}$ $\boldsymbol{(a,b) = (11.25, -0.6453)}$	$R^2 = 0.6170$ $(a,b) = (6.163, -0.2612)$	$R^2 = 0.6594$ $(a,b) = (3.228, -0.1115)$

6.6 Instrument measurements

6.6.1 Measurements using the Corrator and pH transducer

The condensate at each mill is known to have varying compositions during the crushing season owing to the changing composition of impurities in the cane juice, and the subsequent changes in the decomposition reactions during juice evaporation. As a result, markedly different corrosivity characteristics are expected to be imposed on the coupons. For this reason, on-line measurements of pH and corrosion rate using a Corrator were undertaken at all four factories. Because only one set of transducers was available these were moved among the factories. The logistics of visiting mills to check on the transducers and coupons and download the collected data means that the measurement times at individual factories were limited to 10 to 22 days.

For all the tests the Corrator was fitted with two carbon steel electrodes. When comparing the Corrator corrosion rates with the rates measured using coupons the most realistic comparison is to the 30-day rates for the ASME-B36 coupons.

At each factory at the same time that the coupons were installed into the rig the Corrator and pH transducer were installed into line 4 for a period of several days. Unfortunately, at Pioneer Mill, the Corrator data are not available as the transducer was damaged during installation.

The Corrator measures the instantaneous corrosion rate and so often shows a fluctuating signal. It appears that disturbances to the flow rate and short-term fluctuations in pH often disturb the Corrator signal for an extended period before settling down. At all four sites the Corrator data indicated much higher corrosion rates than measured by the coupons.

At each mill site a sample of condensate was obtained, and the pH measured in the mill laboratory. The values were in reasonably close agreement to the on-line pH transducer value.

6.6.2 Results of Corrator and pH measurements

The measurements of corrosion rate and pH for the tests at Isis Mill are shown in Figure 24. During the 2020 season Isis Mill often stopped at weekends and this interruption to crushing is clearly visible from both the corrosion rate data and pH data. The main observations from the measurements at Isis Mill are:

- During crushing the pH of the final condensate averages ~9
- The corrosion rate is highest at the start of crushing after the weekend stop and then steadily declines over the subsequent days.
- The instantaneous corrosion rate varies from ~2 mm/year to 1.5 mm/year over the 5-day crushing period. These values compare with the 30-day coupon rates for ASME-B36 (pipework) of 0.15 to 0.18 mm/year.

