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CS Energy (Callide Power Station)

Cooling Towers CT3 and CT4

Investigation into Failures and Root Cause Analysis

Report No 2210001-RCA1 - Rev 0

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Ray Hartzenberg B.Sc. (Eng), RPEQ

HartzEPM Pty Ltd

Consulting Engineers and Project Managers

PO Box 667 Indooroopilly Centre

Indooroopilly QLD 4068

Table of Contents

List of Figures

List of Tables

Executive Summary

HartzEPM Pty Ltd (HEPM) was commissioned by Norton Rose Fulbright (NRF) to undertake an independent investigation into the root cause of the structural failures of the Callide C CT3 Cooling Tower (CT3), and whether there have been any structural failures of the Callide C CT 4 Cooling Tower (CT4) and, if so, the root cause of the structural failures. The cooling towers were located at the Callide Power Station, near Biloela, QLD.

This report discusses both CT3 and CT4 with more of a focus on CT3 where the failures took place. Since the towers are identical in design, in this report they have been jointly considered unless noted otherwise.

To assist with the preparation of this is report, NRF provided an annexure of factual matters which are to be assumed for the opinions expressed in this report. The factual matters provided includes the operating conditions of the CT3 before the incident.

In addition to the factual matters mentioned above, NRF also provided numerous reports on the cooling towers from 2002 to 2023. A large catalogue of photographs and video footage was provided which showed the condition of the towers at various stages through its life.

The root cause of the failure in CT3 has been concluded to be unfavourable water chemistry. The tower has operated at concentrations of Free Residual Chlorine and pH above the industry recommended levels. This has resulted in the delignification of the timber and loss of member cross-section with a consequent loss of strength.

While the root cause has been identified to be the unfavourable water chemistry, there are other contributing factors that led to the partial collapse of CT3. Those factors include the degraded condition of the CT3 structure, and the difficulties with regard to access in order to inspect and carry out maintenance and repairs.

Failure and Operating Conditions

On Monday 31st October 2022 at approximately 1:20pm, cells 8 and 9 north, i.e. the northern wet zone of CT3 collapsed. At the time of the collapse the following operating conditions were in place:

- Of the 36 hot water basins (HWB), 23 were in service and the remainder were isolated.
- HWB’s in cells 1, 2, and 3 north and south were out of service.
- HWB’s in cells 4 to 8 south, cells 5 and 11 north were out of service.
- During operation, the HWB the distribution valves were throttled to 75% open and were being further throttled to 50% open.
- Overflow slots had been cut into the HWB side walls, which were a secondary control measure to control the water levels in the HWB to the throttling of the valves.
- Twelve Aggreko portable cooling towers were in service being the equivalent of 2 cells.
- Two cooling water distribution pumps were in service.

In the months preceding the collapse the following was observed and/or were the operating conditions of CT3:

- On Tuesday 25th January 2022, an internal collapse occurred in the wet zone on the south side of CT3 Cell 1. The HWB in cell 1 and 2 South had sagged noticeably.
- On Tuesday 1 February 2022, the distribution valve was closed to the south side of cell 1 where the internal collapse occurred.
- CT3 operated as normal with 2 pumps running and with cell 1 south isolated until the planned outage in March 2022.
- During the March 2022 outage inspections and repairs were carried out. Repairs included:
  - Repairs in cells 9 to 18 north and south wet zones.
  - Two columns in cell 11 north side wet zone were repaired and subsequently two more columns in cell 11 north side wet zone were identified as needing repair.
- On Tuesday 5 May 2022 the outage ended, and the tower was returned to service with 1 pump operating. Cells 1 to 3 and 4 to 8 south were isolated.
- On Friday 16 September 2022 the second pump was put into operation and the tower was operated with 2 pumps in service.
- On Friday 30th September 2022 sagging was visually observed in the HWB of cells 5 and 11 north. At this time the operation of CT3 reverted to 1 pump.
- Generally, with 1 pump operating the water depth in the HWB was at half depth and assumed to be 100 to 125mm since no depth measurements were made. With 2 pumps running the HWB was essentially running full to overtopping, i.e., at a depth of 200 mm to 213 mm, the latter of which is the depth of the HWB. The design operating water depth of the cooling tower is 153 mm.
- As a mitigation measure to limit the depth of water in the HWB and to improve the performance of the CT3 the following was implemented:
  - Valves were throttled back to 75% open in order to limit the depth of the water in the HWB.
  - Overflow slots were cut into the side of the HWB. These were 100 mm high and 2000 mm wide and there were two in each cell adjacent to cell divider walls. The purpose of these was to limit the depth of water in the HWB to around 100mm and were a secondary measure to throttling the valves as noted above.
  - The valves were being further throttled to 50% open following overflowing of the HWB.
  - Twelve Aggreko portable cooling towers were put in service to make up some of the lost capacity. This is equivalent to two cells.
- On Friday 28th October 2022 the second pump was put into service and the CT3 was being operated with two pumps.
- As noted above, the collapse occurred on Monday 31st October 2022 at approximately 1:20pm.

Inspections by HartzEPM

HEPM carried out four inspections of the cooling towers as follows:

- HEPM site visit No. 1 was undertaken on 15th and 16th November 2022. This inspection took place externally outside of a 16m exclusion zone. Close up and internal inspection of the tower was prohibited for safety reasons.
- HEPM site visit No. 2 was undertaken on 20th and 21st December 2022. This inspection was undertaken from the walkway in the plenum or dry zone. It generally did not include viewing the wet zone.
- HEPM site visit No. 3 was undertaken on 10th and 12th January 2023. This inspection was limited to cells 17 and 18 in CT3 and cells 1 and 2 in C4 CT. Drift eliminator panels were removed such that the inside of the wet zones immediately behind could be viewed. This inspection was done on three levels for one cooling tower bay, but limited to either the north or side of each cell inspected. Further details of the extent of the inspections are contained in the body of the report.
- HEPM site visit No. 4 was undertaken on 19th and 20th June 2023 as part the preparatory work for the demolition of CT4. The inspection was undertaken on the southern façade of CT4 in order the assess the adequacy of the elements and fastenings, so that workman could safely approach the perimeter of the CT4, to carry out work on services such as pipework and electrical infrastructure.

Structural Condition

Regarding the overall condition of the towers, based on the inspections above and previous reports, the most notable observations include the following:

- Many of the connections observed were loose, with loose nuts and bolts and shear connectors disengaged.
- Columns and girts were misaligned at splice points.
- Undersized washers were used under nut and bolt heads.
- The timber used had defects incongruent with the stress grade for which the tower was designed. The defects included large knots.
- Most notably, many of the timber members had surface erosion consistent with chemical attack. This is potentially widespread in the wet zone.
- Many of the timber strips supporting the fill splash bar had failed leading to widespread collapse of the fill.
- There were columns reportedly “broken” and columns which were buckled.

Based on a limited number of measurements taken during the inspections, HEPM carried out calculations to assess the residual load carrying capacity of the timbers. The timber condition is poor and findings are as below:

- Twenty six percent (26%) of girts have less than 50% of bending strength remaining, while 9% have less than 50% of axial strength remaining.

- Forty eight percent (48%) of girts have between 50% and 70% of both bending strength and axial strength remaining.
- Twenty six percent (26%) of girts have great than 70% of bending strength remaining, while 43% have less than 50% of axial strength remaining.
- The column measured has lost 35% of its cross-sectional area, while the diagonal brace measured has lost more than 20% of its cross-sectional area.

Water Chemistry

Regarding acceptable water chemistry parameters for concentrations of Free Residual Chlorine and pH, NRF have instructed HEPM to adopt the findings contained in the report by Power Plant Chemical Engineering dated 01 December 2023. The report tabulates concentrations from a number of sources and the concentrations assumed to be appropriate is that by Cooling Tower Manufacturer – Marley – 600 Crossflow Cooling Tower User Manual – Preferred Cooling Tower Water Condition Limits For Standard Construction Material, in which the concentration of Free Residual Chlorine is nominated as "1ppm free residual (shock), or 0.4 ppm continuously"

NRF provided data for the cooling water chemistry in various forms and with differing content from November 2000 to October 2022. The chemistry parameters included in the data included parameters such as water pH, SEC, Turbidity, Sodium, Salt levels (Potassium, Calcium, Magnesium, Chlorides, Sulphates and Silica), p-alkalinity, m-alkalinity, and residual free chlorine. In the case of the residual free chlorine data provided covered the period from July 2007 to October 2022.

While there appear to be no firm regulations around the levels of chemical concentrations that cooling tower water should have, there are industry guidelines. The two chemical parameters that are important with respect to their effect on timber cooling towers, Free Residual Chlorine, and pH. For the purposes of this report, we have adopted levels for Free Residual Chlorine and pH of 0.4 to 1.0 ppm and 7.8 to 8.3 respectively. While we have adopted these values for the report, it should be noted that there are no set standards mandating what these levels should be. When these two parameters are both high, then the timbers exposed are highly vulnerable to chemical erosion.

For many years cooling towers CT3 and CT4 were being operated at elevated levels of chlorine up to 4 ppm. Simultaneously high pH levels were also recorded in the range from 7.5 to 8.5. It is noted that the high chlorine levels were implemented to a maintain a legionella count of zero.

The reader is encouraged to read the water chemistry section of the report in detail given the complex nature of the treatments and the changes to the water treatment process over the life of the tower.

CT3 Collapse Triggers

Two dimensional frame analyses were carried for the tower loads in the operating condition. These analyses yielded the design action effects (design forces) in the primary structural members of the tower. In addition, the members capacities were calculated to compare with the design action effects determined in the analyses. This comparison of member capacity and design action effect provides an indication member stress as a fraction of carrying capacity. Of particular interest were the maximum forces in the columns in the wet area. To account for the level of timber erosion and based on earlier measurements, the remaining cross section of the column was assessed to be 80mm x 80mm whereas the original cross section is 100mm x 100mm. The following table shows the findings when HWB loading is applied:

Load Case	Axial Force N* (kN) Ultimate Limit State	Column ultimate axial load capacity ϕN_c (kN) 100 x 100 F8 Full section	Column ultimate axial load capacity ϕN_c (kN) 80 x 80 F8 Eroded Section	Section Utilization Full/Eroded Section. Overstress greater than 5% shown red
Dead Load + 75mm water	43.9	45.0	28.8	0.97/1.52
Dead Load + 125 mm water	45.6	45.0	28.8	1.01/1.58
Dead Load + 175 mm water	47.4	45.0	28.8	1.05/1.64

The table illustrates that the original design of the columns fully utilised the column capacity. With a residual section of 80 x 80 mm, it illustrates that the columns are overstressed with as little as 75mm of hot water in the HWB. When this is considered together with buckled or broken columns in the wet zone, then the water load in the HWB is a likely trigger for the collapse that occurred.

Wind loading was also applied and compared to wind at the time of the collapse. All things being equal the tower was structurally adequate for a permissible wind speed of 96km/h. For the time period from 12h50 to 13h40 on the day of the collapse, the maximum gust recorded was 40.7 km/h at 13h14 at the weather station at Thangool airport. Wind is therefore not considered a likely trigger for the collapse.

Overflow slots were cut into the sides of the HWB, and water would overflow and impact the louvre sheets below. It is difficult to predict the force that the overflowing water imposes on the louvre sheet and therefore the force on the louvre support timber. However, it is considered that the louvre sheet would fail first and act as a fuse, leaving the support members intact. The overflowing water impacting the louvres is therefore not considered a likely trigger for the collapse.

Water hammer was also considered but is not thought to be a trigger for the collapse.

A potential collapse sequence is presented in the report and starts with the collapse of the first vertical column adjacent to the basin wall. Other collapse sequences are possible.

Root Cause

The unfavourable water chemistry is concluded to be the root cause of the failures. The problem with the water chemistry are the high levels of Free Residual Chlorine and high pH. The high chlorine residual and high pH occurred simultaneously and has been prevalent for long periods and likely for the life of the towers.

Considering the age of the cooling towers of approximately 20 to 21 years the following comments are made:

- The advanced chemical erosion has made the defects in the timber prematurely significant. Whereas in a timber cooling tower of similar age, the timber would not have eroded to the extent such that defects such as knots would have resulted in being significantly weak spots in members. It could be expected that there may be an isolated member or members that become of concern which could be safely repaired or replaced before they became critical.

- Chemical erosion causes holes to get larger. Shear disc recesses have also become larger and the contact surfaces thinner or almost non-existent thus making these ineffective and making the joint more prone to failure.
- While regular retightening of the connections could be carried out, there would be a limit to the number of times this could be done with the continuing loss of and the softening of the outer layers of the timber members due to the accelerated rate of chemical erosion. This is further exacerbated by the relatively small size of the washers which has the effect of compressing into the soft timber surfaces and not distributing the pressure under nuts and bolt heads.
- Loosening of the bolts would be exacerbated by the vibrations in the tower due to the operation of the mechanical equipment, and further exacerbated when items such as the fan wearing unevenly thus creating additional out of balance forces. This ought not be significant in a structure where connections are not compromised by excessive erosion.
- The bracing system and the resulting additional flexibility of the structure is not of itself an issue, but in a structure with thinning members and loose connections it exacerbates issues with loose connections, timber defects, creating a loop in which loose connections allows more flexibility, and more flexibility allowing further loosening etc.

It is unusual for a failure such as this to have been the result of a single issue, and more often than not it is a result of a combination of issues. All the of the above issues have contributed to the collapse, however collapse would have been unlikely had the timber not been so adversely eroded by exposure to the high concentrations of chlorine and high pH.

1 Introduction

1.1 Background

Callide Power Station comprises two functioning facilities, Callide B, and the Callide Power Plant (Callide C). At Callide C there are two 18 cell timber cooling towers, cooling towers CT3 and CT4 respectively, which are the subject of this report. The station is operated by CS Energy and located approximately 18 kilometres to the east of the town of Biloela in Central Queensland in the Shire of Banana. Callide C was commissioned in 2001 is owned in a joint venture agreement by CS Energy and Intergen.

Reliable performance of cooling towers in controlling water temperature is an integral part of the steam generation and condensation cycle of power generating plants. The life span and performance of cooling towers are contingent on the quality of the circulating water as well as periodic maintenance of the tower superstructure. Maintenance includes regular inspections of all parts of the structure, replacement of degraded and decayed timber members, re-tightening connections, servicing mechanical equipment and water dosing equipment.

Following a partial collapse in cells 8 and 9 of cooling tower CT3, HartzEPM (HEPM) was commissioned by Norton Rose Fulbright (NRF) to investigate the root causes of the collapse, whether there have been structural failures of cooling tower CT4, and to carry out in inspections of the cooling towers. It is worth noting that a partial collapse occurred in cell 1 in CT3 in early January 2022 prior to the collapse mentioned above.

1.2 Description of the cooling towers

Cooling towers CT3 and CT4 were commissioned in 2001. They are designated as Marley Class 600 design cross flow, induced draft, splash filled type towers. Technical performance specifications from the Callide Power Station Operation and Maintenance Manual by Marley Temcel Australia Pty Ltd shows the following performance criteria:

- Design Flow Rate 40,451 m^3/hr
- Hot Water Temperature 33.14 °C
- Cold Water Temperature 23.00 °C
- Wet bulb temperature 18.64 °C

Based on the Callide Power Station Operation and Maintenance Manual by Marley Temcel Australia Technical Data Sheet, details of the cooling tower structure are as follows:

- Number of cells 18
- Orientation: The towers run lengthwise in an east to west direction. In both towers CT3 and CT4 the cells are numbered from cell 1 (east), to cell 18 (west). Refer to Figure 1.1.
- Dimensions
  - Length 197.70 m
  - Width 26.44 m
  - Height from basin kerb to top of fan stack 18.54 m
  - Height from basin kerb to top of fan deck 14.27 m

  - Nominal cell length — 10.98 m
  - Nominal cell width — 26.44 m
  - Longitudinal column spacing — 1.83 m
  - Lateral column spacing — 1.83 m
- Tower framing
  - Material — Timber
    - Species — Radiata Pine
    - Grade — F8
  - Column size — 100 x 100 mm
  - Bracing size — 100 x 100 mm
  - Transverse girt — 2/100 mm x 50 mm
  - Longitudinal girts — 100 mm x 70 mm
  - Structural connectors — Glass Reinforced Plastic (GRP)
  - Anchor brackets — Stainless Steel
- Structural design parameters and references
  - National Design Specification for Wood Construction 1997 (NDS)
  - AISC Manual of Steel Construction
  - Cooling Tower Institute Standard Specifications, CTI STD-119
  - Marley in-house design standards (based on testing by Marley Cooling Tower)
  - Australian Standard, 1170.2 & 1170.4
  - British Standard 5268 Part 2
  - Design dynamic wind pressure — AS1170 (Load details not shown)
  - Design loading on decks, stairs, etc.
    - Distributed live load — AS1170 (Load details not shown)
    - Concentrated live load — AS1170 (Load details not shown)

Further tower information and data are contained in the Callide Power Station Operation and Maintenance Manual by Marley Temcel Australia in Appendix N.

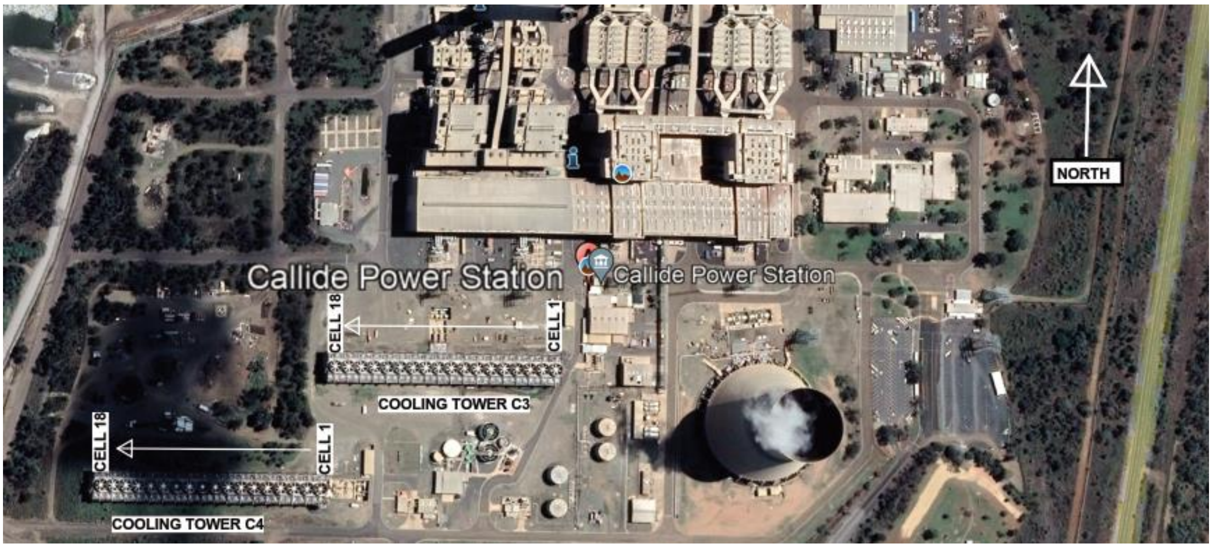


Figure 1.1 Aerial view of the cooling towers showing orientation

Figure 1.2 Cooling Tower CT3 viewed from the north-east showing collapsed cells 8 and 9

Figure 1.3 Cooling Tower CT4 viewed from the south-east

1.3 Scope of Work

HartzEPM was commissioned by Norton Rose Fulbright (NRF) to undertake the following investigations and inspections:

- The root cause of the structural failures of the Callide C CT3 Cooling Tower for the purpose of enabling NRF to provide legal advice to CS Energy and in respect of anticipated litigation which may arise.
- Whether there have been any structural failures of the Callide C CT4 Cooling Tower and, if so, the root cause of the structural failures for the purpose of enabling NRF to provide legal advice to CS Energy and in respect of anticipated litigation which may arise.
- Attendance on site to inspect the Callide C CT3 and CT4 Cooling Towers for the purposes of the investigation. Undergo site inductions and comply with CS Energy's site access requirements.

1.4 Recent incidents at cooling tower CT3

Most recently in 2022 the following incidents occurred in cooling tower CT3:

- A collapse of cell 1 in January 2022 which was reported on by Marley Flow Control in two separate reports the first of which is dated 8 April 2022, and the second report is undated. The findings of these reports are discussed further below.
- In October 2022, subsidence in the hot water basin in cell 11 was noticed and an inspection was carried out. A brief report dated 5 October was prepared following this inspection.
- On 31 October 2022 there was partial collapse of cells 8 and 9 on the north side of cooling tower CT3.

- Other observations as reported in the Marley reports noted above, is that the hot water basins of cells 1, 2 and 7 on the south side of cooling tower CT3 had subsided, as did the hot water basin of the north side of cell 2. This is in addition to the subsidence in cell 11 noted above.

  The findings of these reports are discussed further below.

Figure 1.4 Cooling tower CT3 - Cell 1 internal collapse (2022 Photo)

Figure 1.5 Cooling tower CT3 - Cells 1 and 2 hot water basin subsidence (2022 Photo)

Figure 1.6 Cooling tower CT3 - Collapsed cells 8 and 9 north (2022 Photo)

Figure 1.7 Cooling tower CT3 - Aerial view of cells 8 and 9 collapse (2022 photo)

2 Methodology

2.1 General

The general methodology followed is as follows:

- Request and gather as much information on the cooling towers as practicable. Given the age of the cooling towers it is acknowledged that relevant information may be difficult to find or may not be available at all. Information was provided by CS Energy through Norton Rose Fulbright.
- Carry out a desktop review of the information received.
- Carry out inspections of the cooling towers to confirm details as compared to the drawings provided. Inspections were carried out in both cooling towers CT3 and CT4. Inspections were limited to the plenum areas and to very limited sections of the wet areas but from the plenum, i.e. no access into the wet zone was possible as at the time it was a restricted area. Moreover, the fan deck and hot water basin could not be inspected since these were also restricted areas. During the inspections numerous photographs were taken and timber members were measured, and their conditions visually assessed. From these inspections a condition assessment report was prepared by HartzEPM.
- Develop a causal tree populated with the main problem, inputs, series of "why" questions, to arrive at a root cause. In situations such as this, failure is usually because of a combination of factors.
- The investigation will focus on the following factors to the extent possible depending on the information available and received:
  - Plant related factors:
    - Design
    - Design life
    - The towers as constructed
    - Material selection
    - Material condition
    - Environment – weather and loading
  - Process related factors:
    - Maintenance history
    - Operating conditions
    - Water quality
- The investigation will not include for the following:
  - People or organisation factors that may have contributed to the failure.
  - Repair scope for CT3 or CT4 cooling towers or its components.
  - Reverse engineering of the original design of the cooling towers. It is assumed that the design was adequate at the time of commissioning. The previous report by GHD in 2014, as well as the condition assessment report by HartzEPM will be referenced as required.

2.2 Team Members

Ray Hartzenberg – Team Leader and Principal Structural Engineer

Ray's areas of expertise are in the design management, the design of structures constructed of structural steel, reinforced concrete, timber, and fibre reinforced plastic. Ray has inspected cooling towers in distress and designed repairs and refurbishment for towers around Australia.

Qualifications

B.Sc. (Engineering) – University of Cape Town
Registered Professional Engineer of Queensland (RPEQ)

Raffi Andonian – Principal Mechanical Engineer

Raffi is experienced in the analyses of cooling tower operation in power station applications and in leading teams of multi-disciplinary engineers in the diagnoses of and finding optimal solutions for cooling tower problems. He has a keen attention to detail and in-depth technical analyses. Raffi is working under the direct supervision of Ray Hartzenberg.

Qualifications

Bachelor of Engineering (Mechanical, Hons) - University of Sydney
Master of Engineering (Mechanical) – University of Sydney
Bachelor of Science – University of Sydney

Andrew Nielsen – Senior Structural Engineer

Andrew has experience in structural engineering design, discipline management and project team lead, in the coal seam gas industry, mining/materials handling, highway and railway infrastructure, and commercial and industrial buildings.

Qualifications

Bachelor of Engineering – University of Technology Sydney
Masters Project Management – University of Queensland
Registered Professional Engineer of Queensland (RPEQ)

Declaration

It is declared the HartzEPM has been engaged and is currently providing consulting engineering services for the Callide Cooling Tower Rebuild Project to both CS Energy and the cooling tower contractor, Industrial Water Cooling Australasia Pty Ltd.

3 Cooling towers technical information

3.1 Cooling tower general specification

Cooling towers CT3 and CT4 were commissioned in 2001. They are designated as Marley Class 600 design cross flow, induced draft, splash filled type towers. Technical performance specifications from the Callide Power Station Operation and Maintenance Manual by Marley Temcel Australia Pty Ltd shows the following performance criteria:

• Design Flow Rate	40,451 m3/hr
• Hot Water Temperature	33.14 °C
• Cold Water Temperature	23.00 °C
• Wet bulb temperature	18.64 °C

Based on the Callide Power Station Operation and Maintenance Manual by Marley Temcel Australia Technical Data Sheet, details of the cooling tower structure are as follows:

• Number of cells	18

- Orientation – The towers run lengthwise in an east to west direction. In both towers CT3 and CT4 the cells are numbered from cell 1 (east), to cell 18 (west). Refer to Figure 1.1.
- Dimensions

– Length	197.70 m
– Width	26.44 m
– Height from basin kerb to top of fan stack	18.54 m
– Height from basin kerb to top of fan deck	14.27 m
– Nominal cell length	10.98 m
– Nominal cell width	26.44 m
– Longitudinal column spacing	1.83 m
– Lateral column spacing	1.83 m

- Tower framing

– Material	Timber
▪ Species	Radiata Pine
▪ Grade	F8
– Column size	100 x 100 mm
– Bracing size	100 x 100 mm
– Transverse girts	2/100 mm x 50 mm
– Longitudinal girts	100 mm x 70 mm
– Structural connectors	Glass reinforced plastic (GRP)
– Anchor brackets	Stainless Steel

- Structural design parameters and references
  - National Design Specification for Wood Construction 1997 (NDS)
  - AISC Manual of Steel Construction
  - Cooling Tower Institute Standard Specifications, CTI STD-119

- Marley in-house design standards (based on testing by Marley Cooling Tower)
- Australian Standard, 1170.2 & 1170.4
- British Standard 5268 Part 2
- Design dynamic wind pressure AS1170 (Load details not shown)
- Design loading on decks, stairs, etc.
  - Distributed live load AS1170 (Load details not shown)
  - Concentrated live load AS1170 (Load details not shown)

Further tower information and data are contained in the Callide Power Station Operation and Maintenance Manual by Marley Temcel Australia. Refer to Appendix P - Report titled CS Energy Assessment of Cooling Tower Elements.

3.2 Description of cooling towers

As tabulated above, each tower is 197.7m long and 26.44m wide and constructed out of timber. The height of the top of the fan stack and fan deck above the level of the cold water basin kerb level is 18.54m and 14.27m respectively. There are 18 cells per tower and each cell is 10.98m long and 26.44m wide at the level of the hot water basin. The cooling tower columns are spaced at 1.83m laterally and longitudinally forming transverse and longitudinal frames. There are 108 bays and 109 transverse frames in the longitudinal direction. In the transverse direction there are 10 bays at the level of the cold water basin, with a further two partial bays above the cold water basin wall.

There are 8 levels of transverse girts from the cold water basin up to the level of the hot water basin and these are spaced at 1.83m spacing. There is a further level of girts supporting the fan deck at 1.83m above the level of the hot water basin.

In the longitudinal direction, there are similarly 8 levels of longitudinal girts up to the hot water basin level coinciding with the transverse girts at 1.83m spacing. There is a further level of longitudinal girts at the fan deck level.

Refer to Figures 3.1 to 3.9.

3.3 Cooling tower bracing configuration

3.3.1 Transverse Bracing

From the drawings received it is unclear how the end and cell divider walls are braced transversely. The common method of bracing would be with diagonal braces which is how the intermediate transverse frames are braced. There are two alternative ways the required bracing could have been achieved as described below.

- The end wall is braced laterally by the end wall cladding while the cell divider wall frames are braced by the plywood sheets that separate the cells. This may or may not be the case, however the density of fasteners is low, which suggests that this may not be the case. It is possible that the designer is achieving a partial resistance to lateral forces from the plywood in these locations.
- The fan deck plywood floor acts as a horizontal diaphragm transferring the lateral loads at the end and cell divider walls to the adjacent cells. As above, the density of the fasteners fastening the plywood sheets to the supporting members is also low and therefore the transfer of lateral forces to the substructure may be compromised. Supportive of this method of bracing is the

fact the transverse frames immediately adjacent to the end and cell divider walls, have a total of 3 diagonal braces, refer to Figure 3.2, whereas the rest of the transverse frames have two, refer to Figure 3.3. This implies that cells with 3 diagonal braces are carrying a higher proportion of lateral loading. This is considered to be the most likely manner used by the designer for the transverse bracing of the tower. However, this method provides a circuitous load path to get the loads to ground, rather than the more direct as diagonal braces would do. For example, wind loads imposed on the outer upper half of the side of the tower, would have to be carried up via the columns up to fan deck level, then transferred horizontally through the fan deck diaphragm to the adjacent transverse frame/s, and down to ground through the diagonal braces.

3.3.2 Longitudinal bracing

The longitudinal bracing of the cooling tower is not continuous for the length of the tower. Based on the drawings of the cooling towers, of the 18 cells, cells 1, 3, 5, 7, 12, 16 and 18 have longitudinal braces on all longitudinal frames, refer to Figures 3.5 to 3.8. In cell 14 only three longitudinal frames are longitudinally braced, the edge of the fan deck on both sides and the inclined louvre columns. Cells 8 and 11 are longitudinally braced on two frames, on the edge of the fan deck on both sides. The remaining cells 2, 4, 6, 9, 10, 13, 15 and 17 have all longitudinal frames longitudinally braced. In this scenario the tower relies on the fan deck plywood to act as a horizontal diaphragm over the unbraced longitudinal frames, i.e., the end walls and the cell divider walls. In addition, the longitudinal girts would be required to act as struts/ties to transfer longitudinal loads from the unbraced cells to the braced cells. This is an indirect load path in getting longitudinal loads to ground. In this case the longitudinal loads to be transferred would be those from the operation of the mechanical equipment and wind longitudinal loads at the fan deck level. Longitudinal wind loads on the ends of the cooling tower structure would be resisted by the end cells 1 and 18 longitudinal bracing.