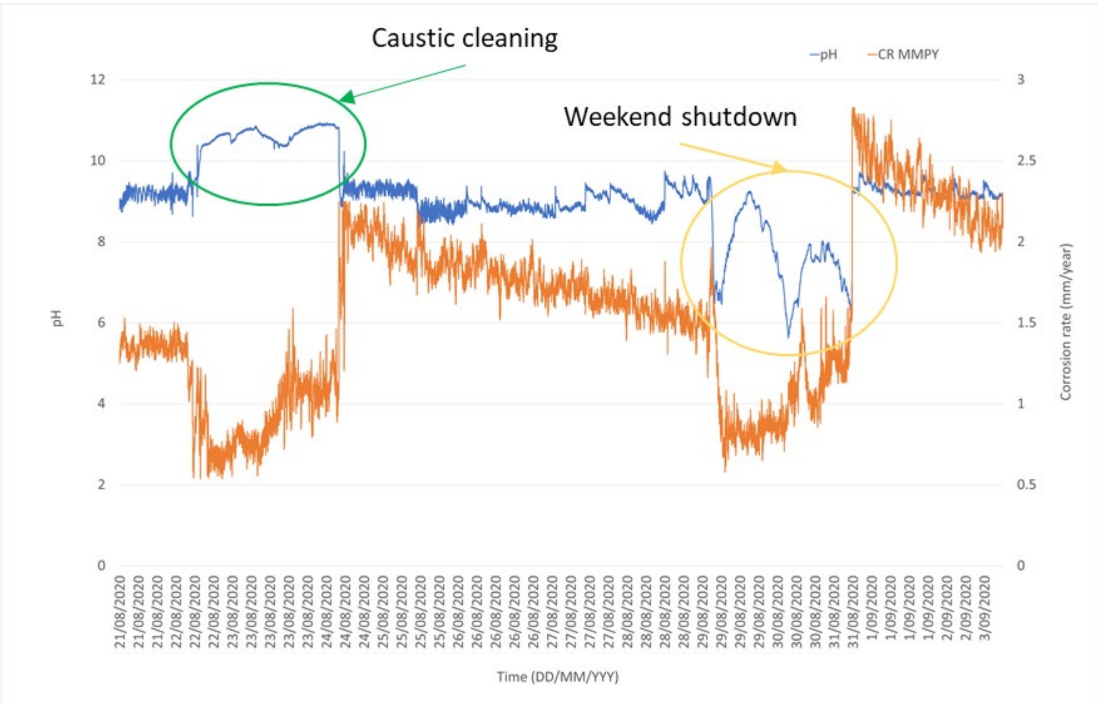

Figure 24 pH and Corrator corrosion rate measurements at Isis Mill.

Figure 25 shows the Corrator and pH data for the final condensate at Invicta Mill. For the test period at Invicta Mill the pH of the final condensate averaged ~7 which is substantially higher than measured previously in several trials (usually pH is 4.6 to 4.8). The instantaneous corrosion rate measurements ranged between 4 and 10 mm/year. These values compare with the 30-day coupon corrosion rates for ASME-B36 (pipework) of ~1.2 mm/year.

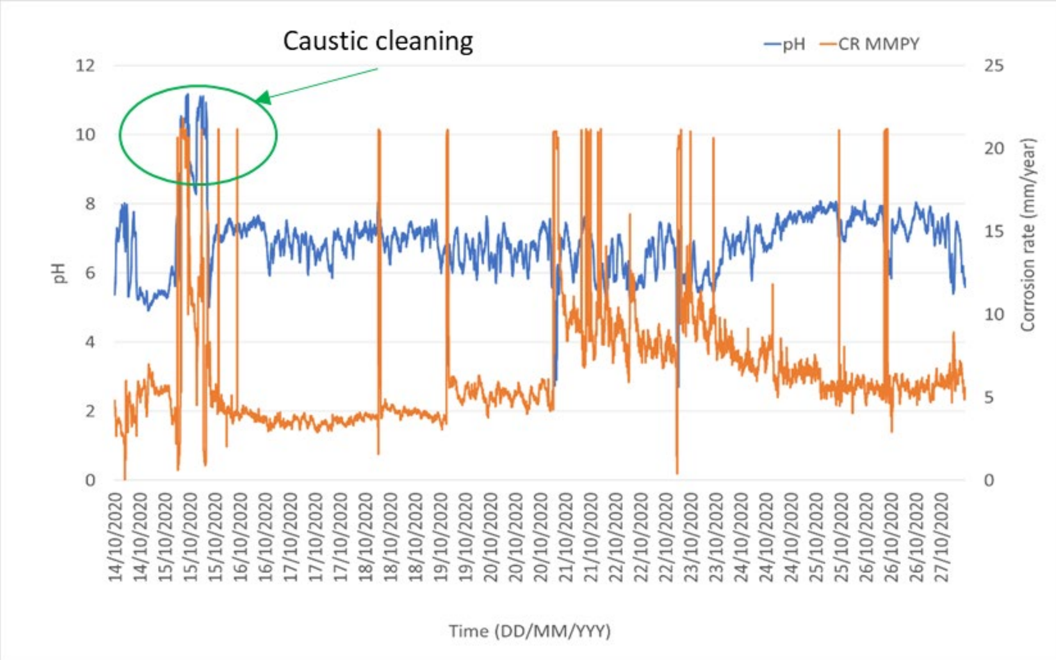

Figure 25 pH and Corrator corrosion rate measurements at Invicta Mill.

As mentioned previously Corrator data are not available for Pioneer Mill. For the period between the chemical cleans with steady juice processing conditions the pH of the final condensate at Pioneer Mill was generally in the range 5 to 6.