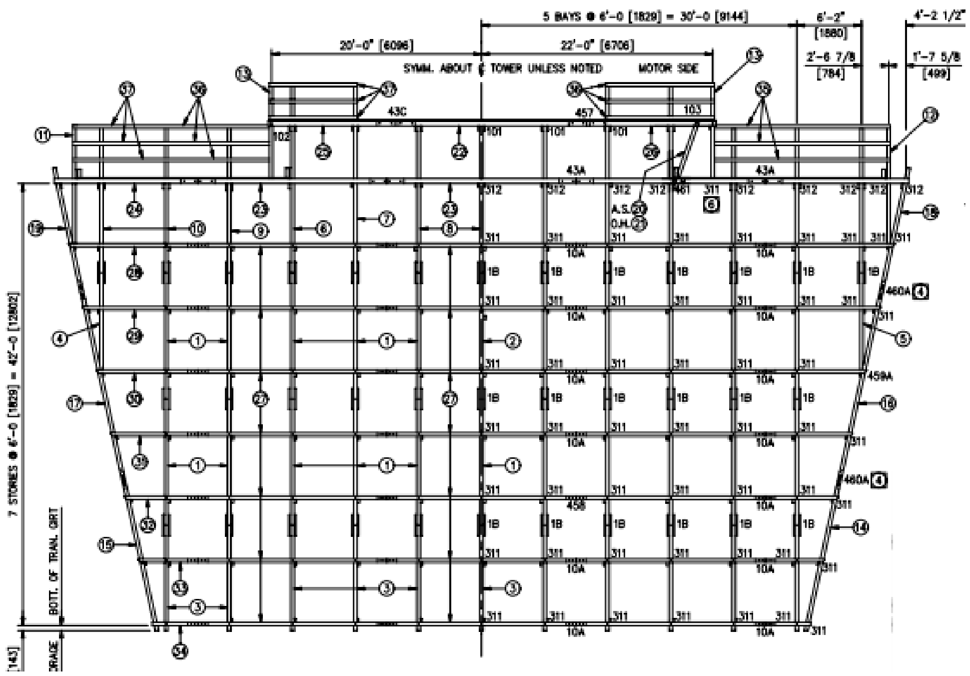


Figure 3.1 Typical end wall framing - note no diagonal bracing

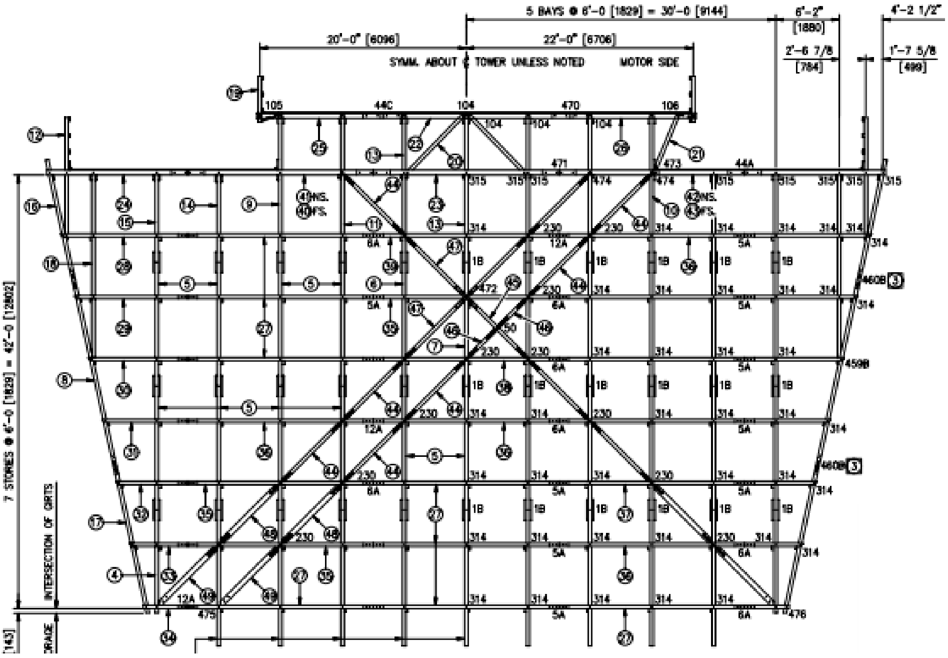


Figure 3.2 Typical frame adjacent at end and at cell divider walls – 3 transverse braces

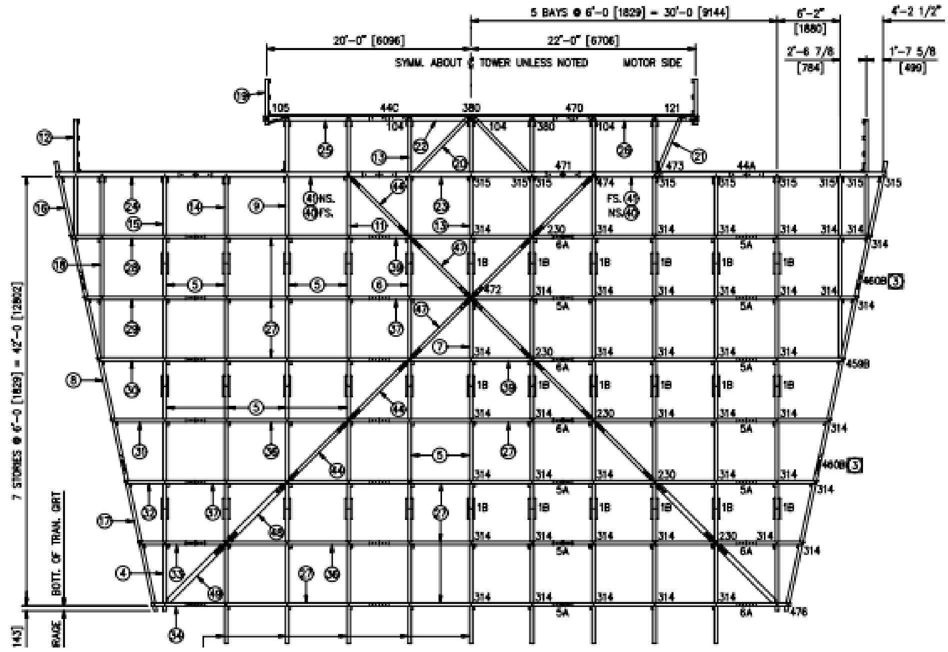


Figure 3.3 Internal transverse frame at cell third points – 2 transverse braces

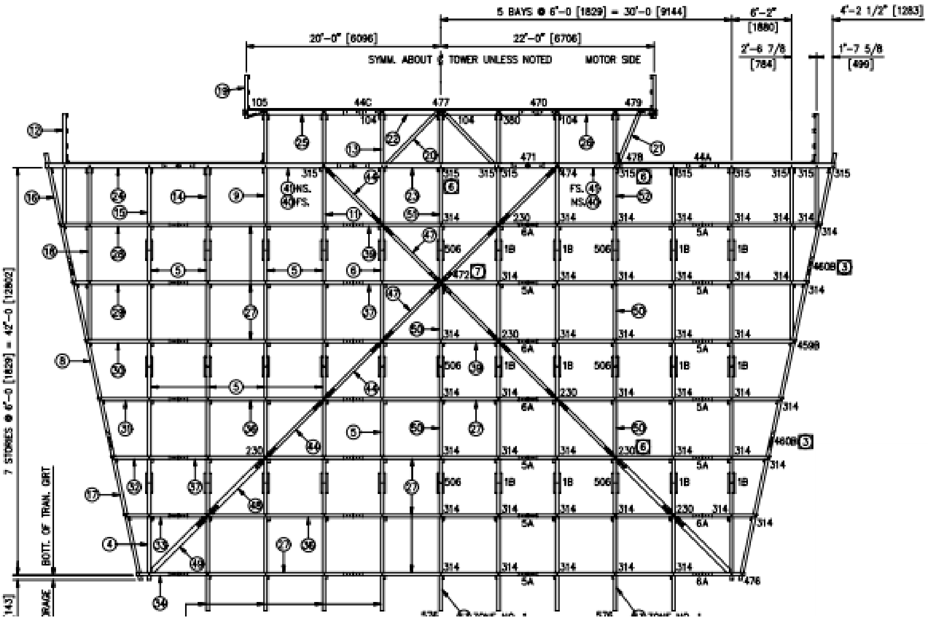


Figure 3.4 Transverse frame under fan - Central column is Fibre Reinforced Plastic (FRP)

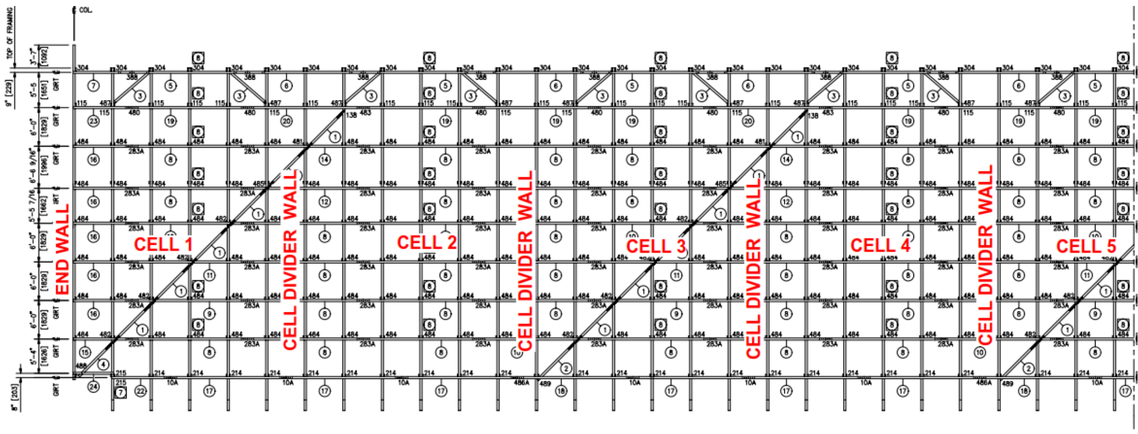


Figure 3.5 Typical longitudinal frame part 1 - Centre of cooling tower

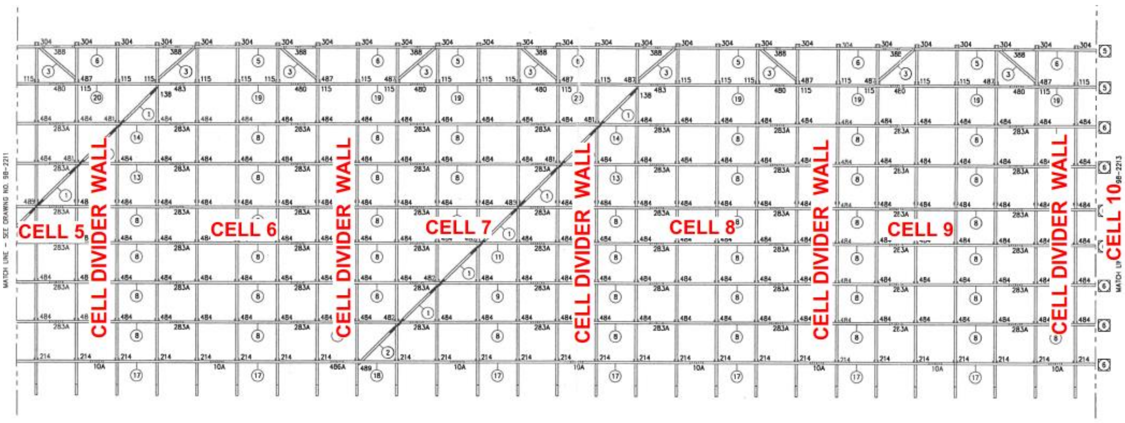


Figure 3.6 Typical longitudinal frame part 2 - Centre of cooling tower

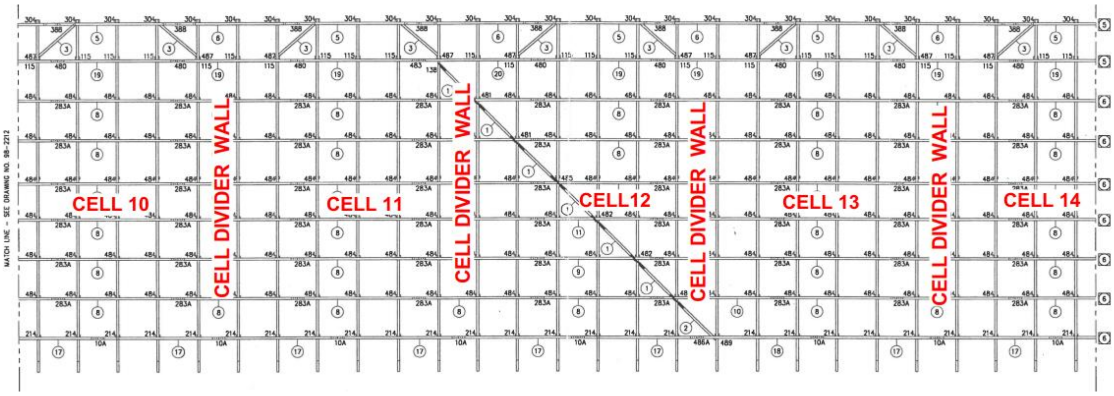


Figure 3.7 Typical longitudinal frame part 3 – Centre of tower

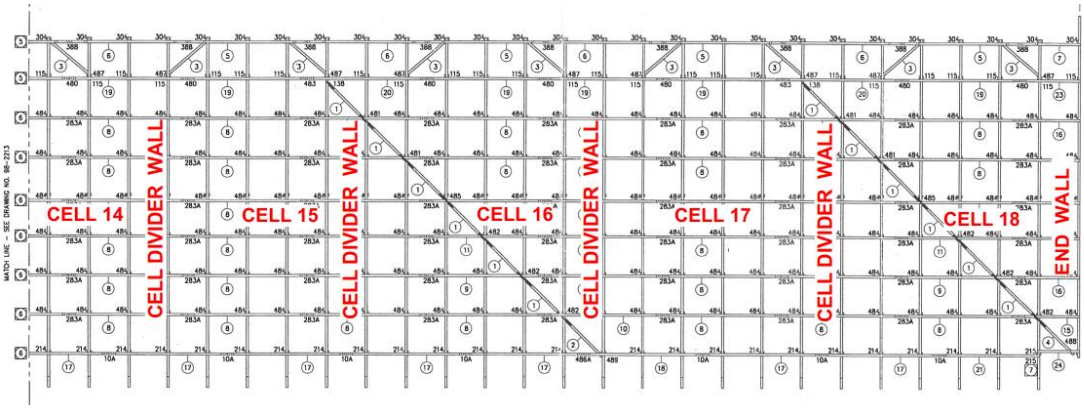


Figure 3.8 Typical longitudinal frame part 4 - Centre of tower

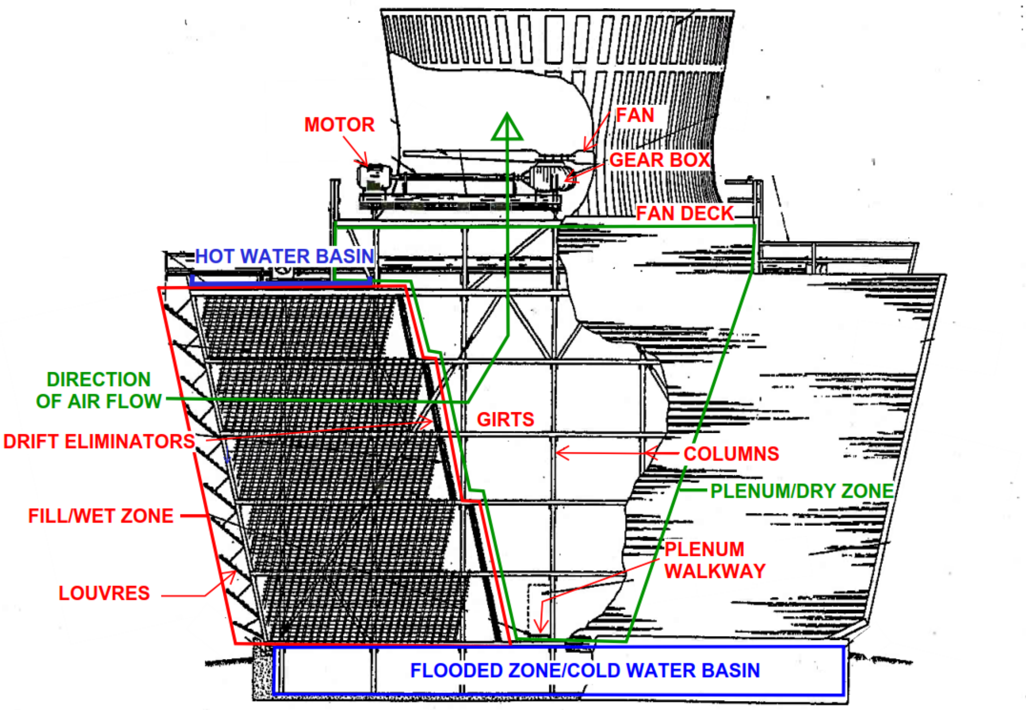


Figure 3.9 Zones and components in the cooling tower

4 Review of existing information

4.1 Information Received

We have been briefed with information and documents from NRF. A copy of the letter of instruction is annexed to this report as Appendix S. The following is a list of documents and photographs received in the lead up to this investigation which we have had particular regard to:

(1) Cooling Tower Inspection Unit 3 Callide C Power Station by Sigma Process Solutions Pty Ltd report number 02/0115 dated 25 July 2002. This report is marked as an "Advanced Copy", however the final copy has not been located.

(2) Cooling Tower Inspection Unit 3 Callide C Power Station by Sigma Process Solutions Pty Ltd report number 06/0139 dated 21 June 2006.

(3) Callide C Cooling Tower Inspection August 2006.

(4) Callide C3 Cooling Tower Inspection by Sigma Process Solutions Pty Ltd report number 09/104 dated Jan 2010.

(5) Callide C Cooling Structural Modelling and Assessment Report by GHD CSE Ref PR/13/157 SAP – 4596113 dated July 2014.

(6) Inspection Report – Wet Area by Marley Flow Control, undated but for inspections carried out between 5/4/22 to 23/4/22. This report was undertaken for cooling tower C3.

(7) Inspection Report Rev 1 by Marley Flow Control, dated 08 April 2022 for inspections carried out between 5/4/22 to 6/4/22. This report was undertaken for cooling tower C3.

(8) Inspection findings report by CS Energy for C3 Cooling Tower Cell 11 dated 5/10/22.

(9) Photographs and drone footage provided by Norton Rose Fulbright.

(10) Photographs recorded during site visits by HartzEPM on 16-17 November 2022, 20-21 December 2022, and 10-12 January 2023.

(11) The original cooling tower drawings by The Marley Cooling Tower Company for the tower structure, and Pacific Power International for the cooling tower cold water basin. The tower structure drawings included the following titled folders:

(i) Frame drawings – shows elevations of transverse and longitudinal frames and locations within the towers.

(ii) Frame timbers – shows complete details of each piece of timber to be cut, grade, cross sectional dimensions, length, bolt hole diameters and location, location in structure.

(iii) Joint timbers – shows complete details of each piece of timber to be cut to form connections between member, e.g., splice plates.

(iv) Timbers other than frames – shows complete details of each piece of timber to be cut, grade, cross sectional dimensions, length, bolt hole diameters and location, location in structure, for other members, e.g., handrail posts, stair members, etc.

(v) Callide joints – shows configuration of joint in the cooling towers.

(vi) Concrete drawings – shows the details of the cold water basin reinforced concrete.

(12) Cooling water data including:

- C3 Free Residual Chlorine from 3 July 2007 to 27 October 2022
- C3 pH & Turbidity from 13 November 2000 to 31 October 2022
- C4 Free Residual Chlorine from 3 July 2007 to 19 May 2021
- C4 pH & Turbidity from 22 August 2001 to 24 May 2021 Extracts from the Water Treatment Plant Manual received on 13th February 2023, document number M/A4 99003-GY14 Rev B

(13) Callide Power Project Unit Nos. 3 & 4 Plant Manuals Circulating Water System Appendix B CW & ACW Pumps Cooling Towers Volume 5 of 5. This document contains the Callide Power Station Operation and Maintenance Manual M98-A-933 & M98-A-940 for Pacific Power International Contract 6002.

(14) Report titled CS Energy Assessment of Cooling Tower Elements Report No. 79-2023-01 dated 14 January 2023.

4.1.2 Review of previous reports

Detailed reviews were carried out of the previous cooling tower inspection reports and these reviews are in Appendix R – Review of Previous Reports.

It is noted that the previous reports provide an important journey through the history of the cooling towers from several perspectives including, observations on the design of the towers, issues encountered over the life of the towers, and maintenance that was required and/or carried out. These reports have been an important part of the information on which the root cause argument has been developed and the reader is encouraged to read the review.

4.1.3 Discussion of previous reports

Based on a review of the reports in Appendix R there are several general observations. Without re-stating issues reported in each, general comments are as follows:

- As early as 12 months into the life of the towers, there were issues that suggested that the design as well as the construction of the towers had some potential issues. Some of the issues are noted above in the discussion of the various reports and are summarised below:
    - Loose and ungrouted anchor plates for the main bracing elements.
    - Trimming of hot water basin support beams without evidence that design checks had been undertaken.
    - Large sags in the cantilevered sections of the fan deck.
    - Cable tray in the hot water basin splash zone.
    - Broken fill support grids.
    - Many of the nuts on the foundation bolts were loose and did not have lock nuts as required by the drawings.

  - For further details refer to the reports in the Appendices.

- Through the life of the towers and up to the present, the middle of the fill zone has not been inspected in detail. Typically, inspections of the fill area were from the perimeter of the cooling towers, and from the cold water basin and therefore of the lower sections of the timber structure. It should be noted that the fill zone will be the most affected zone when it comes to degradation and erosion of timber members.

- In 2006, approximately 4 years after commissioning, the first signs of timber erosion were observed. Both types of erosion were reported, water as well as chemical erosion. Water erosion occurs simply by the mechanical action of moving water on the surface of timber members. Water erosion would accelerate where, for example, a sprayer is faulty or missing and allows a stream of water to fall from the hot water basin directly onto timber members. Chemical erosion occurs when the surface of timber is attacked by high levels of chlorine and high pH, or by other chemicals. In subsequent years this erosion was reported to have progressed further.

- The timber used in construction were reported as having significant defects when assessed to the relevant Australian Standard AS2858 (2007) Timber – Softwood – Visually stress grade for structural purposes. Defects include things such as knots, borer holes, slope of grain, width of growth rings and resin pockets. It was found that, as a result of this assessment, the timber had to be given a strength downgrade from the design grade of F8, to F7. This results in a loss of strength to F7. This results in a 20% loss in bending strength and a 28% loss of axial load carrying capacity. In addition, and from photographs in the wet area, knots have seriously compromised the integrity of members, most notably in columns. This suggests that at the time of fabrication and/or construction, not enough attention was being paid to timber sections, with the result that timber sections that would normally be rejected, were built into the towers.

- In a structure in which there is rotating machinery, it would be prudent to use fasteners which have locking mechanisms such as lock nuts, or, for there to have been an application of an adhesive, e.g., Loctite applied to the bolts at the time that the nuts were installed. This does not appear to have been the case in these structures. Many connections had loose fasteners, even as early as the 2002 report.

- The method of transverse bracing the tower seems unusual. The end wall and cell divider transverse wall frames are not braced with diagonal braces as are the frames internal to the cells. There are two alternative ways the required bracing could have been achieved:

  - The end wall is braced laterally by the end wall cladding while the cell divider wall frames are braced by the plywood sheets that separate the cells. This may or may not be the case, however the density of fasteners is low, and this suggests that this may not be the case. In many instances it has been reported that many of these plywood sheets were either loose or have fallen out.
  - The fan deck plywood floor acts as a horizontal diaphragm transferring the lateral loads at the end and cell divider walls to the adjacent cells. As above, the density of the fasteners fastening the plywood sheets to the supporting members is also low and therefore load transfer of lateral forces to the substructure may be compromised. Supportive of this method of bracing is the fact the transverse frames immediately adjacent to the end and cell divider walls, have a total of 3 diagonal braces, whereas the rest have only two. This implies that cells with 3 diagonal braces are carrying a higher proportion of lateral loading. One of the

reports discussed above, Breezewater 11th November 2015, comments that the fan deck floor is acting as diaphragm. This method provides a circuitous load path rather than the more direct path to get the loads to ground as diagonal braces would do. For example, wind loads imposed on the outer upper half of the side of the tower, would have to be carried up via the columns up to fan deck level, then transferred horizontally through the fan deck diaphragm to the adjacent transverse frame/s, and down to ground through the diagonal braces.

- The longitudinal bracing in the tower is not continuous for the length of the tower. Based on the drawings of the cooling towers, of the 18 cells, cells 1, 3, 5, 7, 12, 16 and 18 have longitudinal braces on all longitudinal frames. In cell 14 only three longitudinal frames are longitudinally braced, the edge of the fan deck on both sides and the inclined louvre columns. Cells 8 and 11 are longitudinally braced on two frames, on the edge of the fan deck on both sides. The remaining cells 2, 4, 6, 9, 10, 13, 15 and 17 have all longitudinal frames longitudinally braced. In this scenario the tower relies on the fan deck plywood to act as a horizontal diaphragm over the unbraced longitudinal frames, as well as relying on the longitudinal girts to act as struts/ties to transfer longitudinal loads from the unbraced cells to the braced cells. This is an indirect load path in getting longitudinal loads to ground. In this case the loads would be those from the operation of the mechanical equipment and wind loads at fan deck level. Longitudinal wind loads on the tower structure would be resisted by the end cells bracing.
- As early as 2006, there were comments in the reports regarding water chemistry. Water chemistry was also raised as issues in subsequent reports in 2010, 2015, 2016 (twice), and 2019. The comments were mostly that pH and chlorine levels in the cooling water were high which has the potential to bring about accelerated chemical erosion of the timber. In a 2006 report, delignification was observed at the bottom of the timber columns in the wet zone, with a recommendation for tighter pH control. The records of the cooling water chemistry show chlorine concentrations and pH higher than the recommended range. This is discussed further in the sections following.

4.2 Critical period in the life of the cooling tower

Based on three of the reports below, we consider the critical time in the life of the CT3 to have been in the period from 2014 to 2016. The reports potentially left conflicting impressions of the tower and if the reader was not a structural engineer, then potentially a false sense of security could be the result. In our opinion there is sufficient information in these reports to warrant a look at significant maintenance and prioritisation of effort. The three reports that are being referred to are those discussed below.

- GHD Structural Modelling and Assessment Report dated July 2014.
- Breezewater Report for Inspections 27 and 28 August 2015.
- Marley Flow Control Inspection Report dated 1 July 2016for CT4 and 17 March 2016 for CT3 Note that the findings of these two reports were similar.

The GHD report assessed CT3 to be working at close to its limit structurally with only 5% reserve capacity. In addition, the report states the there is no redundancy in the structure, which means that if one member suffers a failure, then in theory the surrounding members would also fail, potentially leading to a more general failure. The validity of this finding is a cause for concern for the following reasons:

- The analysis that GHD carried out was based on there being “less than 3mm of rot” in the timber members. In the analysis this was accounted for by applying an additional capacity reduction factor of 0.95. The report describes that “the majority of the timber was found to be in good condition”. The concern with this is that only the dry plenum area was inspected while the wet or fill zone was inaccessible for inspection. It is known from recent inspections that the wet zone degrades much faster than the plenum area. In addition, the overall condition of the tower was based on an assessment of the lower accessible members of the plenum area. It is therefore questionable whether the assessment was accurate and whether it was too optimistic regarding the condition of the cooling tower. The subsequent report by Breezewater in 2015, that the report by GHD “has been, in the majority, discounted as many of the critical areas did not appear to be included in the inspection”. This suggests that the finding in the GHD report that the structure is structurally adequate, is questionable.
- Further to the dot point above and perhaps with the benefit of hindsight, it would have been prudent to carry out a sensitivity analysis. This means carrying out the analysis for differing levels of degradation and assessing the structural adequacy of the tower accordingly.
- The report provided a reasonable assessment of the grade of timber in that the defects such as knots and in service moisture content, had derated the timber from the original F8 to F7. This seems reasonable. What is hard to explain is the selection of the timber strengths from the relevant standard AS1720 current at the time of the report. The parameters reported to have been used in the analysis are a bending strength f'_b = 20 MPa as opposed to 18 MPa, tension strength f'_t = 10 MPa, and compression strength f'_c = 15 MPa as opposed to 13 MPa. These are significant given that the tower was assessed as being close to its structural limit.
- In terms of loading, the report is based on there being 100 mm of water in the hot water basin. The design operating water depth is 153mm, while the overall depth of the hot water basin is 213mm. It is unclear why a reduced depth of water was used on the analysis or whether the operating water depth was reduced to 100mm at the time the report was published. It is understood that slots were cut in the side of the hot water basin wall to limit the water depth to 100mm, but this was only implemented in October 2022.
- An assessment of a low risk of failure for the ensuing 4 years was given. However, no basis was given for this assessment, such as the anticipated level of timber degradation over the 4 year period. It is noted though, that as far as is known, there were no failures in that period.

None of the above considerations taken on its own is necessarily problematic, but the cumulative effect of a combination of these, together with the assessment that the “member forces were found to be approaching their design limits”, should have raised concerns, in particular in the longer term.

The Breezewater Report described the overall condition of the primary structural members as being reasonable though it wasn’t zone specific. It notes however that there were concerns with the wet zone. In particular there was concern with the D-mould semi-circular fill support timbers. At the time and based on inspections of two cells, a number of these timber support were missing at regular intervals and those remaining were close to losing their integrity due to erosion. It is stated in the report that there was a significant short-term risk of fill collapse. It was noted that collapse was happening because there was an increasing amount of fill retaining clips and splash bars accumulating at the pump suction trash screens.

Collapse of the fill would potentially overload those area onto which they would collapse. The loss or movement of fill would impact the efficiency of the towers and pose a significant interruption risk.

Breezewater identified the fan deck flooring as a significant issue because, in their view, it forms a structural diaphragm to transfer horizontal loads to the braced frame. This is reasonable because, as described above not all the tower frames have transverse diagonal bracing. It was also considered at the time that the floor could not accept normal foot traffic, even though an earlier report assessed it to be in fair condition. It is noted that subsequently, the fan deck flooring was replaced, though it is not known if consideration was given to the type and frequency of fasteners to ensure diaphragm action.

Among the recommendations by Breezewater, was for the installation of isolation valve to be installed on each riser pipe, making for better isolation of individual cells for maintenance purposes. Originally the tower relied on isolation from the flow control valves at the level of the hot water basins. These valves are not generally intended to act as isolation valves but have been used as such. The recommendation to install isolation valves was not implemented.

Breeze water predicted in their report that given the risk profile in their report, the limited funding for maintenance would develop into a “major constraint” for the operation of the cooling tower.

The Marley report of 2016 was carried out from the external louvre face from an EWP. During their inspection the water to the cell being inspected was shut off while the fan was running. It is not clear how far into the tower there was sight, but when HartzEPM inspected in a similar manner in June 2023, it was only possible to see as far as the first row of vertical columns. The situation may have different to the Marley inspection.

One of the findings by Marley is that timber had lost 10 mm from the outer layers. This is a loss of cross sectional area of nearly 20% for a column originally measuring 100 x 100mm. For a horizontal girt originally measuring 150 x 50 mm this equates to as loss of section modulus required for strength in bending of 30%. Marley does not see this as an issue, but this is not based on any calculation, nor does it consider the future degradation or performance of those members.

Marley stated that despite the observation that some fill support D-mould timber having broken, the fill cannot move and that the surrounding fill is providing support. This is in contrast to the Breezewater report which predicted a significant short term risk of fill collapse. The report is somewhat contradictory because it reports all fill grid supports are in place, and yet fill bars have come loose. They recommend no fill be replaced at that time while Breezewater suggest full fill replacement.

4.3 Water chemistry

The water treatment at Callide Power Station uses Chlorine gas as a biocide to control Legionella and other microorganisms in the cooling water. Other chemicals are used to prevent scaling in the cooling system.

The primary function of the water treatment plant is therefore to control the level of biocides and other chemicals to within acceptable levels of operation for the control Legionella, as well as ensuring that the cooling tower and other parts of the cooling system are maintained in optimum condition.

Chlorine concentration and high pH are the two most significant water chemistry parameters which detrimentally affect cooling tower timbers. This report therefore focuses primarily on the Free Residual Chlorine concentration and the pH of the cooling water. These parameters are discussed in more detail in the following paragraphs. In addition, turbidity is also discussed because of the potential for the build-up of deposits in pipework and in the hot water basin. These deposits would increase the loading on the structure.

This report does not cover the control of Legionella at Callide Power Station. In respect of this subject, the reader is referred to a report titled "Review of the historical performance of biological control of cooling water (CW) within C3 & C4 cooling towers at Callide Power Station" prepared by Power Plant Chemical Engineering (PPCE) on instructions from Norton Rose Fulbright.

The above report by PPCE examines in detail the levels of Free Residual Chlorine (FRC) and its efficacy in the control of Legionella at Callide C cooling towers. The report also covers the levels of FRC above which the timber structure of the cooling towers are damaged.

Norton Rose Fulbright has advised HartzEPM that the above PPCE report can be referred to and relied upon by HartzEPM in the preparation of this RCA report on the cooling towers at Callide C Power Station. The analysis of the received data (as listed in the following section) in this report is independent of the analysis of data received by PPCE in their report.

The maximum level of Free Residual Chlorine to prevent timber damage used in this report, is same as that used in the PPCE report. Both this report and the PPCE report agree that the cooling towers at Callide power station were operating for extensive periods above the maximum recommended level of FRC.

4.3.1 Water chemistry data received

All the water chemistry data used in this report was provided by Norton Rose Fulbright through CS Energy in the form Microsoft Excel Spreadsheets.

The cooling water parameters recorded in the spreadsheets include the following:

- pH - measure of hydrogen ion concentration or more commonly the acidity or alkalinity of a solution
- SEC – measure of the ability of a solution to conduct electricity which gives an indication of the ionic content in a solution
- Turbidity – the cloudiness or opacity of water due to suspended matter
- Sodium – measure of the levels of sodium ions in water
- Salts including levels of Potassium, Calcium, Magnesium, Chlorides, Sulphates, and Silica
- p-Alkalinity and m-Alkalinity – two different measures of alkalinity of a solution which is an indication of the resistance of a solution to changes in pH.
- Free Chlorine Residual – is the chlorine available to disinfect water. The total chlorine is the sum of the free chlorine and the combined chlorine. The combined chlorine is the chlorine that has been utilized in disinfecting the water. Combined chlorine is chlorine that is bound to contaminants or organic matter, also known as chloramine. Combined chlorine is not available to disinfect water.

The initial data set was provided on 9th December 2022 and was subsequently superseded. We understand that these data sets have been corrected by CSE to include only actual measured values and not hourly interpolations (artificial values) between actual measurements. The data sets have also been corrected to exclude extrapolations to zero when the plant has been off-line due to an outage. The most current data set which this report has used for analysis is therefore summarised below:

Data	Date Provided	Spreadsheet Recording Period of Data
C3 Free Residual Chlorine	8 June 2023	3 July 2007 to 27 October 2022
C3 pH & Turbidity	20 April 2023	13 November 2000 to 31 October 2022
C4 Free Residual Chlorine	8 June 2023	3 July 2007 to 19 May 2021
C4 pH & Turbidity	3 July 2023	22 August 2001 to 24 May 2021

4.3.2 Recommended operating water chemistry parameters

There are no firm recommendations or standards for the allowable concentrations of Free Residual Chlorine or pH in cooling tower water. Usually, the plant operation manual provided usually provided by the cooling tower supplier and builder, would provide these recommendations.

Further, there are general industry guidelines published by various cooling tower supply companies and other industry organisations. The approach in this report is to consider each of these sources and assess recommendations for consistency including the recommendations from the PPCE report. However, as instructed the recommendations for FRC and pH in the PPCE report are those ultimately adopted. In the following sections these are discussed in more detail.

4.3.3 Callide Power Station Cooling tower plant manual

A copy of the document Callide Power Project, Units 3 & 4, Plant Manuals, Circulating Water System, Appendix B, Volume 5 of 5, was provided by Norton Rose Fulbright through CS Energy. This document is dated October 2001 and was prepared by Pacific Power International. It includes a section titled ‘Class 600 – Owner’s Manual’, document reference Manual 92-1317B by Marley.

Water treatment is mentioned in the table of contents with a reference to page 13. However, page 13 does not contain a heading for water treatment. Moreover, the information contained on page 13 is general and does not recommend appropriate levels for the Free Residual Chlorine or pH, or any other chemical parameters.

Page 11 of the same document refers to page 15 for Water Treatment, however it is noted that pages 14 and 15 are missing from the document. It is unclear why this is. The PPCE report also notes these missing pages but, refers to an online manual “SPX Technologies 600 Crossflow Cooling Tower User Manual 2018”. SPX Technologies is an international company owning the Marley cooling tower design. PPCE compares, page by page, the CSE’s manual with that of SPX and states that the SPX manual is ‘likely to be on the same terms as the original Owner’s Manual’. The PPCE report therefore uses the SPX manual’s Free Residual Chlorine limits of 0.4 ppm (for continuous dosing systems) and 1.0 ppm (for intermittent/slug dosing systems).

The SPX manual also refers to a pH range of 6.5 to 9.0 for normal cooling tower construction materials. Note, however, that this in contradiction to the SPX Technologies document "Cooling Tower Fundamentals" referred to in the following sections in which a range of 6.0 to 8.0 is specified for cooling towers.

Page 11 of the CSE manual, under the heading Cold Water Collecting Basin, recommends maintaining a positive Langelier Index or LSI (Langelier Saturation Index) and refers to page 15. The LSI is based on several parameters including Total Dissolved Solid (TDS), Temperature, Calcium Hardness, M-Alkalinity, and pH. The LSI predicts the tendency of calcium carbonate to precipitate, resulting in deposits in pipes, or the tendency to remain in solution. This tendency and the LSI in general are not relevant to the current investigation and is generally not considered further.

No other references are made to water treatment were found in the manual provided.

4.3.4 Callide Power Station Water Treatment Plant Manual – Extracts

Further reference is made to the extracts from the Water Treatment Plant Manual provided by CS Energy through NRF on 13th February 2023. In this document a description is given of the Chlorine and acid dosing systems and procedures. Comments on the contents and requirements contained in this manual are as follows:

- The manual requires that the analysis of the water in the cooling tower basin is to be undertaken daily. The station chemist is to calculate how close the water in the tower is to all chemical operating limits stipulated in Section 1.5.4.1 of the manual. However, as per the PPCE report mentioned above, cooling water samples are collected weekly for analysis with respect to levels of Legionella and other microorganisms.
- The manual states that an "acceptable pH range has been worked out by the plant chemist", though this range is not explicitly stated. The manual further states that "For cooling tower 3 pH Meter (3 QUP40 CQ003) controls the stopping and starting of the Acid Dosing Pump (0 PUN20 AP001) which doses into the forebay of Cooling Tower 3". In addition, it also states that "Upon registration of a pH index of 8.3 the acid pump starts and continues pumping until the pH index is lowered to 8.0." From this it is inferred that the pH range is to be between 8.0 and 8.3.
- To control the Langelier Saturation Index (LSI) between the operating limits $0 < LSI \leq 1.0$ stated in Section 1.5.4.1, the manual states that the pH "setpoints" are nominally between 7.8 to 8.3 at which points the sulphuric acid dosing pumps stop and start respectively. As noted above controlling the LSI is important to prevent scaling. The LSI of the water in the cooling tower is controlled by sulphuric acid dosing. The dosing rate is controlled via the pH readings detected from sampling the circulating water.
- From the above it is inferred that at any time, according to the manual the cooling water pH should be in the range from 7.8 to 8.3. Please note that a report by Sigma Process Solutions in 2006 recommended the pH be controlled between 7.7 to 8.1. CSE appears to have changed the controls to lower the pH range. Please refer to following sections for a more detailed discussion.
- Chlorine is supplied via the pre-existing chlorination plant nearby.

- The chlorination of the cooling towers C3 & C4 follows the same principles as Callide B which has a natural draft cooling tower constructed of reinforced concrete. Callide C3 and C4 cooling towers are induced draft cooling towers and are constructed primarily of timber.
- The manual states that chlorination of cooling towers CT3 and CT4 is required twice a day. The duration of each dose is programmed from the Callide B chlorination plant control system. However, Section 4.4.1.1, page 48, of the PPCE report refers to CSE documents which state that chlorination occurs on a rotational basis for a period of 70 minutes basin C3, 70 minutes basin C4 and these injections occur four time each 24 hour period.
- The manual does not prescribe a range for the Free Residual Chlorine.

4.3.5 Review of the historical performance of biological control of cooling water (CW) within C3 & C4 cooling towers at Callide Power Station – Power Plant Chemical Engineering Pty Ltd

Regarding acceptable water chemistry parameters for concentrations of Free Residual Chlorine and pH, NRF have instructed HEPM to adopt the findings contained in the report by Power Plant Chemical Engineering dated 01 December 2023. The report tabulates in Table 2 concentrations from a number of sources and the concentrations assumed to be appropriate is that by Cooling Tower Manufacturer – Marley – 600 Crossflow Cooling Tower User Manual - Preferred Cooling Tower Water Condition Limits For Standard Construction Material, in which the concentration of Free Residual Chlorine is nominated as “1ppm free residual (shock), or 0.4 ppm continuously”. For pH, the same Marley document nominates pH levels of 6.5 to 9.0.

This is further supported by the paragraphs (i) and (ii) on page 8 of the report where it is stated that the relevant ranges for the Free Residual Chlorine are as stated as above for “standard construction materials”.

Regarding comments for pH levels, the PPCE report discusses this as follows:

- On page 34, it states that the “pH setpoints for cooling tower acid pumps off and on stated as 7.8 and 8.3 nominally) to minimise the risk of scaling of the main condenser”. This contrasts with the levels nominated above and will be considered to be the relevant values.
- On page 27, Table 2 refers to Sections 4.3.1.3.1 and 4.3.1.3.2 which state that Free Residual Chlorine above 1.0 ppm in combination with pH higher than 8.0 will lead to severe deterioration (delignification) of wood.
- On page 37, it discusses the effect of pH on the efficacy of Chlorine gas injection as a biocide. It is shown that the concentration of Hypochlorous Acid (which is the most potent form of biocide with chlorination systems) drops from 80%, approximately 22%, and approximately 3% at pH of 7.0, 8.0 and 9.0 respectively. That is, the effectiveness of Chlorine gas reduces sharply above pH values 7.0 to being negligible at a pH of 9.0.

4.3.6 Cooling Tower Fundamentals - SPX Cooling Technologies, Inc.

Section 1 of the above document, Cooling Tower Basics, contains paragraph G, Maintaining Water Quality, which provides “normal” arbitrarily defined water conditions, in order to establish a basis for the utilization of standard construction materials. By “arbitrarily defined” it is assumed that the conditions have been established through experience rather than by laboratory or other long or short term testing regimes.

The advice in this document is as follows:

- Chlorine, if used, added intermittently, with a free residual not to exceed 1 ppm, maintained for short periods
- A circulating water with a pH between 6 and 8.

This document can be found on the internet at Cooling Tower Fundamentals (spxcooling.com).

4.3.7 *Handbook of Industrial Water Treatment – SUEZ and Veolia*

Chapter 29 – Cooling Tower Wood Maintenance, of the above document provides some advice as to the level of the Free Residual Chlorine. Free Residual Chlorine should be restricted to less than 1 ppm, and preferably to a range of 0.3 to 0.7 ppm.

The document does not specifically mention acceptable ranges for pH levels. However, and importantly, it says that particularly severe chemical deterioration occurs when high Free Residual Chlorine, in excess of 1.0 ppm, occurs simultaneously with pH levels of more than 8.0. The deterioration commonly manifests itself in the form of delignification.

This document can be found on the internet at Water Handbook - Cooling Tower Wood Maintenance | SUEZ (watertechnologies.com)

4.3.8 *Free chlorine residual and pH*

From the discussion above, the following table is produced to check for consistency in the recommendations provided in each of the above documents.

Table 4.1 Comparison of recommended Free Residual Chlorine and pH

Source	FRC Max (ppm)	FRC Min (ppm)	pH Max	pH Min
Callide CT Plant Manual - Manual 92-1317B by Marley	No comment	No comment	No comment	No comment
Callide Cooling Tower Plant Manual Extracts	No comment	No comment	8.3	7.8
PPCE Report	1.0	0.4	8.3	7.8
Cooling Tower Fundamentals SPX Technologies	Not greater than 1.0 for short periods	No comment	8.0	6.0
Handbook of Industrial Water Treatment – SUEZ & Veolia	0.7	0.3	No comment	No comment
Levels adopted for this report**	**1.0***	**0.4**	**8.3**	**7.8**

Note: * The PPCE report concludes a maximum level of 1.0 ppm for FRC intermittently (shock)
**While these values are adopted for the report, there are no set standards mandating what these levels should be and therefore during operation these adopted limits may be exceeded depending on the circumstance.

Legend:

- FRC Max – Maximum Level of Free Residual Chlorine recommended.
- FRC Min – Minimum Level of Free Residual Chlorine recommended.
- pH Max – Maximum pH recommended.
- pH Min – Minimum pH recommended.
- ppm – Parts per million

The basis for the selection of chlorine and pH levels in the above, is in part to not be too onerous when compared to how the towers have been operated, and additionally it is based on experience. Hence when one source has a higher or lower value than another, then within reason the higher or lower value is adopted. When pH becomes high this reduces the effectiveness of chlorine as a disinfecting agent, and therefore a correct balance of chlorine and pH in combination together is important.

4.3.9 Free chlorine residual

Recorded measurements for the free residual chlorine (in ppm) in the spreadsheet is for the period 3 July 2007 to 27th October 2022. Free chlorine residual readings prior to July 2007 were not provided. The provided chlorine data consists of 'Before Dosing' and 'After Dosing' measurements recorded on the same day using PDP residual chlorine method together with collection of water samples for measurement of total bacteria levels (TPC) and legionella pneumophila serotypes (PS) 1 to 14. The samples appear to have been taken on average every 7 days. The following pages contain graphs of Free Residual Chlorine concentrations as well as histograms and pie charts to illustrate the distribution of the data for both before and after dosing.

It is unknown whether the Free Residual Chlorine levels were within recommended ranges from 2001 (commissioning) to 2007 as there are no measurements provided in this period. It is also noted that in both the Callide CT Plant Manual – Manual 92-1317B by Marley, as well as the Callide Cooling Tower Plant Manual Extracts, there appears to be no mention of the operating range for the Free Residual Chlorine. We are not aware of any "set points" for the Free Residual Chlorine, i.e. the levels of free chlorine at which the towers should be operated is not stipulated anywhere and that the chlorine dosing system injects chlorine into the cooling water downstream of the cooling towers at the inlet of the CW pumps on a preset duration and dosing rate for each of the cooling towers B1, B2, CT3 and CT4.

Figures 4.49 and 4.50 below show the Free Residual Chlorine before and after dosing for CT3 and CT4 cooling towers, respectively, as 'Scatter' type of graph for each data points. A line graph has not been created because chlorine is injected into the cooling water on a daily basis, but the measurements taken on an average of every 7 days. Given that there is wide spread of the values, it would unrealistic, therefore, to draw straight lines between points. The graphs in the figures below also plot the operating range for the free chlorine as adopted in Table 4.1. As can be seen, and if the water chemistry data provided is accurate, both towers have operated at concentrations well above that recommended for approximately 14 years (based on data from 2007 to 2021). Readings appear to be regularly as high as 4ppm and on occasion as high as 5 ppm. More recently from May/June 2021 to when the readings to stop in late 2022, they are more in line with recommendations, albeit with intermittent high peaks but always less than 2ppm (refer below for more detailed discussions on the distributions of the measurements).

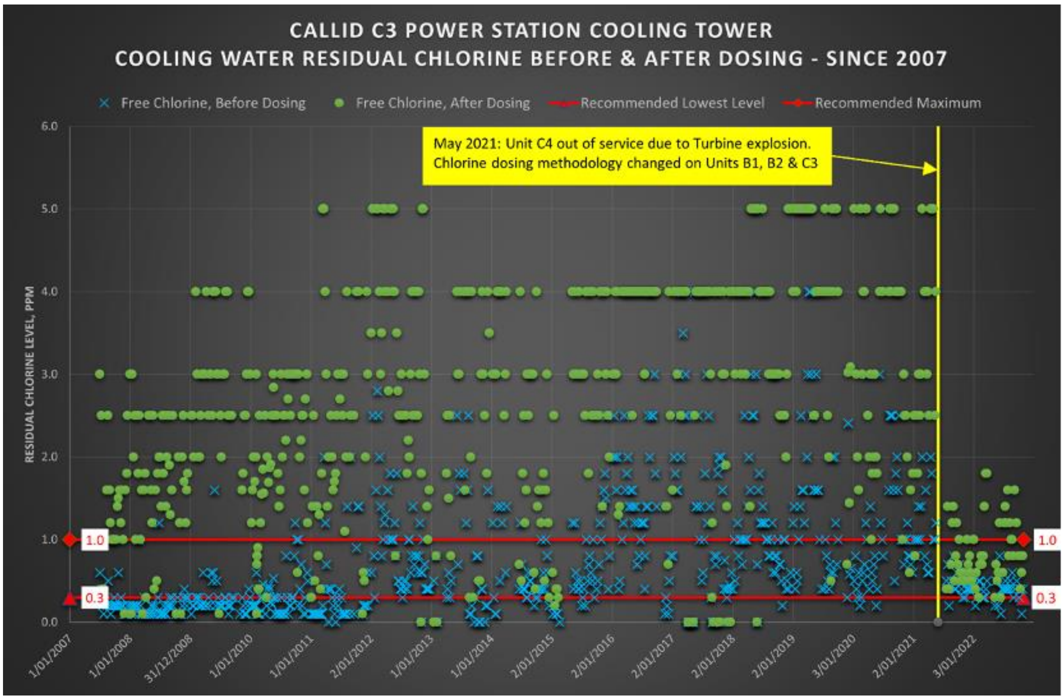


Figure 4.1 C3 Free Residual Chlorine Scatter Chart

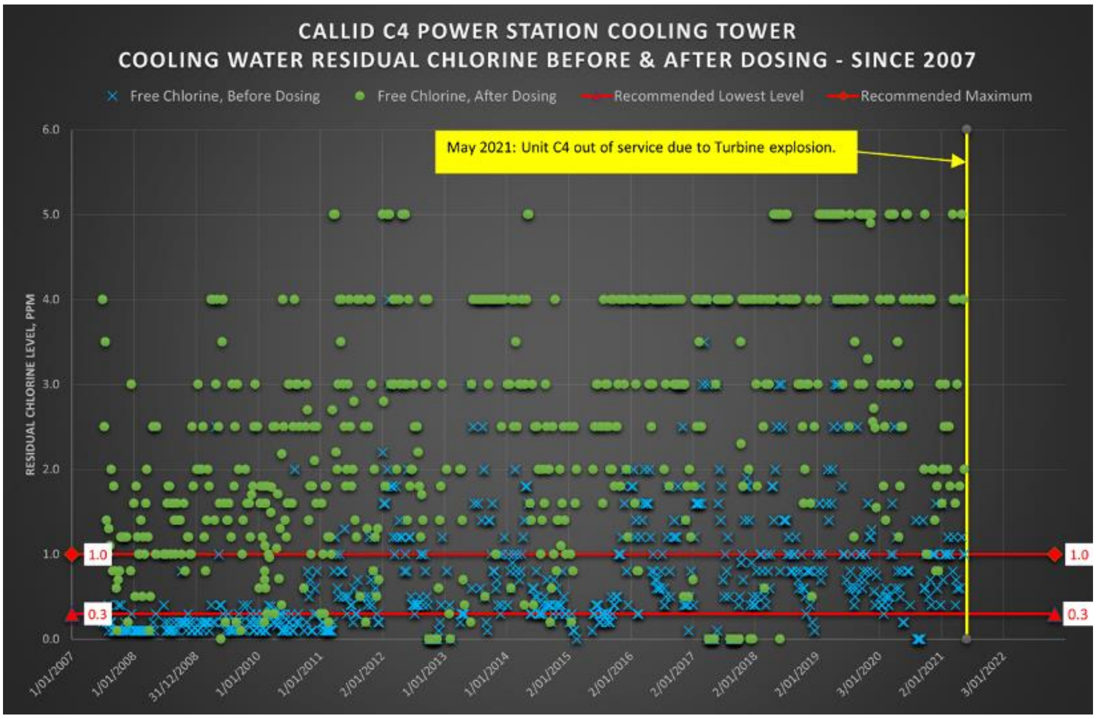


Figure 4.2 C4 Free Residual Chlorine Scatter Chart

4.3.10 Monthly Averages of Free Residual Chlorine

Monthly averages of Free Residual Chlorine (FRC) of all the before and after dosing measurements have been calculated for both cooling towers and these are plotted in the form of line graphs as shown on Figure 4.3 on the following page. The darker shaded area represents cooling tower CT4, and it is overlayed on the graph for CT3 which is the lighter colour. The CT4 graph is slightly transparent and shows the outline of the CT3 graph behind it. The figure also includes column chart inserts for both towers showing FRC overall averages for periods from 3rd July 2007 to 31st March 2015, 1st April 2015 to 31st May 2021 and 1st June 2021 to 27th October 2022. The reason for this split is because there have marked changes in the FRC in 2015 and 2021. For interest, the inserts also show the median, standard deviation, maximum and minimum for each of these time periods.

It is evident from the above graphs that the average monthly FRC levels for both towers have been increasing from levels 0.5 to 1.5 ppm in 2007 to peak of about 3.4 ppm early in 2012 and decreasing thereafter to about 1.0 ppm at the end of 2012. After what appears to be an outage early in 2013, peaks between 2.0 and 3.0 are observed in 2013 and 2014 and thence a reduction to circa 1.0 ppm by early 2015.

After a period of no data in March and April of 2015, the average monthly FRC levels rose to higher levels than seen prior to this date. Peaks above 3.5 ppm and 4.00 ppm are observed in 2017, 2018 and early 2019. Thereafter, the peaks decline circa 2.5 by early 2021.

There was a marked drop in the CT3 cooling tower FRC subsequent to the explosion and forced prolonged outage on May 2021 of the Callide C4 Turbine. We have been instructed that the drop in the chlorine levels after May 2021 was due to changes in the chlorine dosing system by CSE. The graph shows in yellow the time of the C4 Turbine explosion and the stark difference of the monthly average FRC before and after this date.

4.3.11 Comparison of C3 & C4 Cooling Tower FRC Monthly and Global Averages

Figure 4.3 shows that both towers have generally experienced the same trends in the monthly FRC from 2007 to 2021 discussed above. The CT3 cooling tower, in general, has experienced higher levels of monthly average FRC than CT4 but as can be seen from the graph, on other occasions CT4 has experienced some higher values than CT3. On further analysis, Table 4.2 below illustrates that there is only a minor difference in the global averages in FRC for CT3 and CT4. More importantly, the significant differences in the FRC are in the time periods. For example, from 3rd July 2007 to 31st Mar 2015, the average FRC for CT3 and CT4 were respectively 1.38 and 1.33 but these increase sharply to 2.37 and 2.21 for the period between 1st Apr 2015 to 31st May 2021.

It is reasonable to assume from the above that the timber structure of both towers would have had a higher rate of chemical erosion caused by higher levels of FRC during April 2015 to May 2021.

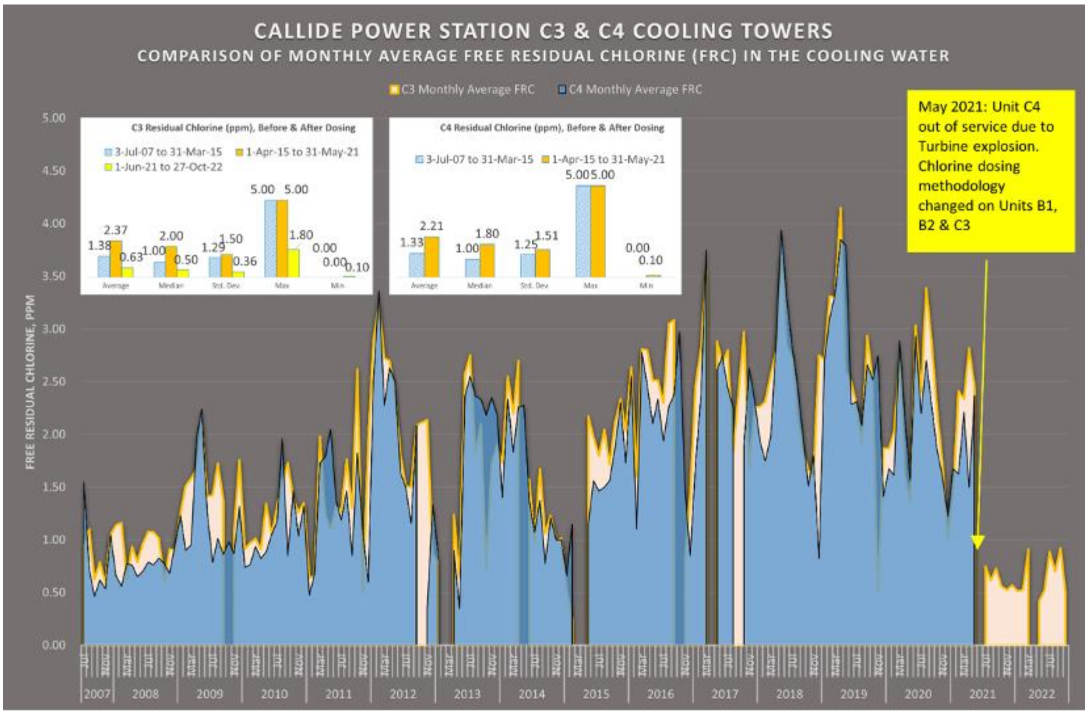


Figure 4.3 C3 & C4 Monthly Average FRC Comparison Chart

Table 4.2 C3 & C4 Free Residual Chlorine Global Averages

	Global Average of Free Chlorine Residual (FRC), ppm		
	3-Jul-07 to 31-Mar-15	1-Apr-15 to 31-May-21	1-Jun-21 to 27-Oct-22
CT3 Cooling Tower	1.38	2.37	0.63
CT4 Cooling Tower	1.33	2.21	C4 Unit Off-Line

Table 4.2 also shows a significant reduction of the average FRC for CT3 cooling tower post May 2021 from 2.37 ppm to 0.63 ppm.

In respect of the increase in the FRC from 2015 to 2019, it is interesting to note that in February 2015 Cyclone Marcia affected the region. There was a substantial increase in the turbidity in the cooling water in the following months and this is discussed in the following sections.

4.3.12 Frequency Distribution of FRC Before and After Chlorine Dosing

Frequency distributions of the FRC in 0.5 ppm bands have been created for both the CT3 and CT4 towers from the provided data. This has been done individually for the before and after Chlorine dosing measurements as well as the combined before and after dosing values. The results are shown in Table 4.3 on the following page as percentage of the data in each of the FRC ranges from 0.00-0.50 to 5.00-5.50.