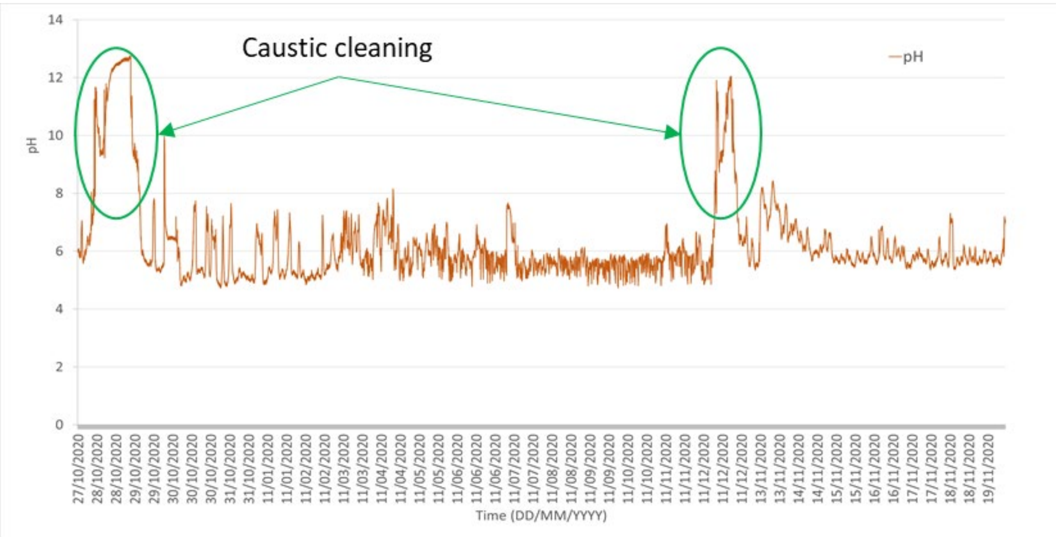

Figure 26 pH measurements at Pioneer Mill.

The pH and Corrator corrosion rate data for Condong Mill are shown in Figure 27. During steady juice processing and between the periods of chemical cleaning the pH of the final condensate was ~5.5. Instantaneous corrosion rate measurements were quite variable, ranging between 5 and 13 mm/year and averaging about 7 to 8 mm/year. These values compare with the 30-day coupon rates for ASME-B36 (pipework) of ~1.8 mm/year.

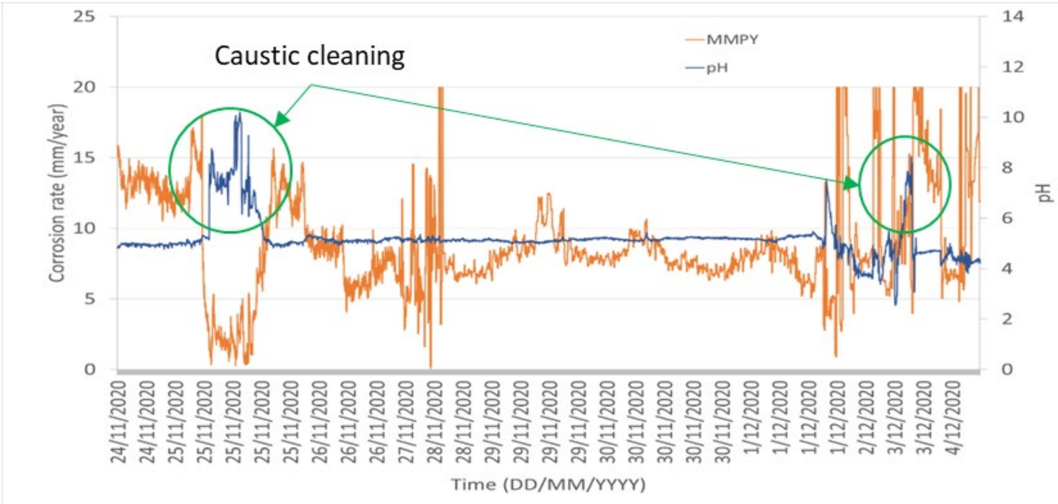

Figure 27 pH and Corrator corrosion rate measurements at Condong Mill.

At all four factories the instantaneous corrosion rates from the Corrator were substantially higher than measured for the coupons of ASME-B36 (pipework). The data are with 30-day exposure (refer Table 6). As was determined for the coupon tests and confirmed by the Corrator data the corrosion rates in the final condensate at Isis Mill were much lower than for the final condensates at the other mills. Unfortunately, without Corrator data for Pioneer it is difficult to rank the instantaneous corrosion rate data for the other mills but in general the Corrator data for Condong Mill is higher than for Invicta Mill which aligns with the coupon data for 30-day exposure of ASME-B36 (pipework).