Histograms have also created and shown on the following pages to show graphically the distribution of the data and to highlight differences and trends. Separate charts have been created for the before and after dosing for CT3 and CT4. However, to facilitate comparison between CT3 and CT4, a combined histogram showing the distribution of both towers has been created. Each histogram shows the global averages, median, standard deviation together with the maximum and minimum for the time periods 3-Jul-2007 to 31-Mar-2015, 1-Apr-2015 to 31-May-2021 and 1-Jun-2021 to 27-Oct-2022.

Cumulative frequency distributions have also been to show the percentage of data above certain levels of FRC increasing in 0.5 ppm increments. The results have been presented on the following pages in the form of tables. A histogram has been shown to compare the CT3 and CT4 cumulative frequency distribution for the aforementioned time periods.

Table 4.3 C3 & C4 Frequency Distribution of Free Residual chlorine

Free Residual Chlorine Range	CALLIDE C3 - FREE RESIDUAL CHLORINE IN COOLING WATER - FREQUENCY DISTRIBUTION								
	03-Jul-2007 to 31-Mar-2015			1-Apr-2015 to 31-May-2021			1-Jun-2021 to 27-Oct-2022		
	Before Dose	After Dose	Total	Before Dose	After Dose	Total	Before Dose	After Dose	Total
	%	%	%	%	%	%	%	%	%
0.00-0.49	69.2%	7.6%	38.6%	14.9%	0.4%	7.8%	63.2%	12.3%	37.7%
0.50-0.99	15.9%	6.1%	11.0%	26.1%	1.9%	14.2%	36.8%	50.9%	43.9%
1.00-1.49	9.6%	10.0%	9.8%	27.9%	4.2%	16.3%	0.0%	29.8%	14.9%
1.50-1.99	3.0%	15.5%	9.2%	11.2%	3.4%	7.4%	0.0%	7.0%	3.5%
2.00-2.49	0.9%	7.9%	4.4%	6.2%	3.0%	4.6%	0.0%	0.0%	0.0%
2.50-2.99	1.5%	19.8%	10.6%	7.2%	9.8%	8.5%	0.0%	0.0%	0.0%
3.00-3.49	0.0%	15.5%	7.7%	4.0%	15.1%	9.4%	0.0%	0.0%	0.0%
3.50-3.99	0.0%	1.2%	0.6%	0.4%	0.0%	0.2%	0.0%	0.0%	0.0%
4.00-4.49	0.0%	12.5%	6.2%	2.2%	46.0%	23.7%	0.0%	0.0%	0.0%
4.50-4.99	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
5.00-5.5	0.0%	4.0%	2.0%	0.0%	16.2%	7.9%	0.0%	0.0%	0.0%

Free Residual Chlorine Range	CALLIDE C4 - FREE RESIDUAL CHLORINE IN COOLING WATER - FREQUENCY DISTRIBUTION								
	03-Jul-2007 to 31-Mar-2015			1-Apr-2015 to 31-May-2021			1-Jun-2021 to 27-Oct-2022		
	Before Dose	After Dose	Total	Before Dose	After Dose	Total	Before Dose	After Dose	Total
	%	%	%	%	%	%	%	%	%
0.00-0.49	65.8%	6.2%	35.9%	18.7%	0.0%	9.5%	N/A	N/A	N/A
0.50-0.99	16.2%	8.5%	12.4%	32.2%	3.4%	18.1%	N/A	N/A	N/A
1.00-1.49	10.0%	22.1%	16.1%	25.6%	3.0%	14.6%	N/A	N/A	N/A
1.50-1.99	3.5%	14.4%	9.0%	11.4%	7.2%	9.3%	N/A	N/A	N/A
2.00-2.49	1.8%	8.5%	5.2%	2.9%	6.1%	4.5%	N/A	N/A	N/A
2.50-2.99	0.9%	12.1%	6.5%	2.6%	9.1%	5.8%	N/A	N/A	N/A
3.00-3.49	1.2%	10.3%	5.7%	4.4%	16.7%	10.4%	N/A	N/A	N/A
3.50-3.99	0.0%	1.2%	0.6%	0.4%	1.5%	0.9%	N/A	N/A	N/A
4.00-4.49	0.6%	13.5%	7.1%	1.8%	36.5%	18.8%	N/A	N/A	N/A
4.50-4.99	0.0%	0.0%	0.0%	0.0%	0.4%	0.2%	N/A	N/A	N/A
5.00-5.5	0.0%	3.2%	1.6%	0.0%	16.0%	7.8%	N/A	N/A	N/A

Free Residual Chlorine	CALLIDE C3 - FREE RESIDUAL CHLORINE IN COOLING WATER - CUMMULATIVE FREQUENCY DISTRIBUTION								
	03-Jul-2007 to 31-Mar-2015			1-Apr-2015 to 31-May-2021			1-Jun-2021 to 27-Oct-2022		
	Before Dose	After Dose	Total	Before Dose	After Dose	Total	Before Dose	After Dose	Total
>0.0	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
>0.5	30.8%	92.4%	61.4%	85.1%	99.6%	92.2%	36.8%	87.7%	62.3%
>1.0	15.0%	86.3%	50.4%	59.1%	97.7%	78.0%	0.0%	36.8%	18.4%
>1.5	5.4%	76.3%	40.6%	31.2%	93.6%	61.7%	0.0%	7.0%	3.5%
>2.0	2.4%	60.8%	31.4%	19.9%	90.2%	54.3%	0.0%	0.0%	0.0%
>2.5	1.5%	52.9%	27.0%	13.8%	87.2%	49.7%	0.0%	0.0%	0.0%
>3.0	0.0%	33.1%	16.4%	6.5%	77.4%	41.2%	0.0%	0.0%	0.0%
>3.5	0.0%	17.6%	8.7%	2.5%	62.3%	31.8%	0.0%	0.0%	0.0%
>4.0	0.0%	16.4%	8.1%	2.2%	62.3%	31.6%	0.0%	0.0%	0.0%
>4.5	0.0%	4.0%	2.0%	0.0%	16.2%	7.9%	0.0%	0.0%	0.0%
>5.0	0.0%	4.0%	2.0%	0.0%	16.2%	7.9%	0.0%	0.0%	0.0%
>5.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Free Residual Chlorine	CALLIDE C4 - FREE RESIDUAL CHLORINE IN COOLING WATER - CUMMULATIVE FREQUENCY DISTRIBUTION								
	03-Jul-2007 to 31-Mar-2015			1-Apr-2015 to 31-May-2021			1-Jun-2021 to 27-Oct-2022		
	Before Dose	After Dose	Total	Before Dose	After Dose	Total	Before Dose	After Dose	Total
>0.0	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	N/A	N/A	N/A
>0.5	34.2%	93.8%	64.1%	81.3%	100.0%	90.5%	N/A	N/A	N/A
>1.0	18.0%	85.3%	51.7%	49.1%	96.6%	72.4%	N/A	N/A	N/A
>1.5	8.0%	63.2%	35.6%	23.4%	93.5%	57.8%	N/A	N/A	N/A
>2.0	4.4%	48.8%	26.7%	12.1%	86.3%	48.5%	N/A	N/A	N/A
>2.5	2.7%	40.3%	21.5%	9.2%	80.2%	44.0%	N/A	N/A	N/A
>3.0	1.8%	28.2%	15.0%	6.6%	71.1%	38.2%	N/A	N/A	N/A
>3.5	0.6%	17.9%	9.3%	2.2%	54.4%	27.8%	N/A	N/A	N/A
>4.0	0.6%	16.8%	8.7%	1.8%	52.9%	26.9%	N/A	N/A	N/A
>4.5	0.0%	3.2%	1.6%	0.0%	16.3%	8.0%	N/A	N/A	N/A
>5.0	0.0%	3.2%	1.6%	0.0%	16.0%	7.8%	N/A	N/A	N/A
>5.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	N/A	N/A	N/A

The following frequency distribution histogram combines the before and after FRC levels for both CT3 and CT4 cooling towers. The data is also presented in the form of a separate frequency histograms for each of the before and after and dosing for CT3 and CT4 are shown on the following pages. A cumulative histogram is also shown for the before and after FRC levels for the CT3 and CT4 cooling towers. Refer to Figures 4.52 to 4.54.

As can be seen from the above tables and histograms on the following pages, in the time period from 1st April 2015 – 31st May 2021, the FRC distribution has increased substantially towards higher levels for both towers. The cumulative frequency distribution chart reveals this trend much better. The increase is particularly apparent for FRC levels above and including 4 ppm. There is a significantly more FRC levels above 4ppm in this time period than from 7th July 2007 to 31st March 2015. Correspondingly, the proportion of FRC measurements in the lowest level of 0.00 – 0.50 dropped substantially between 1st April 2015 – 31st May 2021. Moreover, the average values of FRC, as shown on the histograms, jumped from 1.38 ppm to 2.37 ppm for CT3 and from 1.33 to 2.21 for CT4 from pre-March 2015 to post March 2015. Interestingly, the period average values of CT3 and CT4 do not show much variation when compared to each other. However, more variation is apparent between the towers when comparisons of the monthly average values are made as discussed previously (please refer to the previous combined line graph of the monthly FRC averages for CT3 and CT4).

As discussed before, subsequent to the C4 turbine explosion the FRC levels in the CT3 cooling water dropped substantially. The histogram on the following page shows this period in the yellow columns and is observed, the frequency distribution after the explosion is concentrated in the lower bands of FRC levels. As a result, the average, mean and maximum respectively drop from the pre-May 2021 values of 2.37 ppm, 2.0 ppm, 5.0 ppm to 0.63 ppm, 0.50 ppm and 1.80 ppm to post June 2021. For a more detailed information regarding percentage above particular FRC levels, please refer to the cumulative frequency distribution table shown on the previous page.

The following page shows the after dosing and before dosing histograms for FRC for CT3 and CT4 for comparison. Referring to the after dosing histogram, the same trends can be observed as discussed above with significant jumps in the average values of FRC post March 2015 and significant reduction post May 2021 for CT3. Please refer to the histogram for the actual calculated values. It is interesting to note that in the case of the after dosing, there is very significant shift of the FRC to ≥ 4.0 ppm particularly for the C3 tower for the period 1st April 2015 – 31st May 2021. Also of note is that the minimum values are very low in some instances (0.1 ppm) and it is not certain whether the dosing system or the tower were not operating for some reason or that there was an error in the measurements. The percentage of data in the range 0.0 to 0.49 is small and hence this low value of the minimum should not of concern regarding the results of the analysis in this report.

The before dosing histogram also shows the same trends with respect to the time periods discussed above. Please refer to the shown average values. Interesting to note that the before dosing value maximums for CT3 and CT4 are in some cases 4.0 ppm and in some these cases the after dosing levels have been 5.0 ppm. These occurrences, however, are very low.

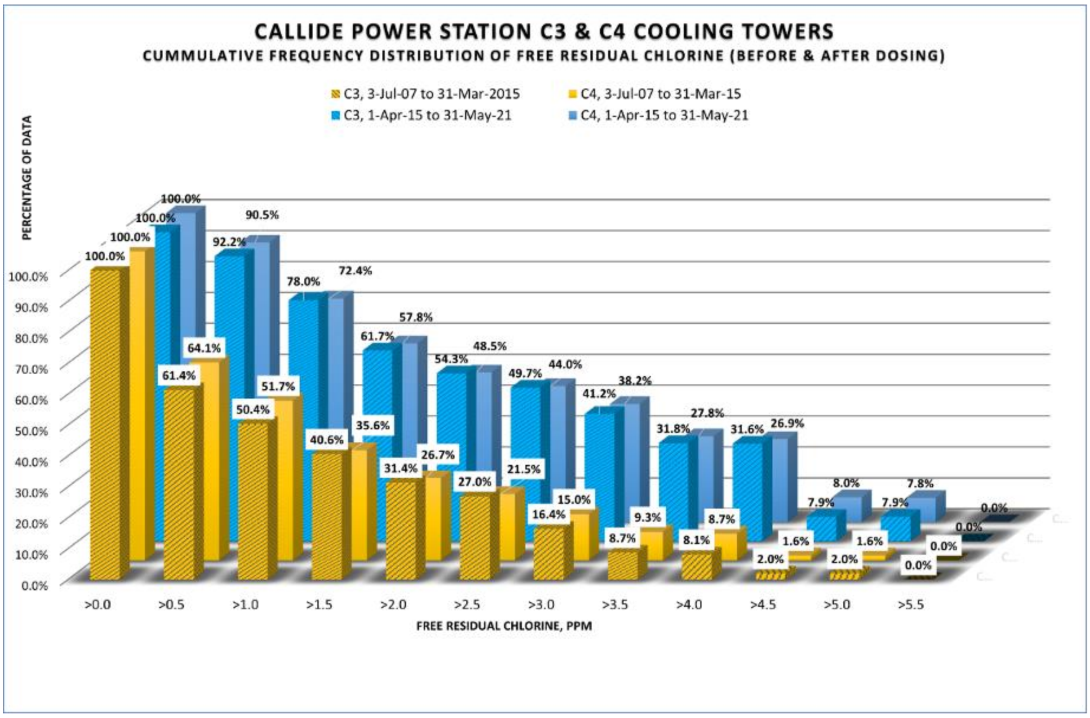


Figure 4.4 C3 & C4 FRC Cumulative Frequency Distribution Histogram

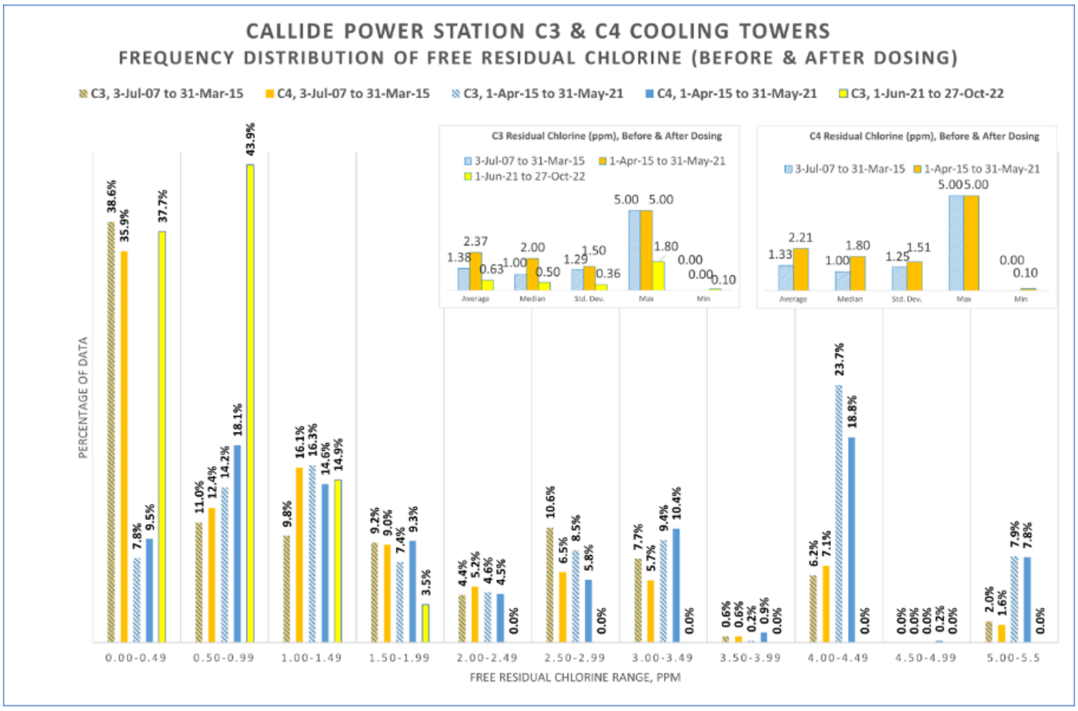


Figure 4.5 C3 & C4 FRC Frequency Distribution Histogram

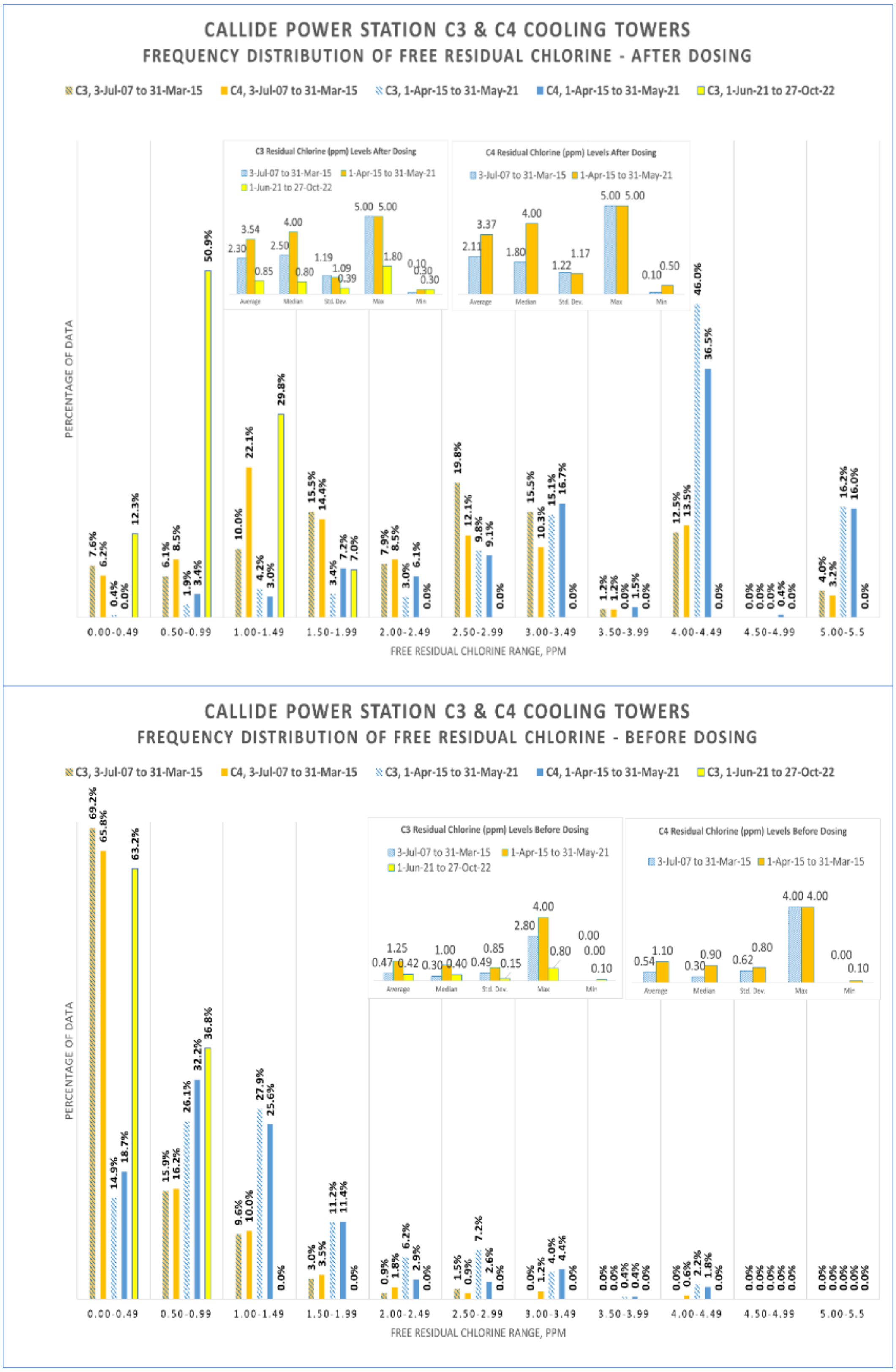


Figure 4.6 CT3 & CT4 FRC Frequency Distribution – Before & After Dosing

4.3.13 *Water pH*

Cooling water pH data was recorded from 13 November 2000 to 31st October 2022 for CT3 cooling tower and from 22 August 2001 to 24 May 2021 for CT4. Prior to 14th July 2014, the average period between readings for CT3 was one month, whereas after this date, the pH readings are on average on a weekly basis. For CT4, the after 10 November 2015, the pH readings are on average on a weekly basis. The pH is presented on a 'Scatter Chart' form on Figure 4.7 on the following page.

A vertical line representing 21st June 2006 is shown on both charts to highlight the fact that the pH control system was changed after a report by Sigma Process Solutions which recommended that the upper and lower values of pH should be 8.1 and 7.7 respectively. There is a visible drop in pH levels after this date but on analysis, 5.6% and 2.3% of the recorded values are still > pH 8.1 for CT3 and CT4 cooling towers respectively.

On closer inspection of Figure 4.7, it is evident that a significant portion of the values for pH lie between 8.0 to 8.5 with regular peaks just above 8.5 prior to 21st June 2006. As shown on Figure 4.7, for CT3 cooling tower, 84% and 18% of the pH are > 8.0 prior to and post this date respectively. The corresponding figures for CT4 are 59% and 9%.

Table 4.4 below shows percentage of data in pH ranges for both towers. Note that, post 21st June 2006, approximately 75.3% of the CT3 data is above 7.5 and ≤ 8.0 showing a drop of pH 0.5 on average post this date. For CT4, 82.4% of the data is above 7.5 and ≤ 8.0 after 21st June 2006.

Table 4.4 C3 & C4 Distribution of pH Pre and Post 21 June 2006

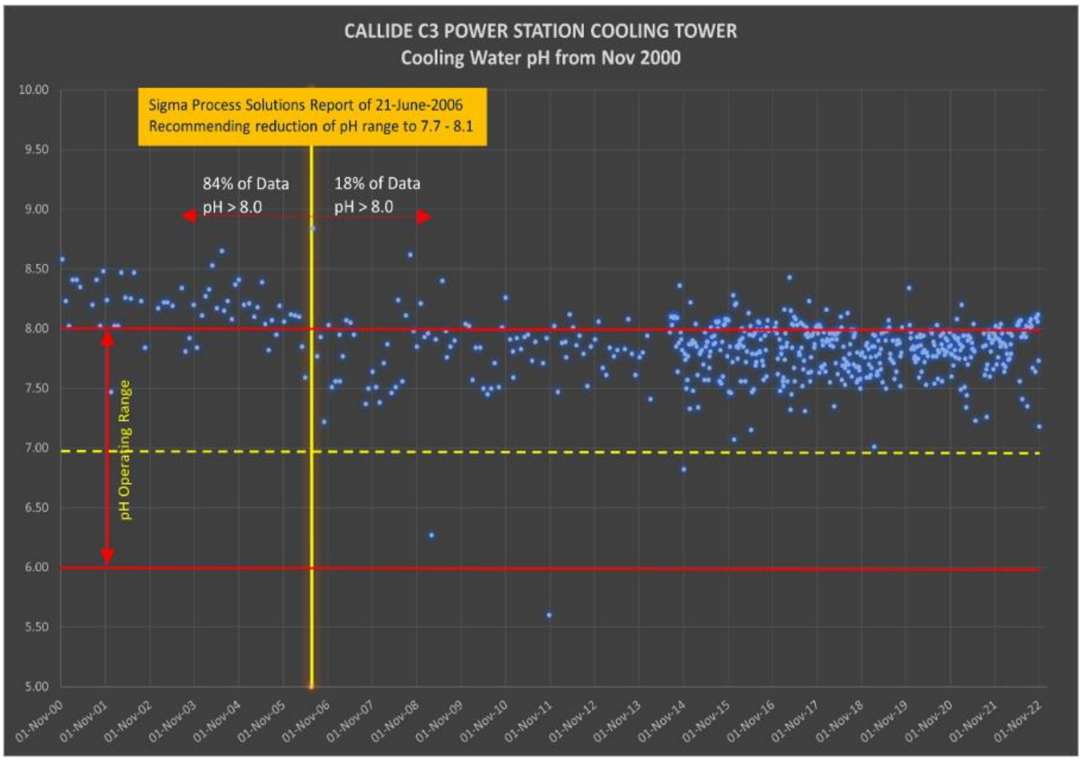
	% of Data in pH Range - C3 Cooling Tower			
	>7 & <=7.5	>7.5 & <=8	>8 & <=8.5	>8.5 & <=9
Pre 21-Jun-06	1.8%	14.3%	78.6%	5.4%
Post 21-Jun-06	5.6%	75.3%	18.1%	0.4%

	% of Data in pH Range - C4 Cooling Tower			
	>7 & <=7.5	>7.5 & <=8	>8 & <=8.5	>8.5 & <=9
Pre 21-Jun-06	2.0%	36.7%	55.1%	4.1%
Post 21-Jun-06	6.3%	82.4%	8.6%	0.4%

Cooling tower CT3 experienced peaks of pH of 8.65, 8.84 and 8.62 in June 2004, July 2006 and September 2008 respectively. The lowest value of pH was 5.6 in October 2011 (slightly acidic) and together with the measurements of 6.3 on 2 March 2009 and 6.8 in November 2014 these are the only three pH measurements where the pH dropped below 7.0. All the remaining pH values are above 7.0.

Cooling tower CT4 experienced peaks of pH of 8.60, 8.61 and 8.69 in January 2005, July 2006 and November 2016 respectively. The lowest value was 5.94 in March 2009. Values of 6.80 and 6.78 were recorded in February 2013 and February 2016. Together with pH of 6.95 in April 2009 and 6.90 in March 2017, these were the only values below 7.0.

When compared to adopted range of pH as per Table 4.1, cooling tower CT3 had 84% of the cooling water pH values above the maximum value of pH 8.0 before June 2006 and 18% above pH 8.0 post June 2006. The corresponding values for cooling tower CT4 are 59% and 9%.



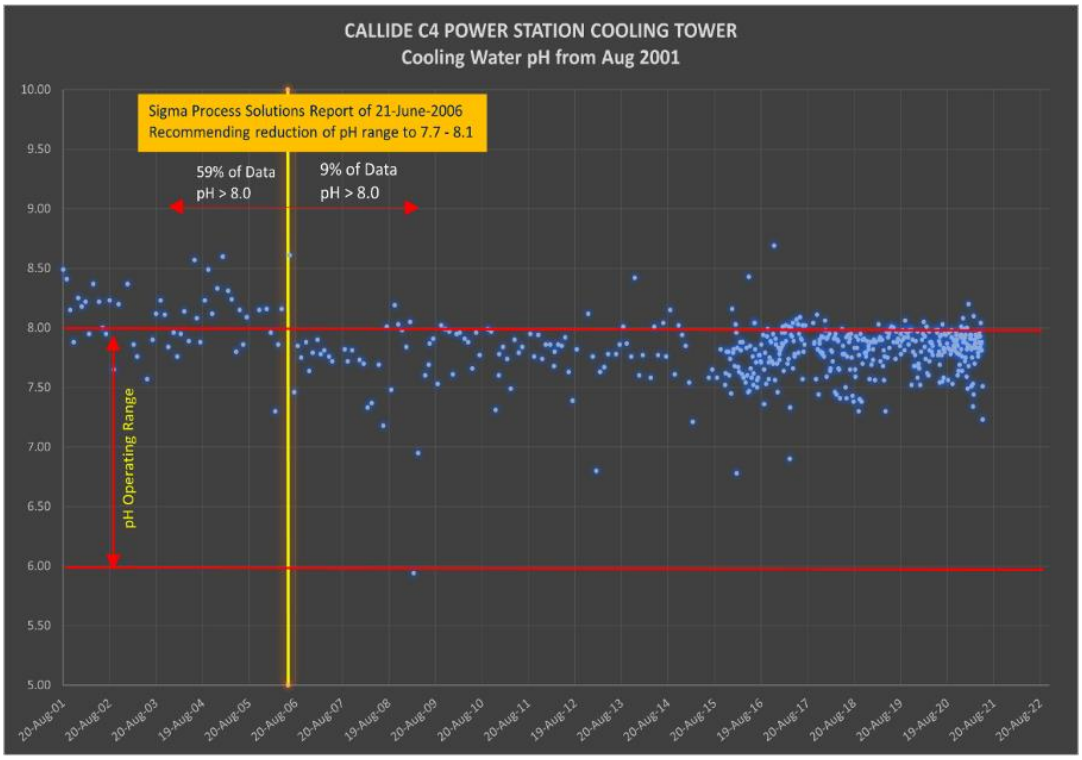


Figure 4.7 C3 & C4 Cooling Water pH Scatter Charts

4.3.14 Other Water Parameters

Another important parameter in the water chemistry of cooling water is turbidity. High turbidity can cause silt deposits on fill and in pipework. With respect to structure failure, they do not have a direct impact on timber degradation. However, where turbidity and siltation are high, it is possible that excessive build-up of deposits on the surface of fill surface may occur. This could lead to additional load to build upon the structure leading to potential overload. Failures of cooling tower structures due to fouling on Fill have occurred in other applications.

High turbidity may also lead to silt build up in the hot water basin thus increasing the load to be supported. It will also potentially cause blockages or restrictions of flow through the nozzles in the HWB or the cross-over water supply pipe which is supported by saddles on the HWB floor. Observations of the photographs provided by CS Energy did not reveal any significant silt deposits on the HWB floor. Due to inaccessibility, it was not possible to inspect any nozzles, nor the cross-over pipe directly but numerous photographs and video footage was viewed, some of which show deposits in the hot water basin.

In these cooling towers, the fill is of the 'Splash Bar' type which is very resistant to fouling. In the areas of the cooling tower which were accessible, no evidence of any significant scaling or silt build up on the fill was found.

The turbidity was provided in the water chemistry data for both the C3 and C4 cooling towers. Figure 4.8 below shows the turbidity from November 2000 to October 2022. Generally, the turbidity is low except for very high peaks in December 2010, March 2013, December 2014, March 2015, February 2016, and April 2017. The turbidity in March 2015 is particularly high. It is probable that these high turbidity values are due to heavy periods of rainfalls which may, or many not, be associated with cyclones in the region.

The correlation between total suspended solids (TSS) in the water to the turbidity (NTU) depends on the type of particles present in the water. Generally, the TSS can be a factor of 1.0 to 3.0 times the NTU. It is safe to assume, therefore, that the during the high turbidity periods the TSS has been very high.

With very high levels of TSS, it is likely that the nutrient levels in the cooling water are also very high. This would then lead to a consequent increase in the bacterial load and the need for increased disinfection.

Figure 4.9 on the following page shows the monthly averages of the turbidity and it also includes the Free Residual Chlorine (FRC) levels as well as the pH of the cooling water in both CT3 and CT4. These three parameters were plotted on the same chart to find out any apparent correlations.

It is not evident that there any correlations between the pH and the Turbidity.

With regards to FRC, there is no observable direct relationship with turbidity. However, it is worth noting that after the very high turbidity peak of 2015, the monthly average FRC jumped significantly from the average value in late 2014. With high turbidity there are higher levels of solids and nutrients which will increase the bacteria count in the cooling water. This could be a possible explanation for the significant jump in the FRC after this very high turbidity peak of 2015, i.e., a higher dose of chlorine may have been made to combat an increase in the potential bacterial count.

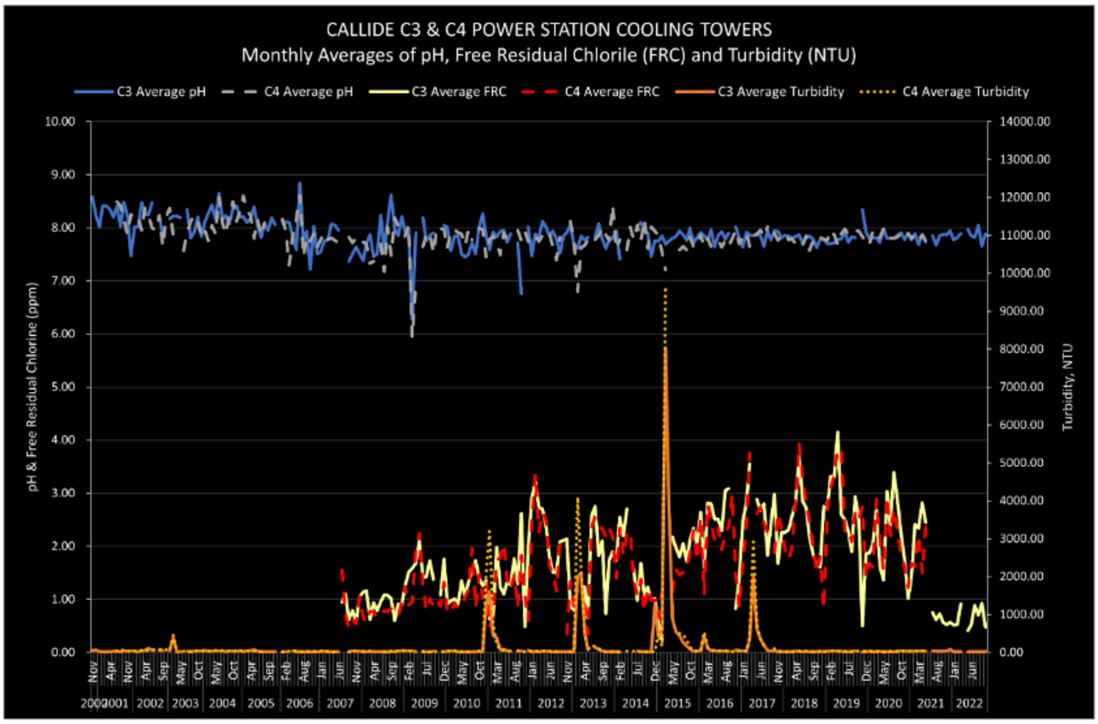


Figure 4.8 C3 & C4 Monthly Averages of pH, FRC and Turbidity

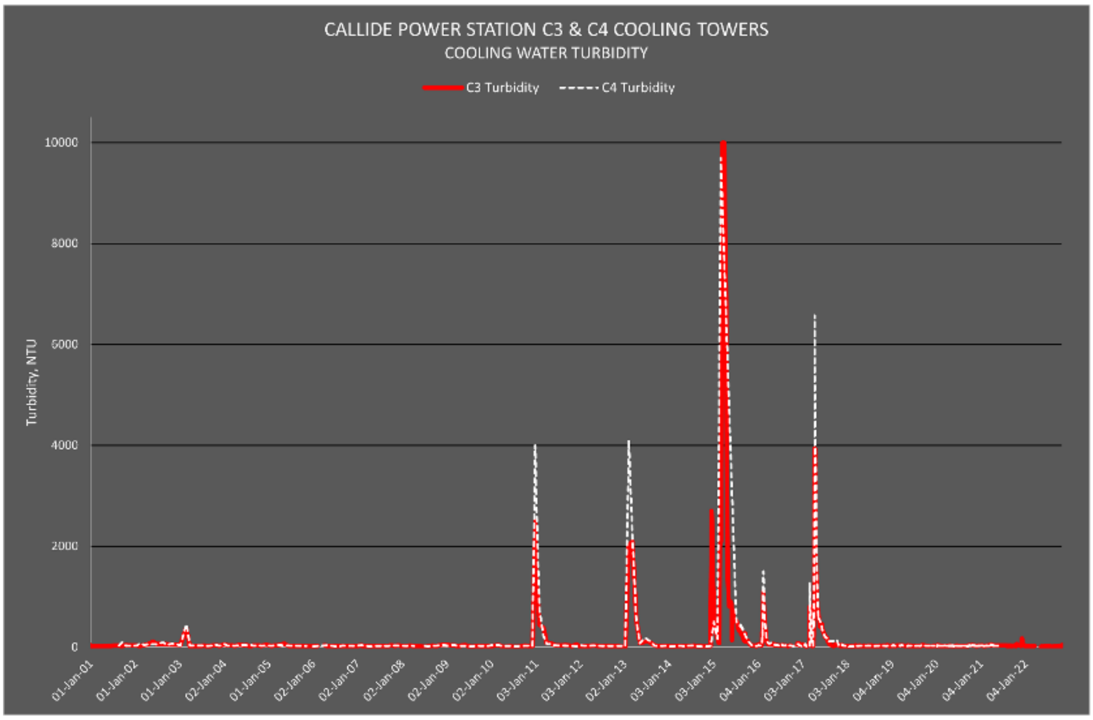


Figure 4.9 C3 & C4 Cooling Water Turbidity

4.3.15 Discussion of impact of free Chlorine levels and pH

Timber will suffer chemical deterioration by oxidizing agents such as chlorine. It will also deteriorate in alkaline conditions. The lignin binding the cellulose fibres in the timber is removed by chemical attack. This process is referred to as 'delignification'. This damage is restricted to the surface of the timber and does not impair the strength of the unaffected areas.

Water flowing over the surface of the timber such as in the wet zone (fill area) washes away the loosened fibres. The result is erosion of the timber surface induced by chemical attack and this is commonly referred to as 'chemical erosion'. Over time, the timber section is thinned and reduced in size. This chemical attack is therefore most frequent in the wet zone.

Chemical attack also occurs in other areas of the structure where alternate wet and dry conditions are present such as air inlet louvres and other external surfaces or warm moist areas of the plenum of the tower. Damage to the timber occurs because of chlorine vapours and entrainment of droplets of cooling water. Where water is not cascading over the surface to wash away the outer delignified fibres, the surface remains fibrous and has a white or bleached appearance.

As discussed in preceding sections of this report, the combination of Free Residual Chlorine and pH above 1 ppm and 8.0 means that timber will deteriorate at an elevated rate due to chemical erosion resulting in delignification. It should also be noted that water erosion will also occur under normal operating conditions in addition to chemical erosion.

Graphs have been provided earlier showing the upper and lower bounds for Free Residual Chlorine and pH are plotted for comparison to the values at which the cooling tower has been operated. To reiterate these upper and lower bounds are 0.4 to 1.0 ppm for Free Residual Chlorine, and 7.8 to 8.3 for the pH.

From the graphs, it is evident that the cooling towers have been operating with high levels of Free Residual Chlorine for a long period, with frequent maximums of 4 ppm with peaks reaching 5 ppm during the middle of 2018. During the same period, it is noted that the pH has been in a range of 8.0 and 8.5 prior to June 2006 and mostly in the range from 7.5 to 8.0 after June 2006. It is noteworthy that a significant portion of the data prior to June 2006 was above a pH of 8.0 and this decreased substantially after June 2006 in both cooling towers.

It is also noteworthy that the Free Residual Chlorine levels have dropped significantly in mid-2021 but still maintained maximums above 1 ppm but below 2 ppm.

Note as well that there are no records for Free Residual Chlorine levels prior to July 2007. Whether these high levels of Free Residual Chlorine have been the case since commissioning is therefore unknown.

Given the above levels of pH and free Chlorine in the cooling water, it is likely that the timber structure of the cooling towers will have experienced substantial chemical erosion. Inspections in the wet zone by HartzEPM and others, have revealed significant chemical degradation of the cooling tower timber structures. This is discussed further in the following sections of this report.

5 Condition of cooling towers

5.1 Inspections by HartzEPM

HartzEPM attended site on four occasions, and these are discussed below.

5.1.1 Site Visit No. 1

Site visit number 1 was undertaken on 15th and 16th November 2022. Raffi Andonian and Andrew Nielsen attended on behalf of HartzEPM. At this time, cooling tower CT3 could not entered because access was restricted by WH&S. The site visit was a briefing meeting, and inspections were carried out externally from outside of the fenced off 16m exclusion zone. At this time, it is noted that the collapse cells 8 and 9 of cooling tower CT3 had occurred on 31 October 2022. No report was produced for CS Energy further to this site inspection. However, based on the inspection the following comments can be made:

- Cooling CT3 was taken offline in March 2022 for an unplanned outage. This was to conduct inspections and observe damage in cells 1 to 7 north side. Planning for maintenance and for the repairs of the damage had commenced.
- There appeared to be a general reduction in the cross section of the timber column cross section from the original 100 mm square to between 85 mm to 90 mm square.
    - The hot water basin distribution valves were throttled back to 75% with the intention to avoid over boarding.
- The original operating design water depth for the hot water basin is 153mm. To reduce the hot water basin water load, CS Energy had reduced the operating depth to 100mm by cutting notches into the hot water basin walls, in which the height of the notch is 100mm above the basin floor. The notches were each 2.0m long, and two were cut into the hot water basin wall per cell. They were located at the start and end of each hot water basin or adjacent to each cells divider walls, i.e. two slots per cell.
- On 28th October 2022 the second cooling water pump for cooling tower CT3 was brought back online. The failure of cells 8 and 9 north occurred on 31st October 2022. Prior to the failure there was nothing unusual. Refer to Section 6 for a description of the operating conditions in the months leading up to the collapse of cells 8 and 9.

While the design operating water depth in the hot water basin is 153mm, the overall depth of the hot water basin is 213mm. Usually cooling towers are designed for a full to overflowing hot water basin, i.e., in this case, a depth of water slightly more than 213mm. In a new or "normally" degraded cooling tower therefore, the load from a full hot water basin is usually designed for.

Regarding throttling back the hot water distribution valves, it was not noted what the over boarding water depth was prior to throttling back the distribution valves, and it is implied that the depth would initially have been more than this. It is understood that the throttling of the valves was to keep the water level to 100mm or less and that overflowing of the HWB at the slots was not to be a routine occurrence.

5.1.2 Site visit No. 2

Site visit number 2 was undertaken on 20th and 21st December 2022. Andrew Nielsen attended on behalf of HartzEPM. For this inspection access was provided to the walkway in the plenum zones of both towers. The direct inspection was therefore of the lower section of the plenum, and there was limited opportunity to make observations into the wet zone. While no report was produced as result of this inspection, an online meeting was held with NRF and CS Energy in which the photos taken were reviewed and discussed. Since the observations were similar to that in a subsequent inspection be HartzEPM. Comments on the findings will be incorporated in the sections following.

5.1.3 Site visit No. 3

Site visit number 3 was undertaken on 10th to 12th January 2023. Raffi Andonian and Ray Hartzenberg attended on behalf of HartzEPM. The intent of the inspections was to provide data in addition to that already available, to provide a condition assessment of the CT3 and CT4 cooling towers. To supplement site visit number 2, this inspection focused in on the wet zone immediately behind the drift eliminators.

A letter report titled Findings on inspections of 10th to 12th January 2023 Revision 2 and dated 13 February 2023, was prepared by HartzEPM, and is included in Appendix E – HartzEPM Structural Analysis and Member Assessment. The report describes the details of the inspections, the areas inspected, and provides an overall assessment of the extent of the timber degradation together with an assessment of the impact on the strength of the primary members.

The following figures are photographs of several observations which appear to occur commonly throughout both towers in the areas inspected and in previous reports.

Among the issues noted are the following:

- Loose connections with loose nuts and bolts, and shear connectors disengaged. Partly due to the erosion timber and likely due to vibrations induced by the mechanical equipment.
- Misalignment of columns and girts at splice points, partly due to the erosion of timber and likely due to vibrations induced by the mechanical equipment.
- Undersized washers used under nuts and bolts. Typically, washer sizes are 24mm in diameter whereas the timber standard AS1170 requires washers with a diameter of 55mm. In some locations washers were omitted or had dislodged.
- There are significant defects in the timber used in the cooling tower, in particular knots and knot clusters. The effect of these knots is to downgrade the timber and in the case the stress grading drops from stress grade F8 to stress grade F7 for those members with those defects. This results in a loss of strength of approximately 18% for axial strength based on the current Australian standard *AS1720.1 Timber Structures Part 1: Design Methods*.
- By far the most significant observation is that of erosion in all the members. Typically, erosion occurs due to the mechanical abrasion of water running over surfaces, as well as due to surface chemical attack. In these towers chemical erosion was observed. Refer to the sections on water chemistry above.

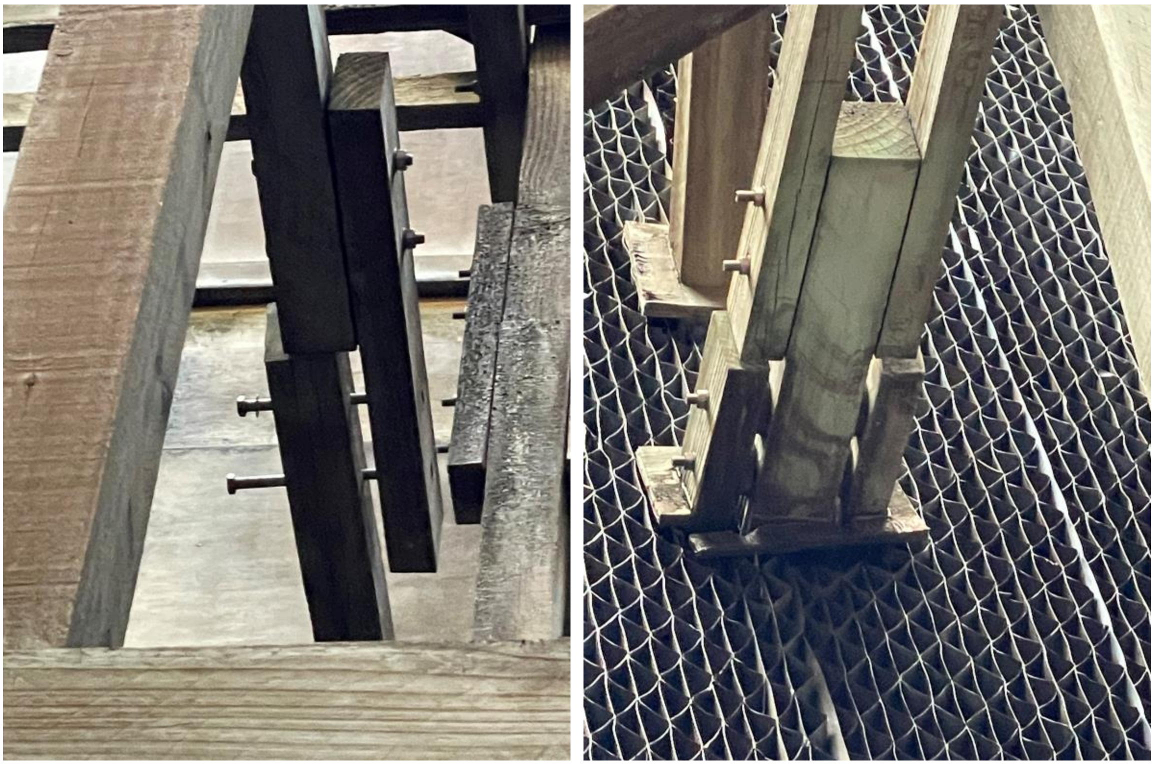


Figure 5.1 Left – Nuts missing, danger of bolts falling out. Right – Loose connection with shear plates disengaged, alternatively these are spacer blocks

Figure 5.2 Left and Right – Loose connections, misaligned girts with shear plates disengaged, alternatively these are spacer blocks

Figure 5.3 Left - Undersized washers. Right: No washer in FRP column

Figure 5.4 Left - No washer or undersized washer penetration. Right Anchor plate with no washers

Figure 5.5 Left and Right - Knots in horizontal girts - chemical erosion

Figure 5.6 Left - Knot in horizontal girt with chemical erosion. Right - Knot in diagonal brace, chemical erosion

Figure 5.7 Transverse girt with chemical corrosion. Timber D-Moulds completely eroded

Figure 5.8 Longitudinal girt with chemical erosion. Twisted end of intermediate girt due to bottom fixing only

Figure 5.9 Longitudinal girt with chemical erosion

Figure 5.10 Transverse girts chemical erosion, original depth 100mm and 80mm remaining

5.1.4 Site Visit No. 4

Site visit number 4 was undertaken on 19th and 20th June 2023. This inspection came about because there was a need to ensure that the southern face of CT4 was safe from falling debris, such that work could be carried out safely adjacent to the southern perimeter of CT4 within the 16m exclusion zone. The inspection was carried out from top to bottom along the southern face of CT4 from an elevated work platform (EWP). During the inspection the EWP was at the limit of its reach and therefore opportunity for close up and internal inspection was limited. The extent of the reach required was to remove broken or loose louvre sheets, and/or to reattach or remove louvre support members which were loose or damaged. The inclined louvre columns, the first full length vertical row of columns adjacent to the cold water basin wall, and the perimeter sections of longitudinal and lateral girts was all that could be observed as light and as obstructions, such as the fill permitted.

Several temporary repairs were made to limit the potential for falling debris during access by workmen to the area below. Given the short time frame for which the repairs were required, any reattachment comprised tying up louvre sheets and louvre support member using wire ties to secure points. The repairs included:

- Removing loose or damaged louvre sheets.
- Refastening louvre sheets that had become loose.
- Removing timber louvre supports where these were overly degraded, especially around fastener points.
- Refastening timber louvre supports to secure points.

During the above activity, as much of the timber was inspected as reasonably could be inspected from the basket of the EWP. As such the inspection was done from a distance and it was not possible to touch, hammer or probe members. The following comments are made:

- In general, the appearance of the timber was similar to that observed in the wet areas of both CT3 and CT4, in which that the timber had undergone chemical erosion. In this sense therefore, similar conclusions as to the cause of the erosion can be inferred.
- The columns, while eroded as noted, did not appear to have undergone similar disturbance to the rectilinear geometry as was noted elsewhere. The exception to this was one vertical in cell 1 where the column has rotated about a splice point. See photos below.
- As in CT3 and CT4, the connections were in poor condition, with gaps between bolted members. Whether nuts were loose is hard to say, since it was not possible to touch.
- The HWB on the southern side of CT4 appeared to be in reasonable condition with no sagging evident.
- Some of the steelwork bracing the riser pipes were severely corroded.

Typical photos are shown below.

Figure 5.11 The reach of the EWP approaching its limit -South facade of CT4

Figure 5.12 Typical damage to louvre sheet

Figure 5.13 Close up of broken louvre sheet - typically damaged sheets were cut and removed

Figure 5.14 Steel brace configuration for riser pipes

Figure 5.15 corrosion in the riser pipe braces

Figure 5.16 Louvre support timber sagging where the FRP plastic tie has come undone

Figure 5.17 Louvre support member that has dropped and FRP tie is hanging free

Figure 5.18 Typical temporary repair to re-support louvre supports using wire ties

Figure 5.19 Remnant of the cell divide plywood potentially. Loose louvre sheet in the foreground

Figure 5.20 Louvre sheet D-mould timber eroded and absent in many locations. Also eroded longitudinal girt and splice

Figure 5.21 Column bent at splice

Figure 5.22 Some sections of fill collapsed though not widespread on this side of CT4

Figure 5.23 Erosion of transverse girts and column. Cut louvre sheet in the foreground

Figure 5.24 View of hot water basin. No evidence of sagging

Figure 5.25 Hot water basin appeared to be in reasonable condition

Figure 5.26 Fan deck appeared to be in good condition

Figure 5.27 Several sections where louvre sheets were removed. Access was granted and riser pipes removed

5.2 Condition assessment by HartzEPM

Based on site visit number 3, HartzEPM prepared a condition assessment report. The report is titled Findings on inspections of 10 to 12 January 2023 Revision 2 and dated 13 February 2023, and is included in Appendix F – HartzEPM Condition Assessment Report.

During the inspection numerous measurements were taken of the timber members, including columns, diagonal braces, lateral and longitudinal girts. Based on these measurements, calculations were carried out to assess the loss of cross section of the members, as a comparison with the original cross section. This gives an indication of the loss of strength as compared to the original strength of the respective members as at the time of the inspection. The findings are discussed in the aforementioned report and are summarised below:

- Twenty six percent (26%) of girts have less than 50% of bending strength remaining, while 9% have less than 50% of axial strength remaining.
- Forty eight percent (48%) of girts have between 50% and 70% of both bending strength and axial strength remaining.
- Twenty six percent (26%) of girts have great than 70% of bending strength remaining, while 43% have less than 50% of axial strength remaining.
- The column measured has lost 35% of its cross-sectional area, while the diagonal brace measured has lost more than 20% of its cross-sectional area.

It should be noted that the number of measurements measured was a relatively small sample, in a limited area in the wet zone, and that the results have been extrapolated to the rest of the cooling towers. The cross sectional assessments discussed above must be considered in conjunction with the substandard quality of many of the timber members, as well as the severely compromised condition of the joints.

5.3 Timber deterioration

There are three main types of deterioration in cooling tower timber. These are chemical, biological, and physical. Often, all three occur simultaneously and it is rare for one type to be present without another. Physical and chemical deterioration are more easily observed, and results in timber being more prone to biological attack. The types of deterioration are discussed below regarding how this would have impacted cooling towers CT3 and CT4.

5.3.1 Chemical deterioration

Chemical deterioration normally occurs in the wet zone where there is continuous contact with cooling water. However, it can also occur in areas which are alternately wet and dry, where chlorine vapours and droplets of water are entrained. Wet and dry areas are typically at air intake louvres, exterior areas and in the plenum zone.

When Free Residual Chlorine are in excess of 1.0 ppm simultaneously with a pH greater than 8.0, then chemical deterioration is particularly severe. The deterioration results in delignification of the timber in which the lignin component of wood is removed, leaving behind loose timber fibres. These fibres are then washed away by the action of the cascading cooling water. The water chemistry section above further discusses in detail the effects of high Free Residual Chlorine and pH levels in timber cooling towers. As can be seen these cooling towers have been subjected to cooling water for a long time with high Free Residual Chlorine levels in conjunction with high pH values.

The delignification process and the consequent loss of timber fibres, results in thinning of the timber. This is turn has caused bolts and nuts to no longer bear onto solid timber and hence connections are no longer tight. Together with vibrations in the tower due to the operation of the mechanical components (fans, motors), and the absence of locknuts or locking adhesive on the nuts, many of the nuts have loosened, and consequently the connections and splices have opened. As a result, in many cases shear connectors are only loosely engaged or not engaged at all, thereby making the bolt shank the only loadbearing element. Without an effective shear connector, this increases the bearing stresses between the timber and the bolt shank to potentially unacceptably high levels. In some instance nuts have fallen off and bolts in danger of falling out completely. As can be seen from observations described above, as well as from earlier reports by others, it is evident that chemical attack and deterioration is prevalent throughout the cooling towers.

5.3.2 Biological attack

Timber which has undergone biological attack typically becomes dark in colour, loses strength, and may also become soft. This is because of organisms that attack timber degrading cellulose by secreting enzymes that convert the cellulose into compounds that they can absorb for growth. As a result, the cellulose content is depleted leaving a lignin rich residue. In cooling towers CT3 and CT4 there were no reported incidents of biological attack, nor was any such attack evident in recent inspections. Moreover, there was no evidence of surface or soft rot nor were any incidences of internal decay evident.

5.3.3 Physical and other factors

There are many other factors that can have a detrimental effect on timber. Comments as follows:

- Exposure to high water temperatures typically above 60° C can change timber structure and accelerate loss of timber material. This results in weakening of the timber and make it more susceptible to biological attack. According to the operations manual the design hot water temperature is 33.14° C and there is no suggestion that water temperatures have exceeded this limit during operation.
- Areas around fasteners such as bolts and nails as well as areas around the shear connectors are susceptible to deterioration and this has been observed through both towers. As has been noted above bolt holes have been eroded loosening up corrections. This erosion around bolts is considered to be due to chemical erosion.
- High concentrations of dissolved salts in cooling water do not tend to attack timber, however in areas of alternate wetting and drying the crystallisation of salts can rupture timber cells. This does not appear to have been the case.

The reference for the above is Chapter 29 – Cooling Tower Wood Maintenance of the Handbook of Industrial Water Treatment by Suez and Veolia – March 2023. This document can be found on the internet at Water Handbook - Cooling Tower Wood Maintenance | S UEZ (watertechnologies.com)

5.4 Quality of timber used

5.4.1 Timber Species

The specified timber used in the original construction was CCA treated radiata pine of stress grade F8. This is a H5 treated softwood with an unseasoned density of 800 kg/m^3. GHD in their 2014 Structural Assessment and Modelling Report, undertook testing and confirmed this to be the case. It should be noted that the stress grade is relevant to the member design and a different parameter applies to the design of timber connections.

5.4.2 Strength Group

The parameter for timber connection design is based on the strength group which, unlike the stress grade, considers the density of the timber. The published strength group for radiata pine is S6 (unseasoned), and SD6 (seasoned) as in AS1720.1 Timber Structures – Part 1 Design Methods. Timber seasoning is the process of removing moisture from timber to prevent it from warping or splitting when it's used in construction. In AS1720.1 seasoned timber is timber in which the average moisture content is nominally between 10 and 15%, while unseasoned timber has a moisture content which nominally exceeds 25%. In an active cooling tower, the timber moisture content is usually above 15% to 20% and therefore the relevant strength group for the cooling towers is S6 because the timber is essentially unseasoned.

5.4.3 Strength Group, Structural Grade Number and Stress Grade

The Structural Grade Number relates to the visual characteristics of the timber including knot sizes, grain straightness, borer holes together with the stress grade. In the 2014 report, GHD used a small sample and visually assessed the timber for defects including knots, borer holes, slope of grain, width of growth ring and resin pockets. The visual structural grading system typically works as follows:

- Structural grade 1 allows a knot size of 25% of the centre half of the timber, and,
- Structural grade 2 allow a knot size of 40% of the centre half of the timber.
- For example, a timber member of 100mm thickness would be allowed a 12.5 mm face knot to achieve a structural grade 1, or an 18mm face knot for it to achieve as structural grade 2.
- Bolt holes are to be treated as knots.

Following the rules, and after assessing the timber defects, GHD concluded that no member in the tower can be rated higher than structural grade 2. Therefore, it can be seen that for unseasoned radiata pine, strength group S6 and structural grade 2, the assessed stress grade of the timber used in the cooling tower is F7.

SEASONED SOFTWOOD

Standard trade name	Source	Average density at 12% MC	Minimum density at 12% MC	Method of assigning F grade	Strength group	Stress grade (F grade)				
						Structural grade number				
						1	2	3	4	5
pine, radiata	Aust	535	400	A	SD6	F8	F8	F7	F5	F4
	NZ	465	350	A	SD6	F8	F8	F7	F5	F4

UNSEASONED SOFTWOOD

Standard trade name	Source	Method of assigning F grade	Strength group*	Stress grade (F grade)				
				Structural grade number				
				1	2	3	4	5
pine, radiata	Aust NZ	A B	S 6 S 7	F8 F8	F7 F7	F5 F5	F4 F4	— —

Figure 5.28 Relationship between strength group, structural grade and stress grade for seasoned and unseasoned timber (AS2858)

The above assessment is based on visual grading and as such can be subjective and conservative. CS Energy had timber tests carried out on samples of timber from the cooling tower by Breitinger Consulting, refer report number 79-2023-01 dated 14 January 2023. These tests have confirmed that the stress grade of the timber tested is F8. However, these tests do not consider the defects directly observed in the tower by GHD and others, as they machine tested strength only.

What can be concluded from the above is that some timber members would be as per the original specification is F8, while other timber members with significant defects as discussed above should be derated to F7. It also appears that there are members with such severe defects, as seen in the photos included above, that should have been rejected and not built in at the time the cooling towers were built.

5.5 Splash bar support system

A discussion on the splash bar support system has been included because there are notable observations with regard to some of the details thereof. It is considered that a separate failure and collapse of the splash bars could occur without the primary structure of the cooling towers also collapsing. Some of the observations is of failed splash bar supports while the primary structure has remained in place.

In general, the splash bars are supported on vertically hung FRP grids. The FRP grids then appear to be supported on thin timber D-moulds with the grids hanging off the D-moulds, and in addition to this, the grids are also side stapled to the timber girts. Many of the D-moulds have deteriorated to the extent they are now largely ineffective or have fallen out completely. The photo below shows the condition of the D-moulds as well as the seemingly irregular staple fixings.

Figure 5.29 Remnants of the D-mould support strips and the staples supporting the FRP grids

At the uppermost section under the hot water, the FRP is supported by nails driven through a thin strip of plywood. This strip of plywood is in poor condition and loose and largely eroded away. While the FRP grids are supported by the nails, and not the timber strip, with the timber strip eroded away, the FRP grids can now fall off the nails and drop a whole tier of fill. See Figures 5.30 and 5.31.