Table 6 Comparison of ASME-B36 (pipework) coupon data and instantaneous corrosion rate by the Corrator

Factory	Corrosion rate via ASME-B36 coupon with 30-day exposure, mm/year	Corrosion rate via Corrator, mm/year
Isis	0.15 to 0.18	1.5 to 2.0
Invicta	1.2	4 to 10
Pioneer	2.4	NA
Condong	1.8	5 to 13

6.6.3 Further analysis of the online pH measurements

Figure 28 presents the on-line pH data as histograms for each factory. It should be noted that these distributions do not represent the entire 2020 season and were for the monitoring periods listed in Table 3. The data in Figure 28 are for the whole of the monitoring period and includes circumstances such as during chemical cleaning or weekend shutdowns. Condensate pH is divided into five ranges to show the frequency of certain pH ranges being experienced by the equipment. At Isis Mill, for more than 95% of the time the pH of the condensate was above 7, representing the least acidic condensate flow among the four tested factories. The final condensate at Invicta Mill A side was below 7 for more than 53% of the monitoring period. The frequency of having final condensate pH below 7 was more than 83% and 94% at Pioneer Mill and Condong Mill, respectively.

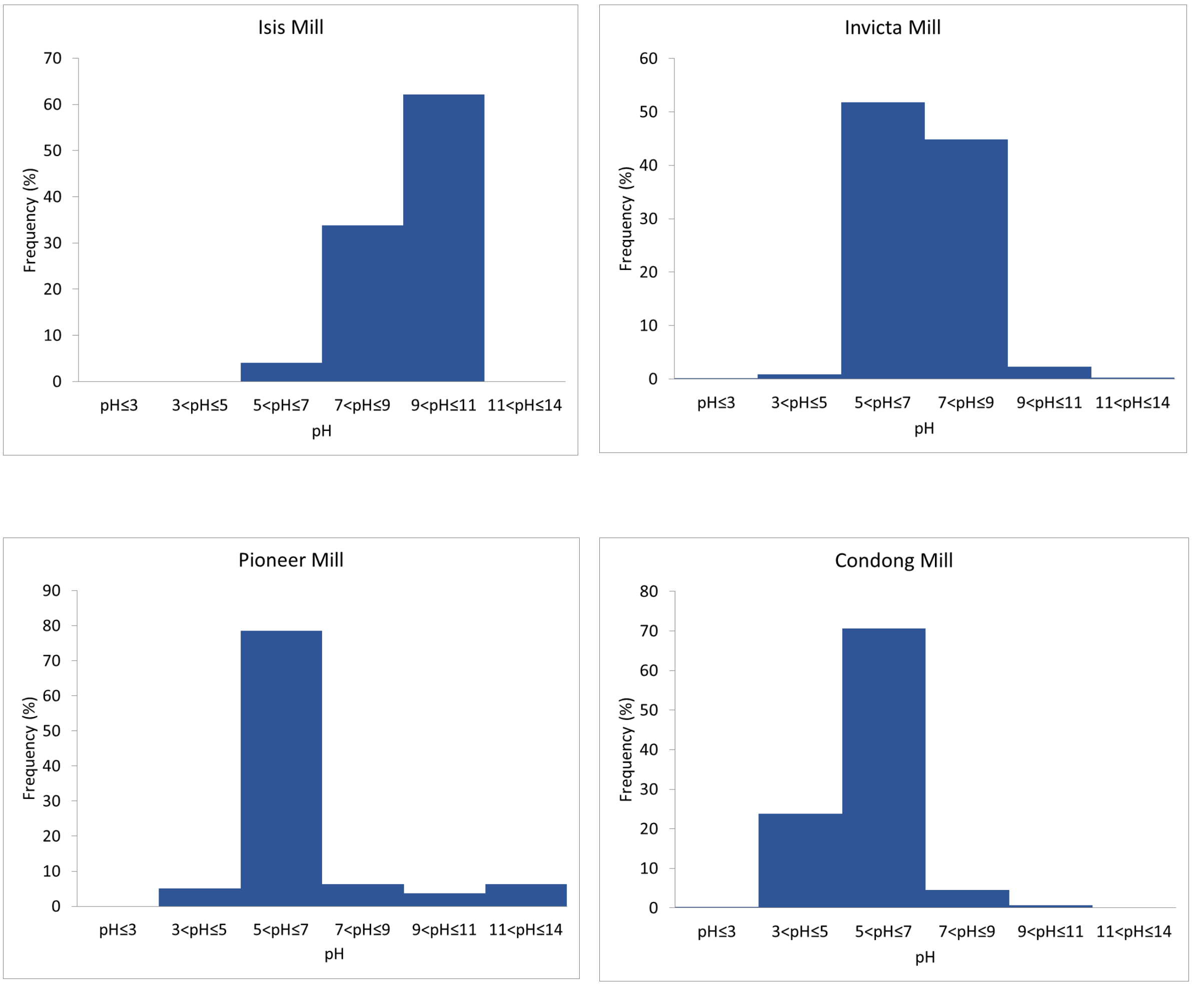

Figure 28 Distribution of on-line pH measurements at four factories.

Figure 29 shows a comparison of the monitored pH ranges for the four factories. The final condensates at Invicta, Pioneer and Condong Mills all had periods where the pH was below 5. Of these mills Condong Mill had the greatest proportion of pH measurements below 5. The lowest median pH was 5.1 which was recorded at Condong Mill. The median pH values for Isis Mill, Invicta Mill and Pioneer Mill were 9.2, 6.8 and 5.8, respectively.