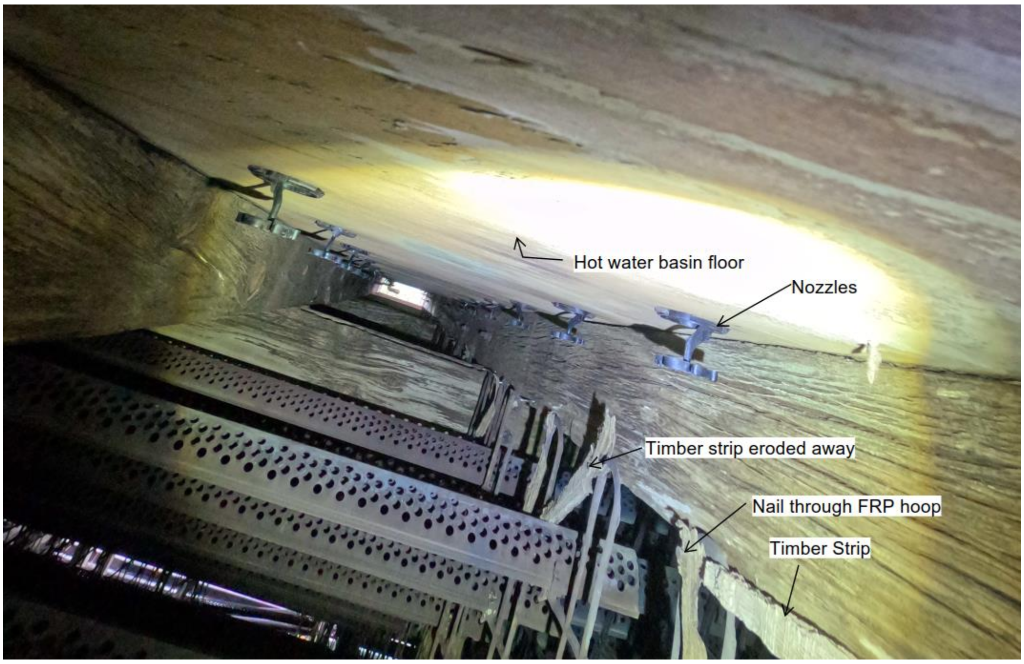


Figure 5.30 Support at top section of FRP grids showing eroded timber

Figure 5.31 Section where the upper fill supports have fallen

As can be seen the condition of the splash bar supports is poor. As such there could be collapse of the fill independently of the tower primary structure. Therefore, when large sections of splash bars collapse it is not necessarily an indication of problems with the primary structure. However, the weight of collapsing tiers accumulating on supports lower down, could overstress those lower supports.

5.6 Design Issues

In reviewing the previous reports, photographs, drawings of the towers which were made available for this investigation, and site observations, a few comments can be made. In general, the comments do not mean that there is an inherent issue with the design of that the design is structurally inadequate from a strength perspective. Rather the comments are about whether the design implemented is considered to be good practice.

5.6.1 Fasteners

The mechanical equipment on cooling including the fan and motor will produce vibrations through the structure. These vibrations will be experienced by the joints. While AS1170.1 is silent on the design of joints subjected to vibrations, AS4100 Steel Structures requires, inter alia, that locking devices are used. This implies the use of lock nuts, or as has been used on other cooling tower joint assemblies, products such as Loctite, or some other thread locking device. This was not done in these cooling towers, hence the combination of vibrations and the erosion of the timber allows the bolts to become loose. The alternative to this is the more frequent retightening of fasteners. It should be noted that in timber cooling towers there is erosion in the timber due the action of the cooling water, and this would require periodic retightening of fasteners. If erosion is accelerated by higher than desired Free Residual Chlorine and pH levels, then the requirement for retightening becomes more frequent. The frequency of retightening is hard to predict and best determined by inspection, in particular in the wet zone.

5.6.2 Cooling Tower Bracing System

In the preceding sections, the way the cooling towers have been longitudinally and laterally braced is discussed. Further comments follow.

5.6.3 Lateral Bracing

It would be considered preferable to have braced the end wall and cell divider wall frames directly by means of diagonal braces as the intermediate frames were. The reliance on the floor diaphragm, while not a design flaw, is questionable.

It is known from previous reports that the original ply flooring which would have formed the floor diaphragm, was reported to be deteriorating as early as 2006. By 2014, the deterioration of the ply was well advanced and the fasteners no longer effective.

In addition, one of the earlier reports noted that the fasteners or nailing pattern and spacing was inadequate to provide diaphragm action. If this condition existed it would have made the tower more susceptible to lateral movements under the action of the fans and motors, and under lateral wind load. Without frequent retightening of bolts this would continue to worsen with movements increasing overtime placing further stresses on already loose connections.

5.6.4 Longitudinal Bracing

As noted above not all cells are longitudinally braced and rely on other members such a floor diaphragms and longitudinal girts to transfer longitudinal loads from longitudinally unbraced cells to braced cells. This is not a design flaw but is a questionable approach as it requires more movement in the structure for these loads to be transferred from an unbraced location to a braced location.

The same transient forces exist in the longitudinal location as in the lateral direction, i.e. vibrations due to mechanical equipment and wind loads. As above as timber erodes and fasteners loosen and are not retightened, the situation worsens over time.

5.6.5 Splash bar support system

As discussed above the splash bar support grids are supported on a thin timber D-mould in combination with metal staples. It is unclear which of these is meant to be the primary support, or if they are meant to be providing complementary support.

The issue with the timber D-moulds is that they are very slender with an original diameter of around 30mm. In August 2015, it was reported that the section remaining was down from 50% to less than 20% of its original size. Observations in 2022 revealed that these sections were mostly completed eroded and unable to support their own weight.

Where metal staples were used, some were still in place providing support while in many cases the staples were not evident. One of the issues were with the staples they did not start out with a certain depth of embedment into the supporting timber girts. As the timber girts were eroded this depth of embedment decreased to the point where many could no longer hold on and lost grip.

6 Cooling Tower CT3 Operating Conditions January 2022 to Collapse 31 October 2022

The following describes the operating conditions and incidents in cooling tower from January 2022 through to the collapse of cells 8 and 9 on 31st October 2022. The following is based on information provided by NRF:

- **Prior to Tuesday 25 January 2022**: CT3 operating with all 18 cells in service and with 2 CW pumps in service.
- **Tuesday 25 January 2022**: CT3 cell 1A (south side) undergoes a "partial" or internal collapse.
- **Tuesday 25 January 2022:** Incident report prepared, and full risk assessment carried out after the collapse and an action list produced.
- **Tuesday 1 February 2022:** CT3 cell 1A distribution valve closed.
- **Sunday 27 March 2022:** Outage commences. Inspection of CT3 for damage and to undertake "minor" repairs. Repairs carried out included:
  - Two columns in cell 11 were repaired. Subsequently further damaged columns were observed in cell 11 from an EWP.
  - Repairs carried out in cells 9 to 18 north and south. The extent of the repairs, members repaired is unknown.
- **Tuesday 5 May 2022:** Outage ends. From this time the operating condition fluctuated. CT3 had one pump in operation for a "few" months and cells 1 to 8 south were isolated. Thus 8 out of 36 hot water basins were not in service.
- **Friday 16 September 2022:** The 2nd pump is brought online. Thus 2 pumps in service.
- **Friday 30 September 2022:** On or about this date, stooping was visually observed in the hot water basins of cells 5 and 11 north. At this time CT3 operation reverted to one pump.
- **30 September 2022:** At a risk assessment two strategies were considered to manage to the depth of the hot water in the hot water basin to reduce load. The first was to throttle the distribution valves to 75% open to the remaining operational cells to maintain the depth of water in the hot water basin to 100mm from the design operating level of 153mm. This was with 12 Aggreko units (portable cooling towers) in service simultaneously. The second was to cut 100mm high overflow slots in the side walls of the hot water basin to ensure that water levels remain at or below 100mm. Regarding the throttling of the valves, throttling was based on the movement of the valve stem from the fully open position and does not imply the same reduction in flow rate. To know the flow relative to the stem movement, the valve characteristic curve is required. This valve characteristic curve describes the relationship between the valve stem position and the flow rate. These curves were not available.
- Between **Tuesday 18 October 2022 and Friday 28 October 2022,** 2m long overflow slots were cut in the sides of the hot water basin. Two slots per cell were at an overflow height of 100mm above the floor of the hot water basin. The slots were positioned to be nominally on either side to the cell divider wall over each cell. The overflows discharged to the outside of the cooling tower with the discharge impacting mainly the upper louvre sheet, with much lesser area of impact on the second louvre sheet below that.

- **Friday 28 October 2022:** The 2nd pump is brought online, and operation is with two pumps and 12 Aggreko units.
- **Monday 31 October 2022:** Cooling tower 3 cells 8 and 9 north collapse. The collapse was limited to the wet area. There was an intent to further throttle the valves to 50% open however prior to this being fully implemented the collapse occurred.
- In summary, at the time of the collapse noted above, the tower was operating with the following configuration:
  - 23 out of 36 hot water basins were in service, i.e., 13 hot water basins out of service.
  - 12 Aggreko units operating equivalent to approximately 2 cells.
  - Cells 1, 2 and 3 were out of service i.e., 6 HWB's.
  - Cells 4 to 8 south, cells 5 and 11 north were out of service, i.e., 7 HWB's out of service.
  - Two pumps in service and the valve throttled back to approximately 75% open on the north side. On the south side the valves were further throttled back such that the depth of the water in the HWB was limited to 100mm. The same was to be done on the north side however the collapse occurred before this could be implemented.

7 Failure Modes

As discussed in Section 5.1 above, it has not been possible to undertake detailed inspections to determine the exact way the collapse has occurred or how it was initiated. The following sections therefore discusses possible failure mechanisms.

7.1 Functions of the members within a cooling tower structure

The primary members in a cooling tower such as cooling tower CT3 are columns, transverse and longitudinal girts, and transverse and longitudinal braces. Secondary members include wall and floor diaphragms consisting typically of plywood sheets and these provide for the transfer of in plane forces from one location to another and then to ground via the primary members, ultimately through the columns and diagonal braces. This has been discussed in sections above and illustrated in the figures included above. A diagrammatic representation around a typical joint is shown in Figure 7.1 below. Refer also to Figures 3.1 to 3.8 in Section 3.

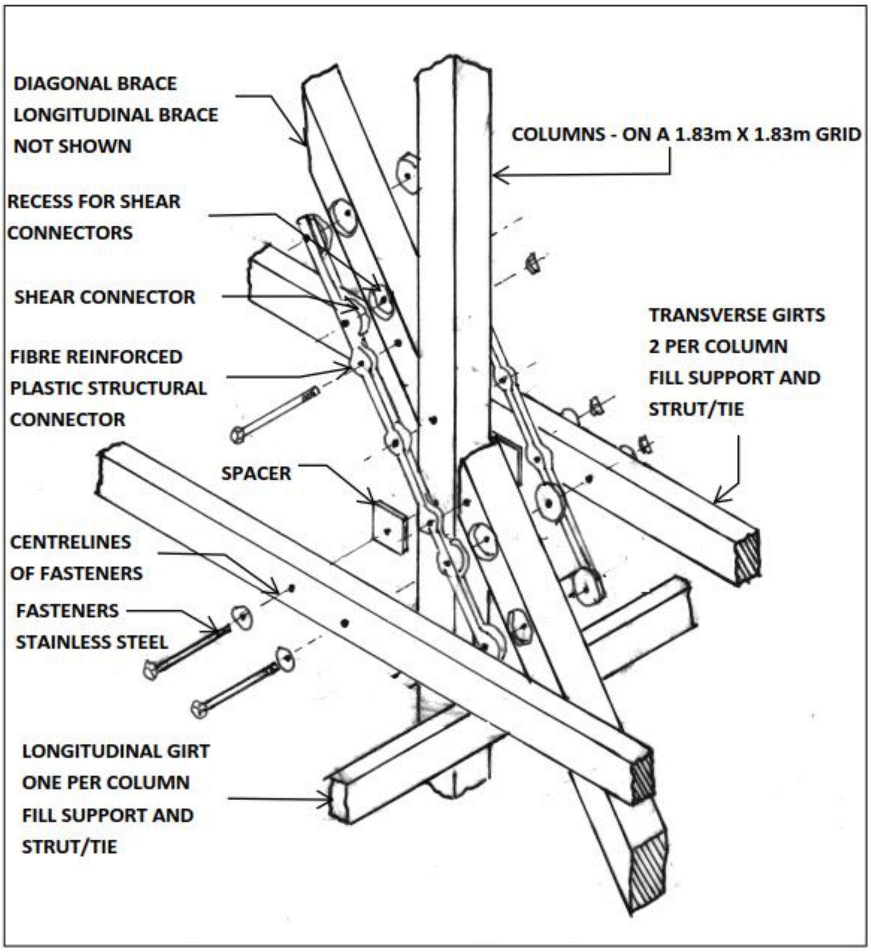


Figure 7.1 Schematic view of members around a typical joint

7.1.1 Columns

The columns are the primary members that transfer loads to the foundations. Columns are primarily members which carry loads referred to as axial loads along their long axes. Axial loads are usually compressive though they can be tensile, and these may or may not include bending acting concurrently with axial loads.

Columns derive their load carrying capacity from the strength and other characteristics of the material used in construction, as well as the cross sectional dimensions of the member. In addition, the unrestrained length of a column has a major impact in the determination of the compressive axial load carry capacity of that column. The longer the unrestrained length, the lower the load is to induce the column to buckle, and failure may occur. This unrestrained length is commonly referred to as the buckling length. In the cooling tower the columns are restrained in both directions by the transverse and longitudinal girts respectively. The transverse and longitudinal braces are similar to columns when placed in compression. When a buckling restraint is rendered ineffective for whatever reason, the buckling length of a column is increased and the compressive axial load carrying capacity is reduced accordingly.

7.1.2 Girts

Similar to columns a similar concept applies to horizontal girts supporting vertical loads. In this case the free length of a member working in bending is critical in the bending capacity of that member and is referred to as the effective length. A member in bending experiences compressive forces in the upper portion of the member, while the lower portion experiences tensile forces. The compressive forces in the upper portion of the member, if high enough, can cause twisting of the member about its long axis, which in turn would compromise the bending strength of the member. The way this potential for this twisting to be controlled, is to limit the effective length of the member by restraining the end of the member. Should this edge restraint be lost or rendered ineffective then the members capacity is diminished.

The buckling, unrestrained lengths of columns and diagonal braces as well as the effective lengths of girts as they relate to the cooling tower are illustrated in Figure 7.2 below.

7.1.3 Louvre Columns

The columns along the perimeter of the tower which directly support the louvre supports and sheets, are inclined to the vertical. These columns would have a natural tendency to fall sideways but for the fact that they are restrained from doing so by the transverse girts. There are two locations along their height where there is a vertical column which is supported on side of the louvre. If the coincident transverse girt in that location fails, or if it's connection fails or becomes loose, then the louvre column would be susceptible to being overloaded and would be required to carry a significant bending moment. This action is illustrated in Figure 7.2 below.

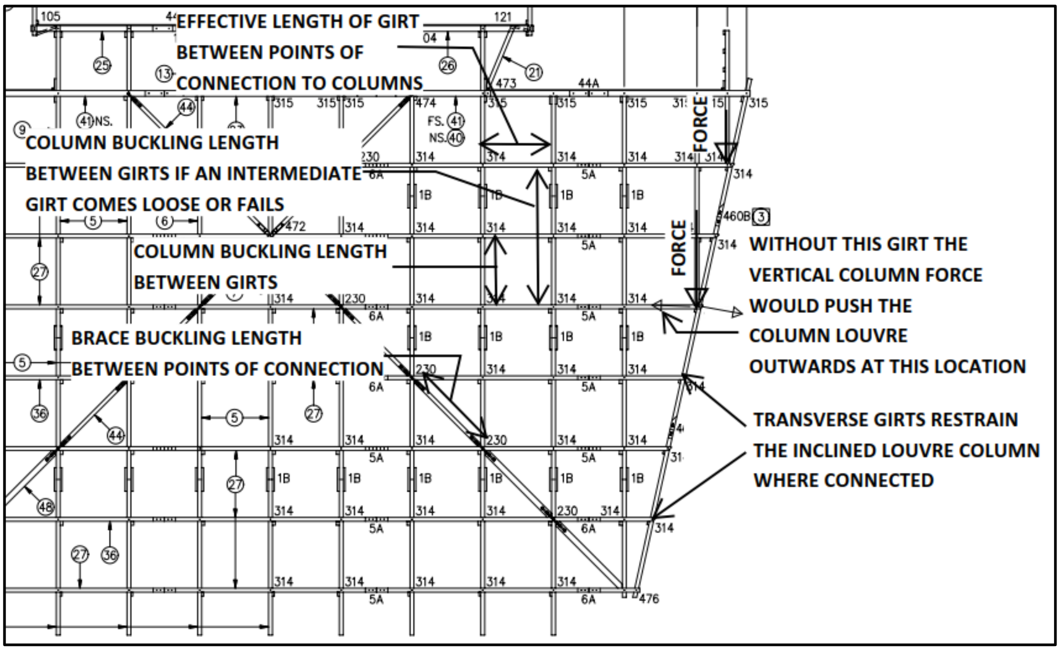


Figure 7.2 Illustration of buckling and effective lengths, louvre column

7.2 Previous and current structural analyses

In their previous structural Modelling and Assessment report of July 2014, GHD reported that, based on their structural analyses of the towers, that as at that time there was no structural redundancy in the towers. It should also be noted that the GHD analyses was undertaken for a depth of water of 100mm in the hot water basin. Cooling tower member forces were found to be approaching their design limits. This was based on an assumed 5% degradation of the tower members. The report further considered the implications of member failure and comments as follows:

- The failure of a transverse girt is not critical from a load bearing perspective. However, a girt failure also results in the buckling length of a column to double and below fill level 5 this increased effective length reduces the column capacity by a very significant 75%.
- The failure of a column between two levels of girts would require the load carried by that column to be redistributed to adjacent columns. As noted, the columns are already loaded close to their design capacity and additional loads would cause an overload. This was critical to columns below fill level 3.
- The failure of a diagonal brace under lateral loads resulted in the loads being redistributed to adjacent intact braces. In this scenario, the forces in the adjacent braces would exceed their design capacity.

It is important to note that the GHD analysis was based on their inspection of the plenum area and not on any of the wet area timbers. As is known the wet area timbers are in worse condition than the plenum areas. Since the time of the GHD report, a portion of the wet area was inspected in 2023 and the timber degradation that has occurred is significantly worse than that assumed by GHD in their report.

In January 2023 HartzEPM carried out limited internal inspections of both cooling towers CT3 and CT4, and prepared a condition assessment report. This report is discussed in a preceding Section 5.2. Regarding the condition of the timbers in the wet zone, the following was assessed:

- Twenty six percent (26%) of girts have less than 50% of bending strength remaining, while 9% have less than 50% of axial strength remaining.
- Forty eight percent (48%) of girts have between 50% and 70% of both bending strength and axial strength remaining.
- Twenty six percent (26%) of girts have great than 70% of bending strength remaining, while 43% have less than 50% of axial strength remaining.
- The column measured has lost 35% of its cross-sectional area, while the diagonal brace measured has lost more than 20% of its cross-sectional area.

This is an indirect measure of the condition on the timbers in both towers and suggests serious deterioration of the timbers so as to render the structures prone to unpredictable structural failures.

It is also noted that the failure in cells 8 and 9 occurred in the North wet zone of CT3 , leaving the structure supporting the fan deck intact. The volume under the fan deck is mostly in the plenum or dry zone where the timbers are in good condition.

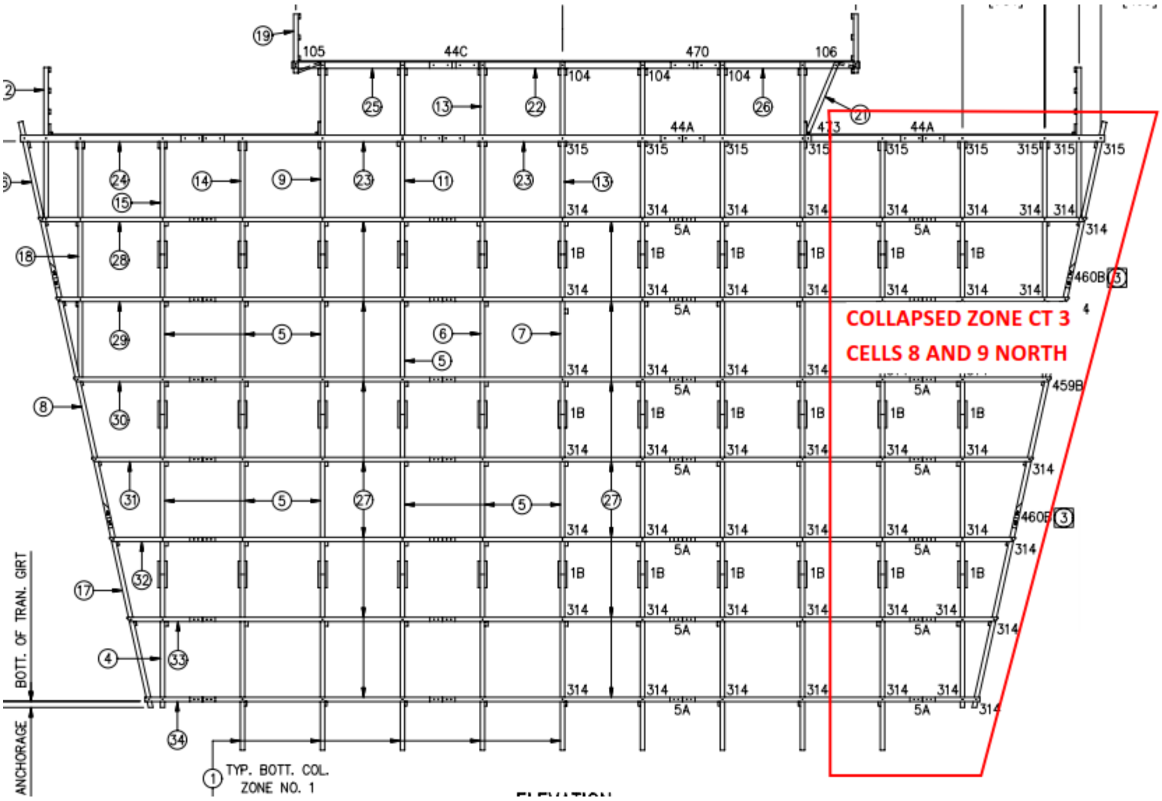


Figure 7.3 Failure zone

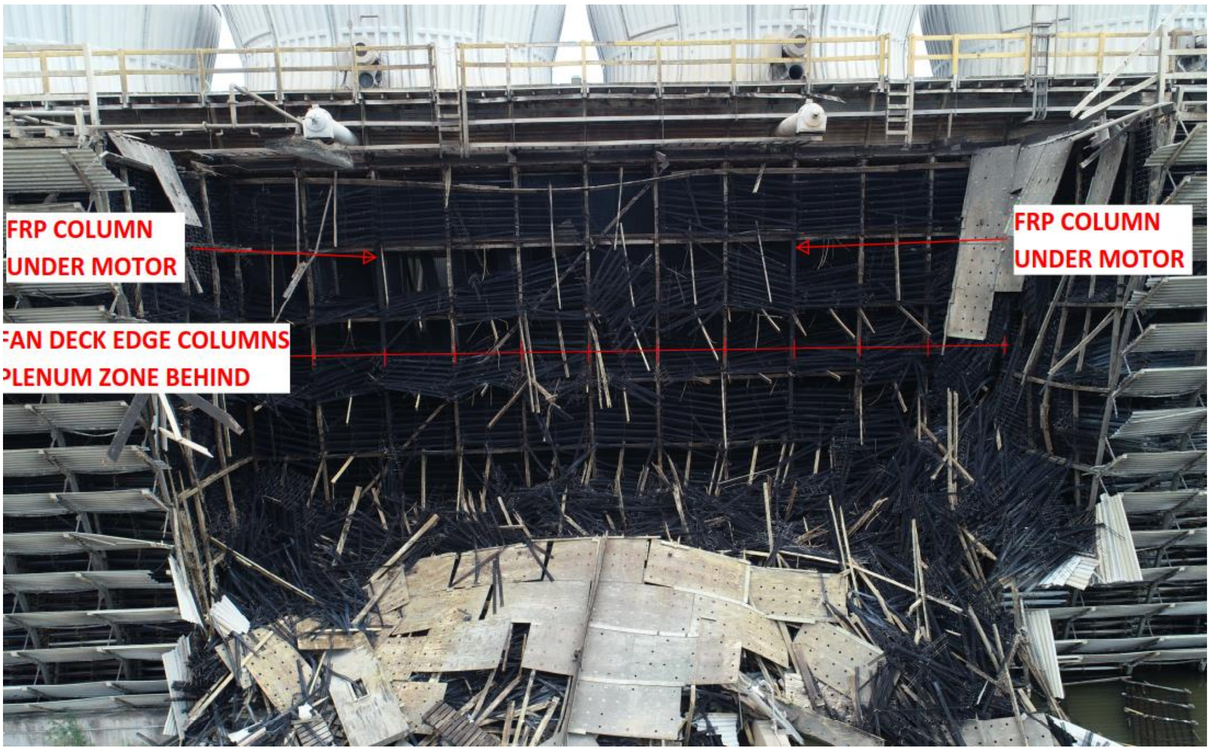


Figure 7.4 Photograph of failure zone

7.3 Potential triggers for failure

This section discusses potential triggers that might have initiated the collapses. The difficulty in this situation is that since the collapses have occurred, access to the collapsed areas has not been possible. Therefore, determining the way the collapses were initiated and occurred is difficult if not impossible. The following discussion therefore is based on the various reports provided, direct observations, structural analyses, and the way structures function.

7.3.1 Hot water basin loads

Two dimensional structural models of 2 typical transverse frames were developed and analysed. The most heavily loaded frame for vertically loading is that beneath the fan supporting the fan gearbox and motor. The most heavily transversely loaded frame is that adjacent to the end and cell divider wall and which has three diagonal braces as opposed to the more usual two. Refer to Figures 3.1 to 3.8. In addition to the usual self-weight of the structure and components, three load cases were run with hot water depths of 75 mm, 125 mm, and 175 mm. Each of these depths are intended to represent the tower under operation with one pump (75 mm), two pumps (175 mm) and intermediate water depth of 125mm. For the water depths analysed, i.e., 75 mm, 125 mm and 175 mm, the increase in column axial load is 4.5% from one water depth to the next. Refer to Table 7.2 which shows the proportion of the water load to the total load. The unfactored maximum axial forces in the timber columns occur under the central frame which also supports the mechanical equipment loads and are as follows:

Table 7.1 Column axial loads and capacities at the ultimate limit state

Load Case	Axial Force N* (kN) Ultimate Limit State	Column ultimate axial load capacity ϕN_c (kN) 100 x 100 F8 Full section	Column ultimate axial load capacity ϕN_c (kN) 80 x 80 F8 Eroded Section	Section Utilization Full/Eroded Section. Overstress greater than 5% shown red
Dead Load + 75mm water	43.9	45.0	28.8	0.97/1.52
Dead Load + 125mm water	45.6	45.0	28.8	1.01/1.58
Dead Load + 175mm water	47.4	45.0	28.8	1.05/1.64

- The above Table 7.2 is for the central frame which supports the mechanical equipment and for the most heavily loaded column in that frame. The most heavily loaded timber column in this frame is the first vertical column adjacent to the cold water basin wall. Other columns in other frames are less heavily loaded to varying degrees and dependent on location. However, the mechanical loads are transferred to ground largely through the columns within the plenum zone and the columns in the wet zone typically carry the hot water basin loads.
- Column ultimate limit state axial compression is calculated as a combined load of 1.2 dead load and 1.0 water load, as required by AS/NZS 1170.0 Structural Design Actions General Principles

- Eroded member section size of 80 x 80mm or 35% erosion is based on observations during HartzEPM Condition Assessment Report in January 2023
- Column ultimate axial load capacity ϕN_c = 45.0 kN with load duration factor k_1 = 0.8 for combined dead and water load as inferred from AS 1720.1 Timber Structures Part 1 Design Methods

The following Table 7.2 shows the water load as a percentage of the total structure dead load plus the water load. As can be seen the water load is a relatively small proportion of the overall load for the three water depths as shown.

Table 7.2 Water load as a percentage of overall load at the serviceability state

Water Depth (mm)	Axial Force N kN Serviceability Limit State DL + Water Load	Axial Force N kN Serviceability Limit State Water Load	Water Load as a percentage of DL + Water Load
0	34.4	0	0
75	37.0	2.6	7.0
125	38.7	4.4	11.3
175	40.4	6.1	15.1

As will be noted from the Table 7.1 above, the full column section is working to full capacity up to 175mm depth of water in the hot water basin. The hot water basin is designed for an operating water load of 153mm, so the results above are consistent with expectations.

However, the eroded columns are significantly overstressed under ultimate limit state dead and water loads. This suggests that for the observed/assumed level of column erosion, the cooling tower column strength was on the design limit without water load being applied. Therefore, the addition of water to the hot water basin could have been the trigger for the collapse of column/s. I am instructed that with one pump operating and prior to cutting the overflow slots, the estimated depth of water in the hot water basin was approximately half of the depth of the basin, or around 125mm. With two pumps operating and prior to cutting the overflow slots the hot water was running full or close to full, i.e. 200 mm and possibly up to 213mm which is the depth of the hot water basin. With these levels of water, i.e. 75 to 213mm, and the numerous damaged columns observed, this would be a potential trigger for a collapse.

7.3.2 Wind loads

Wind loads on the towers are predominantly resisted by the lateral and longitudinal braces. In the two dimensional analysis the wind loads were applied to the side of the tower as well as to the fan stack, and the forces in the transverse braces were determined. The critical or most heavily loaded transverse diagonal brace is in the central frame. The wind loads applied are based on the cooling towers being in wind region B2 in accordance with AS/NZS 1170.2 Wind Actions. The map showing these regions is shown below in Figure 7.5 in which Biloela is underlined in red. As can be seen the site is in wind region B2 albeit just within the demarcation between region B2 and the less onerous region A0. It should be noted that the Marley technical data sheets for these towers is silent on the wind design parameters other than to say that wind loads are in accordance with AS1170. It is also interesting to note that the GHD structural was done with wind region A, which would be equivalent to wind region

A0 in the current code. Using wind region A would underestimate wind loading on the tower. However, the decision to use wind region A may be deliberate to take into account that the sites proximity to that wind region.

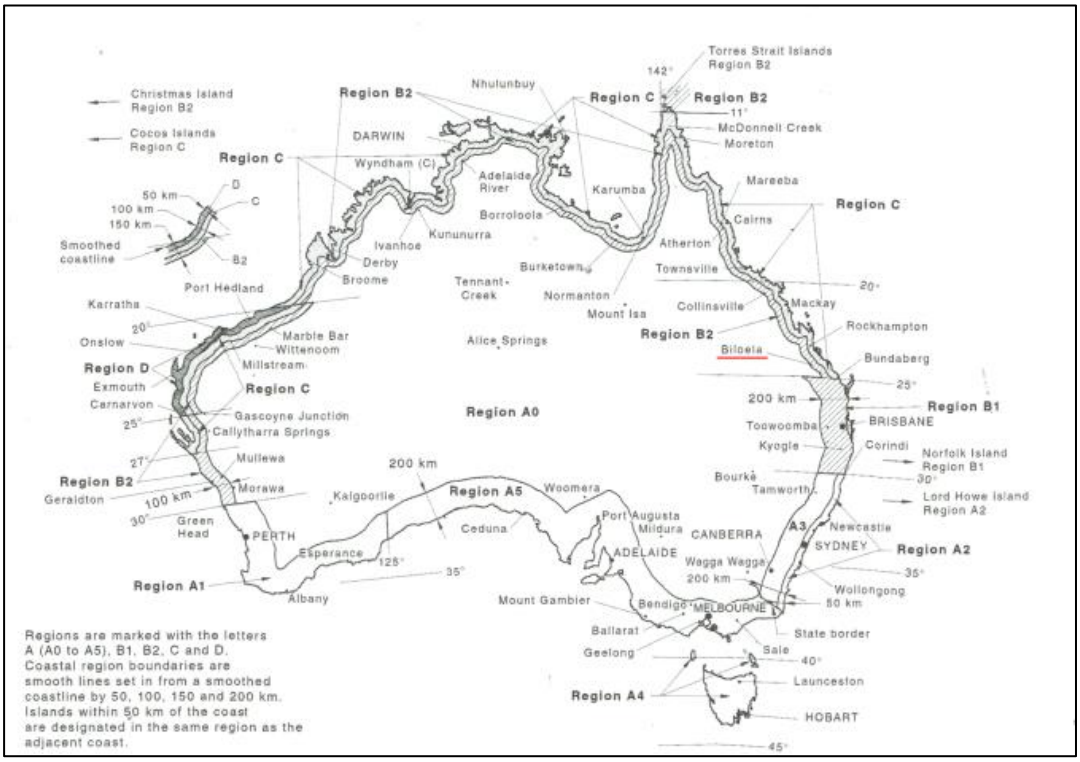


Figure 7.5 Australia's wind regions to AS/NZS 1170.2

The applied force, capacity of the diagonal brace for both a new and an eroded section, and implications for permissible wind speeds on the towers are summarised below.

Load Case	Permissible wind speed ms^{-1}/kmh^{-1}	Axial Force Applied N^*_{WL} kN	Brace ultimate axial load capacity ϕN_c kN 100 x 100 F8 Full section	Column ultimate axial load capacity ϕN_c kN 80 x 80 F8 Eroded Section
Wind Only	46.7/168.2	54.7	28.0	17.6

Comments on the above table as follows:

- The diagonal brace has an ultimate limit state axial capacity of 28.0 kN in compression while the brace is carrying a compression of 54.7 kN. This is for wind region B2 in which the permissible wind speed is 46.7 m/s. If a tolerable permissible wind speed is calculated, based on the axial capacity of the diagonal of 54.7 kN, this tolerable wind speed is determined to be 33.6 m/s. This is the permissible wind speed for wind region A, i.e. suggesting this is the wind speed for which the towers have originally been designed. If this is the case, then there is no issue, and the diagonal brace is working to full capacity in its new condition.

- If the full section is working to full capacity for wind region A, then it is structurally inadequate in the eroded condition. Calculating a tolerable permissible wind speed based on its reduced capacity of 17.6 kN as shown in the table, results in a permissible wind speed of 26.7 m/s or 96.1 km/h.
- Cells 8 and 9 of cooling tower 3 collapsed on 31 October 2022 at approximately 13h20. Wind speeds sourced from the Bureau of Meteorology from the Thangool weather station reveals maximum wind gusts well below 96.1 km/h at the time of the collapse. For the hour 12h50 to 13h40 the maximum gust recorded was 40.7 km/h at 13h14 at the weather station at Thangool airport. Hence it is unlikely wind was a trigger if all diagonal braces were effective.
- There is the possibility that more than one brace had become ineffective. Assuming two braces on either side of the frame under consideration were no longer effective, and the brace in the considered frame has to support additional wind loading in its eroded condition, then a permissible wind speed of 68.1 km/h could be resisted.

The above represents a very idealised situation as there are many possible scenarios that may impact the situation. These include loose connections or connections that have lost bolts or where shear connectors have become dislodged, collapsed volumes of fill resting on braces inducing bending in addition to axial loads, loose connectors across columns, etc. However, it suggests that wind on the day on the day and time of the collapse is an unlikely trigger.

7.3.3 Overflow impacting louvre sheets

There are too many unknowns to model and assess the impact of water spilling over the weirs cut into the sides of the hot water basin and what loads may be imposed on the louvre sheets, their supports, and the inclined louvre columns. Based on physics, the forces so induced depend on the weight of the water falling, the velocity at which it impacts the louvres and the stopping distance or time to stop, and the deflection angle when it impacts the louvre sheets. Based on what has been constructed there is little to no detail of the louvre sheet supports and hence it is difficult to assess which component may have failed first. In addition, the hot water basin weir cut outs only occur at the starts and the ends of the hot water basins and are not continuous along the length of the tower and therefore the load on the tower is thereby limited.

In this regard it is the inclined louvre columns which are in question and their capacity to withstand the weight of water cascading from the hot water basin. This is difficult to assess because analyses can be done on assumed water load as much or as little as required to fail or not to fail. How close this assumed load would be to the in-service load is unknown so the exercise would be of questionable value. From the photo in Figure 7.6 below it appears that only the first louvre sheet is partially impacted by water, and the lower sheets don't appear to be impacted.

Figure 7.6 Overflow through cut outs in hot water basin

It is highly unlikely therefore that the overflow from the hot water basin was in any way a trigger that could trigger the collapse of cells 8 and 9.

7.3.4 Water Hammer

Water hammer is caused by water being shut off quickly or by fast acting valves. Suddenly stopping flowing water sets up a shock wave which emanates through the water causing pipes to vibrate and placing high lateral stresses on the pipe walls and joints. Typically, water hammer could occur when valves are quickly shut off, or during pump start up. Inadequately supported pipes and worn valves could exacerbate water hammer.

In the August 2015 report, Breezewater reported that the cross over pipes have no vibration isolation between the pipe and their supports, i.e., the cooling tower. This is bad for the pipe rather than for the tower because it means that any movement of the structure or water hammer from the pumps, must be absorbed by the pipe. Breezewater further reported that the cross over pipes were beginning to fail and had developed cracks resulting in water dispersing into the plenum area.

It should be noted that on the morning of the collapse of cells 8 and 9, there had been some throttling of the flow distribution valves which started on the South side and finished on cell 18. The rate of change of the water flows is not likely to introduce water hammer. The pump had been operating with one pump running and the second pump was brought back online on 28th October 2022. The collapse occurred on the 31st of October 2022, some three days later.

It is therefore not considered likely that water hammer was a trigger for the collapse.

7.4 Potential collapse sequence

A summary of the condition of CT3 just prior to the collapse is shown diagrammatically below.

Figure 7.7 Cooling Tower 3 Condition Summary October 2022

The summary above in Figure 7.7 reveals the following with respect to the condition CT3:

- In every wet area of CT3 there were columns that were in some way seriously compromised and which could reasonably be considered to be ineffective. More specifically:
  - In the wet areas, an average of 2 columns in cells 9 to 18 south, and an average of 2 columns in cells 4 to 18 north, were reported to be bent or broken in the wet areas. Note that this is an average meaning in some cells there could be one column in this condition but equally it is implied there are more than two columns in this condition in other cells.
  - Cell 1 was not inspected due to having an internal collapse making it inaccessible. However, the wet areas of the remaining cells, cells 2 to 8 south, and cells 2 and 3 north, had many more columns affected and with more severe damage. It was report that most of the louvre and first row of the first row of vertical columns were affected. In particular, cells 2 to 8 south had a noticeable disturbance to the rectilinear geometry with a misalignment in excess of 100mm, described as 'alarming' in the report prepared by Marley Flow Control.
  - The hot water basins of cells 1, 2 and 3 north, and 2 and 11 had subsided. This was noticeable with the naked eye and not by survey. An accurate survey may have detected further subsidence not noticeable by eye. Subsidence such as that observed around the hot water distribution basin, is most likely due to bent or buckling columns.

The following are photographs of some of the damaged sections, in particular columns.

Figure 7.8 Subsidence in hot water basin CT 3 cells 1 and 2 - CS Energy

Figure 7.9 Example of column distortion reported throughout wet areas. Note first vertical column adjacent louvre columns - Marley April 2022

Figure 7.10 Split columns CT3 Cell 7. Note in first row of vertical columns – CS Energy October 2022

Figure 7.11 Bent Column CT3 unknown location - Marley April 2022

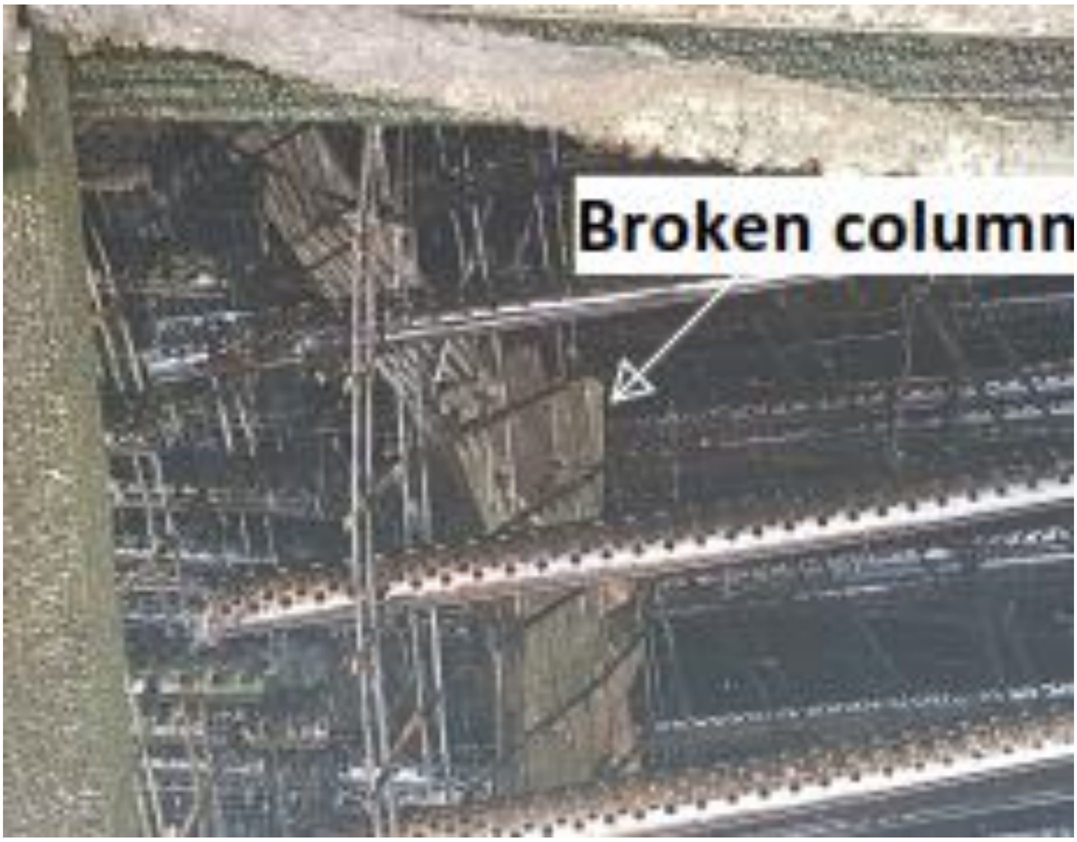


Figure 7.12 Broken Column CT3 Cell 7 - CS Energy

Figure 7.13 Column distortion CT3 location unknown - Marley 2022

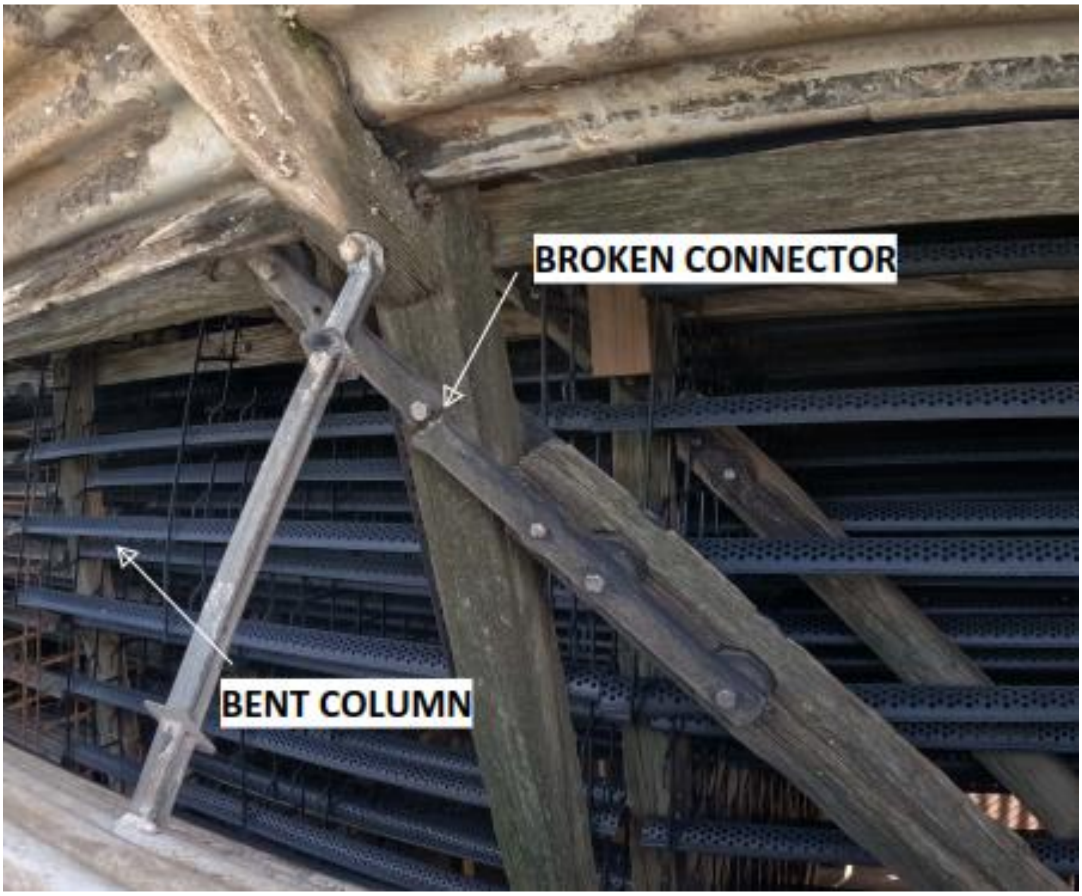


Figure 7.14 Bent column and broken connector - unknown location

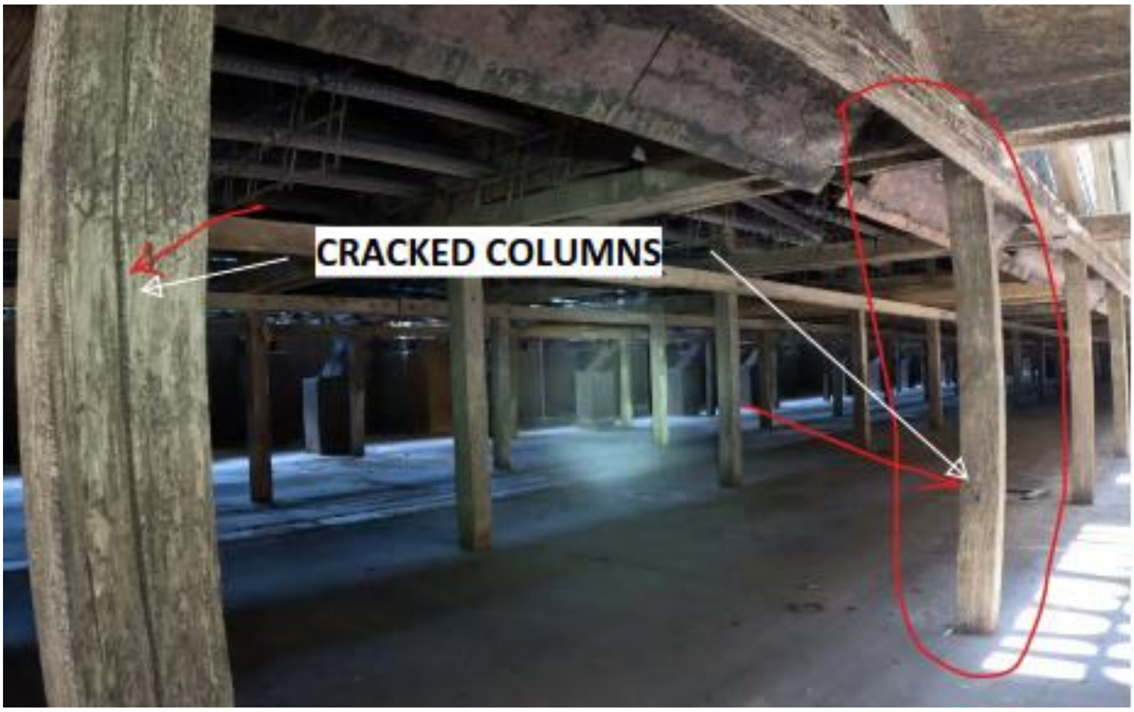


Figure 7.15 Cracked columns in cold water basin - Location unknown

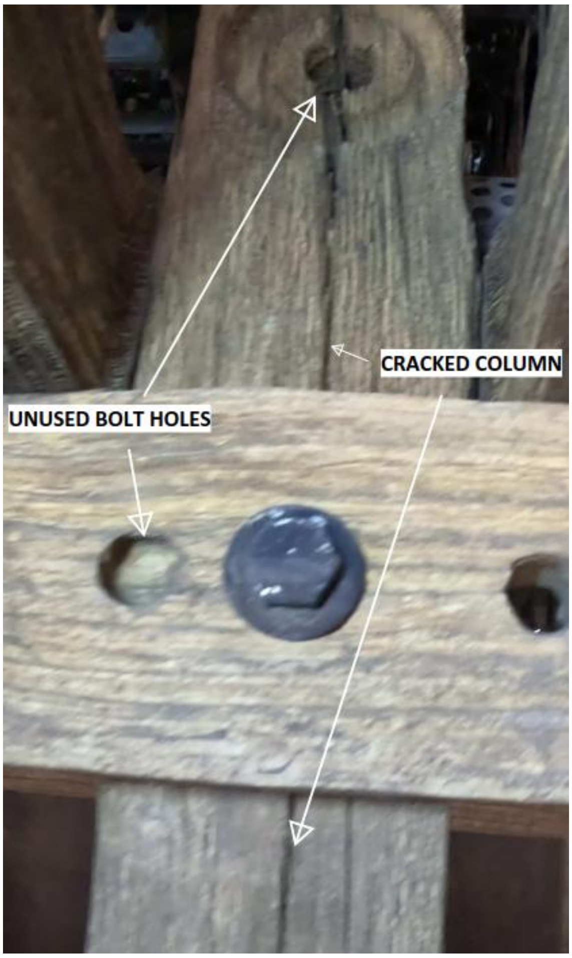


Figure 7.16 Predrilled unused bolt holes and cracked or split column

Figure 7.17 Bent end wall column - unknown location

Figure 7.18 Column/Girt bolt misalignment - unknown location

Figure 7.19 Column split in plenum area

Figure 7.20 Broken anchor plate on a longitudinal louvre brace

Figure 7.21 Broken Connector and part of brace missing

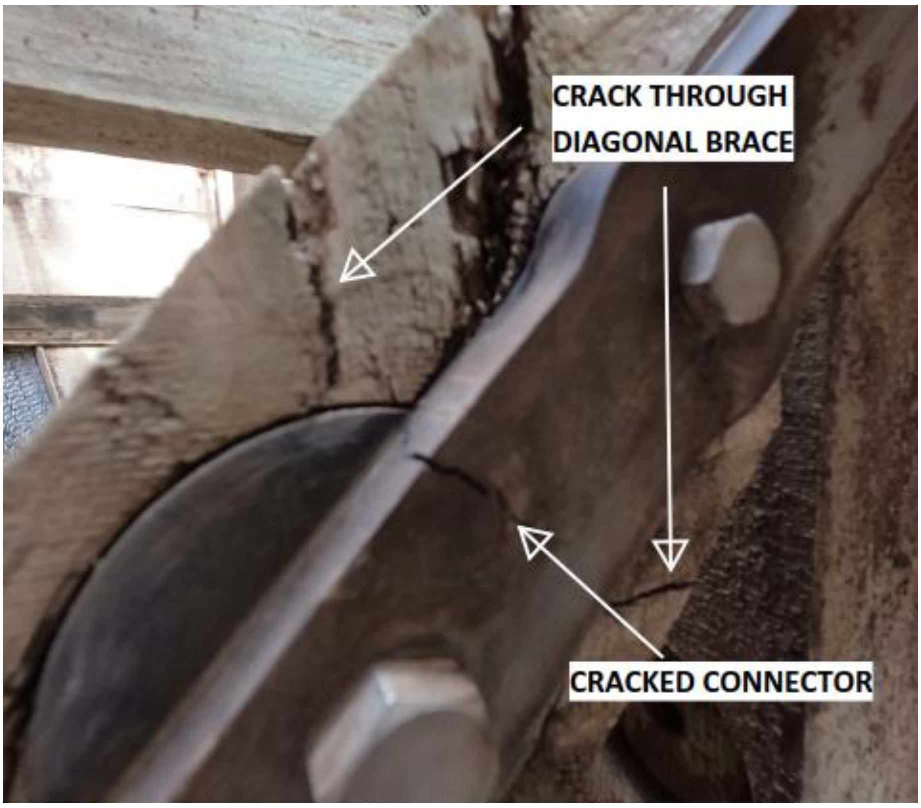


Figure 7.22 Cracked connector and diagonal brace

The functions, interactions and inter-dependencies of the primary structural member were described in a fundamental way in Section 7.1 above. Given this and the known damage that has occurred in CT3 the following is a sequence of events in which the collapse of cells 8 and 9 might have progressed. In particular, the presentation of the following collapse sequence is based on the following:

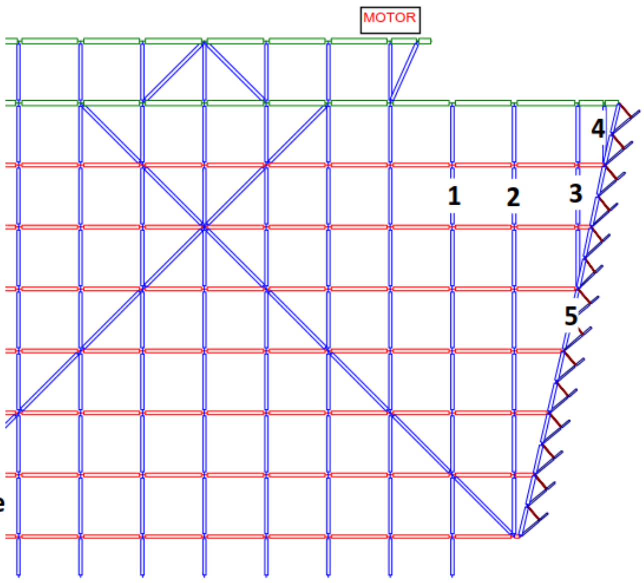
- As can be seen from the photographs and discussion above, the first row of vertical columns shown as column 2 in the depictions below, is known to contain damaged columns. It has been reported that on average approximately two columns per cell were bent or broken in 25 of 36 of the wet zones. In the remainder of the wet zones, column damage was more severe. Refer to Section 7.4 above.
- Columns 2 are more or less central to the hot water basin, and their collapse would likely trigger the collapse of columns on either side as well, i.e. columns 1 and 3 in the depictions below. The collapse of columns 1, 2 and 3 would inevitably lead to the remaining columns 4 and 5 also collapsing. This would be consistent with the collapse that has occurred.
- The collapse of column 5 first could have led to the collapse as has occurred but might have resulted in only column 5 collapsing taking columns 3 and 4 with it, but it is conceivable that columns 1 and 2 could remain standing.
- Column 1 could also have collapsed leading the collapse as observed, however there is no direct evidence that column 1 has been damaged as was observed for column 2. Being further into the wet zone column 1 is not as easily observable as column 2, however it is likely that is has undergone similar damage.

<u>Stage 1: As built</u>
Column 1 is the most heavily loaded.

Column 2 is severely damaged based on reports and photographs.

Columns 3 and 4 is supported on louvre column 5.

Louvre column 5 is held stable by the horizontal girts. (Red members)



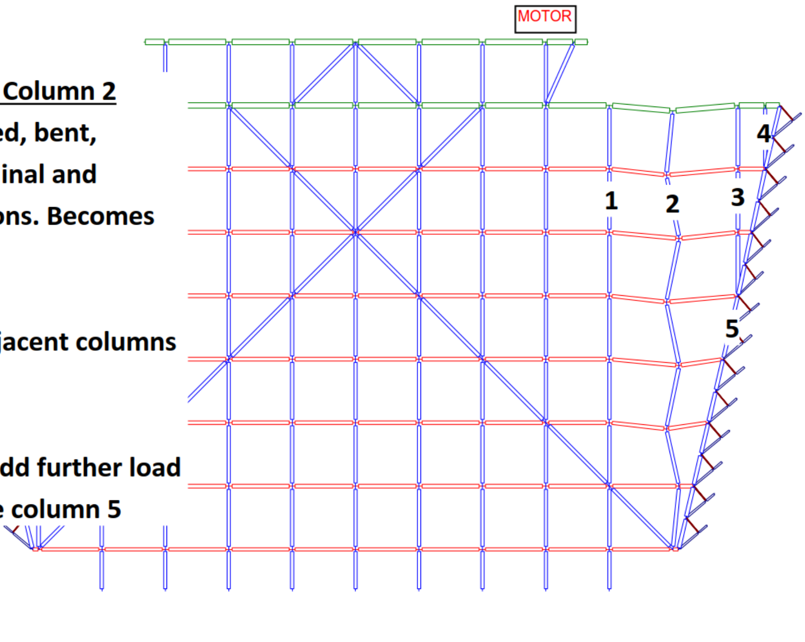
theta: 270 phi: 0

<u>Stage 2: Damaged Column 2</u>

Column 2 is buckled, bent, broken in longitudinal and transverse directions. Becomes non-load bearing.

Load is shed to adjacent columns 1, 3 and 4.

Columns 3 and 4 add further load the inclined louvre column 5



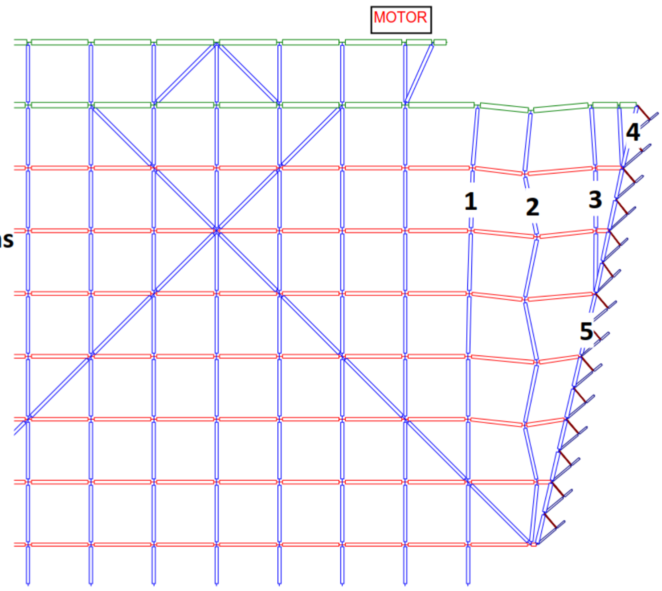
<u>Stage 3: Increased Water</u>

Hot water basin over column 2 sags and water load increases.

Further load shed to columns 1, 3, 4 and subsequently 5

Adjacent columns 1, 3 have likely experienced similar damage as column 2

As columns buckle further water load is added to the hot water basin.