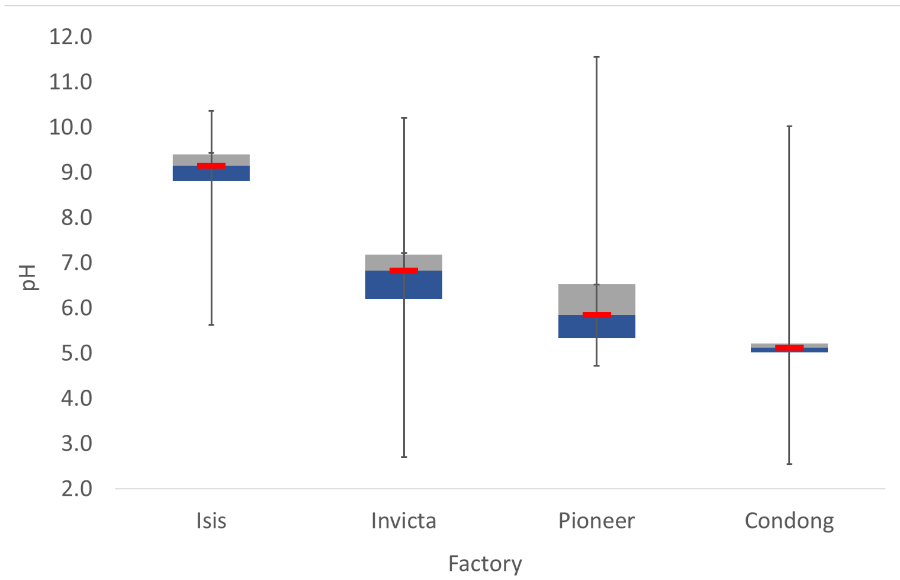

Figure 29 Comparison of measured pH values of the four factories.

7. CONCLUSIONS

The measured corrosion rates in final condensates using the coupon method and the Corrator have shown a very wide range of rates among the four test materials for the four factories. At Isis Mill the final condensate which consistently has the highest pH of the four mills had the lowest corrosion rates for all carbon steel coupon materials and the Corrator.

The final condensates at Pioneer Mill and Condong Mill showed the highest corrosion rates. The corrosion rates of the tube plate coupons at Pioneer and Condong Mills (both steam efficient factories) were 15 times faster than the tube plate coupons at Isis Mill (non-steam efficient factory). Previous studies by QUT have been shown that both Pioneer and Condong Mills experience substantial sucrose and monosaccharide degradation leading to acid formation in the juice, and subsequent volatalisation of these acids into vapour and condensate. Final condensates at Condong Mill have the lowest pH of the condensates at the four mills.

For both Pioneer and Condong Mills it was also determined that the welded tube plate coupons corroded at a faster rate (10 to 30% faster) than the plain section of tube plate material. On the other hand, at Isis and Invicta Mills the corrosion rates of the welded tube plate material and the plain tube plate coupons corroded at similar rates. For both Pioneer and Condong Mills the ASME-B36 pipework coupons corroded at a faster rate (~30% faster) than the tube plate material. At Isis and Invicta Mills the ASME-B36 pipework coupons corroded at a similar rate as the tube plate material.