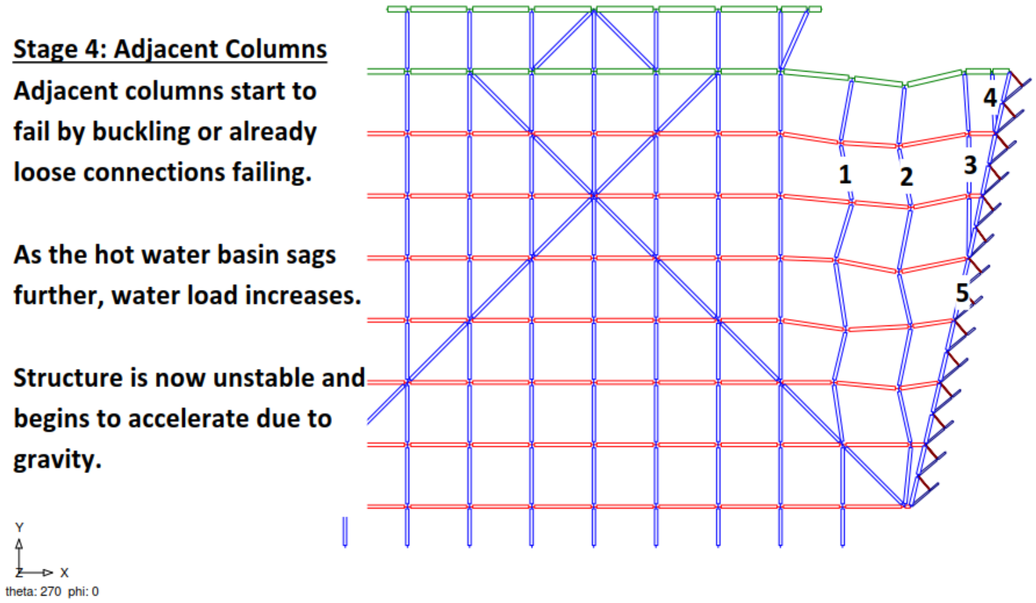


Stage 4: Adjacent Columns

Adjacent columns start to fail by buckling or already loose connections failing.

As the hot water basin sags further, water load increases.

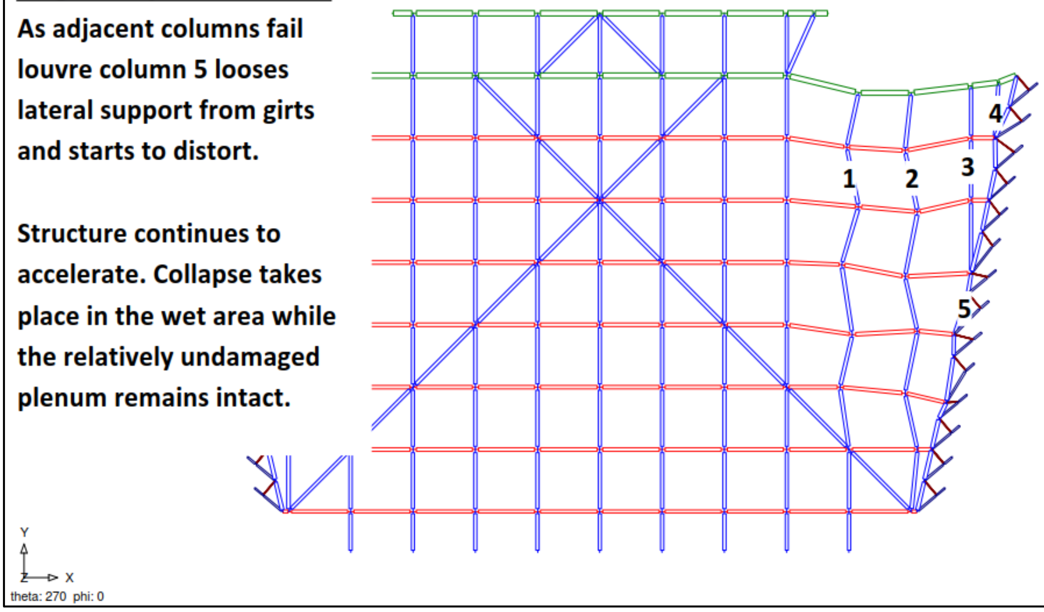
Structure is now unstable and begins to accelerate due to gravity.



Stage 5: Adjacent Columns

As adjacent columns fail louvre column 5 looses lateral support from girts and starts to distort.

Structure continues to accelerate. Collapse takes place in the wet area while the relatively undamaged plenum remains intact.

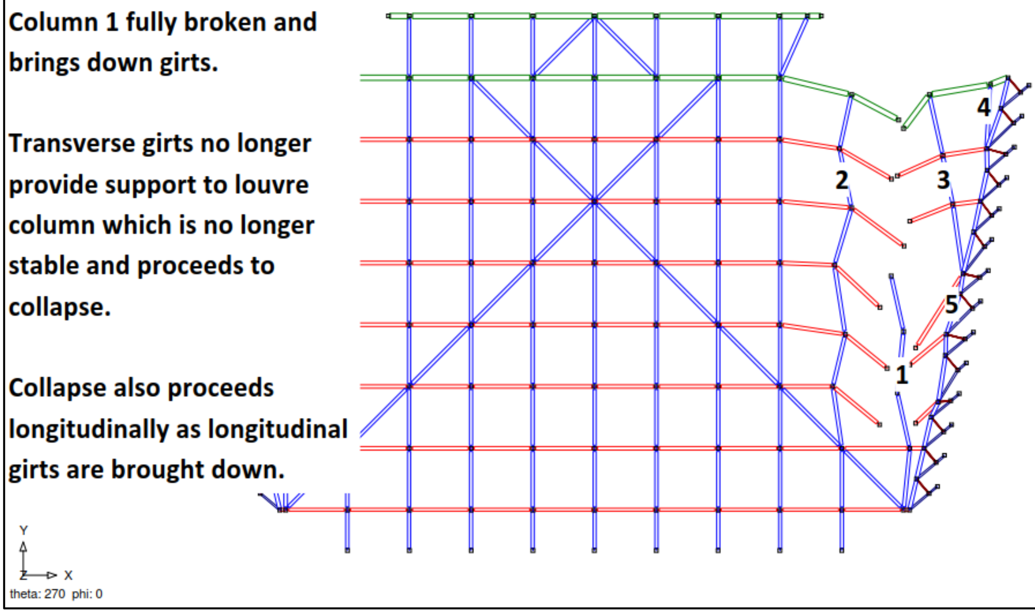


Stage 6: Louvre Column

Column 1 fully broken and brings down girts.

Transverse girts no longer provide support to louvre column which is no longer stable and proceeds to collapse.

Collapse also proceeds longitudinally as longitudinal girts are brought down.

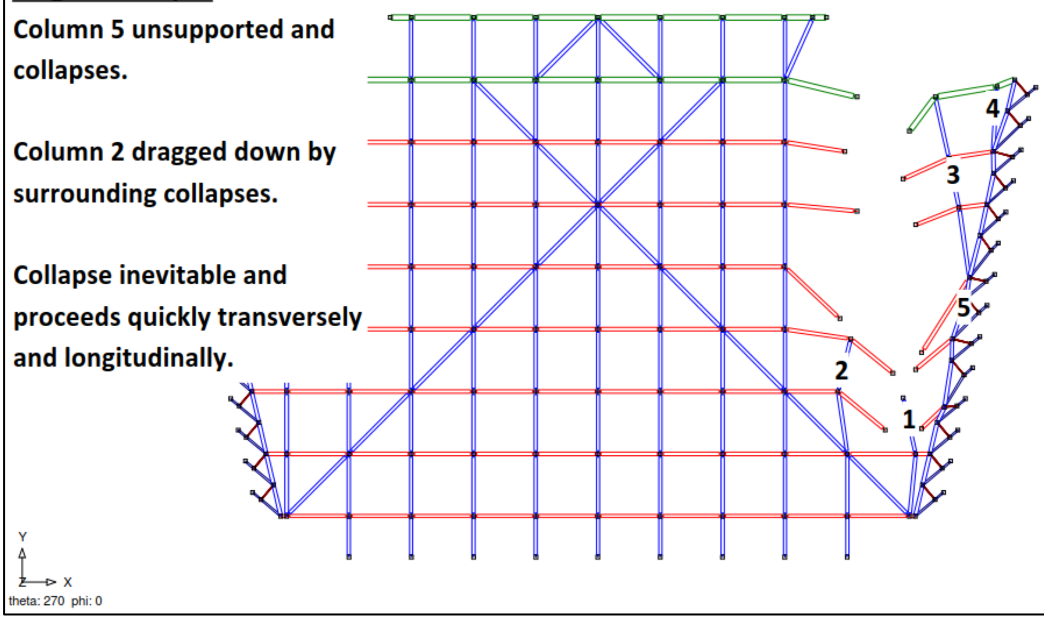


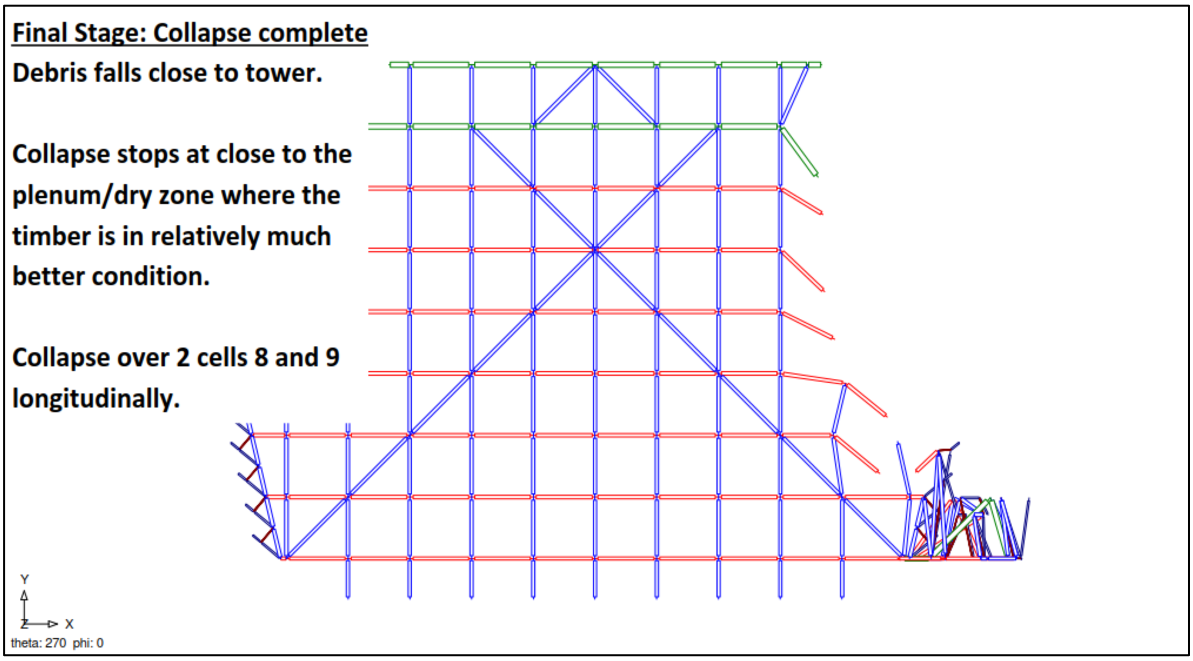
Stage 7: Collapse

Column 5 unsupported and collapses.

Column 2 dragged down by surrounding collapses.

Collapse inevitable and proceeds quickly transversely and longitudinally.





As noted, the sequence shown above is not the only one that could have occurred, and it centres on the known damage to the columns in the wet zone and in particular, the first vertical column from the outside of the tower, or column 1 in the above diagrams. Column 2 was easily observable from outside of the cooling tower as was the louvre column, column 5. It is likely that column 1 was as damaged as column 2 but perhaps not observed as readily. Other points if initiation that are possible are as follows:

- Collapse could have initiated with column 1.
- Collapse could have initiated with the louvre column 5.
- Failure of one or more longitudinal or transverse girts would result in increased columns buckling lengths and therefore column slenderness ratio would increase resulting in a significant loss of column axial capacity.

In addition to the above, other issues that relate to the condition of the structure specifically would have contributed to the collapse have already been discussed and are summarised as follows:

- Missing and/or loose bolts resulting in loose connections.
- Loss of member cross section resulting in a loss of strength.
- Quality of timber with the presence of large knots and knot clusters.
- Broken connectors and anchor plates.

8 Root Cause Discussion

8.1 Root Cause - Background

The purpose of this investigation is to establish the root cause/s of the structural failures of the CT3 cooling tower and whether there have been any failures in the C4 cooling tower, and the root causes thereof.

There have been several reports of structural distress throughout the life of these cooling towers which have been the subject of numerous reports as discussed above. The catalyst for this investigation has been the structural collapse of the north side of cells 8 and 9 of cooling tower CT3 in October 2022. It is noted that there had been an earlier collapse of cell 1A in January 2022. At the time of these collapse cooling tower CT4 was not in service and cooling tower CT3 was then also removed from service after cells 8 and 9 had collapsed. Furthermore, a 16m exclusion zone was placed around both towers and no access was allowed to any part of the towers. In January of 2023 access was regained to both towers but only to the plenum or dry zone, with the wet or fill zone as well as the fan deck and the hot water basin being inaccessible.

One of the difficulties faced with an investigation like this is that, with restricted access, and lack of access to the failure zones for valid safety reasons, close inspections of the members in the failure zone is not possible. Hence identifying the location where the failures initiated and/or the precise failure mechanism is difficult. Even if access were possible, it would still be extremely difficult given the large number of mutually supporting members and their complex interactions. Therefore, it becomes essential to consider indirect scenarios of what might have occurred, based on previous work, photographs, and video images, as well as anecdotes.

8.2 Root Cause – Typical design life

The anticipated life of a timber cooling tower is 20 to 25 years, refer to Chapter 29 – Cooling Tower Wood Maintenance by SUEZ and Veolia. This implies operation within the parameters of the operations manual, as well as regular inspections and maintenance. Once a cooling tower has reached this age, a full and thorough inspection would be carried out and a major refurbishment would likely be required to add a further 20 to 30 years to the life of the structure depending on the nature and extent of the refurbishment.

Apart from the fan deck replacement, hot water basin replacement the towers "have had minimal structural repairs" since commissioning in 2001, from the CS Energy Scope of Work. Additionally, from the review of the reports previously done, the wet zone was only inspected from the perimeters of the tower, and from the plenum area. There have been limited inspections in the internal areas of the wet zone. By inference therefore, there have been minimal repairs in the wet zone since commissioning.

8.3 Root Cause – Water chemistry

One of the earliest and consistent observations in the previous inspections as discussed above, is that chemical erosion of the timber was noted as early as 2006 and became worse with each successive inspection. It is also known that when measurements of free chlorine level residuals were recorded from 13 July 2007 onwards, the towers were being operated at high Free Residual Chlorine levels from then until May 2021 with levels often at 4.0 ppm and higher. After November 2021, the Free Residual Chlorine levels are lower and more in accordance with accepted practice, although there were intermittent but regular peaks, sometimes approaching 2.0 ppm. As discussed above, a target Free Residual Chlorine level would be in the range from 0.4 ppm to 1.0 ppm. While there is no free chlorine data prior to July 2007 it would not be unreasonable to suggest that elevated Free Residual Chlorine levels existed prior to this, though this cannot be confirmed. As has been discussed above Free Residual Chlorine at high levels is highly erosive to timber.

The pH values as recorded are not exceptionally high with most in the range from 7.0 to 8.0 with frequent peaks above 8.0 prior to June 2006. This can be considered to be marginally high and better levels would have been in a range from 7.0 to 7.5. As discussed above chemical erosion is particularly severe when high chlorine residuals exist in combination with high pH, or alkalinity.

The cooling towers have therefore been operating in an erosive environment for an extended period and perhaps for most of their operating lives. This affects the wet zone almost exclusively since in the plenum zone the timber is in fair to good condition. The reports described above and inspections by HartzEPM, reveal extensive chemical erosion in the towers in the wet zone in those areas that could be directly observed. In addition, maintenance and repairs in the wet zone has largely not been carried out due to difficulties with access. The result of this is that eroded or damaged timber could not be replaced or repaired, loose connections could not be retightened, splash bar assemblies could not be repaired where required, etc. It is therefore considered that due to the chemical erosion the tower timbers have eroded prematurely to a state where it is no longer safe to access to carry out repairs. After 20 to 25 years of operation, a cooling tower should still be safely accessible to carry out maintenance and/or refurbishment. There are several other factors which will be discussed in turn below, but it is considered that chemical erosion is the root cause of these collapses.

8.4 Root Cause – Significant other issues

8.4.1 Cooling Tower Maintenance

A detailed discussion about the effect of water chemistry on timber cooling towers is included above. In particular, high chlorine levels together with high pH values which are damaging to timber has been mentioned.

We were instructed that the intent has been to keep the level of the legionella count to zero or close to it. To achieve this, the approach has been to dose the cooling water with levels of chlorine higher than would be desirable to limit degradation to timber. This approach, while it may seem reasonable, should be considered in conjunction with a maintenance regime to consider the increased likelihood of accelerated deterioration of the timber.

The observations with respect to the maintenance of the cooling tower are as described below:

- The original maintenance manual provided by the original cooling tower builder provides a blank inspection checklist, and an Inspection and Maintenance Schedule. The latter makes general recommendations for the frequency of inspection for various parts of the cooling tower including the “structural members”. In the case of the structural members, it recommends semi-annual inspections though it has a general caveat which states “More frequent inspections and maintenance may be desirable”. However, there does not appear to be a programme which provides for a comprehensive inspection and maintenance regime for the cooling towers in particular with respect to the timber. Currently access to the wet zone is difficult because of the obstruction created by the fill medium. As a result, access for routine inspection and maintenance has not generally been available leading to a situation where such inspection has only been carried out either from the internal and dry plenum zone, or from the external perimeters of the tower. Typically, the wet zone has only been accessed when there was some necessary repair to be carried out, e.g. to repair broken columns. While it is difficult to access the wet zone, it is not impossible to do so. For example, it would require shutting down one side of a cell, and perhaps the adjacent two half cells to provide buffers on each side, partial removal of fill in the area to be accessed for inspection, maintenance, or refurbishment. This procedure could be articulated in a documented programme which could form part of the plant operating procedure for implementation. Given the size of these cooling towers, it would be anticipated that such a procedure could be ongoing, but this would depend on how long one such cycle would take to complete, and the rate at which the cooling towers deteriorate. In particular, for the chemical concentrations described above, more extensive monitoring of the cooling towers may have been required depending on site observations, and/or a strict adherence to the recommendations of the maintenance manual.

- The above would require a capital commitment to undertake this work, together with small loss of generating capacity while inspection, maintenance and/or refurbishment is carried out.
- From the various inspection and incident reports, it appears that maintenance as repairs to the timber structure was only carried out then there was a breakage which directly affected the structural adequacy of the timber structure. For example, timber columns which had bowed are broken were stiffened with lengths added either side. Other members, such as horizontal girts or timber straps, both of which support the fill medium, deteriorated to the point where many zones of fill collapsed.
    - As discussed in section 4.2, we consider the critical time in the life of the CT3 to have been in the period from 2014 to 2016. The reports potentially left conflicting impressions of the tower and if the reader was not a structural engineer, then potentially a false sense of security could be the result. In our opinion there is sufficient information in these reports to warrant a look at significant maintenance and prioritisation of effort. Further, the latter reports by Marley Flow Control in 2022 reported some serious issues. These reports included recommendations for sections of the cooling towers to be taken out of service, not allowing personnel onto certain areas of the cooling tower, and for various repairs to be carried out. The reports further identified areas which contained bent and/or broken columns. Figure 7.7 shows the extent of damage diagrammatically just prior to the collapse in October 2022, and which diagram is based on the aforementioned reports.

8.4.2 Timber quality

In previous sections in this report, the grading and the quality of timber used in these cooling towers was discussed. One of the issues noted during inspections, was the numerous defects observed in the timber including large knots and even clusters of knots. The result of this was the derating of timber from stress grade F8 to a lesser grade F7. While this degrades the strength of the timber, it does not account for the loss of member integrity around a knot location. However, this weakness did not manifest early in the life of the tower based on earlier reports and was only reported on later once other issues had taken hold, most notably, advanced erosion of the timber. Figure 1.45 in Appendix R illustrates this where the column has kinked in two locations around sizeable knots. The column in this picture is considered to no longer be effective in carrying load and is either on the verge of collapse or being supported by surrounding members. The point here is the column appeared to have performed adequately in the early stages of the cooling towers life but now is weakened due to loss of material from predominantly chemical erosion. This results in a particular weakness in the timber around the locations of knots.

8.4.3 Loose connections

Loose connections were prevalent in both cooling towers, in both the wet zones and the plenum area. As described above, many nuts were able to be turned by hand and at splice points, significant gaps had opened between splice plates and members being spliced. This has resulted in shear connectors being exposed and, in many instances, becoming disengaged from the joint. The manner in which these joints could have become loose is likely a combination of things as follows:

- Due to vibrations induced by the operation of the fans and motors, and further exacerbated by the fan becoming unbalanced due to wear. This is discussed above in earlier reports. It appears by observation that lock nuts were not used, neither was a thread adhesive used in the timber member connections in the tower. There is a Marley drawing number 96-101506 from 2009 on which the General Notes calls for Loctite to be applied on all framing bolts or for nuts to be "self-locking". The timber code AS1720.1 appears silent on the use of locknut when joints are subjected to vibrations. This is unlike the steel structures code AS4100 which requires nuts with locking mechanisms for joints subject to vibrations.
- Chemical and other erosion of the timber members which softens the outer layers of timber causing the bolts to loosen with the loss of firm contact under the nuts and the bolt heads. This is particularly true in the wet zone. This is not helped because undersized washers were used. In combination with the vibration issues and in the absence of the nuts being locked, this would allow the nuts to loosen further to the extent observed during inspections. Normal maintenance would require that connections are inspected and re-tightened periodically but accelerated chemical erosion would increase the frequency of this maintenance to below that which operational staff would undertake under normal circumstances, or under the recommendations of the operations manual. It should be noted that the operations manual recommends that for structural members, inspections are carried out semi-annually, and that loose bolts are tightened annually.

8.4.4 Design Wind Load

In the Operations and Maintenance Manual Technical Data Sheet, the structural design parameters are noted only as "AS1170", and no detailed information is provided. Under the current Australian wind code AS/NZS 1170.2, the following wind parameters would apply:

- Structure Importance Level 3
- Design working life 25 years
- Wind Region B2
- Annual probability of exceedance 1/500 years
- Annual probability of exceedance for serviceability 1/25 years

- Ultimate regional wind speed 57 m/s
- Serviceability regional wind speed 39 m/s
- Working wind speed 46.5 m/s (167.5 km/h)

Without the original wind design data from the original designer, it is difficult to compare current wind design data with that for which the tower has been designed. It is assumed that the appropriate wind loads were applied to the structure at the time the design was carried out. However, if the above wind parameters do not correspond to the actual parameters used in the design of the tower, then changing the wind region to a more benign A0 classification for comparison yields the following:

- Structure Importance Level 3
- Design working life 25 years
- Wind Region A0
- Annual probability of exceedance 1/500 years
- Annual probability of exceedance for serviceability 1/25 years
- Ultimate regional wind speed 45.0 m/s
- Serviceability regional wind speed 37.0 m/s
- Working wind speed 36.7 m/s (132.3 km/h)

There have been three tropical cyclones that have tracked close to the Biloela area. These were the following and the extreme category, maximum sustained wind speed, and maximum wind gusts are noted with each. Note that the extremes are the peak estimated values as provided by the bureau of meteorology and not in the location of the Callide Power Station. These are as follows in order of occurrence:

- **Tropical cyclone Oswald**
  - 22nd January 2013
  - Maximum category 1
  - Maximum sustained wind speed 65 km/h
  - Maximum wind gust 140 km/h
- **Tropical cyclone Marcia**
  - 20th February 2015
  - Maximum category 5
  - Maximum sustained wind speed 205 km/h
  - Maximum wind gust 295 km/h
- **Tropical cyclone Debbie**
  - 28th March 2017
  - Maximum category 4
  - Maximum sustained wind speed 195 km/h
  - Maximum wind gust 263 km/h

As can be seen tropical cyclone Marcia was the worst of the three noted above. It is reiterated that the wind speeds quoted above are peaks during the cyclone event and not that at Callide.

Further wind speed data has been acquired from the Bureau of Meteorology regarding wind speeds in the Biloela area and is included in Appendix D – .

After cyclone Marcia had tracked through the Biloela area, Frost Engineers conducted external inspections of the cooling and prepared a report dated 28th February 2015. In this report, cyclone Marcia was mentioned, and the report comments that during the cyclone, the Biloela area had experienced wind speeds of approximately 99.6 km/h (27.2m/s). This lower than the working wind speeds noted above of 167.5 km/h for wind region B2, and 132.3 km/h for wind region A0. The point of this is that had the cooling towers been designed for either one of those wind regions, and had normal member erosion occurred, then after 21 years of operation under "normal" operating conditions the tower would still be adequate for that level of wind load, albeit ready for refurbishment. Additionally, there have been no records of cyclones in the area since the last recorded in 2017, being tropical cyclone Debbie in March 2017.

Refer also to Section 7.3.2 for the discussion regarding the wind speeds on the day of the collapse.

8.4.5 Cooling Tower Bracing Configuration

The configuration of the cooling tower lateral and longitudinal bracing has been described in previous sections. As was noted there were sections of where individual cells do not have longitudinal diagonal braces, but instead rely on the longitudinal girts to transfer longitudinal forces to cells where there are diagonal braces. Similarly with the transverse braces, the end wall and cell divider wall frames do not have diagonal braces, but instead rely on floor diaphragm action from the fan deck floor and the hot water basin. While this would not be considered to be a design flaw, it makes the structure more flexible in order for lateral and longitudinal load transfer to take place. This is exacerbated by the dynamic actions of the mechanical equipment, and further exacerbated by the erosion of the members in which connections loosen. With frequent retightening of the connections this would be ameliorated, however, with accelerated chemical erosion this would be difficult to manage.

8.5 Root cause – Conclusion

The unfavourable water chemistry is considered to be the root cause of the failures. The problem with the water chemistry are the high levels of Free Residual Chlorine and pH. The high chlorine residual and high pH occurred simultaneously and has been prevalent long periods and likely for the life of the towers.

Considering the age of these cooling towers of approximately 20 to 21 years the following comments are made:

- The advanced chemical erosion has made the defects in the timber prematurely significant. Whereas in a timber cooling tower of similar age, the timber would not have eroded to the extent that defects such as knots would have resulted in being significantly weak spots in members. It could be expected that there may be an isolated member or members that become of concern which could be safely repaired or replaced.
- While regular retightening of the connections could be carried out, there would be a limit to the number of times this could be done with the loss of and the softening of the outer layers of the timber members due to the accelerated rate of chemical erosion. This is further exacerbated

by the relatively small size of the washers which has the effect of compressing into the soft timber surfaces.

- Loosening of the bolts would be exacerbated by the vibrations in the tower due to the operation of the mechanical equipment, and further exacerbated when items such and the fan wearing unevenly creating additional out of balance forces. This ought not to be significant in a structure where connections not compromised by excessive erosion.
- The bracing system and the resulting additional flexibility of the structure is not of itself an issue, but in a structure with thinning members and loose connections it exacerbates issues with loose connections, timber defects, creating a loop in which loose connections allows more flexibility, and more flexibility allowing further loosening etc.

8.6 Root Cause Analysis Matrix

Callide C Power Station
Cooling Tower 3
Root Cause Analysis Matrix

	Timber Erosion Mainly chemical erosion observed and previously reported.	High levels of chlorine and pH for long periods from 2010 to 2019. Cl 4ppm and pH 8 typical.	Cl concentrations together with high pH is damaging to timber surfaces causing loss of member cross section.	While there are many factors that are relevant, water chemistry is recurring as common to the question of structural adequacy. The cooling tower has stood for twenty years with timber that is questionable with respect to defects souch as knots. Moreover the erosion seen in the wet area is in stark contrast to that in the drier plenum area . The main difference between the two zones is that the wet zone experiences constant chlorine laden water while the plenum area does not. It is only now that chemical erosion has advanced to the point it has that the structural adequacy is questionable and/or lost in the wet zone.
	Many columns observed to be bent, or buckled in all cells. Some observed to be broken.	Columns observed to be chemically eroded, loss of cross section and bent around knots.	A column which is bent experiences secondary bending limiting axial load capacity.	
Callide C Power Station Cooling Tower 3 Collapse of Cell 1 South Collapse of Cells 8 and 9 North	Fill grids supported on timber D-moulds. These have eroded away substantially and dropped fill thoughout the tower.	D-mould have suffered chemical erosion. The majority have dropped with few remaining.	Additonal weight on girts lower down potentially over stressing these and also causing additional column moments.	
	Fill grids also supported on girts with metal staples. Surfaces of girts have been chemically eroded causing loss of grip.	In many areas staples have become loose and fill has collapsed onto lower tiers adding load to girts.	Additonal weight on girts lower down potentially over stressing these and also causing additional column moments.	
	Bolt hole sizes have increased due to chemical erosion. Connections have become loose compromising lateral support.	Columns loss of lateral support means their axial load capacity is significantly reduced when coupled with sectional loss.	If columns are carrying their normal loads with increased effective lengths they buckle accordingly.	

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Appendices

Due to the volume of material, all appendices have been placed on a portable hard disc drive.

Appendix A – Catalogue of Photographs and Videos

Appendix B – Existing Drawings

Appendix C – Water Chemistry Data

Appendix D – Not used

Appendix E – HartzEPM Structural Analysis and Member Assessment

Appendix F – HartzEPM Condition Assessment Report

Appendix G - Cooling Tower Inspection Unit 3 Callide C Power Station by Sigma Process Solutions 2002

Appendix H - Cooling Tower Inspection Unit 3 Callide C Power Station by Sigma Process Solutions 2006

Appendix I - Callide C3 Cooling Tower Inspection by Sigma Process Solutions 2010

Appendix J - Callide C Cooling Structural Modelling and Assessment Report 2014

Appendix K - Inspection Report – Wet Area by Marley Flow Control 2022

Appendix L - Inspection Report Rev 1 by Marley Flow Control 2022

Appendix M – Inspection/Findings Report by CS Energy October 2012

Appendix N - Extracts from the Water Treatment Plant Manual

Appendix O - Callide Power Project Unit Nos. 3 & 4 Plant Manuals

Appendix P - Report titled CS Energy Assessment of Cooling Tower Elements

Appendix Q – Bureau of Meteorology Weather Data

Appendix R – Review of Previous Reports

Appendix S – Final Supplementary Letter of Instruction