The corrosion rates in the final condensates at Invicta Mill are intermediate between the high and low rates shown by the other three mills and the pH at Invicta during the period of on-line testing was intermediate between the values for the other mills. Invicta Mill generally shows relatively low levels of sucrose degradation and the often-present acidic compounds in the final condensate are attributed to the juice composition and perhaps decomposition products formed in the diffuser.

As would be expected the 304 stainless steel coupons showed much lower corrosion rates than the carbon steel coupons. The differences in corrosion rates between the stainless steel coupons and the carbon steel coupons were greatest at Pioneer and Condong Mills with the stainless steel showing 1/1000th the rate of corrosion.

The measurements of corrosion rates in final condensates at the four mills have demonstrated that the acidic compounds produced through sucrose and monosaccharide degradation of juice during evaporation, as has been measured in previous studies at Pioneer and Condong Mills, are highly corrosive and much more corrosive than experienced at non-steam efficient factories such as at Isis and Invicta. The acidic condensates produced at Invicta Mill, while still corrosive, appear to be not as aggressive as those at Pioneer and Condong Mills. In relative terms the high pH of the condensates at Isis Mill has provided a very mild corrosive environment.

The study highlights the need by the industry to determine appropriate solutions to allow factories to pursue high levels of steam economy but at the same time ensure the investment in process plant is secure.

8. RECOMMENDATIONS FOR FURTHER RD&A

The measurements of corrosion rates by both the coupon and Corrator methods have identified that the acid formation in steam efficient factories, under the current procedures being used in Australian factories, does result in very high corrosion rates of carbon steel pipework (ASME-B36) and tube plate material (PT460). Modified designs of evaporators, uses of alternative materials of construction (e.g., 304 stainless steel) and/or chemical dosing to mitigate the acid formation in juice, are potential solutions. It is also noted that Central American sugar factories extensively use ASTM A36 for tube plates in evaporators in combination with stainless steel bodies and bases. Further investigation of the corrosivity, availability, suitability and cost of this tube plate material should be undertaken. The study must also consider the potential galvanic corrosion between dissimilar metals.

It is noted that the use of smaller diameter, longer heating tubes incorporated into the SRI design of Robert evaporator reduces the residence time for juice and the extent of sucrose degradation and subsequent acid formation. The use of falling film tube evaporators instead of Robert evaporators would also provide shorter residence times for juice and reduced sucrose degradation and acid formation. Also, a current SRA project (2017/007) is being undertaken by QUT to identify suitable chemical dosing mitigation strategies to limit sucrose degradation of juice and subsequent acid formation.

Final condensate pipework should be replaced with 304 stainless steel pipe when the carbon steel pipework needs replacing.

It is recommended that a cost benefit analysis is undertaken into the construction of Robert evaporators with 304 stainless steel to compare with the conventional construction of carbon steel bodies and tube plates.

9. PUBLICATIONS

At the time of preparing this report no publication of the results from this project has been made.

Seminars to report the results and application into the industry will be presented to mill staff in all the cane growing regions in the Research Seminar series to be conducted in March/April 2022. A preliminary overview of the project was presented at the Research Seminars in March 2021.

10. ACKNOWLEDGEMENTS

The assistance provided by the management, engineering and production staff at Isis, Invicta, Pioneer and Condong Mills is appreciated.

The technical input from Mr Neil McKenzie of QUT in the design of the experimental rigs is greatly appreciated.

The Design and Manufacturing Centre of QUT manufactured the coupons and the housings. Their attention to detail is greatly appreciated.

The analyses of coupon samples including cleaning of corrosion products were undertaken at QUT Laboratories.

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12. APPENDIX

12.1 Appendix 1 METADATA DISCLOSURE

TABLE 7 METADATA DISCLOSURE 1

Data	Data for corrosion rates of coupons (four materials, four factories and 3 exposure times) Data for on-line measurements of corrosion rates using the Corrator Data for on-line measurements of pH of final condensates Corrosion rate models based on the Power Law
Stored Location	Server for projects undertaken at QUT by the Centre for Agriculture and the Bioeconomy (CAB)
Access	Restricted to CAB staff
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